Probabilistic BDI Agents: Actions, Plans, and Intentions

Blair Archibald, Muffy Calder, Michele Sevegnani, **Mengwei Xu**

Project: Multi-Perspective Design of IoT Cybersecurity in Ground and Aerial Vehicles (funded by Petras)
Project: Science of Sensor System Software (funded by EPSRC)

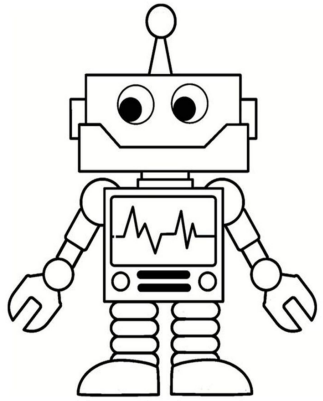
Autonomous Agents

Definition:

An entity

which **perceives** its situated environment,
which **deliberates** accordingly,
which **takes actions** autonomously,

in order to achieve its design objectives



Michael Wooldridge. *An Introduction to Multiagent Systems*. John Wiley and Sons Ltd, February 2002

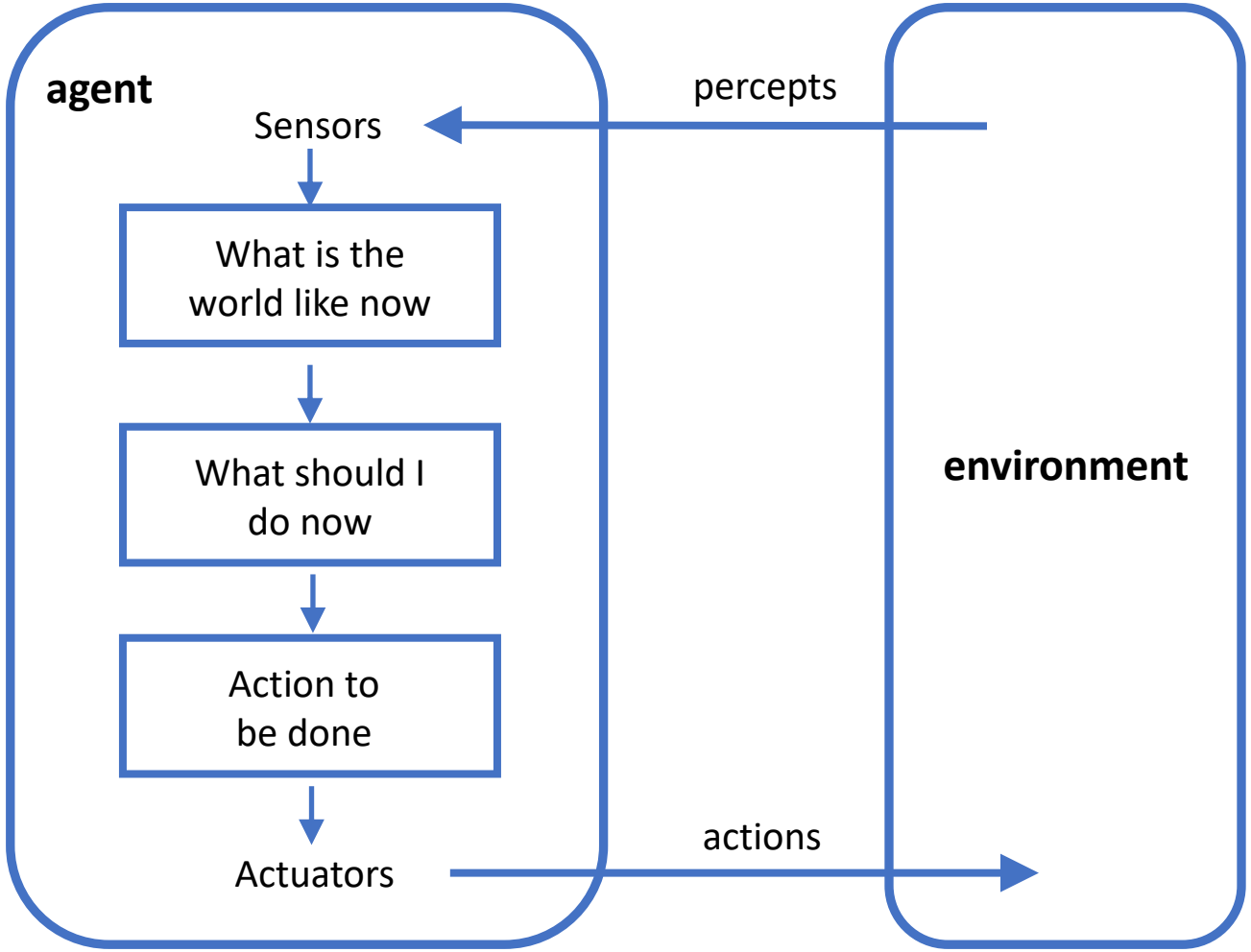
Autonomous Agents

Conceptual Framework

An entity

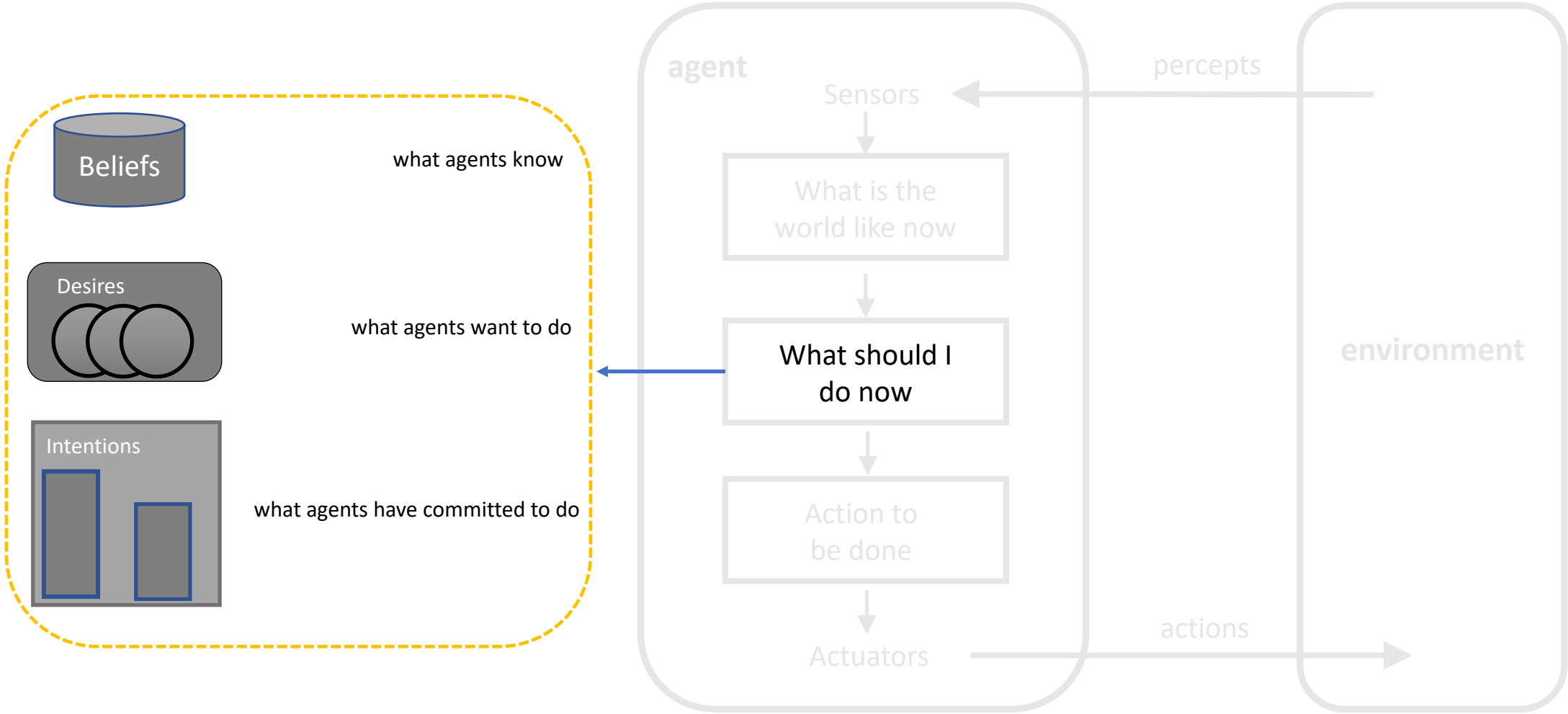
which **perceives** its situated environment,
which **deliberates** accordingly,
which **takes actions** autonomously,

