The Complexity of Asynchronous HyperLTL

Joint work with Gaëtan Regaud (ENS Rennes, France)

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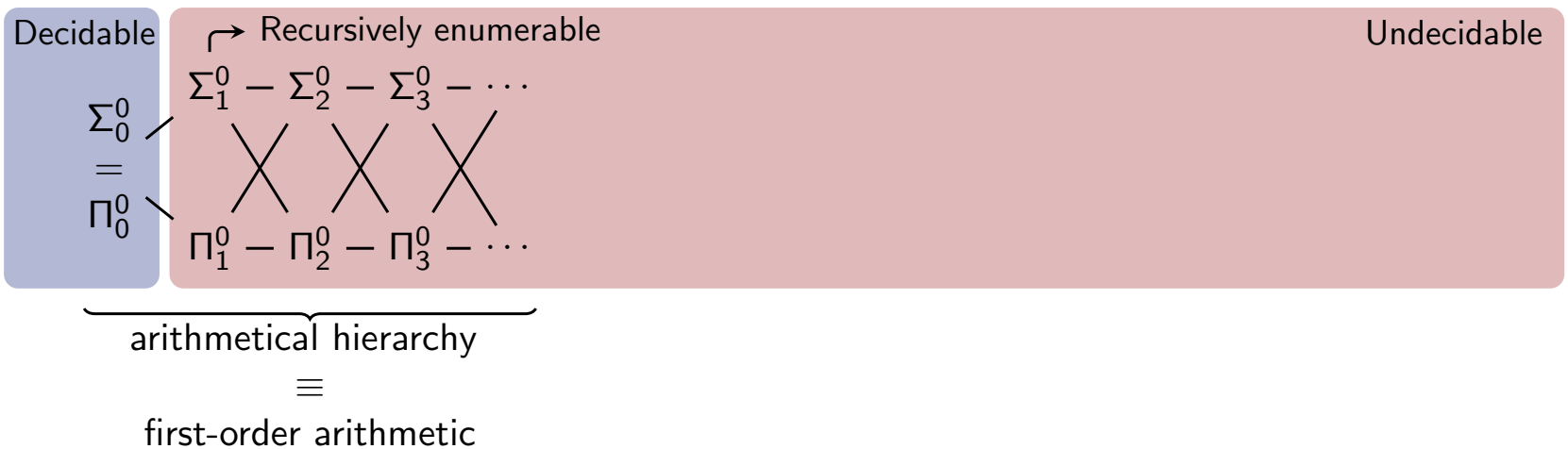

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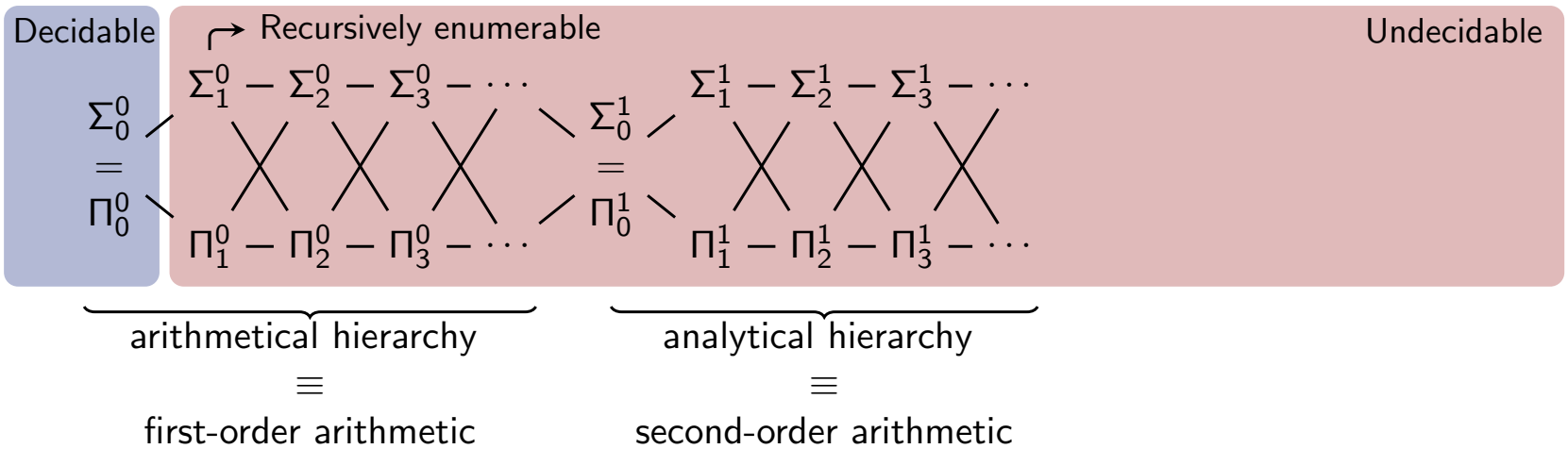

