Closed Loop

Threads from CSGnet

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Members of the Control Systems Group receive Closed Loop quarterly. For more information, contact Ed Ford, 10209 N. 56th St., Scottsdale, AZ 85253; phone (602)991-4860.

CSGnet, the electronic mail network for individuals interested in control theory as applied to living systems, is a lively forum for sharing ideas, asking questions, and learning more about the theory, its implications, and its problems. The "threads" in each Closed Loop, stitched together from some of the net's many conversations, exemplify the rich interchanges among netters. Some issues of Closed Loop also feature research reports by netters, in hopes of initiating new conversations.

There are no sign-up or connect-time charges for participation on CSGnet. The Internet address is "CSG-L@UIUCVMD" while CSG-L@UIUCVMD is the Bitnet address. Messages sent to CSGnet via these addresses are automatically forwarded to over 120 participants on five continents, as well as to hundreds of NetNews (Usenet) sites where CSGnet can be found as the newsgroup bit.listserv.csg-l. CSGnet also can be accessed via CompuServe, AT&T Mail, MCI Mail, or any other computer communication service with a gateway to Internet or Bitnet. For more information about subscribing to CSGnet, contact Gary Cziko, the network manager, at G-CZIKO@UIUC.EDU, phone him at (217)333-8527, or send a FAX to (217)244-7620.

Portable PCT Demonstrations

In "A General Feedback Theory of Human Behavior: Part II," by W.T. Powers, R.K. Clark, and R.L. McFarland *(Perceptual and Motor Skills 11,* 1960, 309-323), the authors describe a series of demonstrations showing the negative-feedback closed-loop operations of a "Portable Demonstrator"—that is, a normally functioning human being. Powers offered additional demonstrations which illustrate the principles of his theory of psychological control systems (now known as perceptual control theory, or PCT) in his 1973 book, *Behavior: The Control of Perception* (Aldine, Chicago; currently available from De Gruyter /Aldine, Hawthorne, New York). In particular, his 'Parable of the Rubber Bands" (pp. 241-244) has provided other perceptual control theorists with a foundation upon which to build both provocative and enlightening "hands-on" illustrations of the control-system basis of human behavior. For example, Philip J. Runkel has used rubber band demonstrations to introduce PCT concepts to behavioral scientists in his *Casting Nets and Testing Specimens: Two Grand Methods of Psychology* (Praeger, New York, 1990), while family counselor Edward E. Ford has written in his *Freedom from Stress* (Brandt Publishing, Scottsdale, Arizona, 1989) of using rubber band demonstrations to teach PCT concepts to his clients.

The following thread from CSGnet explores some possibilities for using the rubber band demonstration and other portable PCT demonstrations—most needing no fancy equipment—as practical means to understanding perceptual control theory and its implications. To introduce the thread, two sets of instructions for rubber band demonstrations are included. Readers who are unfamiliar with "rubber banding" are especially encouraged to read the brief instructions given immediately below (written by Dag Forssell for CSGnet, based on suggestions by Powers and Runkel) and to try the demonstration themselves before proceeding to the thread. Chuck Tucker's instructions for a more elaborate rubber band demonstration originally appeared in *Continuing the Conversation: A Newsletter of Ideas in Cybernetics* (12), Spring 1988, 16-19, and are reprinted here with the author's permission.—Ed.

A Do-It-Yourself Demonstration of the Phenomenon of Control
by Dag Forssell

You can demonstrate control in action to yourself and others, wherever you are, with the simple prop of two rubber bands joined by a knot. Just get a friend to help you play a game. This game will illustrate all of the elements of human control, their interactions and functional relationships.

Get two small rubber bands and join them in a knot. You hook a finger into the end of one rubber band, and your friend hooks a finger into the other. Tell your friend something like: "You are the experimenter. Move your finger as you like. Watch what I do. When you can explain what is *causing* me to do what I do, let me know."

When you sit down with your friend, place yourself so that the knot joining the rubber bands lies above some mark you can see, but which your friend probably will not notice a small mark on a table top or paper, or a piece of lint on your knee, something like that. As your friend's finger moves, move yours so that the knot remains stationary over the mark.

By agreeing to keep the knot over a target, you have adopted a standard for the position of the knot as your want. When something acts to disturb the position of the knot, you will restore the knot to its position over the mark. You will move in any way necessary to do that.

Of course, you can't keep the knot stationary if your friend moves faster than your natural reaction time can handle. Some people playing this game seem to want to move abruptly, too fast. If that happens, ask your friend to slow down. The lessons to be learned will be much more obvious to both of you if you are able to keep the knot continuously over the mark. You might say: "Don't move so fast. I can't keep up with you."

Your friend will soon notice that every motion of his/her finger is reflected exactly by a motion of yours. When your friend pulls back, you pull back. When your friend moves inward, you move inward. When your friend circles to his/her left, you circle to your left. You must do that, of course, to keep the knot stationary. Your action illustrates very plainly the phenomenon of control—that we act in opposition to a disturbance to maintain a perception we want.

Notice that you perform many different acts to maintain your perception of the knot remaining over the mark. You move your finger to the left, to the right, forward, backward, diagonally at varying speeds.

Most people, when they announce that they can explain what is causing you to do what you do, will say that you are simply imitating what they do, or mirroring it, or words to that effect. Some will put it more forcefully: that whatever they do, you are acting in opposition to it. Almost all will say or imply that they are the cause of your behavior.

A few people will notice that the knot remains stationary. That is an excellent observation, but not quite an explanation of cause. Agree, but keep asking: 'What is causing me to do what I do?" Most people will say that your intent is to do something in reaction to them. But then you deny that. They will eventually give up and ask: "All right, what is causing your behavior?" Then you explain that you have been keeping the knot as close to the mark as possible, and that any deviation caused you to do what you did.

No, you tell your friend, your purpose has not been to oppose his or her intention. Your purpose has not been to frustrate him/her. If, instead of his/her finger, a machine had been hooked to the rubber band, you would have moved as you did. Your purpose was to keep the knot motionless over the mark. That's all.

You moved to oppose any motion of the knot away from the mark, not to oppose him/her. Your motivation had nothing to do with what he/she might have been trying to do; you did not care. You watched only the knot and the mark. Indeed, if you had not been able to see your friend's moves, your actions would have been identical. Watching the knot and the dot, you could not pay any attention to your friend's movements.

Reactions of "experimenters" will vary widely. A few will accuse you of being devious and go away grumbling. Most will be surprised, even dumbfounded, to have missed the obvious. A few will find many of their previous ideas so shaken that they will think about it for days or weeks afterward.

Play the game with your friend. Play it with several friends! Suppose you played this game with 10 of your friends. Let us say that one was in fact able to explain (without coaching) that you were only holding the knot steady over the mark and acted to keep it there. That means that nine out of 10 failed to recognize the phenomenon of control when it was right in front of them. They have never been shown what control is or how to recognize it. Without a paradigm of control, they are quite literally blind to a phenomenon that is fundamental for all living organisms.

Let us play the game again, with more visibility for both you and your friend. This time, you experiment on your friend and play the game on a piece of paper with a clearly marked target. Ask your friend to record his or her movements by holding a pen against the paper as he or she moves in response to your disturbing influence on the knot. Now we can focus on your friend's visible behavior and ask the question: 'What can a reasonable observer conclude about your friend based on what the observer can see of your friend's behavior?" What is your answer? Would you agree that you cannot draw any conclusions about your friend from his/her behavior? Your friend's behavior is clearly a product of what your friend wants, combined with the disturbances acting on what your friend is controlling. His/her behaviors are what they have to be under the circumstances, given all of the other elements and their influences.

This demonstration clearly recognizes wants and perceptions, the difference between them, thoughts that provide instructions for action, the variable we control, the actions themselves, other influences on the variable, and the extraneous, sometimes confusing byproducts of our actions.

Demonstrating Control Theory
by Chuck Tucker

In this paper I present the procedures that I have used in classrooms and conferences for demonstrating Powers' control theory. These procedures are derived from his discussion of experiments in *Behavior: The Control of Perception* (1973, 241-244). I have modified them only to the extent that I have written explicit instructions to be used by the demonstrator and a volunteer. I have found the demonstration to be a powerful tool for explaining the fundamentals of control theory. I will present the demonstration exactly as I have done it and mention some implications and possible modifications at the end of this paper.

Materials

This demonstration requires: (1) six sheets of poster paper; (2) twelve 6″ pieces of masking tape, to attach the poster paper to a smooth wall or chalkboard; (3) two short pencils of different colors (I have used black and red); (4) two large rubber bands tied together with a knot; (5) a marking pen; and (6) 5″ x 8″ index cards with instructions. An easel with a pad could be used instead of the poster paper.

Introduction

I think it is very important to get the members of the audience or class involved in the demonstration, so I begin by reading this statement from an index card: "I will, with the help of another person, perform a series of demonstration exercises to illustrate the basic principles of Powers' control theory. The demonstrations are slight modifications of those found in the book *Behavior: The Control of Perception.* I want all of you to take part in these demonstrations. It will not be useful to you unless you do take part. For each demonstration, I want each of you to watch and listen to the volunteer, and answer the question: What instructions or directions is he/she using to perform the movements in this demonstration? The volunteer will be asked to read and follow some directions, and your job is to figure out what instructions are being followed by him/her. I will give you a sheet of paper to write your answers on after each demonstration."

Then I hand out a single sheet of paper to each person, which states:

CONTROL MODEL DEMONSTRATIONS

INSTRUCTIONS: There will be six different demonstrations of a control model. For each demonstration, answer this question about the volunteer: WHAT INSTRUCTIONS OR DIRECTIONS ARE BEING USED TO PERFORM THE MOVEMENTS IN THE DEMONSTRATION? You must watch each one carefully and answer the question for each demonstration after it is completed and before the next one begins. THANK YOU.

DEMONSTRATION I

The instruction(s) used by the volunteer is (are): ________________
____.

The remainder of the sheet has a separate question for each demonstration.

Beginning the Demonstration

I begin the demonstration by reading this statement from a card: "I want someone to volunteer for some demonstration exercises. It will not be harmful to you, and all that is required is that you can read and follow directions. If you wish to volunteer, please raise your hand." I then motion to one of the persons with a raised hand to come to the front of the room, while I say 'Please come to the front of the room." Then I say "Thank you for volunteering." I introduce myself (if necessary) and have the person introduce himself/herself to me. Then I say "Please take these cards and read the top one and follow its directions." I then hand the volunteer a stack of index cards with printing on them.

The Exercises

The first card in the volunteer's stack states: "DEMONSTRATION EXERCISES—MOVE THIS CARD TO THE BACK OF THE STACK AND READ THE NEXT CARD."

The statement on the next card is: 'There are several cards, each containing a different set of directions. Read each card carefully before doing the exercise. I will ask 'Do you understand?' and you should say 'Yes' or 'No.' If you say 'Yes,' I will ask 'Are you ready?' You say 'Yes' or 'No.' If you say 'Yes,' we will do the exercise. Now move this card to the back of the stack and read the directions on the next card."

The next card states: "MOVE THIS CARD TO THE BACK OF THE STACK AND READ THE NEXT CARD."

The next card states: "EXERCISE I—In this exercise, you will be given a pencil. Take it in your hand and place it on the paper, holding it steady until you are asked if you are ready. When you are ready, you will move the pencil so that you draw the *same* diagram that I am drawing. Do this at *the same time* that I am drawing my diagram. Move this card to the back of the stack when you understand this exercise."

While the volunteer is reading this card, I take a sheet of poster paper, write "I" in its upper right-hand corner with a marking pen, and tape it to the wall or chalkboard with a piece of tape on each corner. When the volunteer moves the card, I say, "Do you understand?" If the volunteer says, "No," then I say, 'Please read the card again." After the volunteer has read the card, I again ask, "Do you understand?" I repeat this until the volunteer answers, "Yes." (I have not had to ask a volunteer more than once to reread a card.) After the "Yes" answer, I give the volunteer a black pencil, and I take a red pencil. The different colors allow the audience to distinguish between my drawing and the volunteer's. I then ask: "Are you ready?" and when the volunteer answers, "Yes," I say, "Let's begin."

Standing in front of the poster paper, I slowly begin to make a drawing from an index card without letting the audience or the volunteer see the card. Although my drawing is complicated, it need not be for the demonstration. I try to have a drawing that has straight, sawtooth, and curved lines. I make the drawing about a foot square.

I begin with a vertical line, then make a 90-degree horizontal line, and then several squares which do not overlap. These are followed by several arcs and a sawtooth line, another horizontal line, another vertical line, concluding with an s-shaped line. The drawing is done at a slow pace, and none of the lines repeat the same path, although they do intersect one another. When I finish my drawing, I remove my pencil from the paper, turn to the audience, and say, 'Please answer the question on your answer sheet for Demonstration I." Then I turn to the volunteer and say, "Please read the next card."

The next card states: "MOVE THIS CARD TO THE BACK OF THE STACK AND READ THE NEXT CARD."

The next card states: "EXERCISE II—In this exercise, you will take a pencil in your hand as you did in Exercise I and hold it steady on the paper until you are asked if you are ready. When you are ready, you will move the pencil in the same *directions as my pencil, always keeping your pencil at a distance of one foot (12") and on the same level or same plane as my pencil.* Keep your pencil on the paper at all times. Move this card to the back of the stack when you understand what you are to do in this exercise."

While the volunteer is reading the card, I remove the poster paper for Exercise I from the wall or chalkboard and put up a new sheet marked

"II." Then I ask the same questions that I did for the first exercise, and I stand in front of the paper when the volunteer is ready.

For Exercise II, I make the same drawing as I did for Exercise I. When I complete the drawing, I ask the audience to answer the question for Demonstration II, and then say to the volunteer: "Please read the next card."

The next card states: "MOVE THIS CARD TO THE BACK OF THE STACK AND READ THE NEXT CARD."

The next card states: "EXERCISE III—In this exercise, you will take the pencil in the same hand as in Exercise II, but you will place that hand through a rubber band. Always hold the pencil on the paper so a mark is made by it. I will place my finger through the other rubber band and then on the paper. *Watch the knot between the rubber bands, and always keep it on the same 'spot' or place on the* paper. The knot will move, but keep it in the same place. Move this card to the back of the stack when you understand."

While the volunteer is reading this card, I remove the paper and replace it with another sheet marked "III." Then I ask the familiar questions of the volunteer about his/her understanding. I show the volunteer how to hold the pencil and the end of the rubber band at the same time, and then I stand in front of the paper with my pencil, and begin my drawing.

My drawing for this exercise is quite different from that in the previous exercises. Again I have it on a card, and I look at it while drawing. I begin with a vertical line, then make a right angle with a line toward the volunteer, then make another right angle with a vertical line, and then a horizontal line. I follow these with several arcs, then a horizontal line toward the volunteer, ending with a vertical line and an s-shaped line. I remove my pencil from the paper when I finish my drawing, and I say to the volunteer: 'Please read the next card." I then ask the audience to answer the question for Demonstration III.

The next card states: "MOVE THIS CARD TO THE BACK OF THE STACK AND READ THE NEXT CARD."

The next card states: "EXERCISE IV—In this exercise, you will hold your pencil on the paper in the rubber band as you did in Exercise III. I will make a 'dot with a circle' on the paper. Your task is to keep the knot of the rubber bands exactly over the 'dot' inside of the circle, even when the knot moves. Always keep the knot over the 'dot.' Move this card to the back of the stack when you understand."

While the volunteer is reading this card, I remove the paper and replace it with another marked "IV." In addition, with the marking pen, I make a dot surrounded by a circle in the middle of the paper. Then I ask the same questions of the volunteer as before, regarding his/her understanding. (By this time, no one has ever had any problems following the instructions.) Then I show the volunteer again how to hold the rubber band and the pencil, and I proceed to make a drawing different from those in the previous exercises.

I begin this drawing with several arcs toward the volunteer, then I draw several arcs moving away from him/her. This set of lines is followed by a horizontal line away from the volunteer, a vertical line at a right angle, a horizontal line toward the volunteer at a right angle, and a short vertical line. When finished, I remove my pencil from the paper and ask the audience to answer the question for Demonstration IV; then I ask the volunteer to 'Please read the next card."

The next card states: "MOVE THIS CARD TO THE BACK OF THE STACK AND READ THE NEXT CARD."

The next card states: "EXERCISE V—In this exercise, you will hold the pencil in the rubber band as you did in Exercise IV. I will make the same 'dot with a circle' diagram as I did in the last exercise. This time, your task is different. Your *task is to keep the knot of the rubber bands exactly over the vertical line ABOVE the 'dot' even when the knot moves.* Always keep the knot over the place where the line and circle intersect *above* the 'dot.' Move this card to the back of the stack when you understand."

While the volunteer is reading this, I remove the paper and replace it with another, marked "V." On this paper, with the marking pen, I make a dot surrounded by a circle, with four small lines on the circle, 90 degrees apart from each other. This configuration looks like a target.

When the volunteer understands and is ready, I make the same drawing as I did for Exercise IV. When finished, I ask the audience to answer the question for Demonstration V, and then I say to the volunteer: 'Please read the next card."

The next card states: "MOVE THIS CARD TO THE BACK OF THE STACK AND READ THE NEXT CARD."

The next card states: "EXERCISE VI—In this exercise, you will hold the pencil in the rubber band as you did in Exercise V. I will then make the same 'dot with a circle' diagram as I did in the last exercise. This time, your task is different. *Your task is to keep the knot of the rubber bands inside of the circle even when the knot moves.* Always keep the knot within the circle. Move this card to the back of the stack when you understand."

While the volunteer is reading this card, I remove the paper and replace it with another, marked "VI," then I draw a "target" on the paper. When the volunteer understands and is ready, I make the same drawing as I did for Exercise V. When finished, I say to the volunteer: "Thank you, we have finished all of the exercises. You did very well." I ask the audience to answer the last question on their sheet for Demonstration VI.

When discussing this demonstration, I put the drawings for each exercise up in full view. I have the volunteer standing next to me at the front of the room. After I put up each drawing, I ask, 'What was the instruction he/she used to make this drawing?" and members of the audience are called upon to read their answers. I initially focus on the answers which are in error, and then I mention those which are correct. After getting a few answers which are in error, I ask the volunteer to read the actual instructions. As I discuss each drawing, I follow the same procedure. When I have finished discussing all of the exercises, I then use each exercise as an illustration of control theory.

