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Production Systems in Cognitive Psychology

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Abstract

A *production system* consists of a collection of if-then rules that together form an information-processing, computer simulation model of some cognitive task, or range of tasks. A production system operates by means of a recognise-act cycle, in which the rule whose condition part is satisfied is identified, and its actions taken. Production systems have special properties that make them highly suited to modelling cognition, including their combination of parallel and serial processing, the independence of their rules, and their flexible control. From their origins as models of problem solving, production systems have grown to become a major formalism for modelling cognitive skill and aspects of learning, in areas such written arithmetic, reading, and knowledge-intensive areas of expertise such as chess playing and medical diagnosis. Production systems lend themselves well to the modelling of learning and cognitive development. Since the 1990s, they have become increasingly identified with the topic of integrated cognitive architectures.

3.13.159 Production Systems in Cognitive Psychology

A *production system* consists of a collection of if-then rules that together form an information-processing model of some cognitive task, or range of tasks. Production systems have some special properties that make them highly suited to modelling cognition. From their origins as models of problem solving, production systems have grown to become a major formalism for modelling cognitive skill and aspects of learning. Since the 1990s, they have become increasingly identified with the topic of integrated cognitive architectures.

1. What is a Production System?

A production system is a model of cognitive processing, consisting of a collection of rules (called *production rules*, or just *productions*). Each rule has two parts: a *condition* part and an *action* part. The meaning of the rule is that when the condition holds true, then the action is taken. The basic idea is best illustrated with a non-psychological example. Consider the following simple production system, with just two rules, describing the behaviour of a thermostat in controlling a heating system:

Rule1: if temperature < 20°C turn-on heating.

Rule2: if temperature > 20°C turn-off heating.

When the room temperature is below 20°C, the condition part of Rule1 is true, so the thermostat takes the action specified by the rule and turns on the heating. (The rule is said to *fire*.) When the temperature is above 20°C, Rule2 similarly fires and turns off the heating. Taken together, the two rules specify a process which describes the behaviour of the thermostat.

A production system serving as a cognitive model usually has many more than two rules, perhaps as many as thousands. The production system operates in a cyclic fashion.

First, a rule whose conditions are satisfied is identified. Then, that rule is fired, i.e., its action or actions are carried out. Usually, the actions will change the current situation in some way, so that now a different rule has its conditions satisfied, and the cycle repeats. This process is referred to as the *recognise-act cycle*, because the condition parts of the rules can be regarded as forming an active network which monitors the current situation and recognises when each individual rule is applicable, triggering the act of firing the rule.

1.1 Production System Architecture

A particular production system operates within a definite structure of memories and processes known as its *architecture*. (For clarification of the term 'architecture' used in that sense, see *Architectures of Cognition*). The architecture of a production system includes at least two memories: the *production memory*, and the *data memory*.

The production memory holds the rules. It is taken to be a long-term memory, in that its contents persist over time. Indeed, usually it is assumed that a production rule, once acquired, is never lost from memory.

The data memory holds the dynamic information about the task being worked on. (In the research literature, this memory is often described as the 'working memory', but we avoid that terminology because of the possible confusion with the psychological notion of working memory, with which it has a close but not straightforward relationship — see *Working Memory, Psychology of.*) The data memory is taken to be a short-term memory whose contents disappear with time, indeed possibly during the processing of a task. It holds the information which is tested by the condition part of production rules. In other words, the conditions of production rules consist of tests or patterns which are matched against the contents of the data memory.

1.2 Conflict Resolution

In a production system with more than a small number of rules, it is almost inevitable that sometimes more than one production rule has its conditions satisfied. Such an occurrence is known as *conflict*. Some production system architectures simply fire, in parallel, all the rules whose conditions are satisfied. Most architectures, however, insist that a single rule be chosen to fire.

The procedure for selecting a single rule to fire from those that have their conditions satisfied, is known as *conflict resolution*. Different production system architectures use different principles for conflict resolution, which take account of factors such as the recency of the data being matched against, the activation levels of the data, the complexity of the rule conditions, the order in which rules were acquired, and so on.

2. Origins in Problem Solving

Production systems were introduced into psychology by Newell and Simon (1972) in their study of human problem solving. There is a natural connection between production systems and the way that Newell and Simon analyse their data.

Newell and Simon (1972) recorded participants thinking aloud as they solved puzzles in logic, chess, or cryptarithmetic (where digits have to be substituted systematically for letters to make a correct arithmetic problem). Such recordings are known as *verbal protocols* (see *Protocol Analysis, in Psychology*). Newell and Simon use the protocols to reconstruct the problem-solving steps taken by the participant. They then look for regularities in the participant's behaviour. If, for example, whenever the participant assigns a digit to a letter, he then scans for another place where the letter is used, it is natural to express that regularity in the form of a production-like rule: "*if* digit newly assigned to letter, *then* scan for occurrence of letter". With some further attention to detail, a collection of such rules can be treated as a production system, and it then becomes an empirical question as to how well the production system models the participant's problem solving.

