

# Perceptual Control Theory:

## A model for understanding the mechanism and phenomenon of control

**Comment:** The new beginning is excellent. Also, it's nice to have my name on a paper to which I have made virtually no contribution at all. Maybe that's the way for me to get published;-) rsmarken

ControlParadigm20101013\_1703PST.doc compared to ControlParadigm20101011\_1004PST.doc  
Printed to PDF with Document properties, comments, drawing objects and hidden text but no field codes.

Carey, Goldstein, Marken, Nevin, Powers, Taylor:

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**Comment:** This paper is now 14600 words long, - willampowers99

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The phenomenon of control is integral to psychology. Even a cursory glance through databases and journals reveals a staggering number of references to control. Terms such as *perceived control*, *locus of control*, *cognitive control*, *subjective control*, and *vicarious control* speak directly to the phenomenon. If implicit references to the phenomenon are included, such as *self-determination*, *agency*, *learned helplessness*, and *emotional dysregulation*, the number of references grows exponentially.

Recognition that control has an important place in the process of living, therefore, is undisputed. Curiously, though, while the phenomenon of control is often front and center in research programs, the same cannot be said for the mechanisms of control. For the most part, investigations into the phenomenon of control have proceeded in the absence of a clear understanding of how control works.

In many ways, this puts the cart before the horse. We propose that an understanding of the mechanisms that produce the phenomenon of control should inform any research investigating control. In particular, we have found (and will show here) that a testable model of how control occurs clarifies the diverse interpretations of the phenomenon that have been published, some of which must be misconceptions insofar as they contradict each other, as well as explaining its relevance to so many other important concepts, such as cooperation and conflict. An appropriately rigorous standard for such a model is a requirement to produce working simulations. Conclusions that are supported by testing the performance of a generative simulation justify a degree of confidence that cannot be accorded conceptual or statistical models of the same phenomenon. Other phenomena not usually associated with discussions of control, such as training, learning, and motivation, are also clarified.

Consider an ordinary, everyday situation. I have my finger on a button beside a door. If I pause to think about what I am doing, it seems simple enough: "I'm ringing the doorbell". But is that why I am there? Am I not trying to get someone to open the door? I am visiting Aunt Mary. That is why my finger is on the button. If you were a stranger passing by, you wouldn't know this. You might guess that I am trying to add to the expected vote total for my preferred candidate in an upcoming election, or that I am making some money by delivering pamphlets. You probably would not propose that my objective was simply "to press my finger on a button."<sup>1</sup>

<sup>1</sup>See Vallacher & Wegner (1985); Kozak, Marsh, & Wegner (2006); Marsh, Kozak, Wegner, Reid, Yu, & Blair (2010). Links to the papers are at <http://www.wjh.harvard.edu/~wegner/actid.htm>.

This illustration may seem to belabor the obvious—that in everyday life, people have purposes, that the purpose is what the person is “doing”, and that their actions are the means for doing it. Equally obvious is that one usually cannot determine a person’s purpose by observing their actions. What is perhaps less obvious is that there are three aspects to this, 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”. Although its “why” is obscure to an observer (but not to the doorbell ringer), its “how” is clearly “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 make the bell ring” and “how” is “by moving my hand and arm to the appropriate place”.

If our observer looks at the possible “why” of pressing the doorbell button, another pattern of “what-why-how” emerges, for which making the doorbell ring is the “how”. “What” might be “to get someone to open the door”, or put better “to see someone open the door”. 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, albeit anecdotal and not very scientific. But it can be scientific. The “what-why-how” complex describes “control”. This does not mean forceful dominance of people or the environment, it is a technical term of art that means bringing some particular 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. Indeed, it is what you are doing, on many levels and in many ways concurrently, as you read this paper.

This informal account of what-why-how points to a fundamental model of behavior that has been under development since the early 1950s. It was first published in 1960, and was named Perceptual Control Theory (PCT) during the 1980s by members of the interdisciplinary, international group of researchers and practitioners that have engaged with it. This paper is a summary of the PCT paradigm as it is presently understood in this community of research and praxis, including methodology, results, and applications.

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## Behavior as the means of control

The basic thesis of PCT is not difficult to describe. The behavior of organisms—their observed activity—is not the final product of prior causes. Rather, it is understood to be a variety of means to ends. The ends are manifested to observers of organisms in the way the behavior stabilizes aspects of the local environment against disturbances. From the organism’s standpoint, the ends are certain experiences (or cessation thereof) that are intended or preferred. PCT is about purposive behavior.

What, again, is “control” as used in PCT? Consider another example. I hear music. In the language of PCT, I have a reference value for how loud I like this kind of music. At the same time, I perceive the current loudness of the music. I compare the loudness I perceive with its reference value, and if there is a difference, I do something that changes the physical environment to alter the loudness I perceive.

Maybe I put in earplugs, maybe I move to another room closer to or further from the source, maybe I ask someone to turn the volume knob or turn it myself to make the music I hear louder or softer.

At the same time, other things might influence the loudness I perceive of the music. Maybe someone closes the door of the room where the music is playing, or turns the volume knob. I continuously perceive the loudness of the music, and at any time that it differs from my reference value, which may change from moment to moment, I may behave in such a way as to bring the loudness that I perceive nearer to the reference value that I currently have for it.

What we are describing here is a feedback loop, as illustrated by the diagram of the canonical PCT control loop in Figure 1.

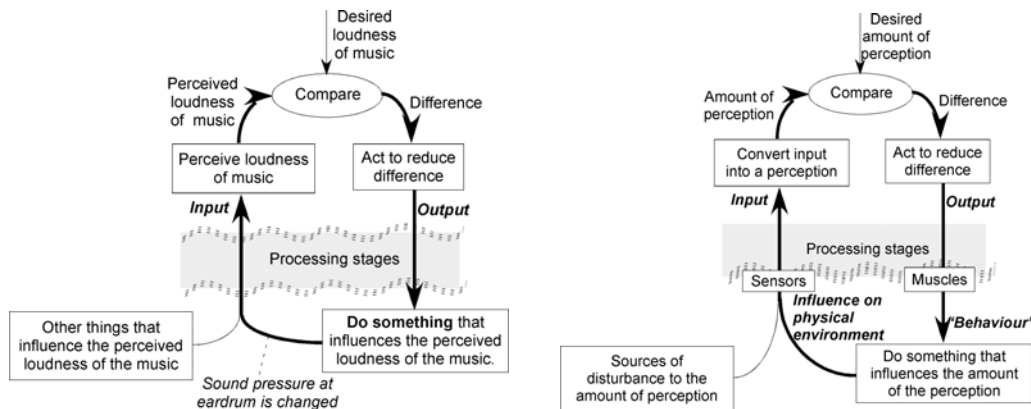


Figure 1. The canonical PCT control loop. (Left) controlling the loudness of music (Right) the generic loop. The key point is that what is controlled is the value of some perception, by means of the behaviour that influences the physical environment.

Not only is it a feedback loop, but the feedback is *negative*. In popular parlance “negative feedback” is equivalent to criticism, whereas “positive feedback” suggests encouragement.<sup>2</sup> In the original engineering meaning, however, positive feedback increases the difference between the reference (desired) amount of perception and the perceived amount, the opposite of what is needed for control, while negative feedback decreases the difference. A negative feedback control system can be designed so it can reduce the difference or error until it is at the limits of measurement (if even the smallest measurable differences are considered worth the energy needed to correct every little error). Only error-correcting or negative feedback results in control.

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Obviously, negative feedback control is not observed for every assemblage found in nature. A living system must have a particular kind of internal organization in order to be capable of controlling. A central concern of PCT from the outset has been to deduce the necessary properties of that internal organization by creating and testing generative working models of the actual behavior of individual organisms. Because behavior both results from changes and is the means to create and stabilize specific

<sup>2</sup>This usage stems from a misunderstanding when the term was taken up by the human potential movement, and has spread thence to fields such as counseling, education, and management.

conditions of the organism and its environment, causality in this kind of system is circular. What appear at first to be ordinary physical consequences of motor activities are recognized to be states of the world, as perceived by the controlling organism, which it actively seeks and defends against disturbances.

In the generic control loop of Fig. 1, we can discern the features of the two main concepts of behavior that preceded PCT. Following the path from “Desired amount of perception” through difference, output, and behavior, we have the same organization proposed by early neurologists and accepted by many modern neuroscientists and cognitive psychologists. According to this view, a high-order plan or goal is converted, step by step, into the simple or patterned behavior needed to achieve it. The other concept is seen by following the path from sensors through intervening processes (omitting the comparison) to the output and the muscles. There we have the organization known as a stimulus-response or input-output system, in which the environment causes behavior through causal paths connecting input to output. Both of these classical ideas omit the feedback path through the environment, although variations on the basic themes have been offered to take the feedback effects—incorrectly—into account. Both of these classical concepts solidified into schools of thought before engineers had discovered the right way to analyze systems having this circular kind of causal organization.

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PCT proposes a new answer to the question of what it is that distinguishes a natural arrangement of matter and energy that is alive from one that is not. 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 the effects of random and otherwise unpredictable disturbances (if they are not too powerful for it) 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 other, higher-order goals. It can control many different variables in parallel at the same level of the perceptual hierarchy, and by those 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.

The biological, psychological, and social sciences have commonly studied organisms as simply one more possible arrangement of matter and energy, subject to the same laws of physics and chemistry as any other arrangement. PCT satisfies this requirement—control systems do not require any violation of the laws of physics and chemistry—but PCT recognizes additional laws that are emergent from the negative feedback control properties of suitably organized physical and chemical arrangements. This enables a systematic accounting for the behavior of organisms, individually and in groups, without which observations of this behavior can only be treated statistically or with unspecific generalizations.

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Comment: This para seems a bit out of place. - bruce.nevin

As has long been known, life is negentropic.<sup>3</sup> Organisms exploit the orderliness in the world around them as a means of increasing their own orderliness and stability. Control theory explains how an organism can impose order on its local world at the expense of order elsewhere. Control does not confer 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 an organism is in control. A car left

<sup>3</sup>Schrödinger, Erwin *What is Life - the Physical Aspect of the Living Cell*, Cambridge University Press, 1944; Brillouin, Leon: (1953) “Negentropy Principle of Information”, *J. of Applied Physics*, v. **24**(9), pp. 1152-1163

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to steer itself would soon run off the road or collide with another car if only momentum, gravity, wind, and potholes affected it. But add a driver to the car, and it—along with a huge number of other cars with drivers—stays on the road in its proper lane for hundreds of miles, traveling to a destination with great reliability. This is a highly improbable outcome when a controlling agent is not present. With control added to the picture, the same outcome becomes highly probable.

Given the fundamental characteristics of negative feedback control, there follow significant differences from other life sciences in how PCT research is conducted; we will return to these later in this paper. At this point it is important to note a shift in perspective that comes with the recognition of the phenomenon of control. Without that recognition, behavior can be considered only from the point of view of an external observer, who as a scientist has little choice but to try to explain the activities of behavior as a mechanistic outcome of external forces acting on an otherwise inert “preparation.” Once we recognize control as a phenomenon, and that it is the perceptual input that is controlled by means of behavioral activities, the relevant point of view becomes that of the organism, not that of an external observer. We cannot account for the *how* and *what* of the organism’s activity until we have determined the *why* of it. How we do this in PCT will be explained in the section on methodology.

By this shift in perspective, PCT reconciles the objective approach of science and engineering with subjective experience. It provides a clearly mechanistic model of behavior that can be implemented and studied as a computer simulation (as we will demonstrate presently), and which also explains how human beings can have goals, intentions, preferences, desires, and other experiences that have sometimes been thought to be figments of the imagination or simply errors of interpretation.

The question naturally arises: if PCT has been building into a coherent model for 60 years or so, with a vigorous research community gathered around it, why doesn't everyone know about it? Perhaps the most important reasons are found in an unfortunate development that occurred almost as soon as control engineers had elucidated the phenomenon of negative feedback control.

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## A discovery abandoned

Devices employing negative feedback control are documented as long ago as about 250 BC, but it was only in the 1930s that the principles were formalized by engineers. This was the basis of the wartime automation revolution of the 1940s. Recognizing the resemblance of electro-mechanical negative feedback control systems to living systems, Arturo Rosenbleuth alerted Norbert Wiener and with a number of others they initiated the new field of cybernetics. A cybernetic revolution in the life sciences began to gather momentum in the late 1940s and early 1950s.

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But the revolution came to a halt, essentially dead, in a decade. Negative feedback control was abandoned as a model of purposive living systems almost as soon as it was adopted by its main original proponent, the prominent cyberneticist W. Ross Ashby.<sup>4</sup> In place of the negative feedback model, Ashby and others offered a different idea. Organisms, they proposed, 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 an idea of brain

Comment: citations for Ashby before and after; and for cybernetics - bruce.nevin

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<sup>4</sup>Ashby (1952, 1956)

operation originally offered by Sherrington in 1906,<sup>5</sup> 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.

