Don't Trust Your Agents, Verify Them

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Outline

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1. Introduction and Motivation
   - Why strategic verification for MAS?
   - From temporal properties to strategic abilities.
   - Domains and challenges.
2. Background: strategic logics and models
   - CTL/ATL intuition, concurrent game structures, strategies & coalitions, modelling assumptions and limits.
3. Strategic verification in VITAMIN
   - Architecture & components.
   - Supported logics and tasks.
   - Verification workflows.

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3. Strategic verification in VITAMIN
   - Architecture & components.
   - Supported logics and tasks.
   - Verification workflows.
4. Hands-on modelling and verification
   - Build a model, write strategic specifications, execute tasks, analyse and discuss results.
5. Discussion and outlook
   - Open research challenges, industrial relevance, Q&A.

Introduction and Motivation

Preface

System Correctness

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Formal Verification

- Provides mathematically precise models of behaviour.
- Enables reasoning about **all possible executions**.
- Model checking is a key technique for exploring system behaviour.

Model Checking (1)

$M \models \varphi$

There are three fundamental parts:

- M: modeling a multi-agent system;
- φ: specifying a property;
- $\models$: verifying that the model M satisfies the property φ.

Model checking (2)

Model

A Kripke structure is a tuple $K = \langle \mathrm{AP}, \mathrm{St}, S_0, R, L \rangle$, where:

- AP is a set of atomic propositions;
- St is a set of states;
- $S_0 \subseteq \mathrm{St}$ is a set of initial states;
- $R \subseteq \mathrm{St} \times \mathrm{St}$ is a transition relation;
- $L : \mathrm{St} \to 2^{\mathrm{AP}}$ is a labeling function.

Model checking (3)

Specification

- Temporal logics allow to describe the order of the events without define the time explicitly.
- The main temporal logics:
  - LTL $\Rightarrow$ in a computation the events are totally ordered.
    Examples: Xp, Fp, Gp.
  - CTL $\Rightarrow$ in a computation the events are partially ordered.
    Examples: AXp, EFp, AGp.

Model checking (4)

Verification

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The challenge is scaling correctness to interacting agents.

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- Modern systems are inherently **multi-agent**:
  - autonomous vehicles and robots
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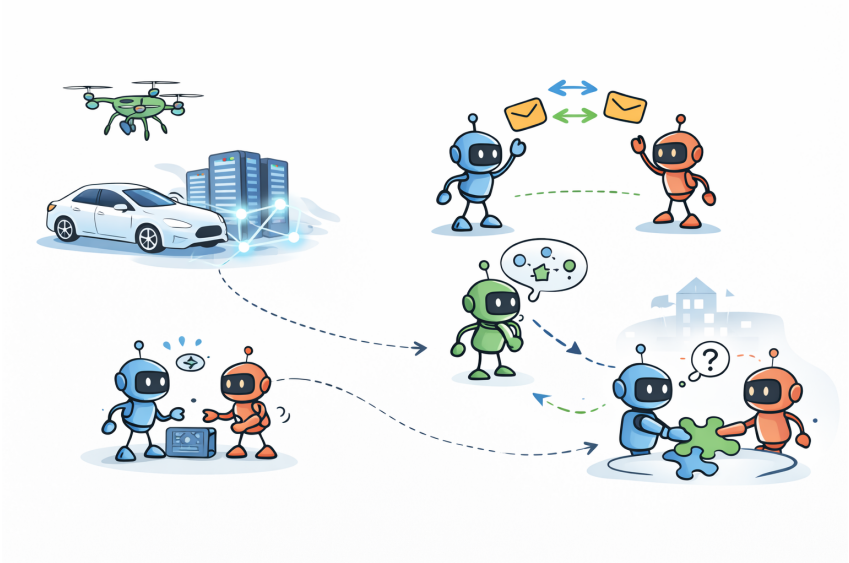

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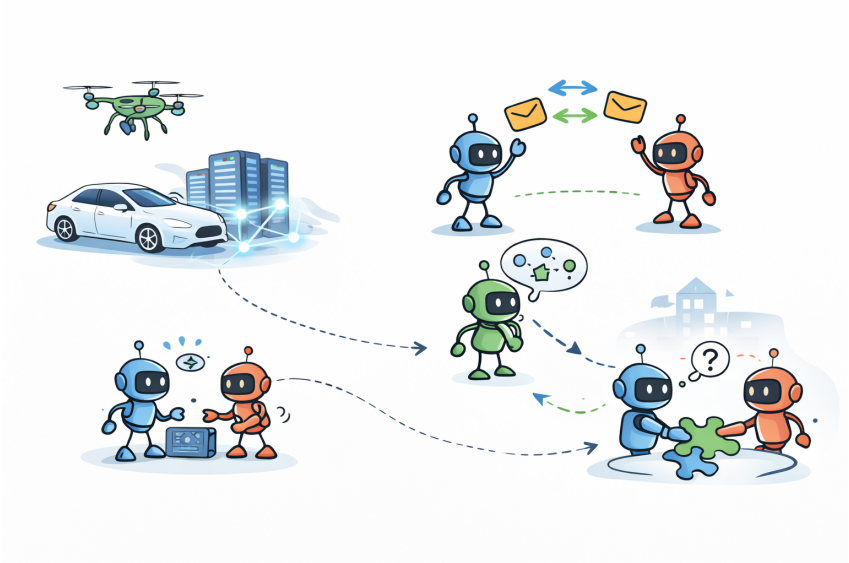

Correctness depends on interactions, not just components.

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Most failures in distributed and multi-agent systems are not caused by incorrect local behaviour, but by **unexpected interactions**.

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The real difficulty lies in composition.

From Interaction to Strategic Behaviour

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  - they plan
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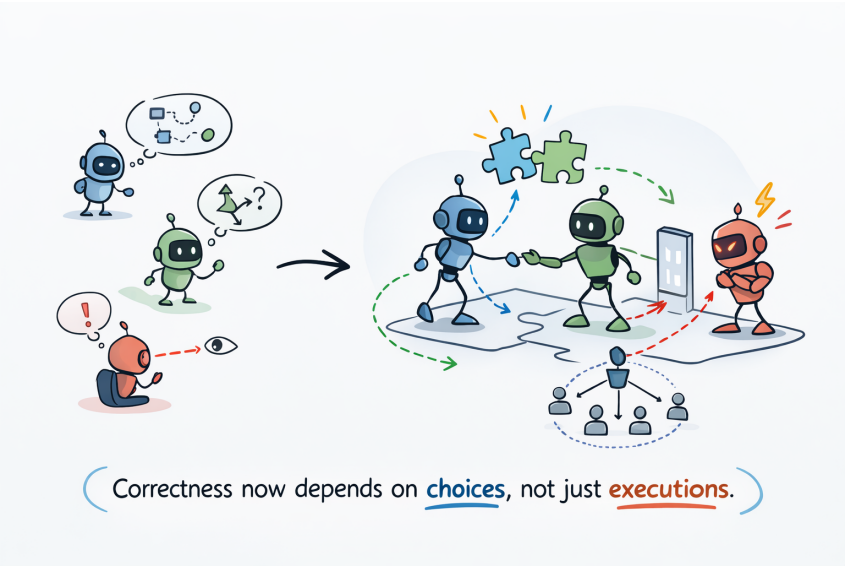

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- Interaction failures are often:
  - rare
  - emergent
  - invisible to testing
- They expose:
  - broken assumptions
  - unsafe compositions
  - missing strategic guarantees

Failures reveal what models and specifications must capture.

Policy Composition Failure: BGP Hijack

Domain: Internet routing **Year:** 2008

What happened

A local routing policy accidentally advertised a more specific prefix for YouTube, which propagated globally and redirected traffic worldwide.

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Verification lesson

Global safety requires verifying **policy composition** among agents.

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Safety depends on the **composition of strategies**, not on isolated agent.