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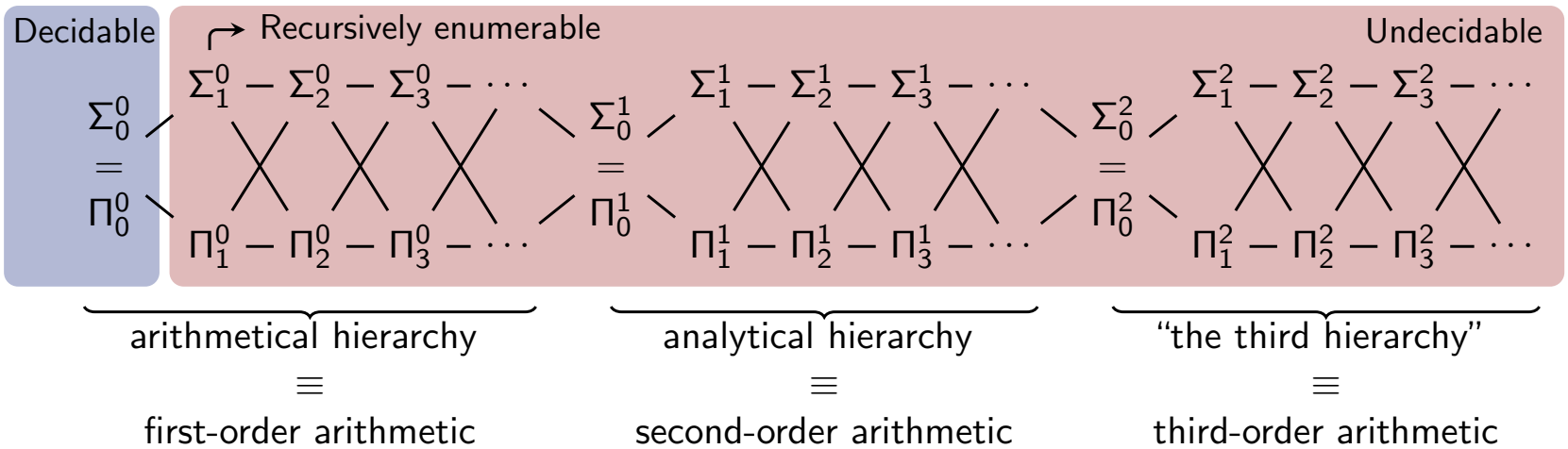

