# How to formally reason about strategic behaviour

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February 7, 2019, University of Sydney

AI is about building agents to do tasks we think require intelligence

# What is an agent?

- An agent is something that *acts*, based on sensing the world.
- An agent is *rational* if it acts to achieve the best (expected) outcome. Russell, Norvig

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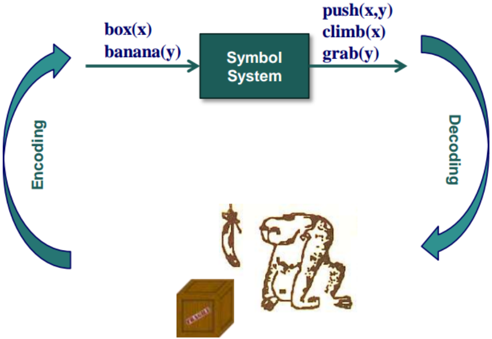


# …Multi-agent systems are everywhere!

Many real and imagined systems consist of multiple agents:

1. **distributed**, i.e., agents have their own view of the world.
2. **goal-directed**, i.e., agents strategise to achieve their own goals.

E.g.

- multiplayer games (winning tasks)
- robot assisted search-and-rescue (co-ordination tasks)
- autonomous transport vehicles (safety tasks)
- voting and auction protocols (fairness tasks)
- rational distributed computing (secret-sharing tasks)
- …

# Research Challenge

How to understand, predict and control agent behaviour?

# Lots of disciplines involved

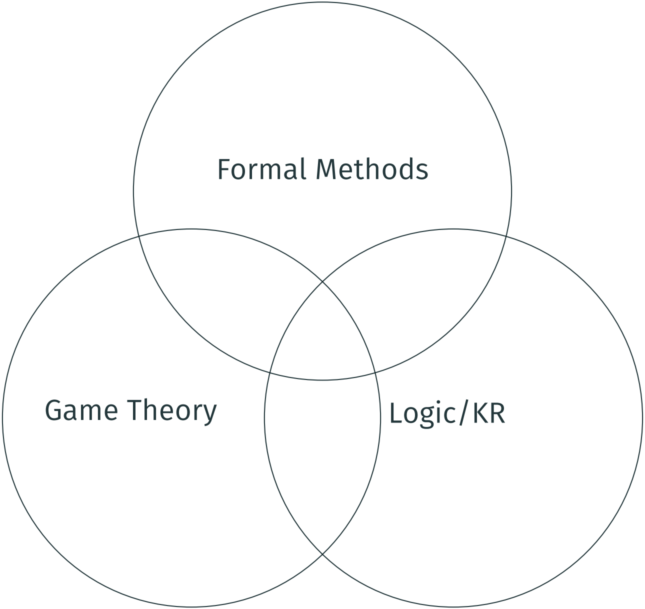
1. Humanities: How do we want agents to behave?
2. Computer engineering: How to engineer such agents?
3. Computer science: How to make sure agents behave as we want?
    3.1 Theoretical foundations
    3.2 Academic tools
    3.3 Industrial applications

# Research Challenge

How to understand, predict and control agent behaviour?

- **Methodology**
  Model agent tasks in logic (for understanding), and devise algorithms (for prediction/control).
- **Difficulty**
  Agents are distributed and goal directed.

# Methodology



# Formal Methods 101

$$\textbf{Model-checking paradigm}^{1} = \begin{cases} \text{model} & M \\ \text{specify} & \varphi \\ \text{algorithm for} & M \models \varphi \end{cases}$$

[1] If formula $\varphi$ talks about strategies, model-checking can usually be adapted to do control (not just prediction).

# Formal Methods 101

$$\textbf{Model-checking paradigm}^{1} = \begin{cases} \text{model} & M \\ \text{specify} & \varphi \\ \text{algorithm for} & M \models \varphi \end{cases}$$

Classical model-checking can't handle the complexities of multi-agent systems.

[1] If formula $\varphi$ talks about strategies, model-checking can usually be adapted to do control (not just prediction).

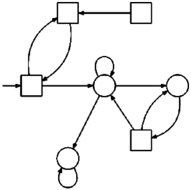
# My current research goals

$$\textbf{Model-checking paradigm} = \begin{cases} \text{model} & M \\ \text{specify} & \varphi \\ \text{algorithm for} & M \models \varphi \end{cases}$$

1. Devise models that capture essential aspects of multi-agent systems.
2. Devise logics that can specify complex agent/system goals.
3. Devise algorithms for model-checking, or prove that none exists.