From that time onward, negative feedback control has been regarded by many as old-fashioned. In 1960, Alfred Chapanis, then president of the Society for Engineering Psychologists, wrote “The servo-model, for example, about which so much was written only a decade or two ago, now appears to be headed toward its proper position as a greatly oversimplified inadequate description of certain restricted aspects of man’s behavior.” This was written in the same year that the first paper leading to PCT was published. Writing in *Purposive Systems*, the 1968 proceedings of the first annual symposium of the American Society for Cybernetics, Ralph Girard, a founder of the Society for Neuroscience and a contributor to the Macy Conferences on cybernetics, said “I have always regarded a drop of water sliding down a slightly inclined plain [sic] as showing all the manifestations of purposeful behavior.”

Even in the book in which he first wrote in 1952 about negative feedback control, Ashby had argued persuasively that the more complex design based on analyze-compute-execute processes would operate faster than the negative feedback control system, eliminating delays, and that it 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. 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 (this explanation would of necessity be limited to organisms that are sufficiently complex to carry out -- instantaneously -- the required analyses and matrix inversions. The cognitive capacities of primitive organisms have consequently been a perennial source of surprise, but puzzlement about this has not led to reconsideration.)

Unfortunately for Ashby’s different idea, real organisms seldom behave as optimal control systems. It is, in fact, easy to design artificial control systems that control much better than people do, but that amounts to making a model of the behavior of a perfect robot in a simple environment, not of a human in a real one. 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 when he explained the importance of negative feedback control in the first part of his first book on this subject, *Design for a brain*. PCT would have been accepted long ago, at least in cybernetics, if he had not written the rest of the book.

## What kind of theory is PCT?

The simplest form of theory in psychology, and the most prevalent, is a set of statements of what will be observed under certain experimental conditions, such as “Mothers hold their babies on the left side.” The only test of such a theory that is possible is to observe whether this is how mothers really behave. It has no generality, no necessary connection to any other observation. Either most mothers do this, or they don’t. Another example is Piaget’s stage theory of the cognitive development of children, that is, a theory of changes in their cognitive abilities and processes. Piaget saw actions as the basis of early development, and mental operations coming in later. Out of this grew his notion of schemas, categories

<sup>5</sup>Sherrington, Charles S. (1906)

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Sherrington:  
<http://brain.oxfordjournals.org/content/130/4/887.full> -- BP  
Ashby:  
Design for a Brain, Introduction to Cybernetics

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**Comment:** Should we say something here about the importance of using functional models rather than persuasive arguments when making inferences and drawing conclusions - timcarey63

Not yet ... not here...  
BP

**Comment:** citations - bruce.nevin

**Comment:** What is the answer to this question? Shouldn't the question be--What kind of theory is PCT? Answer: It is a theory which can explain all behavior at the psychological, biological and social level. Unlike other macro-theories in Psychology, PCT can be very precise and predict what an actual person does in a specified situation, for example, in a tracking task. - dmg801

**Comment:** I think that this section is weak. I don't think that most Psychologists would recognize this description of theory in Psychology. What is the purpose of this section? - dmg801

See Tim's message of 9/15:  
“I wonder if calling it a PCT Paradigm (which I think it is!) is pitching it at the wrong level for current researchers and scientists. PCT is a theory which is unlike other theories in the life sciences as much because of its form as its content. PCT is a meta-theory at the level of S-R theory, however, S-R thinking is so automated in the life sciences (well, psychology ... [1]

**Comment:** I think that this section is weak. I don't think that most Psychologists would recognize this description of theory in Psychol ... [2]

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of knowledge supporting our interpretation and understanding of experience. A schema, according to Piaget, includes both a category of knowledge and the process by which it is established, and new experiences are fitted into existing schemas, adjusting or adding to them as needed. Thus, a child in a family with a pet chihuahua conceives of the category “dog” as short-haired, four-legged, and small, but after encounters with other dogs in the park this schema is modified to accommodate more varieties of dogs.

This theory is supported if in fact it is observed that cognitive development is first based on actions and later on mental operations. It must be tested, but the only test possible is to find whether this pattern is repeated, or fails to repeat, when observed again. There is no hypothesis to test concerning how the child must be internally organized in order to show these patterns under the conditions described. The theory is purely descriptive. There isn't even any statement about how categories exist as elements of behavior or experience—they just exist, along with the knowledge itself, as though given in the environment or innately in the child. So it seems that this sort of theory is about the information content of the brain, not the brain's structure or organization.

PCT advances hypotheses, many of them testable even now, about the structure and organization of the nervous system, including the brain, at the level of functions if not anatomy. If Piaget's “theory” (proposed observation) is correct, we would expect eventually to use PCT to try to explain how the child manages to do these things. From the PCT point of view, Piaget has offered some data that, if valid, require theoretical explanation, not a theory of the same sort as PCT. It describes a phenomenon, but does not explain it. PCT neither supports nor denies theories of the type offered by Piaget: It accepts them to the extent that they are valid, and then, if all goes well, offers an explanation for why or how the phenomenon in question is generated -- and suggests other similar phenomena that might prove to be observable.

**Comment:** Not a good place for references to Plooi, but we should talk about Plooi at some other place. We kind of dropped that ball. - bruce.nevin

[ I eliminated a paragraph bragging about how wonderful PCT is. WTP]

When we look in the behavioral sciences for a theory of the same type as PCT, probably the oldest, dating back to Descartes, is the proposition that stimuli acting on sensory nerves are the cause of motor behavior. Like PCT, this theory is an attempt to explain all behavior, not any particular one. The other main theory of this type, deriving from ideas such as Ashby's analyze-compute-execute hypothesis and Sherrington's map of the brain, is that such stimuli cause centers in the cerebral cortex to generate plans of action, which are then executed by lower systems to produce desired ends. It is with theories at this level of coverage and intent that PCT must be compared, theories of the kind that aim to explain how all behavior is produced, rather than attempting to describe or predict what specific behaviors will be observed under specific circumstances.

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To recapitulate the basic principles of PCT: Behavior is not a linear result of prior causes, it is the variable means of achieving goals that the behaving organism specifies within itself. The activities of behavior are only one among many of the causes that affect some aspect of the environment about which the organism has some preferences; or more exactly, affect the organism's perception of that aspect. The difference between that perception (a neural firing rate) and the preference, an internally specified reference value for that same perception (another neural firing rate) is the cause of the behavioral activities (by way of the propagation of the resulting neural signal downward through the control hierarchy). By this control loop of circular causation, the organism does whatever works to

**Comment:** Shouldn't this be in the beginning of the section? - dmg801

It is at the beginning. This is a recapitulation. Maybe your question is whether it is needed here? It orients the summary and transition paragraph that follows.

maintain that difference at or near zero; behavioral actions vary precisely as needed to achieve consistent aims.

This answers philosophical objections that fortunately are not much heard since the fall of logical positivism into disfavor. Criticisms were made that any notion of goals or purposes must be disallowed in a science of behavior, because it would require the future to affect the present, or effects to become their own causes, or infallible predictions to be made. Those objections may be outdated, but they were responsible for a general rejection of the idea of purposive behavior at the time when important psychological theories were just starting to form. The consequences are still with us. The efficacy of PCT models demonstrates, however, that all that is needed to account for purposive behavior is continuous perception, comparison, and action, all of which go on simultaneously rather than in sequence, and each of which causes and is caused by the others.

## Quantitative and qualitative theories: variables and categories

**Comment:** There's considerable repetition in this section. Purposeful? Or clean it up some? - bruce.nevin  
Yeah, a little cleaning up. -- BP

Following Ashby, the conventional ideas of control most widely accepted today propose that an organism achieves goals in steps, by first analyzing the environment, then calculating the actions and trajectories of action needed to bring the goal-state about, and finally by executing the actions. Despite the doubts raised here, the evidence for this model seems clear: the actions required to achieve a goal-state are indeed produced with the normal result of successful goal-attainment.

**Comment:** citations - bruce.nevin

The evidence, however, is far richer and more informative when we measure the variability of behavior rather than counting instances of "behaviors". Closer inspection shows that the actions are not as regular and repeatable as they seem at first, and that in fact repeated goal-seeking actions have regular effects precisely because they are *not* repeated exactly. The reason is that those regular effects are influenced by more than just the organism's actions; there are also independently varying influences in the environment, including past and present states of the organism itself. Results can be repeated only by varying the actions so that they precisely counter those unpredictable disturbances and changes in environmental conditions which simultaneously are also influencing the result. It is not just that many different actions *can* produce the same result, a qualitative observation that Skinner proposed in his definition of the "operant;" different actions *must* be employed, and just the right different actions each time. As we will see in demonstrations later in the paper, actions must vary quantitatively in exactly the right way if the same result is to recur.

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**Comment:** citation - bruce.nevin  
Also, the demonstrations have not been shown yet., BP

**Comment:** MMT:  
I disagree. I think the main reason is that people concentrate on the effect that the behaviour is intended to accomplish rather than on the detailed mechanism. One "opens a door", one does not "move one's hand to the door handle, try to turn it, seek a key, place it in a lock, turn it, return to turning the door handle..."

I have changed the text in a way that I hope will satisfy Martin. -- BP  
Back to Martin:  
Using your example, one is seen to "turn left". Nothing else. I very much doubt anyone would claim that a driver would execute the same moves of the wheel, accelerator, and brake every time he did the same thing "turn left". Naive understanding often IS PCT- correct: mmtaylor

See my changes above,-- BP

Isn't that a hook for the paper as a whole? I mean to get the reader into why "science" disagrees with the obvious? My professor in grad school considered that the point of scientific psychology was to make precise what any good novelist already knew. If PCT does exactly that, whereas most psychological science does not, maybe it's a way to lead people into the details of PCT. /BN

The only reason that behavior (the observed activity) seems to repeat is that human observers tend to think qualitatively rather than quantitatively. Qualitative thinking is categorical, but behavioral activity does not leap discontinuously from one category to another, it is continuous. A driver making a left turn seems to be generating a stereotyped behavioral pattern that is qualitatively the same each time it is executed, as if it were a simple repetition of what has been done before. This has been taken to imply that repeating the result of the action means that the nervous system must be issuing the same commands to the muscles each time, with the muscles then having the same effects on the environment each time. But that implication is dissipated as soon as an engineer's or a physicist's eye is brought to the scene. The car never approaches the intersection of roads along exactly the same line or at the same speed as the last time; the tires distort, bounce, and slide by different amounts each time they encounter smooth or rough spots on a road that may be dry or slippery; crosswinds require more or less effort to be applied to the steering wheel to achieve the same turning path; the speed of the car influences the



turning radius, as does the number of passengers in the car. Yet somehow every time there is a left turn, the steering wheel turns in just the manner required during that particular turn for the car to move in very nearly the same stereotyped fashion from the lane it is in to its proper place in the crossing lane. It is the result that is stereotyped, not the action that produces it or the neural commands that operate the muscles. Watching a race-car negotiating the turns at the ends of the straightaways, we as amateurs see that the driver actually is turning the front wheels *the wrong way*. Conversely, repeating precisely the same neural output signals or actions each time would not produce the same consistent result. That fact will prove below to have enormous consequences for the theory of reinforcement.

After sufficient quantitative observation of behavior, it becomes clear that it is not an organism's neural outputs or motor actions that repeat, but the consequences of those outputs and actions. The outputs and actions themselves vary exactly as required to keep the consequences the same. The small disturbances revealed by close inspection—as well as some large ones—have multiple independent causes that arise from different environmental sources on different occasions, at unpredictable times, in unpredictable directions, and to unpredictable degrees. Yet what we observe is exactly the kind of variation in behavior that is needed, given all the other influences acting at the same time, to make the critical consequences repeat.

By conventional ways of thinking this is impossible. But control systems do not operate in a simple input-output way. They can control consequences because they continually monitor the state of the consequences, and when that state differs, moment by moment, from what is expected or intended, the difference is used as the basis for altering the action in exactly the way that will keep the difference as small as possible. That is how the needed variations in behavior are produced, and why they do not need to be calculated in advance. Nothing prevents the organism from calculating actions in advance if it has the higher levels of organization needed to do this, but trying to anticipate what actions are going to be needed is very difficult and not likely to work very well or very quickly in a world that is even slightly unpredictable or subject to disturbance. Negative feedback control is by far the simplest, fastest, and most accurate kind of control possible in the real world.

## Symbolic vs. analogue computation in the nervous system

The idea of "computation" of outputs suggests that variables are converted into symbolic representations which are then manipulated according to the rules of mathematics, as in a digital computer, to generate a derived symbolic specification, which is then converted back to terms of action. But PCT assumes analog computation in the nervous system with continuous rather than discrete variables; the mathematics involved in simulations is not intended to represent the physical processes taking place, but only to describe how variables change or to approximate their effects in the language of mathematics. The biochemical processes being modeled are direct physical interactions, not abstract symbolic computations.