Synchronicity

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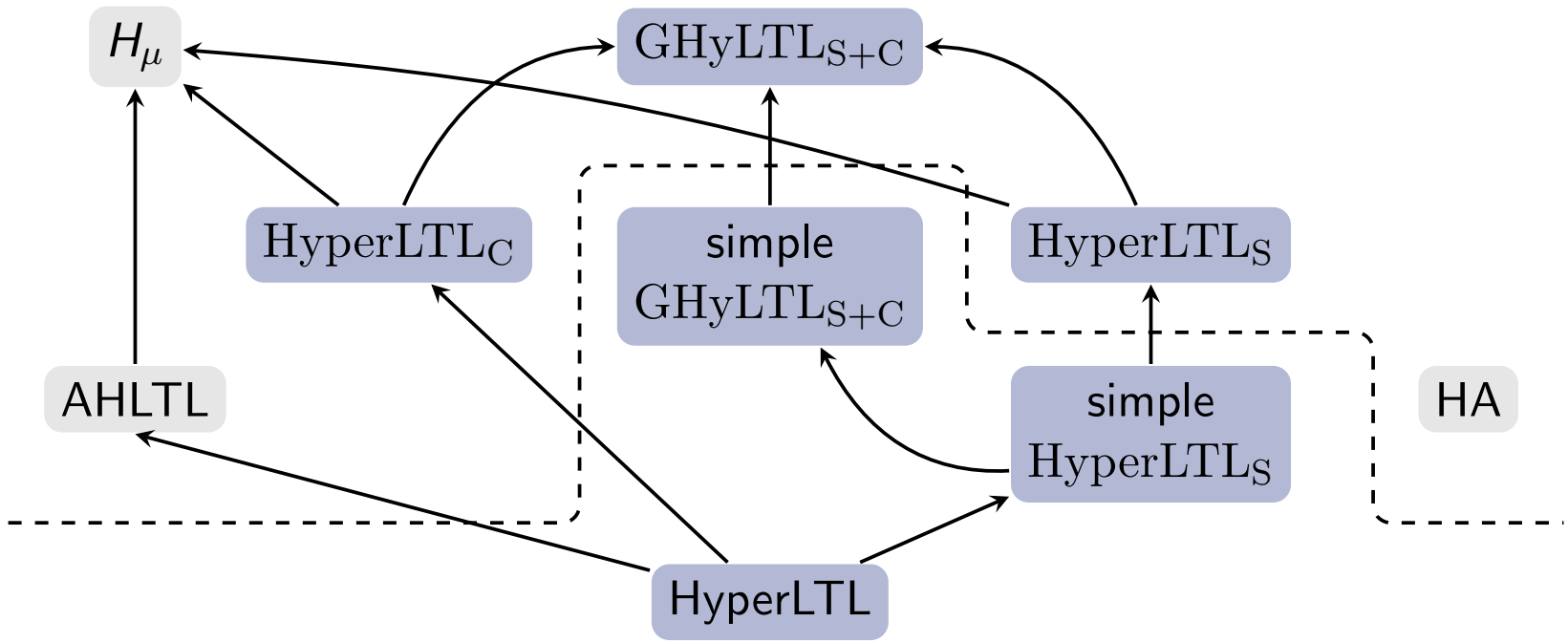
The second generation of **asynchronous** hyperlogics:



Results for Stuttering and Contexts

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Trajectories

Trajectories describe how time passes on different traces.

Example

$$\pi: \quad \emptyset \quad \emptyset \quad \emptyset \quad \{a\} \quad \emptyset \quad \emptyset \quad \emptyset \quad \emptyset \quad \emptyset \quad \cdots$$

$$\pi': \quad \{b\} \quad \emptyset \quad \{b\} \quad \emptyset \quad \{b\} \quad \emptyset \quad \emptyset \quad \emptyset \quad \emptyset \quad \cdots$$

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- With trajectory $\{\pi'\}(\{\pi,\pi'\})^\omega$, $\mathbf{F}(a_\pi \wedge b_{\pi'})$ is satisfied.
- With trajectory $\{\pi\}^3(\emptyset)^\omega$, $\mathbf{G}\,\mathbf{F}(a_\pi \wedge b_{\pi'})$ is satisfied.

Asynchronous HyperLTL (AHLTL)

AHLTL extends HyperLTL with trajectory quantification:

$$\mathcal{O}_0\pi_0\mathcal{O}_1\pi_1\cdots\mathcal{O}_{k-1}\pi_{k-1}\,\mathsf{Q}\,\psi$$

where

- $\mathcal{O}_0\pi_0\mathcal{O}_1\pi_1\cdots\mathcal{O}_{k-1}\pi_{k-1}$ is a block of trace quantifiers (i.e., $\mathcal{O}_j \in \{\exists, \forall\}$) as in HyperLTL,
- Q existentially ($\mathsf{Q} = \mathsf{E}$) or universally ($\mathsf{Q} = \mathsf{A}$) quantifies a trajectory t for the variables $\pi_0, \ldots, \pi_{k-1}$, and
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Fragments:

- E-AHLTL: existential trajectory quantification
- A-AHLTL: universal trajectory quantification

State of the Art

Baumeister, Coenen, Bonakdarpour, Finkbeiner, and Sánchez ('21)

- Model-checking E-AHLTL is undecidable, but
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Bozzelli, Peron, and Sánchez ('22)

- HyperLTL satisfiability can be reduced to E-AHLTL satisfiability, so it is Σ^1_1-hard.

Accessing Trajectories

The quantified trajectory t can only indirectly be accessed:
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2. *Let π be mapped to a trace where the truth value of p changes at every step. Then, $\mathbf{G}(p_\pi \leftrightarrow \mathbf{X}\,\neg p_\pi)$ is satisfied w.r.t. t if and only if time passes on π at every position.*

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This allows us to reduce HyperLTL to AHLTL and to constrain trajectories.

