Chapter 3
Situated Cognition and Bricolage

3.0 CHAPTER OVERVIEW

One example of a prototypical architecture for classical cognitive science is the production system (Newell & Simon, 1972). Early production systems were used to explore the manipulation of mental representations. Thus, logicism is one central characteristic of production system models. As production systems evolved, researchers included elements that modelled perception and action (Anderson et al., 2004; Meyer & Kieras, 1997a, 1997b). However, there were no direct interactions between sensing and acting. As a result, modern production systems preserve logicism and maintain a strict adherence to the sense–think–act cycle. However, some theories that endorse logicism, such as Piaget’s theory of cognitive development, are open to the idea that logicism is founded upon actions in the world. Indeed, computational arguments, as well as numerous results from cognitive neuroscience, support the claim that human cognition involves both sense–think–act and sense–act processing. As a result, new theories are arising in cognitive science in which the external world plays a more important role in cognition. Cognitive processing is seen to be aided or scaffolded by worldly support, and for this reason some researchers claim that the mind has leaked into the world. As well, rather than identifying a unifying theory of mind (a principal goal of production system architectures), some researchers argue that cognition is mediated by a diverse collection of cognitive agents (Minsky, 1985, 2006). Thinking thus is not viewed as the rational application of logical rules, but is instead viewed as a form of *bricolage* in which thinkers choose subsets of processes at hand, some sense–think–act and
other sense–act, and interact with the world to solve problems. How does one study a mind that is both leaky and composed of a collection of non-linear agents? One approach is to adopt a synthetic methodology in which a set of interesting primitive processes is selected, organized into a system, and then observed in action as the embodied and situated system interacts with its environment. It has been claimed that this synthetic approach can lead to simpler theories than would be the case if more traditional analytic methodologies were employed (Braitenberg, 1984). But how, then, do we train students to consider the mind in this different way, and how do we prepare them to study the mind using synthetic methodologies? At the end of this chapter it is proposed that we train them to be bricoleurs to construct and observe simple robots in action. Specific examples of such training are then introduced in this book, beginning with Chapter 4.

3.1 THREE TOPICS TO CONSIDER

3.1.1 Review to This Point

Chapter 1 began by exploring the age-old view that man is different from, and superior to, beast. Many have suggested that the source of this difference is human rationality. It is by virtue of rationality that man controls his environment, while animals are controlled by their environment. We considered potential exceptions to this view, such as the large and complex nests constructed by the social insects. However, we saw that many researchers believe that these intricate structures emerge from the stigmergic control of insects by their environment. But, if the giant mounds of termites can be explained by appealing to straightforward environmental control mechanisms, then why would it be unreasonable to offer similar explanations for human creations?

Chapter 2 explored this question by considering a prototypical example of human intelligence: composing classical music. We saw that the traditional view of composition treated music as the ultimate product of a rational, representational mind. However, these ideas were challenged when the characteristics of modern classical music were examined. We saw that modern music removed itself from the traditions of classical music by abandoning structure, by eliminating the goal of communicating particular messages, by exploring the complex products that could emerge from the interaction of simple processes, and by removing central control from the score in the conductor and distributing control to the performers and the audience. Furthermore, we encountered the argument that these characteristics of modern classical music could also be found in more traditional music if one took the care to search
for them. If it is possible for the composition of classical music to involve processes that are not completely rational, then is it not also possible that this is true of more mundane cognitive activities?

3.1.2 New Headings
Importantly, questions about human rationality do not hinge upon the structure of insect nests or the nature of modern music. We have seen that classical cognitive science views rationality as a fundamental principle of cognition; this is consistent with its reliance upon logicism. To its credit, classical cognitive science has developed influential and powerful theories of reasoning and problem solving that have rationality and logicism as their foundation. Nonetheless, a large number of experimental results concerning judgment, decision making, or problem solving have shown human cognition to depart from rational norms (Hastie, 2001; Mellers, Schwartz, & Cooke, 1998; Oaksford & Chater, 1998; Piattelli-Palmarini, 1994; Tversky & Kahneman, 1974). Many attempts have been made to revise these norms, or to propose alternative representational processes that incorporate additional constraints and move beyond these norms, to accommodate these irrational results within a rational cognitive science.

Of course, these results have also motivated alternative views of the mind. For instance, embodied cognitive science might attempt to explain apparently irrational results by noting these results make perfect sense in the context of an agent and its environment. One purpose of the current chapter is to explore an alternative view of mind that acknowledges the contributions of the environment to cognition.

The emergence of new views of mind has also led to the development of new approaches to its study. In particular, new approaches to modelling have appeared that involve novel relationships between the model and the system being modelled. A second purpose of the current chapter is to discuss the general characteristics of such models. New views of the mind, and new approaches to modelling cognitive phenomena, also raise questions about how these ideas should be introduced to students of cognitive science. A third purpose of the current chapter is to propose a general approach to instruction that is adopted and illustrated in more detail in subsequent chapters.

3.2 PRODUCTION SYSTEMS AS CLASSICAL ARCHITECTURES

3.2.1 The Production System
Let us start by describing the general characteristics of a classical information processing architecture, the production system. Production systems
are powerful architectures that have been used to model many psychological phenomena (Anderson, 1983; Anderson et al., 2004; Anderson & Matessa, 1997; Meyer et al., 2001; Meyer & Kieras, 1997a, 1997b; Newell, 1990; Newell & Simon, 1972). One aim of this chapter is to dispute some of the traditional assumptions of this architecture. The intent is not to attack production systems in particular, or to attack classical cognitive science in general. Rather, we will explore the idea that the foundational assumptions of production systems can easily be modified to show how this presumed classical system can incorporate the general characteristics of alternatives to classical cognitive science.

A production system is a general purpose symbol manipulator (Anderson, 1983; Newell, 1973; Newell & Simon, 1972). Like the Turing machine, and like most digital computers, production systems are defined by a sharp distinction between data and process. In the Turing machine, data are the symbols stored on the tickertape, while process is the set of rules that reside in the machine head. In a modern digital computer, data are the representations stored in random access memory (RAM), while process consists of the basic operations built into the central processing unit (CPU). In a production system, data are symbolic expressions that are stored in a working memory (and in some versions also stored in a long-term memory), while process consists of a set of rules (productions) that are capable of manipulating these expressions to achieve a desired information-processing end. Each production in a production system is a condition–action pair that scans the expressions in working memory for a pattern that matches its condition. If a match is found, then the production's action is carried out. An action usually involves manipulating symbols in working memory (e.g., adding new symbols).

In general, all the productions scan working memory in parallel. When one production finds its condition, it takes control for a moment, disabling the other productions while the controlling production changes memory. Then control is released, and the parallel scan of working memory is reinitiated. Additional control mechanisms can be added to deal with the situation in which more than one production finds its condition at the same time, or when one production finds its condition at different places in memory at the same time. As well, some productions might write goals into the working memory, and these goals can be included as conditions for some of the productions. This permits a hierarchical set of goals and subgoals to control the order in which productions are activated (Anderson, 1983, pp. 7–10).
3.2.2 Classical Characteristics

In addition to contributing to cognitive science by modelling many higher-order cognitive phenomena, production systems have all of the prototypical characteristics of classical information processing. First, they distinguish symbols from processes. Second, they are serial information processors in the sense that only one production can alter working memory at any given time. Third, the entire purpose of a production system is to manipulate symbolic expressions. Fourth, production systems have the requisite computational power. It has been proven that a production system is capable of solving the same problems that can be solved by a universal Turing machine (Newell, 1980).

The purpose of presenting production systems at this point in the chapter is to provide a concrete example to which we can later return. In the pages that follow we will consider some positions that challenge the classical assumptions that production systems embody. We will then see how the traditional notion of the production system can be modified in response to these challenges.

3.3 SENSE–THINK–ACT WITH PRODUCTIONS

3.3.1 An Early Production System

Production systems are prototypical classical architectures in the sense that they adhere to a strict sense–think–act cycle (Pfeifer & Scheier, 1999). That is, the goal of perceptual mechanisms is to generate symbolic expressions about the world to be stored in working memory. Internal mechanisms manipulate these expressions, producing other expressions that can represent plans for action that might affect the outside world.

