PCT for the Beginner

Perceptual Control Theory (PCT for short) is a theory about how organisms work. The basic idea can be stated briefly: organisms act on their surroundings, the environment, so as to control the effects the environment is having on them. This is the exact opposite of the main theory that has been adopted by the life sciences, including neurology, biology, and a large part of psychology. The oldest traditional theory, and still the most widely used, says that the environment near organisms stimulates their senses, causing the organisms to respond -- to behave -- as they do. PCT says that is wrong; instead, organisms generate actions that affect the environment near them, thus altering that environment and creating or changing experiences at many levels in the way desired or intended by the organism. The difference is a matter of which is in control: the organism or the world outside the organism. According to PCT, the organism is the controller. It controls what happens to itself, by using the external world.

At first glance this reversal does not seem reasonable, because the world outside an organism is far larger and far more powerful than any organism can be. An organism can't affect the rising and setting of the sun, moon, and stars. It can't turn back a hurricane, or stop an earthquake. When natural disasters occur, organisms are overwhelmed and die. How can anyone claim that organisms control what happens to them?

This kind of question can actually be applied to any theory about how organisms work. Does "survival of the fittest" really imply that every organism survives, or even that every organism in a "fit" species survives? No. It does not imply that a fit organism can survive every disaster such as falling into a volcano. It means only that more fit organisms survive than unfit ones. It's a matter of degree. For the species to survive, enough individuals must survive to propagate it.

So it is for PCT. Organisms that control have a better chance of surviving than organisms that do not control. There are limits to what this kind of organization can do, but they are much broader than the limits on what organisms that work some other way can do -- for example, hypothetical organisms that simply react to external events as a doorbell reacts to having its button pushed.

PCT says that every behavior produced by any organism has the purpose of affecting some consequence of environmental events, some consequence that has detectable effects desired by or necessary to the organism itself. Organized behavior, according to PCT, is never produced for any other reason. Does this mean that this behavior always works, or that it can still work even when vastly larger forces are also affecting the organism? No, of course not. When such vastly larger forces act, they overwhelm the organism and quite likely the organism will die. Adopting PCT does not require abandoning common sense.

The ability to control gives an organism very powerful ways of surviving. When the great tsunami of December 26, 2004 occurred, we saw horrible scenes of disaster with every tree stripped, every house damaged or destroyed, every dog and cow dead. Yet we also saw a few miserable human beings staggering through the ruins, looking for their friends and loved ones, or just trying to help. There they were, alive and functioning, despite having been overrun by the giant wave. They were the ones who were able to struggle into shelters, up trees, up hills; to run or swim or just hang on; to find a boat or a floating tree-trunk; to modify the effects of the nearby environment on themselves sufficiently to prevent the result from being lethal. Because they could control what happened to them just well enough, they survived even if many didn't. If they hadn't been able to control as well as they did, they would have died, too. Thousands of animals died because they could not control quite well enough -- it seems likely that more human beings survived than larger animals, per capita, simply because human beings can control in more complex ways than animals can.

But lest this advantage be overstated, we should also note that organisms do not necessarily have to have the most complex control systems to survive. It is doubtful that the tsunami bothered seaweed or plankton or fish or bacteria or seagulls very much. One way in which organisms control what happens to them is to alter their own forms from one generation to the next, to avoid the disasters they can't resist. They find niches, places or conditions where they are relatively safer, where disturbances can't reach them or where the same disturbances might instantly destroy a larger or more complex organism. All started off in microscopic form and, where that was the safest form, stayed that way. Others in different places and circumstances grew larger and changed more, enough to give them greater control to deal with greater exposure to deadly disturbances.

In a manner of speaking, there is really only one organism, called Life. Life survives by altering anything, including itself that reduces its capacity to survive. It does this not perfectly and instantly but well enough and soon enough that we human beings and all those other forms we living control systems have taken are still here. That is *why* we are still here. Those that did not control sufficiently well are gone.

How control works

The word control is used in many ways, but there is only one way it is used in PCT. To control something is, in PCT, to act on it in such a way as to bring it to a predetermined state and maintain it there. Controlling is not influencing, affecting, determining, or causing something, because those words can be used properly even if there is no predetermined state and even if the thing under control is not maintained in that state. If a disturbance occurs that tends to change the thing being controlled, a PCT control system will alter its action in just the way required to cancel most of the effect of the disturbance, so the controlled thing or variable doesn't change significantly. This calls for an example.

