**PCT: The Negative Feedback Control Paradigm**

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**1. Behavior as Control**

You see someone with a finger on a button beside a door. You ask yourself: “What is he doing?”, and the answer seems simple: “He’s ringing the doorbell”. This is “the outsider” point of view. But is that what the person thinks he is doing? Maybe he thinks he is trying to get someone to open the door. Maybe he thinks he is visiting Aunt Mary. Maybe he thinks he is trying to add to the expected vote total for his preferred candidate in an upcoming election. Maybe he thinks he is making some money by delivering pamphlets. This is “the insider” perspective. The outsider perspective may not provide a correct prediction of how a person would describe his actions. Both views are needed for a complete picture, but the insider view is the one that PCT emphasizes.

This illustration may seem to belabour the obvious, that in everyday life, people have purposes, and that the purpose is what the person is “doing”. Equally obvious is that another person usually cannot determine a person’s purpose by observing the person’s actions. What is perhaps less obvious is that a purpose can be represented by a “what”, a “why”, and a “how”.

In the doorbell illustration, the first “what” that an observer might guess is “he is ringing the doorbell”. Its “why” is problematic, but its “how” is “by pressing the doorbell button”. However, even this “how” has its own “What-why-how” pattern. “What” is “seeing and feeling my finger pushing the button”, “why” is “to see myself pressing the button” and the “how” is “by moving my hand and arm to the appropriate place” (Figure 1).

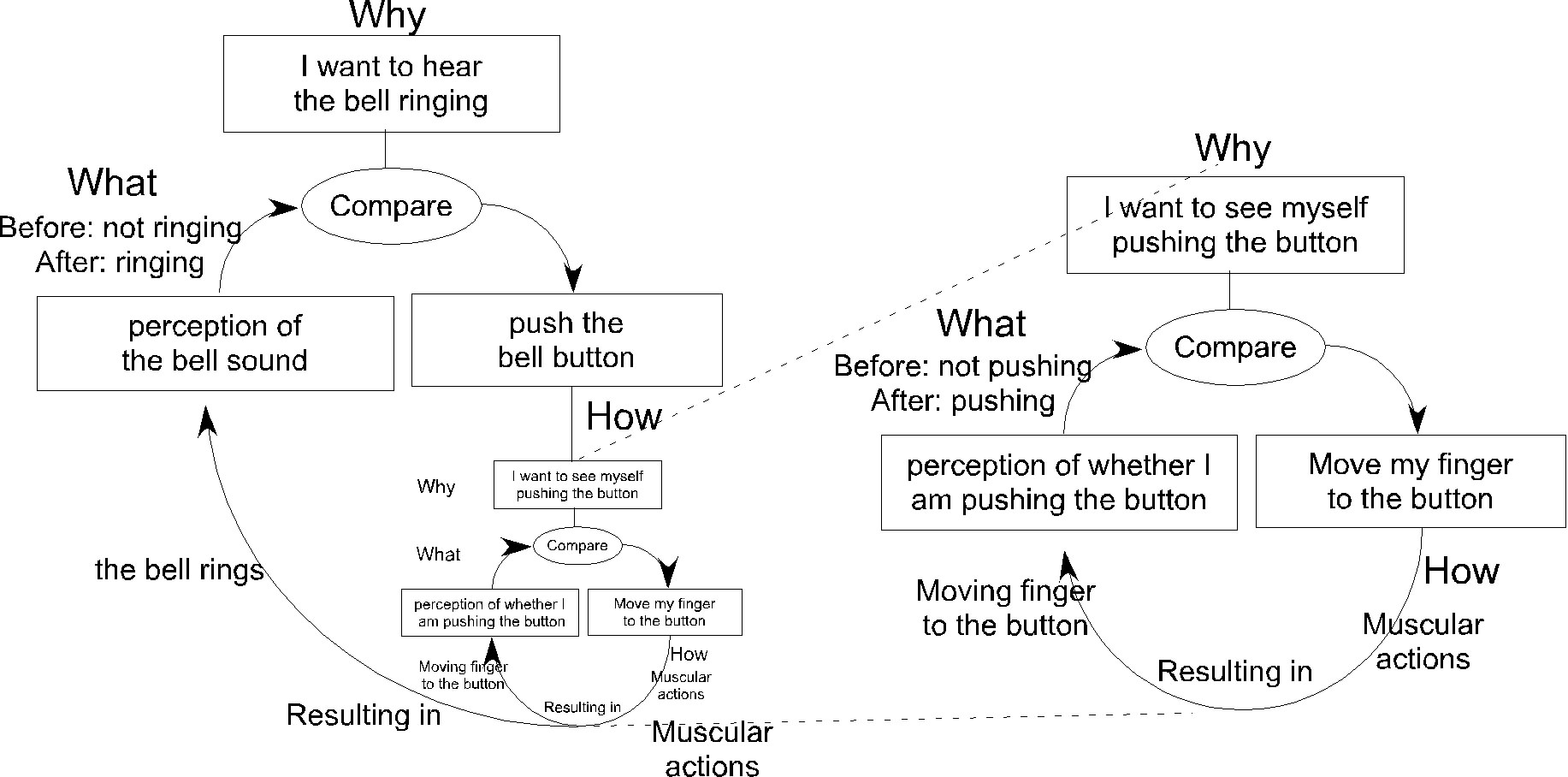
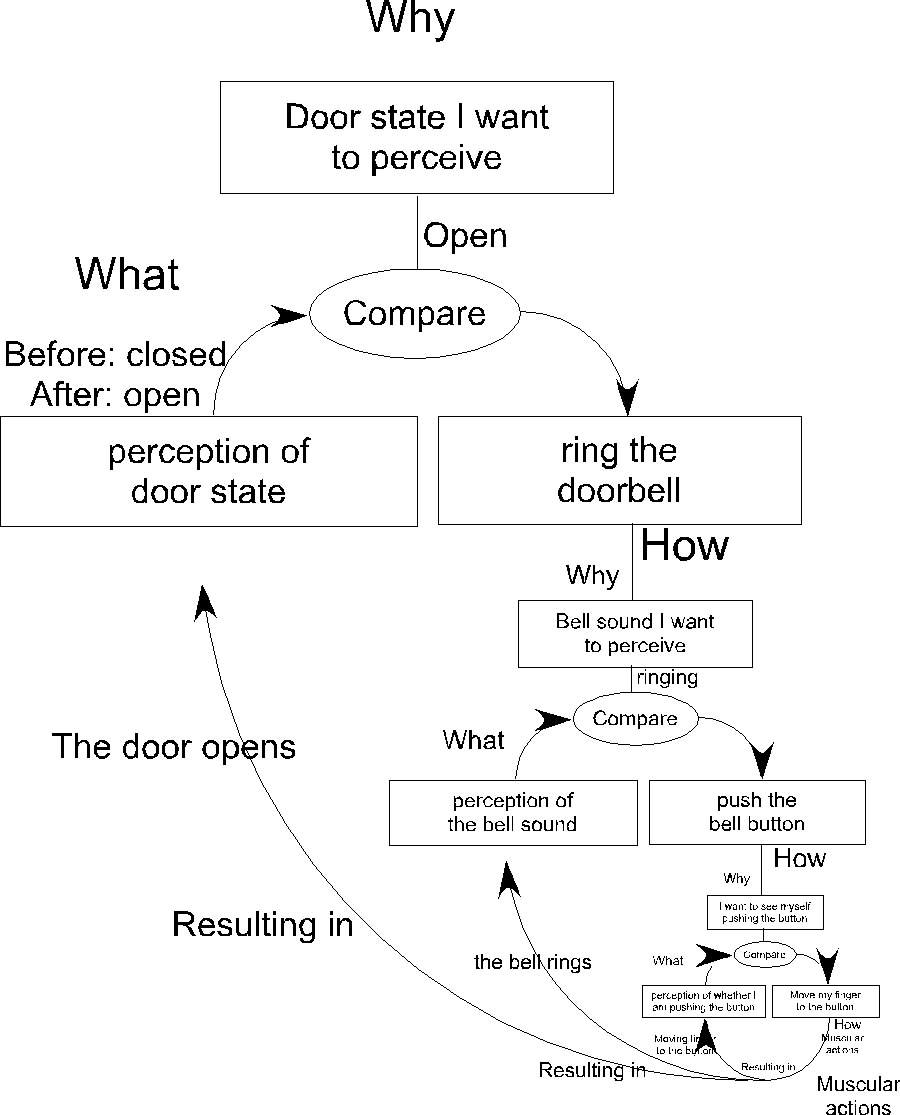


