SYNTHESIS OF TIMELINE-BASED PLANNING STRATEGIES AVOIDING DETERMINIZATION

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TIMELINE-BASED PLANNING

Timeline-based planning is an approach to planning mostly focused on temporal reasoning:

- no clear separation between actions, states, and goals;
- planning problems are modeled as systems made of a number of independent, but interacting, components;
- components are described by **state variables**;
- the **timelines** describe their evolution over time;
- the evolution of the system is governed by a set of temporal constraints called **synchronization rules**.

WHY TIMELINES?

Timeline-based planning systems shine when:

- modeling and reasoning about systems made of many **components**, rather than the behavior of a single agent
- approaching problems where **temporal reasoning** is key

TIMELINES AND SPACE EXPLORATION

Timeline-based planning was born in the space operations field, and has been used in real-world mission planning and scheduling systems, both on-board and on-ground.

N. Muscettola. *HSTS: Integrating Planning and Scheduling*. Intelligent Scheduling 1994

J. Barreiro et al. *EUROPA: A Platform for AI Planning, Scheduling, Constraint Programming, and Optimization*. ICKEPS 2012

S. Chien et al. ASPEN – Automated Planning and Scheduling for Space Mission Operations. 2000

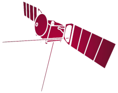
European Space Agency

A. Cesta, G. Cortellessa, S. Fratini, and A. Oddi. *Developing an End-to-End Planning Application from a Timeline Representation Framework*. IAAI 2009

S. Fratini, A. Cesta, R. De Benedictis, A. Orlandini, and R. Rasconi. *APSI-Based Deliberation in Goal Oriented Autonomous Controllers*. ASTRA 2011

DOMAIN EXAMPLE

Mars orbiter



Toy example of a Mars orbiter doing scientific measurements:

1. Three "pointing modes": **Mars**, Slewing, Earth
2. Four "activities": Science, Communication, Maintenance, Idle
3. Temporal constraints:
   - Scientific measurements can be done only when pointing to Mars
   - Communication can happen:
     - only when pointing to Earth
     - only when a receiving ground station is visible
4. Goals:
   - Perform at least a given number of scientific measurements

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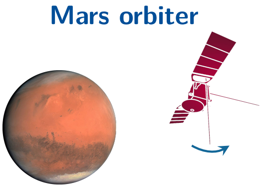

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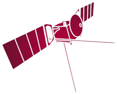

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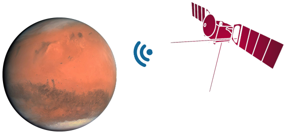

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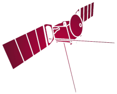


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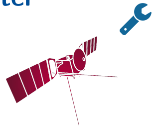

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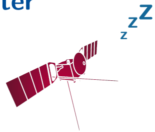

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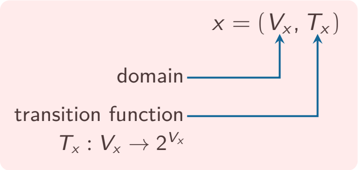
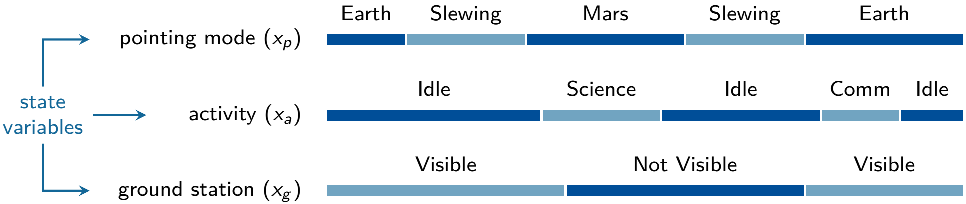
STATE VARIABLES AND TIMELINES

State variables represent the components of the system:



Timelines encode possible evolutions of state variables

- sequences of **tokens**, i.e., time intervals where the variable holds a single value
- token transitions respect T_x
- **tokens have a duration** (positive integer) – **time is discrete**



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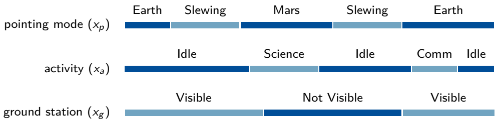

The interaction of the components is governed by the synchronization rules.