The drawings for each exercise are designed to highlight different aspects of control theory. The drawings for Exercises I and II are the same, while the drawing for Exercise III is different, and those for Exercises IV, V, and VI are the same, but different from the others. Exercise I is supposed to demonstrate the "classical" stimulus-response (S-R) model, in that the volunteer imitated my drawing. But it should be pointed out to the audience (the volunteer will usually agree on these points) how slowly the volunteer moved, since he/she had to "see" my drawing before he/she could move. The volunteer usually agrees that this task was very difficult to accomplish. But the most important point to make is that the volunteer could not have done anything without the instruction "draw the *same* diagram that I am drawing." This instruction had to be used by the volunteer as a reference state to control his/her own conduct. This point can also be made for Exercise II, since the drawings are the same.

When comparing the drawings made in Exercises I and II, the audience might judge the reference states to be the same. It should be noted that the volunteer was better able to draw the one in Exercise H in (small) part because of previous experience, but that the instruction for the reference state was very specific. The point to be made is that two instances of similar behaviors can be generated with two different reference states, *but* that the different precisions of the instructions will make a difference in the two actions. Again, although the stimulus-response model seems to be relevant, it can be pointed out that it could not account for a similar behavior resulting from two different instructions; the S-R model would predict similar behavior, due to similar stimuli. These first two exercises, when explained with control theory principles, can counter most arguments for the stimulus-response approach.

The drawing for Exercise III has some lines similar to those in the drawings for Exercises I and II. This was done to illustrate that the volunteer will have a similar drawing even when the reference state, perceptual signals, and sensory signals are quite different. The volunteer could not have "carried over" the entire drawing from the previous exercises. It also can be pointed out that the volunteer's action was quite shaky, due in part to lack of specification of the "dot" and comparative sensory signals. This information can be used when this exercise is compared with the next one.

I made the drawings for Exercises IV, V, and VI the same for several reasons. First, these movements seem to work best for using rubber bands; sawtooth and vertical lines do not produce much movement by the volunteer. Second, I wanted to find out if audiences judge the reference signals for these three exercises to be the same from similar drawings and the target on the paper. Finally, I wanted to see how much "carry over" there might be from practice with different reference states. I use these exercises to show the effect of different instructions and reference states on the perceptions of the volunteer. I have never had a volunteer fail to report the importance of these differences.

The volunteer does *a* much better job with the drawing in Exercise IV, because there is an actual dot on the paper, rather than an "imagined" dot as in Exercise III. Some, but not many, members of an audience are able to distinguish between the instructions for Exercise III and those for Exercise IV. There is very little "carry over" for these drawings, because the volunteer is concentrating on the target instead of my drawing actions. But the instructions for Exercise VI provide a very interesting illustration of control theory.

Exercise VI specifies a reference state with a wide range of movement and very little possibility for error. If the volunteer follows the instructions properly, he/she will not have to move at all. I make my movements in such a way as to keep the knot within the circle at all times. The difference between the drawing for Exercise VI and those for the previous two exercises is usually quite noticeable. Many members of the audience say that the volunteer was confused or made an error. But this exercise is important to illustrate that a reference state (certainly at the higher levels) can be specified as a "range" where a variety of actions can occur before any negative feedback is noticed by the person.

You might think of other ways to treat these diagrams. Remember, even if the volunteer does not use the reference state that is specified in an exercise, he/she will use *some* reference state. In most instances, it is rather easy to determine what the volunteer controlled for in an exercise. I have rarely been wrong when I have guessed the reference state of a volunteer in these exercises.

These exercises, although clearly borrowed from Powers, have some distinct advantages over his for instructional purposes. Among the advantages are: (1) a record (trace) of the movement behavior of both the demonstrator and the volunteer, offering the possibility of precise comparative measurement; (2) reference state instructions are known only to the demonstrator and the volunteer, not to the audience, which takes away the "obviousness" or "oh sure" audience response; and (3) the use of different exercises allows a comparative approach to control theory.

Possible Modifications

One could use a clear plastic board with clear plastic sheets for drawing, allowing the audience to see both the demonstrator and the volunteer from the front. Or a computer and a large screen could be used with a program which would make the drawings while the volunteer was following the instructions by using a joystick. This procedure would also allow for precise measurement of the volunteer's movements, with a printed record of the drawings. I am sure that other modifications could be made to increase the utility of these exercises.

Rick Marken: What we need to do as control theorists is develop more demonstrations of the *fact* of control.

I think that some of the best evidence of hierarchical organization in behavior comes from experiments showing one (or more) control systems operating within the time-frame of other control systems. This is the beauty of some of Bill Powers' "Portable Demonstrator" experiments. The simplest is when E's hand pushes down on S's hand to signal S to move his/her hand down from a fixed position. S's initial reaction is *always* an upward push before downward acceleration—the position control system reacts to the disturbance to position before the higher-order system can treat the disturbance as a signal to change the reference for the position control system.

I think it is important to get people to understand the *phenomenon* of control before pushing the *theory* that is designed to explain it. Telling psychologists that control theory is beautiful and powerful and revolutionary and humanistic and whatever just won't cut it. Theories are interesting to the extent that they explain what you want explained. And control theory explains control; so it would be most useful to show how control is involved in the behavior that psychologists are typically interested in. If psychologists are interested in cognition, then figure out demos that show how control is involved in cognition (we've done some of this, but not nearly enough). In some areas, like operant conditioning, the existence of control is fairly easy to demonstrate. In other areas (like language production), it might be more difficult to show how control is involved. But this must be the approach to promulgating control theory; because people cannot be expected to get interested in a theory if they have no idea what it's for. Indeed, I have more of a problem dealing with people who love control theory *qua* theory (they like the negative feedback and circular causation and all that) and have no idea what phenomenon the theory is designed to explain. I think there is a name for this latter approach to control theory; it's called "religion."

Gary Cziko: You can play with your tongue to see how speech disturbances are corrected. For example, keep the tip of your tongue against the inside of your bottom teeth and talk. I found this very easy to do with almost no sound distortion. Even sounds which normally require the tip of the tongue to move to the top of the mouth (/t/, /1/, /n/) are no problem—the middle of the tongue just comes up instead. For some reason, "gluing" the tip of the tongue against the bottom teeth is much harder, but still intelligible after a little practice. But watch yourself in the mirror if you want some laughs. The facial compensations that I use make me look like I'm snarling. Vowels are quite easy either way. Mustn't there be real-time perceptual control for this to work? Seems so to me.

Bill Powers: I get a very strong sense of the imagined auditory feedback by just mouthing "hello" without any sound (not breathing in or out). I don't actually hear sounds (no intensity or sensation) but the mouthed "hello" is still very plain to me as an imagined auditory experience. Does this work for anyone else? (Of course any other words will do—that's just the one I tried a moment ago.) It's the same imagined auditory experience I get from *reading* "hello." (Come to think of it, there's also an imagined kinesthetic experience in reading "hello" or "hello?" Even more so with "rouge," in French. Next thing, I'll be moving my lips when I read.)

Gary says: "For example, keep the tip of your tongue against the inside of your bottom teeth and talk. I found this very easy to do with almost no sound distortion." Brilliant! Yes, it's easy! There is some distortion of the final result, but I'll bet that if you used Crazy Glue to keep the tip of your tongue fastened to your bottom teeth for a month, you'd be talking essentially normally at the end. What you would be saying is another matter. Any volunteers?

Gary also says: "For some reason, 'gluing' the tip of the tongue against the bottom teeth is much harder, but still intelligible after a little practice." I presume you meant "upper teeth." *Yes,* it's harder—you have to use the lateral margins of the tongue to make a "t," and the vowels get distorted. But it's still quite intelligible.

I just love this kind of simple portable demonstration. It's a complete refutation of the idea that articulation consists of producing a preset pattern of motor outputs, and anyone can do it in two seconds. Absolutely ingenious, Gary.

In the Coin Game [a portable demonstration of PCT's Test for the Controlled Variable], the Subject lays out four coins on a table so that some pattern the subject has in mind is contained in the layout. The Experimenter disturbs the arrangement. If the Subject can no longer perceive the intended pattern, he or she moves one or more coins so that the pattern is again visible. If the Experimenter's move left the intended pattern still visible, the Subject just says "no error." The game is finished when the Experimenter can create disturbances that predictably call for corrective action, and disturbances that predictably result in "no error." The criteria can be adjusted as suits the players and their degree of skepticism.

An example of such a pattern is "at least one right angle." An experimenter unaccustomed to this test for the controlled variable might take half an hour to discover this pattern. Of course, it is possible to devise patterns that are undiscoverable, if you like wasting time. It is impossible to discover what pattern the Subject is controlling if the Subject keeps changing the reference pattern during the game. In such a case, only the Subject and God know what the controlled variable is at any moment. Even in this kind of case, however, the Experimenter can go up a level and approximate a higher-level controlled variable: "Either you've got an extremely obscure pattern in mind, or you keep changing it every time I get close." Playing this game will teach one a lot about how to find controlled variables, and the pitfalls of assuming that "insights" into what another person is doing have any relevance. The Test is all about eliminating wrong hypotheses. When you get systematic about doing that, you can guess very efficiently. If you get hung up on a clever hypothesis, you might take forever to find the right controlled variable.

It is also instructive to discover that a perfectly good verbal definition of a controlled variable that passes every test is not the one the subject used. You say, "It's a zig-zag!" The subject says, "No, it's an 'N' on its side." Of course, it's *really* a "Z." In *fact,* it's the perception that the Subject intends to reproduce, not its description.

Dag Forssell: I would like to build a simple control system demo to fit in a briefcase and be powered by regular house current. How about a joystick-controlled rheostat providing a reference signal to represent the aiming of a cannon? I would like the reference signal to be visible, perhaps in the form of a voltmeter. The gun barrel would be hooked to a rheostat and the signal made visible in the same way; the error signal thus created also would be made visible. An amplifier (with output visible on a watt or amp meter or perhaps through the glow of a lightbulb or tone (pitch, volume) of a small speaker) would drive a motor left or right with proper drive of the gun barrel.

It occurs to me that if the perceptual, reference, and error signals were shown on strings of light-emitting diodes, then the subtraction could be made graphically quite visible.

One of the things I want to come alive is the (rapid) conformance of the perceptual signal in response to a rapidly changing reference signal.

Surely some of the people on the net have thought about this and can suggest designs, components, and sources of supply. Please give me some ideas.

Later, we could create visible conflict between two units and also build a hierarchy.

Wayne Hershberger: Dag, you might want to consider the control systems used to pilot radio-controlled model aircraft. They are battery powered. You would not need the radio, just a servo and a device to provide the servo's reference input. You can purchase a servo in an R/C hobby shop for about $25. You might need to special-order the servo driver. Ace R/C Inc. (Box 511, 116 W. 19th St., Higginsville, MO 64037; phone 816-584-7121) calls their driver a "Servo Cycle." It costs about $30. Ace R/C sells their products as kits or as assembled units. If you were to get everything assembled from Ace R/C, I estimate that it would cost you about $85. You would need: Ace R/C Bantam servo: $26.45; Servo Cycle (with connectors for Ace servo): $32.95; nicad battery pack (4.8 volts DC, 500 milliamps): approximately $20.00; battery charger for nicads: approximately $8.00; plus postage: $3.00.

Gary Cziko: Wayne, could you tell me what such a system as you outline for Dag would actually do?

Wayne Hershberger: Gary, the radio control systems employ *position* servos. Each servo, encased in a small box displacing less than one cubic inch, controls the position of a small arm extending from the case. Four servos are customarily used in model aircraft, with the output arm of each servo linked to one of the four flight controls: throttle, rudder, elevator, and ailerons.

Disassembling a position servo, one finds three components:

(1) an effector—a geared electric motor that drives the output arm about its axis of rotation,

(2) a position sensor—a potentiometer whose wiper is attached to the output arm's axle of rotation, and

(3) a circuit board comprising electronic components that receive the

reference position (signal from a transmitter), compare that reference position with the sensed position, and amplify the error signal to drive the motor.

By wiring electrical meters into the circuit, one can see that the servo draws very little current (about 10 milliamps) when its arm is idling in the reference position, but over 100 milliamps when a load tries to displace the arm.

Gary Cziko: Wayne, are the R/C servos strong enough to interact with a human? That is, could I grab hold of the arm (if only delicately with two fingers) and disturb it and feel it fighting back? For a good demo, it should have enough loop gain and "muscle" so that I can feel it resisting, but not so much so that I can't even budge the arm.

Of course, it would be nice to have it move in more than one dimension to make it seem even more alive.

Bill Powers: Wayne, I've sent for the Ace catalogue. I had always thought that those servos are just up-center-down or on-off. There should be all kinds of neat demonstrations we can come up with using a pre-packaged position servo as the core device. You could use two of them to play the rubber-band game in one dimension. Maybe you could make a balsa-wood jointed arm. More toys!

Dag Forssell: Thanks, Wayne, for the info on servos. I had in fact visited a hobby store and concluded that these servos were stepping motors and not suitable for demo-building. Based on your post, I sent for the Ace catalog. I hope that the ready-made, inexpensive, and certainly compact servos offered by Ace will be suitable.

Bill Powers: Yes, if those little servos can produce enough output force, they will certainly make suitcase demonstrators much easier to achieve. But let's not give up on finding components for designing our own.

Joel Judd: [Excerpts from a manuscript titled "Second Language Acquisition as the Control of Perception":]

I need a volunteer for a harmless demonstration. [What follows is the rubberband demo—a volunteer is asked to hook one finger into a loop, and I hook one of mine into the other. I tell the volunteer to move as he sees fit, avoiding exaggerated or extreme movements, and when he knows what I am doing, to stop.]

What do you observe? (Responses.) You will notice that as long as the rubberband was taut, I moved my finger in a coordinated fashion along with the volunteer's. If you think I was simply mirroring his movements, what would you say if I covered up his hand or used a rubber band with three loops? One could run a correlation on the movements of our two fingers, and find a coefficient somewhere in the neighborhood of .95, or even better. This is an incredible correlation for the behavioral sciences. But what does it tell you about me? It tells you that our finger movements correlated. Somehow that knowledge is not very satisfying. Why was I moving the rubberband as I did? What if I tell you that I was trying to keep the knot over a spot on the board? Now what do you know? Does that change your perspective on this experiment? Now you know *why* I behaved as I did—why, as long as the game was on, I counteracted moves made by the volunteer. Did the volunteer *cause* me to move as I did? Well, yes and no. Yes, in the sense that he caused disturbances to my goal of keeping the knot over the mark. No, in the sense that if "keep the knot over the mark" was not my goal, his movements would not have required any action on my part. I was concerned with maintaining a particular relationship between the knot and the mark on the board. He made it difficult for me to achieve that goal, so I had to *do* something to overcome the disturbances.

The principles I would like to emphasize from this demonstration at this time are three. First, I had a purpose in playing the game. My purpose was to maintain a close match between my goal ("keep knot over mark") and what I perceived with respect to that goal (through vision). My behavior was purposeful. Second, while the behavior had a purpose, it was not controlled, it was only incidental. It was the result of a comparison between my goal and my perceptions. If my perception was "knot over the mark," then little behavior was required; if the perception was "knot far from mark," marked behavior resulted. But what I was controlling is the third principle: perceptual inputs. What I wanted was to perceive the knot over the mark. My observed behavior was only one of several ways that I could have achieved the desired perception (I could move just my finger, my whole body, or even the chalkboard itself). I did not concentrate on the volunteer's finger movements, or on my own. What I did was to check my actual perceptions against what I *wanted* to perceive.

Given such an interpretation of events, what can we predict? We can say that I will do what is necessary and possible for me to do in order to maintain my internal reference or goal. You cannot predict what *exact* physical behavior I am going to exhibit; you can predict (knowing my goal) that I will do *something* to maintain that goal in the face of disturbances.

We saw in the demonstration how the observation of my behavior did not lead you to understand why I was doing what I did (or perhaps you hazarded a correct guess). It was obvious that I was moving in concert with the volunteer, but even noting this (and correlating an extremely high correlation), you learned nothing about my purposes. There are only two ways in which you could find that out. One is to ask me. Of course, I can lie or mislead you, but it is possible to find out one's goals by asking what they are. How often this possibility is overlooked in the social sciences. The other, "purer" way to determine goals is to hypothesize what they are, then apply systematic disturbances to the organism and see if it tries to overcome them—to obtain the goal even though unpredictable obstacles threaten to prevent its attainment. This description of behavior is known as perceptual control theory.

Bill Powers: Joel, if the goal is "keep the knot over the mark," there are several ways to achieve it:

1. Drive a nail through the knot into the mark (no control needed).
2. Shoot a curare arrow into the other person so he/she will stop disturbing the knot.
3. Employ a visual-motor control system and give it the reference-image or goal that we describe as "knot over mark."

Just quibbling.

Gary Cziko: Stand up. Close one eye. Then push on the side of the open eye with your finger. The perceived motion makes you feel a bit unsteady, doesn't it? Now, walk a straight line with one eye open and then, while walking, disturb the eyeball with your finger (give a nice steady push and *hold* it there). You might find that you can no longer walk a straight line. If you are pushing on the right side of your right eyeball, you will likely veer to the right (because your brain thinks your body is leaning to the left, it will "compensate" and send you off to the right). I actually feel that I will fall down if I don't stop walking and don't stop pushing, although some of my colleagues here can continue quite well, but still report how odd it feels.

Let's get some data from others out there on the latest PCT portable demonstration.

Rick Marken: Gary, I damn near knocked myself over when I was walking. What a splendid demo. Everyone should try it—but be *careful.* I am truly amazed at the power of this little demo. I would have imagined that walking could be carried out quite well even if the visual input were disturbed—but no way!

Gary Cziko: To complete the eye-pushing demo, three more steps should be added. First, reverse eyes to see how you now stagger to the other side, to show that this is a systematic effect. Second, walk a straight line with eyes closed and then push on the eyeball. No problem (except for the normal "drift" of trying to walk straight with no visual feedback). Therefore, it is not just pushing on the eyeball which causes the instability. Finally, walk with the one eye open while making lots of saccades. No problem. Therefore, it is not just moving images on the retina which causes the problem. The problem is caused only by having the retinal image disturbed by some "outside" factor.

For even more excitement, try this while riding a bicycle (now I know why I wear a helmet). Doing it while driving a car is also amusing (make sure first that you are insured against PCT demos). Any airplane or space shuttle pilots out there?

Let's see what my list of portable PCT demos looks like now:

1. Powers' classic rubber band demo of keeping the knot of two knotted rubber bands (elastics) over some fixed point with the subject's (controller's) finger in one loop and the disturber's finger in the other. Demonstrator can be either subject or disturber.

