More visible applications in Security? | Insist on you bridging AI and Formal methods.

# PROJECT TITLE: Synthesis of Trustworthy Behaviour of Artificial Agents (SYBA)

## AIMS AND BACKGROUND

*Nature of the challenge.* 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 [2].

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*.

*Focus of this project.* Synthesising and analysing trustworthy artificial agents requires *Temporal-Strategic-Epistemic reasoning on Multi-agent Systems*. The aim of this project is to develop the mathematical foundations and computational techniques for building and analysing trustworthy artificial agents, by leveraging the insights from recent results developed by the candidate on modeling, control and analysis of single and multi-agent systems. There are three specific objectives: 1) discover new classes of systems for which Temporal-Strategic-Epistemic reasoning is decidable and tractable, 2) develop the theory of reasoning about optimal strategies and socially optimal equilibria, and 3) establish scalable algorithms and tools for Temporal-Strategic-Epistemic reasoning.

*State of the art.* Logic-based techniques are a standard approach to modeling, building and analysing computational systems. Indeed, simply formalising the reasoning tasks unambiguously requires a formal language. Not surprisingly, such reasoning is computationally *undecidable* when it involves epistemic reasoning, a fact known since the late 1970s [52]. The historical approach to ameliorate this is to restrict to classes of multi-agent systems in which agents' private knowledge is hierarchical (typically, one assumes some sort of hierarchy on agent observation or information [52, 53, 39, 13, 12]). Although mathematically elegant and well-explored, the *applicability of such assumptions is not very high* since in almost all meaningful scenarios, agents' private knowledge are not hierarchical.

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*Proposed approach.* In a remarkable recent discovery [9, 10] the candidate defined and explored a very general class of systems that does not suffer from this long-standing limitation, i.e., the class in which *agent actions are fully observable*. He proved that *Temporal-Strategic-Epistemic reasoning is decidable and not harder than the non-epistemic case*. Many scenarios already fall into this class, e.g., distributed computing and multi-party computation based on broadcast communication [44, 1], multi-player games with public play such as poker [16], e-auctions with public bidding [26].

Moreover, the importance of this recent discovery is that it charts an unanticipated path for applying logic-based methods to *meaningful classes* of artificial agents in a *large variety of fields*, for instance: models of collaborative robot exploration in controlled but dynamic environments [49]; models of cloud manufacturing [29]; models of collusion in e-auctions and auction-based mechanisms [26]; models of social networks that use broadcast communication, and thus also formalisations of *twitter* [25, 45]; models of secure cloud-storage that use data-dispersal [40] and secret-sharing protocols [1]; models of multi-player games in which bidding and play is public, such as poker [16]. I would finish the paragraph on this one.

(*)

*The candidate.* The candidate is particularly suited to meet this challenge. His background in mathematical logic and formal methods has enabled him to devise effective conceptual frameworks to address problems in AI [56, 7, 21, 6, 14, 33, 14, 9, 10, 12].

**Overall Aim** The aim of this project is to develop the mathematical foundations and computational techniques for building and analysing trustworthy artificial agents, by leveraging the insights from recent results developed by the candidate on automated reasoning for single and multi-agent systems.

"objective(s)" above
"needs" below ||

**Specific Aims** We state and justify 3 specific aims.

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| 1. We need to discover meaningful *new classes* of multi-agent systems for which Temporal-Strategic-Epistemic reasoning is decidable and tractable. |

Synthesis is a seemingly simple form of Temporal-Strategic-Epistemic-reasoning that asks if a given coalition of agents have a strategy ensuring some joint objective. It is known synthesis is intractable and even **undecidable** on multi-agent systems, a fact that has been discovered in multiple contexts, i.e., decentralised POMDPs [11], multiplayer non-cooperative games of imperfect information [51], distributed synthesis [53]).

Since the 1970s researchers have tried to find decidable fragments. The standard approach is to assume some sort of hierarchy on the information or observation sets, e.g., [52, 53, 39, 13, 12]. Although mathematically elegant, the applicability of such assumptions is not very high since agents' private information is typically not hierarchical.

