Human Discovery and Machine Learning

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ABSTRACT

This article studies machine learning paradigms from the point of view of human cognition. Indeed, conceptions in both machine learning and human learning evolved from a passive to an active conception of learning. Our objective is to provide an interaction protocol suited to both humans and machines to enable assisting human discoveries by learning machines. We identify the limitations of common machine learning paradigms in the context of scientific discovery, and we propose an extension inspired by game theory and multiagent systems. We present individual cognitive aspects of this protocol as well as social considerations, and we relate encouraging results concerning a game implementing it.

Keywords: discovery science; Eleusis+Nobel; epistemology; logic; machine learning

INTRODUCTION

The processes involved in scientific discovery such as acquiring knowledge and organizing it within general representations, and the discovery of new facts and theories through observation and experimentation can be seen as those of problem solving (Langley, Simon, Bradshaw, & Zytkow, 1987). Since the inception of artificial intelligence, researchers have aimed at endowing machines with such abilities. Computational scientific discovery became an active field of research when machine learning techniques started showing conclusive results in the late ’70s. These results motivated the simulation of historical discoveries (Langley, Bradshaw, & Simon, 1981; Langley et al., 1987; Lenat, 1983), and since the beginning of the 21st century, research in this domain has been oriented toward the discovery of unknown rules (Simon, Valdés-Pérez, & Sleeman, 1997). Langley (1998) and Langley (2000) provide examples of such discoveries assisted by machines.

Our work follows this line of research, but we place the user at the heart of the system to build interactively with an adaptive problem solver an adequate description model of the studied phenomena: The machine learns at the same time as the user, and this colearning leads to a pertinent understanding of the problem and a pertinent modeling for simulation and predic-
tion. During this interaction, the user acts in turn as a learner or as a teacher. However, instead of focusing on isolated problem solvers and their capabilities, our contribution lies in the definition of an interaction protocol encompassing both human and machine learning, resulting in a formal foundation for discovery platforms. We emphasize the fact that in machine learning as well as human learning, the role of the learner has evolved from a passive role to an active one.

In common machine learning formalizations, a learner can query an oracle to gather data concerning the target function to be learned. This is often unrealistic as the oracle usually needs to be endowed with capabilities that go beyond the power of a universal Turing machine. In the particular context of scientific discovery, where studied problems are not yet solved, no model or theory might be available and a software assistant has to cope in this context with uncertainty, pattern discovery, interactive ontology building (Nobrega, Cerri, & Sallantin, 2003), and so forth. Moreover, to interact with a researcher, it is necessary to produce statements comprehensible to a human and emit scientific judgments about them.

This challenging objective implies a multidisciplinary approach involving logical and epistemic considerations, as well as machine learning theory and multiagent systems. This article attempts to synthesize our work in these domains. Sallantin, Dartnell, and Afshar (2006) described the minimal logical prerequisite to endow a problem solver with a pragmatic logic of scientific discovery in order to interact efficiently with a scientist. We will informally summarize these requirements in the first section. Dartnell and Sallantin (2005) reflected on machine learning paradigms that we will further develop to situate our protocol. An experimentation of this protocol, which was carried out in collaboration with researchers in epistemology and didactics, produced results that were reported in Hagège, Dartnell, and Sallantin (2007) and will also be synthesized to validate the relevance of our platform to human learning (Wang, 2003, 2007a, 2007b; Zhang, Wang, & Kinsner, 2007). We will finally explore new directions in machine learning based on cognitive aspects of the learner to introduce time as a complexity measure and provide general heuristics to help eliminate conjectures during experimentation.

**Logical Prerequisite for an Adaptive Problem Solver**

Common definitions of a problem solver take into account the type of solvable problem that characterizes it as a differential-equation problem solver or a nonlinear-equation system solver: Common problem solvers are designed to perform the computation of a known problem that has already been solved and modeled. So for any presented instantiation of a specific problem, the solver is able to tackle it and produce solutions. An adaptive and autonomous problem solver should be able to acquire new capabilities by learning how to solve new problems, and then use this knowledge and experience to find solutions. To solve a problem, one has to observe the problematic situation, analyze it, and build a language describing the situation and highlighting the dimensions that are pertinent for reasoning. These dimensions determine the definition domain of the variables characterizing the problem and influencing the computation of a solution. This language is used to formulate assumptions and hypotheses that have to be validated by experiments, and compare their results to theoretical computations. The experiments in Figure 1 can reveal contradictions between theory and reality and therefore lead to a revision of the description model and to the formulation of new hypotheses. By analogy with the process of scientific discovery, where neither the ontology nor the theory are known a priori, we define below the functionalities that an adaptive autonomous problem solver should be empowered with to define the process of discovery. It should be able to do the following:

- Build and maintain an ontology of the domain. By ontology, we mean a logical language relevant to observations describ-
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