Synthesis
of
coordination programs
from
temporal specifications

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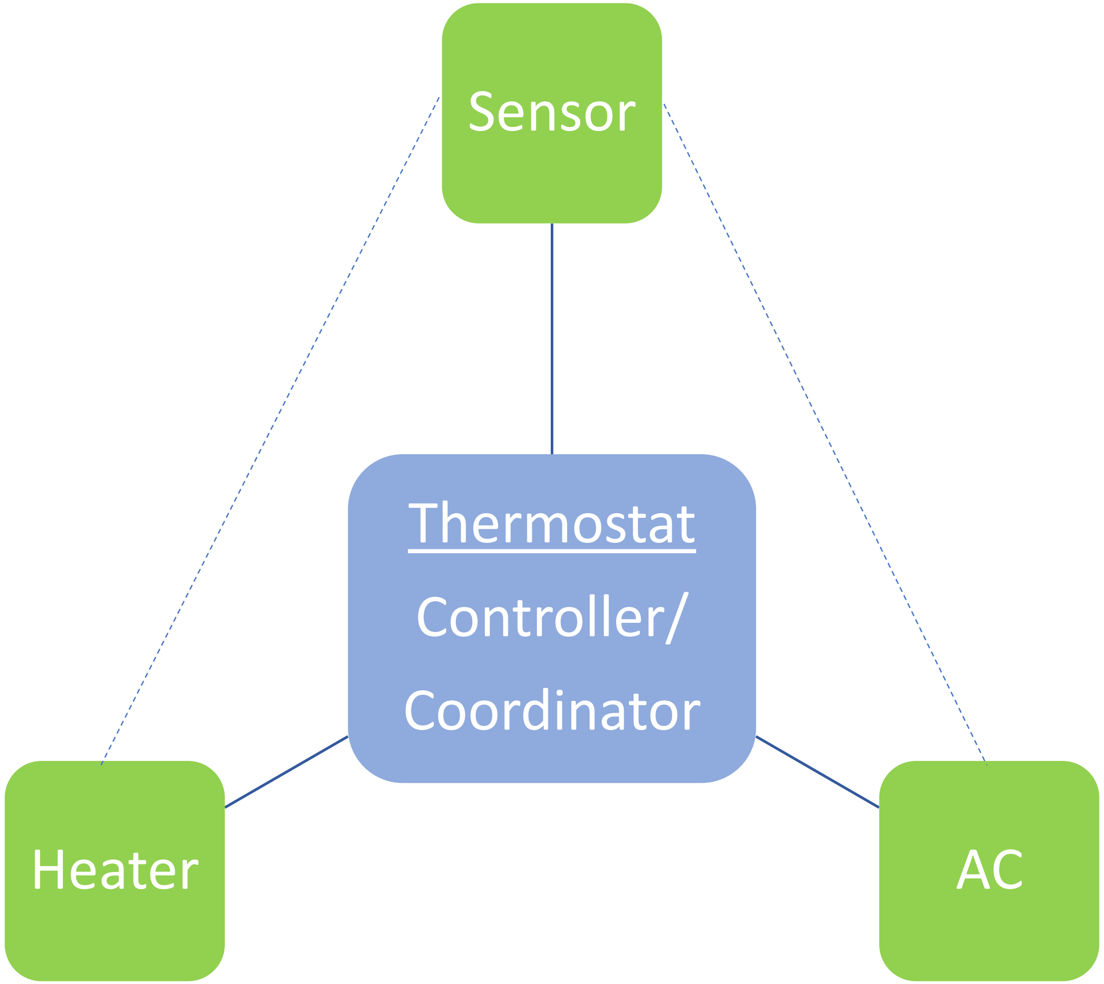
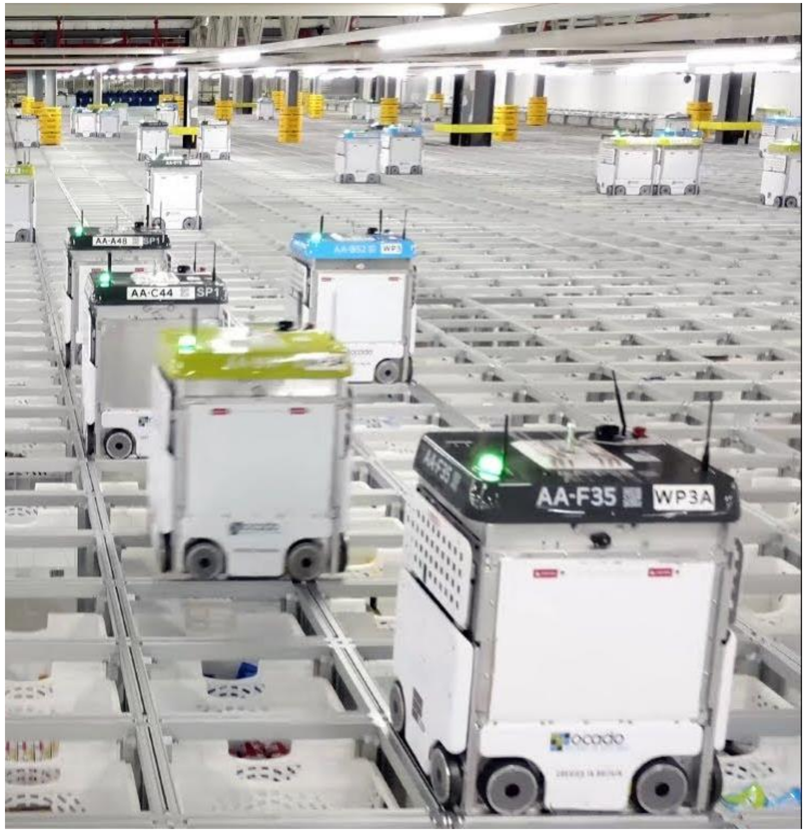
Coordination programs