2. The demonstration of the levels of the hierarchy involving hand movements.

3. Speaking while keeping the tongue in some relatively fixed position, e.g., tip touching upper or lower teeth.

4. Eyeball pushing and walking.

5. Finger pointing. Close one eye. Reach out with one arm with index finger extended and put the finger where it "touches" some distant object. Keep it there and watch how your arm seems to take on a life of its own as it actively compensates for disturbances caused by breathing, heartbeats, body movement, muscle fatigue, etc. Then decide to move your finger a certain distance above or below where it was. When I change the target, I get a feeling of "willing" which is very different from just maintaining the finger in a certain spot. This lower-level maintenance of finger position feels like it is running on a sort of automatic pilot. I do not feel as if I am actually in control of the little movements needed to maintain the finger on the target. And, of course, in a sense I am not. All (higher-level) "I" can do is specify the reference signal for the lower systems, and then they do their jobs without any further assistance from the higher levels.

Are there other portable demos that I have missed? If we get enough of these, maybe PCT will start taking over classic psychology in introductory courses just because it will be so much more fun!

Martin Taylor: The eye-push demo is very reminiscent of one of psychologist J.G. Taylor's demos. Gary's mention of bicycling brought it to mind. Taylor claimed (and demonstrated) that distortions of vision are corrected if and only if the distorted components are affected by behavior as part of the feedback loop involving that behavior. One of the distortions was to wear spectacles with some kind of prism, such as inverting spectacles that interchanged left with right, or up with down, or merely displaced things (say) 20 degrees to the left. He mentions in his book the experience of seeing a narrow strip of floor in front of him (on which he would be walking) seem perfectly normal and flat, while on either side (irrelevant to his walking) the floor seemed to be sloping. At the same time, the surface of a table showed no levelling effect during the 13 days of the experiment. At the table, he indulged in no control behavior (he says) that involved gravity, and thus there was no mechanism for the distortion to correct itself (no feedback to test reality).

But more dramatic is a film of Seymour Papert (of MIT) learning to ride a bicycle while wearing left-right inverting spectacles. At first, as soon as he put on the spectacles, Papert would crash—he applied the wrong corrections. After a while, he could stay on, albeit wobbly. But then he would crash when he took the spectacles off while riding. After more training, he could put the spectacles on and take them off quite freely, while maintaining control. But then comes the kicker—Taylor took the prisms out of the spectacles (the frames were quite heavy), or perhaps he substituted non-inverting prisms. At any rate, Papert's view of the world was normal with or without the spectacles. But on putting the spectacles on, he crashed as in phase one. Taylor took this to mean that the totality of sensation involved in a situation was all part of the control system, and this included having reorganized the system to include what amounted to a switch based on the weight of the spectacles on the nose (Papert "knew" what was in the spectacles, but his fully trained control systems didn't).

Papert, by the way, contributed a mathematical appendix to a chapter of Taylor's book, so he was familiar with the theory, though it is hard to see how this could have contributed to the effects. I certainly would not have allowed myself to keep falling off a bike to support someone else's theory of perception!

Gary Cziko: Here's a demo on "apparent social control."

I ask the audience to close one eye and reach out with one hand with finger extended to "touch" my hand. I then move my hand around and they all follow quite nicely. It almost looks as if my hand is connected to all of their hands (like puppets on strings). I then ask them to raise their hands as high as they can. Then, for contrast, I ask them to shout "Go Illini" as loudly as they can at the count of three (the Illini is the name given to football/basketball teams at my university). I then count to three and... total silence.

So they will do as I ask only if *not* doing so would create an error signal (they want to be cooperative, and audiences are certainly used to moving their hands around). But shouting as loud as you can in a classroom would create more of an error signal (or I suppose I should say an error at a higher level) than the error signal created by not following my shouting request. (I wonder what a roomful of Republicans would do if asked to shout 'long live George Bush!")

Bill Powers: Gary, I love the social-control demo. We need a version of it for the portable demonstration collection. How about giving a pin to someone, and giving him/her instructions to push it all the way into a chair cushion, a rug, and the palm of his or her hand?

Gary Cziko: In my continuing search for portable demonstrations of perceptual control theory in action, I was playing with handwriting this morning. Here are some things to try. I will assume that you all write with your right hand. Lefties need to substitute left for right and vice versa.

1. Write a sentence with your right hand. Notice how easy and quickly you can do this.

2. Write a sentence with your left hand. Notice how much more difficult and slower this is. Nonetheless, if you take your time, you can probably still write quite legibly (I can, anyway).

3. Now write another sentence with your left hand, but write *backwards, that* is, from right to left with the letters laterally transposed (the way DaVinci wrote, I'm told). I found this to be even more difficult than 2. From a motor perspective, we might expect it to be easier, since the actions are the mirror image of what is done with the right hand. But I think it is harder since we simply don't have a good idea of what reversed writing should *look* like. I found that I would often "freeze" at the beginning of a word. I did not "freeze" when I wrote in the normal direction with my left hand.

4. Now try writing some individual words (still lefthanded and backwards and laterally reversed), but now write normally with the right hand the same words simultaneously. You should be able to write quite easily backwards this way, since now you have a "motor" reference level which you can use for the left hand.

5. After a little bit of this, you might find that you can just "imagine" the right hand writing normally and then write backwards with the left hand without much difficulty. But you still probably don't have a good idea of what your backwards writing should look like. So even though you're looking at your left hand write backwards, it seems (to me anyway) that the visual feedback is not used very much. It is sort of like writing normally but with your eyes closed.

6. Now, you can switch back and forth between forwards and backwards writing with your left hand. And it feels quite different. Writing

normally (left to right) with my left hand, I am using primarily visual feedback, since I know what it is supposed to look like. It is quite slow, but I can make it look quite good if I take my time. Writing backwards with my left hand (after using the simultaneous right hand trick) is much faster and feels just fine, but looks pretty awful since I am using proprioceptive feedback, not visual.

In addition to its use as a demonstration of some key PCT ideas, handwriting might be a good way to do research on reorganization. Only pen and paper are needed, and the subject leaves a permanent record of his or her behavior, with no need for fancy computers and C compilers. In addition to the above tasks, you can see reorganization in action by holding a mirror at the head of your paper and writing so it looks normal in the mirror. This makes you write upside down. This is maddeningly difficult. You can see your runaway streaks of positive feedback as you try to make *a* line go down and it keeps ascending faster and faster the harder you try to get it to descend. This reminds me of Martin Taylor's account of Seymour Papert learning to ride a bicycle wearing reversing prisms as eyeglasses, but it doesn't hurt nearly so much to make a mistake.

Joel Judd: I have wished many times for a "real" example of linguistic control to give to the audience (or perform *on* the audience). Nothing fancy, just something that most would agree demonstrates control. I have been looking for something along the lines of James' (18%) Romeo and Juliet description for purposeful behavior. Is there something in some netter's experience which might qualify as such a linguistic example? Perhaps some child's conversation, or something literary? Once one believes in control of perception, examples are all around—but what about some attention-grabber that would be difficult to explain away in other than PCT terms? Thanks.

Bill Powers: Joel, I don't have any clever examples of linguistic control, but maybe a halting attempt will suggest something to you or others. We want to demonstrate perception, reference condition, error, and action to correct the error. So how about using some phrase that everyone knows and putting errors into it: "Now is the time for all men good to come to the country of their aid."

This demonstrates a number of principles.

1. Even though this is not a proper sentence, it will be recognized as "nearly" right. This shows that perception even of sentences has an underlying continuum of variation that we express with terms like nearly correct, pretty close, not so close, pretty bad, and awful.

2. The fact that you know the sentence isn't right implies that you're comparing it with some standard. The "right" sentence isn't (for most

people) vividly in awareness at the moment the mistakes are detected, but some criterion for correctness must be there in some active form.

Given a sense of error in the sentence, you can then point to the causes of the error: in this case, the placement or ordering of the words in the sentence. So to correct the sentence as a whole perception, it's necessary to alter some of the elements of which this whole perception is made: that shows hierarchical control even without trying to pin down just what the levels are.

There are many other ways for this sentence to be in error besides just the ordering of words. If it starts with "Now is time for...," a word has been omitted. If it starts with "Now was...," a wrong tense is present. "Now is the tome..." contains the right word misspelled (interesting, because "tome" is a perfectly good word, but not in this sentence, so we recognize it as almost "time," but with a letter error in it). Each kind of error exposes some aspect of the sentence that you are monitoring for correctness. It also shows that you hold in memory various kinds of criteria for correctness and apply them all in parallel. If the sentence starts with "Now is tome the for...," two errors of different kinds are sensed simultaneously.

Examples of control while constructing a sentence can sometimes be seen when the listener indicates an unwanted response before the sentence has been finished. You say, "Excuse me, could you tell me where, oh, sorry..." as you realize that the person is smiling, shaking her head, and tapping an ear to indicate deafness. It's too late to edit out the futile "oh, sorry," but your first impulse is to do so. Maybe you could set up some kind of role-play to show how this editing on the fly occurs.

Another simple-minded example is like the method Dick Robertson and David Goldstein used to demonstrate control of self-concept. They tried some complicated questionnaire methods which gave the usual equivocal results, then finally decided just to wait for the person to utter a self-description and reply by contradicting it: "No, you're not like that," or something of the sort. I believe that 25 of the 26 people tested responded by saying something to oppose that disturbance.

If you ask someone to explain how a fan moves air (or something simple like that), the person hearing the explanation could respond by saying, "Oh, I see, the air going through the fan makes the blades turn," or something like that. PCT would predict that this unwanted understanding of the communication will call for more communication that is aimed at getting a more correct statement from the other person, and that when the reflected understanding is judged correct, efforts to change the other person's understanding will stop.

Bruce Nevin: Control theory demos typically concern behavior that is closely matched to environmental variables (I hope my epistemological looseness here is forgivable). There isn't much room for variation in a forehand smash in tennis: either you strike the ball so as to put it over the net to the chosen area of the court with desired speed and spin, or you don't.

In the range of variation that an outside observer might judge to be tolerable, one person will control for a more restricted range, and another player might control for a different part of the total range. An opponent or spectator might label person A an "aggressive" player and person B more "laid back," and so on. On a different occasion, player A might "let up" a bit so as to accommodate a less skilled player.

Social behavior of the second sort exploits the range of tolerable variability of control for purposes of constructing a persona and presenting it to others. A self-image.

It is this that is one of the principal motivators of language change and variability.

So we control for what we are paying attention to, and ECS daemons with alternative interpretations don't get heard. We only notice ambiguity when we are paying attention to ambiguity itself, or more commonly when an expected agreement is not reached (but even then far from all of the time). Looked at this way, I doubt there is anything that is not ambiguous.

Somewhere in there is the germ of a demo. A problem with any demo is that our control of language is so exuberantly pandaemonic (massively parallel, as they like to say). One has to account for other parallel threads of interpretation without being able, as in traditional laboratory protocols, to eliminate them from the experimental setting. Some parallel threads are redundant (feature, segment, semisyllable, autosegment, stress group, etc. in phonology) or partially so, and some are competitive (ambiguity). Such an accounting does not make for a succinct, crisp, yet convincing demo. Too many audience yeah-buts are possible. Maybe it's in answering the yeah-buts that you show how parallel pandaemonic control frames the demo.

Rick Marken: It is very easy to demonstrate the illusion of control—just ask someone to track your moving finger with theirs. If they are willing to do that, then you can control the position of their finger—you will experience control and your actions will look like control to an observer. Interestingly, the "subject" will not feel controlled until your disturbances (finger movements) require action that produces a perception conflicting with their ability to control other variables (Bill's example of moving the subject's finger close to a hot soldering iron comes to mind). In such a case, the subject will probably notice your disturbance as an effort to control him/her, and you will notice a loss of control—especially if you really want the subject's finger to be close to the soldering iron.

Chuck Tucker: I have thought some about how to devise rubber band demos for more than two persons. Actually, the ideas for these came from a discussion at a CSG meeting which was given by Ed Ford and his friend, Jim Soldani, who used such demos for people in organizations to show how conflict can arise if people don't understand one another's purpose. These demos can be used to illustrate PCT (obviously), as well as what many have called "social constraints" or "social structures" (which are, in my view, mainly arrangements that someone devises to make it extremely difficult for a person to accomplish his or her purpose), in addition to illustrating conflict and conflict resolution. In these demos, you can give the instructions in verbal, written, or graphic form, or all of these forms, you can have the participants talk to each other or not, you can be one of the participants, and you can try to restrict the "sensory input" of the participants by using screens, blindfolds, or heavy gloves on their hands, or by having them hold the rubber band with a hook instead of with their fingers directly. All of these variations I can see as attempts to illustrate different aspects of the PCT model.

I'll illustrate with a three person demo. Three rubber bands are each knotted on a fourth rubber band (opened up to make a circle) at equal distances from each other. Using the picture of a circle with 360 degrees and treating a line intersecting the circle anywhere as 0 degrees, tie the three rubber bands at 0, 120, and 240 degrees, equally dividing the fourth rubber band into thirds. Now have the participants make triangles of various shapes, have one participant refuse to make a triangle with the others, have them make a triangle and tell them, "Now, hold that position for 10 seconds and remember how that felt, because I will ask you to do it again without being able to see what you are doing." Then blindfold each of them, place the rubber bands on their fingers, and ask them, "Make that triangle again." (Take a picture of each performance, so you can compare them.) The parameters of the activity can be changed by tying three rubber bands at 0, 160, and 200 degrees, then at 160, 180, and 200 degrees, and so on. When these "structural conditions" are set, the types of shapes that can be made will be restricted *unless* the participants devise ways (like crossing over each other's rubber band) to make the shapes; if they are all required to stay on the same plane (another structural condition), then the shapes they can make will be limited.

Now expand this to four participants and start with the simple setup of four rubber bands at 0, 90, 180, and 270 degrees around a fourth rubber band to make a square or other square-like shapes; ask the participants to make a triangle; to make a circle; to make a hexagon; and on and on and on. Do five participants, six, seven, and on and on as long as you have rubber bands.

I believe that these demos are not only very useful in illustrating the ideas of PCT, but are enjoyable and memorable for the participants.

Bill Powers: In the Coin Game, The Test for the Controlled Variable is done with the subject there. The actions of the subject can be perceived as affecting the environment in many ways, and objectively have many different effects on objects, relationships, etc. in the environment. The question is which, if any, of these effects of the subject's actions is under control. The experimenter devises a disturbance that will alter one of those effects. If the effect changes—if the subject does not change the action in a way that prevents the change from taking place—then that effect of the action is not under control.

Use four coins (same or different, as you please). Two people play, an Experimenter and a Subject. The Subject places the coins on a table such that they exemplify a pattern or condition that the subject has in mind. The Subject privately writes down this reference pattern on a piece of paper, and hides it. The Experimenter is to discover what the controlled pattern is, by means of disturbing the arrangement of the coins.

The rules are as follows. One round of the game starts with the Experimenter doing something that alters the arrangement of coins on the table. The Subject looks at the new arrangement, and if the target pattern can still be seen, says, "No error." If the pattern now differs from the target pattern, the Subject makes any rearrangement of the coins required so that the perceived pattern once again matches the target pattern. After either a "no error" response or a corrective move, it is the Experimenter's turn again.

The game ends when the experimenter can demonstrate three different moves predicted to produce a "no error" response, and three different moves predicted to produce a correction. Then the subject displays the written description of the reference condition. No verbal communication except the words "no error" takes place during the game.

You might think at first that it will be easy for the Experimenter to discover the pattern, and compensate by choosing (as Subject) a complex reference condition. I advise choosing a simple reference condition if you want the game to finish in under half an hour, or not be abandoned.

This game illustrates all facets of The Test for the Controlled Variable. Clark McPhail has been using it to teach The Test (he sent me copies of experimental reports by students—wonderful reading, especially the comment by one student that he really admired sociologists for being able to use The Test in their work, because it is so complex).

Martin Taylor: I appreciate the Coin Game. My thesis supervisor did quite extensive studies of this kind of game, perhaps not structured exactly the same way, but very like it. He was studying perception, not control, but the issue is also of determining by such trials the nature of prespecified relationships. I think it was a popular experimental paradigm at the time. The effects of interactions on the kinds of relations that were readily detected or were detected only with difficulty was the point at issue. He *came* up with the notion of integral and separable perceptual dimensions, which seem to be quite important. I can't give any specific references, but if you want to search for them, look for W.R. Garner in the late '50s or '60s.

Gary Cziko: While I don't think that I will ever design a control system, I couldn't help noticing a "digital proportional radio control system" for $49 in *a* local hobby shop and so figured that this might be a way for me to at least interact with one (an artificial one, I mean; I already have lots of experience with the living kind).

This is a Hitec "Challenger 260" two-channel system that includes a pistol grip transmitter (reference-level manipulator) and receiver connected to two servomechanisms (it is made for controlling speed and direction of model boats and cars). Pulling the trigger and turning the wheel on the transmitter move wheels on the two servos. I replaced the wheels with two four-legged spiders that came with the kit and attached rubber bands to one arm on each.

With either the transmitter or receiver turned off, one can easily move the spiders for a total range of about 90 degrees (it's a bit stiff and I don't know how good this is for the servos). But with the both transmitter and receiver on, they really fight to respect their position reference levels. You can feel them vibrate and fight back when you try to disturb then. While it *is* possible to overpower them, I am quite impressed by how strong and stubborn the two little servos really are—the more you try to push them around, the more they push right back at you (very much like most people I know!).

The rubber band is a *nice way* to add disturbances. I can ask someone to pull the rubber band hard any which way, and it makes virtually no difference to the position or pattern of movement that I am sending with the transmitter. This is a very nice demonstration of why controlling reference levels is the way to go. I let the servo control system worry about the rubber band disturber, and it makes no difference to me, the upper-level reference signal supplier.

While Powers' and Marken's computer demos are great, there is something to be said for the real physical interaction that these servos provide. Also, they provide an easy way to give my students hands-on artificial control system experience. Highly recommended.

Dag Forssell: Imagine that you are playing the rubber band demonstration with a strong machine, programmed to go through a set pattern of motion. You have no difficulty, since the machine only influences the position of the knot, through the tension in the rubber band.

Now, "tightly couple" the knot to the machine by substituting a stick (or a rope, as I like to do when demonstrating conflict between two "pullers"). If you still are connected to the knot by a rubber band on your side, you will pull in vain. If the stick is extended to your hand, you will be pulled along, powerless to do otherwise. You are being controlled by the machine with overwhelming physical force, the only way Bill says you can be controlled.