Note. Steps 1 and 2 are useful in themselves! (Knowledge Representation philosophy)

# Models

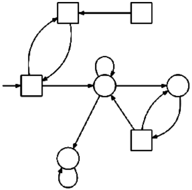


$M = \langle S, \mathrm{tr}, (Obs_a)_{a \in Ag} \rangle$ is a transition system modeling dynamics

| | |
|---|---|
| $S$ | set of states |
| $\mathrm{tr} : S \times Act \to S$ | transition function |
| $Obs_a : S \to \Omega$ | observation function |

Special case: $Obs_a(s) = s$ Full observation

# Models



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- Strategy tells an agent how to act based on its observations
- Strategy for each agent determines a path in $M$

# Logics

New logic: Strategy Logic for agents with partial observation

$$\overbrace{p \mid \neg\varphi \mid \varphi_1 \vee \varphi_2}^{\text{Boolean}} \mid \overbrace{\mathrm{X}\,\varphi \mid \varphi_1 \,\mathrm{U}\, \varphi_2}^{\text{Temporal}} \mid \overbrace{(\exists s)\,\varphi \mid (a_i \mapsto s)\,\varphi}^{\text{Strategic}}$$

# Logics

New logic: Strategy Logic for agents with partial observation

$$\overbrace{p \mid \mathit{not}\,\varphi \mid \varphi_1\,\mathit{or}\,\varphi_2}^{\text{Boolean}} \mid \overbrace{\mathit{next}\,\varphi \mid \varphi_1\,\mathit{until}\,\varphi_2}^{\text{Temporal}} \mid \overbrace{(\mathit{exists}\,s)\,\varphi \mid (a\ \mathit{uses}\ s)\,\varphi}^{\text{Strategic}}$$

# Logics

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Boolean part expresses state properties:

- $\mathit{Crashed}(a_1)$, $\mathit{not}\,\mathit{Crashed}(a_1)$, $\mathit{InRoom}(a_1, r_2)$, $\ldots$

# Logics

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Temporal part expresses agent goals:

- *eventually* $\mathit{InRoom}(a_1, r_2)$, *never* $\mathit{Crashed}(a_1)$, $\ldots$

# Logics

$$\overbrace{p \mid \mathit{not}\,\varphi \mid \varphi_1\,\mathit{or}\,\varphi_2}^{\text{Boolean}} \mid \overbrace{\mathit{next}\,\varphi \mid \varphi_1\,\mathit{until}\,\varphi_2}^{\text{Temporal}} \mid \overbrace{(\mathit{exists}\,s)\,\varphi \mid (a\ \mathit{uses}\ s)\,\varphi}^{\text{Strategic}}$$

Strategic part expresses game-theoretic properties:

- $(\mathit{exists}\,s_1)\,(a_1\,\mathit{uses}\,s_1)\,\mathit{goal}_1$

  "I have a strategy to win" (solitaire)

- $(\mathit{exists}\,s_i)_i\,(a_i\,\mathit{uses}\,s_i)_i\,\mathit{goal}$

  "We have strategies that win" (coordination)

- $(\mathit{exists}\,s_1)\,(\mathit{forall}\,s_2)(a_i\,\mathit{uses}\,s_i)_i\,\mathit{goal}_1$

  "I have a strategy that beats any of yours" (tic-tac-toe)

- $(\exists s_i)_i\,(a_i \mapsto s_i)_i\,\&_i \neg[\neg \mathit{goal}_i \wedge (\exists s')(a_i \mapsto s')\mathit{goal}_i]$

  "We can play NE" (rational secret sharing, fair division, poker)

# Logics

$$\overbrace{p \mid \mathit{not}\,\varphi \mid \varphi_1\,\mathit{or}\,\varphi_2}^{\text{Boolean}} \mid \overbrace{\mathit{next}\,\varphi \mid \varphi_1\,\mathit{until}\,\varphi_2}^{\text{Temporal}} \mid \overbrace{(\mathit{exists}\,s)\,\varphi \mid (a\ \mathit{uses}\ s)\,\varphi}^{\text{Strategic}}$$

Natural, and very expressive

It can express

- state properties,
- (Boolean) agent goals,
- game-theoretic properties (NE, SPE, ESS, Pareto optimality, ...).

# Algorithms for $M \models \varphi$

# Distributed agents make things hard...

# Distributed agents make things hard...

- Multi-player games in TCS (70s) undecidable
- Distributed synthesis in FM (90s) undecidable
- Finite horizon DEC-POMDPs in AI (00s) NEXP-complete

Insight. The source of these difficulties is the ability of agents, each with their own observations of the world, to communicate privately with each other.

# Distributed agents make things hard...

What can be done?