An example is the construction of certain perceptual signals as weighted sums of raw sensory signals. In the symbolic approach, each sensory signal would be modeled as a discrete variable with a particular value; the weighted sum would be created by multiplying each signal by a weight and then adding together all the products to create the sum. The sum would then be converted into a magnitude of a neural signal.

**Comment:** MMT:

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See my changes above,-- BP

Isn't that a hook for the paper as a whole? I mean to get the reader into why "science" disagrees with the obvious? My professor in grad school considered that the point of scientific psychology was to make precise what any good novelist already knew. If PCT does exactly that, whereas most psychological science does not, maybe it's a way to lead people into the details of PCT. /BN

**Deleted:** The only reason that behavior (the observed activity) seems to repeat is that human observers tend to think qualitatively rather than quantitatively. Qualitative thinking is categorical, but behavioral activity does not leap discontinuously from one category to another, it is continuous. A driver making a left turn seems to be generating a stereotyped behavioral pattern that is qualitatively the same each time it is executed, as if it were a simple repetition of what has been done before. This has been taken to imply that repeating the result of the action means that the nervous system must be issuing the same commands to the muscles each time. But that implication is dissipated as soon as an engineer's or a physicist's eye is brought to the scene. The car never approaches the intersection of roads along exactly the same line or at the same speed as the last time; the tires distort, bounce, and slide by different amounts each time they encounter smooth ( ... [3]

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**Comment:** Claims are now more specific. Are you OK with this? - bruce.nevin

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The analog-computing version of this process has no need of the symbolic phase. Two or more signals reach synapses on a target neuron; each signal releases neurotransmitters which result in positive or negative changes in post-synaptic potentials; these changes contribute to the net setting of the firing threshold, which determines how fast the cell will send impulses into the cell's axon to provide input for the next cell in line. The relationship between incoming and outgoing impulse rates is a continuous function; output signals change as the input signals change. There is no pause for a computation phase. Graphs of output changes are nearly simultaneous with input change curves, and overlap in time.

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## Parallel computation

The simultaneity of all processes linking input and output emphasizes another fact about analog computation in the nervous system: all phases of the computation are occurring at the same time rather than one after another as in analytical mathematics. The cells in a nervous system function entirely in parallel, each converting its inputs into outputs at the same time that the others are doing the same thing. A control system made of neurons and muscles functions as a whole, not one part at a time in sequence. If there are time delays, the delays do not imply sequentiality of action; they mean only that the current inputs to some cells are the outputs from other cells as they were some milliseconds in the past. Continuous variations, even if delayed, are still continuous.

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## Multidimensional and multiordinal control

Any single control process can be modeled in isolation, as in the initial diagrams in this paper, but a model of the behavior of organisms must represent many control processes acting at once. In PCT, multidimensional control is modeled not as if complex signals or vectors were under control, but in the style called by Oliver Selfridge "pandemonium" in which many one-dimensional controllers are acting at the same time. Because each controller senses just one dimension of variation, complex control requires many one-dimensional controllers to be working in parallel. While this seems wasteful of neural resources, with considerable duplication of function, the resulting models are in fact computationally simple, and the bottom line is that they reproduce real behavior accurately, the *sine qua non* of model-based analysis.

Comment: citation - bruce.nevin  
[http://en.wikipedia.org/wiki/Pandemonium\\_Architecture](http://en.wikipedia.org/wiki/Pandemonium_Architecture)  
--BP

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The Russian physiologist Nicolas Bernstein anticipated cybernetics in many ways, and in the 1950s came to the same conclusion that was being developed in the ancestral theory that became PCT: behavior has to be multiordinal -- organized hierarchically, in layers. A simple observation led to this conclusion both in PCT and in Bernstein's work: if the spinal reflexes act to stabilize limbs against disturbances, they will prevent higher centers in the brain from using those limbs to carry out behavior. Any disturbance will cause a reflexive reaction against the disturbance. Since the brain obviously does use the spinal systems in producing behavior, there must be a way for the higher systems to operate by incorporating the reflexes, not just by overcoming them or turning them off. This principle can be extended to higher feedback loops, each higher loop presenting the same problem to subsystems above it.

Comment: citation - bruce.nevin  
Bernstein, Nicolas: "Coordination and regulation of movements" --New York: Pergamon Press (1967). --BP

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Bernstein never completely settled this problem. He was on the right track, but he lacked knowledge of the engineering principles of negative feedback control which inform PCT. The secret lies in the reference signal, the (variable) Goldilocks standard against which perceptual signals are judged as being too small, too large, or just right. To use a reflex-type control system as means of control, all that the higher systems have to do is vary the reference signal.

This casts new light on Sherrington's concept of a "final common pathway," which he took to consist of signals carrying commands telling the muscles how much to contract. In a control-system model of the reflexes, the muscles are operated not by reference signals or command signals, but by error signals. The signals from spinal motor cells carried by alpha efferent axons to muscles result from two inputs to the motor neuron: an excitatory input descending from higher centers, and an inhibitory input coming from sensors in the tendons measuring the force applied by the muscle. The net signal leaving the motor neuron represents the excess of excitation over inhibition, and the feedback loop at this level makes the sensed tension in the tendon (due to the force exerted by the muscle) match the constant or changing reference signal received from above. Thus the brain (or a system higher in the spinal cord) sends the motor neuron a signal saying, in effect, "Make the tension signal match *this* signal." The feedback loop alters the output to the muscle, in just a few milliseconds, until the match is achieved. The reference signal is not a command to produce a certain amount of action; it is a request for a certain amount of perceived force or tension. As the reference signal varies, so does the perceived -- and actual -- muscle tension.

This establishes a principle of hierarchical control that seems to apply equally well at many levels of organization. Higher systems act to control their own perceptual inputs by telling lower systems to produce a specific amount of the variable they are specialized to sense, not what action they should perform. What to sense, not what to do. The lower systems, autonomously, act on their environments to make their own perceptual inputs match the specified reference condition of the moment.

## Conflict and cooperation

The concurrent control of input variables by different controllers can result in conflict. An everyday example of conflict within the hierarchy occurs when a parent wants to warn someone of a hazard, which normally calls for a loud voice, but they do not want to wake the baby. Control of the perception of warning the person wants to use a loud voice; control of the perception of the baby sleeping wants quiet. Two control loops are controlling the same environmental variable, the loudness of sounds in the room, trying to produce very different values of that variable. The person may resolve the internal conflict in this case by gesturing to get the person's attention and by whispering. The two controllers may be in different people. You approach an open doorway at the same time as someone else coming the opposite way. One may stand aside and wait, or they may each turn sideways to slip past each other.

Most conflicts are routinely resolved. When a conflict cannot be resolved, neither controller can achieve its goal; both are impaired, and one or both may effectively be removed from functioning. Psychological difficulties with this basis are addressed by the Method of Levels (MOL), which will be described in a later section.

**Comment:** citation called for earlier-- but should we mention Sherrington at that place? - bruce.nevin  
On second thought, maybe not. -- BP

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**Comment:** citations here and elsewhere to B:CP and other PCT literature, but I haven't been marking such places. We need to include PCT literature among the citations. I'm thinking here of the discussion of the spinal reflex, mentioned earlier.- bruce.nevin

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When conflicts between control systems inside one organism or in different organisms are not resolved, the result can be a serious loss of function. Each system tries to make the same physical variable match a different reference condition. If the difference is moderately large, both systems will experience large control errors, because one variable can't have two different values at the same time. As a consequence at least one of the control systems will produce as much output action as possible, limited only by strength and endurance.

Both conflict and cooperation have the same formal description in the PCT model: two or more controllers are controlling their perceptions of one common variable in their environment. In the case of conflict, the control actions of each are a disturbance to control by the other. In the case of cooperation, these conflicts are resolved as they arise, usually by each party taking responsibility for one part of the task that is independent of other parts. When very skillful control is involved on both sides of a conflict, even small differences in the goals can cause large degrees of opposing efforts. This explains why cooperation, even when highly valued, is difficult to put into practice.

The resolution of conflicts requires changes in some part of control systems that create behavior -- the perceptions or the actions must become different in the same environmental situation. In PCT such changes are described as a general process of reorganization.

## Changes of organization

The final facet of PCT is concerned with ontogeny, how a mature control hierarchy changes the way it behaves, or an immature one grows out of the primitive organization of a new organism. In accord with the general principles of PCT, this process of changing control systems is seen itself as a control process, in which variables of basic importance, referred to by Ashby as "critical variables," are maintained near reference states by altering the organization of the organism. The resulting theory of reorganization incorporates one of Ashby's most important ideas, that of "superstability" achieved not through systematic reasoning or direct changes in behavior, but through random variations of the properties of a system.

### NOTE TO CO-EDITORS

The problem that has come up is that the events in operant conditioning are starting to look more and more like ordinary learned control behavior. with reorganization coming in only in terms of acquiring control at certain points in the process. The animal is searching for food because it's hungry. It already knows how to search for food and to narrow the search when something edible is found. Then it has to reorganize to press the lever systematically instead of by accident, and acquire a control system for repetitively pressing a lever to deliver food at a certain reference rate. Once that control system exists, no further learning is required because the system is set up to control for food by repeatedly pressing the bar. It will do so as often as needed and at whatever rate the schedule makes necessary without any further changes. A change in the schedule of reinforcement does not require reorganization unless it increases the control error sufficiently. Organisms learn control, not behaviors.

**Deleted:** A between-organisms example is the conflict between a rat in an operant conditioning experiment and the experimenter. The rat normally behaves in such a way as to maintain its body weight at the "free-feeding" level, but in this case the experimenter adjusts the available food (between experimental sessions) so as to keep the weight at 80% of the free-feeding weight. The experimenter, having complete control over the rat and a decisive strength advantage, does keep the weight at that low level, while the rat ends up simply pressing the lever at the fastest rate it can sustain in a vain attempt to increase the food intake. The rat has lost control of its own body weight. [Footnote: Abbott (unpublished) has shown that apparent changes in pressing rate when a fixed-ratio schedule is varied are due entirely to the time taken to consume the food after each reinforcement. The actual contiguous pressing rate is simply the fastest rate the animal can maintain, and does not change as the schedule changes.]

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This picture is confused by two factors. One is that the rate of pressing appears to increase as the rate of reinforcement increases. Bruce Abbott found that this is an artifact caused by including collection time in the measurement of rate of pressing. Contiguous pressing rate is constant, apparently at the maximum rate the animal can sustain.

The other factor explains why the actual pressing rate is constant: the animal is in conflict with the experimenter. The experimenter is varying the available food in the home cage, between experimental sessions, to keep the animal's weight at 80% or 85% of the weight with ad libitum feeding. It is known that when their own behavior provides all of their food, animals vary their behavior rate to maintain their own weight near the observed free-feeding weight. The experimenter is larger, stronger, and smarter than the animal, and so wins the contest over what the weight will be. Since the experimenter's goal for the weight is lower than that of the animal by a large amount, the animal ends up pressing as fast as it can in a vain attempt to raise its food intake and increase its weight. That is normal behavior for a control system in conflict.

Footnote: Experiments by Collier, and by obesity researchers, and lately by Henry Yin (unpublished as yet) show that on fixed ratio schedules that provide all their food, animals vary their behavior rates to keep the reinforcement rate constant over a wide range of ratios.

If someone wants to take this material and rewrite this section, feel free to do so. I'll have a stab at it offline, and if there are any serious differences with what someone else says I'll just edit that.

The main alternative to the reorganization concept is the idea of reinforcement. This was Thorndyke's "law of effect", picked up and elaborated by B. F. Skinner and many others early in the 20th Century. At first, as Skinner saw it, a hungry rat in an operant-conditioning cage emits different organized actions at random. Eventually one of those actions causes the food-delivering level to be depressed. Food drops into a cup and the rat eats it. It is said that the food reinforces the tendency to repeat the response that occurred just before the food appeared. The term "response" is meant to imply that there was some "discriminative stimulus" occurring at the time of the reinforcement, and that what changes is the tendency of a response to that same stimulus to occur again. The underlying model of behavior is thus the stimulus-response model.

When the rat's explorations bring it into contact with the lever that operates a food dispenser, and a pellet of food drops into a cup where the rat can reach it. The rat seizes the food and eats it, and searches the cup and its vicinity as if looking for more. This abrupt change from the exploring behavior creates the impression that the food has done something to the rat to change its behavior. The rat is now much more likely to contact the lever again because it does not move on to continue exploring but remains near the place where the food appeared. It looks as if the delivery and consumption of the food has increased the probability of repeating the behavior that caused the food to appear. A reinforcement is said, in the world of operant conditioning, to increase the probability of repeating a response to "discriminative stimuli" identifying the particular situation.