Example

Scientific measurements can be done only when pointing to Mars:

$$a[x_a = Science] \rightarrow \exists b[x_p = Mars] \,.\, start(b) \leqslant start(a) \wedge end(a) \leqslant end(b)$$

for all tokens a **where** $x_a = Science$,
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such that b **contains** a.

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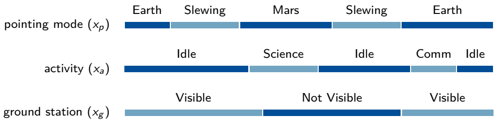

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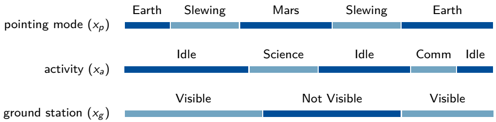

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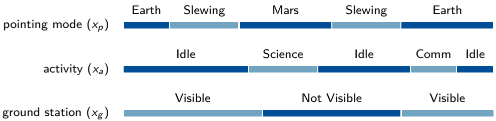

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SYNTAX – SYNCHRONIZATION RULES

Each rule has a fixed structure:

$$a[x = u] \quad \rightarrow \quad \exists b[y = v] \;.\; \langle body \rangle$$

$$\bigvee$$

$$\exists c[z = w] d[k = r] \;.\; \langle body \rangle$$

$$\bigvee$$

$$\ldots$$

optional trigger

existential statements

Example

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SYNTAX – ATOMS

The body is made of a **conjunction** of **atoms** (temporal relations):

$$start(a) \leqslant end(b)$$

endpoint → *start*

token name → *a*

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lower bound
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QUANTITATIVE TIMELINE-BASED PLANNING

Quantitative timeline-based planning problem ***(quantitative atoms allowed)***

Given a set of state variables SV and a set of synchronization rules S,
is there a set of timelines for SV satisfying S?

Theorem [Gigante, Montanari, Cialdea Mayer, Orlandini, ICAPS 2017]

Quantitative timeline-based planning is EXPSPACE-**complete** *(quantitative atoms **allowed**)*

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Automata-based procedure in EXPSPACE [Della Monica, Gigante, Montanari, Sala, KR 2018]

QUALITATIVE TIMELINE-BASED PLANNING

we focus on
qualitative atoms

Theorem [Della Monica, Gigante, La Torre, Montanari, TIME 2020]

Qualitative timeline-based planning is PSPACE-**complete** *(quantitative atoms **not allowed**)*

- automata-based procedure

AUTOMATA-BASED PROCEDURE

The problem is encoded into an **automaton**:

- the encoding produces a **nondeterministic** finite automaton
- the NFA accepts (a word representing) a plan iff the plan is a solution for the problem
- the size of the automaton is **exponential** in the size of the problem
- solving the reachability problem **on-the-fly** gives us the **PSPACE** upper bound

NFA ENCODING PLAN EXISTENCE

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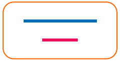

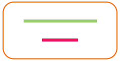

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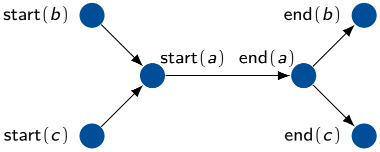

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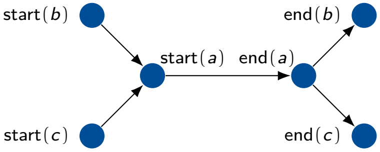

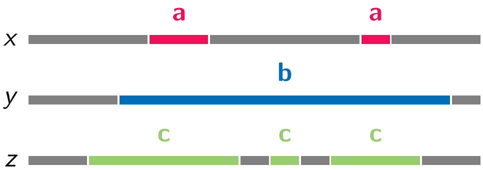

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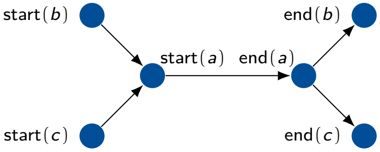

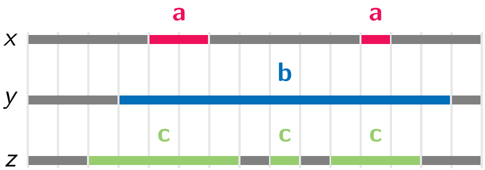

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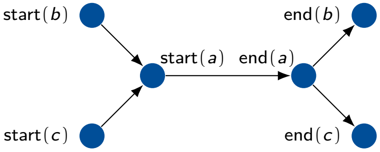