I believe it is important to remember one of the hallmarks of control systems: amplification. This term does not communicate well. I am shifting my language to "the direction of resources" or something like that, with emphasis on resources. Your heating system at home opens a valve to release (and ignite) a stream of natural gas. The stream is not finely calibrated, but it has a powerful influence on the air temperature. If you have an air conditioner working at the same time, set at 68 degrees, while the heater is set at 75 degrees, the two will pull (with tight coupling) on the air-temperature knot with as much influence as each is capable of. If the gas line has the capability to release more resources to raise the temperature than the air conditioner has resources to lower it, then the air temperature will stay at 75 degrees.

The rubber band is such a marvelous tool, because it shows influence without tight coupling. Try the demonstration with a rope and two dots; one dot towards the left as a target for the left person, and one a little to the right (one foot apart if you are at a blackboard with a four-foot rope, which works best, one inch apart if you are on a paper with a short string) as a target for the person on the right. See which person is willing to pull hardest. This person will pull the knot to his/her dot and keep it there. This illustrates the heater/air conditioner conflict.

On another subject, suppose you pull on your end of the bands to keep the knot over the dot. *You* control! I disturb the position of the knot by moving my end. I provide a stimulus, and you respond. My disturbance is a property of the environment, from your point of view. (I can represent any kind of machine or natural effect disturbing my end; I am not trying to control.) So is the quality of the rubber band which converts your action (and my disturbance) into an influence on the knot. As long as you do control, your action will be *what it has to be* to keep the knot over the dot.

Your action is 100% determined by the disturbance and the nature of the rubber band, which are *properties of the environment*. The only requirement is that you do control somehow. The rubber band experiment illustrates the fact that you *do* control. It tells you *nothing* about how you are organized inside to accomplish this control. Therefore, what you see (your erratic movements) is due to properties of the environment, not of the organism (you). This is most clear when you do the rubber band exercise slowly, allowing nearly perfect control. The knot stays steady over the dot, and your actions are perfect mirror images of the disturbance.

In Phil Runkel's book is an excellent, detailed description of the rubber band experiment that is *more instructive* than the way I was introduced to it. You invite a friend to experiment *on you.* "You are the experimenter. Move your finger as you like. Watch what I do. When you can explain what is causing me to do what I do, let me know."

Phil spells out the typical suggestions of friends. I have confirmed this. Saturday, I had a group of six, with no notions of PCT. I used an easel with the above instruction printed in the center. My rubber bands had a yellow ping pong ball over the knot, to make it visible at a distance. I kept the ping pong ball over one letter. All I got was that I was mirroring the experimenter. Of course, the experimenter "causes" me to do what I do. I kept telling them that that was not the cause and challenging them to come up with a better explanation. No luck.

It is true that people cannot see control even when it is staring them in the face.

Starting the experiment this way makes the paradigm shift stand out. You can point out that an absence of a point of view makes it impossible to see the phenomenon. Your ignorance makes you blind—literally!

Only *after* this sequence do I experiment on my friend by asking him/her to keep the knot over the dot. Later, one can point out that the better the control, the less exciting the appearance. Good control is invisible because nothing happens.

Gary Cziko: Dag, another variation of the rubber band demo I often use when presenting to a group is to ask for a volunteer. I then whisper to the volunteer, "Keep the knot over the dot (or other landmark)," and then I disturb. The audience has to figure out what the subject is doing and make guesses, but the *subject* responds as to whether the guess is right or wrong. I can *then* even have someone in the audience be the experimenter.

It's amazing how difficult it is for some people to find the controlled variable. It seems the more psychology one knows, the *less* likely one is to find the answer. That's understandable. But why the very sharp control systems engineer I tried it on gave up after a few minutes remains a mystery to me.

Bill Powers: Try this: Knot three rubber bands together at a common point. Do the experiment on a large sheet of paper or against a blackboard. Use three positions of the disturbing end of the rubber band measured relative to the known target position of the knot: large, medium, and small distance from the knot. Make these positions only about an inch different from one to the next. The positions can be premarked on the paper or blackboard. The experimenter pulls back to each position and records where the subject's finger goes, marking the positions on the paper or blackboard.

In Experiment 1, the disturber loops two of the rubber bands around his finger, leaving one for the subject.

In Experiment 2, disturber and subject get one rubber band each, the third one just dangling.

In Experiment 3, the subject loops the finger through two of the rubber bands, leaving one for the disturber.

To distinguish the data for the runs, label the subject's finger position marks as la/lb/1c, 2a/2b/2c, and 3a/3b/3c.

In all three experiments, the size and direction of the disturbance is the same small, medium, or large amount. The subject, however, will respond very differently in the three experiments, as can easily be seen during the experiment and by measurements with a ruler afterward.

I'm not going to tell what happens. You should be able to reason it out from elementary PCT principles, then verify that your prediction is quantitatively correct, using the method outlined above.

If you get the right answer, you will realize that you don't even need a subject for this experiment: you can play both parts. All subjects who keep the knot over the dot will behave in exactly the same ways in each of the three experiments. These measurements are not measuring any properties of the subjects. I leave it to the advanced student to say what they are measuring.

Rick Marken: Dag does an excellent job with his wonderful variations of the rubber band demo, showing that extraordinarily complex "behavior" seems to be going on when people are doing nothing more than trying to perceive a simple relationship between configurations—"knot on dot."

I believe that one of the problems confronted by those of us who are trying to "sell" PCT with models and demos is the same as the problem we confront when trying to point out to psychologists that there is a phenomenon (called "control") that is going on in front of their eyes that they have not taken into consideration in their attempts to understand mind and behavior. The problem is that the disturbances, constraints, and calibration problems that make control necessary and obvious are simply invisible. When you point your finger at a target, the pointing just seems to happen; the fact that you can repeat this pointing with great precision seems completely unimpressive. You just point at the target again and again. Disturbances (such as changes in your orientation with respect to gravity), constraints (such as the fixed length of the segments of the arm), and calibration problems (like the fact that a neural signal never produces exactly the same amount of muscle tension) go completely unnoticed. When disturbances are visible (such as movements of the target), they look like stimuli guiding the response. It is, thus, very easy for those who want to, to ignore control.

Basically, the problem with demonstrating models of control is the same as the problem of seeing control in normally occurring behavior; what is most amazing about control is what you can't see. And you can't see the amazing aspect of control (disturbance resistance, constraint satisfaction, and calibration compensation) because control itself prevents these things from having any noticeable effect. So it is the fault of control itself that the process of control is invisible.

In order to see control, you must be the agent of disturbance; you must be able to do something that you know should have an effect on a variable if it were not under control. If you think a person is controlling the position of a limb, then you can literally "push" on the limb to see if the push has the expected effect (movement of the limb). This "test" must be done carefully—not too much disturbance (control systems have limits to the amount of output they can produce), with an appreciation that control of some variables occurs more slowly than others (so the disturbance might seem to have an effect but will be slowly cancelled if there is control).

I don't know if there is any really dramatic way to show control; we keep trying, but we obviously haven't found a real "grabber" that would get psychologists to throw up their hands en masse and cry, "Oy vay, I've been missing the point for my whole career; people don't respond to stimuli or generate outputs—they control! Now I have to abandon all my work and start studying control. Damn, how did I miss that—I guess that guy Powers wasn't just a stubborn, contrary, radical outsider after all."

Dag Forssell: Rick, we do not need more startling demonstrations. PCT tells us that all action is initiated by error signals. What we need is to address the error signals that lurk out there in people. A synonym for error signal is dissatisfaction. We need to reach people who are dissatisfied with what they can accomplish, people with a yearning for something better. A better way to deal with each other.

A dissatisfied person will be open to suggestions and interested in trying a different solution. Much of the debate on this net addresses people (directly and indirectly) who are perfectly satisfied with what they know, proud of it and ready to defend it. Forget it. Ask people what problem they are anxious to solve. Ask if they are willing to think for themselves and evaluate an alternative. When people refer to authorities, they are not prepared to think for themselves. PCT does not need anything more than a student who is willing to think for himself/herself and make the effort to understand the evidence.

Our challenge is to tell our story so that people become aware of the error signals they frequently deal with, and understand that we have a permanent solution they might like if they spend a little time looking at it.

Gary Cziko: Rick Marken should already know that my all-time favorite experimental report in PCT is his "The Cause of Control Movements in a Tracking Task" (which is included in his book *Mind Readings).* This is such a neat experiment because it yields results which make absolutely no sense without PCT, since it clearly shows how you can get the same "responses" when the "stimuli" are very different. So I was trying to figure out how this could be done with rubber bands. Here's as far as I got.

Use the classic setup of two rubber bands looped together and thus joined by a knot. The disturber inserts a piece of chalk in his or her end of the rubber band, and the controller does likewise. They start out so that the knot is over the reference spot; the controller is asked to keep the knot there. Then the disturber slowly draws a pattern or letter or writes a short word while the controller compensates (controls the knot). Then they move to a different spot on the board and do it again (same disturbance pattern used).

The purpose of this is to show that while the disturbance and response patterns are (essentially) the same in the two runs, the movement of the knot (the "stimulus") is not the same. This is the magic of control.

While it is easy to get a record of the behavior of the controller and the disturber, I don't see an easy way to get a record of the *knot's* movement. Maybe if I use *two* sets of rubber bands and use long pieces of chalk (attached to the rubber bands at the bottom and top), I can join the rubber bands on another piece of chalk and have it leave a record of the knot's movement. I'll have to try this out. Meanwhile, I would appreciate any other suggestions for this portable demo.

Chuck Tucker: Without modesty, I would refer each of you to my rubber band demo paper in *Continuing the Conversation* (12), Spring 1988. I merely transformed Bill Powers' original demo in *Behavior: The Control of Perception* into several sets of instructions so that they could be used with a group (e.g., a class or conference). Instead of using a chalkboard with the rubber bands (or a single rubber band knotted in the middle), I use 3′ x 5′ drawing paper (which I attach to the board with masking tape) to make a record of the trace of pencils or markers (each person has a different color), then I take down each paper after the demonstration. After all of the demonstrations, I can compare the tracings (you could also reduce the tracings to distribute to the group and also use the tracings in papers you might write about the demonstrations). One way to make a record of the movement of the knot is to videotape the entire demonstration, making certain that the center of the frame is the knot. I would also suggest making the knot a different color from the background and drawing a grid around the target. With slow motion, you could see (and even crudely measure) the movement of the knot. You could also use the video to show to other groups as well as improve upon your procedures.

Bill Powers: Our image of "rubber banding" is unfortunate in one respect, because this demonstration has deliberately been made very simple, to illustrate principles. A more realistic example of rubber banding would give the control system one rubber band attached to the knot, and 20 different people 20 rubber bands attached to the same knot. The control system won't have any difficulty in controlling the knot (unless the combined disturbance results in breaking of the control system's rubber band) because only the vector sum of disturbances matters. Control might actually be easier because independent random disturbances will sum to a net disturbance having much less variability than any one of them has.

But any one person acting as a disturbance, trying to influence the control system's hand position, is going to have great difficulties because of all of the other random disturbances that are present. While control still remains possible, it's no longer possible for the disturber to estimate the best direction to move his/her own hand to achieve a correction of the other's hand position, because there is no longer any best direction. And it becomes difficult for the putative disturber to know what disturbance is actually being applied; perceiving one's own rubber band's tension is no longer indicative of the net disturbance on the other's controlled variable. The only way to make sure of applying a known disturbance is to isolate the control system from all of those other influences.

Chuck Tucker: Instructions for Students for a Rubber Band Experiment:

1. Review the "rubber band experiment" described by Runkel in his book (Chapter 10). You need a rubber band knotted in the middle (called RB below), a target diagram (three examples are given and others suggested), and a table or other flat surface.

2. Select a person, P, with whom to carry out a modification of the RB experiment. Instead of having P guess what is reasonable for your behavior, you will ask P to adopt a particular reference signal and per-

form accordingly.

3. Place a target diagram (see examples below) on the table and ask P to keep the knot in the middle of the RB "over" the center of the target by saying: "Please put your finger in this loop of the rubber band and keep the knot in the center of the rubber band above the 'X' in the middle of the target. I will put my finger in the other end of the rubber band and move my end, but you should keep the knot over the 'X' until I say *stop."* (Pause until both of you have your fingers in the ends of the RB and have placed the RB on the target diagram with their knots over the "X.") Say *"stop"* when you have accomplished one of the purposes described below.

4. Your assignment is to move your loop of the RB such that you can place P's finger (which is inside the other RB loop) over the letters on Diagram A to spell out the word "CONTROL" by having placed his/her finger on these letters in sequence: C, 0, N, T, R, 0, L. When you have done that, say *"stop."* Then ask P: "Do you recall what word you spelled when your finger touched the letters?" Whatever the answer, tell P: "The word you spelled is 'CONTROL.'" Then say to P: "I want you to keep the knot over the 'X' again; I will tell you to stop for each of the letters." Do as above and have P spell "CONTROL," stopping when each letter is touched by his/her finger. *Hint:* If P maintains his/her reference signal (maintaining the knot over the "X"), you should be able to place P's finger over the letters. P cannot control *both* his/her finger *and* the knot: they are connected by P's maintenance of the RB and P's resistance to your disturbance. If P wants to control the knot over the "X," P must resist your disturbance. With ingenuity, you can therefore get P to place his/her loop finger over each of the letters in turn.

5. You can do this assignment with Diagram B (colors) by having P's finger touch a sequence of colors. You can make diagrams of your own with figures (triangles, circles, squares, rectangles) at both ends or with numerals like 1, 2, 3, 4, 5, 6, 7, 8, 9 at both ends, etc., as long as you can get a sequence of moves, remember them, and have P touch them.

6. Repeat this exercise with a total of three persons.

7. Your report should be typed (no more than three pages, double-spaced) and include the following: (a) a description of your procedures, P's verbal and non-verbal actions, and the outcomes for all three persons; (b) based on the observations reported in (a), write a one-paragraph analysis of the hypothesis that you can influence another person only if it serves some purpose which is important to that person.

8. Your could add an appendix to your report describing what happens when you ask P to see if he/she can get you to spell a word, touch colors, figures, symbols, or numerals.

Diagram A

A	R	C	U	L	O	T
N	L	O	C	B	P	F
S	I	Y	O	N	C	V
Q	W	R	T	O	N	D
A	G	E	I	U	Y	S
H	K	Z	L	B	Z	P

X

A	R	C	U	L	O	T
N	L	O	C	B	P	F
S	I	Y	O	N	C	V
Q	W	R	T	O	N	D
A	G	E	I	U	Y	S
H	K	Z	L	B	Z	P

Diagram B

BLACK	WHITE	RED	BLUE	YELLOW
GREEN	ORANGE	BLACK	WHITE	PURPLE
YELLOW	RED	GREEN	BLACK	WHITE
BLACK	WHITE	RED	BLUE	YELLOW
GREEN	ORANGE	BLACK	WHITE	PURPLE
YELLOW	RED	GREEN	BLACK	WHITE

X

BLACK	WHITE	RED	BLUE	YELLOW
GREEN	ORANGE	BLACK	WHITE	PURPLE
YELLOW	RED	GREEN	BLACK	WHITE
BLACK	WHITE	RED	BLUE	YELLOW
GREEN	ORANGE	BLACK	WHITE	PURPLE
YELLOW	RED	GREEN	BLACK	WHITE

Diagram C

@	%	&	*	$	!	?
?	!	$	#	&	%	@
*	&	@	*	?	$	%
@	%	&	*	$	!	?
?	!	$	#	&	%	@
*	&	@	*	?	$	%

X

@	%	&	*	$	!	?
?	!	$	#	&	%	@
*	&	@	*	?	$	%
@	%	&	*	$	!	?
?	!	$	#	&	%	@
*	&	@	*	?	$	%

Instructions for Students for Observing and Recording the Coin Test:

1. Have a person, P, arrange four "coins" on a table (don't use actual money, instead use either quarter-size circular paper disks or same-color poker chips), making a specified pattern which P writes down in advance but does not show you. You might do this by asking a classmate or friend to help you with a class project which will take about twenty minutes and can be done without going to any other place. Besides the "coins," you need a writing instrument, paper, and a table top, flat board, or desk.

Say something like this: "I will give you four disks and a piece of paper. What I want you to do is to think of a pattern in which you can arrange these (name of objects) on this flat surface. But first, I want you to draw and name that pattern on this paper; *do not show it to me.* Next, arrange the (name of objects) in the pattern that you have on your sheet of paper. Then, without having any more conversation between us (except for the announcement 'No change in pattern' when my moving of the disks does not change the pattern) until I say 'Game is over,' I will change the pattern and you are to put the coins back in the pattern after each time I change it. Do you understand this game?" *If not*, repeat the instructions as written above again and clarify where necessary.

2. Your task is to discover what P has in mind without asking any questions or using any verbal communication at all. Your discover pro-

cedure is to change or disturb the pattern among the objects by moving the objects around in some ways and noting what you have done to change the coins. So before you make a change, draw and name the pattern of the objects on a piece of paper without showing it to P; after you make the change, draw and name the pattern that you made with the changes. If your change alters the pattern P has specified, P must correct the error by re-arranging the objects to re-make the original pattern. If your disturbance does not alter the pattern that P has specified, P must announce "No change in pattern."

3. Repeat this process until you are certain that you can: (a) specify and demonstrate three disturbances that will call for P to re-arrange the objects and correct the pattern; this you should be able to discern from what you have drawn on your pad—you will have to change the objects many times to observe three disturbances and three "No change in pattern" instances; (b) specify and demonstrate three disturbances that resulted in P announcing "No change in pattern"; this you should be able to discern from what you have drawn on your pad.

4. Compare your drawings with P's drawing of the pattern and (a) report the extent of agreement, including whether you identified the pattern but named it something other than what P named the pattern; (b) report at least one example of failing to see the pattern to which P returned the objects following a change that you introduced.

5. Your report should be typed (no more than three pages, double-spaced) and include (a) your report of agreement between you and P; (b) your answer to 4(b); (c) a brief statement on what you learned from this experiment; (d) a copy of P's written specification of the pattern; (e) your drawings of three change and three no-change patterns.

In the "coin" test, I tried to imagine what pattern would be "coins" arranged as follows: "All coins exactly where they are and oriented as they are." The only one I can come up with is one where P is controlling for the relationship of the "coins" to the surface; as long as the "coin" is on the surface, then there is "no change." I have tried to eliminate that by having P arrange the "coins" in a pattern and name it, which makes it extremely difficult for P to control for such a reference signal as "relationship to the surface." I have changed the game so that coins are not used, to eliminate "heads and tails" situations, different types of coins, different colors of coins, and other such variables. I would also suggest that one demonstrate this game with those whom you are asking to do it before they do it. In a class, I use either a magnetic board with letters "o" or a felt board with disks. There are ways, in other words, to reduce the variability of patterns for this game. Of course, if you want to introduce a variety of variables that are possible for controlling, then you can make the game more complex.