Figure 1. The person wants to hear the doorbell ringing, but cannot (left), so wants to see and feel a finger on the button (right). When the finger is on the button, the bell rings and the person hears it.

If our observer looks at the possible “why” of pressing the doorbell, another pattern of “what-why-how” emerges, for which pressing the doorbell is the “how”. “What” might be “to get someone to open the door”, or put better “to see someone open the door”.

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*Figure 2. Why did the person want to hear the doorbell ringing? So that someone would come to open the door, which is not yet open.*

And so it goes. Every “what someone is doing” is part of a “what-why-how” structure. In every case, “why” is because some state of the world is not as the person would like it to be, and “how” is a means of making the world a little or a lot closer to what the person would wish.

All of this sounds self-evident, if not scientific. But it can be scientific. The “what-why-how” complex describes “control”, bringing some condition toward a desired state and maintaining it there. That is the engineering definition of control, and the thesis of this paper is that control is what living organisms do.

Since the early 1950s, a basic model of behavior (first published in 1960) has been under development. It was named Perceptual Control Theory (PCT) by members of an interdisciplinary study group that first came to its support during the 1980s. While the theory is quite simple, it departs sufficiently from consensus to have remained outside the mainstream of scientific thought. This paper is a summary of the PCT paradigm as it exists today. It is also a suggestion that PCT has now progressed far enough to claim its place under the sun.