In PCT it is proper to say that the driver of a car controls several variable aspects of the car -- examples are its speed and its position on the road in the left-right or lateral direction. The driver uses the accelerator and brake as the means of controlling the speed, and the steering wheel as the means of controlling the lateral position. Let's focus on control of lateral position.

Driving down a long straight road, the driver attempts to keep the car in what he thinks is the center of its lane. We have to say "attempts" because there are many influences that can push the car to one side or the other, and those influences can be almost as strong as the influence of the steering wheel. If one front tire is soft, the car will tend to veer toward that tire; a tilt in the roadbed or a bump can send the car off its path; a crosswind can apply forces to the car that, by themselves, could easily push the car out of its lane and off the road. The term "influence" is used here because none of these forces on the car is acting alone; the final effect results from all these influences combined, not just from one of them. Note that no one influence, not even the influence of the steering wheel, would be said, in PCT, to "control" the path of the car.

The driver's means of control is the steering wheel and its linkage to the front wheels and tires of the car. By turning the steering wheel, the driver can create a force acting on the car to the left or to the right. This influence on the car's path is the only one the driver can vary; all the others happen independently. What is required if the car is to continue down the center of its lane?

Clearly, the sum of all independent influences, which we can sum up as a net "disturbance," produces a net force on the car to the left or right, small or large. For the car to continue in a straight line, the steering wheel must be turned left or right just enough to create a force opposed to and equal to the current sum of all the independent influences. If this balance is not quite perfect, so the car moves a little to the left or right, the angle of the steering wheel must be adjusted first to produce a restoring force a little larger than the net disturbance (to move the car back where it belongs), then an opposite force to stop the lateral motion, and then once again a force equal and opposite to the net disturbance. When this happens correctly, we can say that the car's lateral position is being controlled relative to a reference position near the center of the lane.

The big question is now how this adjustment of the steering wheel can be produced. Before discussing the PCT solution, let's look at three suggestions that have been offered about how the driver has to be organized inside for this control process to work as we observe it.

The "changes" model

The first kind of suggestion, offered long ago, would lead us to say that the driver must respond to changes in the car's position by changing the wheel angle in the opposite direction, thus opposing the disturbance that altered the car's lateral position. This is actually quite close to the PCT explanation, but it has at least one fatal flaw: the idea that the driver responds only to changes. This is a flaw because each response starts where the previous one left off, so the effects of a series of left and right changes are cumulative. Since the driver cannot sense each deviation with infinite precision, nor produce responses that are precisely calibrated to be exactly proportional to the deviations, there will be small errors after every change, and the total error will simply grow as time goes on and hundreds or thousands of tiny errors build up. There is no anchor for this kind of system; responding only to changes does not restore the car to a particular path. It simply slows the speed with which the car drifts off course. An attempt to drive 20 miles down a straight road in a crosswind by this means would end up with the car in a ditch.

The compensatory response or "cue" model

A second suggestion was that the driver senses *cues* in the environment that reveal the presence of disturbances, and responds to them in the direction that would *compensate* for the effects of the disturbances on the car. This idea is even worse than the first one because it offers a qualitative solution for a problem that is highly quantitative in nature. It is not enough that the driver respond by turning the wheel in the right direction; the wheel must also be turned by exactly the right amount -- otherwise the car will fail to return to the proper path or else will shoot past it. Looking at dust or leaves blowing across the road, or smoke drifting sideways from a chimney, or trees tossing this way and that (all of which have been offered as examples of "cues"), is not going to provide information about exactly how far the steering wheel must be turned, or for how long, and how it must then be adjusted to end the correction. There is no way this kind of model could steer well enough: its errors would accumulate even faster than those of the first model.

The calculate-and-execute model

The third suggestion makes more sense than the first two and conceivably could work. Broadly stated, it says that after each disturbance, the driver observes and analyzes the relationship of the car to the road, and calculates how much the angle of the steering wheel must be changed, and in what time pattern, to restore the car to its proper position in the lane. Then the result of the calculation is executed. This is actually how many scientists now (mistakenly) believe this sort of behavior is accomplished.

