refrigerator's insulator. The more perceptions they control, the more discriminative the membrane, in the same sense that the membranes of cells have pores that open and close to admit or expel specific ions and molecules, but are closed to most. The environment controlled thus by a multitude of controllers at many levels of the control hierarchy becomes ever more open to opportunities and ever less dangerous to the organism. The export of entropy from within the organism is implemented by perceptual control, but the gross effect is of export to a lower-entropy local environment, just as a hotter body can export some of its entropy to a cooler one.

12.4 PCT and the "Free Energy Principle"

In the Overview (Section 1.5) we claimed that PCT encompassed Predictive Coding, or the Free Energy Principle (e.g. Friston, 2010 for a review paper). Let us see how this is true. We will refine the discussion in Chapter 16, where we discuss evolution and reorganization, through which the conditions that are described by Friston come to be the way they are. We will see there that Friston's approach may well be appropriate for conscious performance, where PCT and the Free Energy principle become hard to distinguish.

Considered from a PCT viewpoint, in the first section Friston describes a neccessary consequence of controlling perception, while in the "Optimizing" sections he describes the results of reorganization built upon the results of evolution. Here is a rough translation using some of the language of PCT.

> *Part a of the figure shows the functional relationships among the quantities in a control loop. These include the internal time-varying perceptual values and reference values μ(t) and quantities representing the interface with the environment, sensory inputs and action outputs. The environment is described by equations that specify to effects of the output on its (hidden) complex variables. The complex variables are influenced also by randomly varying disturbances whose variations are represented by a variable θ. The values of these complex environmental variables are represented with precision γ in the perceptual states. Free energy is a function of sensory input and a probabilistic representation in the perceptions μ of the actual states of the hidden environmental variables (the CEVs).*
>
> *The free energy depends on two probability densities, the probabilistic relationship between the CEVs and their corresponding perceptual values and the probabilistic relation between the effects of disturbances and outputs on the CEVs. This latter is produced by a model in the brain, given the variation parameter θ. Part b of the figure provides provides alternative* ***expressions for the free energy to show what its minimization entails: action can reduce free energy only by increasing accuracy*** [MMT Note: Emphasis mine. In PCT-speak action can reduce the total error only by making the match between perception and reference more accurate — a tautology in PCT]. *Conversely, improving the perceptual representation of the real world and the internal model of the effects of action on the environment improves the ability to avoid large effects of disturbance on error values.*

To this point, what Friston says can be put more simply in PCT, largely because Friston follows the "control of output" class of theories, and relies on explicit modelling to decide what to do in order to have some specified effect on the perception. No such modelling is required in PCT, beyond ensuring that at each level of the hierarchy the direction of action keeps the loop gain negative. Having said that, Friston does not specify here any form of brain model. The control hierarchy is just such a model, and reorganization that improves the precision and speed of control (minimizing free energy in the process) will tend toward the effects Friston supposes to be the computational target. The reorganizing process that generates and refines perceptual functions and the parameter values of the inter-level connections (built on similar effects built-in by evolution) does minimize free energy. For PCT, the results of this evolution–reorganization is what Friston describes in his following paragraphs (in a PCT-translation).

Optimizing the sufficient statistics (representations)

> *Reorganization (and evolution) tend to make our perceptions correspond ever better to what exists in real reality* [Note: we discuss the reason for this in Chapter 16]. *The free energy can be expressed as a composite between error variations and the mutual uncertainties between the perceptual functions and the forms of real reality variables that are approximated by the CEV. This means that the agent trends in Bayes-optimal fashion* [Note: this means informationally the best possible] *toward representing real reality in its perceptions, while the error is minimized through action feedback to the perceptual value.*

Optimizing action

> *Acting on the environment by minimizing free energy requires that the action affects more strongly those perceptions that show most error* [Note: Friston's variables are vectors, not scalar variables. Here he seems to be saying two things at once, that greater error leads to more output and that those perceptions exhibiting greater error are given priority]. *This can be seen by considering both the accuracy and level in the hierarchy of the perceptual variables. Crucially, action can affect only accuracy. This means that the brain will reconfigure its perceptual apparatus to create complex perceptions that best correspond to the complexities of the hidden variables of real reality — in other words, to minimize control error overall.*

There is little here with which PCT would differ in principle. The ordering of primacy between free energy and control accuracy might at first seem a difference, but to assert such a difference requires ignoring a feedback loop. Minimizing free energy requires optimal control, and optimal control happens to minimize free energy. PCT derives the need for good control from the requirement of organisms to live in a disturbing world; the free-energy principle derives from the tendency of entropy to increase in closed systems, within which all sources of potential disturbances are included.