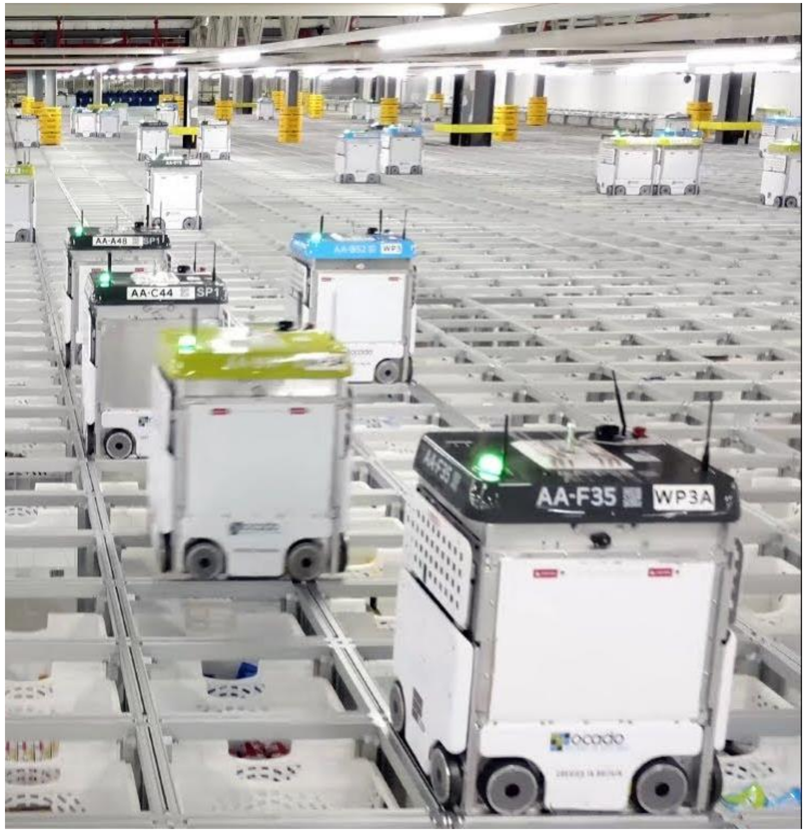
Coordination programs

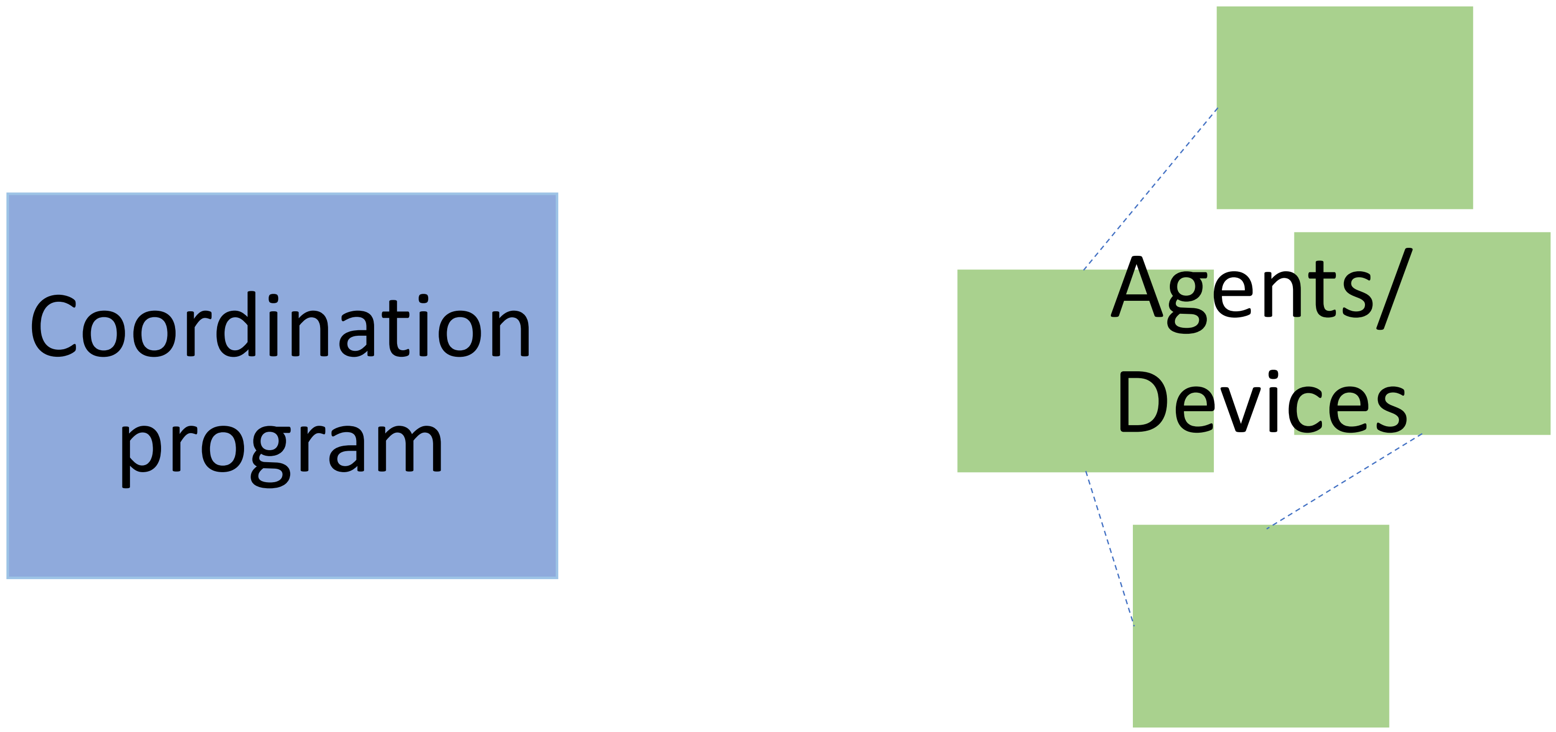


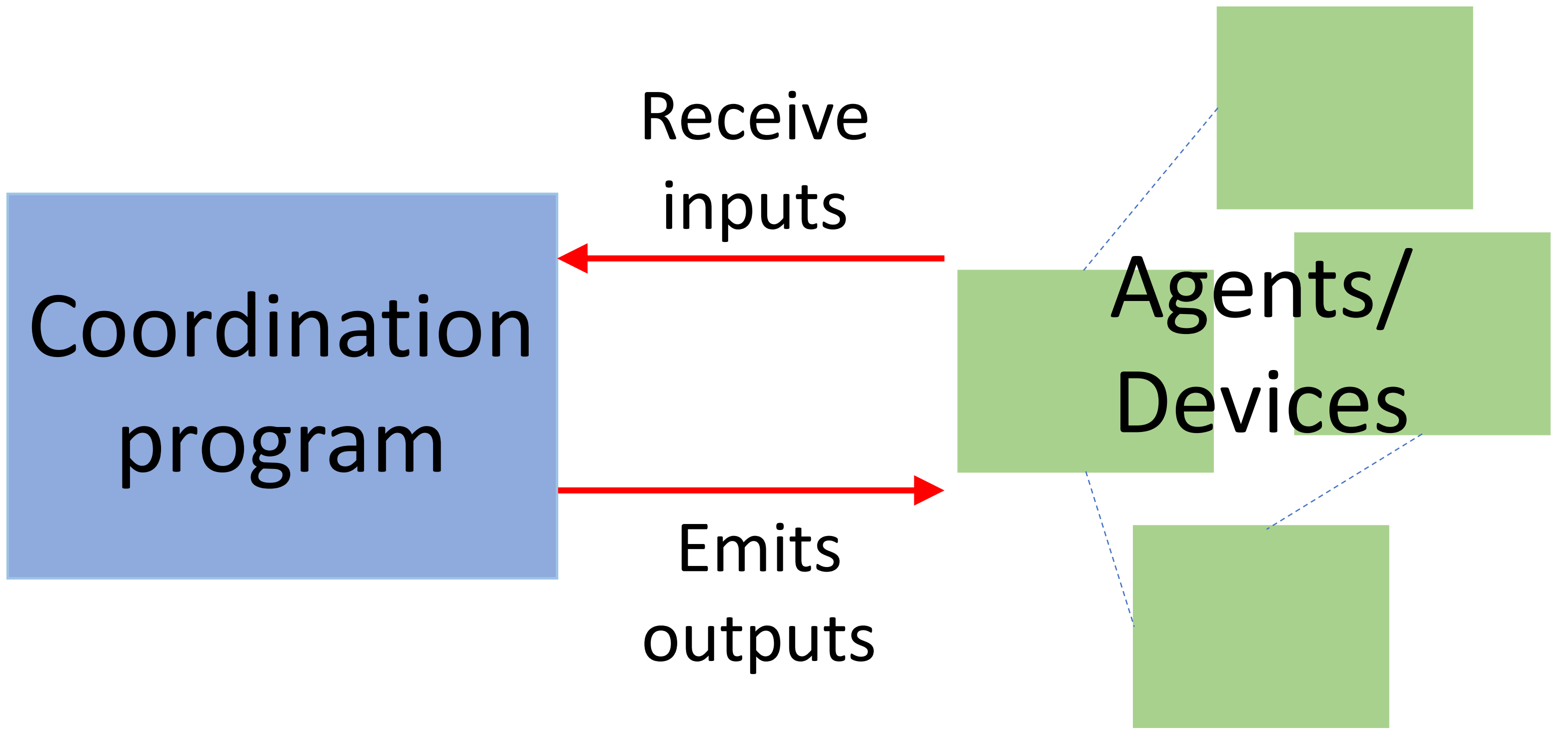
Coordination programs

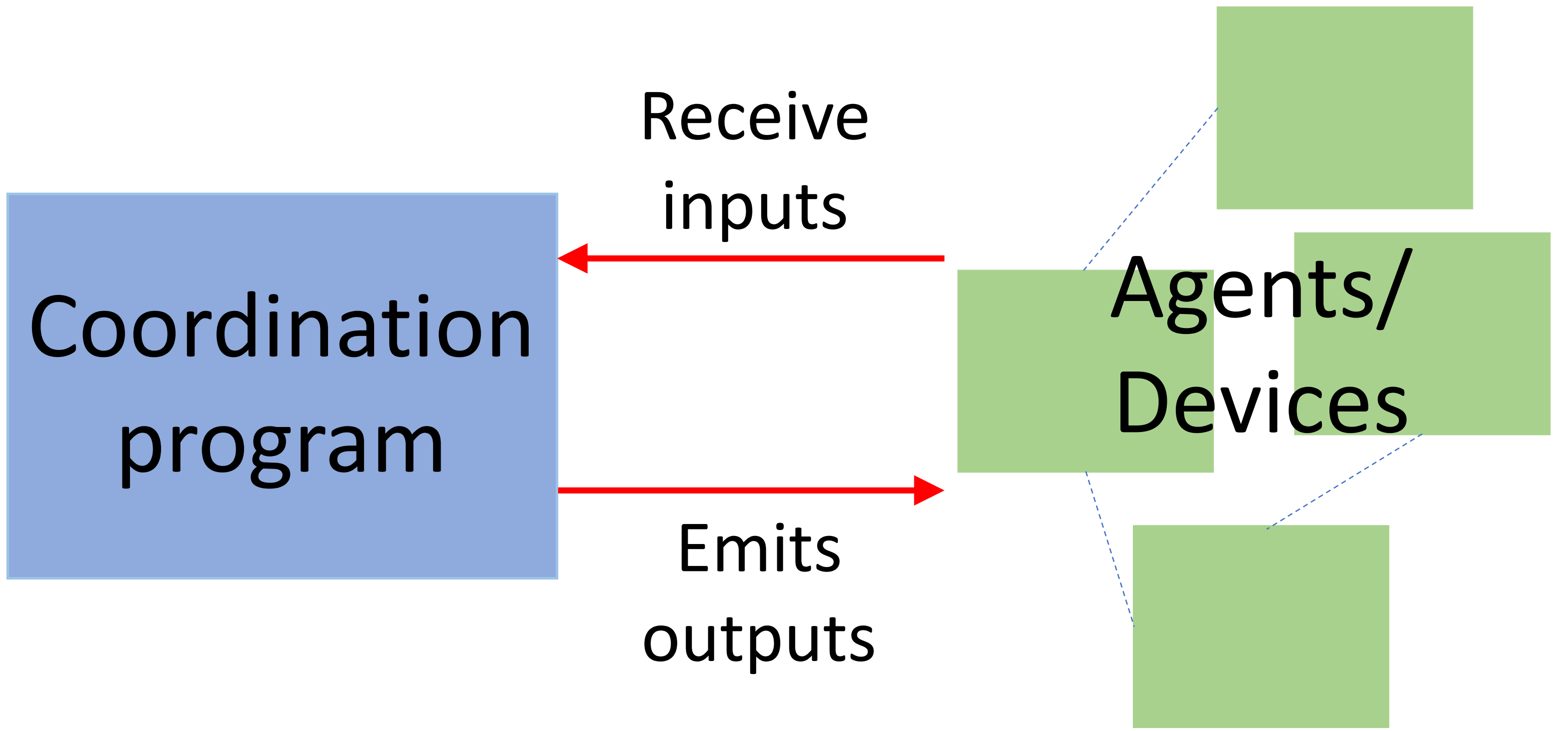


Coordination programs

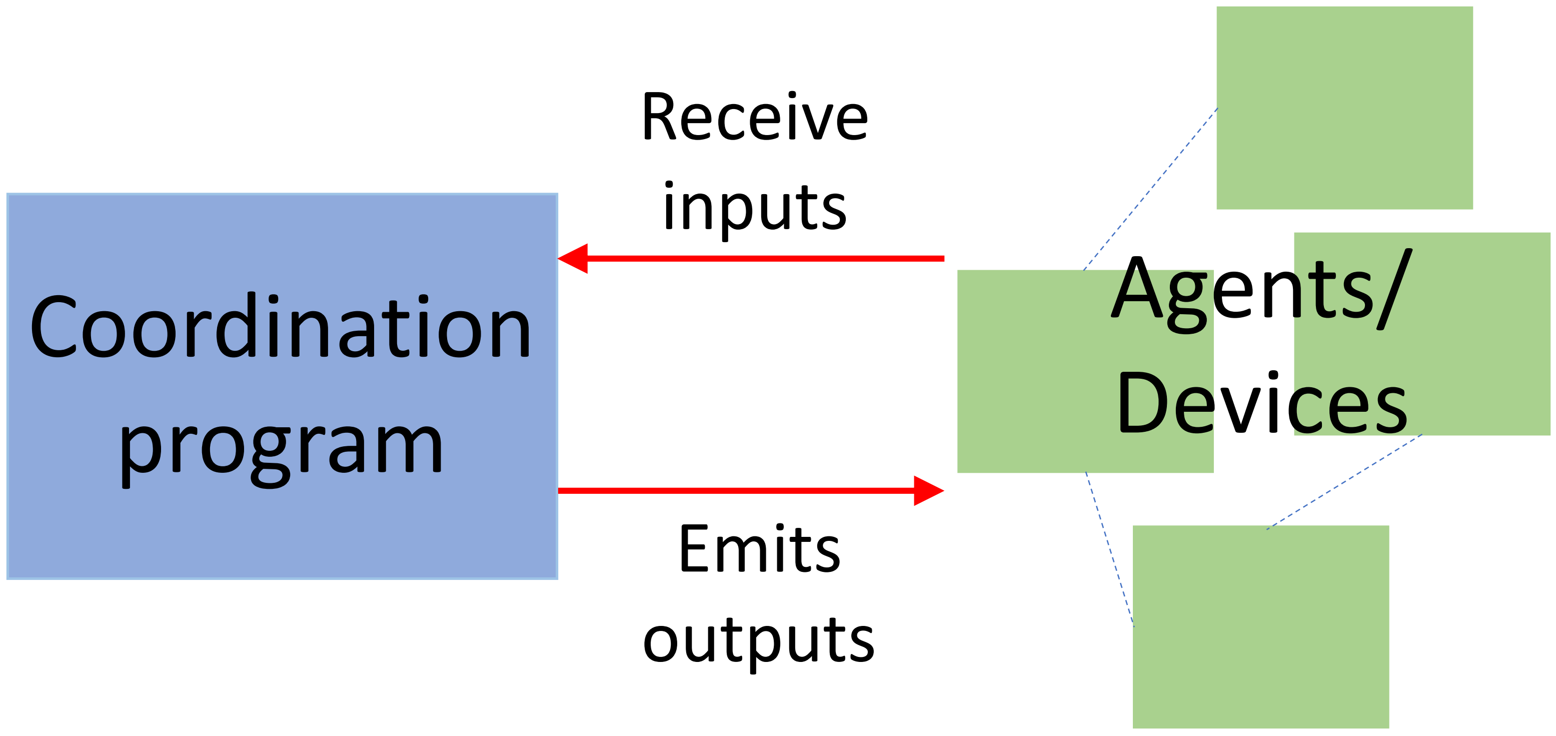



Coordination program
Agents/ Devices


Receive
inputs
Coordination
program
Agents/
Devices
Emits
outputs



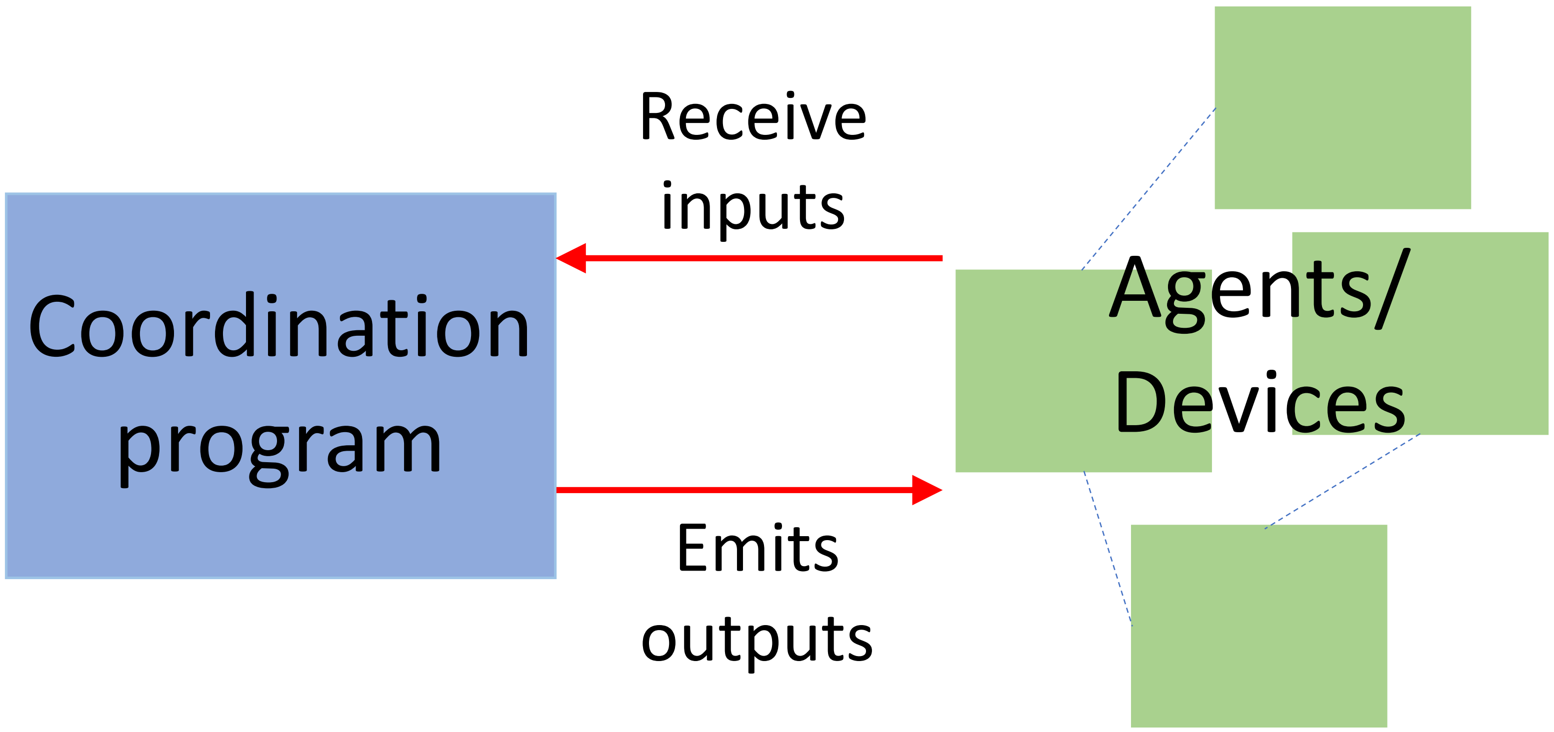
Designing coordination programs is hard



Designing coordination programs is hard

1. Reactive system

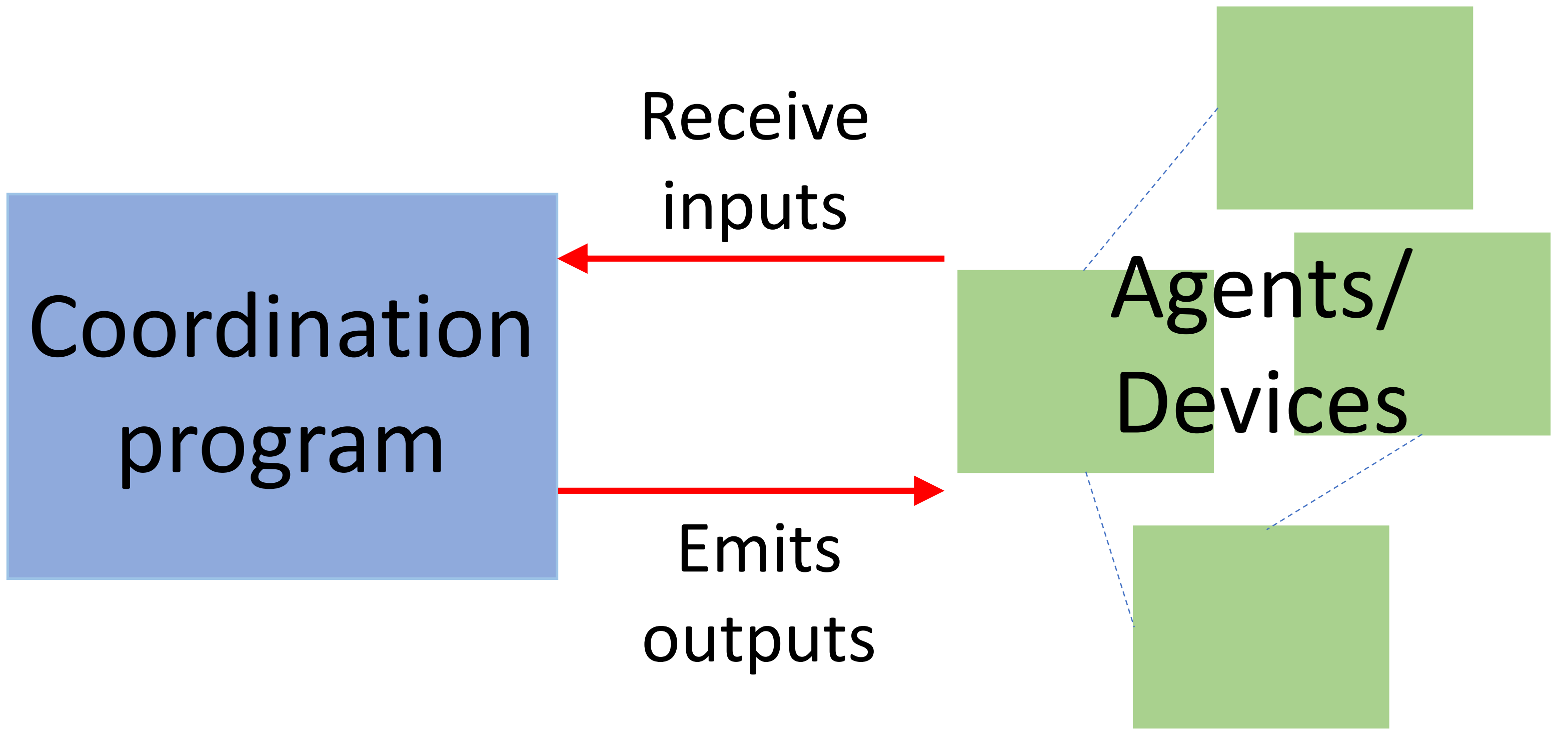
Repeated interaction with agents/devices



Designing coordination programs is hard

1. Reactive system
2. Asynchrony

Each device operates at its own clock



Coordination program has limited visibility:
Sees the interface only

Designing coordination programs is hard