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Verification lesson

Correctness must be verified under **heterogeneous agents and mixed versions**, not idealised uniform deployments.

Smart Contracts: Strategic Exploitation (The DAO)

Domain: Blockchain / smart contracts **Year:** 2016

What happened

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Verification lesson

Strategic reasoning is essential to guarantee global invariants against **adversarial strategies**.

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Domain: Autonomous vehicles **Year:** 2018

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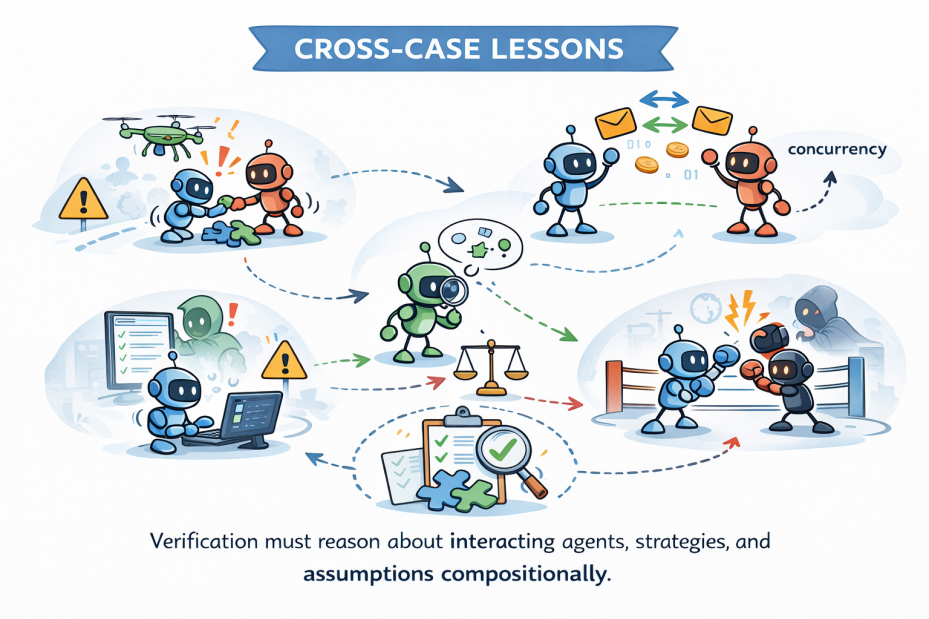
Verification lesson

Safety depends on **authority and strategy composition** between human and autonomous agents, not on any single controller.

Cross-Case Lessons

- Failures emerge from **interaction**, not local bugs
- Partial information and concurrency are the norm
- Strategic and adversarial behaviour cannot be ignored
- Assumptions do not compose automatically



From Failures to Formal Reasoning

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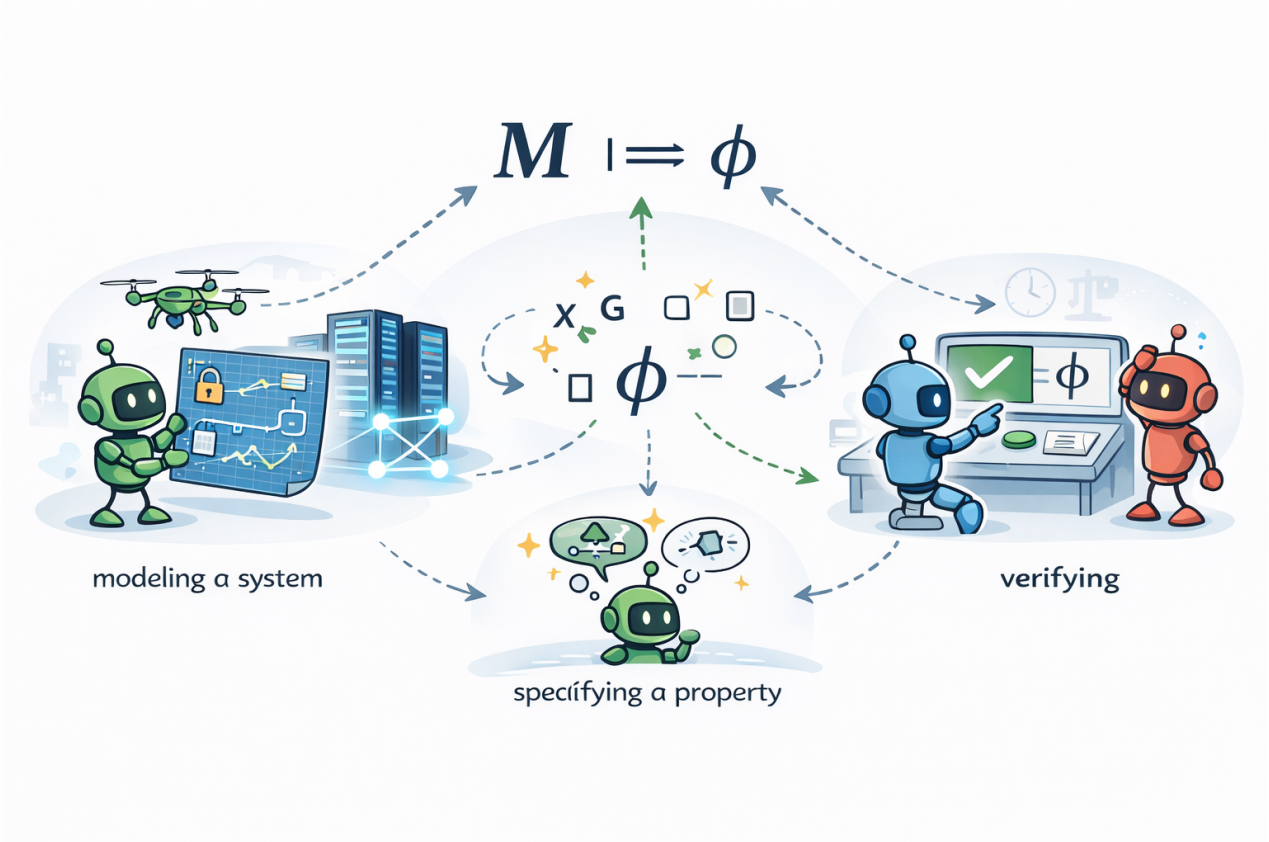
This is the role of model checking.

Model Checking



BACKGROUND: STRATEGIC LOGICS AND MODELS

Multi-agent Systems (1)

Key aspects

- There are many agents interacting among them.
- Each agent selects a *strategy*.
- A *strategy* is a conditional plan that prescribes an action at each step of the Multi-Agent System (MAS).
- The composition of strategies induces a computation.

Multi-agent Systems (2)

Model

- A MAS structure is a tuple $M =< \mathrm{AP}, St, s_I, Ac, Ag, L, tr >$, where:
  - AP is a set of atomic propositions;
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  - L is a labeling function;
  - tr is a transition function.
- The function tr depends on the interaction between the agents:
  - *Turn-based* $\Rightarrow$ The states of the MAS are partitioned between the agents, then the owner of a state determines the move to take and thus the next state of the MAS.
  - *Concurrent* $\Rightarrow$ The agents choose a move (i.e, actions) simultaneously and independently, and the joint action (i.e. the choices together) determine the next state of the MAS.

