Micro-Level Hybridization in the Cognitive Architecture DUAL

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1. Introduction

After a long and exhausting war between the representatives of the symbolic and connectionist approaches (this war stimulated, however, the clarification of the limitations and advantages of both approaches) a growing group of peace-makers emerged who tried to integrate the advantages of both approaches and to fill in the gap between them (Hendler, 1989a, Hinton, 1990, Barnden & Pollack, 1991, Thornton, 1991, Sun & Bookman, 1992, 1994, Dinsmore, 1992, Holyoak & Barnden, 1994). However, a mini-war started between the peace-makers themselves on the issue how to sign the peace treaty: with the surrender of one of the approaches or with their parity. Some researchers supported the connectionist-to-the-top view that symbol structures and symbol processing should emerge from the work of a neural network (called a unified approach in chapters 2 and 4 of this volume and connectionist symbol processing in (Pollack, 1990, Smolensky, 1990, Touretzky, 1990, Smolensky et al., 1992, Smolensky, 1995)), while others supported the synergistic hybrid approach bringing together connectionist and symbolic machines in a single system or model (Hendler, 1989b, 1991, Lange & Dyer, 1989, Sun, 1992). Strange enough no one suggested to build up connectionist systems on the top of a symbolic system.

The former approach is called *vertical integration* in this chapter as it is based on the clear philosophical view that symbols and symbol processing are a macro-level description of what is considered as a connectionist system at the micro level (like the relationships between Newtonian Mechanics and Quantum Mechanics, or between Thermodynamics and Statistical Physics). This approach has the shortcoming of losing some of the advantages of the connectionist approach (e.g. its dynamic properties) when using it for symbol processing.

The latter approach (the hybrid one) is called *horizontal integration* in this chapter as it considers the symbolic and connectionist approaches as being at the same level of description and combines elements of different approaches or systems built up within different paradigms (e.g. a connectionist system performing learning and perception and a symbolic system performing reasoning) in order to use the advantages of both approaches. This approach has, however, no clear and unified philosophy and is often criticized as being eclectic. It needs a general philosophy and a first step in this direction is presented in the next section.

Theoretically there might exist a third approach to integration which is called a *unifying approach* in this chapter (which is, however, different from the unified approach in chapters 2 and 4 referred to here as vertical integration). An approach is called unifying one if it is more general than both the connectionist and symbolic approaches and they can be considered as particular cases of it. One such candidate will be discussed in this chapter.

On the other hand the vertical and horizontal integration approaches might be viewed as complementary and a meta-level integration of these approaches is also possible. Thus Sun (1995) suggests a hybrid approach implemented as a "pure" connectionist system using both local and distributed representations. The meta-level integration possibilities will be discussed further on the example of the architecture described in this chapter.

2. The Micro-Level Hybridization Approach

The author of this chapter considers the symbolic and the connectionist approaches as equally important and equally contributing to the understanding of human cognition. Moreover, he shares the view that no single formal approach can completely describe human cognitive processes, as they are complex enough, and this is the main reason for building hybrid models of human cognition.

The symbolic approach is a discrete one while the connectionist approach is a continuous one and that is why they can be considered as complementary formal descriptions each capturing different aspects of human cognition. (Similarly the light has been described both as a particle and a wave).

Many aspects of human cognition are better described by the symbolic approach while many others – by the connectionist one (ref. chapters 2 and 4). Here only two very important characteristics of human cognition will be stressed. These are often underestimated but are considered as basic features in the DUAL approach.

- The ability to categorize and to describe portions of the continuous world around us as separate entities and relations between them. The symbolic approach is best suitable for modeling this aspect – it describes human knowledge of the world as a system of discrete symbolic structures and human cognitive processes as processes of building and manipulation of such structures;

- The dynamic properties of all cognitive processes which are characterized by continuous and smooth changes of the mental state following both the internal dynamics of the cognitive system itself and the external dynamics of the continuously changing environment – these properties are best handled by the connectionist approach.