**2. How Control Works**

The basic thesis of PCT is not difficult to describe. Rather than being the final product of prior causes, the behavior of organisms is understood to be a collection of means to ends, as suggested in Figures 1 and 2, the ends being control of various states of the local environment and ultimately of the biological states of the organism itself. This requires that the basic organization of a living system be of the kind that is capable of controlling rather than simply responding to inputs or generating patterned outputs (though both of those modes of action can be incorporated into the model, as discussed below). Furthermore, because actions are directed so as to create and maintain specific conditions of the organism and its environment, the logic of this kind of system is circular, cause and effect being subtly rearranged. What appear at first to be ordinary physical consequences of motor activities are seen as goals actively sought and defended against disturbances.

It is the capacity to control that, in PCT, marks a living system as different from other natural arrangements of matter and energy. The kind of control system described in PCT can have purposes of its own -- that is, it can spontaneously select as goals future states of the world around it and alter its own behavior to achieve and maintain such goal-states. It can automatically, without external guidance or instruction, adjust its actions to oppose most effects of random and otherwise unpredictable disturbances quickly and accurately enough to prevent their having any important effects. It can control hierarchically; that is, it can adjust one set of goals as a means of achieving higher-order goals. It can control many different variables in parallel at the same level of abstraction, and by that means control multiple variables of a higher order at the same time. It can learn and adapt: it can alter aspects of its own organization in ways that matter to it less in order to control variables that matter to it more.

In short, the PCT model departs substantively from what has been considered a scientific understanding of organisms for over 100 years. In the past there has been an organized effort to present organisms as simply one more possible arrangement of matter and energy, subject to the same laws of physics and chemistry as any other arrangement. While PCT does not require any violation of the laws of physics and chemistry, it is specifically concerned with emergent laws that grow out of particular physical and chemical organizations.

As has long been known, organisms have the ability to use the orderliness in the world around them as a means of increasing their own orderliness. They can impose order on their local worlds at the expense of order elsewhere. Control does not imply totally arbitrary intervention in the processes of the environment, but it often seems to do so, in that the organism and its world both behave quite differently when the organism is in control. A car left to steer itself would soon run off the road or collide with another car, with only momentum, gravity, wind, and potholes affecting it. But add a driver to the car, and it -- along with a huge number of other cars like it -- stays on the road, in its proper lane, for hundreds of miles and travels to a destination with high reliability. This is a highly improbable outcome when control is not taken into account. With control added to the picture, the same outcome becomes highly probable.

The PCT model departs from conventional understanding in another way. Rather than depicting behavior as a mechanistic outcome of external forces acting on an otherwise inert "preparation", the primary point of view is that of the organism, not that of an external observer. The observer's subjective experience is as much a part of the model as any "objective" properties of control systems. This is the underlying reason for calling this theory *perceptual* control theory.

One of the more obvious facts is the fact that the external world is known to organisms only as it is represented inside them by electrical and chemical signals. In PCT, these internal representations are known as “perceptions”, whether or not they are present in consciousness. That limitation applies not only to organisms in the wild and in the laboratory, but also to the scientists who study them. Clearly, what we experience as the world around us must exist in the form of internal perceptions that only conjecturally and provisionally correspond to distinct entities outside us.

If all that we experience is in the form of internal perceptual signals, which is what neurology tells us, then all we can control is in the same form. In the course of controlling our own perceptions, we act on the world and alter it, so others can see us controlling aspects of their worlds, too. But we can never directly know what we are doing to that outside world as we control what we experience of it. To know that, we would have to experience the outer world without first filtering it through the senses. So far, that does not seem possible.

Figures 1 and 2 showed specific hypothetical examples of “What” perceptions that might be controlled as a small part of “visiting Aunt Mary”. One of these perceptions was that the door be seen to be open. It was not open in the example, but if it had been, with Aunt Mary standing in welcome, then no further action would have been required. As it was, the desired state of the perception differed from the actual state. To reduce or remove such a deviation required action — the “How” of the control system, and this “How” becomes the “Why” for wanting to hear the doorbell ringing. Equally, it could be the “Why” for the person wanting to see and hear himself knocking at the door, or going to an open window and shouting “Hello”.

Generically, every control system has a “What” perception for which there is a desired “Why” state, and a “How” means of acting so as to alter the state of that perception (Figure 3). In most cases, the means of acting is to supply a “Why” to supporting control systems.