Multi-agent Systems (3)

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Depending on the memory, we distinguish between:

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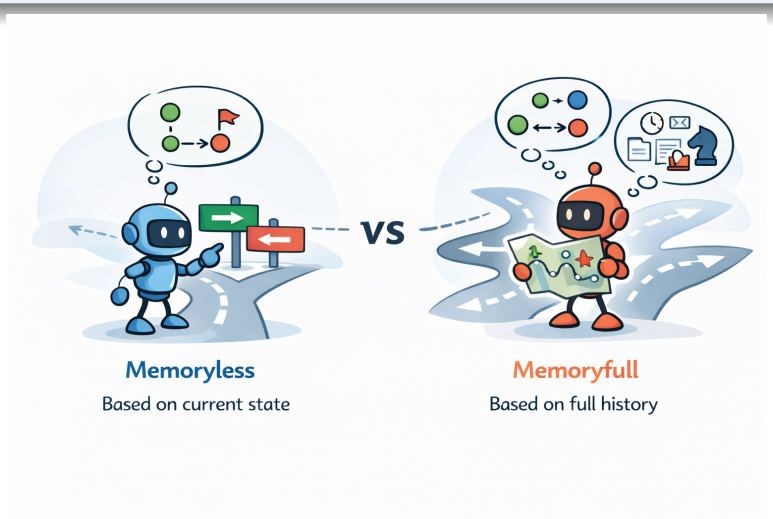
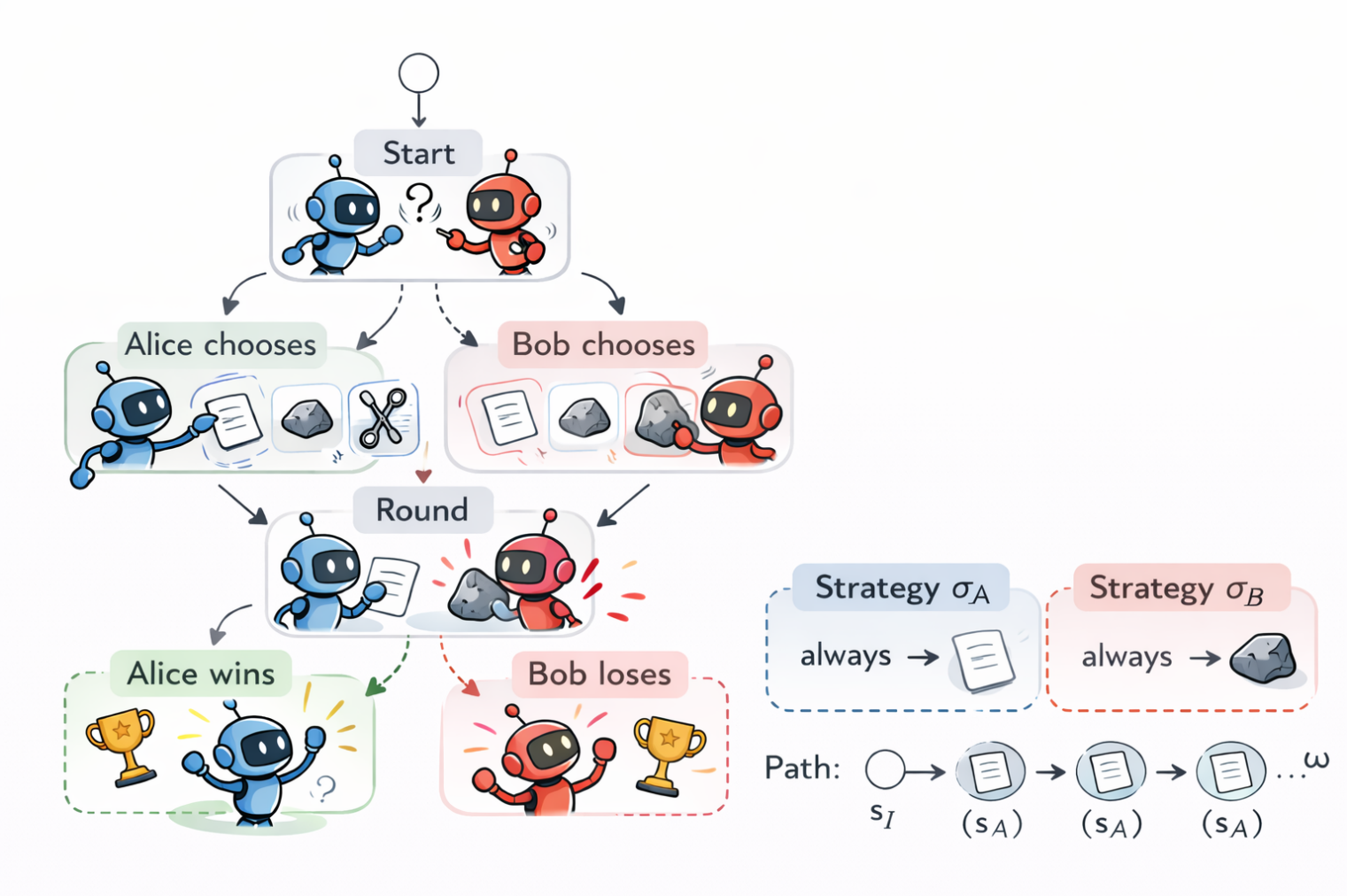
- *Memoryful strategies*
  $\sigma : St^+ \to \mathrm{Ac}$
  Decisions depend on the full history of the MAS.



Example: paper, rock, and scissor (1)



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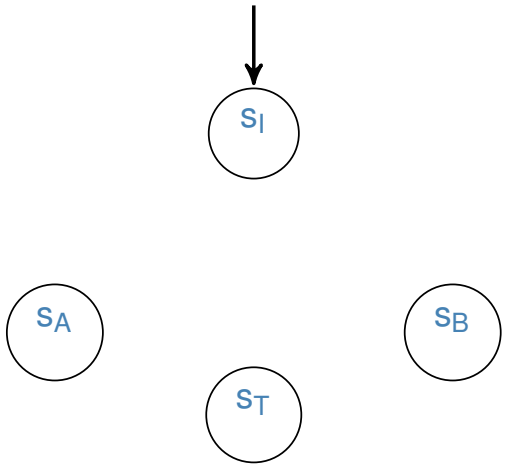

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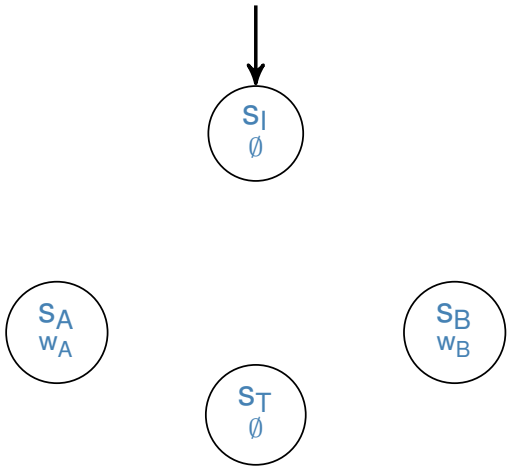

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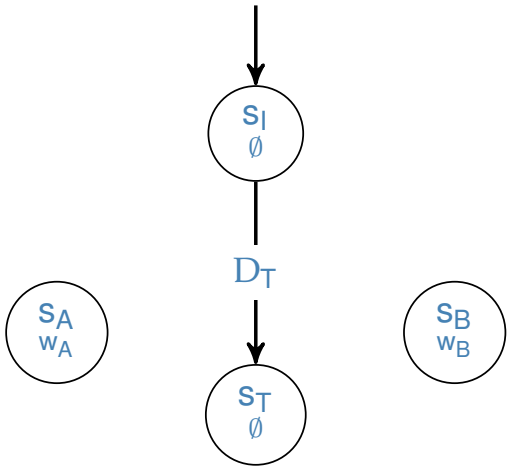

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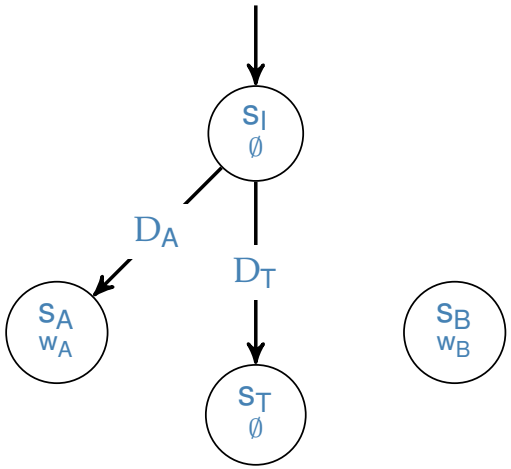