These two features are, however, characteristics of *every* cognitive process and therefore instead of having two or more subsystems each designed according to one of the approaches these characteristics are needed at the micro level so that every macro-level cognitive process can benefit from them. In this way a new idea emerged – to have a DUAListic cognitive architecture consisting of a huge number of small elements (called micro-agents) each of them being hybrid, i.e. consisting of a symbolic and a connectionist part. *In other words instead of hybridization at the macro level a hybridization at the micro level is being proposed.* One important characteristic of all the possible architectures of that kind is that they will produce *emergent computation* reflecting the collective behavior of all micro-agents.

In short, the micro-level hybridization approach is a particular type of horizontal integration which follows the general philosophy that *it is a matter of principle to use two different and complementary formalisms (a discrete and a continuous one) for describing and explaining human cognition* and which integrates symbolic and connectionist mechanisms in modeling *every* cognitive process and therefore it is crucial to ground the hybridization on the micro level.

Now coming back to the possibility of building a unifying approach it seems that the micro-level hybridization approach can also be considered as a first approximation of such a unifying approach. Varying the proportions of symbolic and connectionist processing capabilities of the micro-agents a whole spectrum of hybrid models will arise. In the particular case of micro-agents having only connectionist parts – a purely connectionist system will emerge, while in the particular case of micro-agents having only symbolic parts – a purely symbolic system will emerge. Neural nets are examples of the first class, while cellular automata and classifier systems – of the second type. It is also clear that there is a continuum of possibilities differing in the balance of the symbolic and the connectionist abilities the micro-agents have. Actually, the micro-agents in different models may differ drastically in their symbolic capabilities – starting with simple micro-agents performing only marker passing, going through micro-agents being able to perform some specialized (and possibly complex) procedures and ending with micro-agents being universal Turing machines.

3. The DUAL Cognitive Architecture

The DUAL cognitive architecture (Kokinov, 1994b, c) is one particular example of the micro-level hybridization approach that has been developed and implemented as a generalization of and a common basis for various models of particular cognitive processes: memory (Kokinov, 1989), similarity judgments (Kokinov, 1992), word-sense disambiguation (Kokinov, 1993), and analogical reasoning (Kokinov, 1994a).

DUAL micro-agents consist of a connectionist part (*c-component*) which computes the continuous dynamic changes of the activation levels of the micro-agents and of a symbolic part (*s-component*) which is able to perform local marker-passing and some specialized symbolic procedures. From the symbolic perspective the micro-agents represent various concepts, objects, events, situations, facts, rules, plans, actions, etc. They might represent static facts as well as built-in procedural knowledge. A frame-like representation scheme is used. The connectionist aspect of DUAL is used for representing context (Kokinov, 1994a, 1994c, 1995). Context is represented in a distributed way by the relevance factors of all micro-agents to the current situation. The associative relevance (the degree of connectivity of the particular element with all other elements of the current situation) is used as a measure of relevance. It is represented by the activation level of the corresponding micro-agent. Thus the activation level of the micro-agent within the connectionist aspect represents the relevance of the knowledge represented by the micro-agent within the symbolic aspect.

The micro-agents representing entities being perceived at the moment as well as micro-agents representing current goals of the cognitive system are called *source nodes* and have a constant level of activation for the period of time they are on the input or goal list. There is a relatively slow decay process so that all currently active nodes can be considered as sources of activation for a period of time. In this way the micro-agents with a high level of activation correspond to descriptions tightly connected both with the perceived and memory-activated elements, i.e. they represent elements of the context with a graded degree of membership.

