Once Around the Loop

An interpretation of basic PCT

By Dag Forssell

Elements of the control loop have been labeled slightly different by different people at different times and for different purposes, whether for a very plain explanation or for more mathematical treatment of the physical functions. Here, I will take you by the hand for a descriptive trip around the loop and do my best to put it all together. Embellishments over and above basic Perceptual Control Theory, especially the discussion of the input function, reflect my understanding—the way I think about it as I watch myself and other people acting and interacting.

Please refer to Figure One on page 3.

One thing that sets control in living things apart from other conceptions of control is the internal reference signal, so I'll start with that right at the top.

The ***reference signal (r),*** a neural signal, specifies the state to which the ***perceptual signal (p),*** another neural signal, must be brought. The reference can be thought of as a want, or a goal, or an aim, or a wish, or a desire, or any word that conveys the state of something to be experienced (the words used are not as important as understanding the function of the signals and components). It is like an example of the perceptual signal as it would be if control were successful, but it is set from inside the person as a whole, not by sensory inputs. High-level reference signals involve memory, as when you recall a certain position, move or experience and in essence think: "I would like to feel like that again." As we develop very high level mental concepts such as love, honesty and science, we specify that we want to experience that too. Some low-level reference signals, however, have nothing to do with our mental development and memory, but seem specified by our genetic makeup. We have built-in, intrinsic references for body temperature, CO_2 in lungs and much more.

The reference signal enters the ***comparison function (c)***, as does the perceptual signal. By engineering convention, the reference signal is assigned a plus-sign and the perceptual signal a minus-sign.

The output from the comparison is an ***error signal (e)***. This signal is the difference between the reference signal, what you want to experience, and the perceptual signal, what you experience right now. Since human beings are living control systems, it should not be surprising that we have many terms that reflect this, just as we have many terms that reflect the reference signal. Terms that come to mind are dissatisfaction, unhappiness, unease, something is wrong, hunger, thirst, fatigue… As an interesting aside, note that the reference signal comes from higher-level systems. We don't necessarily perceive it consciously, since awareness does not include all levels of control at any given time. A simple, elementary control system never perceives its reference signal, but since humans have a great many control systems operating at the same time, another part of us may have an idea. What we perceive is a signal that represents what we experience. It seems consistent with experience that we don't necessarily know what we want, but we have a sense that what we experience is wrong. We likely have a stronger sense of the error signal than we do of the reference signal. You may not like a certain dress, but you don't know quite why. You know something is wrong with this one, but you can't say what it is you do want. So you keep trying on different ones until you find one that does not feel wrong. More obvious examples are the error signal called hunger, which indicates a low level of blood sugar. But you have no idea what blood sugar level your system wants. Same for thirst, which indicates too little water in your blood.

The error signal enters an ***output function (o)*** that processes this error signal into output signals that are sent as reference signals to lower control systems if the loop is somewhere in the hierarchy, or to actuators at the interface with the environment of the nervous system. If you think of this diagram as representing a simple physical control system such as the cruise control in your car or the heating system in your home, the output function can be very simple indeed. But here, it represents an extensive neural network in the form of a hierarchy of control systems.

Actuators* can be glands or muscle fibers where energy is used to greatly amplify the signal, converting it into physical effects such as the release of hormones or the contraction of muscle fibers.

Whatever kind of action we talk about, it is often labeled ***output quantity (qo)***. This is something physical. It may be located deep inside your body (but outside the nervous system) such as releasing adrenaline, stomach acid or sweating, or it may be muscle fiber contractions that combine into actions such as movement of heart, lungs, limbs, jaw or tongue as we move about and talk.

Action/output quantity affects the environment in many ways. Some of these are effects we want, others not and many we don't pay any attention to at all.

What we label action/output quantity is what is commonly referred to as behavior. As you can see, PCT provides an explanation for what behavior is, how it works, and what it accomplishes. More on behavior at the end of this trip around the loop.

Unintended effects include muscle fatigue, heat generation and more. For instance, when you wave your arm, you not only control its position and speed, but create air movement, noise and flapping clothes, and your arm may knock something off a table.

Let us skip ahead to consider the ***controlled variable (cv)***, also called input quantity (qi). Generally speaking, the controlled variable is what the reference signal is all about. The reference signal defines how we want to experience something in our environment. Something that can vary and that we can affect or control: what kind and how much.

As noted, action/output quantity has some physical influence on the unintended effects, but we are more interested in the influence on that which we care about—the controlled variable. Whether you put your shoulder to a door to open it, or put on a sweater to feel warm, or eat to reduce hunger pangs, or step on the brake to stop your car, or ask someone to pass the salt (yes other people are often part of our environment and we use them as we attempt to control), the effect of your action on the controlled variable is described by the ***feedback function (f)***. This term is a fancy name engineers use to cover all the physical effects of the action on the controlled variable. Think of it simply as the effect of your action on the controlled variable, the thing you want a certain way. The effect may be immediate and effective as when you grab a glass and bring it to your lips to drink, or it may be totally ineffective as when you thrust your shoulder against a sturdy, locked door, or it may be indirect as when you compliment an official hoping for favorable treatment. For sure, not all attempts to control are successful.