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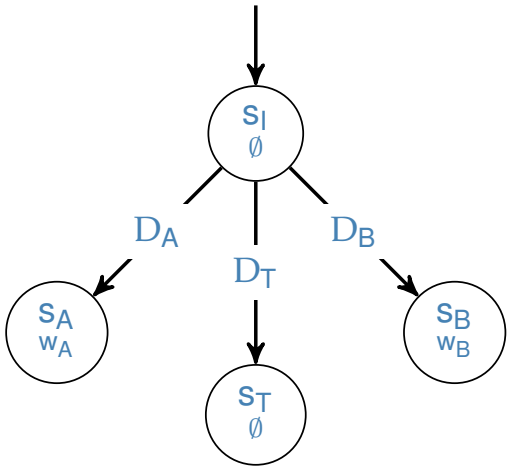

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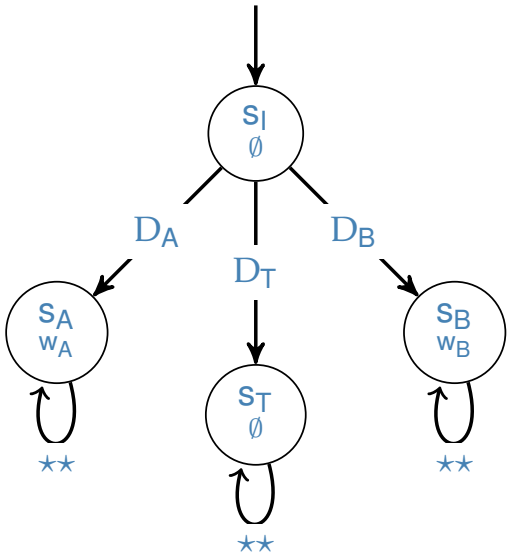

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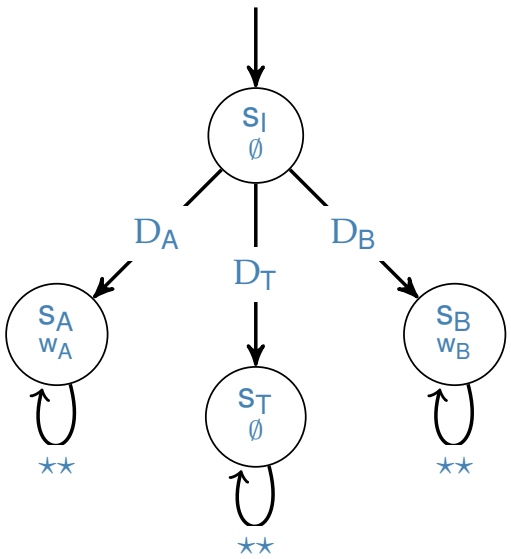

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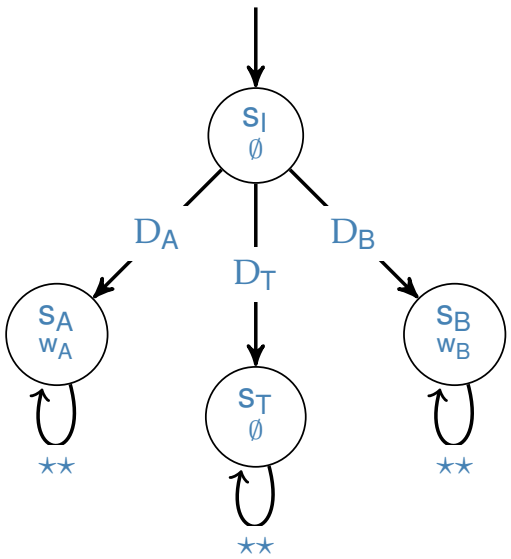

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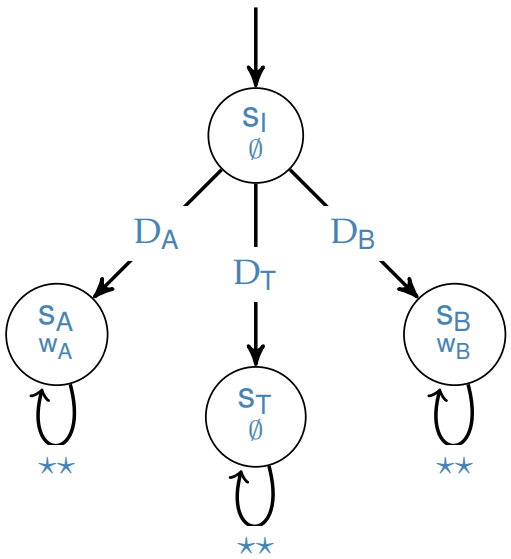

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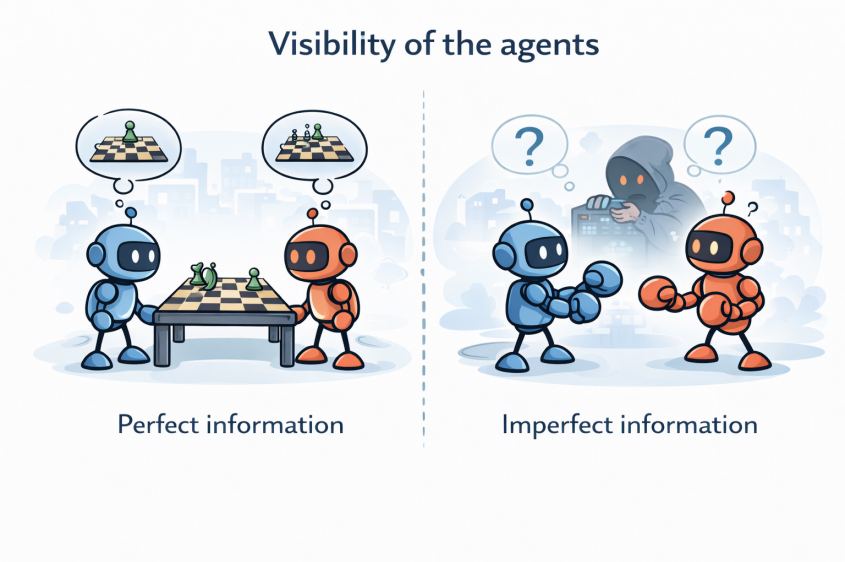
- *Imperfect information* MAS
  Agents often have to decide without all relevant information.



Specifications

Alternating-Time Temporal Logic (ATL*) [AHK02]

- ATL* generalizes CTL* by replacing the path quantification with strategy quantification over coalition of agents.
- It uses the strategy modality $\langle\langle A \rangle\rangle$ and $[\![A]\!]$, with A set of agents.
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Example

$\langle\langle \{\alpha, \beta\} \rangle\rangle \mathsf{G} \neg \mathit{fail}$: agents α and β have a collective strategy that prevents system failure regardless of other agents' strategies.

Verification: Model checking Complexities

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ATL

Strategies \ Information	**perfect**	**imperfect**
memoryless	*PTIME*-complete [AHK02]	P^{NP}-complete [Sch03]
memoryfull	*PTIME*-complete [AHK02]	undecidable [DT11]

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SPECIFICATIONS

Strategy Logic (SL) [MMPV14]

- SL treats the strategies as first-order objects.
- SL extends LTL with:
  - *strategy quantifiers* $\langle\langle x \rangle\rangle$ and $[\![x]\!]$ read respectively as *"there exists a strategy* x*"* and *"for all strategies* x*"*;
  - *agent binding* (a, x) that links an agent a to a strategy associated with a variable x.
- It subsumes other logics for strategic reasoning such as ATL*.
- It allows to represent Nash equilibrium and similar concepts.