A cognitive system built on the DUAL cognitive architecture consists of a large number of simple and highly interconnected micro-agents, each of them performing a specific task and/or representing some specific declarative knowledge. The micro-agents are connected with each other – some of the links are permanent, while others are dynamically created and removed by the micro-agents themselves. Each micro-agent exchanges information only with its neighbors. The behavior of the whole system emerges from the collective behavior of the micro-agents that work in parallel. At each particular moment only some of the micro-agents are active and only they can contribute to the computation. Moreover, every micro-agent acts at its own rate that depends on its activation level. In this way even faced with the same problem at the macro level, the cognitive system will behave differently in different contexts as the activity distribution will be different due to the differences in the perception-induced context (the objects perceived from the environment) and in the memory-induced context (the concepts being active in the preceding memory state). That is, at different occasions different groups of micro-agents with different activity distribution will act together to perform the computation and consequently different behavior will emerge.

The differences in the behavior due to differences in the perception-induced context (reflecting differences in the environment) are called context effects, while the differences in the behavior due to differences in the memory-induced context (reflecting differences in the preliminary setting of the cognitive system) are called priming effects. Both the perception-induced and memory-induced contexts are represented in the same way – by the distribution of activation over the network of micro-agents. That is why the same mechanisms are used for explaining the context and priming effects.

Both the availability of the knowledge structures represented by the micro-agents and the rate of performing of the actions which the micro-agents are capable of are affected by the micro-agent's level of activation. Low activation level will even block both their availability for other micro-agents and their actions. Let us consider a simple example: the context-sensitive behavior of the marker-passing process. All micro-agents are capable of local marker-passing (i.e. they can pass the received markers to their immediate neighbors over specific links). However, their actual performance depends on their activation level, i.e. the rate at which the markers are passed to the micro-agent's neighbors is proportional to its activation level. In particular, the micro-agents will not pass the markers further when their activation level is below certain threshold. As a result in different contexts the markers started from the same nodes and wandering through the same network will pass along different ways, i.e. different results will be produced.

4. The AMBR Model of Analogical Reasoning

AMBR is a computer model of human analogical reasoning built up on the basis of DUAL (Kokinov, 1994a).

The simulation system models human commonsense reasoning, solving problems in the area of cooking and boiling water, eggs, etc. both in the kitchen and in the forest. The knowledge base of the simulation program contains about 300 nodes and 4,000 links. Here are some example situations related to heating water and known to the system from beforehand: A) successfully heating water in a pot on the plate of a cooking-stove, B) failing to heat water on the fire in a wooden vessel, and C) successfully heating water by means of an immersion heater in a glass.

A simplified version of a target problem used in a psychological experiment has been used as a target problem in the simulation: *how can you heat water in a wooden vessel when you are in a forest, having only a knife, a match-box and an axe.* The problem is represented in the following way: the reasoner should look for a situation in which the water is in a wooden vessel and which will cause another situation in which the water will be hot and will still be in the wooden vessel.

The system runs continuously and so its memory is always in some particular memory state when a manually encoded representation of the target problem is presented to it and the corresponding memory structures are being activated, simulating the process of problem perception. In this way both the preliminary distribution of activation in working memory and the activation arising from the perception process are responsible for the resulting memory state which on its turn determines the results of the retrieval, mapping and transfer processes. The retrieval, mapping and transfer processes are emergent processes, they emerge from the collective behavior of the many active micro-agents in the DUAL architecture. Thus, for example, the mapping process involves an emergent subprocess of semantic similarity judgment which is performed by the distributed marker-passing processes described in the previous section. All these processes depend on the distribution of activation which changes continuously and in this way become context-sensitive.

The simulation experiment consists of several runs of the program in slightly different conditions varying the additional input nodes (corresponding to additionally perceived casual objects from the environment) and the distribution of activation at the initial moment (corresponding to different preliminary settings). It has been demonstrated that the behavior of the system varies with the variations of the context in accordance with the psychological data. For example, typically the system finds situation A as a base for analogy and fails in solving the problem (the same happens to most subjects in psychological experiments); with some priming (preactivation of the concept of immersion heater) the system finds the situation C as a base for analogy and finds a solution of the problem (putting a hot knife in the water); and in simulating the perception of a stone during the problem solving process (putting the concept of a stone on the input list) the system finds a different solution (using a hot stone instead of a hot knife).