Unfortunately for this idea, the actual computations required to make this idea work are staggering in their complexity, and the precision of action required is far, far beyond what any driver could produce using muscles and nerves. Not only must the magnitudes of all disturbances be known at all times with high precision (that alone is a show-stopper), but the aerodynamic and inertial properties of the car, the steering linkage ratios and degree of play, and the properties of the muscles that work the driver's arms must be known with equal precision. Large matrices of simultaneous equations must be solved, and then, once the required steering wheel angle or force is known, the driver must create the calculated patterns of angles or forces without any errors. Perhaps an artificial system backed up by a fast and powerful computer (with a lot of knowledge about physics built in) could make this work for a while, but as a model of a real driver's way of steering a car it is entirely implausible.

The PCT model

That brings us to the PCT model. The PCT model uses an organization called a "negative feedback control system," which was first analyzed as a formal and general control system design in the 1930s, and which the people who invented the three explanations given above evidently did not know about or simply misunderstood. Perhaps the problem was that intelligent and creative people like to find their own explanations for new phenomena, so when they found what seemed to be an explanation they failed to look further for an idea that would work better. The negative feedback explanation never occurred to them. When they did hear about it, they rejected it because they thought they already had a perfectly good explanation (never having seen what a really good explanation looks like).

Negative feedback is good, positive feedback is very bad, if you're designing control systems. If a crosswind is blowing the car to the right, the driver must respond by establishing an angle of the steering wheel to the left (the negative of right). If the driver were organized for positive feedback, the deviation to the right would result in a steering effort to the right, which would increase the deviation even more, which would cause more steering effort to the right, with an inevitable result that hardly needs to be spelled out.

Negative feedback simply means reacting to deviations in the direction that is opposed to the deviations, rather than the direction that increases the deviations (which would be positive feedback in engineering terms, even if not in popular usage). The deviation itself is the basis for the action, so there must always be some small amount of deviation -- but it can be so small as to be barely detectable. This way of achieving control dispenses with all the complex calculations that the calculate-and-execute model requires. This idea bears a family resemblance to the first idea described above, but we aren't finished yet.

The control system detects deviations and acts according to their direction and size. This means it acts when disturbances occur. Disturbances start to produce deviations, and the first tiny deviations cause actions that tend strongly to restore the controlled thing to its proper state, automatically opposing the disturbances without even having to know what they are. This is a simple, fast, effective way of controlling things that is used in almost all artificial control systems.

The idea of a "deviation" implies not only something variable that is being controlled, but something that does not depend on the controlled variable: the standard with reference to which the deviation is measured. Clearly there must be a second input to the control system beside the measure of the thing being controlled: a reference input that defines the goal of control. In the case of the driver, it specifies where the car is intended to be in its lane. That is the anchor that prevents the car from wandering gradually off the road. Note that if the reference standard changes that, too, creates a deviation which the control system will act to correct.

The problem that most likely delayed acceptance of the PCT solution is that in a negative feedback system something strange happens to cause and effect. They go in a circle. The driver's hands cause the steering wheel to turn and the front wheels to angle right or left. That produces a force that makes the car deviate to the right or left. And that deviation causes the driver's hands to move the steering wheel. Result: the movement of the driver's hands causes the movement of the driver's hands.

Prior to the invention of the theory of negative feedback control, there was only one way to handle this circle of causation: break it up into a sequence of events. First the driver's hands move the wheel and create a force on the car. Then the force on the car causes the car to deviate. Then the deviation causes the driver's hands to move the wheel again, or some more. Now we don't have the driver's hand movements causing the very same movements; the sequence makes each effect separate from its cause.

That approach is satisfactory in all respects but one: it doesn't describe what actually happens. This same flaw appears in all three of the explanations described above. If you drive or watch a driver, you don't see a sequence made up of steering movements alternating with changes in the car's position. You see both happening at the same time. While the driver is turning the steering wheel, the position of the car is changing. As the car's position approaches the correct position, the steering wheel smoothly comes to a final steering angle where it becomes constant. Everything is changing or stops changing at almost the same time. There is no sequence.

