Abstract

This document describes my main research interests, organised by theme. My background is in theoretical foundations of rigorous systems engineering, i.e., the development of methods for the representation, reasoning and control of complex systems. The common thread in my research is the development and analysis of *logic-based* methods for *infinite* systems. Since 2015, I started focusing on problems in Artificial Intelligence, particularly regarding representation, verification and synthesis of *multi-agent systems (MAS)*.

1 Algorithmic Model Theory

My early 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 [13, 19, 21, 22, 23, 24, 25, 26, 27, 34]. I have also worked on extensions of automatic structures to include oracle computation [28, 33].

2 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 needed to reason about them.

2.1 MAS with incomplete information

Incomplete-information refers to uncertainty about the structure of the system. 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'95, 1995) from ring topologies to arbitrary topologies [1, 2, 10]. Other work on this topic studied the relative power of standard communication-primitives assuming an unknown number of agents [12], as well as the complexity of model-checking timed systems assuming an unknown number of agents [11]. I also contributed to a book on this topic [16, 17].

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 [35]. In followup work I explored this theme further, including finding ways to model agents on grids — the most common abstraction of 2D and 3D space [6, 7, 31].

2.2 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") [8], and on systems with public-actions (such as certain card games, including a hand of Poker or a round of Bridge) [14]. The importance of this last work is that it gives the first optimal-complexity decidability result for strategic reasoning about games of imperfect information in which the agents may have arbitrary observations (all previous results put some restriction on the initial observations of the agents [30, 32, 15, 36, 29], thus severely limiting their applicability). I currently have two further works on this topic under review, i.e., both on epistemic extensions of strategy logic.

2.3 Logics with Counting Quantifiers

I have a long-standing interest in logics with quantifiers that count. E.g., the usual first-order quantifier $\exists x$ can be generalised to the counting quantifier $\exists^{\geq k} x$ which says that "there are at least k many x". Concretely, I have studied logics that count strategies [3, 4], paths [5], strings and sets [34, 20].

In particular, I recently established and studied a logical formalism, called "graded strategy-logic", that is rich enough to count equilibria [3, 4]. The importance of this result to equilibrium selection is that it gives a computational way to decide if a given game has, e.g., a unique Nash equilibrium.

2.4 Planning and Two-player Graph-Games

Planning in AI can be viewed as the problem of solving a 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), and I generalised classic results about mean-payoff games to so-called first-cycle games [9].

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