3. Properties of Production Systems

A production system specifies a computational process, and is therefore a kind of programming language. However, production systems differ from ordinary computer programming languages in a number of ways:

(a) *Parallel and Serial Processing.* Production systems exhibit aspects of both parallel and serial processing, corresponding to the two phases of the recognise-act cycle. The recognise phase, i.e. the testing of conditions, occurs in parallel, across possibly hundreds of thousands of rules. In the act phase, a single rule is chosen for firing, so the actions are carried out one at a time.

(b) *Independence of the Rules*. Each rule in a production system is potentially independent of all the other rules. Each rule can be written to be self-contained, expressing an item of knowledge which the problem solver is postulated to know.

(c) *Interruptible and Flexible Control.* A production system is not forced to follow a fixed control structure, such as a rigid hierarchy of routines and subroutines. Because the processing at each step is determined by what the rule conditions “recognise” in the data memory, the control can be very flexible. For the same reason, it is interruptible. If relevant information appears in the data memory, the production system can abandon its current line of processing and follow a new one.

These and other properties make production systems well suited to the modelling of cognitive performance and cognitive skill.

4. Models of Cognitive Skill

Production systems have been written to model many different cognitive skills. Although although only a few researchers have actually written production system models, their influence, as with other forms of computer modelling, has been far beyond their number. Production systems have now become a medium of choice for theorizing about cognitive skill, especially for skills requiring a large body of knowledge. This section summarises just a small sample of the published work.

4.1 Written Subtraction

A model of errors in children's written, multi-column subtraction illustrates how some of the properties of production systems support their application as cognitive models. Young and O'Shea (1981) present a simple production system, of around a dozen rules, for performing subtraction correctly. They proceed to show how small perturbations of the model reproduce many of the errors commonly found in 10- to 12-year-olds' performance.

Several of the most common errors arise by simply omitting one or more rules from the production system. For example, if the rule is omitted which initiates borrowing when the lower digit is larger than the upper, then the model never borrows but instead just subtracts the smaller from the larger digit in each column — a mistake common among children. The implication is that some children have failed to acquire the appropriate rule. Other errors arise by adding erroneous rules, or erroneous versions of rules, to the production system. For example, children who usually subtract correctly but simply copy the lower digit when subtracting from zero can be modelled by adding the corresponding zero-pattern rule to the production system. Although inappropriate for subtraction, that rule is appropriate for addition, suggesting that some children have not acquired sufficiently distinctive conditions for the rule.

The ability to add and remove rules in this fashion and still leave a model which runs and faithfully reflects children's behaviour, depends critically upon several of the properties of production systems mentioned above. In the paper, the authors discuss the crucial role of the independence of the rules, of the flexible control structure, and of the particular conflict-resolution principles used in the model.

4.2 Reading

Reading is another practically important cognitive skill which has been modelled with production systems. Just and Carpenter (1987) present an ambitious model of the reading and comprehension of single sentences and connected text. Their production system provides an integrated model of the cognitive processes involved in reading, from word encoding and lexical access, through syntax and semantics, to textual understanding. Many aspects of the model are based upon data from participants' eye movements (see *Eye Movement in Reading*).

4.3 Knowledge-Intensive Cognitive Skill

Production systems are well suited to building models which encode and deploy large amounts of knowledge. For this reason, they are frequently used in the construction of *expert systems*, a branch of applied Artificial Intelligence which developed in the 1970s at around the same time as production sytems were making their appearance in psychology (see *Expert Systems*). On the same grounds, production systems are much used in psychological models of expert skill, such as medical diagnosis, chess playing (see *Chess Expertise*), and many other domains of knowledge.

5. Learning and Development

The ability to add rules to a production system, mentioned in Sect. 4.1 in the context of subtraction, raises the possibility of modelling certain aspects of learning and cognitive development by "growing" a production system, one rule at a time, to correspond to the gradual acquisition of a cognitive skill. Some of the earliest applications of production systems were in the field of learning and development (see Klahr et al. 1987). It continues to be an active area of research. Simon and Halford (1995), for example, report on several computational models of the mechanisms of developmental transition, among which production systems figure prominently.

6. The Emergence of Cognitive Architectures

Since the 1990s, production systems have become increasingly identified with the newly emerging topic of integrated cognitive architectures, of which the main exemplars are Soar (Newell 1990) and ACT (Anderson and Lebiere 1998) (see *Architectures of Cognition; Cognitive Theory, Soar; Cognitive Theory, ACT*).

The primary advantage of locating a production system within a broader, more encompassing theory is that the architectural details of the production system are determined in a principled way, and fixed. In consequence, the architecture of the production system becomes theory-laden, no longer serving just as a convenient and expressive notation but also carrying part of the burden of explanation. This removes extraneous degrees of freedom from the modeller, thereby leading to stronger explanations and theories.

See also: Artificial Intelligence, in Cognitive Science.

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