Satisfiability

Recall:

Lemma (Bozzelli, Peron, and Sánchez ('22))

E-AHLTL satisfiability is as hard as HyperLTL satisfiability, i.e., Σ^1_1*-hard.*

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Proof sketch

- Every satisfiable AHLTL formula has a countable model.
- Express the existence of countable models in arithmetic.

“Small” Models

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- W.l.o.g. $\varphi = \forall \pi_0 \exists \pi'_0 \cdots \forall \pi_k \exists \pi'_k \, \mathsf{Q} \, \psi$ with quantifier-free ψ.
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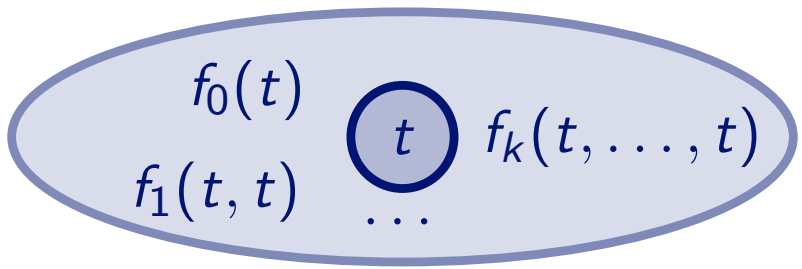

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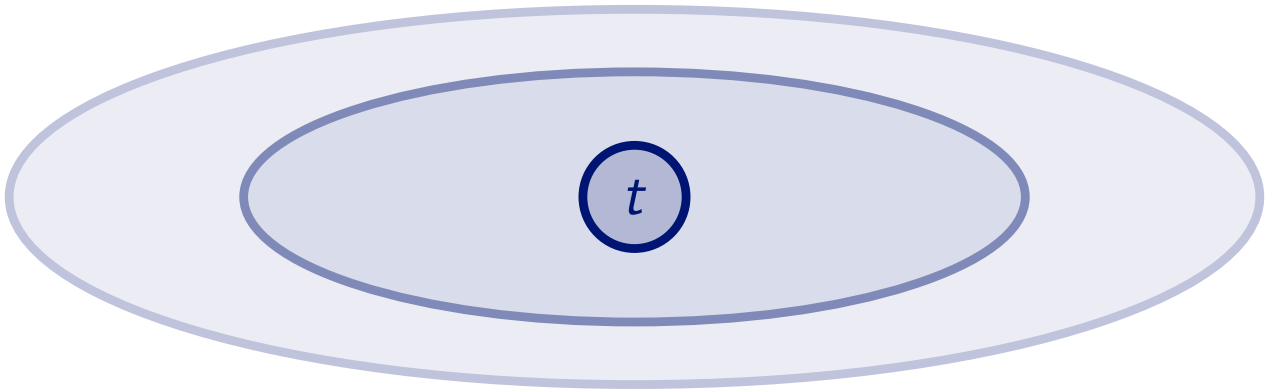

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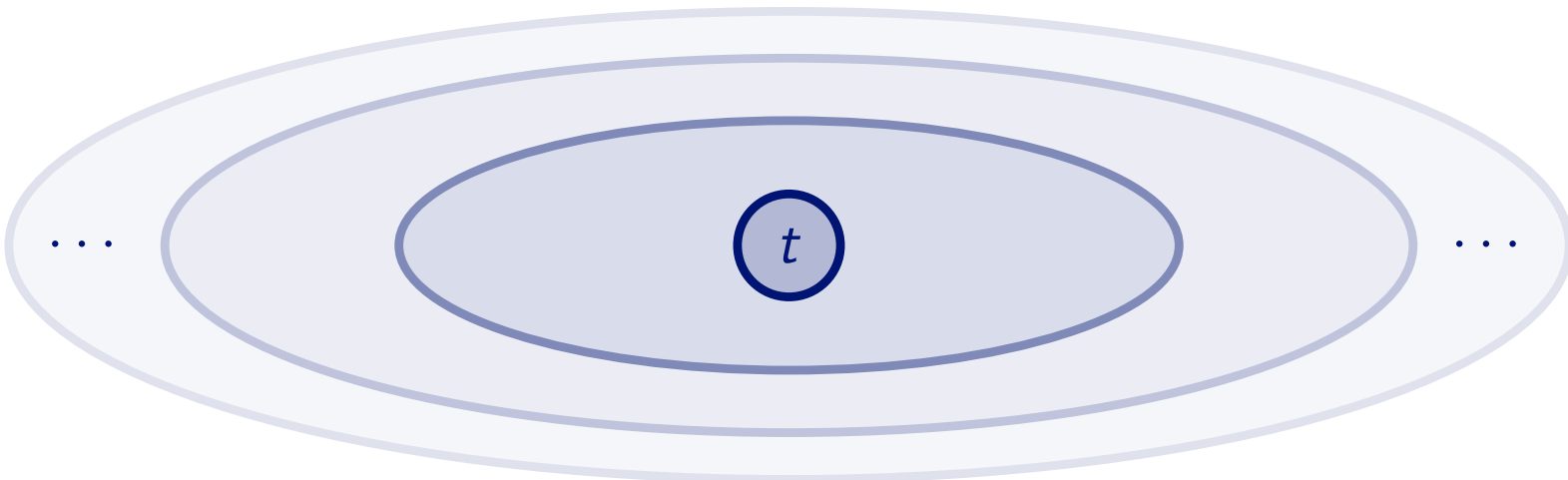