1. Restrict observability
2. Restrict private communication

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What can be done? Restrict observability

How? Hierarchical observation/information

# Distributed agents make things hard...

What can be done? Restrict observability

How? Hierarchical observation/information

- Peterson, Reif ('79)
- Pnueli, Rosner ('90)
- Kupferman, Vardi ('01)
- Finkbeiner, Schewe ('05)
- vdMeyden, Wilke ('05)
- Berwanger, Mathew, vdBogaard ('16)
- Berthon, Maubert, Murano, R., Vardi (LICS '17)

Observation. Mathematically elegant, but none of the examples mentioned have hierarchical observation

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How? Broadcast-communication/public-actions

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How? Broadcast-communication/public-actions

- Lomuscio, vdMeyden, Ryan, Wilke ('00, '05) Broadcasting
- vDitmarsch, vdHoek ... Public Announcements Logic (DEL)
- Kominis, Geffner ('15,'17) Public Actions (Planning)
- Belardinelli, Lomuscio, Murano, R. (AAMAS '17, IJCAI '17)

# Models

Model: Public action transition system $M$ — the last action of each agent is observable to all agents.

E.g.,

- community-card games (bridge, poker)
- broadcasting distributed systems (secret-sharing protocols)
- epistemic puzzles (muddy children)
- auctions (open-outcry)

Many examples

# Algorithms for $M \models \varphi$

Theorem. $M \models \varphi$ is decidable if $M$ is a public-action transition system.

Complexity?

- In $(k+2)$-exptime in the model and the formula, and $(k-1)$-expspace-hard in the formula, where $k =$ quantifier-block depth of formula.

In fact. Computational complexity is similar to fully-observable transition systems!

Middle ground.

Fully observable TS $<$ Public Action TS $<$ Unrestricted TS

# Proofs

- Q. How did you come up with the algorithms?
- A. We used the automata-theoretic approach to model-checking.[2]
- Q. But what do the algorithms actually look like?
- A. Operations on automata that run on trees.
- Q. ??
- A. Think of it like manipulating **regular expressions** that match trees instead of strings!

[2] for which Vardi and Wolper won the Gödel prize for outstanding papers in TCS.

# Summary

- Current research goal

  Devise models, logics and algorithms for understanding, predicting, and controlling behaviour of agents in multi-agent systems.
- Challenge

  Combination of partial observability and private communication.
- Solutions

  Impose hierarchical observation, or restrict private communication, and use automata.

# Future research goals

Capture quantitative aspects

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## Capture quantitative aspects

1. Agents: Probabilistic (instead of just deterministic)
2. Tasks: Optimisation (instead of just Boolean)

# Future research goals

Context. Many protocols rely on coin-flips.

Project. Develop *Probabilistic Strategy Logic* for reasoning about stochastic multi-agent transition systems.

Methodology. Study restrictions on memory of probabilistic agents and reduce to reasoning about polynomial inequalities.[3]

[3] Formally, reduce $M \models \varphi$ to the first-order theory of real arithmetic, which is solvable in EXPSPACE by work of Tarski/Seidenberg.

# Future research goals (speculative)

Context. MDPs, POMDPs, DEC-POMDPs are important models.

Challenge. Agent goal is to optimise expected-reward, which is a very “low-level” specification.

Project. Unify reward- and declarative-specifications.

Methodology. ???

# Overview of recent research lines

Formal methods …

…for strategising agents with qualitative temporal goals

AAMAS'16/'17/'18, IJCAI'17, LICS'17

# Overview of recent research lines

Formal methods …

…for strategising agents with quantitative temporal goals

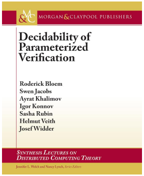
IJCAI'17, CSL'18

# Overview of recent research lines

Formal methods ...

...when the number of agents is not known apriori

CONCUR'14,VMCAI'14,ICALP'15,M&C'15 (book), IJCAR'16, VMCAI'18

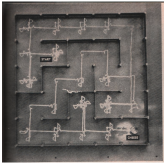


# Overview of recent research lines

Formal methods . . .

. . . when the environment is partially-known

PRIMA’15 (best-paper), AAMAS’15/’16, IJCAI’16/’17




European Commission

# What sort of researcher am I?

- I'm part of a growing group bringing insights from formal methods to bear on problems in AI.
- I'm rooted in Formal Methods and Knowledge Representation philosophies.
- My focus has broadened over time:
    1. Automata for reasoning about mathematical structures
    2. Logic/automata in Formal Methods
    3. Formal Methods and Artificial Intelligence

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# Future research goals

Academic Tools

# Future research goals

Context. Existing tools for multi-agent systems (*MCK* vdMeyden et. al.; *Eve* Wooldridge et. al.; *MCMAS* Lomuscio et. al.) can't handle logics and models above.

Challenge. High computational complexity, complex constructions.

Project. Engineer practical algorithms by translating to optimised tools, such as planners.[4]

Methodology. Give new semantics for logics based on finite paths of $M$.

De Giacomo, Vardi IJCAI '13/'15/'16

McIlraith,... AAMAS/IJCAI/KR '18

[4] Planning in AI is a form of synthesis.