The role of working memory (and operations upon it) as a mediator between sensing and acting is illustrated in Figure 3-1A below. This figure illustrates the main properties of early production systems used to model human cognition (Newell & Simon, 1972). The “thinking” component of the model is the large grey box that contains both a working memory and a procedural memory (i.e., a set of productions). The double-headed arrow indicates that control can flow from working memory to procedural memory, and vice versa.

The single-headed arrows illustrate that sensing adds content to the working memory, and that the contents of working memory later cause actions upon the world. Early production system models did not elaborate theories about sensing or acting, in spite of the fact that their developers recognized a need to do so. “One problem with psychology’s attempt at cognitive theory has been our persistence in thinking about cognition without bringing in perceptual and motor processes” (Newell, 1990, p. 15).
From Bricks to Brains

3.1a

Procedural Memory

Working Memory

THINK

SENSE  

ACT

WORLD

3.1b

Declarative Memory

Fact 1
Fact 2
Fact 3

Procedural Memory

Working Memory

THINK

SENSE  

ACT

WORLD

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3.3.2 The Next ACT

Figure 3-1B illustrates the general properties of the next stage of production system models, Anderson’s *adaptive control of thought* (ACT) architecture (Anderson, 1983). Two of its major innovations are represented in the figure: the introduction of a declarative memory to serve as a store of knowledge that was independent of productions, and the introduction of learning mechanisms (indicated by the one-headed arrow from the procedural memory to itself) that permitted new productions to be added. Of course, ACT included other innovations, such as new formats for the elements that were represented in the “thinking” part of the system. However, the early ACT architectures remained true to their antecedents by acknowledging the existence of sensing and acting, but also by failing to elaborate the nature of these components. The ACT architecture “historically was focused on higher level cognition and not perception or action” (Anderson et al., 2004, p. 1038).

3.4 LOGIC FROM ACTION

3.4.1 Productions and Logicism

Researchers who employ production systems are searching for a unified theory of cognition (Anderson, 1983; Anderson et al., 2004; Newell, 1990). “The unitary approach holds that all higher-level cognitive functions can be explained by one set of principles” (Anderson, 1983, p. 2). Of course, in a production system some behaviours (e.g., errors, latencies to perform various tasks) are the result of memory limitations, or the timing of certain operations (Meyer & Kieras, 1997b).

Nevertheless, the basic claim of a production system theory “is that underlying human cognition is a set of condition-action pairs” (Anderson, 1983, p. 5). The crucial behaviours to be explained by a production system are not found in (for instance) memory limitations, but are instead grounded in how the productions themselves rationally manipulate representational content. “All the behavioral flexibility of universal machines comes from their ability to create expressions for their own behavior and then produce that behavior. Interpretation is the necessary basic mechanism to make this possible” (Newell, 1980, p. 158). Production systems realize a commitment to logicism, a logicism instantiated as a particular representational theory of mind.

3.4.2 Logic as Internalized Action

However, logicism can be rooted in non-logical action. Consider Piaget’s theory of cognitive development (Inhelder & Piaget, 1958, 1964; Piaget, 1958, 1964).
According to Piaget, children achieve adult-level cognitive abilities at the stage of *formal operations* sometime in their early teens. This stage is formal in the sense that the child operates on symbolic representations. Furthermore, these operations are logical in nature. Formal operations involve completely abstract thinking, where relationships between propositions that represent the full range of possibilities are considered. “Considering possibilities” involves representing potential states of affairs in an organized combinatorial matrix. Different locations in this matrix encode different combinations of values of whatever variables are critical to the problem at hand. The INRC group is a set of four logical operations (identity, negation, reciprocal, and correlation) that permit the child to manipulate the combinatorial matrix, moving from one location to another, organizing it into logically significant groups. Clearly, the stage of formal operations is representational, and is an expression of logicism.

However, the route to formal operations begins with direct interactions with objects in the world (the *sensorimotor stage*). These objects are later internalized as symbols in the *preoperational stage*. In the next stage (*concrete operations*) these symbols can be manipulated, but these manipulations are not abstract: they bear “on manipulable objects (effective or immediately imaginable manipulations), in contrast to operations bearing on propositions or simple verbal statements (logic of propositions)” (Piaget, 1972, p. 56). According to Piaget, the roots of logic are the child’s physical manipulation of his or her world. “The starting-point for the understanding, even of verbal concepts, is still the actions and operations of the subject” (Inhelder & Piaget, 1964, p. 284).

For example, through their actions, children naturally group (classify) and order (seriate) objects. Classification and seriation are operations that can be defined in precise, formal terms. Piagetian theory attempts to explain how, as a child develops, their classifications and seriations conform to formal specifications provided by logic or mathematics. Piaget concludes that such formal abilities are “closely linked with certain actions which are quite elementary: putting things in piles, separating piles into lots, making alignments, and so on” (Inhelder & Piaget, 1964, p. 291).

Production systems, like most classical theories, emphasize thinking at the expense of sensing and action. Theories like those of Piaget provide alternatives in which humans are agents who act upon their world. This doesn’t mean that all sense–think–act cycles should be abandoned. Rather, it raises the possibility that they should be supplemented with sense–act processes.
3.5 AN EPIC EVOLUTION

3.5.1 Productions, Sensing, and Action

Production system researchers should, rightly, object to the criticism that they ignore sensing and acting. The omission of sensing and acting from such models was merely historical: central processes were simply modelled first (Anderson et al., 2004; Newell, 1990). Modern production system architectures do include sensing and acting.

3.5.2 The EPIC Architecture

Consider the EPIC (for executive-process interactive control) architecture (Meyer & Kieras, 1997a, 1997b). EPIC is designed to model temporal regularities observed when humans perform single or multiple tasks. One main focus of EPIC has been modelling the psychological refractory period (PRP). Imagine a subject who is simultaneously performing two tasks (e.g., making one response to stimulus 1, and a second response to stimulus 2). The stimulus onset asynchrony (SOA) for this subject is the duration from the onset of stimulus 1 to the onset of stimulus 2. When the SOA is long (1 second or more), the time taken to make the response for either task is similar. However, when the SOA is short (0.5 seconds or less) the latency for the second response is longer than that for the first. This increase in response latency when SOA is short is the PRP.

EPIC is very similar to the production system that was illustrated in Figure 3-1B. EPIC consists of declarative, procedural, and working memories. The major innovation of EPIC as a production system is that it permits productions to act in parallel. That is, at any time cycle in EPIC processing, all productions that have matched their conditions in working memory will act to alter working memory. This is important; when multiple tasks are modeled there will be two different sets of productions in action, one for each task.

EPIC also extends earlier production systems by including sensory processors, such as virtual eyes and ears. These sensory processors use table lookups to classify some physical aspect of the world, and then add symbols to working memory to represent this physical quality. For example, at first the virtual ear will indicate the presence of a signal by writing the string “AUDITORY DETECTION ONSET” to working memory. Later, the identity of the signal will be represented (e.g., by writing “AUDITORY TONE 800 ON” to memory).

Another EPIC extension is the inclusion of motor processors. This recognizes that action can provide constraints on performing cognitive tasks. For example, in EPIC a single motor processor controls both
“virtual hands.” This permits interference between two tasks that involve making responses with different hands.

Motor processors take symbols from working memory. For instance, the string “LEFT INDEX” in working memory is an instruction from the “cognitive processor” (i.e., the three memories working in unison) to perform some action with the left index finger. The motor processors convert working memory symbols into symbols that can be used to control a motor system, and place these into a memory buffer devoted to the motor system. This permits sequences of motor actions to be planned and stored, and also permits actions to be repeated by using the motor buffer directly to run a motor program that has already been created. Motor processors also send information back to working memory for central processes to monitor the progress of requested actions.

The preparation and activation of motor commands, as well as the transfer of information from sensory processors, are all operations that take specific amounts of time. When the EPIC architecture is used to simulate human performance on multiple tasks (producing what Meyer and Kieras (1997a) call the strategic response-deferment model), additional assumptions are used to coordinate the different tasks, and these assumptions also have temporal implications. As a result, this architecture can successfully simulate the reaction time regularities observed in a number of experimental studies of the PRP.

3.6 PRODUCTIONS AND FORMAL OPERATIONS

3.6.1 Sense — Think — Act

While the inclusion of sensing and acting components in models like EPIC (Meyer & Kieras, 1997a, 1997b) is commendable, it is accomplished by shoehorning them into the classical conception of mind. Figure 3-2 provides an illustration of an EPIC-like production system to help make this point. To simplify matters, it only illustrates a single sensor and a single motor processor.