in order to achieve its design objectives



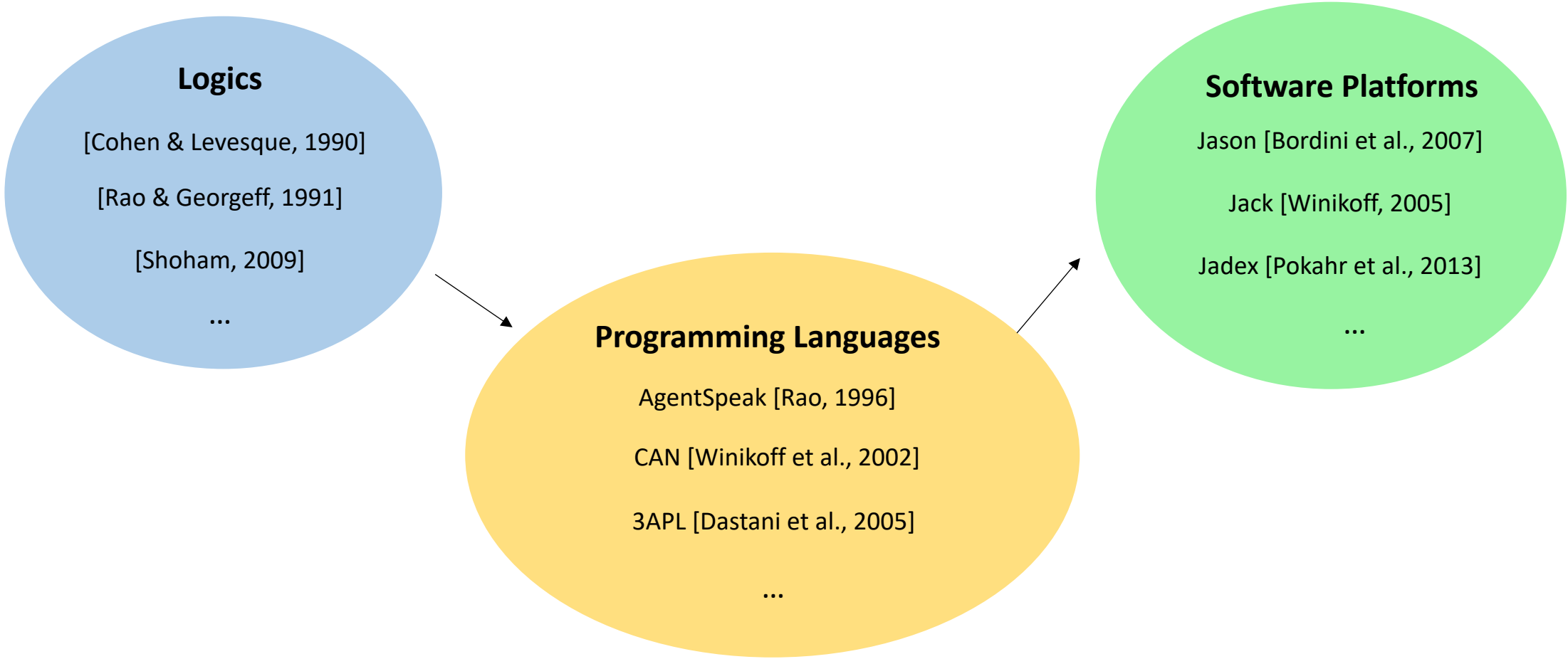
Autonomous Agents

Belief-Desire-Intention (BDI) Framework



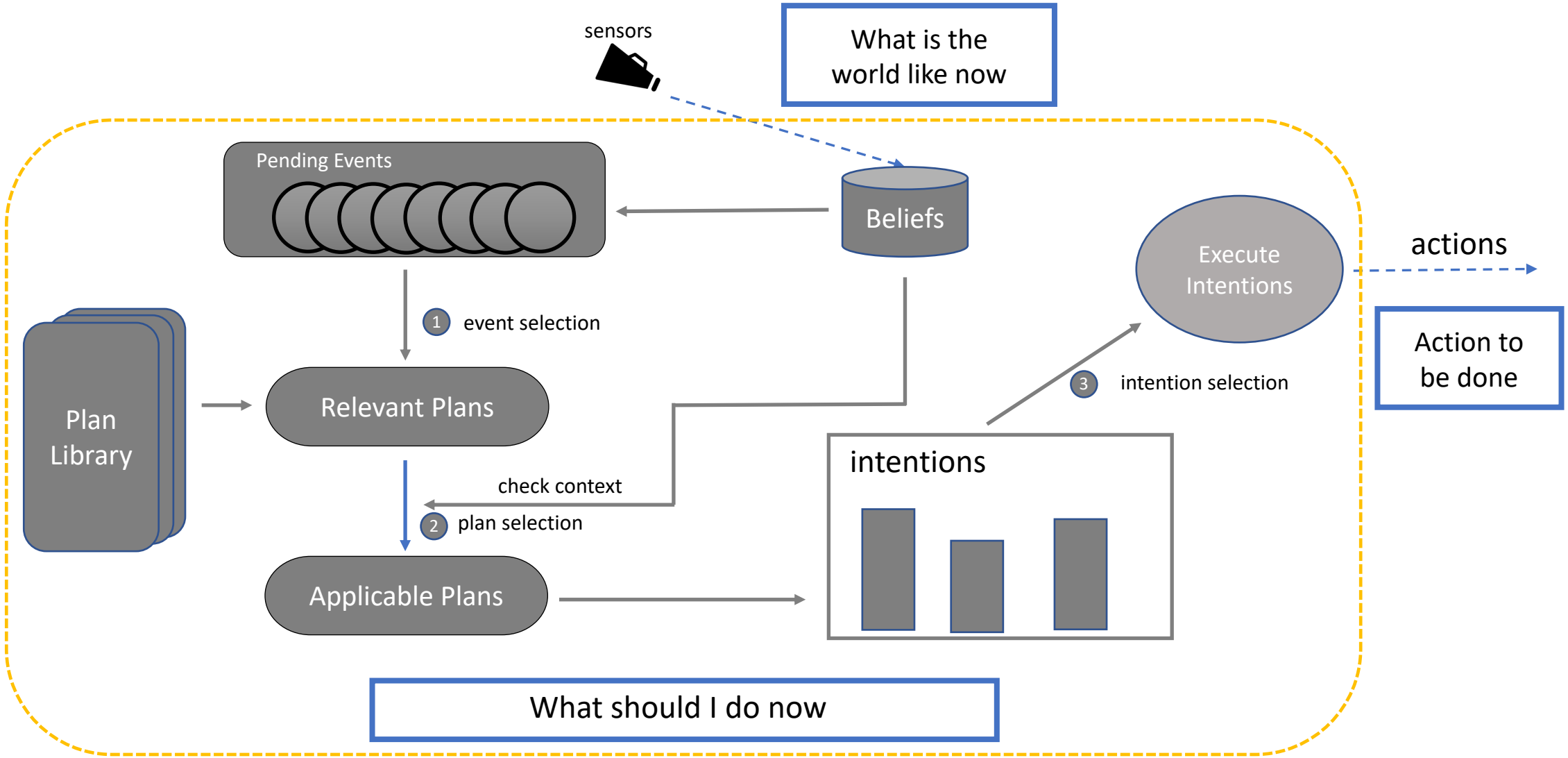