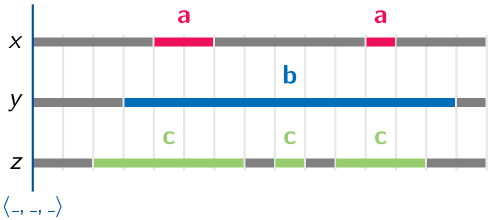

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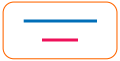

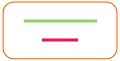

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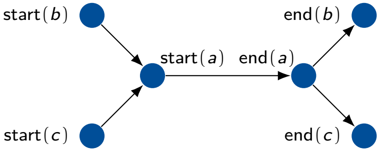

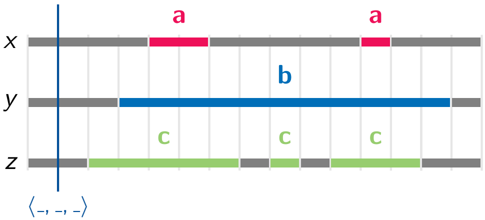

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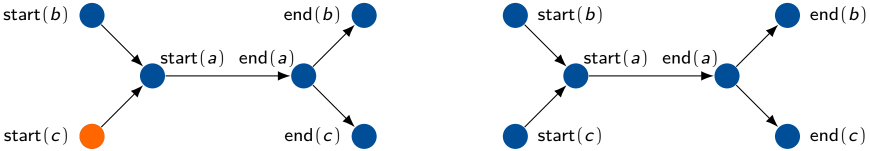

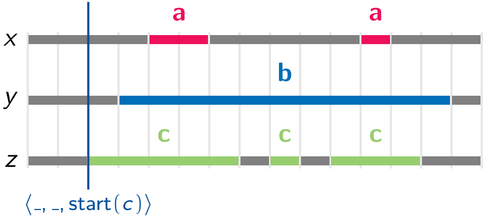

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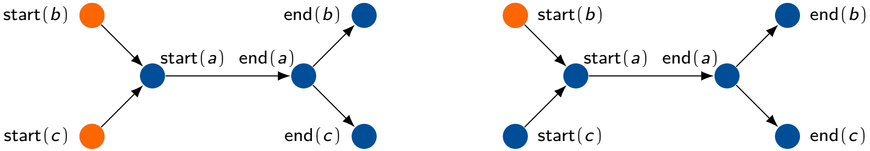

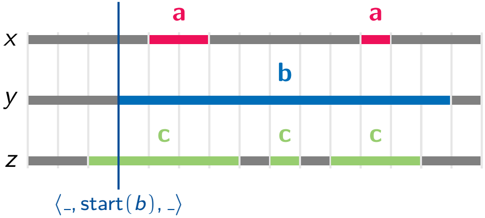

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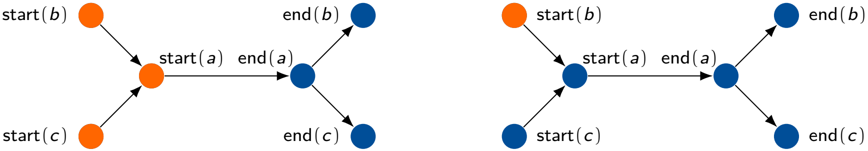

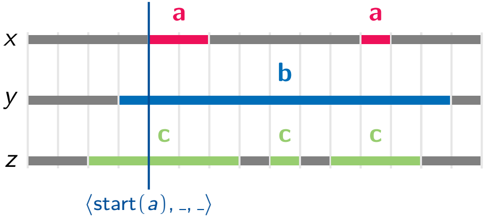

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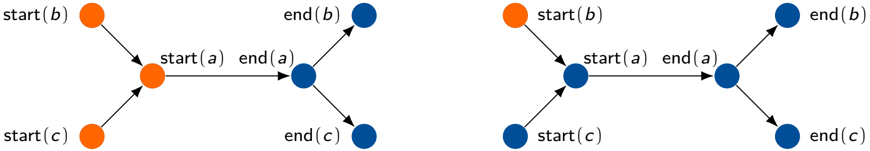

