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A Unified Ontological-Semantic Substrate for Physiological Simulation and Cognitive Modeling

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Abstract

This paper briefly describes a system that provides a constructive proof of the versatility of ontologies and ontology-based knowledge resources. The Maryland Virtual Patient (MVP) environment models a team of automatic and human agents diagnosing and treating a virtual patient. It uses a uniform ontological substrate to support both the simulation of the world outside the cognitive agents – specifically, physiological processes in the "body" of the virtual patient – and perception, reasoning and action in the "minds" of the virtual patient and other intelligent agents.

Introduction

The term ontology has come to be used so broadly that calling a resource an ontology carries little information without further specification. Our ontology, work on which was started in the early 1980s, was initially intended as a substrate for natural language processing[1]. It has been recently extended to model a society of simulated embodied artificial intelligent agents in the Maryland Virtual Patient (MVP) environment[2,3,4,5] (inter alia).[§] The human agents play the roles of an attending physician and, optionally, a human mentor. The artificial agents play the roles of virtual patients (VPs) and additional members of a medical team, such as lab technicians and medical specialists. The environment also features an automatic tutor agent. The VP agent is at present the most fully developed and the most complex of the artificial agents. A core application of the MVP environment is to help teach medical students cognitive decision-making skills in diagnosing and treating patients. To make this process as close as possible to the experience of treating humans, we have simulated both the patient's "body" and its "mind."

The processes involved in the two kinds of simulation cover the VPs' physiological processes; perception (interoceptive perception and language understanding); reasoning (including decision-making and memory-related operations); and action (physical, verbal and mental). All these processes are supported in the MVP environment by a single set of knowledge resources based on an ontology. In developing the MVP environment, our initial hypothesis was that the above processes could be modeled within a unified, knowledge-based paradigm. Our vested interest in seeing this hypothesis validated was the substantial economies we expected in the knowledge acquisition task. As it happens, the hypothesis was indeed constructively validated in the proof-of-concept MVP system, in which all the above processes have been implemented on the basis of a minimal extension of the OntoSem ontology, which was originally developed to support language understanding.

The Ontology. The OntoSem ontology currently contains about 9,500 concepts – described using, on average, 16 properties each – which are divided among objects, events and properties. Most of the concepts are general-purpose, with the exception of several hundred from the medical domain that were added to support the MVP project. The ontology shares its metalanguage with two other knowledge bases: a lexicon and a language-independent fact repository. There is a many-to-one linking from the lexicon to the ontology, as descriptive specifications of lexical meaning are permitted.[6] OntoSem's metalanguage is unambiguous, which permits reasoning about language and the world to be carried out without the interference of lexical and morphosyntactic ambiguities.

The Fact Repository. The distinction between descriptions and assertions, standard in AI and cognitive modeling, is the criterion for recording a knowledge element as an ontological concept (a description) or an ontological instance (an assertion, stored in the fact repository). This distinction proves useful in modeling all the processes necessary for supporting the MVP environment. For example, the preferred mode of modeling language understanding in our approach is to use the OntoSem analyzer to generate disambiguated text-meaning representations (TMRs) from input texts, store the TMRs in the fact repository, then use the fact repository as a source of heuristics for all further processing, including subsequent language understanding itself. In other words, the fact repository both helps the processing of new texts and is augmented by semantic information obtained from those texts.

A non-linguistic example of the use of the ontology vs. fact repository distinction is authoring libraries of specific MVPs on the basis of a "prototype" disease stored in the ontology.

[§] Patent pending.

Artificial Agent Capabilities in MVP

Several types of processes in the MVP environment are supported by ontological representations of typical sequences of causally and temporally connected events, often referred to as causal chains, scripts or plans.[7] These processes include physiological simulation, the reasoning used for language analysis, and the reasoning used for decision-making. In this section we present brief examples in each of these domains to show how the ontology seamlessly ties together a complex multi-agent system.

Physiological Simulation. Physiological simulation in the MVP environment is implemented using ontological representations of complex events. As an example, consider the representation of the complex event SWALLOW. The SWALLOW script includes many subevents (muscles contracting, nerves firing), conditionals (food cannot pass if there is an obstruction), loops (peristalsis throughout the segments of the esophagus), and so on, this script is conceptually straightforward in that every event must occur in the order specified, given that its preconditions are met, with no optional or variously ordered events. (For lack of space, we show only a few of the dozens of subevents, omit variable bindings, local properties and property facet markers.)

```
(swallow
  (has-event-as-part
    oropharyngeal-phase-of-swallowing
    esophageal-phase-of-swallowing))
(oropharyngeal-phase-of-swallowing
  (has-event-as-part
    motion-event:mouth_to_pharynx
    contract-muscle:contract_pharynx
    motion-event:pharynx_to_larynx
    relax-muscle:crico_relaxes
    relax-muscle:LES_relaxes))
(esophageal-phase-of-swallowing
  (has-event-as-part
    peristalsis:from_larynx
    contract-muscle:crico
    peristalsis:R  ; Regular peristalsis in the esophagus
    peristalsis:to_stomach))
(motion-event:mouth_to_pharynx
  (agent            human-a)
  (theme            bolus-a)
  (instrument       human-a.tongue)
  (source           human-a.mouth)
  (destination      human-a.pharynx)
   (duration        (value 0.08)(default-measure second))
   (effect
   (location (domain    bolus-a)
             (range     human-a.pharynx))))
(contract-muscle:contract_pharynx
 (agent  human-a))
 (theme (set (element human-a.pharynx-constrictor-muscle)
             (cardinality >1))))
 (effect  (openness
             (domain  human-a.pharynx. epiglottis)
             (range    0)))
…)
```