However, we recently [9, 10] defined and explored a class of systems in which all agent actions are fully observable to all agents, and proved that one can do analysis, i.e., Temporal-Strategic-Epistemic reasoning is **decidable and not harder than the non-epistemic case**.[1] Many scenarios already fall into this class, e.g., distributed computing protocols and multi-party computation that are based on broadcast communication [44, 1], multi-player games with public play such as poker [16], e-auctions with public bidding [26]. That said, the importance of this result is that it lays the algorithmic and theoretical foundations for analysis of *many meaningful* classes of agents since, notably, we are no longer bound by the restriction that agents' observations need be hierarchical.

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| 2. We need to define, analyse, and tackle the problem of reasoning about optimal strategies and *socially optimal equilibria*. |

In order to have evidence that one agent's behaviour is better or worse than another, or whether a collection of agents are acting in the good of society, we need to be able to measure the quality of agent strategies against each other. This, in turn, would be facilitated by endowing agent objectives with a quantitative component. Although most work in verification deals with qualitative objectives, there has been a recent focus on verification of quantitative models of programs [34, 4]. However, this has yet to be clearly generalised to Temporal-Strategic-Epistemic reasoning for multi-agent systems. Building on more classic work [5, 48], the candidate recently introduced expressive logics that can be used to reason about socially optimal equilibria in cases agents have qualitative objectives [6, 9, 12]. This, together with recent insights from quantitative verification [61, 34, 46, 4], lays the foundation for designing useful logics and measures of strategy-quality for reasoning about socially optimal equilibria. An example where equilibrium is a central notion.

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| 3. We need to establish *scalable algorithms and tools* for Temporal-Strategic-Epistemic reasoning. |

To accomplish Temporal-Strategic-Epistemic reasoning for multi-agent systems, including reasoning about social equilibria, we need scalable algorithms and tools. Since the worst-case complexity of such reasoning is typically very high, we need tools that can deal with large but "easy" cases. This grand challenge is being met by a number of branches of computer science, notably the Automated Planning community in Artificial Intelligence.

**Automated Planning is a form** of **synthesis** (and thus a form of temporal-strategic reasoning) that is central to the development of agents. It is a branch of Artificial Intelligence that addresses the problem of generating a course of action(s)? to achieve a desired goal, given a description of the domain of interest and its

not sure

[1] Previously it was only known that, in a similar setting, one can do multi-agent epistemic planning [37] and synthesis [63].

I've been told "desire" is not the proper word.

initial state. The Automated Planning community has developed a "science of search", based on heuristic-search and symbolic methods, that efficiently plans for most problems of practical interest [31, 41]. The most successful of this technology is for "classical planning", i.e., single agent, deterministic environment, with perfect information, and simple reachability goals, and "fully observable non-deterministic planning" (which amounts to the case of one agent in an adversarial environment).

Previous work has reduced planning with temporal goals or epistemic goals to classical and fully-observable nondeterministic planning [8, 59, 37, 19]. This lays the foundation for refining and extending the translations to handle full Temporal-Strategic-Epistemic reasoning for multi-agent systems.

## CANDIDATE

**Leadership** I have previously held two individual fellowships: a 3-year New Zealand Science and Technology Postdoctoral Fellowship (NZ$ 224532), and a 2-year Marie-Curie Postdoctoral Fellowship co-funded by the National Institute of Higher Mathematics (€107000). I was project co-ordinator for the *Handbook of Model Checking*, edited by Ed Clarke et. al., and published by Springer (Dec 2017).

**High quality research outputs** In theoretical computer science and Artificial Intelligence, top conferences are highly prestigious venues for dissemination. I regularly publish in conferences of the highest level, e.g., I published 5 CORE A* papers in 2017 and 5 CORE A* papers in 2016. According to google scholar: I have 785 citations (391 since 2012), my H-index is 15 (12 since 2012), and my Phd Thesis has 72 citations. In my field it is expected that authors are ordered alphabetically. That said, my contribution to my published papers always meets and often far exceeds an equal division of labour.

I quote the following endorsements:

> *I give this application my wholehearted support. Sasha is an highly motivated, extremely active researcher, with a superb technical grasp of issues in logic, AI, and game theory.*
> Michael Wooldridge (Oxford University)

> *His research papers on these lines are effectively changing the discipline by providing very significant results in the community of formal aspects of Artificial Intelligence.*
> Alessio Lomuscio (Imperial College London)

**Research training, mentoring and supervision** I worked closely with a PhD student of Erich Gradel's (Tobias Ganzow) and solved a 12-year open problem [30]. I have been sought as a referee for the IRISA Master Research Internship 2017 (France). I have mentored 1 Msc Internship (2017), 1 Undergraduate thesis (2017), and 7 undergraduate students doing research (2012, 2009).

more details about the topics?