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$\langle\langle \mathsf{x} \rangle\rangle \langle\langle \mathsf{y} \rangle\rangle [\![\mathsf{z}]\!] (\alpha, \mathsf{x})(\beta, \mathsf{y})(\gamma, \mathsf{z})(\mathsf{G} \neg \mathit{fail})$: α and β employ strategies x and y, respectively, ensuring non-failure regardless of γ's strategy z.

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Strategy Logic

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Enhance model checking complexity by reducing expressiveness

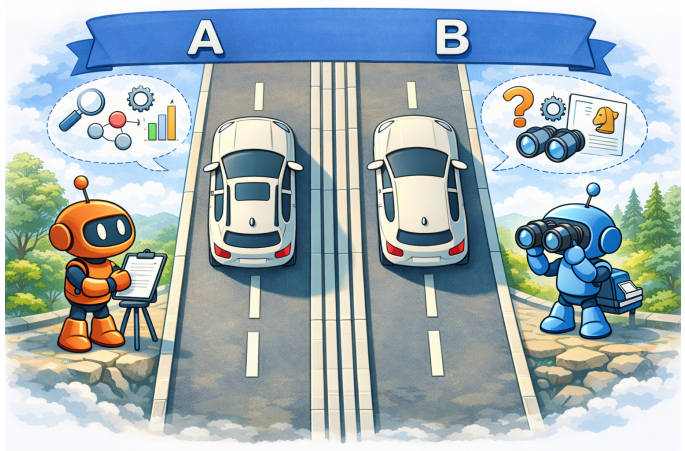
- SL[1G] model checking with perfect information and memoryfull strategies is $2EXPTIME$-complete [MMPV14].
- SL[SG] model checking with perfect information and memoryfull strategies is $PTIME$-complete [BJK$^+$19].

Why do we use logics for strategic reasoning?

WHY DO WE USE LOGICS FOR STRATEGIC REASONING?

Example

- 2 vehicles: A and B.
- B is in front of A.
- Goal: A wants to pass B (atom g).
- A Actions: pass (p), not pass (np).
- B Actions: accelerate (a), not accelerate (na).



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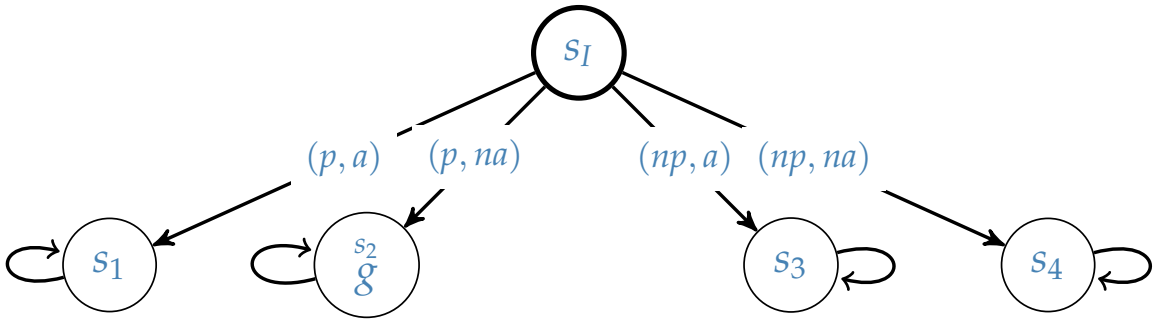
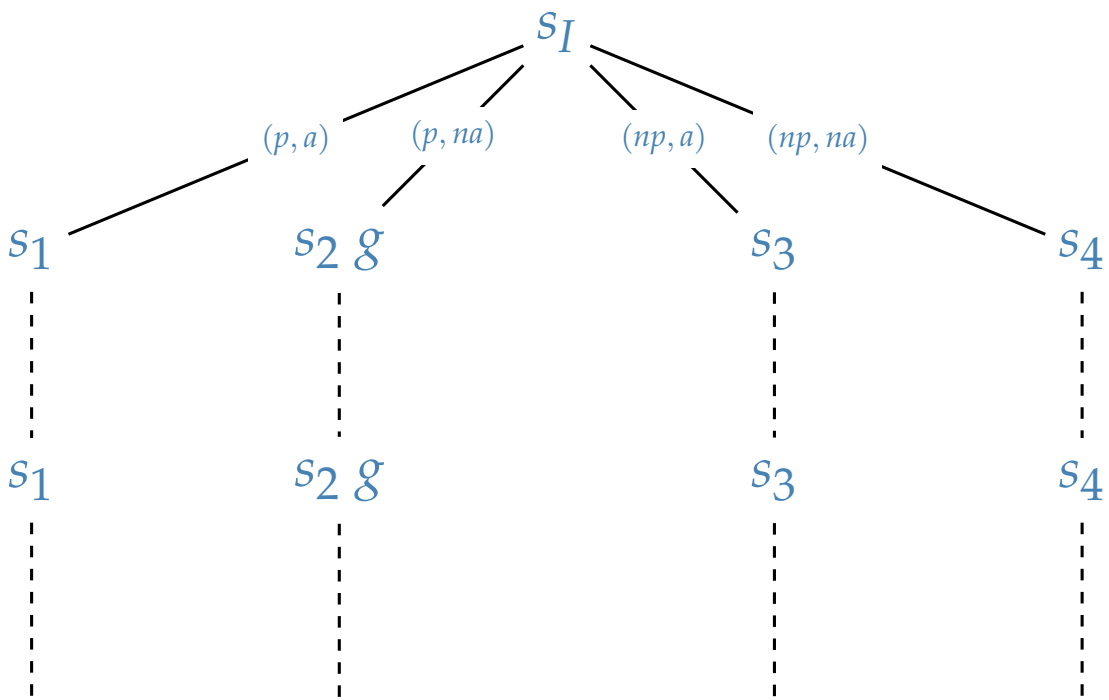
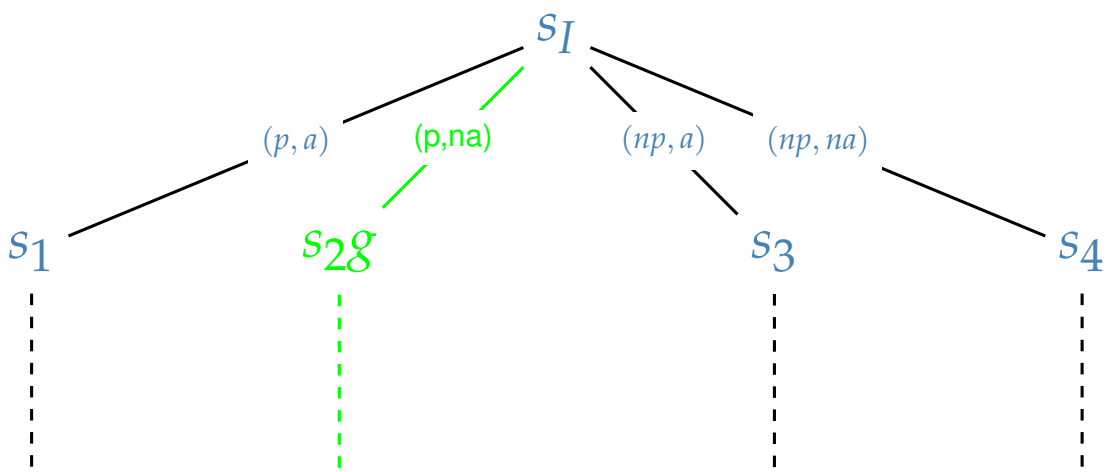