1. Reactive system
2. Asynchrony
3. Partial information

Specifying intent of a coordination program is easier

E.g. “Thermostat should maintain ambient temperature”

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Can we automatically generate a coordination program from a high-level specification?

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Coordination synthesis

Contributions

Formulate, solve, and demonstrate coordination synthesis

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Formalize coordination synthesis

"Easier to specify" formalization

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Design efficient automata-based synthesis algorithm

Accounts for all three challenges – Reactive, asynchrony, partial information

Prior work accounts for at most two

Contributions

Formulate, solve, and demonstrate coordination synthesis

Formalize coordination synthesis

"Easier to specify" formalization

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Conduct case-studies on prototype implementation

High-level specification

Intent of coordination program

Linear Temporal Logic (LTL) [Pnueli, FOCS 1977]

High-level specification

Intent of coordination program

Linear Temporal Logic (LTL) [Pnueli, FOCS 1977]

Device description

Communicating Sequential Processes (CSP) [Hoare, CACM 1978]

- Rich structure: asynchrony, non-determinism …
- Communication model: Message passing
- Interface: Visible and hidden actions

CSP processes [Hoare, , CACM 1978]

Processes: $P, Q, R, \ldots$

- Public actions $(a_0, a_1, \ldots a_n)$ and Private actions $(b_0, b_1, \ldots b_n)$