Belief-Desire-Intention Framework

Overview



Autonomous Agents

Belief-Desire-Intention (BDI) Framework

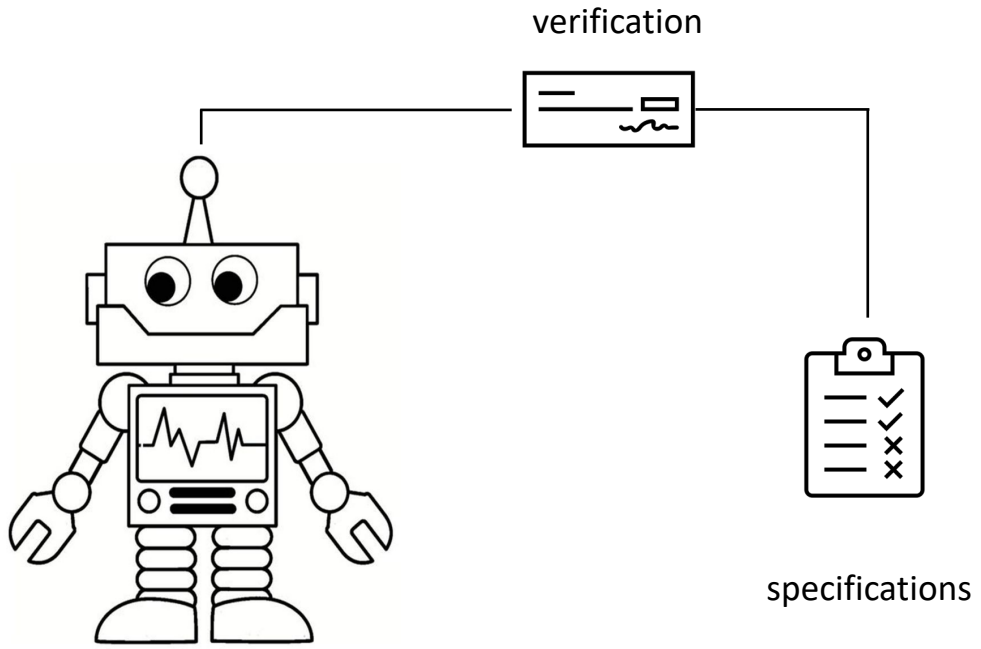


Building Trustworthy BDI Agents

Question