The most important difference, I think is that PCT necessarily embodies the free energy principle, whereas Friston uses that principle in a way that leads to an emphasis on prediction that some defined form of output should produce certain effects on perceptual values and causes "surprise" when it doesn't. In that form, Friston appears to be arguing for control of output, which directly contrasts with the basic premise of PCT, that input is controlled, not output.

Whether this is a critical issue, as Powers has asserted, depends very much on whether the speed of computing the proper output value is fast enough to deal with the speed and magnitude of disturbance variation. Considering that we are dealing with myriads of perceptions that might be in error, or for which predictions of their values result in surprise that must be minimized, such speed of computation seems unlikely to be achieved in the neural network of the brain, whereas it is trivial to determine the direction of the error, all that perceptual control requires.

When we come to our re-examination of reorganization in Chapter 16, we will find that the Friston free-energy approach seems to describe conscious control in much the same way as does PCT. Conscious control is of perceptions whose perceptual functions may not exist in the hierarchy so far reorganized, using actions that must be thought out, using components that already have been reorganized into the hierarchy.

Most of the computation required by the free energy principle has already been done and incorporated in the control hierarchy, leaving only the unfamiliar part for on-line computation to determine reference values for actions that would be predicted to reduce error in this not-yet-reorganized elementary control unit. If those actions do not reduce the error, their failure is quite legitimately call "surprise". If they do, and a similar situation recurs, there is less computation to do — or to put it another way, the same synapses will be used and thus strengthened, or not used and thus weakened — each time it happens. A new Elementary Control unit is being created and merged into the hierarchy. I am not clear how the free energy principle leads to a parallel process, though it might.

12.4 Uncertainty and information around a control loop

From an information-theoretic viewpoint, the through flow of energy can be ignored, though the export of uncertainty cannot. The control circuit analogue of Figure 12.2 is suggested by Figure 12.3. As in Figure 12.2, the environmental variable CEV in question may be a single scalar-valued quantity or a whole vector of them. A disturbance (D) has a certain bit-rate (Section 11.2) when observed by the processes of the loop. The controlled perception has a lower bit rate, because uncertainty of the output (O) matches that of the disturbance, and the uncertainty of the CEV that is observed is U(D|O). Ideally, this conditional uncertainty cannot be less than the disturbance bit-rate times the loop transport lag, because there is nothing the control loop can do about any change in the CEV that is perceived at one moment until the effect of that change has travelled round the whole loop.

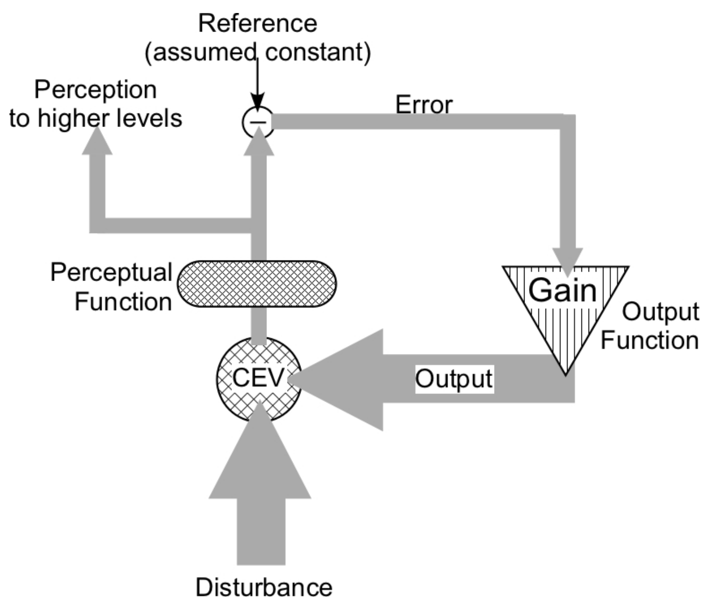

Figure 12.3 Schematic of the uncertainty levels in and around a control loop. The arrow widths represent relative uncertainties. The uncertainty out of the CEV is that of the perception if noise in the path from the sensors through the perceptual function is ignored. The output function achieves its increase in uncertainty by accumulating in some way (such as a leaky integrator) the error values in recent history.

In Figure 12.3, the energy flows are ignored, but one aspect of the diagram needs explaining: the increase of uncertainty introduced by the output function. Since, if the output is to oppose the