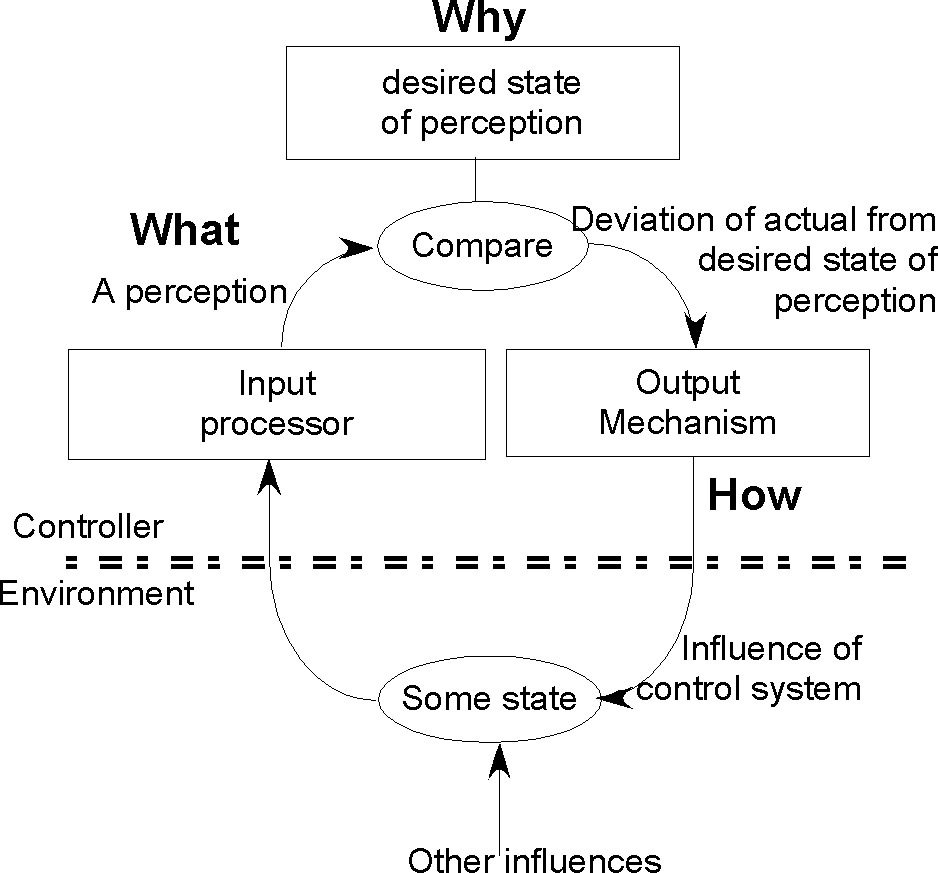


Figure 3. A Generic control system. The perception (“What”) is influenced both by external influences and by the output mechanism (“How”) of the control system. “How” usually supplies “Why” to supporting control systems rather than acting directly on the environment. The control system’s output brings the perception near its desired state (“Why”) no matter what external influences may disturb it.

The PCT view of human behavior and existence seems in better agreement with individual experience than the views that went before it. A clearly mechanistic model of behavior that can be implemented and studied as a computer simulation also explains how human beings can have goals, intentions, preferences. and desires, experiences sometimes thought to be figments of the imagination or simply errors of interpretation. The objective, engineering approach to behavior is brought together in PCT with subjective experience to create a richer picture of human existence than previously available.

The question naturally arises: if PCT has been building into a coherent model of control for 60 years or so, why doesn't everyone know about it? The answer may be that everyone does know about it, but that it has been misinterpreted and mischaracterized so much that its real potential has gone unrealized.

**3. The premature end of PCT**

The idea of negative feedback control was formalized by engineers in the 1930s, after having existed in many recorded forms since about 250 BC. “Negative feedback” should not be confused with criticism, which is sometimes called by that name. In the control sense, “Positive feedback” increases the discrepancy between the desired and actual state of the controlled variable, while “negative feedback” reduces the discrepancy. By the 1940s it had given rise to the automation revolution of the World War Two years . The resemblance of negative feedback control systems to living systems brought forth cybernetics, and a revolution in the life sciences began to gather momentum in the late 1940s and early 1950s.

Within another ten years, the latter revolution was essentially dead; negative feedback control was abandoned as a model of living systems by its original proponent, the prominent cyberneticist W. Ross Ashby.