**National and International standing** I serve as PC member of CORE A* conference in Artificial Intelligence and Multi-agent systems (i.e., IJCAI 2017, AAAI 2017, AAAI 2018, AAMAS 2018). I have chaired one national conference on theoretical computer science (ICTCS 2017, Italy) and one international workshop on strategic reasoning (SR 2017). I conceived and organised a Workshop on Formal Methods in Artificial Intelligence (FMAI 2017). I have served as an external reviewer for the Icelandic Research Fund (IRF 2017). I have been invited to talk at various universities, including UNSW (Australia), IMT Lucca (Italy), Sapienza University of Rome (Italy), Université Paris-Diderot (France), and Oxford University (UK).

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## PROSPOSED PROJECT QUALITY AND INNOVATION

Every society that has embraced the digital world faces the issue of whether, or to what extent, it can trust the behaviour of artificial agents. The challenge of building trustworthy artificial agents cannot be met without having some formal guarantees on their behaviour. There are two fundamental parts to this problem: automatically synthesise agent behaviour, or part of their behaviour, from unambigious declarative specifications; analyse behaviour of built or existing agents. This project will advance the state of the art of the mathematical foundations and computational techniques for building and analysing trustworthy agents from Temporal-Strategic-Epistemic specifications. In particular, it will provide extend the use of logical methods to the analysis of multi-agent systems coming from a variety of fields, including high-level robot control, trustworthy social-media bots, collusion-free e-auctions, and safe and secure cloud storage. Safer and securer interactions with artificial agents are clearly in the interests of society.

Also something about environmental questions?

**Project Quality** The objectives of the project are to generate new mathematics, algorithms, and tools for describing, reasoning-about and building trustworthy agents. This will be done using methods and insights from Logic and Formal Methods (including program synthesis), and Game Theory (including its development in multi-agent systems).

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| 1a. In order to discover richer decidable classes, I propose to **generalise** systems in which all actions are fully observable. |

I recently explored the class of systems in which all actions are fully observable [9, 10]. This class already includes formalisations of many important scenarios, notably distributed computing protocols that use broadcast communication [44], including rational distributed computing and multiparty computation [1], as well as multi-player games of imperfect information that use public bidding [16]. I now outline the first directions I will pursue in order to expand this theory to encompass even more scenarios:

1. Incorporate stochastic initial states, which is **widely applicable**. Indeed, not only do finite horizon stochastic systems fall into this setting [42], but so do probabilistic multi-agent systems, called decentralised partially observable Markov decision processes [50], which are a framework for modeling uncertainty with respect to outcomes, environmental information and communication. That is, this extension will addresses the problem of ensuring **agents behave well in unknown environments**.
2. Incorporate symmetric and asymmetric encryption, which is applicable to online **privacy and security**. Indeed, private-keys can be stored in an agent's private state, and thus private-key encryption can already be simulated by fully observable actions. Furthermore, public-key encryption consists of public keys that can be widely disseminated, and thus encrypting with a public key can be modeled as a public action.
3. Limiting the number of non-public actions, which is applicable to design and analysis of **collusion analysis** in e-auctions. For instance, the Vickrey auction [26] is a type of sealed-bid auction, in which each bidder submits a written bid without knowing the bids of the other bidders. The highest bid wins but the price paid is the second-highest bid. Vickrey-Clarke-Grove (VCG) auctions are generalisations of Vickrey's auctions to multiple items. It is known that Vickrey-Clarke-Grove auctions provide bidders with an incentive to bid their true value. It is also known that these auctions are vulnerable to *collusion*: if all bidders reveal their true values to each other, using a *limited number of non-public actions*, they can lower some or all of these values, while preserving who wins the auction. Thus, collusion analysis gives the auctioneer, and thus the market, confidence that bidders cannot game the system.

   a bit hard to read.
4. Tuning the amount of observability of actions. Indeed, although systems with hidden actions are undecidable and fully observable actions are decidable, there is likely a measure of "action observability" that can be tuned so that one can incorporate systems in which certain actions are partially observable (but not completely hidden). Whatever this measure will look like, the result will be a **deeper understanding** of the borders between decidability and undecidability for various systems.