The simulation system has demonstrated both AMBR's capability of analogical problem solving and its ability to produce priming effects in accordance with the data produced in psychological experiments. The simulation experiments have made also a prediction about some specific context effects (the perception of a stone will increase the probability for generation of a solution involving stone although the concept of a stone is not explicitly mentioned in the problem’s description).

5. Cognitive Rationale and Psychological Experiments

The basic motivation for developing DUAL and AMBR is to propose architectures and models that will reflect both human ability to perform specific tasks (in AMBR’s case – analogical problem solving) and the dynamics of that performance.

Psychological experiments (Kokinov, 1990) have demonstrated strong priming effects on problem solving. Moreover, they have demonstrated a particular dynamics of these priming effects: the degree of that effects decreases in the course of time according to an exponential law, i.e. the memory-induced context changes in a continuous manner.

Recent experiments (Kokinov, Yoveva, 1996) have confirmed AMBR’s prediction about the context effects. Moreover, it has been demonstrated that elements from both the central and the peripheral parts of the perceived environment can cause context effect and change human behavior, however the degree of these context effects decrease from the center towards the periphery in a continuous way.

The system’s behavior is in accordance with all these findings. It is the combination of discrete symbolic abilities (like mapping of two structures and transfer of their parts) and their continuous dynamics which is reflected in DUAL and AMBR by the symbolic and connectionist aspects, respectively.

6. Summary

The basic claim of this chapter is that modeling human cognition requires at least two complementary formal descriptions: a discrete and a continuous one, reflecting two different basic properties: the ability to categorize and the dynamics of the cognitive processes. Moreover, both formalisms are needed in describing each particular cognitive process. For this reason a micro-level hybridization approach has been proposed. The basic idea is that cognitive processes emerge from the collective behavior of a great number of micro-agents each of them being hybrid (having a symbolic and a connectionist component). The DUAL cognitive architecture is one particular example developed within the micro-level hybridization approach. Several cognitive models have been built up on the basis of this architecture. They were able to reproduce some patterns of human behavior, including its dynamics and context-sensitivity.

The micro-level hybridization approach is considered also as a way of unifying symbolic and connectionist processing. This approach can also be combined with connectionist symbolic processing approaches to produce “pure” connectionist system that will, however, keep dualistic representations and processing mechanisms.

Historically, John Anderson (1983) can be considered as the precursor of such type of micro-hybridization approach. However, his ACT* architecture has a central mechanism – the interpreter – and cannot be described as producing emergent computation. Moreover, the connectionist type of spreading activation is restricted only to the declarative memory.

An approach much more similar to DUAL has been proposed by (Hofstadter & Mitchell, 1994, Mitchell, 1994, Hofstadter, 1995, French, 1995). The micro-agents in Copycat and Tabletop are called “codelets” and perform simple symbolic tasks, their performance is determined by their “urgency” which a numeric value although it is not computed by a connectionist type mechanism. The declarative and procedural knowledge is, however, separated and different mechanisms are used for their activation.

Smolensky, who follows the vertical integration approach, has recently argued for integrating the symbolic and connectionist principles of processing (Smolensky et al., 1992, Smolensky, 1995) considering them as dualistic and equally important. This is, however, a direction of integration orthogonal to the one presented in the current chapter.

Moreover, in the future development of DUAL the micro-level hybridization approach can be combined with the vertical integration approach: this is the meta-level integration possibility mentioned in the introduction. The idea is to implement both the connectionist and the symbolic parts of the micro-agents by neural networks but keeping the properties of both parts different – the ability for structure representation (e.g. Smolensky’s tensor product representation) and the ability for continuous dynamic change of context. Activation (which might be the same physical variable) is used for two different purposes in both cases – for representation and for relevance, respectively. To keep this difference between the representation and the dynamic parts of the micro-agents seems important according to the general philosophy of horizontal integration approach proposed in this chapter.

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