<sup>7</sup>Trying to explain this fact is a good test of one's understanding of PCT.

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~~Deleted:~~ The main alternative to the reorganization concept is the idea of reinforcement. When a behavior occurs that has a reinforcing effect, it is said that the probability of that behavior's occurring in the presence of the same discriminative stimuli is increased. This was Thorndyke's "law of effect," picked up and elaborated by B. F. Skinner and many others early in the 20th Century. Skinner summed up reinforcement by saying that behavior is controlled by its consequences.¶

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~~Deleted:~~ There is one major flaw in this concept which has already been noted here. Repetition of a particular set of muscle tensions is not likely to result in repetition of previous consequences of the same tensions. Viewed qualitatively as countable categories, "behaviors" like pecking a key or pressing a lever do seem to repeat, and the repetition is what appears to result in more reinforcement of the same behavior<sup>6</sup>. But many ... [4]

~~Comment:~~ An animal maintained by the experimenter at 80% of free-feeding body weight has lost co ... [5]

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~~Deleted:~~ We now have two explanations for this opening sequence in the operant conditioning process. § ... [8]

~~Comment:~~ Don't take any of this as finished -- I'm still looking for the right organization of this section - ... [9]

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There is, however, another interpretation that can be put on these observations. Reorganization is a process by which the properties of neural functions are changed, rather than simply switching from one whole behavior pattern to another. In a reorganizing control system there will be changes in each major function, particularly in the perceptual input functions which determine the kind of variable that will be controlled, and in the output function which determines how errors are converted into reference signals for lower-order systems.

The initial “establishing condition,” it is proposed, has left the animal in the cage with a significant error signal in the control system that normally guides the acquisition and consumption of (in the present case) food. The persistent error signal actuates a set of already-organized control systems that produce what we observe as exploration and searching of the vicinity. As long as the error signal persists and the rat can still function, the search continues. The control system for doing this search, we can assume, is already organized, so reorganization per se is not necessary unless this search system completely fails.

When during the search sequence the rat contacts the food-delivery lever and the food is delivered and consumed, there is a small decrease in the error signal driving the search. Evidently, even this small decrease is enough to terminate the search and cause a switch to another mode of behavior more restricted in its range. The rat begins to search in a more detailed way around the lever and the food cup, a change of behavior which does indeed increase the probability of actuating the dispenser again in one way or another. The probability, however, is not directly changed; it is changed by altering the conditions that affect the probability: the behavior is altered in a way that keeps the animal moving around near the lever. The control system doing all this already exist.

What we need to know to sketch in the theory of reorganization is only that deprivation of food results in behavior that looks very much like a search for food, and that finding food reduces or even terminates the searching movements because it reduces the error that is driving that behavior. This model leads us to expect essentially the same series of events that the theory of reinforcement suggests, so at this point either theory would be acceptable.

When we follow the behavior to later stages of learning, however, we encounter anomalies that the theory of reinforcement is unable to explain. If food-reinforcers first increase the probability of lever-pressing from some initially low or zero value, and then later increase and maintain higher and more systematic rates of pressing, we would expect the same relationship to continue to hold. If the rate of reinforcement increases, the behavior rate should also increase, and conversely for decreases. But that that is not what happens.

When the animal gets all its food from lever-pressing, it comes to press the lever at a constant rate on the average, generating and consuming the food at some average rate. The result, which has been confirmed in experiments with obesity, is to keep the body weight very constant for long periods of time. Furthermore, if food is consistently added to what the behavior is producing, even by tube feeding, the behavior rate does not increase, but instead decreases just enough to keep the total food intake constant and the weight constant. Conversely, consistently removing food (lowering the rate of reinforcement) does not lead to slower lever pressing, it leads to faster lever pressing, so that again the original rate of food intake is maintained. Obese rats with hypothalamic lesions maintain a higher body



weight, but they, too, defend it against disturbances in either direction, keeping their total food intake constant.

Experiments with rats obtaining all their food by lever pressing (Collier, 19xx) showed that these animals maintain an approximately constant food intake when the ratio of presses to pellet deliveries (set by the apparatus) ranges from 1:1 to 5000:1.

The PCT model explains this behavior as control of perceived food intake, or or some variable directly dependent on food intake. It is simply another demonstration of negative feedback control. However, negative feedback control does not explain how this control system came to exist when it did not exist before. We have been assuming that control systems exist; first one for searching out food, then another for carrying out a short-range search, and finally another that maintains the food intake at some specific level even under varying conditions. But unless these control systems were inherited intact, we still have to account for how they came to be organized as they are.

The worst case for a learning theory is that in which the organism needs to learn some control process that has never been learned before, that can't be extrapolated or generalized from past experience, and that can't be worked out logically either because it is unique or because the organism has not developed (or may never develop) any capacities for using logic. This problem led to a control-system theory of the most basic kind of learning, the kind that has to precede the learning of all systematic methods of learning. It is this sort of worst-case learning that is usually meant when the term "reorganization" arises in PCT discussions. The first version of this theory was not given much weight early in the development of PCT, but later, under the tutelage of a small bacterium, it developed into a testable model of basic learning.

## **\E. coli reorganization**

B. F. Skinner explained the acquisition of the first successful behavior in conditioning experiments by saying that organisms spontaneously produce random variations of behavior. PCT adopts that idea but in a different form: the basic theory of reorganization is that the organization of the system (and hence its behavior) varies randomly at a rate that depends on the amount of "intrinsic error." Starvation is an instance of such a challenge to the state of the organism. Deprivation is not just an "establishing condition" as Skinner called it. It causes control errors that bring reorganizing processes into action.

Intrinsic error means a difference between the state of some critical variable, such as blood sugar, and a genetically-determined reference condition. This difference results in random changes of organization. The kind of learning involved is fundamental, the kind that occurs when there is no systematic method available for higher levels of control to pursue, and when there is no prior experience to guide changes. This has long been known as "trial and error" learning. Because the changes are unstructured, they are not constrained by anything but the existing organization, so the possibility of finding solutions to new control problems is maximized.

Clearly, if the random changes of organization produce new behavior patterns that eliminate the deficit in blood sugar, the intrinsic error driving those changes will be eliminated and the changes will stop. That will leave the latest result of reorganization in effect, and behavior will show the new patterns

from then on, just as if something had told the organism that the new pattern was a good one. But doubts about this idea are well justified; it doesn't seem very likely to work.

This concept has been part of PCT since the first published paper in 1960, but it seemed at first too inefficient. Not until 1980 was it taken seriously. In that year, Daniel Koshland published a small book on bacterial chemotaxis which contained a principle that vastly increases the effectiveness of random reorganization.

The bacterium *E. coli* cannot steer, but it can make its way up and down chemical gradients very effectively. It does so by swimming in a straight line and occasionally "tumbling," changing direction in a way that Koshland reported was actually random. The explanation of the gradient-climbing is found in the fact that *E. coli* senses the rate of change of concentration of chemical substances that is induced by its swimming in the gradient. If the rate of change of an attractant is positive, *E. coli* continues in a straight line. The attractant is diffusing radially from a source in the fluid medium, so the straight-line path of the bacterium may be visualized as a tangent line across concentric circles around a point, gradually reaching a closest approach to the source. As the path starts to draw away from the source, the time rate of change of concentration goes negative, and *E. coli* immediately tumbles.

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Since the tumbles change the direction of swimming at random, the result is just as likely to be worse as better. If the rate of change is still negative, however, another tumble ensues immediately, and tumbles keep repeating until the rate of change is once again positive. The bacterium does not swim far—a few body lengths—before tumbling again, so it does not travel much between successive tumbles. The result is that it travels much farther and faster up than down the gradient. For repellents, meaning substances that *E. coli* avoids, the relationships are reversed. According to Koshland, *E. coli* can behave in this way in relationship to more than 20 different substances simultaneously.

To translate this principle into terms of reorganization, the spatial dimensions in which *E. coli* moves become parameters of control systems. Swimming in a straight line becomes adding small increments again and again to each parameter being varied, the direction of travel in parameter space being determined by the relative positive or negative amount of change per iteration in each dimension. A tumble corresponds to altering randomly the proportions in which different parameters are changing. To make sure the process does not overshoot its purpose, the amount added to each parameter is reduced as the control errors decrease.

In comparison simulations, the *E. coli* principle has proven to be over 50 times more efficient than a method based on random point-mutations of parameters. This is because it makes use of information about the changing size of control errors. A slow progressive parameter change that continually reduces control errors simply continues as long as improvement continues. Only when the control error worsens does a "tumble" take place, and then tumbles occur rapidly until the errors are declining again. The 50-fold gain in efficiency is seen when only two parameters are varying; the larger the number of parameters being reorganized, the greater is the gain in efficiency. It is possible that this principle will provide the final rebuttal to arguments that natural selection with random variability of individuals in a population is unlikely to account for the facts of evolution. If evolution is actually carried out at the level of the genome by an organism-generated process of *E. coli*-type reorganization, it may easily prove to be as efficient as necessary. (The idea that organisms generate their own evolution is not entirely new.)

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In recent years, feedback phenomena have claimed more and more attention as researchers discover closed loops of causation as isolated phenomena at every level of organization in living systems. PCT shows how these observations fit into a systemic whole, but to grasp this we must begin with simple cases. The following example is taken from a suite of demonstrations (Powers, 2008), more of which will be discussed later.

## Simulations and models

In the following demonstration of a negative feedback control model, 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 a single experimental run are shown in the upper plot of Fig. 1. 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.

There is a consistent small time delay, hard to see in Fig. 1, between target movements and cursor movements (upper plot). The delay is not removed by anticipatory mouse movements as Ashby and others after him claimed would happen. In the upper part of Fig. 1 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.

**Comment:** The transition here is too abrupt and I think the following section needs to be moved to where the other demos are - willampowers99

I just moved the section title and its preceding transition para up to here. However, more needs to be done. The section on anomalies of reinforcement has affected the flow. This section talks about an anomaly of the calculate /BN Somewhere about here we need Rick's e-coli demo - MT

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**Comment:** Bruce Abbott -- the background of the plots needs to be gray to increase the contrast with the light-colored plots - willampowers99



Fig. 1. Analysis of human tracking run and fit of negative feedback control model to the data.

The lower plot compares real human performance with the performance of a computer implementation of a negative feedback control system controlling proximity of the cursor to the target, resisting unpredictable random disturbances to the target position just as the human subject did. The same target movements are used for model and human runs. The model's simulated mouse movements (blue) are compared with the person's real mouse movements (green). They are very nearly identical, with the same delay relative to the target movements. (The vertical scale is somewhat expanded, making this easier to see.) 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. This same model will work perfectly well with the delay set to zero. But it will work too well: with all the remaining parameters optimized, the mismatch with the real behavior rises from 3.6% to 6.0%. The delay is real.

Soon after control theory started to appear in the psychological literature, various commentators noted that all real systems contain time delays. It was thought, apparently, that with any time delay at all, a negative feedback control system would have to become unstable. Error-correcting actions would start too late to prevent disturbances from having immediate effects, and would persist after disturbances disappeared, generating self-disturbance; and the time delay would convert negative error-opposing feedback into positive error-amplifying feedback, with the likely result that the whole system would oscillate violently. "Feedback is too slow" became a mantra for those resisting the new propositions.

While time delays can result in pathological behavior, all that is needed to correct it is to make the output driven by the error signal proportional to the time-integral of the error rather than to the error itself. This is equivalent to making the rate of change of output proportional to error. The constant of proportionality is adjusted so that during the time-delay that exists, the feedback effects from the output cannot change by more than the size of the perturbations caused by the disturbance. We will show this in greater depth in the next section.

This adjustment is sufficient to stabilize the system given any fixed or maximum time delay in its response. Even more important, as we have seen above and will further demonstrate presently, a working model of a control system incorporating this principle can reproduce experimental behavior of a human participant, including delays, with an accuracy of three to four percent of the range of variation of observed disturbances and responses, equivalent to a 25 to 30 sigma fit of model to data. There can be no practical possibility that this model fits the observations by chance, since  $p < 1E-12$  or much less.

So while it is true that the success and stability of a control process depends on a number of static and dynamic aspects of the system and its environment, and that general treatments of the stability and accuracy of control systems can become very complex, nevertheless in applying control theory to organisms there is a shortcut to a solution: the living system's performance is observed to be stable and accurate, so a biological answer to the problem of stability, even if unknown, clearly exists. Given that observed performance is stable, and that we know of one way of stabilizing a model that accurately reproduces real behavior, we are assured that PCT gives a correct general picture of how control works without requiring that the exact method of achieving stability be known.