The resulting classes that could be handled by such extensions are truly impressive. We list just some:

- various models of collaborative robot exploration in controlled but dynamic environments [49, 38],
- various models of cloud manufacturing [29],
- various models of collusion in e-auctions and auction-based mechanisms [26],
- various models of social networks that use broadcast communication, and thus also formalisations of *twitter* [25, 45],
- various models of secure cloud-storage that use data-dispersal [40] and secret-sharing protocols [1],
- various models of multi-player games in which bidding and play is public, such as poker [16]. same comment as (#)

1b. In order to discover tractable classes of agents, I propose to **restrict** to sub-systems of those in 1a.

The complexity of Temporal-Strategic-Epistemic reasoning for multi-agent systems identified in 1a is expected to be high. To achieve better computational complexity I propose to restrict them to sub-systems, while still maintaining the features in 1a that allow one to model systems from a wide variety of fields (e.g., that agent's observations need not be hierarchical). In particular, I will start by restricting to classes in which:

1. the set of initial states is homogenous [43]. This is applicable to situations in which agents are initially ignorant of each others local states;
2. the size of the epistemic states is bounded, which is applicable to situations in which each agent has full observation except of its *own* finite state; → explain more as it is weird.
3. the strategies considered do not depend on the full history, but on a bounded summary of the history. Besides lowering the complexity, this assumption reflects the assumption of **bounded rationality** [58].

2. In order to reason about socially optimal equilibria, I propose to enrich the models and specification languages with costs/rewards and analyse these with measures of **strategy quality**.

Agents are typically "self-interested", and thus they may not act in a way that is socially optimal. Moreover, it is often not possible to ascribe agent behaviour as simply being good or bad. Thus, I will explore measures of strategy quality and algorithms for synthesising socially optimal strategies. Although many game-theoretic solution concepts, such as Nash equilibria, can be expressed in recently introduced strategic logics [48], and their epistemic extensions [12, 10], these logics can only express qualitative agent objectives. Thus, I will define and explore logics that can reason about quality of agent behaviour. In particular I will extend and evaluate state-of-the-art proposals for measuring quality of strategies to full Temporal-Strategic-Epistemic reasoning for multi-agent systems, i.e.: the logic $\mathsf{LTL}[\mathscr{F}]$, and extension of $\mathsf{LTL}$ with a set of quality operators $\mathscr{F}$ [4], that was designed to reason about the quality of programs and can be used to reason about the **quality of agent behaviour**; the logic $\mathsf{LTL}_f$ with costs [17], that allows one to reason about non-Markovian objectives; logics that combine qualitative behaviour (expressed for instance in $\mathsf{LTL}$ or $\mathsf{LTL}_f$) and quantitative, expressed for instance as long-term average of the cost of some resource [33] or as the total cost of some resource [18].

3. In order to establish scalable tools and algorithms, I propose to **translate** Temporal-Strategic-Epistemic reasoning to Automated Planning.

I will extend and refine the translations that handle temporal goals and epistemic goals [8, 59, 19] to full Temporal-Strategic-Epistemic reasoning for the multi-agent setting. I will do this by leveraging the automata-theoretic approach to model-checking of strategic epistemic logics [10, 12], as well as search through strategy-space [15]. One parallel direction to meet this objective is to explore generalisations of specification formalisms over finite traces [24, 22, 23], adopted in automated planning [8, 59, 3, 19]. Indeed, specifications on finite traces allow one to avoid notorious difficulties of infinite-traces [57], namely complementation of Büchi-automata [60]. In particular, I will define and study "epistemic strategy logic over finite traces", and extend the mentioned translations to this logic.

how about other fields model-checking with counter-examples/witnesses generation?

**Project Innovation** The scientific innovation of the project is demonstrated in three ways.

1. The project will develop a new mathematical and algorithmic theory for the design and analysis of meaningful multi-agent systems.

2. The project will advance the study of automatically finding socially optimal equilibria in which agents have a mix of qualitative and quantitative objectives.

3. The project will leverage the successful theory and technology of Automated Planning for the design and analysis of multi-agent systems.

Thus, the project has conceptual innovation by supplying viable frameworks for computer scientists and engineers to think about the behaviour of the agents they build, as well as technological innovation in leveraging Automated Planning to automated reasoning about artificial agents.

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