$$P = action_0 \rightarrow Q_0 \mid action_1 \rightarrow Q_1 \mid \ \ldots \ \mid action_n \rightarrow Q_n$$

"Process P evolves to process Q_i on $action_i$"

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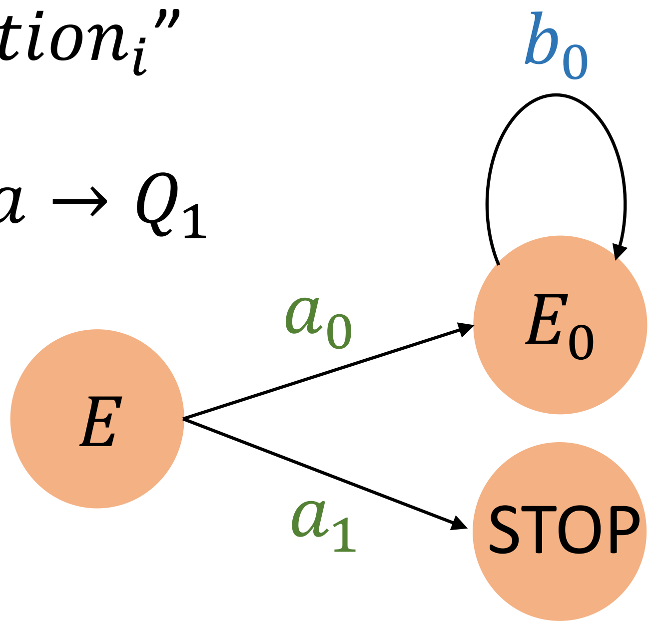
- Allows structural non-determinism: $P = a \rightarrow Q_0 \mid a \rightarrow Q_1$

Example: $E = a_0 \rightarrow E_0 \mid a_1 \rightarrow STOP$

$E_0 = b_0 \rightarrow E_0$



CSP interactions [Hoare, 1978]

Synchronized public actions

- Processes evolve together on public actions

  Let, $P_0 = a \rightarrow Q_0, \quad P_1 = a \rightarrow Q_1$ then $(P_0 \mid\mid P_1) = a \rightarrow (Q_0 \mid\mid Q_1)$

CSP interactions [Hoare, 1978]

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  Let, $P_0 = a_0 \to Q_0, \quad P_1 = a_1 \to Q_1$ then $(P_0 \,||\, P_1)$ no evolution