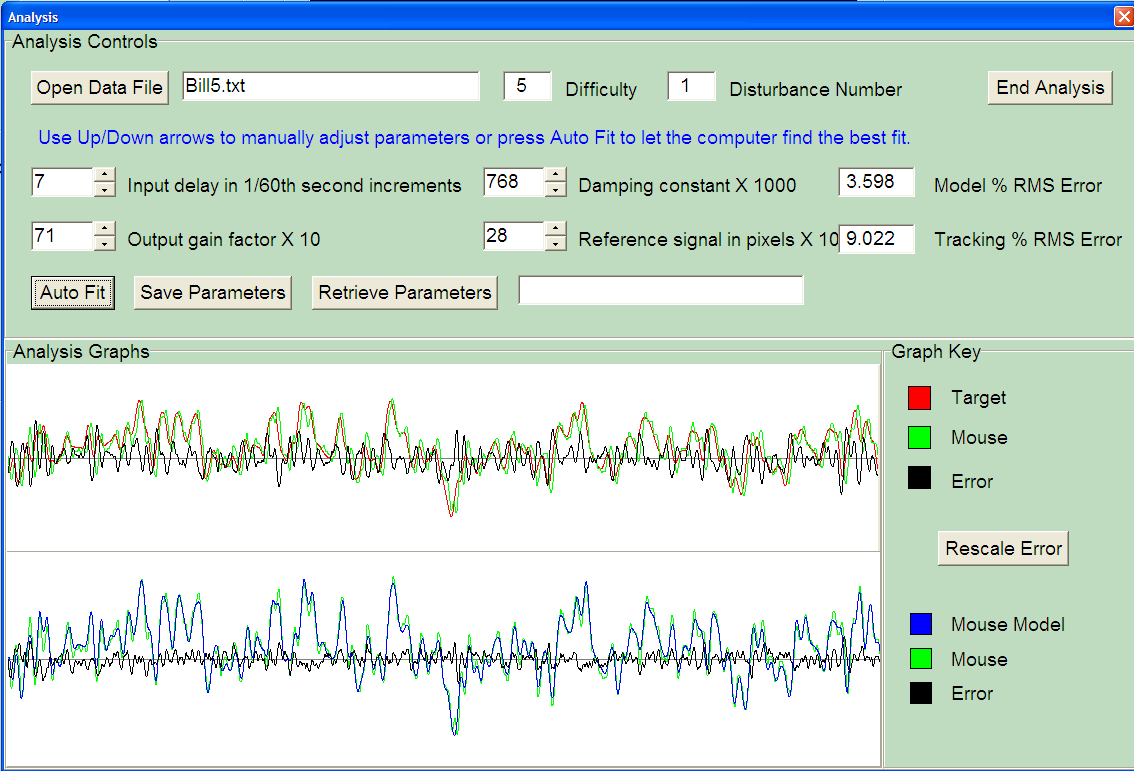
In its place Ashby and others offered a different idea: the idea that organisms analyze the environment, determine what actions would be needed to produce desired results, and then issue the commands necessary to make the muscles generate those actions. This represented a return to the original idea of brain operation offered by Sherrington in 1906, in which the cerebral cortex formulated general commands that were then elaborated, level by level, into the detailed commands reaching the "final common pathway" to produce organized behavior. Ashby argued persuasively that this more complex design would operate faster than the negative feedback control system, eliminating delays, and would be more accurate since it did not need to allow any errors to occur. It could even, he proposed, anticipate disturbances and generate actions to oppose them at the same instant they occurred.

From that time onward, negative feedback control has been regarded by many as old-fashioned, having been replaced by a more modern kind of control system that could achieve optimal control, the most accurate and swift control theoretically possible, at the least cost. Since evolution would naturally have shaped organisms to operate in the best possible way, it was assumed that this model should also be used to explain the behavior of organisms, at least those with sufficient complexity to carry out the required analyses in real time.

There was only one drawback to this advance in control theory when used as a model of organisms: real organisms seldom behave that way. It is, in fact, easy to design artificial control systems that control much better than organisms do. To make a model that behaves as much as possible the way a real person does in, for example, a tracking task, it is necessary to resurrect the negative feedback control model. Ashby had the right idea the first time, and threw it away.

In the following demonstration of a negative feedback control model (Powers 2008), a person uses a mouse to make a cursor track a moving target for one minute. Data are sampled 60 times per second. The data for the experimental run are shown in the upper plot of Fig. 4. The red trace shows the target movements; the green trace shows the mouse and cursor movements. The black trace shows the difference between target and cursor -- the tracking error.

Even to the naked eye, it's clear that there is a time delay between target movements and cursor movements. The delay is not removed by anticipatory mouse movements as Ashby claimed would happen. In the upper part of Fig. 4 the results of fitting a negative feedback control model to the data are summarized; the best-fit delay in the model's response is 7/60ths of a second, which is 7 frames of the computer display running at 60 Hz, or 116 milliseconds. That is how far behind the target movements the participant is moving the cursor, on average.



*Fig. 4. Analysis of human tracking run and fit of negative feedback control model to the data.*

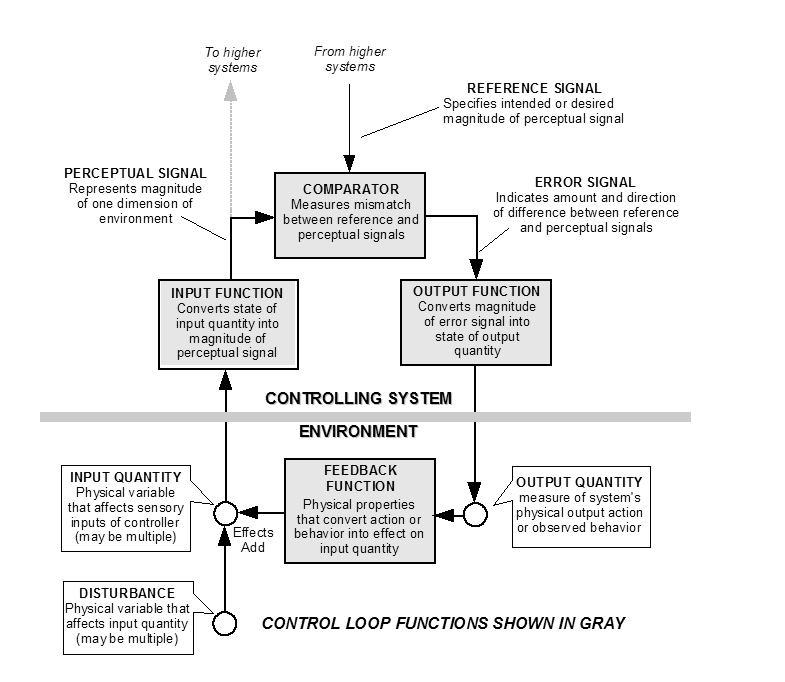
In the lower plot, the model's simulated mouse movements (blue) are compared with the real mouse movements (green). They are very nearly identical, with the same delay relative to the target movements. The mean difference between model and real behavior is 3.6% of the range of target movement. In this run, the target movements are rapid enough (maximum difficulty) that the tracking error is 9% of the target range; the model fits the real data well within the tracking error, showing that the model is making similar mistakes. The delay is real.