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**Comment:** Bruce Abbott -- I think the plot amplitudes should be made equal (as large as possible) to avoid this explanation - willampowers99

**Comment:** should we say "person's data" rather than "real data"? Isn't the simulated data just as "real"? - timcarey63

**Comment:** should we say "person's data" rather than "real data"? Isn't the simulated data just as "real"? - timcarey63

**Deleted:** Ashby's analyze-calculate-execute hypothesis is inadequate on at least two grounds; that it does not model actual behavior, and that it cannot model

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**Comment:** Substantiating this claim would take too much discussion, I vote to delete this paragraph about the German temperature controller - willampowers99

All we need is a reference to a simple organism controlling in a way that would require complex computations in Ashby's model. Will that take a lot of discussion? /BN

**Comment:** - willampowers99

**Deleted:** such inverse kinematic/dynamic and planning computations. A homely example will suggest the difference in complexity. A certain apartment complex in Germany installed a building heating system which worked by measuring outside air temperature and calculating heat losses from the engineered insulative properties of

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**Deleted:** building envelope, then adjusting a furnace to counteract the losses. The same work is commonly done by negative feedback control loops, where the sensor and actuator in each space in the building is the simple analog device called a thermostat that doesn't even have a microcomputer in it.¶

¶ In addition to Ashby's abandonment of classical control theory as a model of organisms, certain misconceptions about negative feedback control that ha... [14]

**Comment:** Richard Kennaway -- can you compute the actual number? - willampowers99

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**Comment:** - willampowers99

The very simple model that provided the illustration above exemplifies 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, the power that it proves to have as an aid to understanding far exceeds what its simplicity seems capable of providing. It is important to understand both the simplicity and the power of a model constructed in this way, so we will take some time to study that here. Figure 2 shows a generic model of a single control system, one system among many at one level among many: the building-block of the hierarchy of control systems that constitutes PCT.

**Comment:** This is where I think the whole section on the tracking experiment should start, - willampowers99

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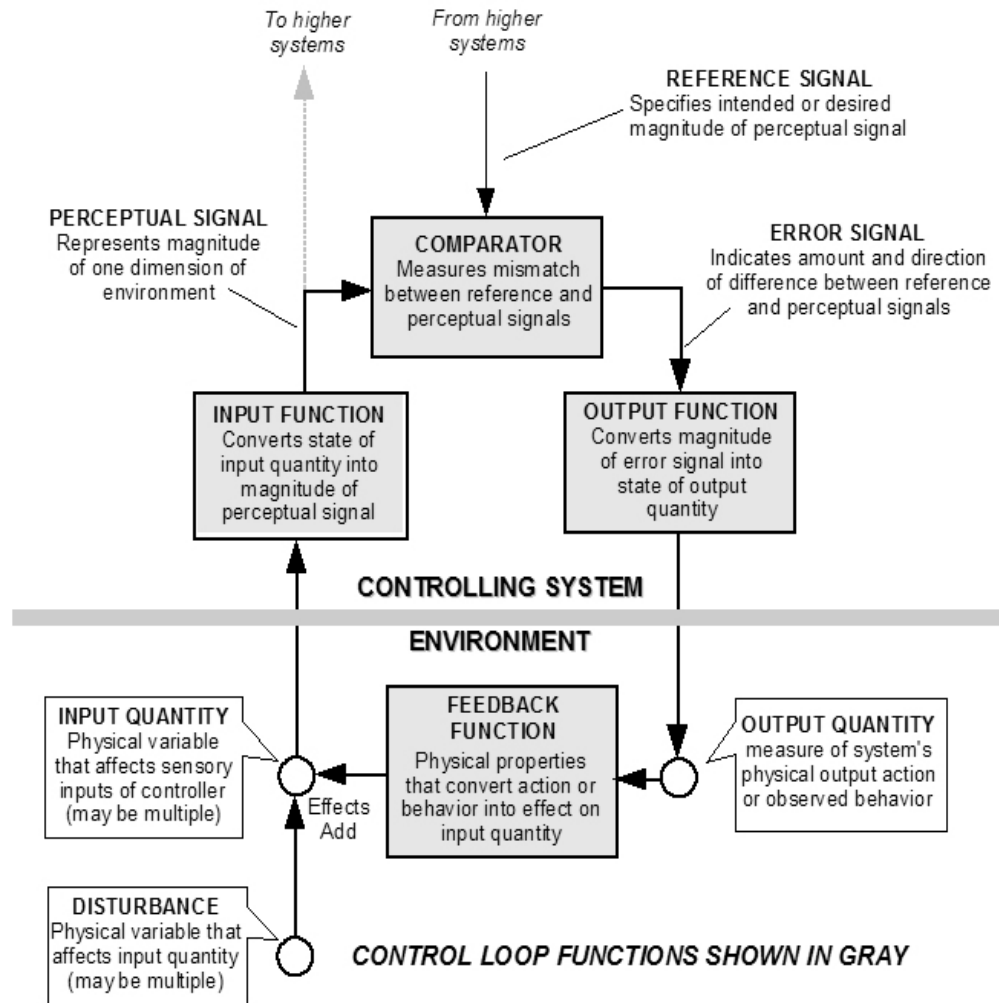


Fig. 2: The basic organization of a negative feedback control system.

The model assumes that inside the participant there is a perceptual signal, some kind of neural signal that literally and quantitatively represents (is an analog of) the input quantity. Applied to the tracking task, the input quantity is the vertical distance between the target position **T** and the cursor position **C**, and the random variation of the target position acts as a disturbance of that input quantity. This suggests that quantitatively the perceptual signal **p** represents the cursor position **C** minus the target position **T**, as expressed in the equation  $p = C - T$ .



Actually, of course, as we have noted, there is a delay involved in going from the perception of target and cursor to the signal representing the distance between them. (This delay is incurred at lower levels of the hierarchy that have been omitted from the present discussion for the sake of simplicity.) If the delay is  $\tau$  seconds, the working perceptual signal at time  $t$  represents the target-to-cursor distance at a prior time,  $t - \tau$ , so the correct equation as used in the model is

$$1. p(t) = C(t - \tau) - T(t - \tau)$$

The basic negative feedback control system receives a reference signal ( $r$ ) from elsewhere within the organism which specifies the currently intended or desired magnitude of the perceptual signal. 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):

$$2. e = r - p$$

Experiment has shown that in the best model for the output function the mouse velocity is proportional to the error signal. A positive error (perception less than reference) causes an upward velocity of the cursor that is proportional to the error by a gain factor  $G$  (that is,  $V_{\text{cursor}} = G * e$ ).

The next position of the cursor  $C_{\text{new}}$  is the current position  $C_{\text{old}}$  plus the velocity  $V_{\text{cursor}}$  times the duration  $dt$  of one iteration of the program. Making the substitution for  $V_{\text{cursor}}$  yields a third equation:

$$3. C_{\text{new}} = C_{\text{old}} + G * e * dt$$

That is the totality of the simplest version of the model: a set of three simple equations or program steps which, evaluated over and over with the same pattern of target positions that the human participant experienced, duplicates the participant's actions in the tracking task above within 4.0% of their peak-to-peak range, in great detail. The model whose performance is illustrated in Figure 1 adds one more term to equation (3), a damping factor  $d$ , and that is what reduces the discrepancy between the model and the human participant to 3.6%, a small but consistent improvement. With this damping factor, the third equation (as it actually is implemented in the demonstration program) is

$$3'. C_{\text{new}} = C_{\text{old}} + [(G * e) - (d * C_{\text{old}})] * dt$$

It is remarkable that these simple equations do so well in simulating real behavior, considering that we are ignoring possible nonlinearities such as the Weber-Fechner law, potential noise in the system, continuously varying angles at the joints, and many other possible causes of poor performance of a simple linear model. In this light, examine the lower plot of Fig. 1 again, showing the mouse/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. 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. There must be something fundamentally right about this hypothetical model.

## A set of demonstration programs

Of course, tracking experiments involve only a very narrow range of behavior. They are a legacy from the engineering psychologists and physiologists of the 1950s, some of whom had worked in the war years on problems of aiming guns to track enemy targets. However, it must be acknowledged that we are in a position analogous to that of Galileo with his pendulums and inclined planes. As they are demonstrated and accepted, the principles of PCT can be applied to any behavior at all, but the most reliable experiments are still simple ones that can be implemented on a computer. Even so, many of the computer demonstrations of control processes that have been made publicly available by PCT researchers involve other kinds of behavior.

**Comment:** Right after the header is where I think the whole section on tracking should be moved, I tried to do it and screwed up the file, so I leave this to my betters. -- BP

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 the most effective way of understanding what PCT is about.

**Comment:** Let's move this to Dag's site to have a more official-looking domain name. - bruce.nevin  
OK, or to the Manchester Univ. web page. -- BP  
I've deleted the note promising to consolidate into one executable. Just a reminder here. /BN

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## “Responding” to an invisible stimulus

The first three demonstrations in the set 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 aligned with a stationary target and stabilize it against an invisible disturbance. After the 30-second experimental run is finished, a graph of the results appears. Figure 3 shows the result of one run. It differs from what you see when you exercise the program because the disturbance and the subject’s resistance to it both differ from one run to another.

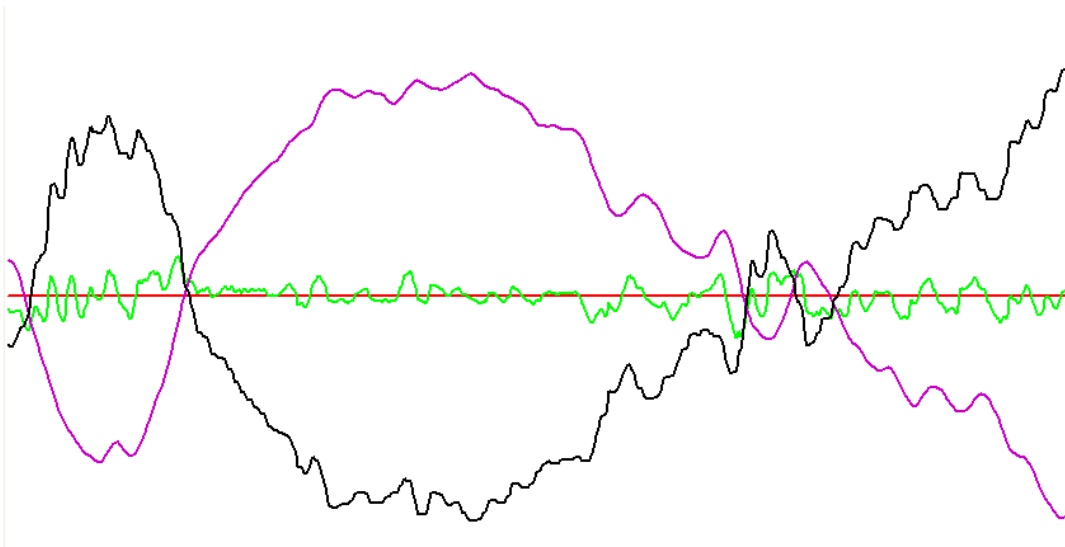


Fig. 3: Compensatory tracking. Black line shows mouse movements, green line shows cursor movements. Target position is horizontal red line. The purple trace shows an invisible disturbance that varied during the run: mouse position relative to the centerline is equal and opposite to the disturbance at 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) which, without these efforts, would move the cursor up and down. The green line shows the resultant 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 the green cursor 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 the cause of the perturbations of the cursor, 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 in this demonstration. This is emphasized by the fact that one's performance improves over repeated exercise of these demonstrations, even though a new disturbance pattern is generated each time any step of the demonstrations is re-run. Learning takes place in that the relationships between signals change (the functions change form), but there is no pattern of behavior to learn: what is learned is control.