It is evident in Figure 3-2 that both sensing and acting are mediated by central cognitive processing. Sensing transduces properties of the external world into symbols to be added to working memory. Working memory provides symbolic expressions to be interpreted by motor processors. Thus working memory centralizes the “thinking” that maps sensations onto actions. There are no direct connections between sensing and acting that bypass working memory.

When sensing and acting are placed in a sense–think–act cycle, embodied cognitive science (sometimes called situated action [Vera & Simon, 1993]) becomes rooted in symbol manipulations. “It follows that there
is no need, contrary to what followers of SA [situated action] seem sometimes to claim, for cognitive psychology to adopt a whole new language and research agenda, breaking completely from traditional (symbolic) cognitive theories. SA is not a new approach to cognition, much less a new school of cognitive psychology” (Vera & Simon, 1993, p. 46).

3.6.2 Formal Operations

Making situated action “cognitive” by forcing sensing and acting to be mediated by symbol manipulations is analogous to the formal operations proposed by Piaget that were discussed in Section 3.4. In models such as EPIC, the bulk of sensation and action have been internalized as symbol manipulations. EPIC uses completely virtual sensors and actors. The assumption is that if these virtual components were replaced with real sensors and actors, then the main results of EPIC would still hold.

However, this is not necessarily the case. First, in order for the sense–think–act cycle to work, a detailed internal model of the external world must be constantly maintained. As the complexity of this model increases (e.g., by increasing the number or complexity of sensors), a number of logical and practical problems emerge (Brooks, 1999, 2002; Clark, 1997; Pylyshyn, 1987). In general, more and more resources are required for modeling, and as a result action becomes slower and slower.
Second, the sense–think–act cycle usually requires the use of a common language (e.g., the symbols in working memory). However, simple and fluid interactions between sense and action may result when one considers specialized coordinate systems (Hutchins, 1995). “Intelligence and understanding are rooted not in the presence and manipulation of explicit, language-like data structures, but in something more earthy: the tuning of basic responses to a real world that enables an embodied organism to sense, act, and survive” (Clark, 1997, p. 4). We see next that neuroscientists have uncovered evidence for such earthy processing in the human brain.

### 3.7 EVIDENCE FOR SENSING AND ACTING WITHOUT THINKING

#### 3.7.1 Classical Modularity

An influential idea in cognitive science is that of modularity (Fodor, 1983). A module is a domain-specific system that solves a very particular problem, is incapable of solving other information-processing problems, and is usually associated with fixed neural architecture.

The modularity proposal is usually incorporated into the “sense–think–act” cycle of classical cognitive science (Dawson, 1998). Specifically, most modules solve particular perceptual problems (sense). The output of these modules is then passed on to visual cognition or higher-order cognition for inferential or semantic processing (think). The results of this higher-order processing are then used to generate actions (Wright & Dawson, 1994). However, this is not the only way in which modularity has been incorporated into cognitive science.

#### 3.7.2 Visuomotor Modules

Research on the vision of the frog has established the existence of processors that do not appear to feed into higher-order thinking mechanisms, but instead serve directly as “sense–act” or visuomotor modules (Ingle, 1973). Ingle surgically removed one hemisphere of the optic tectum of a frog; the optic tectum is the part of the frog brain most responsible for visual processing. Ingle’s lesion produced a particular form of blindness in which the frog pursued prey presented to the eye that was connected to the remaining tectum, but did not respond to prey presented to the eye that was originally connected to the ablated tectum.

Ingle found that, over time, the nerve fibres from the tectumless eye grew to be connected to the remaining optic tectum on the “wrong” side of the animal’s head. As a result, when a target was presented to this eye, the frog was no longer blind to it. However, the animal’s motor
responses were aberrant! The frog always moved toward a location that was mirror-symmetrical to the actual location of the target, and this incorrect response was shown to be due to the topography of the regenerated nerve fibres. This result demonstrated that the frog optic tectum converts a visual sensation directly into a motor response. “The visual system of most animals, rather than being a general-purpose network dedicated to reconstructing the rather limited world in which they live, consists instead of a set of relatively independent input-output lines, or visuomotor ‘modules’, each of which is responsible for the visual control of a particular class of motor outputs” (Goodale & Humphrey, 1998, p. 183).

Such results, and conclusions, are not limited to the frog. Parallel results have been found in the gerbil (Mlinar & Goodale, 1984). As well, studies of brain-injured patients have demonstrated that the human visual system may also be organized into visuomotor modules (Goodale, 1988, 1995; Goodale & Humphrey, 1998; Goodale, Milner, Jakobson, & Carey, 1991).

For instance, Goodale and his colleagues have studied one patient, DF, who suffered irreversible brain damage that dramatically impaired the ability to recognize visual shapes or patterns. However, DF’s visuomotor abilities were not impaired at all. Another patient, VK, had the exact opposite pattern of dysfunction after a series of strokes. VK had normal form perception, but her visuomotor control—in particular, her ability to form her hand to grasp objects of different shapes—was severely impaired.

Goodale and Humphrey (1998) have argued for the existence of two complementary visual systems, one responsible for controlling object-directed action, the other responsible for creating an internal model of the external world. “Although there is clearly a division of labor between the perception and action systems, this division reflects the complementary role the two systems play in the production of adaptive behavior” (p. 203). This view, called the duplex theory, supports roles for both sense–act and sense–think–act processing. Such a view is not evident in modern production system models such as EPIC, which require that all perception and action be mediated by central cognitive processing.

3.8 ACTION WITHOUT REPRESENTATION?

3.8.1 Multiple Visual Pathways

There are two parallel physiological pathways in the human visual system (Livingstone & Hubel, 1988; Maunsell & Newsome, 1987; Ungerleider & Mishkin, 1982). One, the ventral stream, seems to process visual form (i.e., specifying what an object is), while the other, the dorsal stream, seems to process visual motion (i.e., specifying where an object is).
These pathways are distinct: brain damage can produce deficits in motion perception, but not affect form perception, or vice versa (Botez, 1975; Hess, Baker, & Zihl, 1989; Zihl, von Cramon, & Mai, 1983). Similarly, cell recordings have revealed neurons that are sensitive to stimulus movement, but not to form (Albright, 1984; Dubner & Zeki, 1971; Maunsell & van Essen, 1983; Rodman & Albright, 1987; Zeki, 1974).

Historically, these two streams were considered to be representational: the ventral stream represented information about form, while the dorsal stream represented information about motion or location. Furthermore, the two streams were only sensitive to the information that they could represent. Goodale’s contribution to this literature is to reconceptualize the pathways.

In the duplex approach to vision (Goodale & Humphrey, 1998), the two pathways are sensitive to similar information, but use different transformations to perform distinct, though complementary, functions. The ventral stream creates perceptual representations, while the dorsal stream mediates the visual control of action. “The functional distinction is not between ‘what’ and ‘where’, but between the way in which the visual information about a broad range of object parameters are transformed either for perceptual purposes or for the control of goal-directed actions” (Goodale & Humphrey, 1998, p. 187).

3.8.2 Blindsight

Additional evidence supports Goodale and Humphrey’s (1998) position. Consider the phenomenon called blindsight (Weiskrantz, 1986, 1997; Weiskrantz, Warrington, Sanders, & Marshall, 1974). A patient who exhibits blindsight claims to be unable to see presented stimuli. That is, visual experiences have been ablated as the result of brain injury. However, these patients still demonstrate some ability to point to or detect visual stimuli. Blindsight occurs in human patients who have had damage to their primary visual cortex, and can be created experimentally in primates by surgically removing their visual cortex (Stoerig & Cowey, 1997).

Blindsight must be mediated by neural pathways not affected by the damage to primary visual cortex. Such damage has severe effects upon the ventral stream of processing. However, a variety of results suggest that much of the functionality of the dorsal stream remains intact (Danckert & Rossetti, 2005). “Action-blindsight depends on the integrity of residual pathways that terminate in the dorsal ‘action’ stream” (Danckert & Rossetti, 2005, p. 1041). These results, and the phenomena associated with blindsight in general, are completely consistent with
Goodale and Humphrey’s (1998) claim for a non-representational stream responsible for visually guided action.