Aristotle once declared that men have more teeth than women have. This proposition was based on philosophical principles and arguments, experimentation being considered an inferior approach in his time. However, real men do not have more teeth than women, whatever logical reasoning may say. When we look at actual human data, we find that the analyze-calculate-execute idea is also mainly a product of logical reasoning.

**4. Simulations and models**

The model mentioned above is part of a method of analysis that originated in the "operations research" of World War II and the field of engineering psychology that grew up right after the war. Like PCT itself, it is basically a simple idea. But also like PCT, it proves to have far more power as an aid to understanding than its simplicity seems capable of providing. It is important to understand both the

simplicity and the power of a model constructed in this way and we will take some time to study that here. Figure 5 develops Figure 3 to show a more complete generic model of a single control system, the building-block of the hierarchy of control systems that constitutes PCT.



*Fig. 5: The basic organization of a negative feedback control system*.

Applied to the tracking task, the model assumes that inside the participant, there is some kind of neural signal **p,** a perceptual signal (the “What” of Figures 1 –3) that literally and quantitatively represents the vertical distance between the target position **T** and the cursor position  **C.** The varying target position acts as a disturbance to the distance, which is the input quantity in the diagram.

The model also assumes that there is a delay involved in going from the perception of target and cursor to the signal representing the distance between them. If the delay is **tau** seconds, the working perceptual signal at time **t** actually represents the target to cursor distance at some prior time, **t - tau,** so the equation as used in the model is actually

**1. p(t) = C(t - tau) - T(t - tau)**

The basic negative feedback control system receives a reference signal (**r**) from elsewhere which specifies the intended or desired magnitude of the perceptual signal. The reference signal is the “Why” of Figures 1-3. The "comparator" emits an error signal **e** indicating the magnitude and sign of the difference between **r** and **p (**the time index is omitted but understood):

**2. e = r - p**

The output function produces the “How” of Figures 1-3. The best model for the output function shows mouse velocity as proportional to the error signal. A positive error (perception less than reference) causes an upward velocity of the mouse and cursor (**Vcursor)** proportional to the error by a gain factor:

**Vcursor = gain\*e**

The next position of the cursor is the current position plus the velocity times the duration (**dt**) of one iteration of the program:

**3. C(new) = C(old) + Gain\*e\*dt**

And that is the totality of the simplest version of the model: a set of three simple equations or program steps which, repeated over and over with the same pattern of target positions that the human participant experienced, duplicates the participant's actions within 4.0% of their peak-to-peak range, in great detail. If we add one more term to **3** to add a little damping to the controller, the error is reduced to 3.6% (as shown in Fig. 1), a small but consistent improvement.

That is a remarkable result, especially considering that we are ignoring possible nonlinearities such as the Weber-Fechner law, possible noise in the system, changing angles at the joints, and many other possible causes of poor performance of a simple linear model. Examine the lower plot of Fig. 1, showing the mouse or cursor positions of the real person and the model. The black trace representing the difference between model and person consists mainly of small high-frequency oscillations that are too fast for this system to suppress (the subject, WTP, has congenital "essential tremor"). Within the bandwidth of good control, the errors must be far smaller than the 3.6% to 4.0% of the range of target movement that is measured.

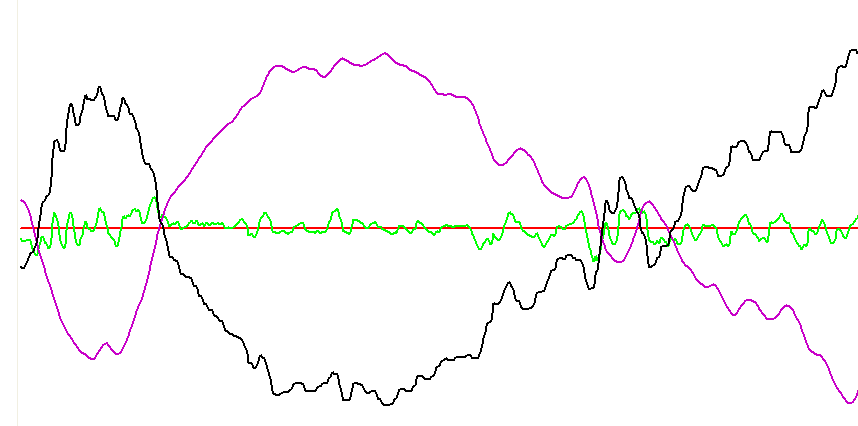
This point is worth emphasizing. In the general case, if control is good, the behavior is very little dependent on the specifics of the internal circuitry of the control system. Fitting the model to the data observable from outside the subject (the locations of the target and cursor, together with the experimenter’s knowledge of the disturbance) permits reconstruction of properties of the feedback loop such as loop delay and gain, but not of individual elements within the subject. We shall return to this point when we discuss the “behavioral illusion”.