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Comment: In this learning, what changes? - bruce.nevin

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## Hierarchical control through reference signals

In demonstration 5, the participant is told to make the cursor descend from the top to the bottom of a range marked off in seconds, so that it passes each mark on schedule. An unseen 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. Figure 4 shows the appearance of the screen at about the 12-second mark. 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

Comment: I see Bruce managed to substitute the altered figures without the red line - willampowers99

Fig. 4: Demonstration 5 at green cursor begins at the down by unseen resisting these it smoothly downward so mark at the indicated time.

about the 12-second mark. The start line and is moved up and disturbances as the subject, disturbances, attempts to move as to reach each successive

The graph for one run of Figure 5.

demonstration 5 is shown in

GO

Start here

5 sec

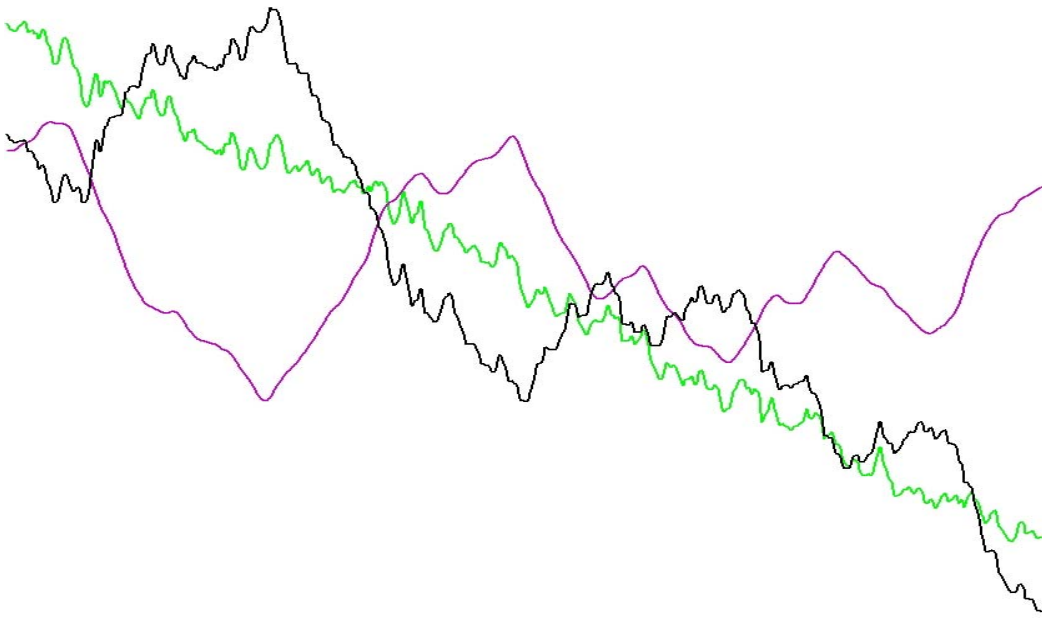
10 sec

15 sec

20 sec

25 sec

30 sec



*Fig. 4: One run of demonstration 5. The mouse cursor (green) approximates a steady progression from top to bottom (y axis) over the time elapsed (x axis). Effects of mouse movements (black) add to effects of the disturbance (purple) to accomplish this descending movement. No stimulus corresponds to this result, and no planning is possible.*

The black trace showing the mouse movements executed by the subject's hand does not resemble either a mirror image of 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 this result cannot be accounted for in terms of responses to any visible stimulus, nor could the mouse actions have been planned in advance and then executed.

This demonstration shows what is meant by control through varying reference signals. The steady downward velocity of the green cursor bar is, according to PCT, the controlled variable for some system fairly high in the perceptual hierarchy, having to do with control of rates of change of position. This system generates a slowly-varying reference signal for a lower system concerned with maintaining the cursor in some particular position against disturbances. This lower system is just as in the previous demonstration, except that now the "particular position" where the lower system is maintaining the cursor is being changed through time by the higher system. In both cases, the lower system acts to make the cursor position match the reference position at all times (as well as it can). The difference is that in the previous demonstration the reference is stationary, but in this demonstration a higher-level system is changing the reference signal in the direction from positive toward negative, so that the lower

system creates the requested perception of a slowly descending cursor—by, of course, using a still a lower level of organization to move the mouse up and down in whatever way works to make the cursor on the screen actually descend.

That the cursor is under positional control at all times is shown by the way it resists a disturbance that is trying to push the cursor up and down, away from its steady descent. The mouse position varies oppositely to the disturbance, not only canceling it as in the first demonstration, but also adding enough additional variation to maintain the steady downward velocity. This happens automatically at the level of position control. The higher control system concerned with downward velocity does not have to do much to resist residual effects of disturbances. Most of the resistance has been accomplished at the lower level.

In addition to illustrating principles of control, these demonstrations are examples of the rigorous testing that PCT has undergone. As mentioned earlier in this paper, our attempts to prove that PCT is wrong are essential to doing science. Building and testing accurate models of individuals' behavior is at the heart of the theory and the experimental methodology of PCT. The remaining demonstrations illustrate some of the other principles that we have discovered and tested, and which, so far, have withstood all attempts to prove them wrong.

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## Challenging PCT with experiments and simulations

The first book-length treatment of what is now known as PCT (Powers 1973, 2002) was finished before the advent of inexpensive desktop computers and the exponential growth of computing speed and memory storage. Some 12 years later, the first interactive computer demonstrations of the principles of PCT began to take shape, in time for the first meeting of the Control Systems Group in 1985. At this meeting, a tracking experiment was shown in which a subject used a joystick to make a cursor on the computer screen track a moving target, the controlled variable being the separation of cursor from target and the reference condition (defined by instructions) being zero separation. Demonstration 4, the first one that we discussed above, recapitulates that demonstration.

This was also the first instance of a computer simulation of a PCT-type control system designed as a model of the person doing the tracking task. The parameters of the simulated control system were an integration sensitivity and a constant reference signal which were adjusted to make the performance of the model match the real ~~person's~~ performance with as little difference as possible. The RMS difference between modeled joystick movements and the real movements could be reduced to less than 10 per cent of the range of movement of the target. More recent versions have reduced the RMS error of fit to less than 4 per cent.

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The most important aspect of this early simulation was that it could be used with either a single smoothed-random disturbance moving the target, or with a second uncorrelated disturbance added that made the cursor movements differ randomly and by large amounts from the joystick movements. With the second disturbance acting, the subject would move the joystick in a way that corresponded neither to the target movements nor to the second disturbance, but was exactly the movement needed to minimize the tracking error.

This demonstration illustrated the important point that the behavior observed in a control situation generates a regular result without itself being regular. This is the main feature of PCT that distinguishes it from the calculate-and-execute models of control behavior: it is not possible for the organism to calculate in advance the joystick movements that will be required, because the disturbances are being generated from random numbers during the experimental run, and are unknown in advance. A calculate-and-execute model necessarily fails in the presence of unpredictable disturbances. This is only noticeable if working models are made and tested.

Among the demonstration programs introduced so far, of particular interest is the demonstration called “Square circle”. In this demonstration, a white dot is used by the participant moving a mouse to trace the sides of a red square. At the end of one complete tracing, the path of the mouse is revealed: it is a circle. In a variant mode, the revealed path is a triangle—a bit more difficult to execute, but even more unexpected by the participant. The point is to show that what a person *experiences* as his or her own behavior is actually the perception that they are controlling, not their actions, which are often markedly different from it.

Other demonstrations are distributed with (Powers 2008). In one of these, the participant's task is to keep a small green circle aligned inside a slightly larger red circle in one corner of the screen. A white tracing shows the actual path of the mouse, which at the end of the run is seen to spell out in script the word “hello.” This is caused by a patterned disturbance of the green circle which traces out “hello” upside down and backward. Even though the observed behavior of the participant (the movement of the mouse) is essentially unrelated to the control task being accomplished—the behavior as the person experiences it—nonetheless, when we overlay the disturbance on the mouse movements they are very highly and negatively correlated (in the - 0.99s).

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The first demonstration of the (Powers 2008) set may be the most philosophically interesting. Here a red ball is shown drifting left and right while it rolls vertically and changes shape from short and wide to tall and thin. Each aspect is affected by a smooth disturbance, the three disturbances being uncorrelated. The mouse affects all three variable aspects of the ball—shape, orientation, and position—at the same time and by the same amount. The participant's task is to pick one of those aspects and keep it constant: shape as *round*, position as *centered*, or orientation as *level*. That this can be done at all is of considerable interest, but of equal interest is the fact that the computer can determine reliably which single aspect is being controlled and which two aspects are varying as side-effects. The computer deduces which effect of the action was intentional and which others were merely side-effects.

Comment: the term “LCS III set” needs to be introduced earlier, - willampowers99

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“Intention,” in PCT, refers not to behavioral acts but to the consequences of those acts. The intended consequence of controlling the orientation of the red ball is to keep its axis pointing toward the viewer. Because each aspect of the ball is being influenced by a different pattern of disturbances, the same actions that stabilize orientation *can't* simultaneously stabilize position or shape; in fact they increase the variance of those two variables because they *aren't* systematically opposed to the relevant disturbances. The result is a rather puzzling combination of correlations: the actions that stabilize orientation correlate almost perfectly (-0.99) with the disturbance that tends to alter orientation, yet those actions and those disturbances show only a low correlation, close to zero, with the orientation that is being controlled. The mouse movements correlate much better with the aspects that are *not* being controlled.<sup>7</sup>

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To return to a subject at the beginning of this paper, a general-purpose demonstration called “LiveBlock” shows a basic control system as a “live block diagram”. Here we have a control system with an adjustable transport lag, time constant, gain factor (output amplification), and environmental feedback factor, plus an adjustable reference signal and disturbance. The model runs continuously in the background so the effects of changing system parameters and independent variables can be seen as they occur. The method of stabilizing a system with time lags in it is illustrated, as are many other basic properties of a negative feedback control system. It is hoped that this demonstration can finally counteract many of the false ideas offered over the past 60 years about the limitations of negative feedback control as a model of behavior.

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## The methodology of PCT research

Near the beginning of this paper, we made note of an inherent difficulty of the experimental investigation of living things. An organism controls its own perception of some aspect of its environment, but that privileged point of view from inside the observed organism is unfortunately not available to scientific observers. As observers of the organism we do not have access to that perception, we only have our own perceptions from our own points of view, external to the organism. For that reason it has been crucially important to devise tests for determining which aspects of its perceived environment the organism is controlling.

The principal datum in PCT methodology is the controlled variable. All of the demonstrations that we have reviewed have clearly displayed three variables: the controlled variable (i.e. distance between the mouse cursor and the target), the disturbance (producing movements of the mouse cursor independent of the user’s movements of the mouse), and the relevant behavioral actions (indicated by the changing mouse position). Obviously, the disturbance can’t be identified until we know just what the controlled variable is and what the mouse movements are. If the user, unbeknownst to us, is ignoring the moving target and instead trying to draw a large circle with the mouse cursor, the measured and graphed results will not make sense to us. There will be no relationship between what is expected to be controlled (the position of the cursor relative to the target) and what the subject is actually controlling (following the outline of an imagined large circle). Since even in this simplified, artificial, two-dimensional laboratory environment it is difficult to see what is actually under control, we would expect more naturalistic settings to present even more difficulties. Yet the technique for determining what perceptual variable is being controlled is essentially the same everywhere. The requirements are few. We must be able to make intelligent estimates of which aspects of the environment the organism can perceive and influence with its activities, and we must be able to also influence those aspects of the environment.<sup>8</sup>

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The fundamental step of PCT research, the Test for controlled variables, is the *gentle* application of control with the purpose of disturbing the state of a variable that the researcher surmises is already under control by the observed organism. If the organism resists the disturbance and restores that variable to the state that it desires, that is evidence that the experimental action disturbed a controlled variable. It may take a number of variations of the disturbance to isolate just which aspect of the environmental situation is under control. And then it must be realized, in addition, that the perception

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**Comment:** What aspect of “the environment” corresponds to a person’s self-image? Each perceptual level is the environment for the level above it. In the study of self-image by Robertson et al. , the disturbance consisted of words which were like the person or not like the person. If they were not like the person, the person would make a correction; if they were like the person, no correction was made. - dmg801

<sup>8</sup>Insofar as each level of perception is the environment for the next higher level in PCT, the test for the controlled variable may involve environmental variables that are only available to the person being studied (as in Robertson et al. 1999).

of the environment by the observer is not the same as the perception of the “same” environment observed by the organism.

In order to build working generative models of behavior, like the simulations we have been exercising, there is one further requirement. We must be able to measure these influences affecting the state of the environmental variable that we have decided to test. Until a simulation produces very nearly the same numbers as were produced by measurement, it needs refinement; and when it does, we have a strong basis for the claim that the simulation models essential aspects of the unseen internal structure of the organism whose behavior we measured, and that of other organisms like it.

Our understanding of the inner workings of a hierarchical perceptual control system reorients our thinking in a number of fields.

## Relation of PCT to Conventional Psychology

PCT terms originate in the field of engineering and are based on the concept of a negative feedback control system. The following table of correspondences suggests how PCT could integrate the field of Psychology.

Table 1. Correspondence of key terms in PCT to concepts in conventional psychological theories

Conventional Psychology	PCT
Stimuli	Input quantities; perceptual input
Sensation, Perception, Cognition	Perceptual Signals
Motivation	Reference Signals
Emotions	Error Signals, Perceptual signals associated with conflict
Behavior	Output quantities
Learning and Development	Reorganization

The PCT way of describing a person is useful in various applications of PCT, including psychotherapy.

The PCT way of doing research differs from Conventional Psychological approaches in the standard set for what is a good result. The correlation between actual behavior and model behavior in the PCT work done with pursuit tracking is in the .90 and higher range. This shows that it is possible to obtain much higher correlations than is typically obtained in Conventional Psychology research when one has an understanding of the mechanisms involved within the person as described by a correct functional model. The “revolutionary” aspect of PCT is the message that one should continue research until the correlation between theory and data moves into the .90 range and higher so that one can make predictions for an individual, not just “on the average”. By striving for this goal, Psychology will be on much firmer ground when applications are attempted.