Healthy subjects can also provide support for the duplex theory. In one study (Pelisson, Prablanc, Goodale, & Jeannerod, 1986), subjects reached toward an object while detailed measurements of their movement were recorded. However, the experimental method was such that as subjects reached, the object’s position was changed—but only when a subject’s eyes performed a saccadic eye movement. This manipulation resulted in subjects not being consciously aware that the object had actually moved. Nevertheless, their reach was adjusted to compensate for the object’s new position. “No perceptual change occurred, while the hand pointing response was shifted systematically, showing that different mechanisms were involved in visual perception and in the control of the motor response” (Pelisson et al., 1986, p. 309).

3.9 A NEED FOR ACTION

3.9.1 Incorporating Action

The earliest production systems were prototypical examples of classical cognitive science (Newell, 1973; Newell & Simon, 1972). They have evolved into architectures that explicitly include sensing and acting (Anderson et al., 2004; Meyer & Kieras, 1997a, 1997b). However, this is accomplished via an explicit sense–think–act cycle, and ignores the possibility of sense–act processing. An alternative to the classical approach is called embodied cognitive science (Agre, 1997; Brooks, 1999, 2002; Clancey, 1997; Clark, 1997, 2003, 2008; Pfeifer & Scheier, 1999; Robbins & Aydede, 2009; Varela et al., 1991). Embodied cognitive science recognizes the importance of sensing and acting, but reacts against central cognitive control. Its more radical proponents strive to completely replace the sense–think–act cycle with sense–act mechanisms. “In particular I have advocated situatedness, embodiment, and highly reactive architectures with no reasoning systems, no manipulable representations, no symbols, and totally decentralized computation” (Brooks, 1999, p. 170).

That some behaviour results from sense–act processing is supported by research on multiple perceptual streams in the brain (Livingstone & Hubel, 1988; Maunsell & Newsome, 1987; Ungerleider & Mishkin, 1982), the hardwiring of sense–act reflexes (Ingle, 1973; Mlinar & Goodale, 1984), and the cognitive neuroscience of visually guided action (Goodale, 1988, 1990, 1995; Goodale & Humphrey, 1998; Goodale et al., 1991; Pelisson et al., 1986). However, embodied cognitive scientists are not primarily motivated by such evidence. Instead, they see good computational reasons for removing central cognitive control. “The realization
was that the so-called central systems of intelligence—or core AI as it has been referred to more recently—was perhaps an unnecessary illusion, and that all the power of intelligence arose from the coupling of perception and actuation systems” (Brooks, 1999, p. viii).

3.9.2 Advantages of Action

Survival depends upon swift action. Attempts to employ the sense–think–act cycle in early mobile robots (Moravec, 1999; Nilsson, 1984) produced systems that took too long to think (see the discussion of Shakey in Section 7.2.2), and therefore could not act appropriately in real time. “The disparity between programs that calculate, programs that reason, and programs that interact with the physical world holds to this day. All three have improved over the decades, buoyed by a more than million fold increase in computer power in the fifty years since the war, but robots are still put to shame by the behavioral competence of infants or small animals” (Moravec, 1999, p. 21).

Some argue that this is due to the computational bottleneck caused by the cost of maintaining an internal model of the world. This bottleneck might be removed by using the world as its own model. This eliminates the costly need to internalize it (e.g., Brooks, 1999), making actions faster and more adaptive.

Slow action might also characterize unifying theories of mind (Anderson et al., 2004; Newell, 1990). This is because they need to mediate all sensing and acting via a common symbolic framework. In addition to the cost of maintaining this framework, its generality may ignore faster solutions that are possible with more specialized processing. An alternative is to use specialized external devices to reduce cognitive demands, and to speed information processing up (Dourish, 2001; Hutchins, 1995). “By failing to understand the source of the computational power in our interactions with simple ‘unintelligent’ physical devices, we position ourselves well to squander opportunities with so-called intelligent computers” (Hutchins, 1995, p. 171).

This raises another crucial advantage of action: extending the capacity of central cognition by using external objects to support computation. This is called cognitive scaffolding (Clark, 1997), and we will now turn to exploring its implications.

3.10 THE EXTERNAL WORLD AND COMPUTATION

3.10.1 Worldly Support for Cognition

Nobel laureate physicist Richard Feynman once took an advanced biology course (Feynman, 1985). He presented a seminar about a paper on
nerve impulses in cat muscles. To understand the paper, he had gone to the library to consult “a map of the cat.” Feynman began his presentation naming various muscles in a drawing of an outline cat. He was interrupted by his classmates’ claiming they already knew this. “Oh,’ I say, ‘you do? Then no wonder I can catch up with you so fast after you’ve had four years of biology.’ They had wasted all their time memorizing stuff like that, when it could be looked up in fifteen minutes” (Feynman, 1985, p. 59).

Feynman’s tale illustrates that there are different approaches to solving information-processing problems. One could memorize all of the information that might be required. Or, one could reduce cognitive strain by using the external world. One doesn’t have to (internally) remember all of the details if one knows where they can be found in the environment.

The world is more than just a memory. Hutchins (1995) describes a task in which a navigator must compute a ship’s speed using the measure of how far the ship has travelled over a recent interval of time. One solution to this task involves calculating speed based on internalized knowledge of algebra, arithmetic, and conversions between yards and nautical miles.

A second approach is to draw a line on a three-scale representation called a nomogram. The top scale of this tool indicates duration, the middle scale indicates distance, and the bottom scale indicates speed. The user marks the measured time and distance on the first two scales, joins them with a straight line, and reads the speed from the intersection of this line with the bottom scale. In this case “it seems that much of the computation was done by the tool, or by its designer. The person somehow could succeed by doing less because the tool did more” (Hutchins, 1995, p. 151).

3.10.2 Scaffolding

The use of external structures like the nomogram to support cognition is called scaffolding (Clark, 1997, 2003). The exploitation of the external world to support thinking has a long history in developmental psychology. For example, in Piagetian theory sensorimotor stage processing predominantly involves scaffolding, while concrete operations represent a stage in which previously scaffolded thought is internalized.

Such a view is more explicit in other theories of cognitive development (Vygotsky, 1986). Vygotsky, for example, emphasized the role of assistance in cognitive development. He defined the difference between a child’s ability to solve problems without aid and their level of ability when assisted as the zone of proximal development. Vygotsky argued that
the zone of proximal development was crucial, and noted that children with larger zones of proximal development did better in school. He criticized methods of instruction that required children to solve problems without help. “The true direction of the development of thinking is not from the individual to the social, but from the social to the individual” (p. 36).

Vygotsky is also important for broadening the notion of what resources were available in the external world for scaffolding. For example, he viewed language as a tool for supporting cognition: “Real concepts are impossible without words, and thinking in concepts does not exist beyond verbal thinking. That is why the central moment in concept formation, and its generative cause, is a specific use of words as functional ‘tools’” (Vygotsky, 1986, p. 107). Clark (1997, p. 180) argues that intelligence depends upon scaffolding in this broad sense: “Advanced cognition depends crucially on our abilities to dissipate reasoning: to diffuse knowledge and practical wisdom through complex social structures, and to reduce the loads on individual brains by locating those brains in complex webs of linguistic, social, political, and institutional constraints.”

### 3.11 SOME IMPLICATIONS OF SCAFFOLDING

#### 3.11.1 The Leaky Mind

The scaffolding of cognition causes cognitive scientists to face a number of important theoretical issues. First, where is the mind located (Wilson, 2004)? The traditional view — typified by the production system models that we have briefly considered — is that thinking is inside the individual, and that sensing and acting involve the world outside. However, if cognition is scaffolded, then some thinking has moved from inside the head to outside in the world. “It is the human brain plus these chunks of external scaffolding that finally constitutes the smart, rational inference engine we call mind” (Clark, 1997, p. 180). From this perspective, Clark describes the mind as a leaky organ, because it has spread from inside our head to include whatever is used as external scaffolding.

The leaky mind has a profound impact on classical cognitive science. For example, in the classical approach it is standard to assume that mental states are realized as brain states (Wilson, 2004). Leaky minds mean that this commonplace view of realization has to be revisited.

#### 3.11.2 Group Cognition

The scaffolding of cognition also raises the possibility of public cognition, in which more than one cognitive agent manipulates the world that is being used to support information processing. Hutchins (1995) provides
an excellent example of this in describing how a team of individuals is responsible for navigating a ship. He argues that “organized groups may have cognitive properties that differ from those of the individuals who constitute the group” (p. 228). For instance, in many cases it is very difficult to translate the heuristics used by a solo navigator into a procedure that can be implemented by a navigation team.