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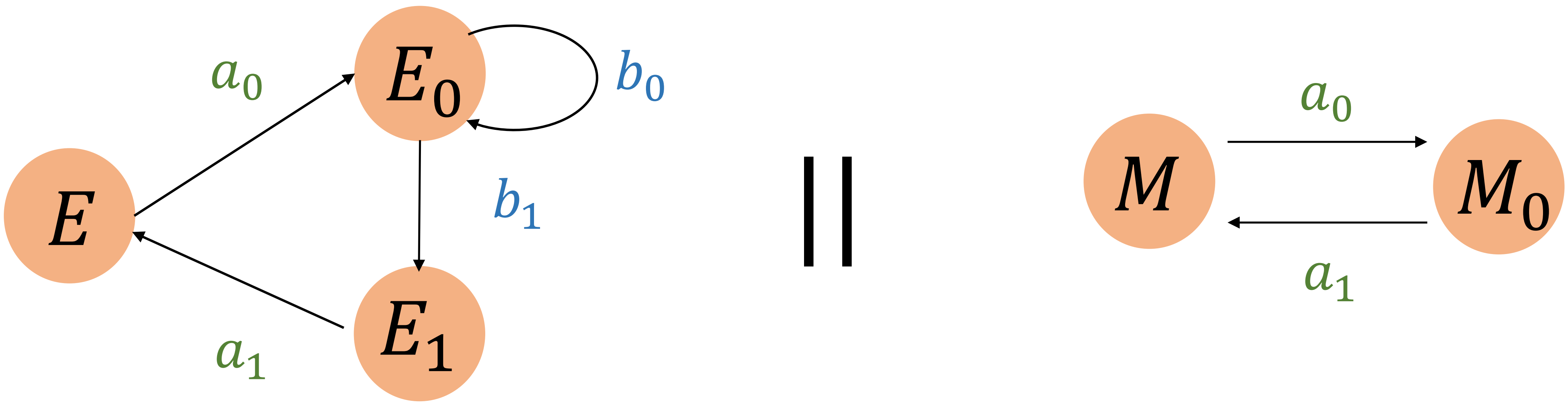
Internal private actions

- Process with private action evolves by itself

  Let, $P_0 = b \rightarrow Q_0, \quad P_1 = a \rightarrow Q_1$ then $(P_0 \mid\mid P_1) = b \rightarrow (Q_0 \mid\mid P_1)$

Example



$a_0 b_0 b_0 b_0 \ldots$

$a_0 b_1 a_1 \ldots$

$\ldots$

Coordination synthesis

Given a CSP environment description

E = E1 || E2 || … || En

and an LTL specification **S**,

Generate a coordinator (CSP) **M** s.t.
E || M satisfies **S**

Challenge I: Partial information

Coordinator may not know the current state of **E**

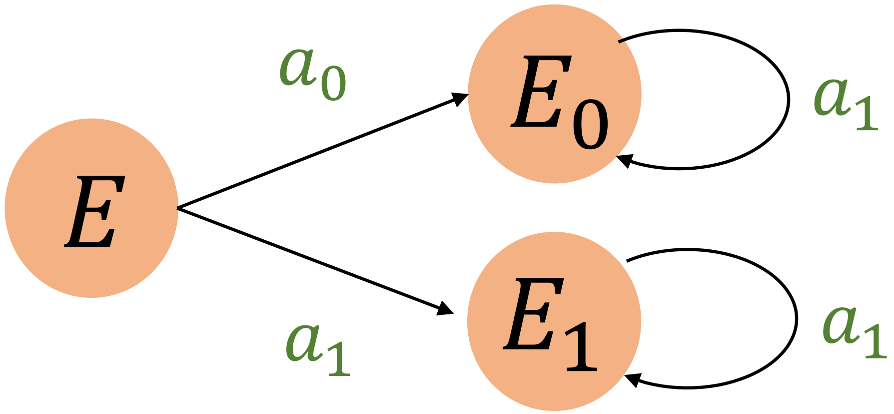
- Structural non-determinism:
  Evolution to multiple states

- Internal actions:
  Evolution due to internal actions is unknown to coordinator

Challenge II: Deadlock freedom

Coordinator must guarantee no deadlock despite partial information

$$
\begin{aligned}
E &= a_0 \to E_0 \mid a_1 \to E_1 \\
E_0 &= a_1 \to E_0 \\
E_1 &= a_1 \to E_1
\end{aligned}
$$



Challenge II: Deadlock freedom

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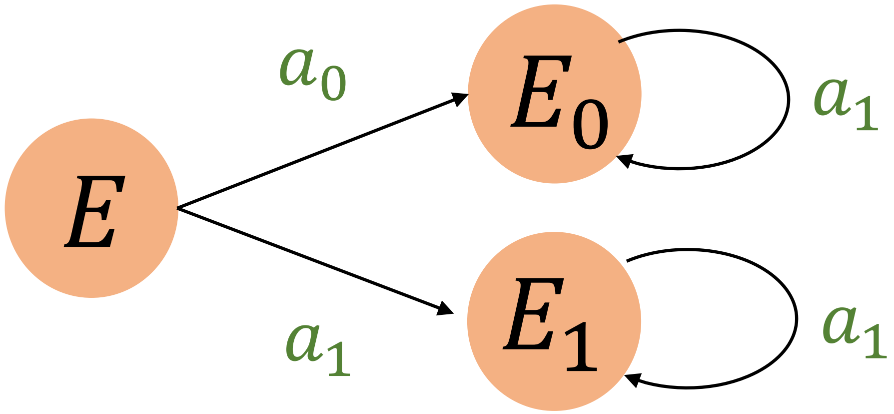

$$M = a_0 \to M$$

$E||M$ deadlocks

Challenge II: Deadlock freedom

Coordinator must guarantee no deadlock despite partial information

$$E \;= a_0 \to E_0 \mid a_1 \to E_1$$
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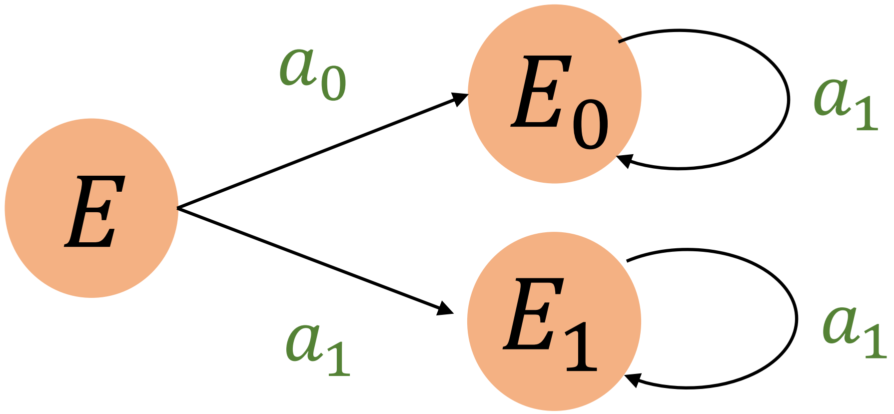


$$M = a_0 \to M$$

$E||M$ deadlocks

$$M = a_1 \to M$$

$E||M$ does not deadlock

Challenge III: Asynchrony

Coordinator doesn't know how many or which actions have taken place

a_0 a_1 a_2 a_3 ....