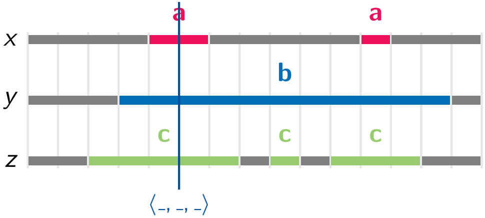

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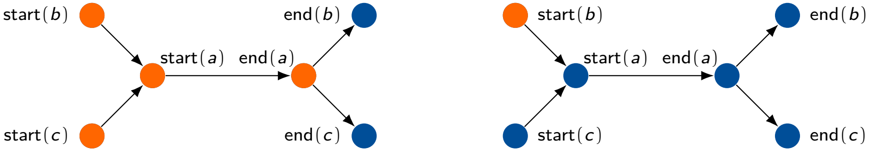

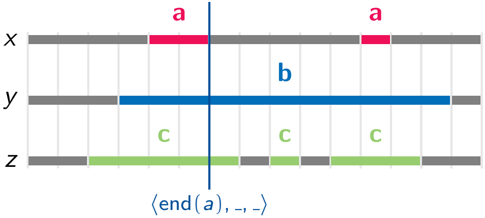

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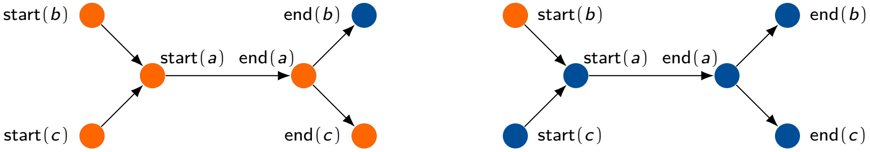

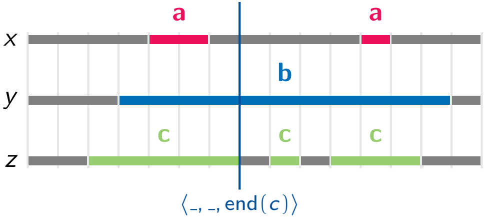

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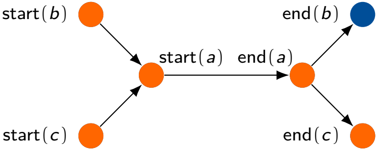

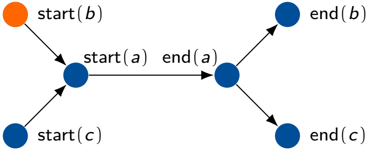

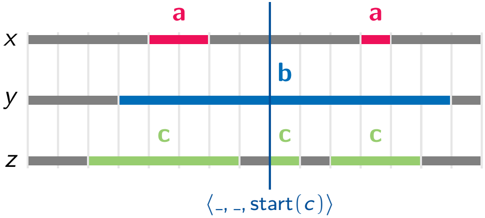

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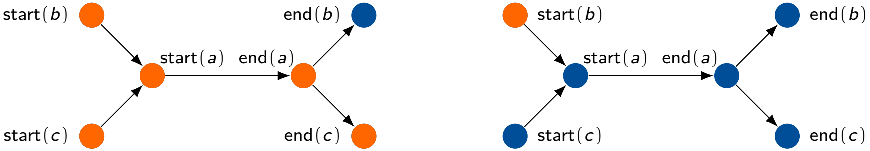

