P.1.1 Measurement and perceptual control

What do we mean when we say "control" or "perceptual control". Here is a hypothetical situation to which we will return from time to time. It illustrates a control loop in which all the components are open to public view (which is not true of the control loops with which we will be largely concerned). The example also illustrates the close link between control and measurement, a link that is not always appreciated[1].

Oliver wants to see how heavy is a rock he has picked up. To do that, he simply puts the rock on the left pan of a pair of scales and adds and subtracts weights to the right pan until the scale ceases to tilt one way or the other or until he has no smaller weights available. At that moment, the weight of the rock is less than sum of the weights in the right pan that tips the scale one way, and more than the sum of weights that tips it the other way. The weights are labelled, so Oliver can add them up to find that weight of the rock is somewhere between the two sums. To make his job easy we give Oliver weights of 2kg, 1kg, 500g, 250g, and so forth, down to some minimum that determines how closely Oliver will be able to determine the weight of the rock, which he hopes will be less than 4kg, the biggest weight he can measure.

We can diagram Oliver's weighing process as in Figure P.1. Oliver can see the scale indicator, and can act by putting weights in the right pan or taking weights off.

1. The mathematically inclined may see the example as a mechanization of a "Dedekind cut" (Dedekind, 1901) that defines a real number by dividing the number line into rational numbers that are larger and those that are smaller than or equal to the number in question. In the control example, the weights used are analogous to the rational numbers in the Dedekind cut.

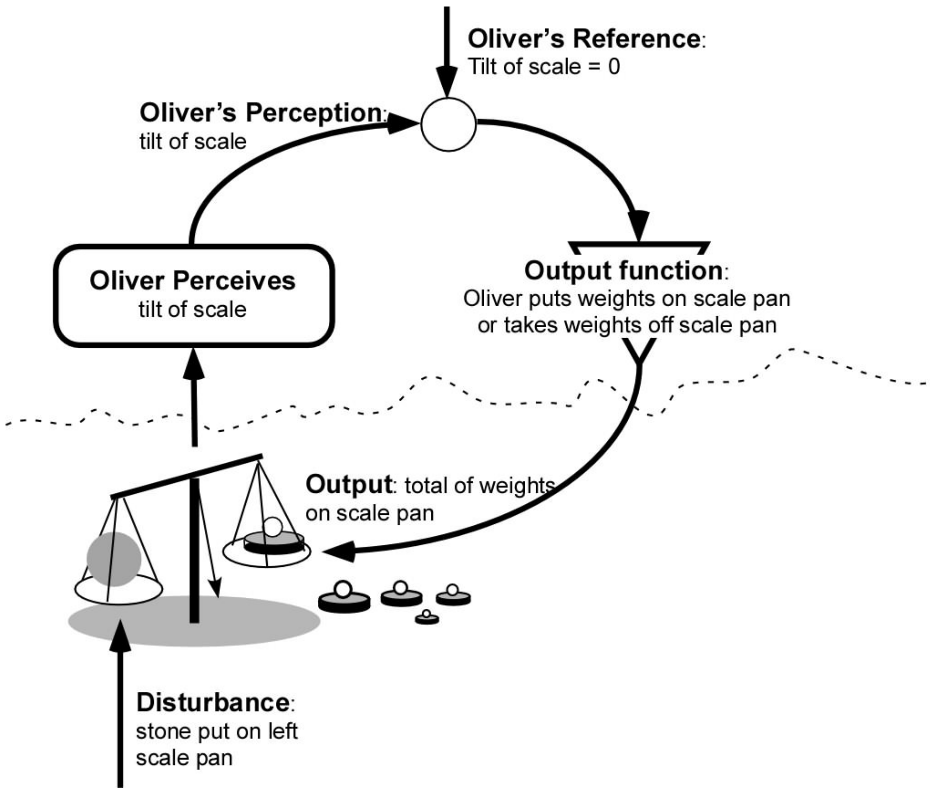

Figure P.1 The perceptual control loop that describes Oliver weighing a rock. This is a prototype for every instance of measurement in which the result is compared to some reference scale or value. It takes longer to make a fine measurement than to make a coarse one on the same thing. This is equally true of artificial scales and of perception by an organism.

Let us examine what is going on while Oliver is performing the weighing operation. When he puts a weight onto the pan, the scale will tilt either to the rock side or to the weight side. Oliver wants to perceive the scale pointer vertical, the two pans level with each other. Of course, unless he is incredibly lucky, the scale pointer will never be exactly vertical, but that is what he would like to perceive. We call what he wants to perceive his "*reference value*" for that perception. What he does perceive, his "*perception*" is the actual angle of the scale pointer, and if it isn't where he wants to perceive it, the difference is called "*error*". If the error is positive, the rock being heavier than the weight in the right pan, Oliver acts to correct the error by adding the next lighter weight as in Figure P.2; if the error is negative, Oliver acts to correct it by taking the last weight off the pan and adding the next one. These weight changes influence the angle of the scale pointer, completing a "*negative feedback loop*". In fact it is a canonical "*Perceptual Control Loop*".