Unwinding of the model



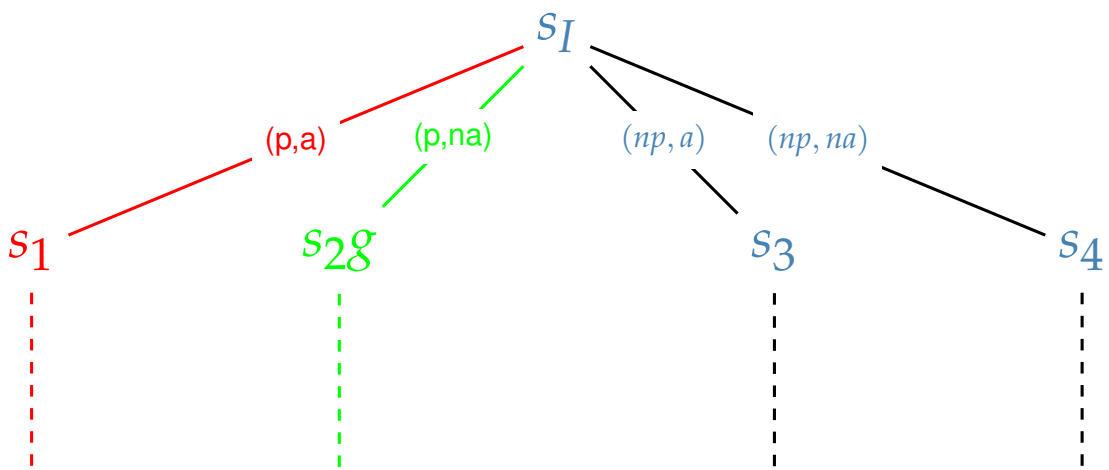
What can we do with CTL?

- The formula $EF\ g$ is verified in the path: $s_I, s_2, \ldots$



What can't we do with CTL?

- Is there a strategy for A to achieve g?
  - if A select the action p then we need to verify the formula in the paths: $s_I, s_1, \ldots$ (false) and $s_I, s_2, \ldots$ (true);



Comparison between CTL and ATL

Summary

- The formula in CTL $EF\, g$ is true.
- The formula in ATL $\langle\langle A \rangle\rangle F\, g$ is false.
- In the model there is a path where A can pass B but there is no strategy for A to pass B!
- With CTL we cannot verify properties on subsets of paths.

STRATEGIC VERIFICATION IN VITAMIN

State of the Art: Tool-Centred Verification

- Formal verification of Multi-Agent Systems (MAS) is supported by tools such as **MCMAS** and **STV**.
- These tools demonstrate that **strategic and epistemic verification is feasible in practice**.

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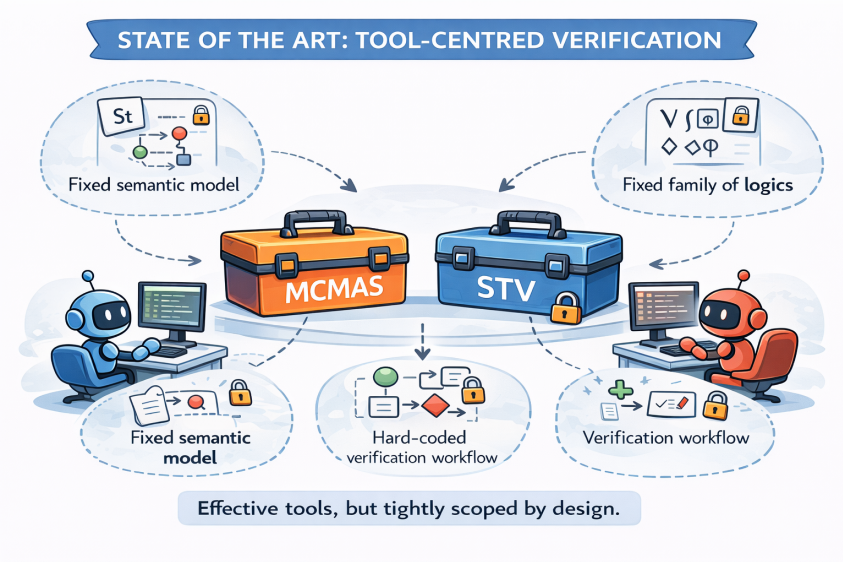

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- Provide **sound and efficient** verification within their scope
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Key observation

Existing tools are *highly effective* when used as intended.

Evidence: Feature Comparison

Feature	MCMAS	STV	VITAMIN
GUI	(✓)	✓	✓
Internal documentation	(✓)	×	✓
External documentation	×	×	✓
Modular architecture	×	×	✓
Cross-platform	×	✓	✓
API / integration	×	×	✓
Support for non-experts	×	×	✓

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- **Takeaway:** current tools are *not designed* for extensibility and reuse across verification scenarios.

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  - compositional verification
  - systematic experimentation
  - non-expert users

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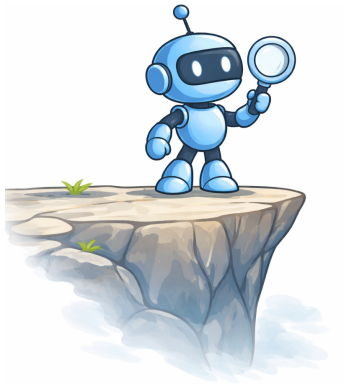

This calls for a framework, not another monolithic tool.

From Limitations to Design Goals

Observed problems

- **Hard-coded** verification pipelines
- **Tight** model–logic **coupling**
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- **Compositional** architecture
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User roles

- End-users (expert / non-expert)
- High-level developers (models, logics)
- Low-level developers (optimisation)

Supported Logics: Evidence of Generality

Logic	VITAMIN	MCMAS	STV
CTL	✓	✓	×
ATL	✓	✓	✓
SL	✓$^{\text{lim}}$	✓$^{\text{lim}}$	✓$^{\text{lim}}$
CTLK / ATLK	×	✓	✓$^{\text{lim}}$
ATLF	✓	×	×
RBATL	✓	✓	×
RABATL	✓	×	×
NatATL	✓	×	×
OL	✓	×	×
OATL	✓	×	×
NatOL	✓	×	×
capATL	✓	×	×
NatSL	✓	×	×
WATL	✓	×	×
TOL	✓	×	×
POL	✓	×	×

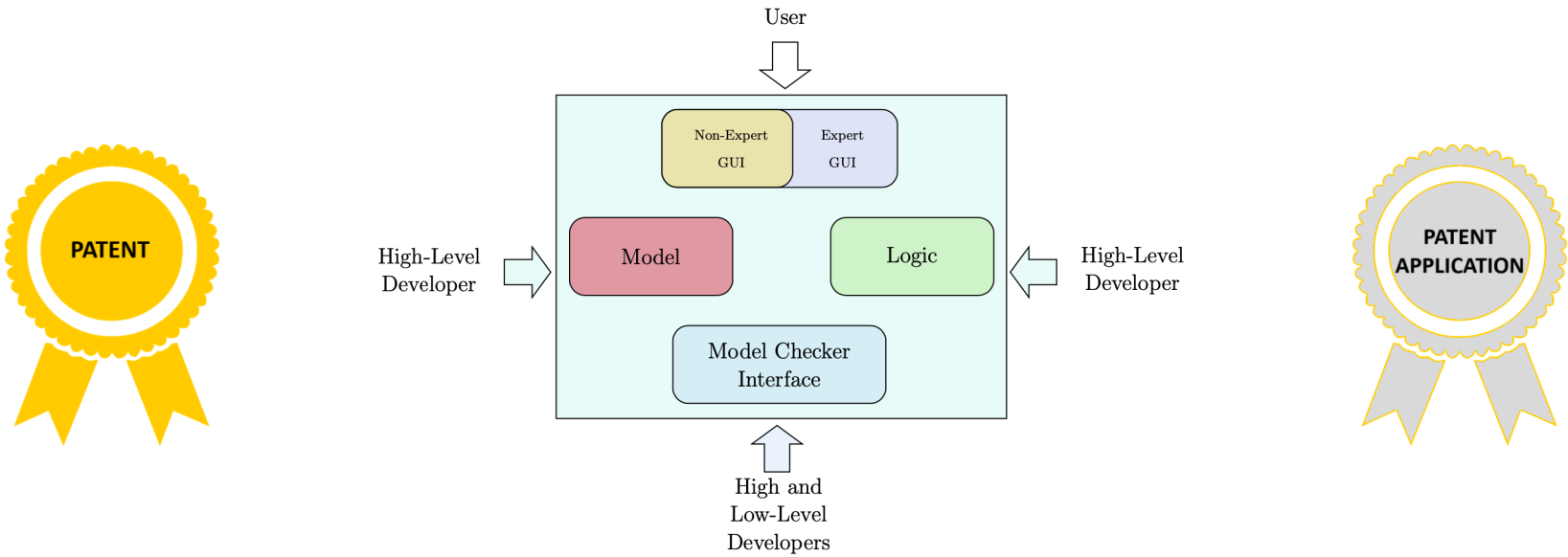
Legend: ✓ = native; ✓$^{\text{lim}}$ = partial/limited; × = not supported.

