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A weighted causal theory for acquiring and utilizing open knowledge

Jianmin Ji, Xiaoping Chen *

University of Science and Technology of China, Hefei, China

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ABSTRACT

Motivated by enabling intelligent robots/agents to take advantage of open-source knowledge resources to solve open-ended tasks, a weighted causal theory is introduced as the formal basis for the development of these robots/agents. The action model of a robot/agent is specified as a causal theory following McCain and Turner's nonmonotonic causal theories. New knowledge is needed when the robot/agent is given a user task that cannot be accomplished only with the action model. This problem is cast as a variant of abduction, that is, to find the most suitable set of causal rules from open-source knowledge resources, so that a plan for accomplishing the task can be computed using the action model together with the acquired knowledge. The core part of our theory is constructed based on credulous reasoning and the complexity of corresponding abductive reasoning is analyzed. The entire theory is established by adding weights to hypothetical causal rules and using them to compare competing explanations which induce causal models satisfying the task. Moreover, we sketch a model theoretic semantics for the weighted causal theory and present an algorithm for computing a weighted-abductive explanation. An application of the techniques proposed in this paper is illustrated in an example on our service robot, KeJia, in which the robot tries to acquire proper knowledge from OMICS, a large-scale open-source knowledge resource, and solve new tasks with the knowledge.

1. Introduction

McCain and Turner's causal theories [1] are devoted to be a nonmonotonic formalism for representing causal knowledge, which can be used to formalize knowledge of actions in order to enable a robot/agent to reason about changes of the environment [2]. The language of causal theories has been extended to handle multi-valued constraints [3] and enable nested expressions of causal relations [4].

Generally, one can use a causal theory to represent an action domain and specify wanted goals, where a causal model of the causal theory corresponds to a solution to achieve these goals. One problem with the approach is that frequently there exist no solutions because the action domain does not contain enough knowledge to derive these goals. To remedy this, we propose the *extended causal theories* to support the augmentation of a causal theory by gaining additional causal knowledge from open-source knowledge bases. An extended causal theory is intended to find out a subset for causal laws from open-source knowledge bases, called *knowledge gap*, to make the causal theory have a causal model and the subset be minimal (in the sense of set inclusion) w.r.t. all possible such sets of causal laws. Intuitively, one wants to add new

* Corresponding author.
E-mail addresses: jianmin@ustc.edu.cn (J. Ji), xpchen@ustc.edu.cn (X. Chen).

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causal knowledge as little as possible, because adding more would lead to an additional cost of efficiency and a higher risk of introducing irrelevant knowledge. For example, suppose a robot is required to "get food from refrigerator" and is not equipped with the knowledge of how to accomplish the task. In that case, the robot can find a suggestion from the Open Mind Indoor Common Sense (OMICS) databases [5] that "first open the refrigerator door, then take the food". After adding the corresponding knowledge to the local knowledge base of the robot, the robot would compute a solution to accomplish the task. It is better not to add other suggestions to the local knowledge base, like "find an object by first thinking where the object is likely to be" or "offering drink when one feels thirsty".

We further develop the formalization, called *weighted causal theory*, by assigning each causal law of open-source knowledge bases a (nonnegative) weight, which specifies how "special" the piece of knowledge is. For instance, an instruction for a new task only involving primitive actions of the robot is more special than an instruction for the same task involving other unprimitive tasks. The main task of a weighted causal theory is to find out a knowledge gap, called *weighted knowledge gap*, such that the knowledge gap has the minimum accumulated weight w.r.t. all other knowledge gaps. We show that the computational complexities of the most problems related to this task are hard for the second level of the polynomial hierarchy, i.e. Σ_2^P-hard. Therefore, motivated from the application of service robots in domestic environments, we identify a special sort of weighted causal theories and provide an algorithm for computing weighted knowledge gaps in polynomial time w.r.t. the size of such weighted causal theory. Later, we illustrate the proposed approach in an example on our service robot, KeJia, in which the robot tries to acquire proper knowledge from OMICS and solve new tasks with the knowledge.