**Comment:** What aspect of “the environment” corresponds to a person’s self-image? Each perceptual level is the environment for the level above it. In the study of self-image by Robertson et al., the disturbance consisted of words which were like the person or not like the person. If they were not like the person, the person would make a correction; if they were like the person, no correction was made. - dmg801  
“What people say about me” is in the environment. /BN

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**Comment:** We don’t perceive error signals, but the surmise is that perceptual signals may arise in consequence of or in association with poor control. How to say that briefly in a table ... is it OK to be a bit loose about this at this point? - bruce.nevin

**Comment:** We don’t perceive error signals; specifically, they are never perceptual input to a comparator. Perceptual signals may arise from bodily states associated with poor control and conflict. These are then recognized (variously) at higher levels as feelings and emotions. Whether adrenalin-arousal is interpreted as anger, fear, excitement, etc. depends upon what is currently being controlled at those higher levels. See Chap. 17 B:CP (2nd ed.) - bruce.nevin

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**Comment:** I disagree with this change. See W.T. Powers manuscript on Emotions: PCT vs. Tradition ... [15]

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## PCT Applied to Psychotherapy

The field of **diagnosing and treating** psychological **affords** an excellent example of **how** PCT can provide a unifying framework to an otherwise fragmented area of research and practice. It is widely recognized, for example, that current classificatory systems of psychological disorders such as the **DSM IV**<sup>9</sup> do not easily map onto the lived experience of psychological distress. **Despite the invocation** of concepts such as **'comorbidity'**,<sup>10</sup> there is a growing awareness that this system of classification is unsatisfactory in important ways. **In recent years there has been great interest in processes that are said to be "transdiagnostic" across DSM categories as an explication of underlying pathways by which diverse symptoms become manifested.** A PCT account of such processes explains why this approach has merit and why categorizing symptoms is problematic.

We have already outlined in detail **how** behavioral output varies in order to control perceptual input. **Consequently,** internal problems of control do not give rise to recognizable, standardized symptoms. **That is why there is so much variation within current classificatory categories of symptoms. This also accounts for the lack of clear differentiation between categories. In the real world, where unpredictable disturbances to control occur, behavior must vary as a person repeats attempts to solve a given problem.** The appearance of symptom patterns is analogous to the appearance of constellations in the night sky. **They are arbitrary groupings in the eye of the beholder that reflect no underlying order or structure.** Categories of behavior—that is, of variable control system outputs—cannot reveal the order or structure of internal malfunctions.

There is a developing acknowledgement that it is the distress associated with particular symptoms rather than the symptoms themselves that needs to be understood. Auditory hallucinations, for example, are experienced **commonly** in the general population.<sup>11</sup> Who has never had cause to complain of being unable to stop a tune from replaying itself in imagination? **Auditory hallucinations can even be helpful.** A singer who can't mentally "hear" a note before singing it will not sing very well. **However, when a person is distressed by auditory hallucinations, the distress is problematic.**

**Psychotherapy has focused, understandably, on pathology.** PCT contributes a useful perspective in understanding psychological disorders by first providing a model of satisfactory psychological functioning. **PCT understands dysfunction in terms of disruption of successful control.** Conflict between control systems, **as we noted earlier,** is problematic because it effectively removes the control abilities of both systems. **Conflict is usually transitory. It is when conflict is unresolved and becomes chronic that the symptoms recognized as psychological disorder become apparent.** Distress then results from **the person's inability to control experiences that are important to them.**<sup>12</sup>

**Comment:** Tim, Recently, I heard Bill say that knowing what people are similar to the person in therapy, is not helpful. Each person must be assessed uniquely. And what worked with similar people, may not work with the person in treatment. The DSM-IV approach is to find out what people are like the one in treatment. The PCT approach is to find out what the person in treatment considers to be the problem and what aspects of the person's life is out of control. - dmg801  
Do you want to try to work this thought into the text? /BN

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**Comment:** - willampowers99

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**Comment:** citations needed - bruce.nevin

**Comment:** Tim, Recently, I heard Bill say that knowing what people are similar to the person in therapy, is not h (... [18]

**Comment:** - willampowers99 The term seems to mean bridging or disregarding the DSM categories.

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**Comment:** We haven't discussed imagination, so hallucinations can't be seen as a basically normal process - willampowers99

**Comment:** We haven't discussed imagination, so hallucinations can't be seen as a basically normal process - willampowers99 (... [20]

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**Comment:** This follows from the rest of the para. But are we saying that it's fine for the two Christs of Ypsilanti to think they're Jesus so long as (... [22]

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<sup>9</sup>American Psychiatric Association (2000).

<sup>10</sup>A relatively empty term meaning simply that one or more disorders or diseases are diagnosed in addition to a primary one.

<sup>11</sup>How perceptions may be registered and controlled in imagination [was discussed earlier][is beyond the scope of this paper but discussed elsewhere (citation)].

<sup>12</sup>Other problems that can also arise, such as feeling overwhelmed by environmental forces, require more extended discussion than is possible within the scope of this paper.

Conflict, as it is conceptualized in PCT, occurs between two control systems at the same level. These control systems, however, are located within a hierarchical network of control systems so their conflicted arrangement will influence and be influenced by lower and higher level systems. This account of psychological distress may explain why no reliable biological markers of mental illness have ever been discovered. From a PCT perspective, control systems that are in conflict are not dysfunctional or broken. In fact, it is quite the reverse. The better the control systems are **each able to control**, the more intense the conflict will be. Some kinds of mental illness, perhaps most, may be not a result of broken brains but of well functioning control systems locked in chronic conflict.

It is the hierarchy that provides a clue as to where treatments should focus to help conflicts resolve. Systems at one level receive their references from the next higher level. When **two** control systems are conflicted, it is the signals being sent **to each** from the next highest level that need to be altered.

**Most therapies assume that attention to problems facilitates change, and people in general tend to be most aware of painful or dramatic consequences of conflict. This is seldom helpful in itself. Attention is drawn to the symptoms rather than the causes of loss of control, symptoms such as apathy, confusion, fear, or despair. Often a person will try to strengthen the “good” side of a conflict, which usually just makes conflict more extreme because the other side resists the effort to change and starts to look good for other reasons.**

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PCT suggests use of the learning process of reorganization that was explained previously. **This is the change mechanism that resolves conflict. One way it can do this is** by modifying components of higher-level control systems that set reference signals for others a lower level. The therapeutic approach that is based on the principles of PCT is called the Method of Levels (MOL). Its principle is to redirect **attention ‘up a level’ to the control systems responsible for generating the conflict, away from a preoccupation with the symptoms and the immediate efforts on both sides of the conflict. It appears that reorganization and awareness are linked in such a way that it is the systems that are in awareness that become the particular focus of the reorganizing processes.**

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**Consider wanting to stop smoking to avoid lung disease and at the same time wanting to continue it to relieve withdrawal symptoms caused by smoking; or wanting to leave a partner to avoid abuse and, at the same time, wanting to stay with the partner for the sake of love. Ultimately, attempts to modify the actions of conflicted systems, or to give preference to one goal by will power, cannot permanently alter the conflict. The conflict is resolved only when awareness is shifted to the level above the conflicted systems so that reorganization can be directed to the systems creating the conflict—the systems that are establishing these conflicting goals. Hence the name, the Method of Levels.**

For the person in therapy, MOL is an experience of describing in detail a current area of distress to a therapist who understands PCT. The therapist’s approach is an unusual blend of questioning about subjective experiences and selectively drawing a client’s attention to seemingly tangential or peripheral comments the client might make—comments that the therapist familiar with PCT recognizes as possibly **reflecting involvement of a higher-level system. In this way, the client shows the therapist what path to follow, and when the therapist helps them focus in the right place, their own reorganizing capabilities generate new perceptions and goals that may resolve the conflict, or uncover the deficiency that causes trouble.**

MOL has been used over a number of years by different clinicians in a variety of clinical settings. Evaluations have been conducted of the way in which MOL is experienced by routine clients in routine clinical contexts.<sup>13</sup>

**Comment:** I trust we don't study only clients with positive results - willampowers99

**Deleted:** . Details about MOL and its use in clinical practice are available elsewhere

**Comment:** citation - bruce.nevin

It is telling that despite the demonstrated effectiveness of psychotherapy there is still no generally accepted account of how these effects are achieved, and in fact, it has been shown that psychotherapies based on quite different models of disorder can have similar effects. There has been an increasing call to move away from developing new techniques and strategies and instead to focus on underlying common principles and mechanisms. PCT provides a common underlying process (conflict) and a common change mechanism (reorganization) that might be particularly significant for understanding this peculiar situation. The paradigm of perceptual control may provide the means to make sense of these otherwise puzzling results.

Recent research in neurobiology has indicated that psychotherapy can have effects in the brain that are similar to the effects that pharmacology achieves. Again, this result would come as no surprise from a PCT perspective. The hierarchy of PCT is a hypothesized neuronal architecture which is equally applicable to thoughts being explored or selective serotonin reuptake inhibitors being ingested.

It is certainly the case that, at this stage, PCT perhaps raises more questions for research than it answers in this field. Do conflicts at different levels of the hierarchy, for example, result in different types of distress? Does the rate of reorganization affect the experience of conflict? What influences the mobility of awareness such that some conflicts are resolved satisfactorily while others become chronic? The possibilities for new research, as usual with new ideas, proliferate.

While some of the propositions about the application of PCT principles to psychotherapy remain speculative, there is also indirect but strong evidence for this approach. Problems of control (such as behavioral control, impulse control, emotional control, and thought control) are widely recognized as important in psychological functioning. Many approaches to psychotherapy use conflict formulations to explain psychological distress. Many approaches also discuss the importance of awareness in resolving problems as well as recognition of the need to consider problems from higher levels of thinking (such as important life values or belief systems). Finally, there is a growing body of literature that recognizes that the change involved in the resolution of psychological distress is not a linear or predictable process.

In fact, full-time MOL practitioners, most of whom came from other schools of thought, agree that MOL is probably an explanation of why other therapies succeed when they are successful, and why they fail -- they fail to be consistent with MOL. Many therapists have independently developed methods that come close to MOL, simply by weeding out what doesn't work. For some, such as Rogerians, a switch to pure MOL would involve only minor changes. For others, of course, such a switch would call for so many deviations from customary practice that it would be essentially impossible.

Exploring psychological disorders and their treatment from the perspective of perceptual control provides a new direction for psychotherapy researchers and practitioners. There is a growing possibility that it will enable a clearer understanding of the nature of psychological distress that is developed from

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<sup>13</sup>For details about MOL and its use in clinical practice, see Carey (2006).

a model of function rather than dysfunction. It may also promote the distillation of the important components of psychotherapy such that therapists can be clearer about their roles and treatments can become more efficient. Moreover it can, and already does, provide a guide regarding the purpose of psychotherapy. PCT, then, will have an impact on long standing debates such as the dodo bird hypothesis.<sup>14</sup> A unifying focus such as the one provided by PCT will allow a more consistent and coherent approach to emerge that will go a long way towards preventing the debilitating impact of psychological distress that is currently on the increase in many countries.

Comment: What is the dodo bird hypothesis? - willampowers99

Comment: What is the dodo bird hypothesis? - willampowers99  
[http://en.wikipedia.org/wiki/Dodo\\_bird\\_verdict](http://en.wikipedia.org/wiki/Dodo_bird_verdict)  
Is the footnote sufficient? /BN

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There may also be other implications of this approach that cannot be easily predicted at this stage. Perhaps the stigmatizing nature of mental illness will change with a more accurate explanation of these problems that is inherently psychological (yet firmly grounded in neurobiology) and intuitively optimistic and hopeful. The nature of the delivery of psychological treatments might also change as researchers and clinicians become more familiar with the reorganizing capabilities of individual systems. Perhaps we will learn to use both psychotherapy and pharmacotherapy more judiciously. While the outcomes may not be entirely obvious there seems to be sufficient justification at this stage to step into the paradigm of control and to build our knowledge of the mechanisms of psychotherapy from the foundations of these functional and rigorously tested models.

## Mental Illness and Psychiatric Diagnostic Categories

### Rewards and Punishments

### Health and Disease

### The future of PCT

Comment: Is "how to get started" adequately covered in the "Challenging" and "Methodology" sections above? If more is needed, perhaps it should be an expansion of the latter. - bruce.nevin

## PCT Research--how to get started

### Resources

[This is promised in "Challenging PCT with experiments and simulations".]