I am also posting three revised diagrams for the rubber band experiment. These diagrams have the symbols/colors in a mirrored reverse arrangement. This arrangement makes it possible for the E to place his/her finger on a spot on his/her side of the diagram, and the P will have his/her finger on that same spot in mirror image, be it symbol, letter, color, or whatever. The E does not have to watch the finger of the P, but simply his/her own finger. This is a way to show that E can control for a particular symbol, and, if P is controlling for the knot over the "X," then P's finger will be on the same symbol as E's.

Diagram A

A	R	C	U	L	O	T
N	L	O	C	B	P	F
S	I	Y	O	N	C	V
Q	W	R	T	O	N	D
A	G	E	I	U	Y	S
H	K	Z	L	B	Z	P

X

P	Z	S	L	Z	K	H
S	Y	U	I	E	G	A
D	N	O	T	R	W	Q
V	C	N	O	Y	I	S
F	P	S	C	O	L	N
T	O	L	U	C	R	A

Diagram B

BLACK	WHITE	RED	BLUE	YELLOW
GREEN	ORANGE	BLACK	WHITE	PURPLE
YELLOW	RED	GREEN	BLACK	WHITE
BLACK	WHITE	RED	BLUE	YELLOW
GREEN	ORANGE	BLACK	WHITE	PURPLE
YELLOW	RED	GREEN	BLACK	WHITE

X

WHITE	BLACK	GREEN	RED	YELLOW
PURPLE	WHITE	BLACK	ORANGE	GREEN
YELLOW	BLUE	RED	WHITE	BLACK
WHITE	BLACK	GREEN	RED	YELLOW
PURPLE	WHITE	BLACK	ORANGE	GREEN
YELLOW	BLUE	RED	WHITE	BLACK

Diagram C

@	%	&	*	$	!	?
?	!	$	#	&	%	@
*	&	@	*	?	$	%
@	%	&	*	$	!	?
?	!	$	#	&	%	@
*	&	@	*	?	$	%

X

%	$	?	*	@	&	*
@	%	&	#	$	!	?
?	!	$	*	&	%	@
%	$	?	*	@	&	*
@	%	&	#	$	!	?
?	!	$	*	&	%	@

Bill Powers: Here's an example of the bandwidth of a control system. Hold up your forefinger about 18 inches in front of your nose and move it slowly from side to side over a total distance of three or four inches, like a slow metronome. Now, keeping the average position and the amplitude of movement the same, gradually speed up the movement, like a metronome going faster and faster. Keep going faster until you absolutely can't do it any faster. At that point you will be using your whole arm, and you will feel quite large muscular efforts, even though the movement from side to side is still only three or four inches (try to keep it that way).

The fastest movement you can produce is at a frequency essentially equal to the bandwidth of your finger position control system. Obviously, you can perform this back-and-forth pattern at any slower speed (lower frequency) with no great difficulty, right down to zero frequency (stationary finger). But when you try to produce an oscillating movement at a frequency higher than the bandwidth, your control system simply won't obey. You can *imagine* a faster movement, but you can't *produce* a faster movement.

Why is there a bandwidth? One explanation might be that your muscles simply can't reverse the motion of your arm any faster, because they reach the limits of force that they can produce. If that were the only limit, you ought to be able to move your finger faster if you move it over a span of only a quarter of an inch instead of three to four inches. The maximum force needed to maintain an oscillation goes as the square of the frequency, so when you move your finger one-tenth as much, you should be able to oscillate your finger about three times as fast.

In fact, you can move perhaps a *little* faster, but certainly not three times as fast. You can oscillate your finger with an amplitude of, say, four inches or less at about four to five cycles per second, but not significantly faster, *even* for the smallest movements (I assume you're not a concert pianist, and anyway, concert pianists don't have much occasion to practice sideways trills).

If you increase the amplitude to a foot or eighteen inches, you will indeed find a decreasing speed limit set by muscle strength; the force required increases linearly with amplitude in a linear system (which your arm is not). At large amplitudes of movement, you slow down because your muscles won't produce enough force to maintain the same frequency of oscillation you can maintain with a small amplitude. But below a certain amplitude, the speed limit is no longer set by muscle force. Something else is limiting the speed.

When you slowly speed up a small movement, keeping its amplitude the same, you'll notice another phenomenon. At low frequencies, you see a finger waving slowly back and forth. But at the highest frequency you can produce, you can see the finger only at the end of each movement, where it reverses. Between those positions it's just a blur; you can see right through it. Obviously, you couldn't track anything with your finger at that speed, because you couldn't see its movements, much less track irregular movements of something else. What you're seeing is the bandwidth of your visual perceptions of position. The frequency at which your finger just ceases to be a blur and becomes a finger again is the bandwidth of retinal position detection (actually, you have to suppress eye movement by fixating on the background to find the true bandwidth, Which is quite low, only two to three Hz).

It's interesting that the bandwidth or maximum frequency for small movements is higher than the bandwidth for retinal position detection. Something is limiting kinesthetic control at a frequency higher than that at which position control takes place, but at a lower frequency than is set by muscle strength. This probably involves a perceptual limit, too, in that kinesthetic position sensors do have speed limits, but more likely it is caused by temporal filtering that is required in order to make the kinesthetic control systems (that position your finger in the dark) *stable.*

The kinesthetic position control systems contain time delays of something like 50 milliseconds of neural transit time and synaptic delay around the loop. The muscles themselves have viscous damping. The noisy nature of neural signals, trains of impulses, requires that some smoothing take place in order to turn barrages of neural impulses into smooth changes in neurochemical concentration levels. All of these factors mean that there is an unavoidable lag in these systems of about 100 milliseconds, part of it a transit-time delay, and part of it an integrative or smoothing lag. That would imply that to switch as fast as possible from one position to another under kinesthetic control should take a little longer than 100 milliseconds, and to switch back another 100 milliseconds, for a total of 200 milliseconds for one cycle of a repetitive movement. That would give a frequency for continuous switching of four to five Hz, which is pretty close to what you see when you do it. Not bad for a ball-park estimate.

You can easily see the relationship between speed of movement and bandwidth. Try the experiment again, with small movements, only this time switch as fast as possible from one position to another four inches away, pause, then switch back as fast as possible, and pause. You're trying to generate a square wave. At low frequencies, each switch is discrete. You finger blurs over to the other position and is stationary for a while, *then* blurs back again. But as you increase the frequency of the square wave, still making each movement as fast as you can, the movements begin to blend into a continuous movement, so that when you reach the maximum frequency you're back to a continuous sine-wave movement. In fact, even at the low frequencies, each switch has been like half a cosine wave—a high-frequency cosine wave at just about the bandwidth frequency. So the slow square wave you started with was rounded off a little, and that rounding-off means that the movements actually never exceeded the maximum bandwidth for continuous oscillations.

It is possible for you to generate oscillations at higher frequencies. The only way to do it, however, is to destabilize your spinal control systems, the lowest level of control. If you press your hands together very hard and maintain the push until the muscles begin to fatigue, you might see "clonus" oscillations, at a frequency of about eight to 10 Hz. This results from changing the force-tension curve in the muscles enough to make the control systems unstable. They break into spontaneous oscillation. But you can't produce this kind of frequency voluntarily. (You might see lower-frequency oscillations—the next level might get unstable first. Shivering is probably a clonus oscillation of this kind, produced by destabilizing the control systems in some other way. So climb naked into the refrigerator if you want to see 10-Hz oscillations).

For visual tracking using control of finger position to follow a target, you obviously have to be able to see a finger while it's moving. This means that the bandwidth for following a randomly moving target is about two to three Hz, the frequency at which the finger just stops being a blur. This bandwidth is set by perception and output functions, not muscles. The kinesthetic systems clearly have a wider bandwidth; they can execute faster movements than you can control visually. And the lowest level of kinesthetic control, the spinal reflexes, have the widest bandwidth of all.

What's most interesting to me is that these nested bandwidths are just about what is necessary to maintain stable control at each level. There would be no point in being able to see movements beyond a bandwidth of two to three Hz because the kinesthetic control systems used by a visual-motor control system have a bandwidth only slightly higher—four to five Hz. Therefore, we *don't* see faster movements! In fact, if we could see faster movements, the bandwidth of the visual control systems would be so high that the lags of the lower control systems would be too long for stable control at the higher level. In technical terms, at a frequency where the phase shift of a sine-wave disturbance passing around the loop is 180 degrees, the gain would still be above one. Negative feedback would turn into positive feedback at that frequency, and the whole system would oscillate. Oscillation is not good for control.

Rick Marken has explored several of the higher levels of perception, showing that as the (hypothetical) level increases, the bandwidth of perception continues to decrease. This is only logical, once you do some experiments yourself. For example, while moving your finger back and forth as fast as you can, *vary the amplitude* between, say, a four-inch amplitude and a two-inch amplitude. Obviously, you can't even *see* "amplitude" in a time smaller than the fastest oscillation. And to vary amplitude, you have to have a couple of oscillations of each size. In principle, you could do one large oscillation and one small one, and so forth. In practice, you can't perceive changes in amplitude that fast. So you can't control amplitude as fast as you can control position. Rick's demonstrations are simple and elegant, as usual, showing the effect clearly. So naturally he can't get them published.

The relationships between bandwidths at different levels are, once you understand why they exist, perfectly simple and logical. It seems that bandwidth follows from physical principles and obvious relationships among physical phenomena, such as between frequency and amplitude. It's obvious that you can't change amplitude in less than one complete cycle, because amplitude doesn't even exist until at least one cycle is completed. Ho hum.

But remember that this is a constructed reality we're talking about. This relationship holds because of the way we perceive amplitude as a function of movements. Having constructed a perception of amplitude, we then discover that it has properties, and that it is related to lower levels of perception such as movement and position. The ho-hum self-evident relationship suddenly becomes evidence about how perception is constructed—much more so than evidence about the natural universe. The bandwidth relationships also tell us that higher perceptions must be functions of lower ones, and that higher control systems use lower ones to accomplish their control. The evidence just continues to pile up that we are looking at—and *with—a* hierarchy of perceptual control systems.

When is the world going to wake up to what is going on here?

Gary Cziko: I did it! I just designed the most awesome manual PCT demonstration of all time. And you just need three pencils, four rubber bands, and two pieces of paper taped together (on the other side) to make a long sheet about 22 inches high and 8-1 /2 inches wide (or just use two attached fan-fold computer sheets).

Take the three pencils and attach them to each other like rungs on a ladder using the rubber bands. Now get your long piece of paper and draw a line horizontally across the middle (just above or below the seam of the two sheets). This is the target line. Place the paper on a table and tape down the corners so that it won't slide about.

Take one end-pencil and have your subject take the other end-pencil. Put your pencil point above the target line at the extreme left side of the paper and have your subject put his or her pencil point below the target line so that (a) all pencils are perpendicular to the paper, (b) the middle pencil point is on the target line, and (c) the rubber band connecting the subject's pencil to the middle ("cursor") pencil is perpendicular (at a 90-degree angle) to the target line. Tell your subject to maintain these two perceptual variables (cursor pencil point on target line and rubber band at 90-degree angle) as you *slowly* trace out an approximation to a sine curve above the cursor from one side of the paper to the other. Make sure that all three pencil points are making contact with the paper and leaving a trace (felt-tip pens leave nice traces with little pressure).

After you've done this once, *do it again,* this time making sure that you, as experimenter, follow the same line as you did the first time.

You will now have before your very eyes a very remarkable piece of paper. Above the target line, you will see an approximate sine wave drawn twice (they will look more like one line if you're a really good disturber). These are records of the two *disturbances.* Below the target line, you will see two mirror images of the approximate sine curve drawn twice. These are records of what the subject *did.* They will probably be more irregular than the disturbances, but there should be an obvious similarity between the two response curves. In the middle, you will have two "cursor" lines, which are records of what the subject saw during the two trials. These two lines should not have any discernible pattern to them. In addition, they will *not be similar to each other* (if they are, this is an indication that you disturbed too fast and the subject lost good control).

This is very strange indeed, since the subject's responses are *similar* on the two trials and yet what he/she saw (the cursor pencil point) during the two trials was very *different.* How can the subject respond similarly on two trials when what was seen (the "stimulus") was so different? If anyone can come up with an explanation of this which does not look like a closed-loop negative-feedback model, please let us here on the net know about it.

Your subject might find it difficult at first to control both the position of the cursor pencil on the target line and the angle of the rubber band, so you might want to let him or her practice first using the eraser ends of the pencils. Alternatively, you can practice yourself and let your participant be the experimenter.

This is a manual (i.e., non-computer) approximation of the task and analysis used by Rick Marken in "The Cause of Control Movements in a Tracking Task," available in his book, *Mind Readings*. Rick showed in a similar task using a computer and game paddle that the correlations between cursor variations (here, middle pencil variations) were usually less than .20, while correlations between response variations were always greater than .99.

Now comes the fun part. If you are a psychology student, show this demonstration to your local non-PCT psychology professor (if these are hard to find, please let us know where you are located) and ask him or her to explain the findings. He or she will most certainly have to say that the two sets of cursor variations are similar, even though they are not. If he or she doesn't believe they are not similar, show him or her Marken's paper with the fancy computer and game paddles and correlations sometimes to *four* decimal points; he reports one correlation between cursor variations of .0032 with a corresponding correlation between response variations of .997. If your non-PCT psychology professor is really sharp, he or she will quickly point out that a correlation of .0032 can be statistically significant with a large enough sample). If he or she is not that sharp (or much sharper), he or she should be quite shaken up.

Greg Williams: Gary says: "This is very strange indeed, since the subject's responses are *similar* on the two trials and yet what he/she saw (the cursor pencil point) during the two trials was very *different.* How can the subject respond similarly on two trials when what was seen (the 'stimulus') was so different?" The two "responses" to the two "very *different" "stimuli" are* not the *same,* only *similar.* Skinnerians would have no problem with the *fact* that (even slightly) *different* "responses" resulted from different "stimuli." And if you show them results where successive "responses" are *identical,* yet the "stimuli" in each case are different, they will talk about "stimulus generalization" or say that the organism can "lump" different-appearing stimuli (to the experimenter) into *one* kind of "discriminative stimulus." But it gets even worse. If successive "responses" are judged as different by the experimenter, they might say that they really are all in the same "operant" set of responses.

Gary also says: "If anyone can come up with an explanation of this which does not look like a closed-loop negative-feedback model, please let us here on the net know about it." At the level of the observed phenomena, it is obvious that the "stimulus" in your experiment is affected by the "response." Skinnerians have no problems with such situations, which they call instances of "self-stimulation." But at the generative-model level (should any of them dare to speak thereof, lest they lose their "Skinnerian" labels!), some of them might argue that the "discriminative stimulus" is "middle pencil point moving (either direction) away from the middle line" and that the (ongoing) "operant" (set of "responses") consists of "actions to move the middle pencil back toward the middle line." Such a generative model makes no explicit reference (no pun intended) to postulated internal (to the organism) states. (PCTers, of course, will immediately note the *implicit* reference level. Skinner used to argue that bringing in such hypotheticals would add nothing to the "analysis of behavior," and, worse, would tend to distract one from the data. I still think he had a point, *to* a *degree.* Yet, by hewing to that line so cautiously, he was unable to explain the existence of particular "wants"—to which I quickly add that he did not *want* to explain that). Also, the typical Skinnerian would want to claim that the person would "respond" to the "discriminative stimuli" because of *previous* reinforcements having to do with his/her relationship to the experimenter. Regardless, Skinner's notion of "operant" *sets* of *outputs,* each of which result in the same *outcome,* was a significant step toward replacing specification of outputs with control of perceptions.

Bill Powers: Gary, a very nice implementation of Rick's experiment. I'm sure that demonstrating it is much simpler than explaining it in words.

Thinking about your description of what happens, and about Rick's experiment, I first thought that the failure of the "cursor" movement to predict the behavior must be due to the fact that control is good enough to bring the error down to the noise level of the system. This is the general explanation I've been entertaining, for some time, for the phenomenon of low correlation between behavior and the variable that it controls.

There is, however, another possibility: chaos. Most of the control systems we've investigated are modeled best by a system that integrates the error signal to produce output. Integrals are known for hypersensitivity to initial conditions, one brand of chaos. When error is near zero, any slight perturbation will lead to an output that drifts away from the optimal setting one way or the other, which way depending on the sense of the perturbation. The result is that the perturbations due to noise are greatly amplified; the system disturbs itself and these disturbances result in a continuous wandering of the controlled variable in the vicinity of its reference level. So the wanderings are actually much larger than one would predict from the basic signal-to-noise level of the neural signals. They are large enough, in fact, to be comparable to the amount of error required to produce the output that opposes disturbances. I suspect that this is a better explanation of the low correlation between action and the controlled variable.

Rick Marken: Gary says: "I did it! I just designed the most awesome manual PCT demonstration of all time." Nice work! Looks like the end of psychology as we know it, right? Wrong! Greg points out: "Skinnerians would have no problem with the fact that (even slightly) different 'responses' resulted from different 'stimuli.' And if you show them results where successive 'responses' are *identical,* yet the 'stimuli' in each case are different, they will talk about 'stimulus generalization' or say that the organism can 'lump' different-appearing stimuli (to the experimenter) into *one* kind of 'discriminative stimulus.' But it gets even worse. If successive 'responses' are judged as different by the experimenter, they might say that they really are all in the same 'operant' set of responses."

Greg makes an excellent point: psychologists in general (and Skinnerians in particular) are not going to be persuaded by these demonstrations of principles, because it is very easy to say it's just "stimulus generalization" or "discriminative stimuli" or "operants" or whatever. You can't "persuade" people with these demos unless they are (1) willing to be persuaded, and (2) willing to deal with the problem *quantitatively*.

Gary, your demo shows that sensory input is not the cause of behavioral outputs, no matter how ridiculously counterintuitive this seems. But will this demo convince a psychologist who is busily doing research based on the assumption that o = f(i)? *No way.* S/he can always describe the results *verbally,* invoking the shibboleths of scientific psychology: "stimulus generalization," "response generalization," etc., and get back to work.

As Greg said, demos like this are no problem for the scientific psychology establishment. I confidently predict that if you (Gary, or anyone else) try this demo with a standard psychologist, they won't even break stride; they'll have a quick explanation, see no problem, and go off, comfortable in the knowledge that there is no problem at all. I don't think any demo—no matter how clever—will ever wake the psychological establishment from its dogmatic slumbers. Only those who are willing to learn—and are willing to think quantitatively—have any hope.

I say this, Gary, so that you won't be too frustrated when you find that your brilliant demo produces virtually *no* revelations among your colleagues.