A more complex type of physiological simulation-supporting script is a disease script, which not only has more parameterizable features but can also be modified midstream by external factors, like medical interventions or changes in the person's lifestyle.[2,3]

Cognitive Capabilities. Viewed in a simplified manner, the cognitive capabilities of a VP are implemented as an infinite perception– decision-making–action loop. In the MVP environment, the world that is perceived by the VP is constrained to its own body (interoception) and to its language-based interactions with the agents playing the roles of medical personnel. The VP's reasoning covers not only goal-oriented decision making, it is also central to language analysis and generation. The VP's actions include dialog-related verbal actions, manipulating the agenda of goals and plans, remembering events and facts, and a few physical events – such as presenting to the MD – that are not simulated in great detail at the moment.

Modeling Perception I: Interoception. Interoception connects the "body" and the "mind" of the VP by signaling the agent's becoming aware of a symptom (e.g., pain), understood as a side effect of its physiological state. Procedurally, the moment the VP perceives a symptom, the latter is added to its short-term memory. This triggers the addition of an instance of the goal *be-healthy* onto the agenda, with the symptom as a parameter. What is important for this paper is that the ontologically grounded format in which symptoms are formulated is identical to that of text meaning representations (produced by the language analysis system) and elements of the fact repository.

Modeling Perception II: Language. Many aspects of language processing – from disambiguation[1] to paraphrase detection[5] to reference resolution[8] – can be supported by knowledge like that provided by the OntoSem ontology. For lack of space, we briefly discuss just one aspect of the OntoSem ontology – multivalued selectional restrictions – and two of the many types of language processing it permits.

(i) *Resolution of type incongruity.* Type incongruities are situations in which typical semantic constraints are not met: dogs can eat newspapers, even though the THEME case role of the ontological concept INGEST should be constrained to food or drink; parrots can speak, even though humans are the only full-fledged agents of speaking; babies and dogs can earn money (e.g., as clothing models or in pet food ads), even though they are hardly typical agentive workers.

In cases where extensions of meaning can be foreseen, they can be encoded using multivalued selectional restrictions. In OntoSem, these are implemented using *facets* of property values, which reflect the different confidence levels in semantic decisions. Thus, the INSTRUMENT case role of the event PAY can be constrained to MONEY on the DEFAULT facet, but also license GOODS on the SEM facet and SERVICE on the RELAXABLE-TO facet. Of course, many such extended meanings cannot be anticipated and must be processed using runtime reasoning, which is an ongoing line of work in OntoSem.

(ii) *Reference resolution.* Among the most difficult aspects of reference resolution is selecting the most appropriate antecedent from among a list of candidates when the standard non-semantic heuristics fail to come up with a strong preference. Multivalued selectional restrictions can sometimes cast a deciding vote. For example, whereas the typical agent of a surgical procedure is a surgeon, any doctor – or, in a pinch, any person – can perform some types of surgery. If a text included a sentence like *He botched the surgery,* and if there were several potential antecedents for *he* that had similar non-semantic scores, any candidate known to be a surgeon should be preferred; barring that, anybody known to be a physician, though not known to be a surgeon, should be preferred; and barring this, any human, not known to be either a physician or a surgeon, should be preferred (this example is simplified to save space; the actual combination of heuristic evidence is much more complex). The relevant ontological concept (once again, simplified) is:

```
PERFORM-SURGERY
  AGENT  DEFAULT          SURGEON
         SEM                      PHYSICIAN
         RELAXABLE-TO     HUMAN
```

Whereas the facets SEM, DEFAULT and RELAXABLE-TO are used in the ontology, the fact repository uses the facet VALUE whose semantics is that of actuality, not typicality.