VITAMIN in One Sentence

VITAMIN is not just a model checker, but a compositional **framework** for **designing**, **experimenting** with, and **deploying** strategic verification solutions for Multi-Agent Systems.

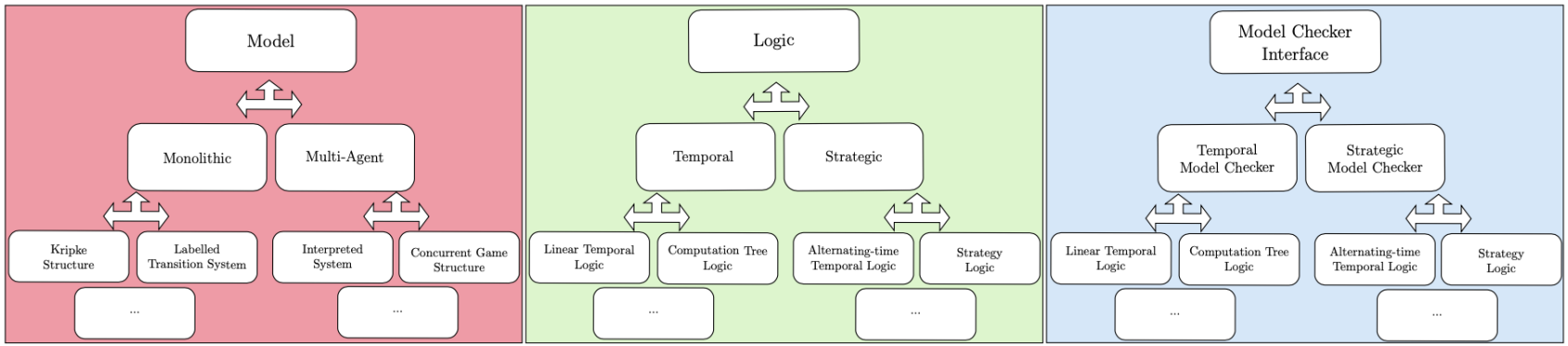
VITAMIN

- VITAMIN (VerIficaTion of A MultI-ageNt system) since **2022**
- Highly compositional and supports various logic and models
- User-friendly experience for both developers and end-users