Very nice work, though.

If people don't want to believe in control, then they don't have to. I think people throughout the behavioral sciences have a serious commitment to the input-output view of behavior (and it is a "view"—just as much as feedback control is a view). No amount of evidence can "demolish" someone's world view; people who wanted to view the earth as a fixed sphere at the center of the universe had no trouble dealing with evidence suggesting that it was not; moreover, some of the most compelling evidence was in favor of the stationary earth view—just as some of the most compelling evidence is in favor of the input-output view.

Ed Ford: Gary, Chuck, and all of you other PCT demonstrators, I have a different way of demonstrating PCT with rubber bands. Take two rubber bands (I prefer big ones) and knot them together. Ask the participant to hold the ends of the rubber bands, one in each hand, facing you. With his/her hands outstretched, the knot will be directly in front of both of you. Then point your finger at the knot and ask him/her to keep the knot directly in front of the tip of your finger. Begin moving your finger and he/she will automatically look at the relationship of the knot to the tip of your finger. Next, ask him/her to look at his/her left hand and watch its actions while trying to achieve the same goal of keeping the knot at the tip of your finger. Obviously, he/she can't. In fact, there is a strong internal urge to take a look at the knot-fingertip relationship. Thus, he/she will perceive the need for feedback and the inability to achieve goals by watching behaviors. I've found this to be the best way to lay to rest the idea that we control our actions.

An alternative is to get two people to participate. Begin with the two rubber bands knotted together. She holds the end of one rubber band, and he holds the end of the other rubber band, with the knot between them. Again, you point your finger, with the tip being right at the knot. Move your finger around; they have to keep the knot right at the tip of your finger. Now, ask them to achieve the same goal by watching their actions and to concentrate on how they move their hands as they attempt to reach their goal. Or tell them to watch each other's actions. Or ask one of them to close their eyes and the task for the other becomes more difficult. Move your finger about. Again, the internal desires on their parts to look at the knot show the need for feedback to achieve internal goals and the inability to control by concentrating on the actions. I find that when you ask people to switch from watching the knot and its relationship to the tip of your finger to watching their hands move, it becomes so obvious how we control for input, not output. The nice thing about these demonstrations is that you don't need a chalkboard, you can demonstrate most anywhere (with the exception of a phone booth), and you still maintain control over the disturbance.

Bill Powers: Ed, those new rubber band demos will take their places in the fundamental set. I think that Occam's Law, saying that we should choose the simplest and most parsimonious explanation covering the facts, ought to be supplemented by Occam's Economic Law, saying that the way of communicating the explanation should cost as little as possible. You have taken a demonstration that could be done on a $2000 computer and have managed to show every major point using equipment costing about 10 cents. Very, very nice.

Ed Ford: I'd like to add an additional feature to my version of the rubber band demo. You can show others what it is like to try to control another's actions. I had my wife, Hester, hold the two knotted rubber bands, and my son, Joseph, point his finger while Hester tried to follow the finger (as he moved it about) with the knot. I then gently said, "I'll help," and I took her arm to help her achieve her goal. Anyone want to guess the response? "Hey, I can do this myself" is what she said. Her attention immediately went from her chosen goal of trying to follow the pointed finger of Joseph with the knot to getting me off her back. I suggest when you try this that you use someone with whom you have already established a close and warm relationship. I don't want to be sued. Bill, you can't get that out of a $2000 computer.

Bill Powers: Ed, what's nice about the rubber band experiment is that you can demonstrate just about all of the features of PCT with it. Your latest is a fine example.

Gary Cziko: Bill Powers has made some illuminating arguments [not quoted in this thread] about how a feedback system can be expected to be faster than an open-loop, ballistic system. I've found what I think is a simple way to demonstrate this, to which I would like to get some reactions.

You need a large, smooth table, two coins, and a stopwatch. An assistant to work the stopwatch might also be useful. Stand or sit beside the table. Next, take two coins (B for ballistic and F for feedback) and put them on one side of the table, with one coin directly above the other. Now slide one coin (B) from where it is to the other side of the table ballistically; this means giving it a quick push with your finger so that it slides shuffleboard-style across the table and comes to rest where the laws of physics say it must. The time taken from the initial push to the final stop should be timed. Now move the remaining coin (F) from where it is (and from where B started) to the new location of coin B and time how long it takes. Do this as quickly as you can while keeping your finger on the top of the coin as you slide it across the table. Compare the two times.

When I do this, I get times for coin F which are *always* faster than coin B, feedback taking only about 60% of the time of ballistics (for example, 0.86 seconds for coin B, compared to 0.52 seconds for coin F). It seems that the two coins take off at about the same speed, but that coin B starts to slow down immediately after the push, while coin F continues to accelerate until getting very close to the target, where a very sophisticated braking system takes over to decelerate the coin sharply right before the target.

Somehow I feel that the physics of coins sliding on tables doesn't make this a watertight demo showing that closed loop can be faster than open loop (limbs don't have much friction, do they?), but I'd like people to try the demo and get some reactions from the more physically enlightened people on the net.

Rick Marken: Gary, the coin-sliding demo is absolutely your best yet!! I love it. I hope it holds up to the scrutiny of the physically inclined types. But I think there are all kinds of possible variations on it that can satisfy even the most hard-nosed members of the net. It's really ingenious, Gary; nice going.

Robert Clark The various rubber band demos are fabulous! I particularly like Ed's recent one, taking one band in each hand. Especially the reaction to "help." I am reminded of the leader-follower" demo with the Portable Demonstrator. Do you remember this, Bill? It requires two subjects who first work with ordinary finger-tracking separately with the experimenter. Then one subject, Joe, is asked to lead the tracking, and Pete is asked to follow. After they settle down, the experimenter calls, "Pete," who is now to be the leader, with Joe the follower. Again, after settling down, the experimenter calls, "Joe," and Joe and Pete change roles. Make the changes rather slowly at first, so that it becomes easy—then gradually increase the pace.

It isn't easy to adjust a remembered skill to an unfamiliar situation. I am reminded of the time it occurred to me to carefully apply my ball-throwing sequence, right-handed, to my left arm. I thought I might be able to do this, since I am generally rather ambidextrous. It took careful and detailed reworking of the remembered movements to apply them to the other side. It worked much better than I expected! But I found that I had to have *no* witnesses (distractions? violations of my self-image?), and it felt so strange that I never tried it again! But there are many such reworkings possible. In school, we played with "talking backward." I have found since that this is not uncommon, but we did not reverse the spelling, we reversed the sequence of phonemes! "Nack ooyah cawt zdrawacab?" Not easy! With experimenting to acquire a stock of remembered performances, "Ti zih tahn draha!"

Bill Powers: Bob Clark says: "I am reminded of the 'leader-follower' demo with the Portable Demonstrator. Do you remember this, Bill?" Yes, indeed, and thanks for bringing it up. It's been a long time since I mentioned it, however, and it really does belong in the portable demo collection. Just to expand a little on your brief description: The object of the demonstration is to see how long it takes people to switch roles, namely, from leader to follower. B moves a finger arbitrarily in space while A tries to keep a forefinger aligned with B's finger. This results in B tracing out some pattern in space, while A's finger lags behind it a little, always trying to catch up. Then, on a signal from a third party, the two participants swap roles. Now A is moving a finger in arbitrary patterns, while B tries to track it with a finger as closely as possible. Clearly, it is now A who creates an arbitrary pattern in space, while B's finger lags a little behind it, always trying to catch up.

The third party keeps giving the signal at variable intervals, and the participants keep swapping roles, until they are executing the swap as fast as possible. The claim that Bob and I would make is that the minimum possible time required for this swap is longer than the time taken to change any lower-level control process. The time should be longer, for example, than the time required to correct the error when tracking a regular pattern over and over, with the disturbance being a sudden stop in the target pattern. And that time is longer than it takes to track a target that moves in random jumps to fixed positions, which is longer than the time it takes to respond to a downward push by swinging the arm rapidly downward, which is longer than it takes for a directly disturbed arm to begin to move back toward the undisturbed position. So we would seem to have five nested and demonstrable levels of control with progressively longer reaction times, the fifth being the role-swapping, and the lowest being the position reflex. A proviso is that all of these tasks should be well-learned, so we aren't looking at reorganization along with the control actions.

I just checked this out with my wife, Mary, and it still works. While checking it out, it occurred to us to wonder what would happen if one of the people simply changed roles without warning the other and without any external signals. With different pairs of people, the results might be different, but in our case the results were hilarious. I won't spoil it for you by describing it.

Gary, your coin-sliding demo inspired me to think up another demo that shows a little more of the effect you want. We happen to keep around the house various toy trains, for purposes of grandparenthood. I picked a wooden train car about six inches long, weighing about a pound, with wooden wheels and a convenient hook at each end. To each hook I fastened a string of three rubber bands, fairly weak. I set the car on a table, on its wheels. Then, using both hands, I stretched out the rubber bands so the car came to a balance point between my hands.

There are now two ways to move the car: (1) Move both ends of the rubber bands by a fixed distance to one side and let the car end up where it will; (2) Watch the car and move your hands (keeping tension between them) so as to bring the car to a fixed position.

If you try to move the car as fast as possible by the first method, you can make two marks on the table and move your hands to the marks as rapidly as possible. The car will be accelerated in the direction your hands move, reaching maximum velocity just as the tensions in the two rubber bands are equal. It will then proceed past the midpoint until its velocity is reduced to zero by the growing tension in the trailing rubber band. It will then accelerate back the other way, and so on in diminishing oscillations to an end-point.

Using the second method, you mark the final position of the car resulting from the first method, then reset the car to its original position. Now you watch the distance between the car and the mark, and move your hands in parallel, maintaining tension between them, to bring the car to the mark. It will move to the mark and stop there with no oscillations. With practice, you can make it do this far more rapidly than you can get the car to the mark the other way.

This would be even more dramatic if the rubber bands were very weak and the wheel bearings good. You would have time to accelerate the car toward the final position by moving your hands far to one side, to get a strong acceleration, and then far in the other direction to slow the car to a stop, your hands returning to the correct final position automatically.

The only way to make the first method work almost as well as the second method would be to generate an arm-movement waveform just right to produce a high initial acceleration, and then at just the right time, a high final deceleration. In other words, provide a central pattern generator of high precision that produces the same arm positions as the control system generates without pre-programming.

This is why people have been driven to proposing motor programs instead of systems that just issue a "position" command. The motor programs are supposed to compensate for the dynamics of the controlled variable, as well as the kinematics of the jointed limbs. Once you start down this trail, still thinking of commanding output, you are driven step by logical step until you fall into the hole. Your basic premise leads you to propose a pattern generator of incredible precision, and a program of equal precision that bases its command outputs on unobtainable data of just as great precision—and it requires you to ignore all long-term disturbances.

The second method is not only simpler and faster, but it can work indefinitely (no cumulative computation errors) and it can achieve good final precision using low-precision output effectors, even in the presence of environmental nonlinearities and disturbances.

Robert Clark: Bill, your more complete description of the leader/follower demo is helpful. I would join in your claim that "the minimum possible time required for this swap is longer than the time taken to change any lower-level control process." The "lower-level control process" consists of tracking the leader's finger. This requires control of muscle variables, position variables, and time variables.

The follower has formed recordings from observations and, perhaps, tracking experiences. He can select one that might produce acceptable results. He uses this to provide reference levels to produce his tracking movements. As the pattern changes, different recordings are needed. It takes more time for these changes than it takes for lower-level (muscles, positions) changes. To the follower, this is still the tracking demo.

The leader also has a supply of recordings available from his experiences, etc. His assignment as Leader calls for him to select one to be tracked by the follower.

Warning! If your subjects are unfamiliar with participating in such demonstrations, there can be some unexpected side effects. For example, some people avoid the role of leader. Being a follower might be acceptable, but being the leader introduces some intrinsically different perceptions. The particular behavior depends, of course, on the specific individual. As switching becomes faster, the participants might become confused and conflicts (internal) might develop.

I suggest that you examine your own—remembered—internal experiences when you have been a participant in this demo.

Ed Ford: More on the rubber band demo: I spent the last week in Michigan, training 32 teachers, counselors, and administrators in control theory (among other things). I showed the rubber band demo, where a teacher held two knotted rubber bands stretched out, with the knot directly in front of her chest. She had to keep the knot right at the tip of my moving finger. When I asked the participant to watch the action of her right hand instead of the knot, I began watching her eyes. I could see her eyes occasionally sneaking a look at the knot. Thus, she was able, by sneaking an occasional look at the knot in relation to the dot, to achieve her goal, but with less efficiency. I wanted to force her to just watch her actions, so I got someone else to take my place by moving his pointed finger in front of the knot. Then I took a piece of cardboard (about 12 x 8 inches) and placed it between her eyes and in front of the knot. Now she couldn't see the knot and the tip of my finger, and her ability to sneak glances was eliminated. Her inability to keep the knot over the dot became far more pronounced; in fact, she couldn't do it at all. That demonstrated clearly that we need feedback to achieve a goal, and that watching our behavior has nothing to do with controlling a variable.

Rick Marken: Here is a portable demo which could easily be turned into a computer demo. Just have the subject track your finger with her finger (I just did this with my daughter) as it makes a regular pattern (an approximately 8-inch-diameter circle seems to work nicely). Move your finger at the rate of about one cycle per second—slow enough for good control, but fast enough so that knowing the circular movement pattern really helps. Then stop your finger at an unpredictable time. Your subject's finger not only takes a while to stop (about 1 /2 second), but while it is moving, it is tracing out an obvious *curve,* even though there is no target present to track. So the movement after the signal to stop is still controlled relative to a reference circular movement. There is "anticipation" that the target finger will not only continue to move, but that it will continue to move in a circle. (I put "anticipation" in quotes, because this could be modeled without any explicit computation of predicted target position at all—the model just controlling a higher order variable that could be called "relative circular motion.")

Now do the same thing, but use irregular movements of your "target" finger. Try to move you finger at about the same rate at which you were moving it to make the circle. I did it by writing out some words in the air. Now, when you stop the finger, you will find that the subject moves very little *after* the stop. This is because (in theory) the tracking is now being done at a lower level; if target movements are sufficiently unpredictable, there is nothing the subject can control except the distance between target and finger (a configuration). So there is no change in the variable to be controlled when the target finger stops; the distance between target and finger is all that must still be controlled. But when the target was a circle, the stopped target changes the variable controlled from "circular pattern" (probably an event-level perception) to no pattern.

Anyway, it's a nice way to spend a few minutes with your kids. My daughter got a kick out of seeing her finger keep moving in a curve after mine stopped; even though she was trying very hard *not* to let that happen. I didn't mind humiliating her in this way, because she keeps beating me at every computer game I've got.

Bill Powers: I sent the critique below to Dag Forssell after seeing the video tape of his "Purposeful Leadership" presentation to a group of Edward Deming aficionados. [Excerpts from the critique are reprinted here.—*Ed.]*

I would start the actual introduction to control theory by laying out your strategy to the audience and getting their agreement with it. What I would say would go something like this:

"In the rest of this presentation, we're going to go through two stages of development. In the first part, I'm going to teach you the basic principles of perceptual control theory. To do this, it's best to focus on a simple example and make sure you understand every aspect of it, so this phenomenon becomes familiar to you, and so you begin to know what to expect. Please don't worry about what this has to do with Deming's Total Quality Management (or whatever). I promise that we'll get to that. What I say about the Deming approach will make a lot more sense to you later if you just focus for now on grasping certain relationships that are basic to perceptual control theory. I hope you will interrupt, ask questions, ask me to repeat anything, no matter how simple, that you're not perfectly clear about. The better you understand what you see in this segment, the easier it will be for you to see the parallels when we start talking about real life. So for about the next half hour, let's all concentrate on a single goal, together, which is to master some basic principles and make sure that everyone understands them. The payoff will come in the half hour that follows. I want to hear that you're willing to do this: to forget Deming for half an hour, and work only on understanding the basics of PCT. How about it?"

Then I would go directly to the rubber band experiment. When you do it, you should have clearly in mind a sequence of basic principles that you want to demonstrate and explain. Don't worry about what you're going to say (output). Just be very clear at every stage exactly what you want the audience to understand. You are very good at this; you don't need to worry about your words.

The first part can go pretty much as you did in the video. Set up the task with a volunteer, and spend 20 seconds moving the rubber band around while the subject keeps the ping-pong ball on the target. Then ask the audience to explain it, as you did in the video. Be sure to emphasize that the question is, "What was the relationship between me, as the experimenter, and the volunteer, as the subject? What you would say is causing the subject to behave that way?"

With that finished, after no more than a minute, start explaining, and do so in much more detail than on the video. Say: "Watch what my hand does, what his/her hand does, and what the ball in the middle does. Notice that as I pull gradually back on my end, the subject pulls gradually back on the other end. Notice that the ball stays pretty much in one place. Now, as I raise (lower) my hand, notice that the subject lowers (raises) his/her hand. And notice that the result is *always* that the ball remains in the same place."

Then explain, right there, that you asked the subject to keep the ball in a specific place. You did *not* ask the subject to move the hand in any particular way. You told the subject what to *perceive,* not how to *act.* And right at that point, *prove* that the subject is not reacting to your hand movements. Bring along a sheet of cardboard with a notch in one side. Hold the cardboard at right angles against the paper with the notch directly over the ball so the subject can see the ball, but not your end of the rubber band. And demonstrate that the subject can still keep the ball in one spot without being able to see what your hand is doing. When everyone in the audience agrees that the subject doesn't need to see the disturbance, hold the cardboard so the subject can see your hand but not the ball, and *prove* that control gets much worse when the subject can't see the ball but can see your hand. Check with the subject: "Can you see my hand? Can you see the ball?" Then check with the audience to be sure they get it: that the subject really has to see the ball in order to control it well. You're trying to establish some clear basic facts. This should have taken no more than 10 minutes.

Now you can start drawing your diagram. The ball is there in the environment, so draw a ball. The subject has to perceive the ball, so draw a perceptual function and explain that it creates the perception inside the person of the ball outside the person. Now ask, "Where is the target?" The audience will, of course, point to the target circle on the paper. But you say, "Wait a minute before you decide," and you whisper to the subject to keep the ball six inches to one side of the target, then spend 10 seconds showing the result. Then you ask the audience, "What do you think I told the volunteer?" Most of them will guess right; if they don't, tell them what you said.

Now ask again: "What does the subject want and where is that want?" What you want them to say, somehow, is that it's inside the subject. The subject is perceiving the distance between the ball and the target and obviously wants to see a particular distance, not necessarily zero, as you have just shown. When you look at the *piece* of paper, you see the actual distance, but you don't see the wanted distance. So where is it?

