Neurosymbolic Integration: The Knowledge Level Approach

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Abstract. The time when the connectionist and symbolic perspectives of Artificial Intelligence (AI) competed against each other is now over. The rivalry was due essentially to ignorance on the implications of the knowledge level, as introduced by Newell and Marr. Now it is generally accepted that they are different and complementary forms of modeling and operationalizing the inferences in terms of which a problem solving method (PSM) decomposes a task. All these tasks, methods, inferences, and formal operators belong to a broad library of reusable components for knowledge modeling. The final configuration of a problem solving method, with symbolic and connectionist components, is only dependent on the particular balance between data and knowledge available for the specific application under consideration. Various approaches have been explored for neurosymbolic integration. In this paper we propose a classification of these approaches (unified, hybrid and system level) and strongly support that the integration has to be made at the knowledge level and in the domain of the external observer (the "house" of models).

1 Historical Perspective and Problem Statement

The purpose of knowledge engineering, the applied part of Artificial Intelligence (AI), is to build computable models of non-analytical human knowledge using symbolic, connectionist or hybrid PSMs. Analytical knowledge is dealt with by other branches of computation. Starting from the identification and preliminary analysis of the problem to be solved, the subsequent phases are: (1) knowledge modeling at the knowledge level and in the external observer domain (EOD), (2) operationalization of the inferences generated by the PSM used to decompose the task (still at the knowledge level, but now in the domain proper of the formal tools used), the own domain (OD), and (3) implementation of the formal counterpart of the model, passing from the knowledge level to the symbol level (the program), were both types of inferences end up being numeric.

In the development of these three phases there are two paradigms, which constitute two ways of modeling, operationalizing and programming the solution of a task [9]:

1. Symbolic computation, thick “grain” and programmable in a declarative manner.
2. Connectionist computation, small “grain” and partially “self-programmable” through learning. Here, a part of the knowledge is preprogrammed in the net structure itself. The rest of the knowledge is obtained by the net when trained with labeled data.

At the end, at the level of electronic processors, all computation is neither symbolic nor connectionist but numeric. Symbolism and connectionism are born in the domain of the external observer (the knowledge engineer) when nouns (concepts) and inferential verbs are associated to data structure and to the processes that handle them using precompiled semantic tables. That is to say, the difference between number (“labeled line”) and message appears in the domain of the human when we assign meaning to the entities of the input and output spaces, both being spaces of representation. Consequently, it is here, at the knowledge level and in the modeling and operationalization phases where the integration has to be made.

Knowledge modeling and operationalization started being connectionist with the pioneer works of W.S. McCulloch and W. Pitts [8], when in 1943 they introduced the first formal model, which we would today call minimal sequential circuit. This work constitutes the beginning of the connectionist approach to knowledge modeling and cognition. Much more recently this perspective has been integrated with the so called “situated cognition” [1] where more emphasis is put on the mechanisms underlying perception, decision-making and action control by means of feedback mechanisms than in the representational perspective of knowledge modeling. That is to say, in connectionism we look for nets of adaptive processors capable of solving problems (recognizing characters, inferring in a distributed manner) and learning by reinforcement and self-organization. In current terms we would say that this approach looks for PSM close to the physical (physiology or hardware) level, where structure and function coincide. It is at the source of distributed AI and it uses logic and analytics as the way to represent knowledge, a part of which is distributed in the net connections. The Hebb conjecture on the associative character of learning and the analogical models of Rosenblatt (perceptron and δ rule), Widrow-Hoff (Adalines and RMS rule), as well as some other proposals from Kohonen (associative memory and self-organizing feature maps) completed the panorama of the neurocybernetic stage of connectionist modeling [3].

Following this neurocybernetic precedent, the year 1956 is usually considered the year of the birth of the symbolic perspective of AI that in the first period (1956-1970) focused on problems characteristic of formal domains. In the mid-sixties, gradual changes took place in the symbolic perspective of AI, bringing them closer to the problems of real world and attributing increasing importance to the specific knowledge of the domain and, consequently, to the problems associated with its representation in terms of a “set of symbols” and subsequent use of these symbols in “reasoning”, without any reference to the neurophysiology and the mechanisms from which this knowledge emerges. This perspective gave rise to the “symbolic stage” (1970-1986) during which the emphasis was on technical tasks in narrow domains and programs to solve these tasks (“knowledge based systems” or “expert systems”). Knowledge modeling in the symbolic perspective is descriptive (facts plus rules) and different to the embodied character of connectionism.

Around 1986 there is a strong rebirth of connectionism, first as a competitive alternative to symbolic AI and then as a set of alternative or complementary methods