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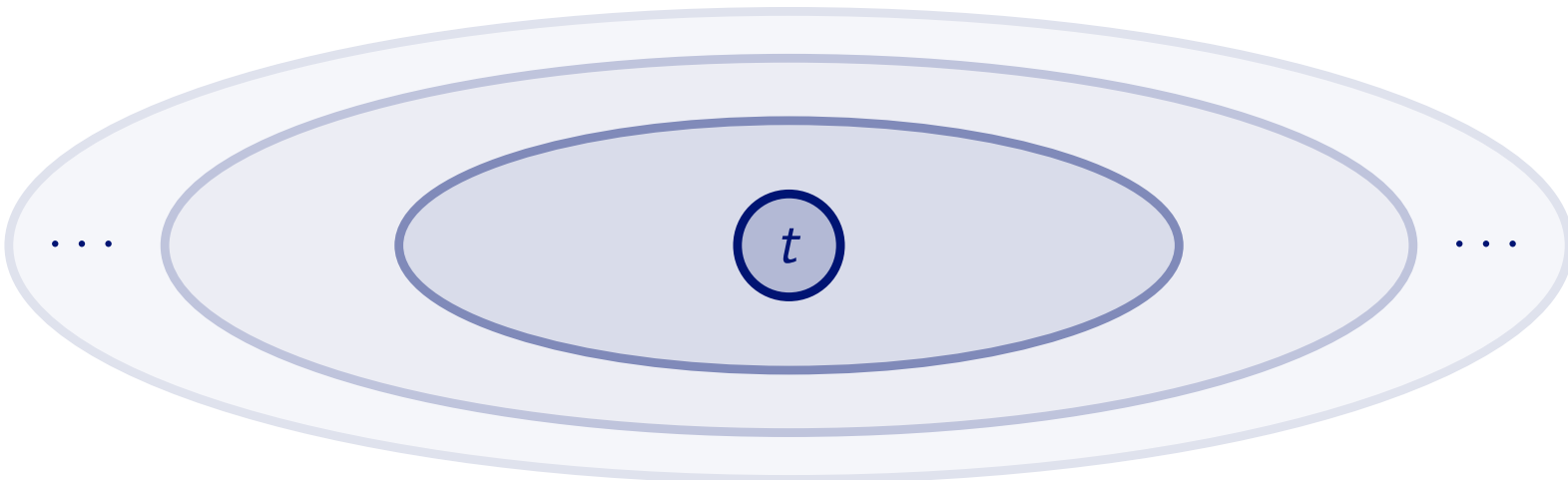

The limit is a model of φ and countable.

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- For A-AHLTL satisfiability, the trajectory needs to be quantified universally: $\exists T\, \exists \mathcal{S}\, \forall t\, \forall \mathit{Tblx}\, \psi'(T, \mathcal{S}, t, \mathit{Tblx})$ with first-order ψ'.

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- One can write a formula of second-order arithmetic that checks whether a trace comes from a given transition system.
- Assignments and trajectories can be encoded as sets of natural numbers.
- Hence, the whole semantics of AHLTL can be encoded in second-order arithmetic.

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The result for E-AHLTL follows by duality.

Results

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AHLTL	Σ_1^1-hard/in Σ_2^1	T2A-equiv.	T2A-equiv.
A-AHLTL	Σ_1^1-hard/in Σ_2^1	T2A-equiv.	T2A-equiv.
E-AHLTL	Σ_1^1-complete.	T2A-equiv.	T2A-equiv.

Future Work

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