**A set of demonstration programs**

The tracking experiment is a legacy from the engineering psychologists and physiologists of the 1950s. It is still useful, but its use as a common demonstration has left an impression that PCT can explain only tracking behavior. In fact the principles of PCT can be applied to any behavior at all, as illustrated by the variety of applications described in a Special Issue of the International Journal of Human Computer Studies devoted to PCT ([date and volme]) but progress is slow and the most reliable experiments are simple ones that can be implemented on a computer.

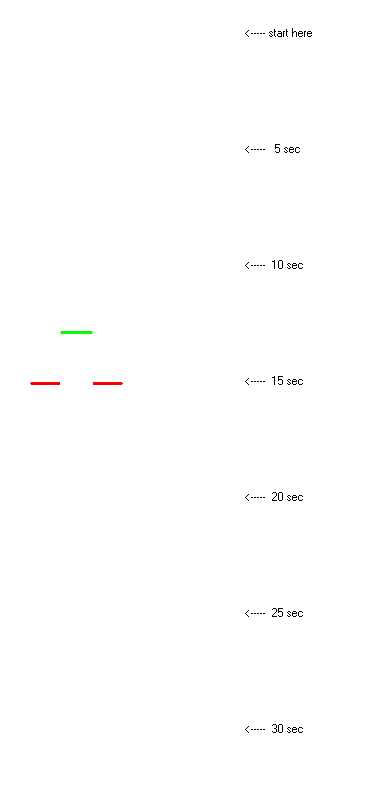
One set of them can be downloaded from http://www.billpct.org/PCTDemo3.exe to run on a Windows computer. The reader is advised to do so now because actually running the demonstration is probably one of the most effective ways of understanding what PCT is about. Click on "demo1.exe" to start the program. '[Note -- the file name will be changed to avoid clashing with LCS3 programs and only an executable file will be needed]

The first three demonstrations explain how the mouse affects the cursor on the screen and the way numbers are used to determine positions. The first control task, step 4, is a tracking task: "compensatory" tracking in which the goal is to hold a cursor at a stationary position against an invisible disturbance. After the experimental run is finished (it takes 30 seconds), a graph of the results appears:

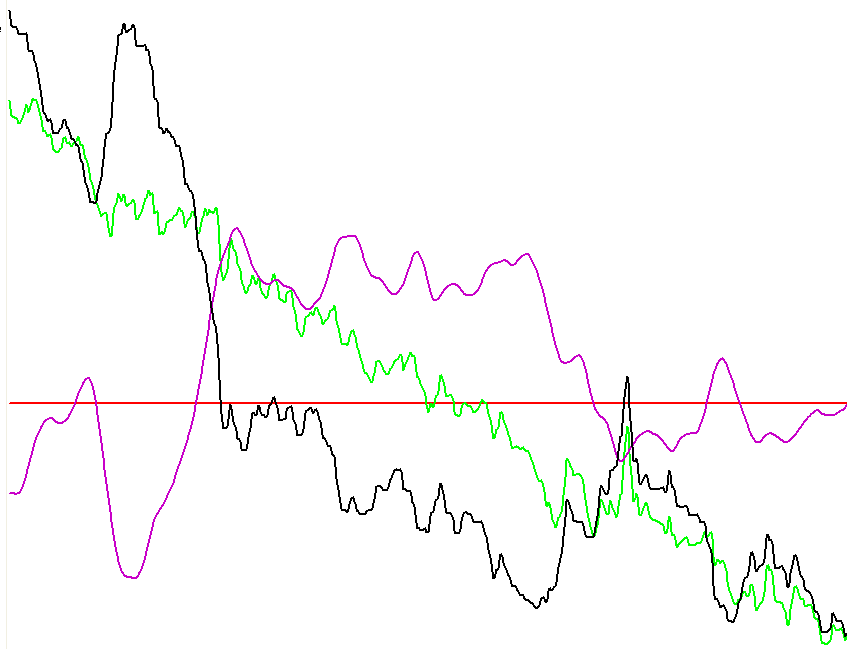


*Fig. 6: Compensatory tracking. Black line shows mouse movements, green line shows cursor movements. Target position is horizontal red line. The purple trace shows an invisible disturbance that varied during the run: mouse position relative to the centerline is equal and opposite to the disturbance at all times down to a moderate level of detail.*