The possibility that group abilities are qualitatively different from those of a group’s component individuals is an example of a central theme in embodied cognitive science, emergence (Holland, 1998; Johnson, 2001; Sawyer, 2002). We have already been introduced to emergence in both the behavioural products of social insects (Detrain & Deneubourg, 2006) and in the musical processes of minimalist music (Reich, 2002).

The computational power of groups over individuals is growing in importance, and can be found in discussions on collective computation and swarm intelligence (Deneubourg & Goss, 1989; Goldstone & Janssen, 2005; Holland & Melhuish, 1999; Kube & Zhang, 1994; Sulis, 1997). For cognitive science, it raises the issue of whether there might exist a “group mind” that cannot be associated with an individual (Wilson, 2004). It also raises the possibility of collective human cognition that is a product of stigmergy.

### 3.11.3 Specialized Cognition

Public cognition can proceed in a variety of ways. The most obvious is when two or more individuals collaborate on a task using a shared environment (Hutchins, 1995). Less obvious is the contribution, over time, of specialized environmental tools used in scaffolding. Hutchins stresses the cultural and historical nature of these tools. For instance, he notes that navigation is impacted by the mathematics of chart projections that was worked out centuries ago, as well as by number systems that were developed millennia ago.

Hutchins (1995) suggests extending the parable of the ant (Simon, 1969) that was introduced in Section 1.12. Instead of watching a single ant for a brief period, Hutchins argues that we should instead arrive at a beach after a storm, and watch many generations of ants working on this *tabula rasa*. As the ant colony matures, the ants appear smarter, because their behaviours are more efficient. But this is because “the environment is not the same. Generations of ants have left their marks on the beach, and now a dumb ant has been made to appear smart through its simple interaction with the residua of the history of its ancestor’s actions” (Hutchins, 1995, p. 169).
3.12 STIGMERY OF THOUGHT

3.12.1 Environmental Import

Scaffolded cognition disrupts the classical approach’s reliance on the sense–think–act cycle. The purpose of this cycle is to use central cognitive processes to control sensing and acting. However, with scaffolding, such central (and internal) control is lost. Thinking becomes the result of action on the world, not the control of it. Scaffolding raises the possibility that the sense–think–act cycle can be replaced with sense–act processes that interact directly with the world, and not with an internal representation of it (Brooks, 1999). This emphasizes a completely different notion of control: the world elicits actions upon itself. This is another example of stigmergy (Theraulaz & Bonabeau, 1999) that was introduced in Chapter 1. Indeed, traditional production system control is internally stigmergic, because the contents of working memory determine which production (or productions, as in the case of EPIC [Meyer & Kieras, 1997a]) will act at any given time. When working memory leaks into the world via scaffolding, cognitive control becomes as stigmergic as a wasp nest’s control of its own creation.

We can now reformulate our earlier production system illustrations. Figure 3-3 is a recasting of Figure 3-1B; its working memory has leaked into a scaffolding world. This is shown by extending the working memory “box” so that it includes at least a subset of the external world.

The second alteration evident in Figure 3-3 is that procedural memory has been generically described as a set of primitives that sense and act. Their behaviour is identical to that of the productions in classical theories (Anderson, 1983, 1985; Meyer & Kieras, 1997a, 1999; Newell, 1990; Newell & Simon, 1972): when a triggering condition is sensed, then some action is carried out. However, there is no need to commit to the claim that these are productions in the traditional sense.

Rather, the key claim to make is that there are four general types of these primitives, and these types are defined in terms of whether they interact with internal or external memory. One primitive is like the traditional production: it senses information in working memory, and also acts on this working memory. The other three are less traditional. One type senses information in working memory, but acts on the world. One type senses information in the world, but acts on working memory. The final type senses and acts on the world.

Figure 3-3 is extremely simple, and is not intended to illustrate a complete architecture. Its purpose is to highlight the coexistence of two different types of processing, involving two different notions of control. One is the sense–think–act cycle, represented by primitives
that sense internal information. The other is sense–act processing, represented by primitives that sense external information. It is this second type of processing that brings the environment (and stigmergy) to the forefront via scaffolding. It is also this second type of processing that is excluded from the production system architectures that have been discussed in preceding pages.

3.13 BRICOLAGE

3.13.1 Resource Allocation

Figure 3-3 indicates that there are two different styles of processing available: sense–think–act or sense–act. Scaffolding raises the possibility of sense–act processing, but also raises the issue of the degree to which such processing might be combined with the more traditional sense–think–act cycle. Even when sensing and acting are included in production systems (Anderson et al., 2004; Meyer & Kieras, 1997a) they are under cognitive control. Unified theories of mind (Anderson, 1983; Newell, 1990) rely on sense–think–act processing; sense–act processing is absent from such models. Behaviour-based robotics architectures (Brooks, 1989, 1999, 2002), which reacted against classical theories, rely completely upon sense–act processing, and deliberately exclude the sense–think–act cycle. In short, radical classical approaches, and radical reactions to them, deny the simultaneous existence of both processes.
More moderate views, such as the duplex theory that we have introduced (Goodale & Humphrey, 1998), and Figure 3.3, acknowledge the complementary existence of both types of processes, and must therefore go on to consider their allocation. “Minds may be essentially embodied and embedded and still depend crucially on brains which compute and represent” (Clark, 1997, p. 143).

One example of both types of processing being active at the same time is horizontal décalage from Piagetian developmental theory (Flavell, 1963). A horizontal décalage occurs when a child can use a more advanced level of operations to solve one problem, but cannot do so for a related problem. For example, children conserve quantity or mass earlier than they conserve weight. Given that it can be argued that Piaget’s earlier stages of development involve more sense–act processing than do later stages, the existence of horizontal décalages suggest that cognitive development can exhibit periods during which sense–act and sense–think–act cycles coexist.

3.13.2 Thought as Bricolage

Cognitive scientists are not the only ones faced with allocating resources between sense–act and sense–think–act cycles. If both are available to a cognitive agent, then the agent itself has to flexibly allocate these resources as well. An agent might solve a problem with sense–think–act processing at one time, yet solve it with sense–act processing at another, and therefore be able to choose processing types. Even more plausibly, both types of processes might be in play simultaneously, but applied in different amounts when the same problem is encountered at different times and under different task demands (Hutchins, 1995). Resource allocation might depend upon something like the 007 principle (Clark, 1989): “Creatures will neither store nor process information in costly ways when they can use the structure of the environment and their operations upon it as a convenient stand-in for the information-processing operations concerned. That is, know only as much as you need to know to get the job done” (p. 64).

The sense–act operators in Figure 3.3 comprise a finite set of “tools” available for information processing. At a given point of time, a subset of these tools is employed. Depending upon the subset that is selected, a problem could be solved with sense–think–act cycles, with sense–act processes, or with some combination of the two.

Such information processing—the selection of a subset of available operators—is akin to the notion of bricolage (Lévi-Strauss, 1966). A bricoleur is an “odd job man” in France. “The ‘bricoleur’ is adept at performing
Chapter 3

Situated Cognition and Bricolage

3.14 The Power of Bricolage

3.14.1 The Savage Mind

The notion of bricolage was introduced in The Savage Mind (Lévi-Strauss, 1966). Lévi-Strauss was interested in explaining the practice of totemism, in which individuals or groups in a society are given names of animals or plants. He found that totemism was based upon sophisticated classification systems. “Native classifications are not only methodical and based on carefully built up theoretical knowledge. They are also at times comparable from a formal point of view to those still in use in zoology and botany” (p. 43). Furthermore, the logic of totemism involved mapping relationships between classified items in the world to analogous relationships between groups.

For example, imagine that one clan was assigned an eagle totem, while another was assigned a bear totem. These totems capture second-order properties, or differences between pairs of categories: a characteristic used to distinguish the two clans is mapped onto an observed difference between eagles and bears in a detailed classification scheme (Lévi-Strauss, 1966, Chapter 4).

