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Research Statement

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Overview

Systems built on the insights of Artificial Intelligence are increasingly deployed in the world as agents, e.g., software agents negotiating on our behalf on the internet, driverless cars, robots exploring new and dangerous environments, bots playing games with humans. There is an obvious need for humans to be able to trust the decisions made by artificial agents, the need for meaningful interactions between humans and agents, and the need for transparent agents.

This need can only be met if humans are able to model, control and predict the behaviour of agents. This challenge is made all the more complicated since: 1) agents are often deployed with *other* agents leading to *multi-agent systems*, 2) agent behaviour is complex, and extends into the future, leading to *temporal reasoning*, 3) agents are often "self-interested", leading to *strategic reasoning*, 4) agents may have uncertainty about the state, or even the structure, of other agents and the environment, leading to *epistemic reasoning*.

I approach these questions by developing and applying formal and logical methods to modeling and reasoning about multi-agent systems. I also pursue more foundational/speculative questions such as "What is synthesis and how should it be formalised?".

Current Research — Formal methods for multi-agent systems

Multi-agent systems (MAS) involve multiple individual agents (these may be people, software, robots) each with their own goals. Such systems can be viewed as multi-player games, and thus notions from game-theory (e.g., strategies, knowledge, and equilibria) are used to reason about them. Agents in realistic MAS often lack information about other agents and the environment, and this is often categorised in one of two ways: a) *incomplete information* and b) *imperfect information*.

a) MAS with incomplete information

Incomplete-information refers to uncertainty about the environment (i.e., the structure of the game). I have considered two sources of incomplete information for MAS.

First, the *number of agents* may not be known, or may not be bounded a priori. In a series of papers, I have contributed to a generalisation of a cornerstone paper on verification of such systems ("Reasoning about Rings", E.A. Emerson, K.S. Namjoshi, POPL, 1995) from ring topologies to arbitrary topologies [1, 2, 8, 3]. Other work on this topic studied the relative power of standard communication-primitives assuming an unknown number of agents [10], as well as the complexity of model-checking timed systems assuming an unknown number of agents [9]. I also contributed to a book on this topic published by Morgan & Claypool in 2015 [14, 15].

Second, the agents may be operating in a *partially-known environment*. For instance, the agents may know they are in a ring, but may not know the size of the ring. I launched the application of automata theory for the verification of high-level properties of light-weight mobile agents in partially-known environments [29]. In follow-up work I explored this theme further, including finding ways to model agents on grids — the most common abstraction of 2D and 3D space [4, 5, 26].

b) MAS with imperfect information

Even if agents have certainty about the structure of the system, they may not know exactly which state the system is in. This is called imperfect information and the associated logic for reasoning about such cases are called *epistemic*. I have studied strategic-epistemic logics in a number of works, namely, with a prompt modality (thus allowing one to express that a property holds "promptly" rather than simply "eventually") [6], and on systems with public-actions (such as certain card games, including a hand of Poker or a round of Bridge) [13, 12]. The importance of these last works is that they give the first decidability (and sometimes optimal complexity) results for strategic reasoning about games of imperfect information in which the agents may have arbitrary observations. In contrast, following classical restrictions on the observations or information of agents, I have also shown how to extend strategy logic by epistemic operators and identified a decidable fragment in which one can express equilibria concepts [12].

Foundations of Automated Planning

Planning in AI can be viewed as the problem of finding strategies in succinct representations of one- or two-player graph-games. In this model vertices represent states, edges represent transitions, and the players represent the agents. I have contributed foundational work to such games. Concretely, I recently extended the classic belief-space construction for games of imperfect-information from finite arenas to infinite-arenas [18] (infinite arenas often arise in the study of MAS with incomplete information, see above). I have also used these ideas to elucidate the role of observation-projections in generalised planning problems [17, 16]. I have generalised classic results about certain games with quantitative objectives (i.e., Ehrenfeucht and J. Mycielski. Positional strategies for mean payoff games. International Journal of Game Theory, 8:109–113, 1979) to so-called first-cycle games [7].

Past Research — Algorithmic Model Theory

My prior work contributed to a research program called "Algorithmic Model Theory" whose aim is to develop and extend the success of Finite Model Theory to infinite structures that can be reasoned about algorithmically.

Specifically, my PhD work pioneered the development of "automatic structures": this is a generalisation of the regular languages from sets to mathematical objects with structure, such as graphs, arithmetics, algebras, etc. The fundamental property of automatic structures is that one can automatically answer logic-based queries about them (precisely, their first-order theory is decidable). I gave techniques for proving that structures are or are not automatic (similar to, but vastly more complicated than, pumping lemmas for regular languages), I studied the computational complexity of deciding when two automatic structures are the same (isomorphic), and I found extensions of the fundamental property, thus enriching the query language [11, 19, 20, 21, 22, 23, 24, 28]. I have also worked on extensions of automatic structures to include oracle computation [25, 27].

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