Expansion

a_0 b_0 a_1 b_1 a_2 b_2 b_3 a_3 ....

Every valid expansion satisfies **S**

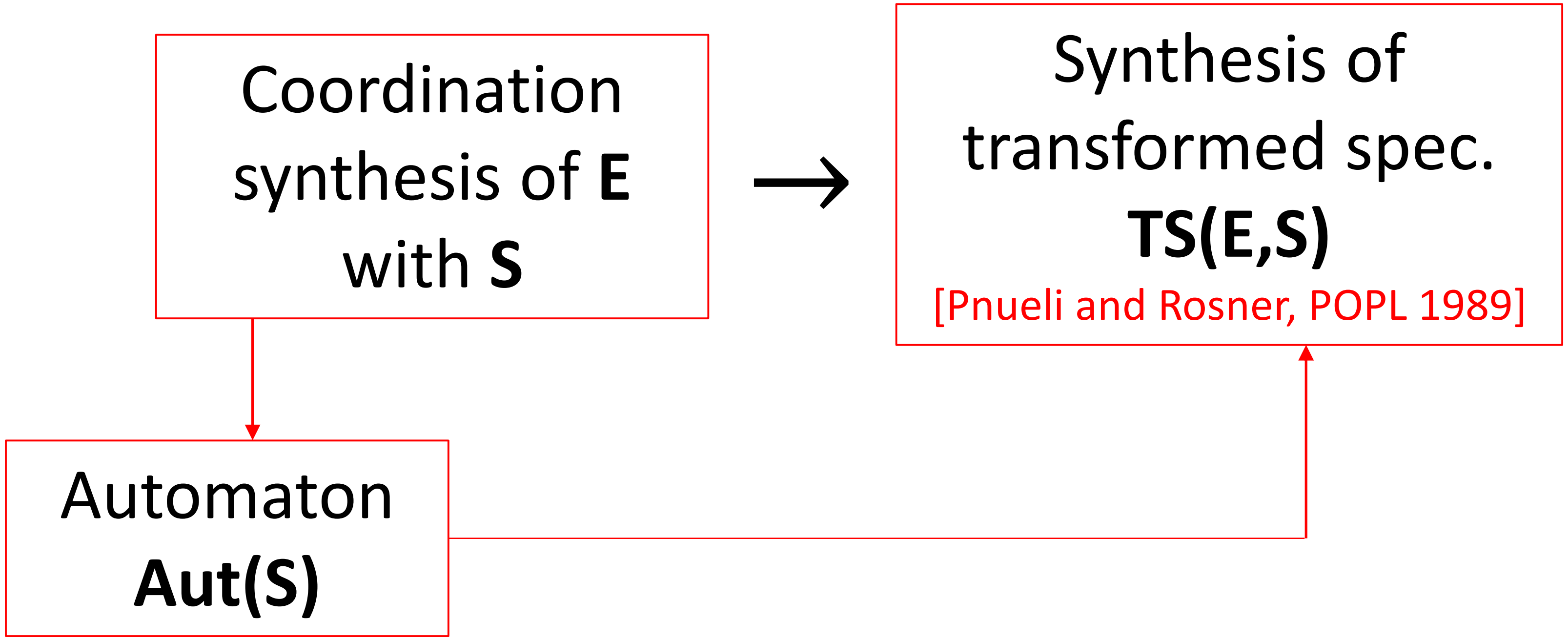
Core technique

Coordination synthesis with **E,S** reduces to Synch. synthesis with **TS(E,S)**

Coordination synthesis of **E** with **S**	→	Synthesis of transformed spec. **TS(E,S)** [Pnueli and Rosner, POPL 1989]

Core technique

Coordination synthesis with **E,S** reduces to Synch. synthesis with **TS(E,S)**



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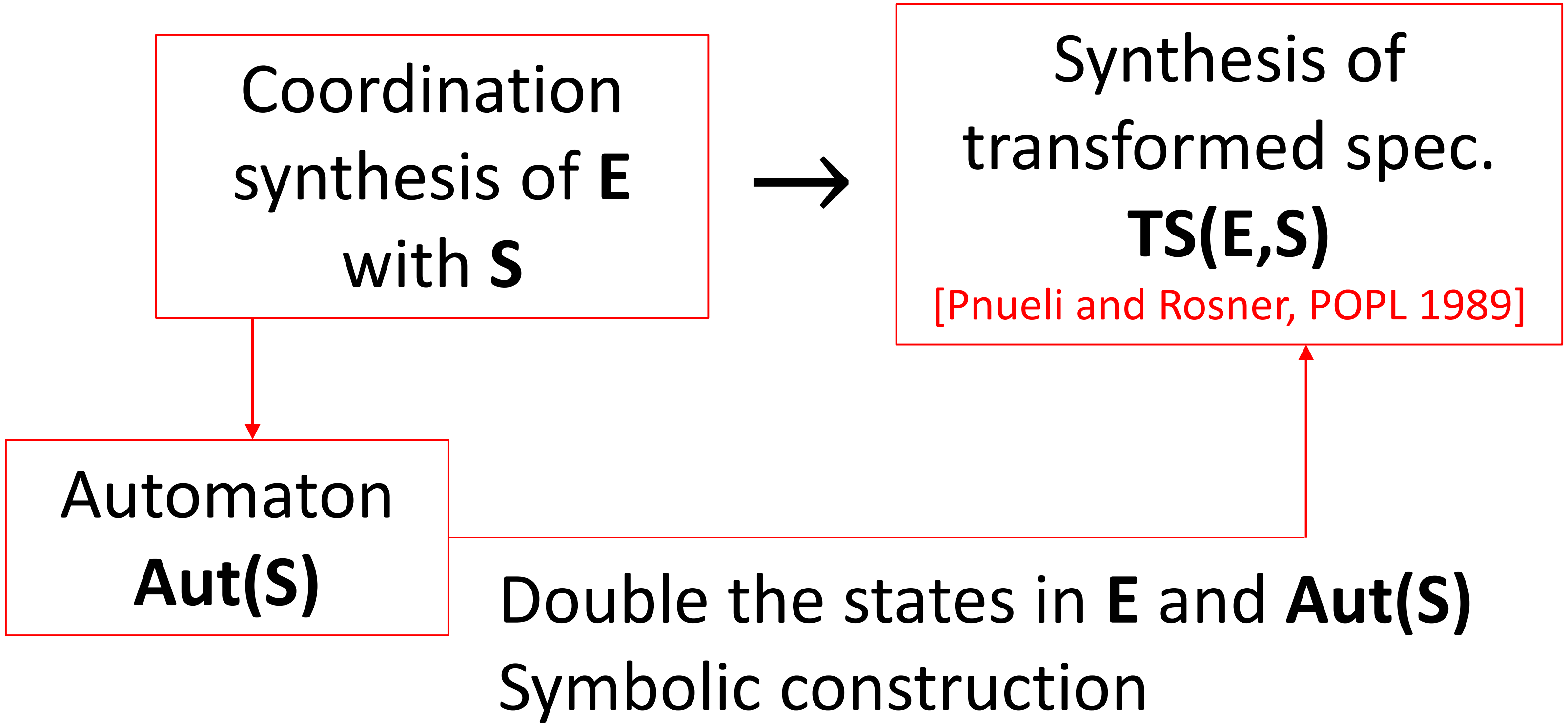
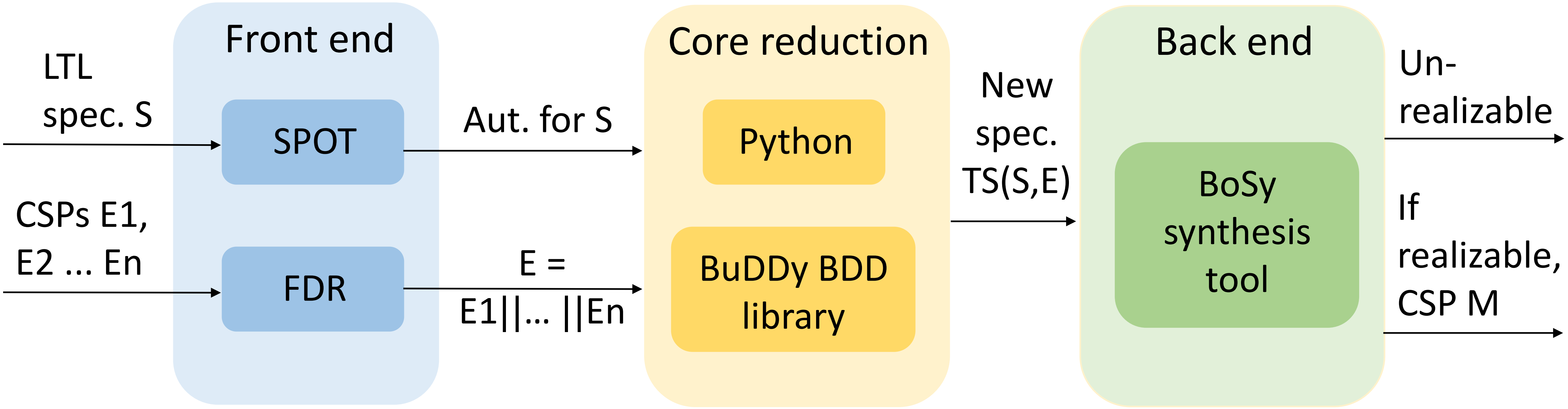