Lévi-Strauss (1966) argued that the regularities governing totemism established that such thought was not primitive. Nevertheless, when he used the analogy of the bricoleur to illustrate “primitive” thinking as being different from scientific thought, Lévi-Strauss still cast it in a negative light. “The ‘bricoleur’ is still someone who works with his hands and uses devious means compared to those of a craftsman” (pp. 16–17). The problem was that the bricoleur is limited to a fixed set of materials at hand. These components or tools can be rearranged, but cannot be extended. “The engineer is always trying to make his way out of and go beyond the constraints imposed by a particular state of civilization while the ‘bricoleur’ by inclination or necessity always remains within them” (p. 19).

3.14.2 Power from Non-linearity

The view that the bricoleur is constrained by finite materials fails to recognize that, in particular circumstances, finite resources provide surprising power. Consider a set of sense–act operators in Figure 3-3 as a
finite resource. One characteristic of these particular operators is their non-linearity: they follow an “all or none law,” and only carry out their action when particular triggering information has been sensed (Dawson, 2004). Such non-linearity is a source of incredible computational power; the collective power of simple non-linear operators is huge.

For example, artificial neural networks are comprised of very simple, non-linear components. As a result they can solve the same problems as a universal Turing machine (Cybenko, 1989; Hornik, Stinchcombe, & White, 1989; Lippmann, 1987; McCulloch & Pitts, 1943). Even critics of connectionism (Fodor & Pylyshyn, 1988) have noted that “the study of Connectionist machines has led to a number of striking and unanticipated findings; it’s surprising how much computing can be done with a uniform network of simple interconnected elements” (p. 6). In general, interactions between non-linear components produce complex emergent phenomena such that the behaviour of the whole goes beyond, or cannot be predicted from, the behaviour of the component parts (Holland, 1998; Luce, 1999).

_Bricolage_ is receiving renewed respect (Papert, 1980; Turkle, 1995). Papert notes that “if _bricolage_ is a model for how scientifically legitimate theories are built, then we can begin to develop a greater respect for ourselves as _bricoleurs_” (p. 173). Turkle describes _bricolage_ as a sort of intuitive tinkering, a dialogue mediated by a virtual interface. “As the computer culture’s center of gravity has shifted from programming to dealing with screen simulations, the intellectual values of _bricolage_ have become far more important. ... Playing with simulation encourages people to develop the skills of the more informal soft mastery because it is so easy to run ‘What if?’ scenarios and tinker with the outcome” (p. 52). We will shortly argue for the use of _bricolage_ to further our understanding of embodied cognitive agents.

### 3.15 THE SOCIETY OF MIND

#### 3.15.1 Agents and Agencies

Unified theories of mind aim to provide an account of cognition that explains a diversity of phenomena by appealing to a single set of rules. “All the higher cognitive processes, such as memory, language, problem solving, imagery, deduction and induction, are different manifestations of the same underlying system” (Anderson, 1983, p. 1). However, theories that view the mind as a collection of non-linear operators do not necessarily share this goal. Consider, for example, Minsky’s _society of mind_ (Minsky, 1985, 2006).

The society of mind is a theory that grows from a basic assumption:
“Any brain, machine, or other thing that has a mind must be composed of smaller things that cannot think at all” (Minsky, 1985, p. 322). Minsky then proceeds to generate hypotheses about what these smaller things might be, how they might interact, and what these interactions can produce.

Minsky (1985, 2006) proposes that the basic building blocks of the mind are agents. An agent is given a very vague definition: “Any part or process of the mind that by itself is simple enough to understand” (Minsky, 1985, p. 326). However, in practice an agent is analogous to a production, a sense–act operator from Figure 3-3, or a unit in an artificial neural network. That is, an agent is a simple device that receives input, makes a decision on the basis of this input (i.e., it is non-linear), and then sends an output signal.

Minsky (1985, 2006) proposes a large number of different types of agents, each associated with performing different kinds of tasks. His collection of agents includes censors, demons, direction-nemes, memorizers, micronemes, nemes, nomes, paranomes, polynemes, pronomes, recognizers, sensors, and suppressors. Luckily, Minsky (1985) also provides a glossary to help manage the diverse nature of his theory!

The power of a society of mind comes from organizing a number of agents into groups called agencies. Again, Minsky (1985, 2006) proposes a diversity of agencies, involving different organizational principles, and designed to accomplish different higher-order tasks: A-brains, B-brains, cross-exclusions, cross-realm correspondences, frames, frame arrays, interaction-squares, k-lines, picture-frames, transframes, and uniframes.

An agency is an explicit example of a whole transcending the computational power of its parts. Early on, Minsky (1985) describes an example agency for building with toy blocks called Builder. “If you were to watch Builder work, from the outside, with no idea of how it works inside, you’d have the impression that it knows how to build towers. But if you could see Builder from the inside, you’d surely find no knowledge there. You would see nothing more than a few switches, arranged in various ways to turn each other on and off” (p. 23).

Interestingly, though the society of mind is untraditional in its construal of thinking, it is still presented as a traditional sense–think–act model. However, sense–think–act processing is not a necessary characteristic of this theory. If agents could interact with the environment as well as with each other, then even greater computational surprises would emerge from a society of mind.
3.15.2 Explaining Mental Societies

The diversity at the heart of the society of mind poses problems for explaining cognition. Minsky (1985, p. 322) argues against unified theories modelled after physics: “The operations of our minds do not depend on similarly few and simple laws, because our brains have accumulated many different mechanisms over aeons of evolution. This means the psychology can never be as simple as physics, and any simple theory of mind would be bound to miss most of the ‘big picture’. The science of psychology will be handicapped until we develop an overview with room for a great many smaller theories.” However, Minsky leaves an unanswered question: How do we make such room in our theories?

3.16 ENGINEERING A SOCIETY OF MIND

What is required to explain a society of mind? Minsky (1985, p. 25) sketches a general strategy: “First, we must know how each separate part works. Second, we must know how each part interacts with those to which it is connected. And third, we have to understand how all these local interactions combine to accomplish what that system does — as seen from the outside.” What tactics might we employ to carry out Minsky’s strategy?

3.16.1 Reverse Engineering

One popular approach is called reverse engineering. Reverse engineering takes Minsky’s strategy in the opposite order. It begins with observations of what the system does from the outside, and then uses these observations (usually collected with clever experimental methodologies) to infer interactions between parts. Ultimately, it attempts to ground this analysis in a set of primitives — that is, the basic parts of the system.

Classical cognitive science makes extensive use of reverse engineering. Most cognitive theories are the product of a general approach called functional analysis (Cummins, 1975, 1983). Functional analysis proceeds as follows: First, a general function of interest is defined. Second, this general function is decomposed into an organized system of subfunctions capable of carrying out the general function. Subfunctions themselves might be further decomposed into organized systems of sub-subfunctions. This analysis proceeds until the final stage of subsumption. When a subfunction is subsumed, it is explained by appealing to physical laws, and cannot be decomposed into any smaller functions.

The earliest production system models of cognition were achieved by functional analysis. For instance, human subjects solved cryptarithmetic problems, thinking aloud as they worked. Their verbalizations were
transcribed and analyzed to identify a likely set of productions being used to solve the problem. In one famous example, a set of only 14 different productions produced a remarkable fit to how a single subject solved a single cryptarithmetic problem (Newell & Simon, 1972).

The problem with reverse engineering is that it often runs into the frame of reference problem (Pfeifer & Scheier, 1999). The frame of reference problem occurs when the parable of the ant (Simon, 1969) is ignored, as was briefly discussed in Chapter 1. When functional analysis is performed, it is typical to place all of the complexity inside the cognitive system, and ignore potential accounts of this complexity that might be provided by including environmental factors. As a result, it has been argued that theories that are produced via analysis are more complicated than necessary (Braitenberg, 1984).

3.16.2 Forward Engineering

An alternative approach that is deliberately designed to avoid the frame of reference problem is to perform forward engineering. In forward engineering, one follows Minsky’s strategy in his stated order. A set of building blocks is created, and a system is built from them. The system is then observed to determine whether it generates surprising or complicated behaviour. This has also been called the synthetic approach (Braitenberg, 1984). It is not as widely practised as reverse engineering. “Only about 1 in 20 ‘gets it’ — that is, the idea of thinking about psychological problems by inventing mechanisms for them and then trying to see what they can and cannot do” (Minsky, 1995, personal communication).