The main point of this demonstration is the way the participant moves the mouse so as to cancel the effects of an invisible disturbance (purple line) on the cursor, where the green line shows the cursor position during the 30 seconds of the experimental run (from left to right). There is no stimulus on the screen that corresponds to the purple disturbance plot, and clearly cursor position represented by the green line would be of no use in indicating the magnitude or direction of the disturbance. Thus there is no basis for claiming either that the mouse movements were a response to some varying stimulus, or that the participant's brain was planning the actions needed to keep the cursor near the target. The information required to carry out either of those modes of action is simply not available to the participant. This is emphasized by the fact that in these demonstrations, a new disturbance pattern is generated each time any step of the demonstrations is re-run. *There is no pattern of behavior to learn: what is learned is control.*

In demonstration 5, the participant is told to ignore the red target line and make the cursor descend from the top to the bottom of a range marked off in seconds, trying to make the cursor pass each mark on schedule. A disturbance is still being applied to the cursor, so the participant must move the mouse so as to resist the effects of the disturbance and keep the cursor descending at a uniform rate.

The appearance of the screen at about the 13-second mark is shown to the right (the participant is told to ignore the red target lines). The participant is counting off the seconds, trying to make the green cursor move down so it passes each arrow at the time marked beside the arrow. The result is shown below left:



The black trace of the mouse movements shows that they do not resemble either the disturbance pattern in purple or the pattern followed by the cursor in green. The result when the mouse movements are added to the disturbance is the requested slow movement of the cursor from high to low, as shown by the diagonal green line. But again, it is clear that neither responses to any visible stimulus nor actions planned in advance and then executed could possibly account for this result.

**5. More about Perceptual Control Theory**

Multi-layer parallel control

The behavioural illusion

Testing for controlled variables

**5. Learning from computer demonstrations [maybe that is the above Simulations and Models section]**

**5. “Responding to Stimuli” and generating patterned outputs**

[I think Bill should write this section. Or I will if I get the time. This section should address the idea that PCT doesn’t apply to certain kinds of behavior, like that which occurs in psychological experiments, because it is open loop. Behavior tha looks open loop comes in two flavors; behavior that seems to be a response to stimulua and behavior that seems to be generated as a programmed pattern of movements. The “response to stimuli” behavior is seen in psychological experiments. It looks like a response to stimuli but PCT suggests that the is a purpose – a controlled variable – involved. Programmed output behavior is seen in everyday life; people who seem to be producing patterned outputs spontaneously. But PCT suggests that this behavior also has a purpose; the controlled variable is the patterned output that you see, produced by variable means that you don’t see. This closed-loop view of the apparently open-loop nature of S-R and programmed response behavior can be tested using the test for the controlled variable (which was described above, right?).

**8 Application to computer-human interfaces**

**9. Application to Psychotherapy**

PCT has been applied to individual therapy and the therapy is called “Method of Levels Therapy.” A person enters therapy because there are significant life experiences which are not under control to a satisfactory degree, which results in the person not functioning well. MOL Therapy works on the idea that there are error signals within the person, which causes body stress and which causes the experience of strong negative feelings/emotions. In MOL Therapy, the problems with functioning and the negative symptoms are viewed as a side effect of a person’s problems with controlling important life experiences. They are not therapy goals per se. When a person regains control of important life areas, functioning is restored and symptoms remit.

The normal change process within the person, namely, reorganization, is not reducing the error signals. Theoretically, in PCT, this can happen when there are internal conflicts between control systems at the same level, which results in a person’s awareness focusing on the wrong part of the perceptual control hierarchy. Awareness on the right areas of the perceptual control hierarchy is considered necessary for change to happen within a person. The main job of the therapist is to help the person resolve the internal conflicts so that a person can redirect awareness and see things in a new, different way. When this happens, the normal change process becomes “unstuck” and the person can make changes which reduce the error signals. The person regains adequate control of the life experiences and therapy becomes unnecessary.

The selection of “problems” within MOL therapy is done by the patient/client, not other people, including the therapist. The person engages in a discussion of a problem experience (a “foreground” topic), and the therapist helps the person keep focused on present-time experiences as the experience is discussed. The therapist helps the person become aware of all the associated experiences as the problem is discussed, especially experiences at a higher level (“background” topics). This is called “going up a level” and the person discovers a higher level perception (the “why”) behind the problem experience. The higher level perception becomes the new topic and the process is repeated.

MOL Therapy has been utilized by therapists in the USA, England, Scotland and Australia. The reader is referred to Carey ( ) for book length descriptions of MOL Therapy. The reader is referred to Goldstein ( ) for case studies in the USA using MOL Therapy involving Anxiety Disorders. Mansell ( ), and Tai ( ) have successfully applied MOL Therapy to cases of severe mental health problems such as Bipolar Disorder and Schizophrenia.

Research involving MOL Therapy is at the beginning stages and looks promising. MOL Therapy is derived from PCT, but can be seen to have features reminding one of Client Centered, Cognitive Behavioral, Experiential and Psychoanalytical Psychotherapies. Work to extend MOL Therapy to marriage, group and family therapy is starting. MOL Therapy emphasizes the role of the client/patient in making changes and emphasizes the normal change process within in each person. The unpredictability of the change follows from the nature of reorganization.

**10. Summary and take-away points**