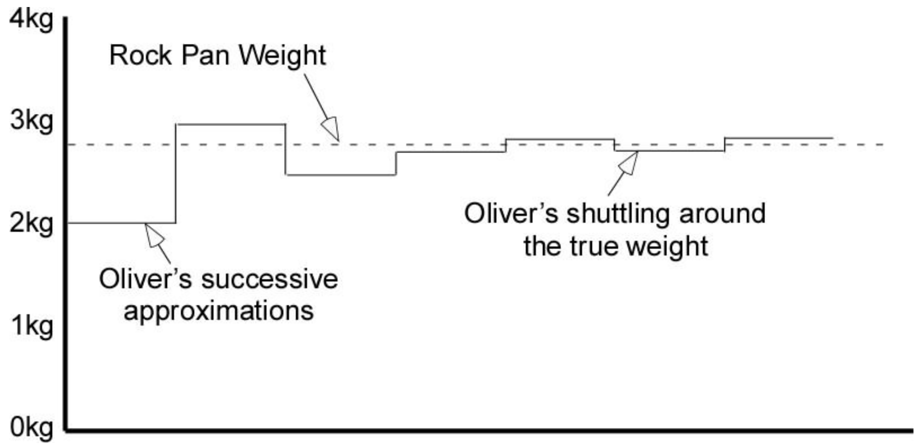

Figure P.2 The total weight in the scale pan as Oliver places and removes weights to balance the weight in the pan containing the rock.

The loop has negative feedback because Oliver's actions always reduce the absolute magnitude of the error. If his actions consistently made a positive error more positive or a negative error more negative, the loop would have positive feedback. The set of weights in the pan, if the scale remains centred, can be read as the weight of the rock in kg represented in binary notation, a 1 representing a weight that remains in the pan, a zero a discarded weight. If what remains in the pan is, say, the 1, 1/8, 1/16, 1/64, ...kg weights, the rock weighs (in binary) 1.001101… kg.

Of course, physically, the scale will never be exactly centred, but if including Oliver's smallest weight makes the right pan too heavy, and taking the smallest off makes the pan too light, Oliver knows that the true weight of the rock is between the two values so obtained, and he can't do any better than that. He has run up against a problem faced by every measuring instrument, limited resolution. One's eye has a certain blur, and can't distinguish two dots from one if they are closer than that; one's ear cannot discriminate between two pitches if they are too similar, and so forth. Oliver's scale is a perceiving aid that allows him to judge the weight of the rock more finely than he could by simply hefting it, just as a microscope or telescope is a perceiving aid that allows us to discriminate things that are too similar for the eye to discriminate[2].

What is Oliver asking, really? He isn't really interested in the pointer. He is interested in the weight of the rock. The pointer only tells him whether the weights in the right pan total more or less than the weight of the rock, a *relationship*. Oliver wants to perceive — has a reference value for — the relationship to have the value "equality", and he keeps changing the relationship from "too heavy" to "too light" and back again by adding and subtracting weights on the right pan. He can't perceive the relationship directly, but he can perceive whether the pointer is on one side

2 We aren't, at this point, interested in the scale as a "weight-microscope", so much as in its use to demonstrate a control process, but the "weight-microscope" concept should nevertheless be kept in mind.

or the other of vertical. What matters to Oliver is simply the count of the weights when they total the same as the weight of the rock.

Oliver's control of the relationship is a "higher-level" control loop that uses the scale operation as a "lower-level" supporting control loop in a trivial hierarchy. Oliver doesn't actually have to move the weights himself. He could have a machine or an assistant perform the supporting loop, telling the supporter only "too heavy" or "too light" and letting the supporter translate that into the appropriate action with the weights. We will see a lot of such hierarchic control structures as this work progresses.

Figure P.1 contains an arrow labelled "Disturbance", which is almost the final piece in the description of a standard control loop. Imagine that some prankster keeps randomly adding or subtracting small pebbles or sand grains to or from the left-hand pan containing the rock, while Oliver wants always to keep the relationship between the weights in the two pans at "equality", and therefore the pointer maintained at vertical. The prankster is the source of a "disturbance", an influence that would change the value of the pointer angle perception if it were not countered by adding and removing weights to compensate. In a control loop, the "output" always opposes the effect of the disturbance.

The prankster is not the disturbance. The disturbance is the change in weight caused by the addition or removal of the sand or pebbles. The prankster is simply the source of the disturbance. Oliver does not know anything about the prankster, or even that there is a disturbance. All he knows at any moment is that the scale pointer now shows "too heavy" or "too light", and he (or his assistant) must add and subtract weights on the right pan to keep the pointer near its reference value.