Forward engineering addresses the frame of reference problem because when complex or surprising behaviours emerge, pre-existing knowledge of the components—which were constructed by the researcher—can be used to generate simpler explanations of the behaviour. “Analysis is more difficult than invention in the sense in which, generally, induction takes more time to perform than deduction: in induction one has to search for the way, whereas in deduction one follows a straightforward path” (Braitenberg, 1984, p. 20).

3.17 SYNTHESIS IN ACTION

3.17.1 Cricket Phonotaxis

In later chapters we will explore historical examples of forward engineering, including Braitenberg’s Vehicle 2 (Braitenberg, 1984) and Grey Walter’s cybernetic animal Machina speculatrix (Grey Walter, 1950a, 1950b, 1963). For the time being, though, let us briefly consider how the synthetic approach is used to study an interesting insect behaviour. Female
crickets track down a mate by listening to, and following, a male cricket’s song. Crickets have an ear located on each foreleg, and can use differences in stimulation of each ear to compute directional information. This ability is called phonotaxis (Webb, 1996). Many researchers are interested in determining the mechanisms that mediate cricket phonotaxis.

Phonotaxis depends crucially upon the structure of the male cricket’s song. The cricket’s familiar “chirps” are pure tone signals that have a frequency of 4–5 kHz and are delivered in bursts or syllables that are 10–30 ms in duration (Webb & Scutt, 2000). If the frequency of the song, or the interval between repetitions of syllables, is disrupted then so too is phonotaxis. Webb notes that researchers typically propose that phonotaxis is mediated by mechanisms used to localize a call, as well as additional mechanisms that operate in parallel to analyze the signal. Signal analysis is assumed, for instance, to explain how a female cricket chooses to follow one song when several male crickets are attempting to attract her at the same time.

3.17.2 Robot Phonotaxis

Barbara Webb and her colleagues have used forward engineering to study cricket phonotaxis by building call-following robots, beginning with wheeled devices (Webb, 1996; Webb & Scutt, 2000) and later using six-legged machines (Horchler, Reeve, Webb, & Quinn, 2004; Reeve, Webb, Horchler, Indiveri, & Quinn, 2005). This research is motivated by a simple guiding hypothesis: the female cricket moves toward a song by sensing whether it is coming from the left or the right, and by turning in the sensed direction. Consistent with the synthetic approach, these robots begin with very simple circuits: “a more powerful way to explore the actual functional roles of the neurons is to look at what behavior it is possible to obtain with gradual elaborations of simpler circuits” (Webb & Scutt, 2000, p. 250). Surprisingly, a four-neuron circuit can model cricket phonotaxis without requiring separate song analysis.

The model uses two auditory neurons, each receiving signals from one side of the cricket. Two motor neurons cause the robot to turn in a particular direction. An auditory neuron excites the motor neuron on the same side, and inhibits the other motor neuron. All four components are highly non-linear, generating action potentials at frequencies that are governed by external stimulation, and by internal signals, which vary over time. To cause a turn, one auditory neuron must repeatedly “spike” before the other in order to produce a motor neuron spike.

The robot successfully demonstrates phonotaxis (Webb & Scutt, 2000). However, it also behaves as if songs are being analyzed. When song
syllable interval is modified, the robot’s phonotaxis is impaired. As well, the robot meanders to non-directional songs presented from above, which is usually taken as evidence of song analysis in real crickets. The robot can also choose, moving in the direction of a single song when other similar songs are being played from other speakers at the same time.

How is this simple circuit capable of performing song analysis? Responses of the robot depend upon the temporal properties of the model, which are affected by the separation of ears on the robot, and the latencies of the model’s neurons. These temporal properties result in sensitivity to very particular temporal properties of songs. That is, the circuit analyzes song structure “for free” because of its dynamic, temporal properties. “Thus it is clear from our results that much of the evidence for the standard ‘recognize and localize’ model of phonotaxis in crickets is insufficient to rule out an alternative, simpler model” (Webb & Scutt, 2000, pp. 265–66).

3.18 VERUM-FACTUM

3.18.1 Synthetic Psychology

The use of robots to study cricket phonotaxis (Webb & Scutt, 2000) illustrates synthetic psychology (Braitenberg, 1984). In synthetic psychology, a system is first constructed from a set of interesting components. The behaviour of the system is then observed and explored, usually by embedding the system in an interesting or complicated environment. For instance, Webb and Scutt manipulated the location, number, and nature of calls being presented to their cricket robot. Non-linear interactions between components, or between the system and its environment, can produce behaviour that is more complicated than expected. For example, Webb and Scutt’s system was designed to localize sounds, but also behaved as if it analyzed sound properties. Finally, the fact that the system is both simple and constructed by the researchers means that simpler theories can be proposed to account for complex or surprising behaviour.

3.18.2 Vico’s Philosophy

The synthetic approach has been described as “understanding by building” (Pfeifer & Scheier, 1999). The idea that the route to understanding a system comes from our ability to construct it is not new. It is rooted in the philosophy of Giambattista Vico, who was an early-eighteenth-century philosopher. Vico reacted against the seventeenth-century philosophy of René Descartes, which inspired the logicism of classical cognitive science (Devlin, 1996). For example, Vico believed that if
Cartesian methods were taught too early, they would stifle a student’s imagination and memory (Vico, 1990). Indeed, Vico developed a metaphysics and theory of mind that attempted to replace Cartesian views (Vico, 1988), and attempted to explain societal creations, such as law (Vico, 1984).

Vico’s philosophy is based on the central assumption that the Latin term for truth, verum, was identical to the Latin term factum. As a result, “it is reasonable to assume that the ancient sages of Italy entertained the following beliefs about the true: ‘the true is precisely what is made’” (Vico, 1988, p. 46). This assumption leads to an epistemology that resonates nicely with forward engineering. “To know (scire) is to put together the elements of things” (p. 46). Vico believed that humans could only understand the things that they made, which is why he turned his philosophical studies to societal inventions, such as the law. A famous passage (Vico, 1984, p. 96) highlights Vico’s philosophical position: “The world of civil society has certainly been made by men, and its principles are therefore to be found within the modifications of our own human mind. Whoever reflects on this cannot but marvel that the philosophers should have bent all their energies to the study of the world of nature, which, since God made it, he alone knows.”

This view also resulted in an embodied view of mind that stood in stark contrast to the disembodied view espoused by Descartes. For instance, Vico recognized that the Latins “thought every work of the mind was sense; that is, whatever the mind does or undergoes derives from contact with bodies” (Vico, 1988, p. 95). Indeed, Vico’s verum-factum principle is based upon embodied mentality. Because the mind is “immersed and buried in the body, it naturally inclines to take notice of bodily things” (Vico, 1984, p. 97).

Classical cognitive science, with emphasis on the rule-governed manipulation of symbols, has evolved from Descartes’ view of the rational, disembodied mind (Descartes, 1637/1960). Reactions against classical cognitive science are in essence reactions against the Cartesian mind. “The lofty goals of artificial intelligence, cognitive science, and mathematical linguistics that were prevalent in the 1950s and 1960s (and even as late as the 1970s) have now given way to the realization that the ‘soft’ world of people and societies is almost certainly not amenable to a precise, predictive, mathematical analysis to anything like the same degree as is the ‘hard’ world of the physical universe” (Devlin, 1996, p. 344). Perhaps it is fitting that the synthetic approach is rooted in a philosophy that reacted against Descartes, and which attempted to explain regularities in this “softer” domain.
3.19 MIND AND METHOD

3.19.1 Mind

Consider the possibility that intelligence must be explained using a society of mind (Minsky, 1985, 2006). In such a theory, the mind is composed of a diversity of agents that are non-linear in nature, that interact with one another, and through these interactions produce surprising, complex, emergent results.

That the mind might be of this nature is not a radical idea. Production systems, old and new (Anderson, 1983; Anderson et al., 2004; Meyer & Kieras, 1997a, 1997b; Newell, 1973, 1990; Newell & Simon, 1961, 1972), can be considered to be particular instances of societies of mind. Individual productions serve the role of agents; they are non-linear in the sense that they only perform their actions when their conditions are precisely matched. Productions interact with one another via their manipulation of working memory. Production systems are powerful in the sense that small numbers of productions are capable of producing sophisticated behaviour. Production systems are surprising because working memory’s stigmergic control of productions make it impossible to predict what a complete system will do without actually running a simulation.