Given a causal theory A and a candidate set T of causal laws, the paper considers the problem of finding a proper set $E \subseteq T$ such that $A \cup E$ has a causal model. It is similar to the problem of finding an explanation for an observation in abductive reasoning. Eiter et al. [6] provided a formalization of abductive reasoning based on default logic and analyzed the complexity of the main abductive reasoning tasks. Due to the requirements of the motivating application, our formalization is based on causal theories and weights w.r.t. candidate causal laws which need to be considered further during the reasoning. Hobbs et al. [7] proposed a formalization called "weighted abduction", which assigns a cost to each of the atoms by assigning a weight to each atom in the body of a Horn clause. Then it computes an explanation with the lowest accumulated cost for each atom in the explanation that is calculated. In weighted causal theories, weights are directly assigned to candidate causal laws. There have been many efforts that share common concerns with open knowledge [8–12]. However, to authors' knowledge, this paper is the first work on formalizing the problem based on causal theories with weights.

Section 2 reviews causal theories. Section 3 presents the formalization of extended causal theories and knowledge gaps/rehabilitations, complexity results, and a polynomial time algorithm for a special sort of extended causal theories. Section 4 extends the work by assigning weights to corresponding causal laws and also provides a polynomial time algorithm for a special sort of new causal theories. Section 5 introduces the problem of using open knowledge for service robots in the domestic environment and shows how weighted causal theories can be conveniently used to formalize the problem. Section 6 draws conclusions.

2. Causal theories

The language of causal theories [1] is based on a propositional language with two zero-place logical connectives $\top$ for tautology and $\bot$ for contradiction. We denote by *Atom* the set of atoms, and *Lit* the set of literals: $Lit = Atom \cup \{\neg a \mid a \in Atom\}$. Given a literal l, the *complement* of l, denoted by $\bar{l}$, is $\neg a$ if l is a and a if l is $\neg a$, where a is an atom. A set I of literals is called *complete* if for each atom a, exactly one of $\{a, \neg a\}$ is in I. In this paper, we identify an interpretation with a complete set of literals. Let I be an interpretation and F a propositional formula, I *satisfies* F, denoted $I \models F$, is defined as usual.

A *causal theory* is a finite set of *causal laws* of the form:

$$\phi \Rightarrow \psi, \tag{1}$$

where ϕ and ψ are propositional formulas. Intuitively, the causal law reads as "ψ is caused if ϕ is true". A causal law of the form (1) is *definite* if ψ is a literal and ϕ is a conjunction of literals. A causal theory is *definite* if all causal laws in it are definite. As a syntax sugar, a causal law with variables is viewed as the shorthand of the set of its ground instances, that is, for the result of substituting corresponding variable-free terms for variables in all possible ways.

Let T be a causal theory and I an interpretation. The *reduct* T^I of T w.r.t. I is defined as $T^I = \{\psi \mid \text{for some } \phi,\ \phi \Rightarrow \psi \in T$ and $I \models \phi\}$. T^I is a propositional theory. We say that I is a *causal model* of T if I is the unique model of T^I. A causal theory T is *consistent* if it has a causal model.

For example, let T_1 be the causal theory whose signature is $\{p, q\}$: $\{p \Rightarrow p, q \Rightarrow q, \neg q \Rightarrow \neg q\}$. Let $I_1 = \{p, q\}$, $T_1^{I_1} = \{p, q\}$ and I_1 is the unique model of $T_1^{I_1}$, then I_1 is a causal model of T_1. Let $I_2 = \{\neg p, q\}$, $T_1^{I_2} = \{q\}$, both I_1 and I_2 are models of $T_1^{I_2}$, then I_2 is not a causal model of T_1. We can see that T_1 has two causal models $\{p, q\}$ and $\{p, \neg q\}$.

For any causal theory T and a propositional formula F, we say that T *credulously entails* F, denote $T \vdash_c F$, if there exists a causal model I of T such that $I \models F$.

The credulous entailment is nonmonotonic in the sense that, after adding other causal laws a propositional formula may no longer be entailed. For example, a causal theory $T = \{p \Rightarrow p\}$, its only causal model is $\{p\}$ then $T \vdash_c p$. Let $T' = \{p \Rightarrow p, \top \Rightarrow \neg p\}$, its only causal model is $\{\neg p\}$, then $T' \vdash_c \neg p$ and $T' \nvdash_c p$.