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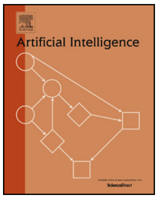

Robot task planning and explanation in open and uncertain worlds

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ABSTRACT

A long-standing goal of AI is to enable robots to plan in the face of uncertain and incomplete information, and to handle task failure intelligently. This paper shows how to achieve this. There are two central ideas. The first idea is to organize the robot's knowledge into three layers: instance knowledge at the bottom, commonsense knowledge above that, and diagnostic knowledge on top. Knowledge in a layer above can be used to modify knowledge in the layer(s) below. The second idea is that the robot should represent not just how its actions change the world, but also what it knows or believes. There are two types of knowledge effects the robot's actions can have: epistemic effects (I believe X because I saw it) and assumptions (I'll assume X to be true). By combining the knowledge layers with the models of knowledge effects, we can simultaneously solve several problems in robotics: (i) task planning and execution under uncertainty; (ii) task planning and execution in open worlds; (iii) explaining task failure; (iv) verifying those explanations. The paper describes how the ideas are implemented in a three-layer architecture on a mobile robot platform. The robot implementation was evaluated in five different experiments on object search, mapping, and room categorization.

1. Introduction

A long-standing challenge robotics poses for AI is how to act in uncertain and unfamiliar environments. As an example, imagine a robot that is switched on in an unfamiliar building, without a map, and given the task of finding a particular object. Questions that roboticists must answer include the following: *How should the robot integrate different kinds of information, such as commonsense knowledge and sensory input? How can the robot plan in the face of uncertain knowledge? How can the robot plan to achieve the task when it does not know about all the required objects and places? How can the robot deal with task failure intelligently?* This paper gives answers to all these problems, using two core ideas. The first idea is to organize knowledge into three levels, such that knowledge in a higher level enables reasoning about knowledge at lower levels. The second idea is to give the robot models of the effects of its actions on what it knows. One class of knowledge-modifying actions is assumptive actions. We show how planning with assumptions, combined with layered knowledge, solves several problems

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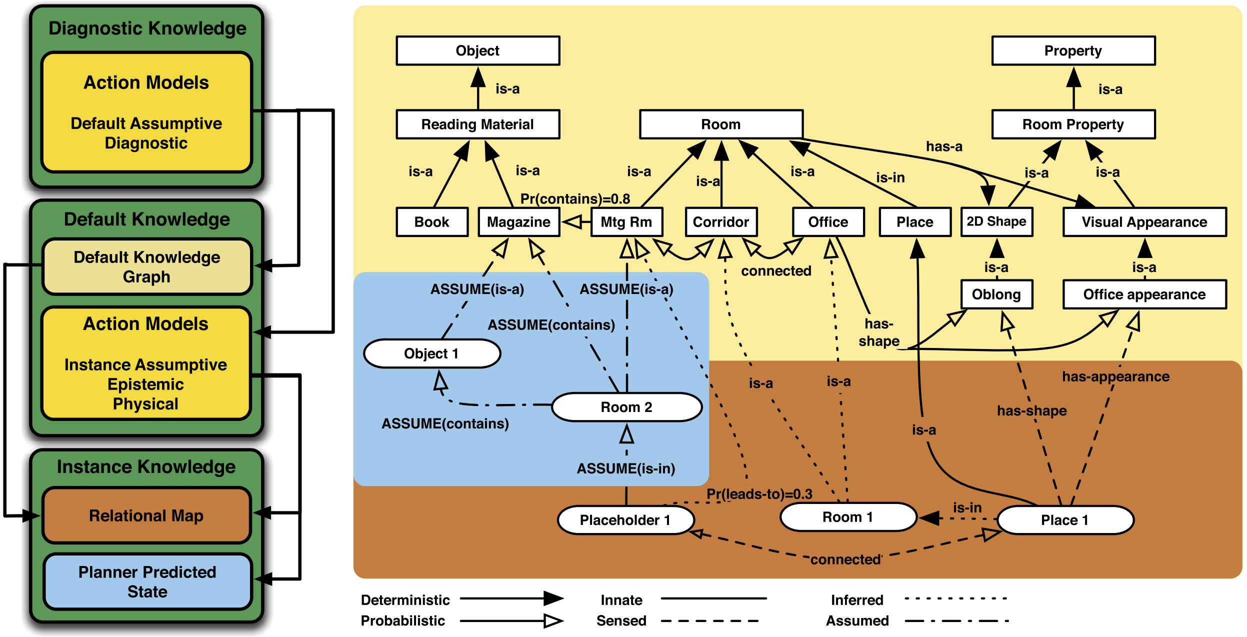

Fig. 1. **(Left)** The instance-default-diagnostic (IDD) knowledge schema, showing action models (yellow), general knowledge (cream), instance knowledge about the current state (brown), and predicted state (blue). **(Right)** Example state information in the concrete instantiation of the IDD schema used in this paper. The blue box represents possible instance knowledge assumed to be true by the planner in order to achieve the robot's goal (find a magazine). The right panel summarizes the robot's belief state at the start of the running example (see Fig. 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in AI for robotics: (i) planning and acting under uncertainty, (ii) planning and acting in open worlds, (iii) explaining task failure, and (iv) verifying explanations.

1.1. IDD—a schema for robot knowledge

We propose a three-layer organization of knowledge: *instance*, *default*, and *diagnostic* (Fig. 1). We refer to this idea using the term *IDD schema*. Knowledge at a higher level is used to modify knowledge at lower levels. Knowledge is of two types: representations of state, and representations of the effects of actions on state. The *instance layer* contains only state information, describing the current environment. This state information includes the locations and categories of specific objects, rooms, and places in the current building, the whereabouts of particular people and what they know. The *default layer* contains general knowledge about categories—for example, which types of objects are typically found in kitchens. The default layer also contains knowledge of action effects on the instance state. This could be knowledge of the physical effects of actions, such as moving the robot, or of the knowledge effects of actions, such as asking where a particular object is. These knowledge-modifying (or epistemic) actions also include the ability to make *assumptions* about the existence of specific object instances—for example, assuming that there is a dining room in a particular house. Finally, the *diagnostic layer* contains only action knowledge. First, it contains assumptive actions for creating new general knowledge—hypothesizing that cornflakes boxes can often be found in dining rooms. Second, it contains the action models from the default layer augmented with possible causes of failure—the robot could not see the cornflakes box because it was hidden inside something. These two types of diagnostic knowledge can be used in conjunction with the other knowledge layers to help explain task failure. The robot could, for example, explain that it cannot find the cornflakes box because someone put it in a cupboard that it assumes is in the dining room. This diagnostic knowledge can also be used to hypothesize new default knowledge: the robot could hypothesize that cornflakes boxes are often kept in cupboards in dining rooms. Default and diagnostic knowledge are separated to enable efficient reasoning: simpler default knowledge is used most of the time, and more complex diagnostic knowledge is used only when needed.

1.2. An instantiation of the IDD schema

The schema above could be implemented in many ways, depending on the representations chosen. In this paper, the following choices have been made (Fig. 1) for the implementation of our robot system called *"Dora"*. First, in the in-

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