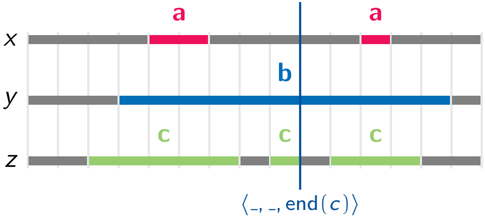

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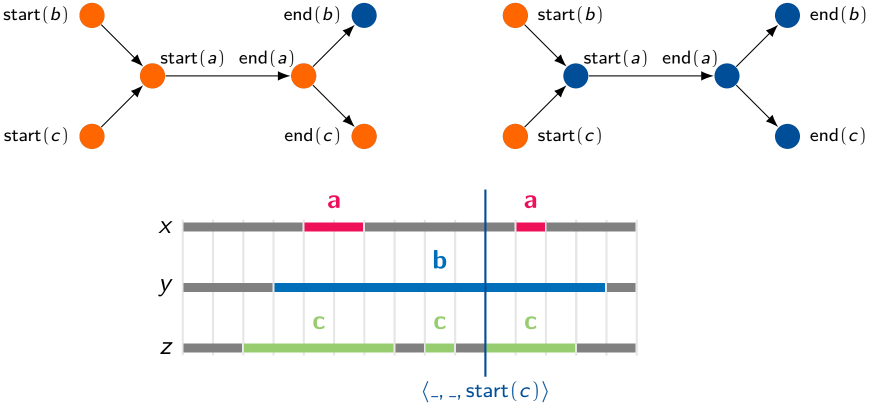

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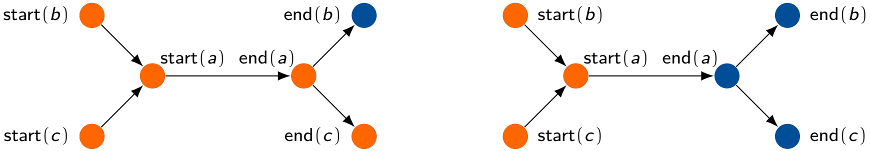

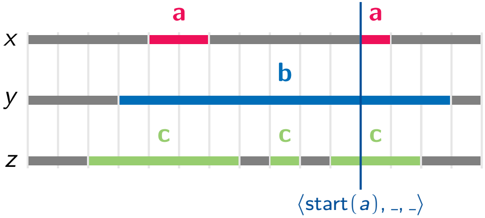

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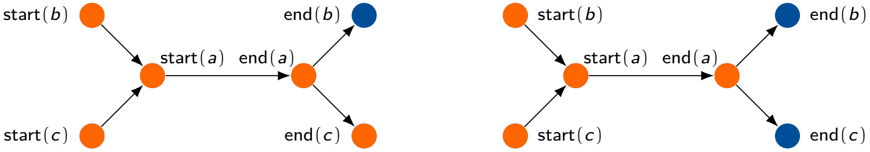

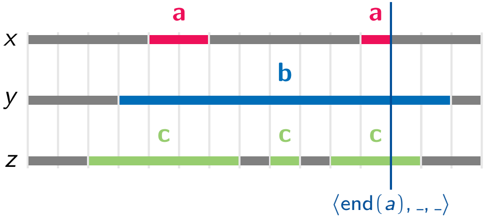

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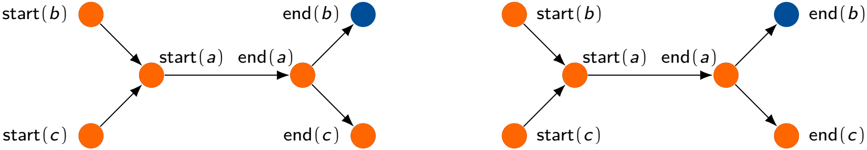

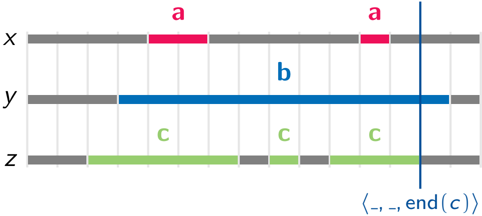

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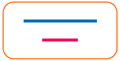

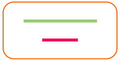

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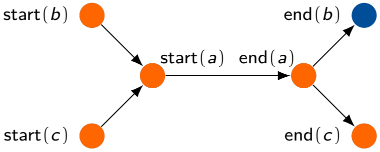

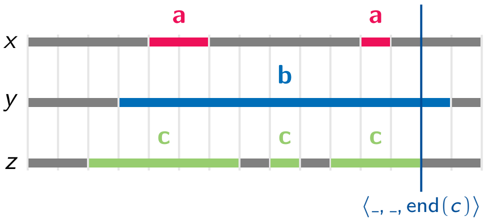

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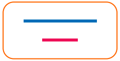

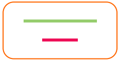

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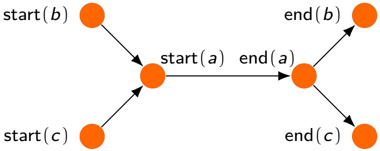