Consider now that human intelligence might result from a society of mind that is not limited to the sense–think–act cycle of classical cognitive science (Pfeifer & Scheier, 1999). At least some of cognition is likely scaffolded (Clark, 1997; Hutchins, 1995; Wilson, 2004) and involves sense–act processes. In this view, some of the mind has leaked into the world, and the world can be directly accessed so that computational resources are not used to build internal representations of it (Brooks, 1999).

In embodied cognitive science, the environment is part of intelligence (Varela et al., 1991). Problem solving occurs by seeking solutions in actions on the world. This is exploited when, for example, children learn about geometry by programming a LOGO Turtle (Papert, 1980, 1993). “To solve the problem look for something like it that you already understand. The advice is abstract; Turtle geometry turns it into a concrete, procedural principle: Play Turtle. Do it yourself. In Turtle work an almost inexhaustible source of ‘similar situations’ is available because we draw on our own behavior, our own bodies” (Papert, 1980, p. 64). Again, this idea is not new. For instance, we have seen that the developmental theories of Piaget and Vygotsky recognize that thinking develops from action on the world.

The importance of the embodied view is its increased emphasis on the environment, which seems missing from the classical sense–think–act
cycle. Embodied cognitive science recognizes that complex behaviour can result when a cognitive system interacts with its environment, as typified by the parable of the ant (Simon, 1969).

This view that intelligence is the product of an embodied society of mind suggests that thinking is bricolage. Available are a set of primitive operations, some sense–think–act and others sense–act, which can be drawn upon to solve information-processing problems as they arise. Learning to think becomes learning to choose what operations to use at any given time. This in turn may depend upon internally represented goals, or upon externally present stimuli or aids. “The process reminds one of tinkering; learning consists of building up a set of materials and tools that one can handle and manipulate. Perhaps most central of all, it is a process of working with what you’ve got” (Papert, 1980, p. 173).

3.19.2 Method

If intelligence is the product of an embodied society of mind, if cognizing systems are bricoleurs, then how should cognitive science proceed? One promising approach is for researchers to think like the systems that they study—to become bricoleurs themselves. The synthetic approach, which assembles available elements into embodied agents whose surprising behaviour exceeds what might be expected of their simple components, is an example of a cognitive science that depends upon ‘tinkering’.

3.20 SYNTHESIS AS PROCESS, NOT AS DESIGN

3.20.1 Synthesis Is Not Design

Most models in classical cognitive science are derived from the analysis of existing behavioural measurements (Dawson, 2004). In contrast, models created using the synthetic approach involve making some assumptions about primitive capacities, building these capacities into working systems, and observing the behaviours that result. In synthetic psychology, model construction precedes behavioural analysis. With the synthetic approach, “the focus of interest shifts from reproducing the results of an experiment” (Pfeiffer & Scheier, 1999, p. 22).

What does the focus of interest shift to when the synthetic methodology is employed? Pfeiffer and Scheier (1999) argue that a key element of synthetic psychology is design. “What we are asking is how we would design a system that behaves in a particular way that we find interesting” (p. 30). However, this design perspective is in conflict with the spirit of synthetic psychology. This is because if one designs a system with particular goal behaviours in mind, then one might be blind to interesting unintended behaviours that the system produces.
A former student’s project in a robot-building course illustrates the problems with synthesis as design. She built two Braitenberg Vehicle 2s (Braitenberg, 1984) from LEGO components, as will be described in detail in the next chapter. These robots can produce behaviour in which they move toward light. Her design goal was to mount a light on the back of one of these robots in order to cause the other robot to follow it closely. That is, her desire was to create a “robot convoy.”

However, this goal proved difficult to achieve. The behaviour that she desired (i.e., following) was never produced. As a result, she crafted new lighting systems, powered by battery packs that she created herself, to create more potent stimuli for one of the robots to follow. This engineering did not produce the desired result either, and this student became very frustrated.

However, when others watched her machines in action at this point, they saw complicated interactions between robots that were clearly affected by the mounted lights, but which were quite different from the (intended) following behaviour. It was only when an outside observer—not committed to her design perspective—pointed out these interesting emergent behaviours that the student was able to break free from the constraints of her design, and document the robot behaviour that she definitely did not intend.

The synthetic approach, when dominated by design, is analogous to the serialist reaction to Austro-German music (see Chapter 2). In this musical example, one rigid set of rules was replaced with a different set that was no less rigid. Conducting synthetic psychology with design in mind is no different than using analytic models to reproduce experimental results. That is, both modelling approaches evaluate the quality of the model in terms of its ability to meet predefined criteria (e.g., fit extant data, or accomplish a design’s objective).

3.20.2 Synthesis as Process

Synthetic psychology might better be conducted in a fashion analogous to the minimalist reaction to both Austro-German and serialist music. Recall from Chapter 2 composer Steve Reich’s notion of choosing musical processes, and then setting them in motion. In this musical approach, Reich was content to let the resulting composition run itself. As a result, he was able to experience auditory effects that emerged from the processes from which the composition was constructed. This approach was successful because of the care that Reich and other minimalists took to choose the musical processes in the first place. Rather than begin with an overarching design, synthetic psychologists should begin with
a carefully selected set of processes (e.g., agents in a society of mind),
set them in motion, and be open to the surprising behaviours that are
most certain to emerge.

3.21 BUILDING BRICOLEURS

3.21.1 Cartesian Alternatives

There is a deep Cartesian bias underlying most of modern cognitive sci-
ence (Devlin, 1996). Descartes’ dualism now exists as the distinction be-
tween the internal self and the external world, a distinction that agrees
with our everyday experience. However, some have argued that our notion
of a holistic internal self is illusory (Clark, 2003; Dennett, 1991, 2005;
Minsky, 1985, 2006; Varela et al., 1991). “We are, in short, in the grip of a
seductive but quite untenable illusion: the illusion that the mechanisms
of mind and self can ultimately unfold only on some privileged stage
marked out by the good old-fashioned skin-bag” (Clark, 2003, p. 27).

For researchers, the frame of reference problem is one consequence
of not challenging this illusion (Pfeifer & Scheier, 1999). Our Cartesian
bias, coupled with traditional analytic methodologies, causes us to ig-
nore the parable of the ant (Simon, 1969), to assign too little credit to
the world, and to assign too much credit to internal processes.

Classical cognitive science views thought as the rational, goal-driven
manipulation of symbols by a mind that can be studied as an abstract,
disembodied entity. New approaches in cognitive science react against
this Cartesian-rooted position. Embodied cognitive scientists comfortably
view thought as bricolage involving a collection of non-linear processes
that have leaked outside of the “skin-bag” into the world.

This alternative view has led to methodologies that replace analysis
with synthesis. Systems are first constructed from collections of non-
linear components, and are then situated in an interesting world (Brait-
enberg, 1984). Do unexpected behaviours arise when simple agents are
in a world that they can sense and manipulate?

3.21.2 Students as Bricoleurs

If seasoned researchers frequently face the frame of reference problem,
then imagine the challenge facing students who are beginning to learn
about embodied cognitive science. Everyday experience provides con-
vincing support for our self-concept, and our brains are so proficient
at exploiting the world that we are often unaware of scaffolding. Clark
(2003, p. 48) asks “how can we alter and control that of which we are
completely unaware?” Further to this, how can we teach students about
a view of mind that they may not naturally experience?
One approach would be to merely tell students about this view. Clark (2003, p. 33), however, is of the opinion that this will not suffice: “We cannot understand what is special and distinctively powerful about human thought and reason by simply paying lip service to the importance of the web of surrounding structure. Instead, we need to understand in detail how brains like ours dovetail their problem-solving activities to these additional resources, and how the larger systems thus created operate, change, and evolve.” Our view in the current book is that to “understand in detail” is to experience.

One can provide hands-on experience of embodied cognitive science. Tools such as LEGO Mindstorms enable students to build simple robotic agents, situate them in manipulable environments, and observe the surprising results. Such agents provide concrete examples of scaffolding and the perils of the frame of reference problem. Robot design and exploration also provides first-hand experience of bricolage: students use the materials at hand to build robots and their environments.

The next few chapters provide some examples of robot projects that have been used to allow students to experience embodied cognitive science. They provide theoretical and historical contexts, as well as detailed instructions for construction. For those readers not able or not inclined to build these machines, the following chapters also provide example videos of robot behaviour that illustrate key themes. However, consistent with Vico’s verum-factum principle, building and exploring the projects that follow is much more rewarding than merely reading about them.