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Kozak, M., Marsh, A. A., & Wegner, D. M. 2006. "What do I think you're doing? Action identification and mind attribution". *Journal of Personality and Social Psychology*, 90, 543-555;

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<sup>14</sup>The proposal that all therapies are equally effective, depending upon the practitioner, and "all must win prizes". See [http://en.wikipedia.org/wiki/Dodo\\_bird\\_verdict](http://en.wikipedia.org/wiki/Dodo_bird_verdict).



<p>Marsh, A. A., Kozak, M. N., Wegner, D. M., Reid, M. E., Yu, H. H., &amp; Blair, R. J. R. 2010. "The neural substrates of action identification". <i>Social Cognitive and Affective Neuroscience</i> 2010; doi: 10.1093/scan/nsq004.</p>	<div>Deleted: (</div> <div>Deleted: ).</div>
<p>Robertson, R. J., Goldstein, D. M., Marmel, M., &amp; Musgrave, M. 1999. Testing the self as a control system: Theoretical and methodological issues. <i>International Journal of Human-Computer Studies</i>, 50, 571-580.</p>	<div>Deleted: (</div> <div>Deleted: )</div>
<p>Sherrington, Charles S. 1906. <i>The integrative action of the nervous system</i>. New York: Scribners. Repr. 1947 New Haven, CT: Yale University Press.</p>	<div>Deleted: (I</div> <div>Deleted: )).</div>
<p>W. Ross Ashby. 1952. <i>Design for a brain</i>. London: Chapman &amp; Hall. Repr. 1960, New York: Wiley.</p>	<div>Deleted: (</div> <div>Deleted: ).</div>
<p>W. Ross Ashby. 1956. <i>An introduction to cybernetics</i>. London: Chapman &amp; Hall.</p>	<div>Deleted: (</div> <div>Deleted: ).</div>
<p>Powers, William T. 2008. <i>Living control systems III: The fact of control</i>. New Canaan, CT: Benchmark Publications.</p>	<div>Deleted: (</div> <div>Deleted: ).</div>
<p>Carey, Timothy A. 2006. <i>The Method Of Levels: How To Do Psychotherapy Without Getting In The Way</i>. Hayward, CA: Living Control Systems Publishing.</p>	<div>Deleted: (</div> <div>Deleted: ).</div>
<p>American Psychiatric Association. 2000. <i>Diagnostic and Statistical Manual of Mental Disorders DSM-IV-TR</i>, Fourth Edition (Text Revision).</p>	<div>Deleted: ¶</div> <div>¶</div>

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**Page 6: [1] Comment**

I think that this section is weak. I don't think that most Psychologists would recognize this description of theory in Psychology. What is the purpose of this section? - dmg801

See Tim's message of 9/15:

"I wonder if calling it a PCT Paradigm (which I think it is!) is pitching it at the wrong level for current researchers and scientists. PCT is a theory which is unlike other theories in the life sciences as much because of its form as its content. PCT is a [meta](#)-theory at the level of S-R theory, however, S-R thinking is so automated in the life sciences (well, psychology anyway) that almost no-one would recognise it as a theory. I'm convinced that when people hear about PCT they compare it to other theories that they know of such as Attachment Theory or the Theory of Planned Behaviour. PCT, however, doesn't come in at this level - it comes in at the level of S-R or linear causality. Pitching the PCT paradigm then against the S-R paradigm is not really pitching like against like." /BN

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**Page 6: [2] Comment****10/14/2010 12:02 AM**

I think that this section is weak. I don't think that most Psychologists would recognize this description of theory in Psychology. What is the purpose of this section? - dmg801

See Tim's message of 9/15:

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The only reason that behavior (the observed activity) seems to repeat is that human observers tend to think qualitatively rather than quantitatively. Qualitative thinking is categorical, but behavioral activity does not leap discontinuously from one category to another, it is continuous. A driver making a left turn seems to be generating a stereotyped behavioral pattern that is qualitatively the same each time it is executed, as if it were a simple repetition of what has been done before. This has been taken to imply that repeating the result of the action means that the nervous system must be issuing the same commands to the muscles each time. But that implication is dissipated as soon as an engineer's or a physicist's eye is brought to the scene. The car never approaches the intersection of roads along exactly the same line or at the same speed as the last time; the tires distort, bounce, and slide by different amounts each time they encounter smooth or rough spots on a road that may be dry or slippery; crosswinds require more or less effort to be applied to the steering wheel to achieve the same turning path; the speed of the car influences the turning radius, as does the number of passengers in the car. Yet somehow every time there is a left turn, the steering wheel turns in just the manner required during that particular turn for the car to move in very nearly the same stereotyped fashion from the lane it is in to its proper place in the crossing lane. It is the result that is stereotyped, not the action that produces it or the neural commands that operate the muscles. Conversely, repeating precisely the same neural output signals or actions each time would not produce the same consistent result. That fact will prove below to have enormous consequences for the theory of reinforcement.

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There is one major flaw in this concept which has already been noted here. Repetition of a particular set of muscle tensions is not likely to result in repetition of previous consequences of the same tensions. Viewed qualitatively as countable categories, "behaviors" like pecking a key or pressing a lever do seem to repeat, and the repetition is

what appears to result in more reinforcement of the same behavior<sup>1</sup>. But many experimentalists including Skinner noticed quickly that animals in conditioning cages do not actually repeat the same motor behavior again and again. They do succeed in making contacts beneath a key or lever close to deliver reinforcers, but the actual motor behavior used to do this can vary enormously. A rat can operate the lever by leaning on it, chewing it, sitting on it, or standing on it with a front or rear paw. The approach to the lever depends on immediately prior activities and many other factors. The categorization of diverse actions as “lever presses” by the observer conceals these differences by focusing on the result instead of the action, so that in fact the manner of recording data can attribute a specific rate of lever-pressing to the animal, the total number of presses divided by the total time of counting, even though the animal spent part of that time having a nap.

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Page 13: [5] Comment

An animal maintained by the experimenter at 80% of free-feeding body weight has lost control of its total food intake.. See above.under Conflict and Cooperation - williampowers99

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Taking this variability into account, we observe that a free-feeding animal at normal weight does whatever it takes to receive enough food in the artificial environment of the laboratory. It varies its motor behavior, without any particular repetition, in exactly the way required to make the same consequence occur under changed conditions. This can be done once the system acquires the required negative feedback control organization and reorganization ceases.

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The mechanism behind reorganization is not obvious. When a hungry rat is put in an operant conditioning cage for the first time, the first thing it will do is to carry out what looks like a systematic search of the cage. What is causing this search to take place? PCT suggests the same answer that common sense would suggest: it is looking for food. It probably learned long ago, or perhaps even inherited, a moderately complex set of control systems that is brought into play when hunger persists for any length of time without the opportunity to feed. It might search because of many other reasons, but food deprivation, if it exists, suggests a particularly likely reason that would call for a search even if nothing else did. A formal PCT description would propose that there is a “food” reference signal and a “no food” perceptual signal, which together imply an error that will drive the output, which may be a random process or a systematic search process involving lower orders of control. The search brings the rat to different places in the cage one after another as long as the hunger persists. When food is found, the “food” reference signal is matched by the perception that food is present, and the error goes to zero. If food deprivation was the primary cause of the search, the rat ceases to explore the cage and now its activities focus on the location where it was when the food appeared and the searching ceased. This is the main phenomenon that has persuaded many behavioral scientists that something must have

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<sup>1</sup>Reinforcement is an example of positive feedback. More reinforcement means more behavior of a certain kind; more of that behavior means more reinforcement. This is an unstable, error-increasing kind of organization which can only produce the maximum possible behavior or none at all.

happened when the search ceased, some reinforcing effect, that tells the rat it should repeat the behavior that was going on when the food was found.

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We now have two explanations for this opening sequence in the operant conditioning process. Since both explanations predict the same result, there is little to choose between them. However, if we follow both threads farther into the process of creating and maintaining the new behavior pattern, anomalies begin to show up in the traditional explanation.

Page 13: [9] Comment

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Don't take any of this as finished -- I'm still looking for the right organization of this section - willampowers99

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~~If reinforcement increase the likelihood of a repetitious behavior, we should observe that the rate of repetition starts out slowly, then as it produces more reinforcements, increases. Initial experiences suggested that this was, indeed, the case. If an animal could obtain food on a ratio of ten presses of a lever for each pellet of food, the first success would take a long time to lead to the next one, but after enough time the presses would be occurring at a brisk rate. If the "schedule of reinforcement" were then changed so the ratio was only five presses per pellet, the presses would occur faster, apparently because of the increased reinforcement rate.~~

Page 13: [11] Comment

I'm having doubts about this whole theme. We need Bruce Abbott's original discussion of this phenomenon. - willampowers99

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~~However, it has been discovered that the apparent increase in pressing rate is illusory, caused by the custom of calculating pressing rate as total presses in a session divided by total time in the session. Examining the detailed record of presses during sessions with different ratios has shown that the contiguous pressing rate, periods when presses occur without interruption, is the same regardless of the ratio. The apparent change of pressing rate with changes in the schedule is the result of including the collection time, the time taken for the animal to collect and consume the pellets, in the calculation of pressing rate, (total presses)/(total time). After every n presses, there would be a collection period that added a little time to the denominator. The more reinforcements that occurred per unit time, the ratio, the larger the denominator became, so it seemed that fewer presses were occurring per unit time. Higher ratios mean a lower rate of reinforcement, and this, misleadingly, corresponds to the lower behavior rate. But the animal is simply pressing the lever as fast as it can between collection times.~~

## E. coli reorganization

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B. F. Skinner explained the acquisition of the first successful behavior in conditioning experiments by saying that organisms spontaneously produce random variations of behavior. PCT adopts that idea but in a different form: the basic theory of reorganization

is that the organization of the system (and hence its behavior) varies randomly at a rate that depends on the amount of “intrinsic error.” Starvation is an instance of such a challenge to the state of the organism. Deprivation is not just an “establishing condition” as Skinner called it. It causes control errors that bring reorganizing processes into action.

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~~building envelope, then adjusting a furnace to counteract the losses. The same work is commonly done by negative feedback control loops, where the sensor and actuator in each space in the building is the simple analog device called a thermostat that doesn't even have a microcomputer in it.~~

In addition to Ashby's abandonment of classical control theory as a model of organisms, certain misconceptions about negative feedback control that have gained currency are an additional obstacle to its acceptance. Early in its history, various commentators noted that all real systems contain time delays. It was thought, apparently, that with any time delay at all, a negative feedback control system would have to become unstable. Error-correcting actions would start too late to prevent disturbances from having immediate effects, and would persist after disturbances disappeared, generating self-disturbance; and the time delay would convert negative error-opposing feedback into positive error-amplifying feedback, with the likely result that the whole system would oscillate violently.

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I disagree with this change. See W.T. Powers manuscript on Emotions: PCT vs. Traditional Explanations and the accompanying figure. Maybe WTP can rule on this change. Error signals is certainly an important term in PCT and gives rise to the perception of feelings in the body as shown by the graphic. - dmg801

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disorders and their treatment is

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the way in which

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Diagnostic and Statistical Manual of Mental Disorders – Fourth Edition, Text Revision)

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While

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“comorbidity” have been invoked to explain the lack of correspondence between diagnostic categories and experience,

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Exploration of common or “transdiagnostic” processes has been a recent innovation that has attempted to explicate underlying pathways of symptom manifestation.

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Tim,

Recently, I heard Bill say that knowing what people are similar to the person in therapy, is not helpful. Each person must be assessed uniquely. And what worked with similar people, may not work with the person in treatment. The DSM-IV approach is to find out what people are like the one in treatment. The PCT approach is to find out what the person in treatment considers to be the problem and what aspects of the person's life is out of control. - dmg801

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the fact that

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There is a large amount of variation within current classificatory categories as well as a lack of clear differentiation between categories;

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Behavior must vary in

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, categories

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will

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We haven't discussed imagination, so hallucinations can't be seen as a basically normal process - willampowers99

See the footnote for two ways we might address this. Pick one. /BN

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Sometimes, auditory		
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are associated with debilitating distress and, at other times, they are a benign, perhaps		
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experience.		
Page 29: [22] Comment		10/14/2010 12:02 AM
This follows from the rest of the para. But are we saying that it's fine for the two Christs of Ypsilanti to think they're Jesus so long as its not distressful to them? Distress to others is a common factor in diagnosis, isn't it? I can imagine someone who sets out to free people from their imprisonment (entrapment in the body, e.g. by killing them) with perfect equanimity, no conflict. Psychiatry is often handmaiden to the law. Will a reader raise such concerns?- bruce.nevin		
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Whereas current models of psychological dysfunction have been constructed by investigating one or more dysfunctional manifestations,		
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by considering the way		
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which the process		
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can be disrupted. As was previously discussed, conflict		
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While conflict of this nature		
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will		
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, and distress will result		
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an		
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of an individual		
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. Other problems can also arise (such as feeling overwhelmed by environmental forces) but a discussion of these other problems is beyond the scope of this paper		



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