Chapter 3: Computational Building Blocks

Schema theory and opposition space provide languages for describing computation processes and grasps, respectively. In this chapter, we outline their primary features.

Schema Theory

Schema theory (Arbib, 1989) provides a language for describing functional decompositions of sensory and motor processes. An individual *schema* is a parameterizable description of an encapsulated computational element. Schemas are *active* in the sense that not only do they contain state information (data), but also the programmatic description for gathering and manipulating the data. In addition, schemas may be defined hierarchically (composed of a network of *sub-schemas)*.

A *schema instance* is a parameterized copy of a *schema* that performs the specified computation based upon the schema description and the provided parameters. These active entities are created through a process of instantiation and activation. Instantiation, also referred to as *priming* in (Dakin, 1986), is performed by the parent schema and involves preparing the schema instance for execution by creating the actual copy of the structure and providing the instance with the appropriate parameters and input/output ports. *Activation* of the schema instance marks the point at which it begins to execute. This event is potentially contingent upon a triggering signal or the state of other schema instances.

This influence of activation based upon the state of other schema instances is what we refer to as schema coordination. Typically, these schemas have been instantiated by a common parent and must work together to perform the designated task (*schema cooperation*). Cooperation can mean one of two things. First of all, two schemas can execute simultaneously, solving different parts of the problem or blending their results together into a single common output. Second, two schemas may execute at different times, each handling separate temporal components of the computation.

Besides cooperation, two primed schemas may represent completely different solutions to a given problem, and a decision must be made as to which is most relevant to a particular situation. This resolution process (*competition*) may be left to the schemas themselves, to be decided based upon locally available state information.

From a biological stand-point, however, schema theory does not provide a sufficient language for mapping between schemas and neurons. Although we allow a schema to be implemented as a neural network and then connect it into a network of other schemas, this is typically done at a functional level and does not address how individual neurons might participate in several schemas in a graded fashion. What is missing is a bridge from the functional level of analysis to an implementational one. We will address this issue as we develop our model in Chapter 5.

Opposition Space and Virtual Fingers

The problem of describing grasping movements has been approached by a number of researchers (Cutkosky, 1989; Napier, 1956). One such formalism, called *opposition space*, begins by identifying the primitive oppositions that can be applied by the primate hand (Iberall, Bingham, & Arbib, 1986; MacKenzie & Iberall, 1994). A primitive opposition consists of a pair of forces that are applied to the target object. The three oppositions available to the primate hand are:

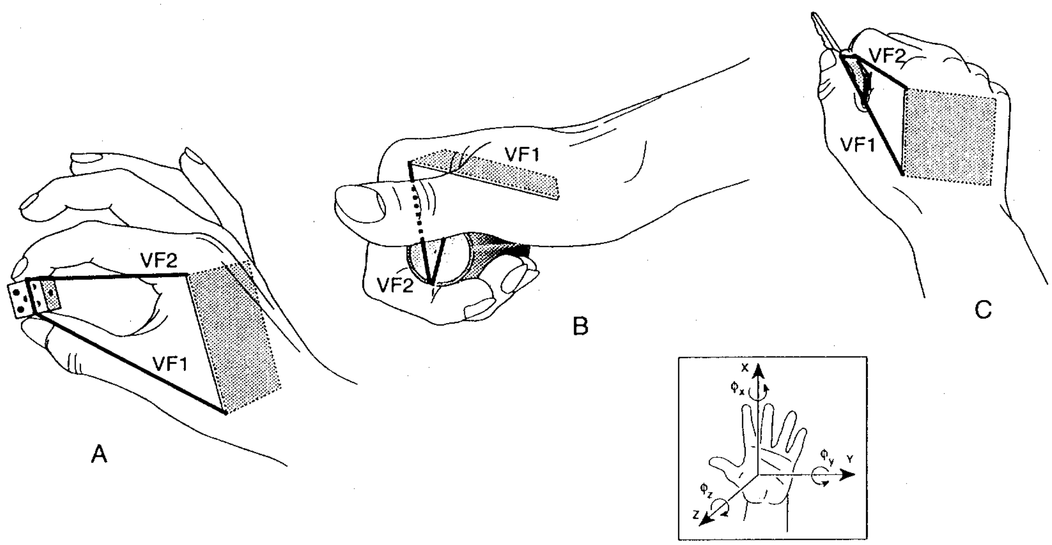

Figure 3.1: The three primary oppositions and their corresponding virtual fingers: pad opposition (A), palm opposition (B), and side opposition (C). From figure 2.7 of (MacKenzie & Iberall, 1994).

1. The *pad opposition* (Figure 3.1 A), in which the thumb is opposed by one or more fingers. A precision pinch (usually involving the index or middle finger opposing the thumb) is one example of a pad opposition.
2. The *palm opposition* (B), where the fingers oppose the palm (the thumb is not involved). A *power grasp* is one example.
3. The *side opposition* (C), in which the side of a finger is used to oppose the thumb or another finger. A *lateral pinch* involves the thumb opposing the side of the index finger.

The term *virtual finger* is used to describe (in abstract) the physical entity that is used in applying the force. Thus, each opposition involves the use of two virtual fingers (VF1 and VF2 in the figure). In the case of the pad opposition, the two virtual fingers are the thumb and any subset of real fingers. For the palm opposition, the two virtual fingers are the palm itself and a subset of the real fingers. A virtual finger can also counteract task-related forces or torques without opposing a second virtual finger (this is referred to as VF3). This is the case for grasps that oppose gravity, such as when carrying a suitcase.

Given these notions of oppositions and virtual fingers, a grasp can then be described (in opposition space) as the combination of:

1. One or more oppositions.
2. The mapping of real to virtual fingers for each opposition.
3. The virtual finger state variables.

It is important to note that a grasp may consist of multiple oppositions (1). For example, a common grasp that is used with a screw driver is one in which a palm opposition (with the ring and little fingers opposing the palm) is used to grasp the handle, and a pad opposition (index finger opposing the thumb) stabilizes and guides the tip. The virtual finger state variables include the VF length, orientation, and width, as well as the orientation of the surface at which contact is made, a measure of the forces that can be applied by the VF, and the sensory inputs that are available for controlling grasp.

A key point regarding this description scheme is that it defines a hierarchy of grasp description. As we proceed from element #1 to #3, more and more details of the grasp are provided. This might suggest a way of thinking about the representation of grasp at a neural level. As we have already seen in Chapter 2, neurons in F5 have a tendency to align themselves with the type of grasp that is executed by the monkey. Further details of the grasp coding might be captured within sub-populations of these grasp-oriented cells (although we have not yet seen this in F5, this is suggested by the size-selective cells observed in AIP). In addition, the opposition space representation may also tell us something about how neurons might be shared between different grasp instantiations. Two grasps that share some components (e.g., an opposition or a virtual finger with a certain set of real fingers) could overlap in their neural representation, sharing neurons that are responsible for controlling precisely these common elements.