The engineers of the 1930s (and some of their predecessors back into the 19th Century) found the mathematics that could handle this simultaneous closed loop of causation without having to change it into a fictitious sequence. They used simultaneous differential equations, and started the automation revolution that advanced rapidly during World War 2 and is still with us. With that mathematical tool we can now show that a negative feedback control system acts as a single unit with all variations, at input, output, internally, and externally, occurring at the same time. That is the basic fact we need to know here.

Now when we think of control, we don't think of a sequence, but of a process that starts with one situation and simply changes smoothly into another one. Your actions cause whatever you're controlling to approach the state you want, the action changing smoothly all during the approach and stopping just as the intended result is achieved. Or if not smoothly, then in steps during which all the changes still occur at the same time while changes are happening. When varying disturbances appear, the opposing actions change right along with them, keeping them from having much effect.

We have another word for controlling: *doing*. When we "do" something, we are actually controlling something, making it happen by acting on the world. If disturbances come up while we're acting, we simply make the action a little different and keep going. If somehow the action isn't quite right, so the "doing" starts to change, we make another adjustment and keep going. Controlling is so natural and so easy that it doesn't seem to take any effort. We just make it happen.

This is bringing us near the end of understanding the basic organization of PCT. The basic model can be laid out now very easily.

Perceptual control theory

The basic PCT model applies to one single control process; it is part of a larger model called "Hierarchical PCT" or HPCT that is made of many levels, each level containing many basic control units. By defining the parts of the basic model appropriately, however, we can apply it to any particular control process, something as simple as a spinal reflex, or something as abstract and general as controlling a self-concept. At any level of complexity, the basic parts of the model are the same.

First there is *perception*. To control something, you have to perceive its present state. Then there is *action*. To control something, you must act on the world in such a way as to alter the perception -- get more or less of it. And that leaves one loose thread to be gathered up.

How does the driver know when an action is called for? The control task was defined as keeping the car in its lane, but how does the driver know whether the car's position is right or left of where it "should be"? What tells the driver where it should be? The answer has already been given several times.

It's easy for the driver to see where the car *is* in relation to its lane. But nothing in the scene outside tells the driver where the right position is. That has to be learned, and more important, it must exist in the driver as a kind of standard against which the currently-perceived position is judged. The current perception is *compared* with the standard and the difference determines which way the action will go and how much action there will be. So negative feedback control is made up of three basic processes: perception, comparison, and action. They all go on at the same time. The external world supplies a fourth concurrent process: the feedback effect of the action on the perception.

The driver must have a mental picture of how the scene in the windshield will look when the car is in its lane. We call this a "reference perception" or "reference signal", or we attach the name of the controlled perception: "reference position." When the actual perception matches the internally-generated reference perception, the car is as close as this driver can get it to being in its lane. If it's not really in its lane, the driver won't know that, and will faithfully control the car so it's a foot or three feet to the right or left of where a driving instructor would prefer to see it. How mistakes like that get fixed is a different story having to do with "reorganization", a subject we will not open here. The point is that the driver controls not the actual position of the car, as some external observer might see it, but *the perceived position*. And that, in a nutshell, is why this theory is called *perceptual* control theory. We control the perceived world, and only approximately the actual world.

Obviously, reference perceptions must be adjustable. If they weren't, a driver could never get out of a lane once in it. To take an off-ramp at a cloverleaf interchange, something must change the reference position. As the reference position changes, the action of the control system makes the real-world change, which causes the perception to change so it tracks right along with the change in the reference position. The actions make the actual perception continue to match the changing reference perception all the way up the ramp, onto the frontage road, along the streets, around the corners and home.

It should not come as a surprise to hear that this changeable reference perception, or reference signal, or reference position, is being altered by another control system, a higher-level system that is concerned not with staying in a traffic lane but with getting home. The getting-home control system is *using* the staying-in-the-lane (or elsewhere) control system as part of its means of control. It gets home by, in part, adjusting the position on the road where the lower system is told it wants to be.

That is a taste of how the hierarchy of control works, and is not part of this discussion. And it is a good place to stop.

Note:

Bill Powers sent me this document for editing in 2007. The eventual end product turned out to be a much shorter paper. This document is what Bill originally sent me. My only editing has been to add Bill's copyright, format the document, including the headers, remove some extra spaces between words, and delete a couple of unnecessary commas. Otherwise, it is the document Bill sent me. I think it is a worthy addition to his writings.

Fred Nickols (13 Nov 2015)