Now you go back to the diagram, and you show arrows entering the perceptual function from both the ball and the target. You label the *perceptual* signal "perceived distance." And now you *can* add the reference signal, labeling it "wanted distance." Emphasize that this wanted distance is now inside the person's head. Then the question is, "So what?" You have here the perceived distance as it is at any moment. You also have here a specification for the wanted distance. Something has to happen right here if there's to be any basis for action. What operation has to be performed? The answer you want to extort is "comparison." Somehow the person has to bring these two things together, the want and the perception, and judge how they are different. If the actual distance is greater than the wanted distance, the action has to make the distance smaller; if less, the action has to make it greater. So the action has to be based on the difference between the want and the perception. It doesn't depend just on the perception; it doesn't depend just on the want. It depends on the difference between them. Draw the comparator box, label the output "difference," and draw the arrow from the comparator to the output function.

Now ask what the rule has to be for converting the difference into an action, just in one dimension. This is not hard to figure out; if the perceived distance is less than the wanted distance, move your hand one way; if it's greater, move your hand the other way. Make sure everyone understands. Everyone should be nodding. If they aren't, ask what the problem is and fix it.

The last step is to close the loop. Notice that when the subject's hand moves, it moves in the right direction, and that the result is to return the ball to the target. You can illustrate this with the stimulus-response demonstration, suddenly pulling back on your end, suddenly relaxing again.

Now apply a very slow change in the disturbance and show that the ball remains near the target. "Notice that the perception and the action happen at the same time. You can't separate out the disturbance, the change in perception, the comparison, and the change in action. They're all happening at once. You understand how each part of this control system works; now when you see them all operating at the same time, you can see that the result is continuous control, in either one (pull back) or two (move up or down) dimensions. Or more."

Now show the relationship between the disturbance and the action. Explain why it now makes sense that keeping the ball over the target requires the subject's end of the rubber bands to move oppositely to yours. The subject is just correcting movements of the ball. This is the illusion of cause and effect. It seems that your hand movements are causing the subject's hand movements. But if you realize that the subject wants the ball to be in a specific place, in between the cause and the effect, of course you understand why the movements are as they are. When you understand what the subject perceives and wants, and what the subject has to do to make the perception match the want, you understand all of the relationships between apparent causes and apparent effects.

At this point, you can test their understanding. Either really, or as a thought experiment, ask them what will happen if your wife, Christine, knots another rubber band near the ball and pulls upward on it. How will the subject's hand behave? And why? If they have any problem, ask what will happen to the ball when Christine pulls, but the subject doesn't respond. Then ask what the subject has to do to get the ball over the target again (pull downward). It would be very nice to get the audience to make the prediction, and then actually do it and show that they are right. "Were you just guessing what would happen?" No. They *knew* what would happen. How did they know? Because they knew where the volunteer wanted—intended—the ball to be.

Now you can say: 'When we started this demonstration, I asked you to explain what the subject did. A lot of suggestions were heard. Now, if I ask you again to explain what the subject did, what will you say? What caused the subject to behave that way?" And you should get nothing but right answers.

At this point, you might take five seconds and ask: "Have you ever heard of a theory of behavior that lets you explain what anyone is doing, however simple, and *know* that you have the right explanation?"

The final point can now be made. Give the subject the pen, as in your video, and get a trace of the subject's actions as you create some random disturbances. Now you have to make this point very clearly, hammer it home, be sure that every person gets it. You say: "If you had just walked into this room, and were told that this is an accurate trace of the subject's exact actions, what could you say about what the subject was doing?"

This is the conclusion of the demonstration. Make sure that all of the people understand why observing actions doesn't tell you either what the person wants or what the person is perceiving. It doesn't tell you what the person is doing—what those actions are accomplishing that the person wants to perceive as being accomplished.

Close by telling them what comes next. "You now understand the basic concept called perceptual control theory. There is a lot more to learn, but what you know now will always remain true. People act in order to make their perceptions of the world match what they want those perceptions to be. You can't understand their actions unless you know what they are controlling, and the specific target. When you do manage to figure out what they're controlling, you can explain an enormous number of cause-effect phenomena—you can see what the cause is disturbing, and how the apparent effect, the actions of the person, are counteracting that disturbance.

"After the break, we're going to start applying what you know to the Deming Philosophy. We will look for parallels between what you saw in this very simple demonstration and what you see people doing in business management situations. We'll do a little role-play first, then apply perceptual control theory to the situation, and then do another role-play later to show how a person who knows PCT will act differently. We'll talk about Profound Knowledge and what all of this has to do with Deming's insights. We can't possibly cover all applications of PCT in the time left, but perhaps you are beginning to suspect even now that these applications will penetrate into every corner of life, in business and outside it. I have been developing my understanding of PCT for several years and still have much to learn. I envy you, because the initial experience of seeing a real theory of behavior unfolding for the first time is one that can't be repeated."

Then the break; give them time to talk about it with each other and let it soak in for a short time.

Robert Clark: Dag, you have changed my view of the rubber band demos. I had realized, of course, that they are useful and supplement the Portable Demonstrator that we used some 30 years ago. But when you introduced the "double ball" version, it added a new dimension. With the single ball, the lower orders of control can be demonstrated by suitable adjustment of the timing and the patterns used by the demonstrator. However, without losing any of them, the second ball makes the subject a full participant. He or she is asked to "select which ball to control"! This can be carried further by suggesting that he or she change, from time to time, which ball he or she is controlling. Another step: switch who is the demonstrator and who is the subject, done on the command of a third party.

Good show Dag, I appreciate the opportunity to know about your activities.

Gary Cziko: Dag and Bill, I was interested in hearing of the new uses of the trusty old rubber band demo. Here's another twist (or rather, slip). In this demo, the subject is told beforehand to keep the knot over some inconspicuous (to the audience) target, and the audience is trying to guess what the subject is "doing" as the demonstrator disturbs by pulling on his or her end of the rubber band.

Instead of using two rubber bands tied together, use three tied together end-to-end. Have the subject hold the end loop of one as usual, but you (the experimenter/demonstrator) hold on to the second knot, *not* the end of the third rubber band. (Got that?) Don't loop any fingers through, but hold on to the second knot between your thumb and index finger (as you would normally hold on to a string), with the third rubber band concealed within your hand.

Now do the demo as usual. When someone from the audience invariably says that the subject is simply mirroring your movements, stop at a position where there is good tension on the bands and then gradually let the third rubber band slip through your fingers and then hold again as the end arrives between your index finger and thumb. While the rubber band is slipping through your fingers, the audience will see the subject move his or her hand toward yours *while your hand remains still.*

So much for the "experimenter's *hand* as stimulus" explanation of the subject's behavior.

Rick Marken: Using the rubber bands, you can show that the position of the knot (p(t)) is always a result of what the subject is doing to his or her end of the rubber (o(t)) and what you are doing to the "disturbing" end of the rubber band (d(t)). You might be able to show (when you move the disturbance slowly) that the position of the knot does not change as you might expect it to if just the disturbance were acting. For example, when you pull gently to the left, the knot might be expected to move correspondingly to the left. But the subject might be able to notice that sometimes the knot is actually moving to the right (due to the added effects of their own actions) while you are pulling to the left. This means that the position of the knot is not a stimulus that "tells" the subject how to pull on their rubber band to correct the disturbance. So the stimulus-response view of control cannot be preserved even when the actual variable (the knot) that the subject is controlling is discovered.

But the deeper point is that perception is just there—it is neither right nor wrong, good nor bad, in error nor not in error—it is not *informative;* it just *is.* The position of the knot is just the position of a knot—but once you have a reference regarding where it should be, then it seems as if some knot positions are definitely "wrong," and one particular one is "right." This is a tough point to demonstrate, because people don't care much about the position of knots, and when you tell them this it seems pretty trivial. But try to explain that this applies *to all* perceptions that are controlled, and you will get some strong reactions. People who are controlling for the neatness of their house have a difficult time believing that the neatness of the house is just a perception—when the house looks "messy," that perception seems just plain wrong. It is difficult to demonstrate that perceptions are just perceptions, and that they only become "good" or "bad" or "right" or "wrong" (i.e., they only become informative) with respect to one's own references for them. That fact is easy to demonstrate with "knot" positions, but a hell of a lot more difficult to demonstrate with political, religious and economic "positions."

Bill Powers: Dag, I will work with you to make the demo section of your 'Purposeful Leadership" presentation an effective teaching tool. How effective it is will depend on how well the audience understands it, and on how well they can relate the principles embodied in the demo to other situations.

The point of the demos is twofold. First, you're just demonstrating a phenomenon of control, which is interesting in its own right, as you have found. Second, you're establishing a way of talking about the elements of and relationships in a control process, so you can use this way of talking later and remind people of what they learned through reminding them of their experiences with the rubber bands. The more clearly you establish what you're talking about in the beginning, the more easily the audience will understand what comes next. I'm going to lay out a strategy for doing this in a period of about an hour. The following segment might seem long and detailed to you. You might worry that the audience will wonder what this is all about, but don't worry. They will be interested because they are learning something.

First, you must carefully show the audience the physical elements of the rubber bands, so they will know what is important to notice:

a. The experimenter's end of the rubber bands.

b. The participant's end of the rubber bands.

c. The ball in the center of the rubber bands.

d. The effect of the experimenter's action on the ball.

e. The effect of the participant's action on the ball.

f. The combined effect of both actions on the ball.

You can do this part alone. You can stand facing the audience with one end of the rubber bands in each hand. Hold one end of the rubber bands still and move the other end, being sure you point out that you can both stretch it and move it up and down. Show that when you move your hand by a certain amount, the ball moves in exactly the same way, but by almost exactly half the amount. Show that this is true when you move either end, holding the other end still. Then return to holding one end still while you move the other end.

Now talk briefly about variables. You can say that you're affecting the ball with your actions. But what is it about the ball that you're affecting? It always has the same color; it's always round; its price is still whatever it is. What you're altering about the ball is its position, either up and down or side to side (illustrating as you speak with the appropriate move). It's only the position that is varying. The position can vary in two ways: up-down or side-to-side.

Here's an example of how the spiel might go: "So we can say that there are two independent *variables* involved. They are independent because you can change the up-down position without affecting the side-to-side position, and vice versa [illustrating as you speak]. So we are really talking about two variables here. If we know both variables, the up-down position and the side-to-side position, we know where the ball is in each of the two ways it can move, and that's all we care about right now.

"Now look at the hand holding the movable end. We say that this hand is carrying out an action. In this experiment, however, we're only interested in the action as it can affect the two variables that define the ball. We're interested in the *position* of the hand. This is a variable, too, and, in *fact, it's* two variables. The hand can move up-down or side-to-side [illustrating as you speak]. So we speak of the action that affects the ball in the same way we speak about the ball: in terms of variables. At any moment the hand variables are set in a certain way. As a result, when the ball variables are in a certain condition, the ball is in a certain position.

"All of this elaborate analysis is meant to let us see something that's not usually understood very clearly: the difference between an influence and an influence. When you understand what that means, you'll already understand something important about human relationships.

"Look at the moving hand. Obviously, when the hand moves, the ball moves. So would you say that the hand position is an influence on the ball's position? Isn't this like saying that the driver's steering efforts are an influence on the way the car moves, or the teacher's personality is an influence on the students? This is one of the ways we use the word 'influence.' We point at the cause of something else and say that the cause is an influence on the something else. The moving hand is an influence on the position of the ball.

"But now look at the ball. When the ball moves, you would say that it's being influenced by something. You can focus on the effect of moving the hand and call that effect the influence of the hand. What do we now mean by the influence? We mean the behavior of the ball that is caused by the hand. What is the influence of the hand on the ball? Just look at the ball and you can see it: the ball moves. There is the influence of the hand.

"So now we have an influence in two different places: in the thing that's causing the ball to move, and in the movements of the ball. We can say that the teacher's strong personality is an influence, but we can look at how the student's behavior changes, and say, 'That change in behavior is the influence that the teacher had.'

"How do you influence people? Well, in the first place, you don't influence people, you influence variables—you influence something *about* the person that is variable, like the person's behavior or attitude toward you. You can't influence the person's height or age very much.

"Assuming we realize that we're always talking about variables, we influence people by acting in a certain way on them. But does this influence necessarily have any influence? When you apply an action that is supposed to be an influence, is the other person's behavior always influenced? Not by a long shot, and here's the reason. (Now you move both ends of the rubber band around so the ball remains stationary.]

"Look, I'm applying an influence to the ball with my right hand, but its position isn't being influenced any more. The position of my right hand changes, but the position of the ball doesn't. Suddenly my influence on the ball has lost its influence. This is very mysterious. What has happened?"

The audience, of course, can see you moving your other hand. Ask them to explain why your right hand has lost its influence on the ball. Tell them to go ahead and say why, even if it's perfectly obvious. Say it out loud, put it into words. But pin them down to an exact statement. Sure, it's because your other hand is moving the other way. But show them that if your right hand moves to the right, the left hand moves to the left; if the right hand moves up, the left hand moves down. Show them again what would happen if the left hand didn't move (the ball moves to the right), and then what happens when the left hand moves (the ball moves back to the left).

Then explain that each hand has a variable position, and each hand affects the variable position of the ball in each of the two possible ways. The only way for the ball not to move is for the variations in left-hand position to be exactly *equal and opposite* to the variations in the right-hand position. Only that will leave the ball in the same position, if the two rubber bands are identical. The *influences* of the two hands on the ball are equal and opposite, with the result that there is no influence on the ball.

"So the next time you try to get a vendor or an employee or a customer to behave in a certain way, you will think of this, won't you? What you say or do might be an influence on the behavior of the other person, but it might not have any influence. Why not? Because there might be another equal and opposite influence coming from somewhere.

"Now we're going to find out where the most important equal and opposite influence comes from. May I have a volunteer from the audience, please?"

Now you turn to the easel with the paper on it, draw a target circle, and take the volunteer aside and whisper the simple instruction. You can explain out loud that you and the volunteer are going to keep your hands lightly touching the paper. Assume the position.

When you apply disturbances, apply them very slowly and smoothly. Adjust your speed so the volunteer can keep the ball over the circle very accurately. Don't let transients occur; they're confusing at first.

'Now watch. I pull back, using the influence I have on the ball to make the ball move. I move my hand up, influencing the ball to move up. I move down, around in a circle, all different ways. And you can see the influence on the ball that my hand is having, right? [Turn to the audience and raise your eyebrows and ask, inviting an answer, "Right?" Get the audience to point out that you're not having much influence.] Wrong. So even though I'm varying my hand position up and down and side to side, the ball isn't varying that way. Why isn't my influence having any influence? [Audience, even if you have to drag it out of them: "Because Jim is moving his hand the other way."]

"Yes. I'm applying an influence to the ball, but the ball isn't moving because Jim is applying an equal and opposite influence to the same ball. It's just the same as when I had hold of both ends of the rubber bands, but now Jim is playing the part of my other hand.

"Why do you think Jim is doing that? [Audience: "Because you told him to."]

"Yes, but what exactly do you think I told him to do? What would you guess the exact instructions were?"

Now there is a period of discussion while people volunteer guesses. Some will guess right, some will guess wrong. Just let the guesses accumulate for a minute or two, without commenting.

"Ok, you've told me your guesses, and you've heard other people guessing. Is there anyone who wants to change the guess now? OK. Jim, what did I ask you to do? ['Please keep the ball as exactly over the circle as you can."] Thank you. Some of the people out there think you're a liar, but I know you're not.

"I didn't tell Jim how to move his hand. I asked him to produce a certain effect on the ball, and he evidently agreed to try. He evidently succeeded very well. But *how* did he succeed? What was he doing, inside, that created the result you saw? Now we're looking for something besides just a description of what we all could see happening. We're asking how Jim could be organized so he was able to do what you saw him doing. We're looking for an explanation of what we saw.

"You've all heard explanations of human behavior, according to one theory or another. You've probably found some explanations more convincing than others. I'd like to find out now what sort of explanation you think would apply to this little experiment. How do you think Jim works, which would explain what he was doing? For example, how many of you think that Jim could keep the ball over the circle with his eyes closed? [Get a show of hands.] Nobody thinks you could do it, Jim. Let's get into position, and you close your eyes and carefully follow this instruction; listen carefully: keep the ball exactly over the circle. [Jim closes his eyes, and you start moving your end of the rubber band around. This will provoke a bit of laughter.]

"Well, it's pretty obvious that Jim can't follow the instructions with his *eyes* closed. We have made a great discovery: when Jim closes his eyes, he becomes deaf.

"All right, if that's not it, what do we know now? Why did Jim have to see what was going on? [More comments from audience.]

"Let's try to get very specific. What exactly did Jim have to see in order to do what he did? [Get more guesses—your hand, the ball, the rubber bands, whatever.]

"Well, let's test a couple of these ideas. If Jim had to see my hand, then it wouldn't make any difference if *he* couldn't see the ball, right? So we can just dispense with the rubber bands and the ball, and Jim can move his hand the way he thinks he needs to move it when I move my hand. When I say 'freeze,' Jim, just rest your hand on the paper and hold it there, and I'll do the same. Here we go. [Perhaps it would be good for you both to have dry markers, to mark the position.]

"Freeze. Now, with my other hand, I connect the rubber bands the way they were, and let's see where the ball is. [This is *one* reason for making sure that Jim can control very easily and accurately.] Well, not too bad. Are you satisfied with that, Jim? If not, go ahead and put your hand where you think it should be. (Jim corrects remaining error.]

"Now, some other people said that Jim was looking at the ball. Suppose that's true: he can see the ball, but not my hand. I'll hold up this piece of cardboard with a notch in it, and Jim, you position yourself so you can see the ball but not my hand or arm. Ready? Here we go. [Experiment proceeds: use slow, large disturbances. The piece of cardboard should be large enough to conceal entirely your half of the playing field.]

"All right, we have the evidence now. What's your conclusion? [Get some conclusions.] Of course, we can use the last resort: Ask. Jim, while you're keeping the ball over the circle, are you looking at my hand or at the ball? ['The ball."]

"Jim has served us well, but it's time to see if he's the only person in the world who can do this task. Let's thank Jim, and ask for another volunteer. [New volunteer.]

"OK, just a, quick check: keep the ball exactly over the circle, Jane, while I hold up the cardboard—be sure you can't see my hand or arm. [A few seconds of demo.] Good, you work the same way Jim does. Would you like to try it with your eyes closed? No, I didn't think so.

"Can we agree now that watching the ball is sufficient? In other words, Jane doesn't *have* to see my hand, and it probably wouldn't make much difference if she could, because she could hardly keep the ball centered any better. Jane, why don't you sit down here for a little while, because I want to draw a diagram before we go on. [Draw the rubber bands and ball with the target circle a little off from the ball.]