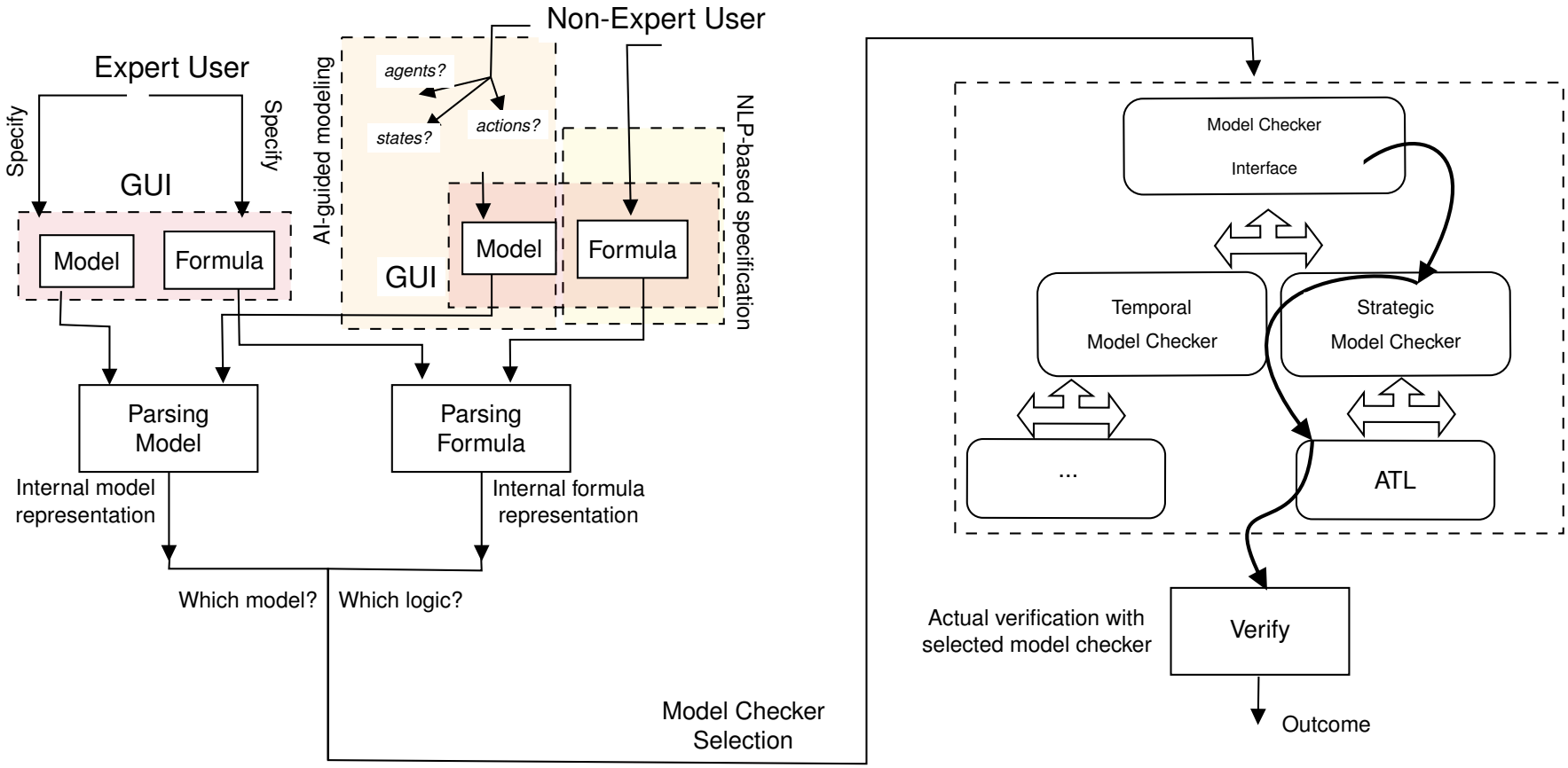


Advantages of VITAMIN

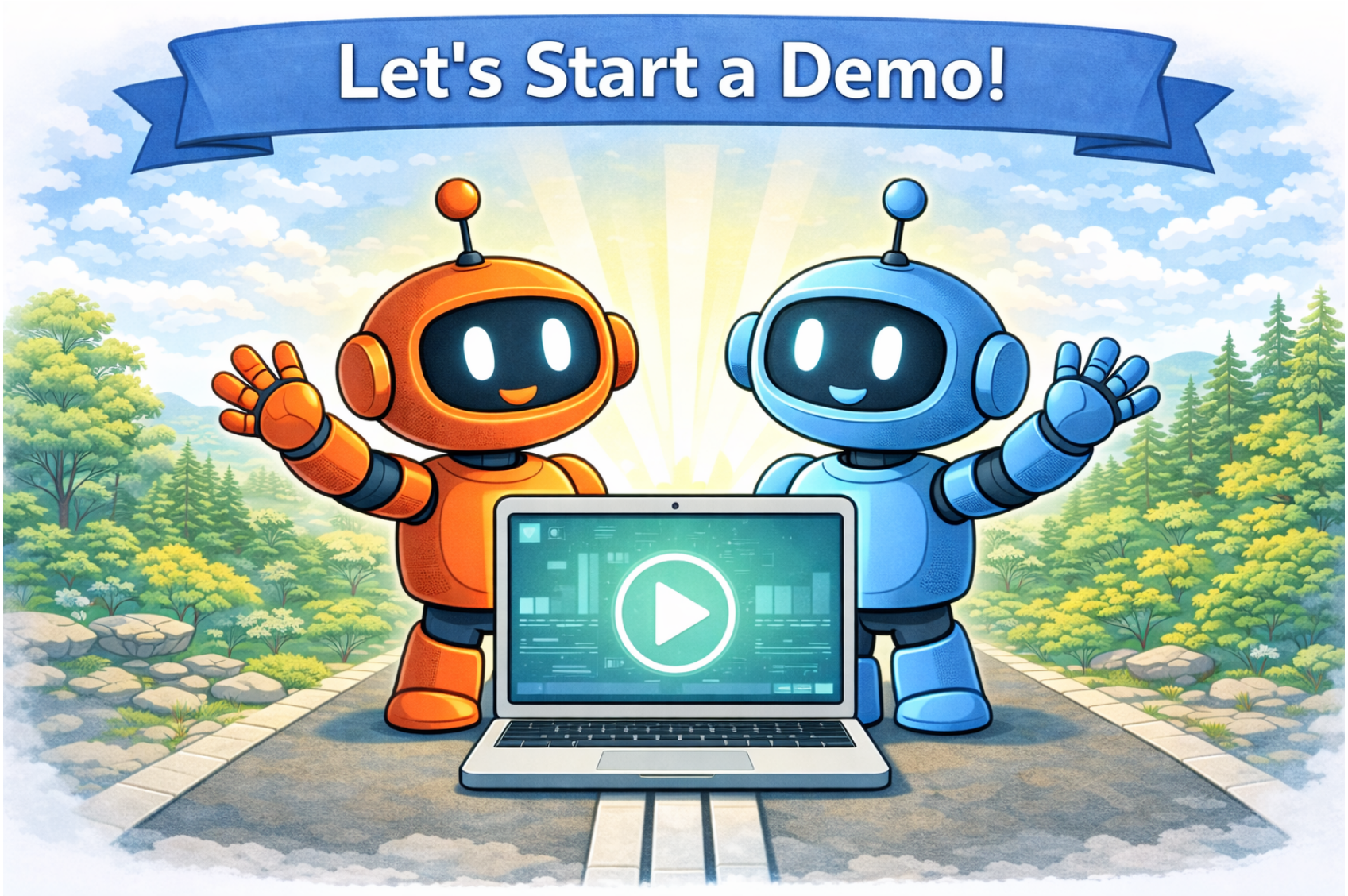
- Generalises MAS verification without being tied to specific logic or model formalisms
- Enhanced user experience guiding the entire verification process
- Compositional nature allows for straightforward extension



Verification Flow



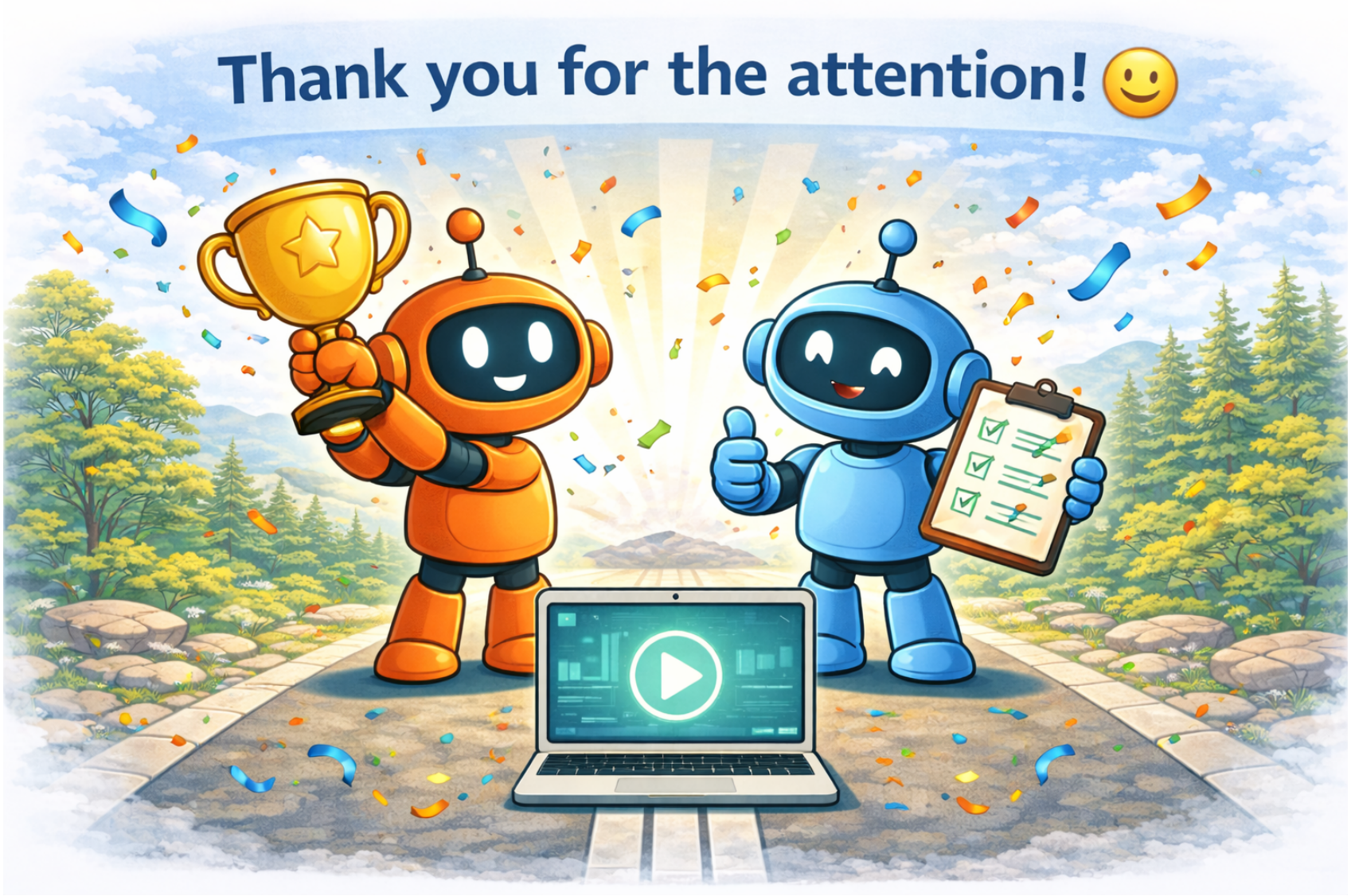
DEMO



Future Directions

Future Directions

- **VITAMIN**, key goals we aim to achieve:
  - Use AI to assist users in generating formal models and formulas.
  - Low-level development with symbolic & abstraction methods.
  - Use AI to optimize the verification process, making it scalable.
  - Ensure the tool is robust, easily extensible, and deployable.


Thank you for the attention!

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