You may not be the only thing affecting the controlled variable. Our world is full of ***disturbances (d)*** that influence the controlled variable separately and independently. While you may be controlling all the leg movements required to walk across the deck of a ship and keep your balance, the deck may be heaving and wind gusting. These disturbances affect your balance at the same time, so you have to adjust your action to compensate. When driving from A to B, you steer the car to stay in its lane. Disturbances that independently affect the steering of your car include wind, slopes and ruts in the road, so you have to compensate—not to mention major disturbances such as other cars and people that get in the way so you have to compensate by changing your path or speed. The way all these disturbances affect the controlled variable is represented by the disturbance function, which is equivalent to but different from the feedback function.

The arrows in the environment merely indicate the direction of the effects of the physical influences for the purposes of control.

As you can see, the controlled variable is subject to influences from you as well as from other people and things in the environment. The current state of the controlled variable is sensed by ***sensors*** at the interface between the environment of the nervous system and the nervous system itself. Sensors include nerve cells on the retina in your eyes, in your ears, nose, mouth, skin, tendons in all your limbs, and sensors deep within your body sensing carbon dioxide in your lungs, temperature in your body, adrenalin levels, heart contractions and much more.

Signals from all these sensors are processed by the ***input function (i)***. In a very simple control system such as your home heating system, the sensor and input function together consist of a thermometer that measures temperature, the controlled variable. But here the input function, when representing the entire hierarchy, should again be thought of as a neural network that receives the various signals and constructs interpretations of them using both the current input and signals retrieved from memory. The latter is obviously required when we communicate using

**Actuate:* To put into motion or action; activate.
Actuator: Converts a signal or current into action or physical effect.

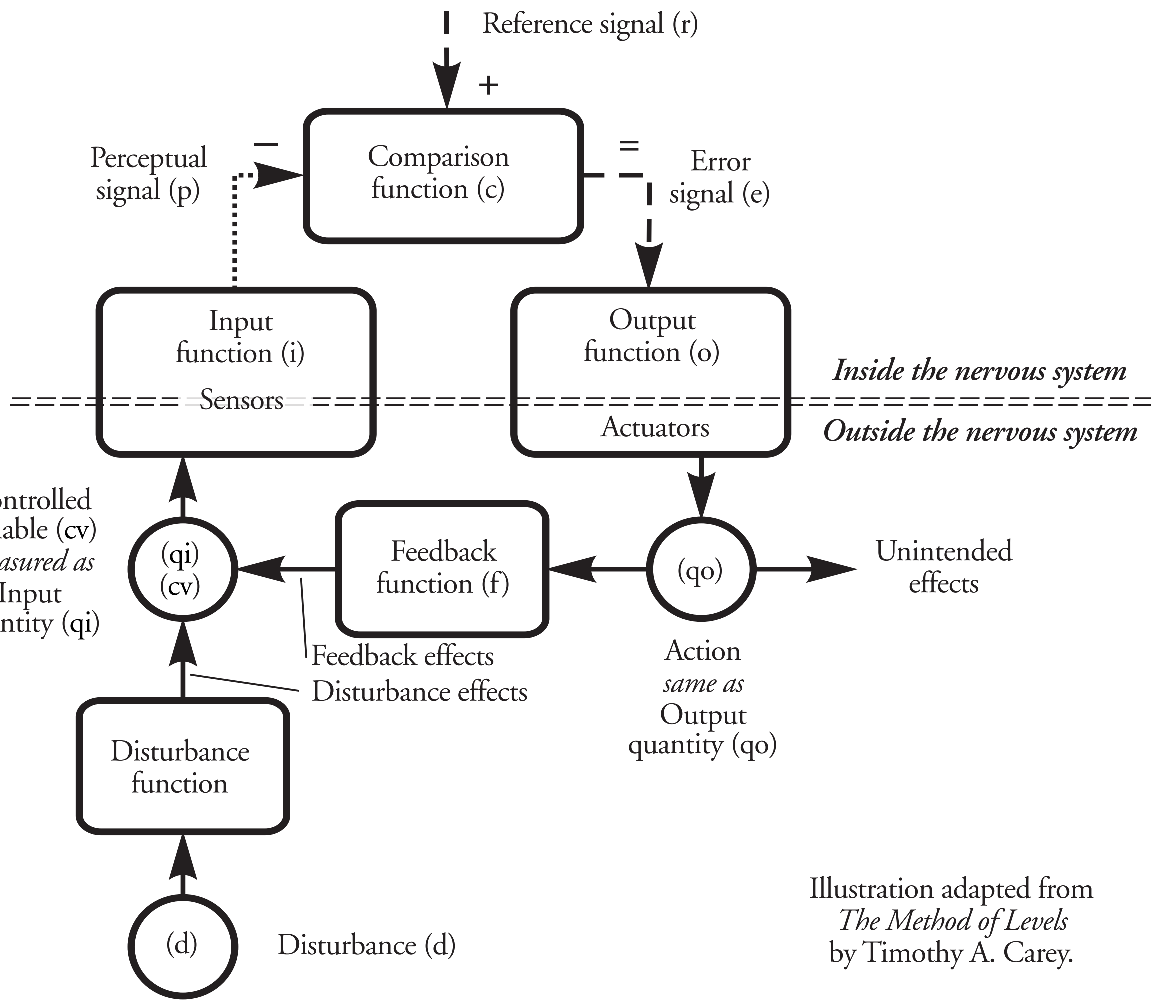

Figure One A closed causal loop: A basic control system acting on the environment.