"We've established that Jim and Jane look at the ball during this task. So they were looking at something in this region. [Draw a circle around target circle and ball.] Jane, did you also need to see where the target is? ["Yes."] Jim, you too? ["Yes."]

'Now, what does 'seeing' mean? We see with our eyes, of course, but what gets into our eyes has to get into the brain, too, before any perception happens. So let's draw a box up here, with an arrow representing light rays coming into the box, and an arrow coming out that represents what the brain knows by way of these light-waves. Right at the end of the arrow coming out of the box, I'll draw what the brain would be seeing right now, based on how the diagram looks. Here's the ball, and here, away from it a bit, is the circle.

"Jane or Jim, or both: if this is what you saw, what would you be trying to do? [Reply: Get the ball over the circle.] How would I draw a picture of that? [Reply: Draw the ball inside the circle.] Like this? [Above and to the right of the picture of the perception, draw two concentric circles.] So here we have a picture of how the ball and the circle actually look right now [indicate perception], and here we have a picture of—what? Jane or Jim, or anyone? [Wait for: How they are supposed to look, etc.]

"Would it be accurate to say that this [reference picture] is how you wanted them to look? ["Yes."] Is this how they always looked? ["No."] Well, then, how did you know how they were supposed to look? Before you answer, Jane, will you come up here again and do a short run with me? [This time, move your end just rapidly enough so that the ball wobbles all around the circle]. Now, how did you want the ball and circle to look? [Jane tells you or points to picture.] Most of the time, how *did* it look? [Indicates perception somehow. If she doesn't point to the pictures, you do it.]

"OK, you knew it should look like this? [Point to reference picture.] And most of the time it actually looked more like this? [Point to perceptual picture.] Good. Well, if most of the time it looked like this [perception], how did you know about this? [Point to reference picture.]

"Let's switch to another example for a moment. Most of you drive cars. When you are going along a straight road, you steer the car to keep in its lane. What are you seeing out the windshield in front of you? [Get descriptions.] Now, consider: How do you know where the car is in its lane? [More.] And finally, how do you know where it *should be* in its lane? [Etc.]

"All of this is building up to a point that a lot of you might have seen by now. The remaining question is: *Where* is this knowledge of the way the car and road, or the ball and circle, should look? ["In your head."] In your head. Can all of you imagine a ball centered in the circle, right now? Can all of you imagine the way the car and road look when you're in the right position on the road? And where is that imaginary picture, right now? In your head—or at least, not anywhere in the room outside you. Even if you don't actually see an imaginary image, there's knowledge, somehow, of how the *scene* should look when it's right. Right?

"You're now ready to understand the theory of human behavior that's behind this presentation. Just a few more steps.

"First, let's start using some consistent terminology. This arrow in the brain, up here, that shows how the ball and circle actually look right now, we'll call the *perception.* Notice that we don't call the actual ball and circle down here, the real ones, the perception. The perception is what the brain, up here, knows about the world, down here.

"If the picture of the actual situation is the perception, then what can we call this other [reference] picture? It's not a perception of the actual ball and circle. It's an imagined perception. We judge the perception of the actual ball and *circle* with reference to this other picture, which just sits there unchanging, telling us how the actual perception should look, not how it does look. So let's call this other picture the 'reference perception.' Or we could say 'the reference condition of the perception,' or just 'the reference condition.' The key word is *reference,* because it's with reference to this [reference picture] that we judge this [perception).

"Now, I ask you: Is this [perception] the same as this [reference]? How do you know that? What would you call the process you carry out in order to decide that they're not the same? [Hope to get "comparison."]

"We call it comparison, and when we draw models, we draw a box right here, which receives information from the perception and from the reference, and compares them. We call it a *comparator.* And what comes out of the comparator? [Draw arrow.] Information about the difference between the perception and the reference. If there's no difference, no information comes out. If the perception is different, this arrow carries just the information about the difference. We can call this arrow a difference signal—in control theory it's called an *error signal,* and you can use that term, too, as long as you understand exactly what it means. It doesn't mean mistake or blunder, it just means that there's a difference. If there's any amount of error signal up here, we know that the real ball, down here, is not in the same position as the circle—or at least it isn't perceived that way.

"While we're at it, let's identify this other box down here. It's called an input function or a *perceptual function.* It receives light-rays or other physical information about the world and converts it into some sort of representation in the brain. It creates a perception, or as we sometimes say, a *perceptual signal,* that continuously indicates the state of the outside world. Right now, your brains contain some perceptual signals that indicate how my words are sounding and how I look as I stand up here. Obviously, everything in this region of the diagram is the brain [draw a big circle], and the rest is outside the brain.

"So, way down here, we have the actual circle and ball. Information conies from them into this perceptual function, creating this perceptual signal that always indicates the relationship of the circle and ball. Up here we have another signal, the reference perception or condition that's showing how the perception *should* be. And here is the comparator receiving both of those signals, comparing them, and spitting out a signal that represents how much difference there is—how far from the reference condition the perception is, and in what direction. These so-called signals are simply currents flowing through nerve fibers in the brain. But we don't have to worry about neurology here; this is about organization.

"Now, if the perception looks like this, and the reference looks like this, what should Jim or Jane do? Obviously, move the arm so that the ball goes this way, toward the target. It would work equally well if the arm could make the target move the other way, toward the ball. And where is the information that tells which way to start moving? Right here, in the error signal coming out of the comparator.

"All we have to do is hook up this difference or error signal to Jane's arm muscles in the right way, and the arm will automatically move the ball, and keep moving it until there's no more difference signal to tell the arm to move some more. Let's watch it happen.

"Jane, if you'll assume the position....

"Center the ball. Thank you. Now we'll do this a little differently, in stop-motion. First, close your eyes. [Move your end of the rubber bands to move the ball.] Now open your eyes and make what you see look right. Now close your eyes again. [Move in a different direction.] Open again. Close again. Open again. [Etc.] Thank you.

"By stopping the motion, we can see what's going on. Each time Jane opens her eyes, she sees a different picture of the ball and circle. The reference condition is the same, so the comparator puts out a different error signal each time. This results in a different motion of the hand each time, and it's always in the right direction to make the perception move toward the reference condition. [Point to the right places on the diagram as you talk.]

"When we stop the motion like that, we see what looks like a series of stimuli followed by responses. But when we do it in the natural way (Jane, one more time, please, with eyes open), you can see that there are no stimuli and responses. The difference or error is never allowed to get very big, unless I start moving this end of the rubber bands too fast. In fact, Jane is acting continuously to keep that error or difference signal from ever getting very large.

"By doing that, she is keeping the perception of the ball and circle very close to this reference picture. It takes only a very tiny error to make Jane's arm start moving to correct it; the effect of the movement is always just right to keep the error small.

"This is how you drive a car, isn't it? You don't wait for the wind or a tilt in the road to put you in the wrong lane, and then steer back. As soon as you can detect any difference between where you perceive the car to be and where you want it to be, you alter your steering efforts just enough to prevent that change from getting any bigger. So your car hardly wanders at all. At least that's how I hope you drive. These little corrections are quite automatic. You don't have to know about these signals in the brain or how they're hooked up. All you have to do is pick a reference condition. This little circuit here will then make sure that what you perceive matches what you intend to perceive. This little circuit is called a negative-feedback control system. This reference signal is where you put your intention in.

"One last look. Jane, I'd like you to go into slow motion. Do everything just the same, but slow down your actions as if you have to push your arm through heavy syrup. Let's try it. I pull back on my end, and you slowly bring the ball back to the circle. You don't have to wait for my motion to finish; you can start acting right away, but make your action very slow. [If this doesn't work, you can change roles.]

"Now, you can see how disturbing the ball creates a little error, which starts the arm moving the right way. After a while the error is gone again. While my arm is moving, there's a continuous error, which is keeping her arm moving the other way; when my arm stops, she catches up and the error disappears. Thanks, Jane, it's been great.

"That was like seeing a slow-motion film of a control system in action. There's always a little error, a little lag, but not very much. The action is always pretty much equal and opposite to the disturbance, and the error is always pretty close to zero.

'Think back now to where we started, almost an hour ago. Jim got up here and moved his end of the rubber bands around, and you saw what he was doing, but did you understand what you were looking at? Now we have a model to explain what's happening. You can see why Jane or Jim's arm seemed to be mirroring my motions, as if imitating them. You can see why Jim acted to prevent me from having any influence on the position of the ball. You can see that what mattered was not how my arm moved, but how the ball moved. The actions of Jim and Jane were controlling the ball, not just reacting to my arm movements. They didn't even need to see my arm or what it was doing to the rubber bands. All they needed was to see where the ball was, and know where they wanted it to be. That explains everything you saw.

'When engineers work with systems organized like the one in the diagram, they bring all sorts of complications into it. Things like differential equations, Laplace transforms and z transforms, Bode plots, sampling theory, and even information theory. But they're talking about the same system you see here, behaving just as you saw it behave, organized exactly as you see it organized in this diagram. A closed circle of cause and effect. Perception, comparison, and error driving an output—although, of course, they wouldn't talk about perceptions. You now understand the essence of this sort of system in just the way an engineer might understand it, and if you've followed the presentation, your understanding, you can be sure, is correct.

'The last thing we have to do is bring in a few more terms, and then we will be armed and ready to tackle the application of this concept to human behavior in the areas that interest you.

"At my end of the rubber bands, we have something we will refer to as the *disturbance.* We call the position of my end of the rubber bands the disturbance because it disturbs the ball, or *would* if there were no other influences acting on the ball.

"At the other end, we have the person's action. The term 'action' means just what the person's muscles are directly causing to happen, positioning the hand. We can talk about the action without talking about any other effects it might have. The action is also an influence on the ball, but as you have seen, the behavior of the ball isn't the same as the action itself.

"And in the middle, we have the *controlled variable.* In this case, the controlled variable is the position of the ball relative to the circle. We call it a variable because it is capable of varying. We call it controlled because the actions of the person control it. The actions bring the controlled variable to a specific condition, and they vary in whatever way is needed to keep that variable in the same condition. That's what we mean by control.

"So, in the environment of the person, we can see a disturbance, a controlled variable, and an action that is producing the control. In our model of what goes on inside the brain, we can see a perception that represents the controlled variable, a reference condition or signal that represents the intended state of this perception, and an error or difference signal that drives the action. Put all of these elements together, and they add up to an explanation of the behavior you have been seeing. Put them all together, and you have a revolution in the behavioral sciences, which we're soon going to begin applying. Any comments or questions? We can take 10 or 15 minutes for them if you wish. I could go on with this presentation for about three days, so don't worry that we'll fail to *meet a* schedule. We'll just get as far as we can. The most important thing is that you understand, not that we finish an agenda."

After the talk and milling around is done: "Now, let's talk about what behavior is. I need another volunteer just for a couple of minutes. You? Good, come on up. You will see that perceptual control theory, which is what we're talking about, gives a person a lot of confidence. It works with any randomly selected person.

"Here's a dry marker. Hold it against the paper while you move your end of the rubber band, so it leaves a trace. Keep the ball exactly over the *circle,* right. Now, just keep it there for a while. [Put in a slow but broad pattern of disturbances.]

"Thank you—that's all. Now, suppose that someone had just come into this room and heard me say, This trace was created by Pete's hand in the experiment you just saw.' What might that person conclude about Pete's behavior?

"You can't say that Pete's behavior didn't produce this wavering and wandering trace. It did. But is that what Pete was doing? Was he really just making this squiggle on the paper? There's a saying among the adherents of PCT (which is what we call perceptual control theory) that goes: 'You can't tell what a person is doing just by looking at what the person is doing.' Here's a beautiful example of that. What Pete did was to move the dry marker around and leave this trace. But what he was *really* doing was keeping the ball over the circle. You, who know about the controlled variable that Pete was concerned with, understand that. But the person who came in late didn't see the controlled variable. The only evidence left is the record of Pete's actions, which tells us exactly nothing about what Pete was controlling by means of those actions.

"So, you can't tell what a person is controlling just by looking at that person's actions. This is a profoundly revolutionary idea. In most ordinary aspects of life, we look at the people around us and we think we can see what they are doing. We look at their 'behavior,' in quotes. But what are we really seeing? We are seeing their actions. We are not seeing the variables that are being perceived by those people, and being controlled so that the perception is kept near some reference condition. Only the person we're looking at knows what perceptions exist, and what state of those perceptions that person would prefer to experience. Only that person can see the relevance of the action to maintaining control over a particular perception. We, observing from the outside, can't see the purpose of the actions.

"Imagine that we went through another session with this demonstration, but held a big piece of cardboard up so the audience couldn't see the ball and circle. You could see my hand on one side, and Pete's hand on the other side, and you could see them moving, but that's all. Wouldn't it seem that Pete's hand movements were being caused by mine? It would look as though Pete were watching my hand movements and responding with symmetrical hand movements of his own. If you had to draw a diagram of what was going on, you'd draw it like this: [Draw the rubber bands and ball. Draw a line from the disturbing end to a box and from the other side of the box to the action end.] The box is Pete. The movement of my end of the rubber band is sensed by Pete, and this stimulates him to move his end of the rubber bands. We have a nice simple cause-effect diagram, and Pete is just a link between the cause and the effect. If you grind that concept into your mind and really come to believe in it, what will happen when we take the piece of cardboard away? You'll see that the stimulus not only makes Pete's hand move, but tends to make the ball move because of the connecting rubber band. You'll see that Pete's hand movement also tends to make the ball move, but the other way. What an odd coincidence! The ball doesn't move at all, or hardly at all.

"Now, if keeping the ball directly over the circle were vital to Pete's health and safety, you might begin to wonder how the stimulus knows that it should cause Pete to move his hand in just the way that's in his own best interests. You'd try to find an explanation that seemed less outlandish, one that didn't make it seem that Nature was being altruistic. So you might propose that keeping the ball over the mark was reinforcing to Pete. Whenever Pete didn't move the right way, the reinforcement wouldn't happen, so that wrong behavior would die out. Only the response to the stimulus that happened to keep the ball over the circle would be reinforcing, so that response would eventually be the only one left.

"You can see how it goes. Once you get a model firmly in mind and decide to believe it, all of your explanations from then on have to fit that model, even though they leave you with other mysteries. Just why should a ball being over a circle be reinforcing to Pete? You can't answer that question. All you know is that this explanation seems to work.

"We now have here a roomful of people who understand the control-theory explanation of what *we've* seen. You can compare the PCT explanation with the one we've just been through. While you're doing the comparison, consider this.

'The reinforcement explanation and the cause-effect model are the ones in which nearly every scientific psychologist has believed for most of this century. It's the one you learned in school. It's woven into our language and beliefs in ways that are so taken for granted that they're almost unconscious. Have you ever thought that by applying incentives to someone, you can get that person to behave differently? Have you ever explained your own behavior by pointing to something in your environment, and saying, 'That's why I did it'?

"Long ago, before anyone in this mom was born, the great minds of psychology and biology held up a big piece of cardboard. They said, 'ever mind what's behind this piece of cardboard. Just look at this end of the rubber bands and that end of the rubber bands. Isn't it obvious that movements over here are causing Pete to move his hand over there? You don't need to talk about purposes and intentions and desires and wants and wishes. All you need to do is observe what causes what. Then you will be able to predict and control human behavior.'

"Everyone in this room who has studied Total Quality Management knows what is wrong with that. People are not simply boxes with inputs and outputs, devices that can be made to act in certain ways by applying the appropriate stimuli. People have goals and desires and wishes and purposes and hopes and intentions. You ignore them only at great risk. The principles that Dr. Deming has given us are based on a deep awareness that people are not the kinds of devices that conventional science has told us they are.

'People are control systems. Deming realized this without having any formal understanding of why he knew they are as they are. He knew psychology was an important leg on which his approach stands—but he also knew that the psychology he needed was not the one that existed.

“PCT explains human behavior in a way that completely contradicts all conventional concepts, but which completely agrees with Deming’s intuitive assessments. Perhaps even knowing only what you have learned in our simple little demonstrations, you can begin to get a feeling for how PCT is going to alter the psychological approach to management, and, for that matter, to getting along with people in general.

“Let’s take a stretch and have some coffee for a while. When we come back, I’ll give you just a brief look at some of the ways PCT could be applied, and is being applied. Don’t expect to become experts in the final half hour. All I hope for is to stimulate your imaginations, so you will begin to see what lies ahead. You can probably guess that learning how to turn this new understanding into practical action takes more than an introductory session. But I’m sure that by the time we finish, you’ll be able to go home and work out a lot of the implications for yourself, and start putting PCT to work.”

Dag, that was more or less a role-play—what I’d say if I were doing the demo part of the presentation. Of course, I’d speak differently from the way I write. The things to pay attention to are the pace and the plan. One thing at a time, always aimed at the next thing, and all working toward the final conclusions. A lot of patience and details, with demonstrations of everything. A lot of interaction with the audience. Always demonstrating exactly what you mean, never just generalizing. What you want is for the audience, at the end, to understand what they have seen in every detail, and to make the connections between the specific things they’ve seen and the parts of one elementary diagram. You want certain terms to be familiar—it doesn’t matter if the terms are technical, there’s no need to search for the magic word that will make it easy for them. You show them what each word means, and they’ll understand.

I advise you to study this presentation, so you see how points to be made later are prepared early on, and how one idea leads to the next logical idea. Notice carefully that the only generalizations are at the very end, after all of the specific hard-core ideas are laid in. And they are very sparing.

You’re welcome to use any aspect of this material in any way that will help you. I hope you’ll try it out, and try to develop the sense of single-minded development toward one rather simple and specific goal: getting the audience to understand the organization of one simple control behavior. Once they understand that, they will grasp everything else you have to say very easily.

The Control Systems Group is a membership organization which supports the understanding of cybernetic control systems in organisms and their environments: *living control systems.* Academicians, clinicians, and other professionals in several disciplines, including biology, psychology, social work, economics, education, engineering, and philosophy, are members of the Group. Annual meetings have been held since 1985. CSG publications include a newsletter and a series of books, as well as this journal. The CSG Business Office is located at 73 Ridge Pl., CR 510, Durango, CO 81301; the phone number is (303)247-7986.

The CSG logo shows the generic structure of cybernetic control systems. A Comparator (C) computes the difference between a reference signal (represented by the arrow coming from above) and the output signal from Sensory (S) computation. The resulting difference signal is the input to the Gain generator (G). Disturbances (represented by the black box) alter the Gain generator output on the way to Sensory computation, where the negative-feedback loop is closed.

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