Modeling the VP's Decision Making. When making decisions, the VP uses both knowledge it is aware of and knowledge that it might not be expressly aware of. The kinds of conscious knowledge that the VP uses for making decisions are: (a) an inventory of ontologically grounded goals and an inventory of plans that the VP knows are instrumental in attaining a particular goal; (b) information about the VP's physiological state, particularly the intensity and frequency of symptoms, as perceived via interoception and remembered in its memory; (c) information available to the VP about certain properties of tests and treatments for its condition: pain, unpleasantness, risk and effectiveness; if this information is not available to the VP, the VP has the option of activating a plan of determining the values for these parameters; in the current implementation, this involves asking questions of the agent playing the role of attending physician; and (d) two time-related parameters: the follow-up-date, i.e., the time the doctor told the patient to come for a follow-up, and the current-time of the given interaction. The largely subconscious traits the VP uses in decision-making are: (a) character traits like trust, suggestibility and courage; and (b) certain physiological traits, like physiological-resistance (e.g., how well the MVP tolerates chemotherapy), pain-threshold (how much pain the MVP can tolerate) and the ability-to-tolerate-symptoms (how intense or frequent symptoms have to be before the MVP feels the need to do something about them).[4]

Discussion

Much recent work on ontology has been devoted to compiling "ontologies" – under any definition of the word – as quickly and inexpensively as possible. Most such efforts exploit machine learning techniques and, as would be expected, produce noisy results that are useful for some applications but will certainly not support simulation or high-level reasoning by an advanced, conversational intelligent agent. In this paper we have attempted to show that keeping human acquirers (largely) out of the loop is not the only way to keep ontology development from being prohibitively expensive. Another way is to manually or semi-automatically create resources but reuse them across modules of an environment. In the case of MVP, the physiological, general cognitive and language processing capabilities of all the agents rely on the same ontological substrate, the same organization of the fact repository (agent memory) and the same format of knowledge representation. This uniformity not only provides significant savings in development, testing and debugging time, it also facilitates interoperability. The MVP system provides a constructive proof of the versatility of ontologies and ontology-based knowledge resources.

Naturally, when starting to develop our first medical application we sought domain-specific ontologies that might be incorporated into our general purpose ontology. Two large and well-known resources are MeSH, the National Library of Medicine's (NLM's) tree of medical subject headings, arranged hierarchically, and Metathesaurus, NLM's ontology of hundreds of thousands of medical terms along with their synonyms and morphological variants (hereafter referred to together as M/M). These resources overlap in part (MeSH being much smaller) and use the same concept identifiers (CUIs).[9] After experimentation with these resources – which reflects the best understanding of them we could acquire in a limited time – we concluded that importation would not benefit our system for the following reasons: (a) M/M is geared toward the needs of library science, not having the semantic precision to support high-level reasoning by artificial agents; (b) the content is English terms, including all synonyms, which introduces the language issues that our language-independent ontology avoids; (c) there are very few properties, and 61% of properties (at the time of our experiment, in 2005) had no properties at all; (d) there is no division of concepts and instances; (e) the is-a relation is not interpreted as strictly in M/M as in OntoSem: e.g., in the following are all siblings: Gait; Lower extremity pain walking; Lower limb length difference; Barefoot walking; and Extensor thrust[10]; (f) many concepts in M/M contain a very large set of parents – i.e., 651,000 have one or two parents but another 30,000 have 3 or more parents, with the following reckoning (number of concepts: number of parents): 17075:**3**, 6787:**4**, 3434:**5**, 1907:**6**, 1203:**7**, 715:**8**, 432:**9**, 1,000:**>=10**. As mentioned earlier, many of these "parents" are not parents in the narrow sense of the term used in OntoSem but, instead, concepts related in some unspecified way: e.g., of the 38 root nodes of the hierarchy, a number are sources of information, like SNOMED Intl. 1998 and Medical Entities Dictionary; (g) the physicians collaborating in the work found the content too noisy to be helpful; and, as would be expected of any large resource, (g) there are many errors that would need to be cleaned manually to keep our ontology to its current standard: e.g., over 14,000 concepts are parents of themselves. In terms of utility to our ontology, the UMLS resources have a similar status as WordNet[11] has for building our lexicon: acquirers can use them to provide ideas for resource development, but no automatic, full-blown incorporation can be usefully carried out.

There is, however, one resource that has been very useful in our work: the Foundational Model of Anatomy (FMA)[12]. FMA provides both inheritance (is-a) and meronymic (part-of) trees for elements of human anatomy, as well as a number of other properties like distal to/proximal to, has mass, and so on. The names of concepts are English terms. Synonyms and some foreign language equivalents are included, but they are linked to the "preferred term," making this truly an ontology rather than a word net. In supplementing the OntoSem ontology for use in the medical domain, we are consulting the FMA model because, first, it represents a fine organization of anatomical concepts and, second, we aim to keep our knowledge resources compatible with what we believe will become the accepted standard. However, it would be incorrect to assume that FMA answers all our needs in the medical domain: it treats only anatomical objects, whereas we need a full treatment of relevant events and their relationship to objects, both anatomical and extra-anatomical. In addition, as might be expected, our collaborating doctors do not agree with all of the decisions of the FMA developers with respect to the specific needs of our environment.

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