Implementation

Prototype **CoSy** (**Co**ordination **Sy**nthesis)

- Core reduction in Python
- BDD-based symbolic reduction



Thermostat

How will coordination synthesis help?

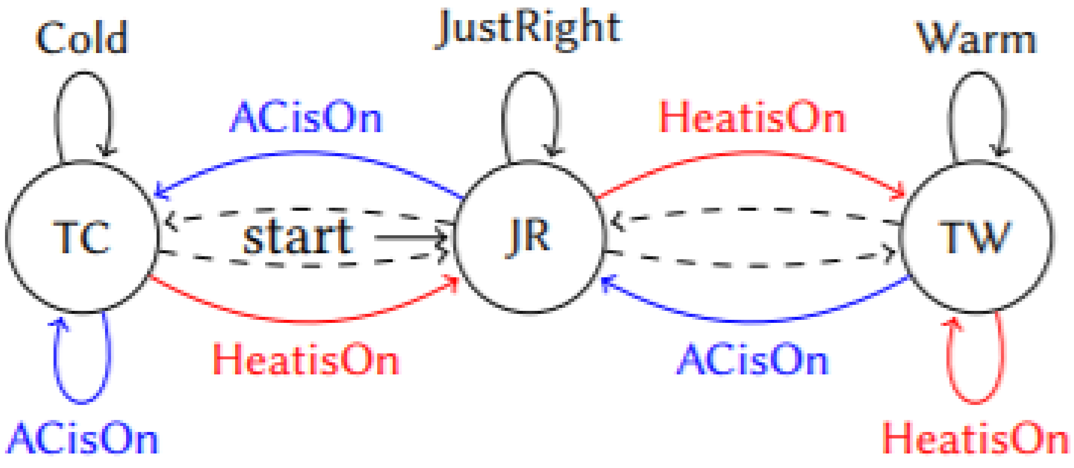


Fig. 6. Room temperature Sensor process (JR: Just right, TW: Too warm, TC: Too cold).

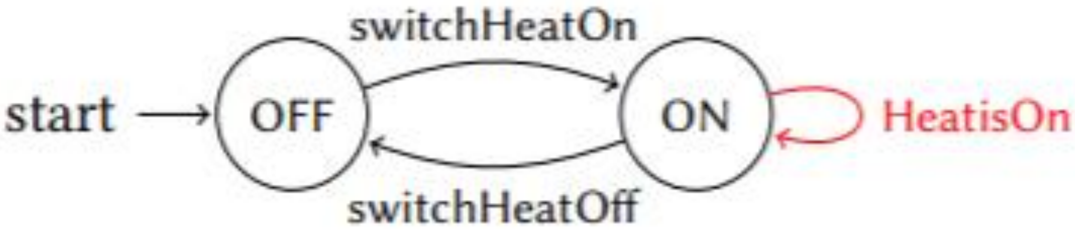


Fig. 7. Heater process.

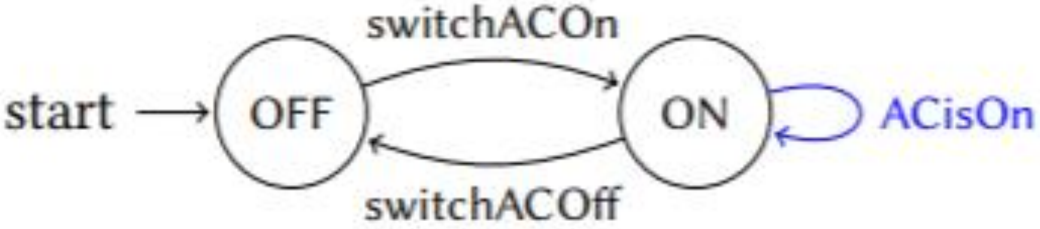


Fig. 8. AC process.

Thermostat case study

Phase I

Maintain ambient temperature

Thermostat doesn’t interact with all devices

+

Phase II

Thermostat must interact with all devices (Fairness)

AC and Heater are switched on at the same time

+

Phase III

Energy efficient

SATISFIED!

Coordination synthesis, in a nutshell

- Modelling
  - CSP environments – Interface, non-determinism, private/public actions
  - LTL specifications – Expressive
- Algorithm
  - Efficient automata-based reduction to synchronous synthesis
  - Prototype + Case studies demonstrate utility
- Complexity analysis
  - PSPACE-hard in size of E
  - Algorithm is exponential in E, number of devices