Note: This illustration can be seen as a single elementary control system, consisting of a few neurons and muscle fibers acting at the interface with the environment, or as a summary of an entire hierarchy, thousands of control systems at many levels, acting in complex ways on the environment.

Arrows in the nervous system indicate neural signals carrying information from one function (neural network) to another. Arrows in the environment indicate physical links that give the output of one function a physical influence on a physical variable. The circles show where physical variables are, or where they could be measured. Functions in the environment usually indicate physical laws that determine how physical variables at the output of the function depend on physical variables at its input.

language. Sound vibrations are sensed by neurons in our ear at the interface with the world outside the nervous system. As these signals are processed up the hierarchy of the neural network, their meaning has to come from prior experiences stored in memory. The fact that memory must be involved begins to explain how we can create high-level perceptions from sensory input such as sound and light any number of ways depending on what memories are evoked. We can replay songs and events from memory, can anticipate what a speaker will say next as we listen, and can visualize wet sand between our toes, a beach, waves, and a sailboat on the horizon while closing our eyes wherever we are. Seems to me that a major part of the perceptions you create when you hear and see someone communicate may come from your memories of prior interactions, while only a small part of your overall impression may come from current sensory input. This provides for sometimes rather subjective interpretations of the world around us and explains how two persons can hear or see “the same thing,” yet construct completely different meanings. We are very capable of “hearing” and “seeing” that which we want or expect to hear and see, as it relates to past experience and convictions. Progressing up the hierarchy of perceptual levels proposed in PCT, signals from sensors combined with signals retrieved from memory are ultimately displayed in our brains in living color and three-dimensional sound as well as non-visual, non-verbal impressions, thoughts, principles, and systems understandings. This is what we experience. This is what gets compared to the reference signal.

While a description like this can give the impression that the loop operates step-by-step, all signals and functions operate simultaneously, continuously in a seamless flow where everything influences everything else all the time.

That’s once around the loop the way I understand it.

Now that we have a rather comprehensive idea of how elements interact in a fully functional control system such as a living organism, I will comment on action, which is commonly spoken of as behavior. Action or behavior is what is visible to an outside observer. What’s inside is invisible. Therefore, attention gets paid to action/behavior and the rest of the system ends up being largely misunderstood in our society today. Parents, educators, spouses, politicians, police—all strive to change the behavior of others (and end up creating lots of conflict in the process). The idea that behavior is controlled by the individual and can be modified by others is widely accepted. But do people control their behavior? Are people even aware of their action/behavior in such a way that it is reasonable to say that they can and do control their behavior?

As you can see from this trip around a control loop, action follows from the comparison of the reference signal (the current want), with the current perceptual signal (the sense of what is right now). Automatically!

The input function of the controlling system perceives nothing but the controlled variable. It does not perceive its own action. Just the same, the thermostat in your home heating system perceives air temperature but knows nothing about the furnace and its behavior. The heating system controls its perception of temperature. It most certainly does not control its behavior. Neither do you.

We are most aware of what we perceive or experience. We can also be aware of what we want or intend through thinking and imagination (PCT deals with these, too, but not this paper). We are much less aware of what we actually do. While the low-level systems controlling movement of our limbs perceive their inputs, not their action outputs, we can be aware of our action/behavior by in effect watching ourselves act because we have massively parallel input functions and perceptual pathways. But to be somewhat aware of what we do, we must make a deliberate effort to pay attention. Normally we don’t. When you left your house on vacation, you may remember that you intended to turn off the stove, but not whether you actually did. You can’t usually remember many details from your last drive or walk to the office, because your system in action automatically brought you where you wanted to be. You did not have to pay attention to your actions to get there.

Action/Behavior is the (automatic) means by which we act on our world in order to experience it the way we want it. Thus we control what we perceive.

Behavior is the control of perception.

One obvious consequence of this understanding of what behavior is, how it works, and what it accomplishes, is a change of focus from action/behavior (which is of little interest), to understanding and wants (a complex system of reference signals) because the latter drive the system, depending also on current circumstances. Changing from trying to modify behavior to asking questions, exploring a person’s wants and the personal reasons for them, makes a huge difference to personal relationships, personal effectiveness, and conflict resolution.

For more on the effect of focusing on what people want, I recommend Jim Soldani’s paper on *Effective Personnel Management.*

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Appreciation is due Tim Carey, who inspired me as I worked on Figure One for *The Method of Levels*, and Bill Powers, who reviewed this explanation.