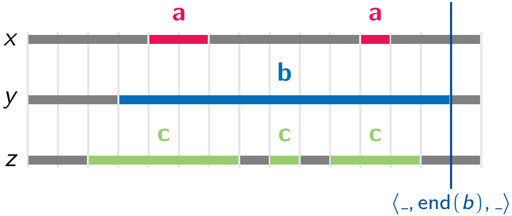

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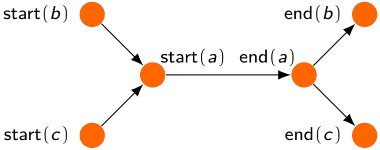

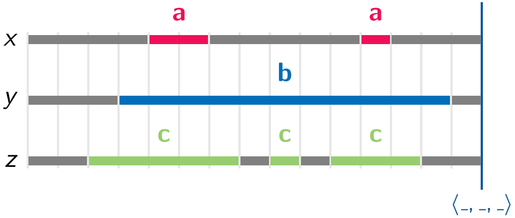

PLAN SYNTHESIS

To **synthesize** a plan (possibly against an adversarial environment) one needs **determinism**

- DFA provides **strategies** (functions)
- determinization costs an exponential in space
    - a 2-EXPTIME trivial solution to the synthesis problem

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To **synthesize** a plan (possibly against an adversarial environment) one needs **determinism**

- DFA provides **strategies** (functions)
- determinization costs an exponential in space
  - a 2-EXPTIME trivial solution to the synthesis problem
- **alternative**: direct encoding of plan existence into DFA
  - **eager rules for determinism**

A SYNTACTIC RESTRICTION: EAGER RULES

Definition (eager rules for trigger tokens)

A. Token a is a trigger token, token b is not

1. atoms $\mathsf{start}(b) \leqslant \mathsf{start}(a)$ and $\mathsf{start}(a) \leqslant \mathsf{end}(b)$ imply atom $\mathsf{start}(b) = \mathsf{start}(a)$
   - if a is required to start during b, then *eager rules* also require that a and b start together
2. atoms $\mathsf{start}(b) \leqslant \mathsf{end}(a)$ and $\mathsf{end}(a) \leqslant \mathsf{end}(b)$ imply atom $\mathsf{start}(b) = \mathsf{start}(a)$
   or atom $\mathsf{start}(b) = \mathsf{end}(a)$
   - if a is required to end during b, then *eager rules* also require that the start of b coincides with the start or the end of a
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   or atom $\mathsf{start}(b) = \mathsf{end}(a)$
   - if a is required to start/end not later than b, then *eager rules* also require that b coincides with the start or the end of a

A SYNTACTIC RESTRICTION: EAGER RULES – CONT'D

Definition (eager rules for non-trigger tokens)

B Neither a nor b is a trigger token

1. atoms $\mathsf{start}(b) \leqslant \mathsf{start}(a)$ and $\mathsf{start}(a) \leqslant \mathsf{end}(b)$ imply atom $\mathsf{start}(b) = \mathsf{start}(a)$
   - if a is required to start during b, then *eager rules* also require that a and b start together
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   - if a is required to end during b, then *eager rules* also require that the start of b coincides with the end of a

ALLEN RELATIONS IN THE EAGER FRAGMENT

graphical representation	Allen's relation	*a* is trigger	neither *a* nor *b* is trigger
	*a before b*	✓	✓
	a after b	✓	✓
	*a meets b*	✓	✓
	a met-by b	✓	✓
	*a ends b*	✗	✗
	a ended-by b	✗	✗
	*a begins b*	✓	✗
	a begun-by b	✓	✗
	*a overlaps b*	✗	✗
	a overlapped-by b	✗	✗
	*a during b*	✗	✗
	a contains b	✓	✗
	*a equals b*	✓	✗

CONCLUSIONS

- A direct DFA encoding of the plan existence problem for the **eager** fragment of qualitative timeline-based planning
- An EXPTIME procedure for the **synthesis** problem for the eager fragment of qualitative timeline-based planning

Future challenges

- A direct DFA construction to deal with the **whole qualitative** timeline-based planning (if any)
- Study of the **quantitative** version of timeline-based planning

Thank you

Questions?