Building Trustworthy BDI Agents

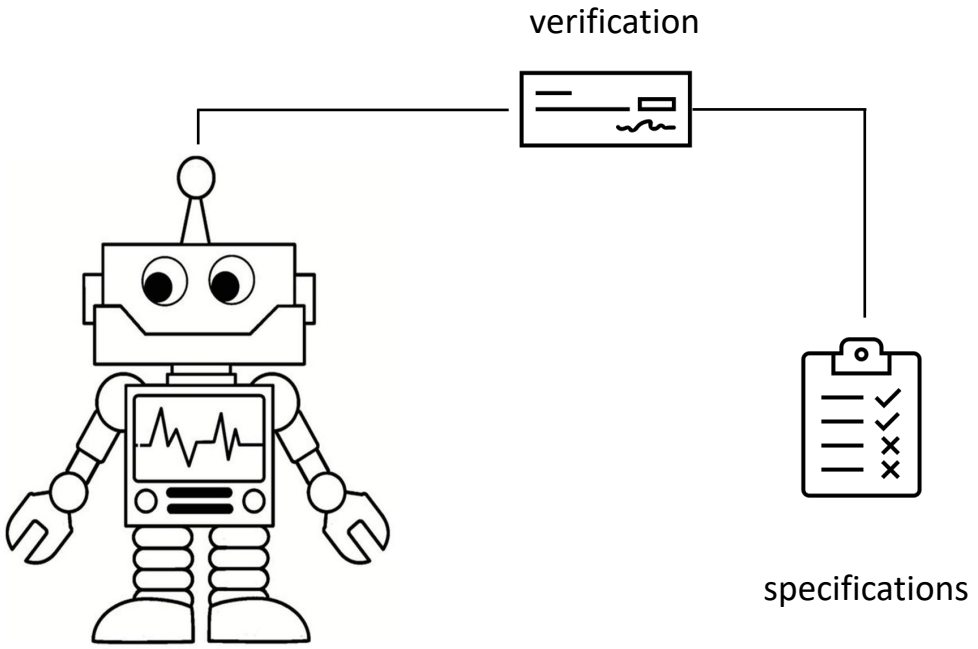
Solution



Building Trustworthy BDI Agents

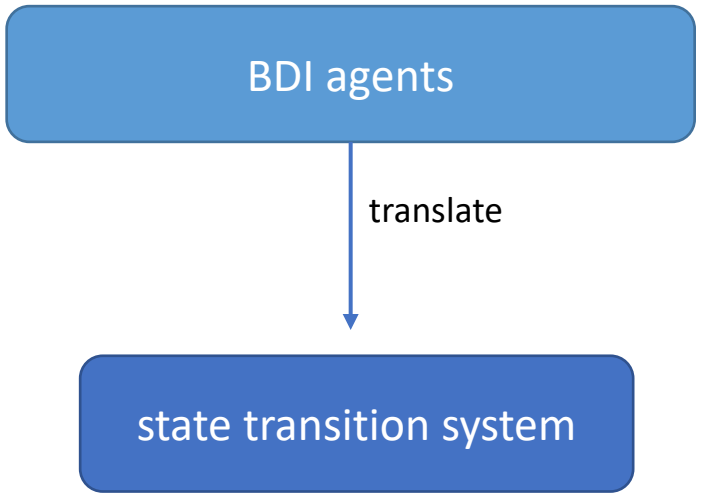
Solution

complete confidence



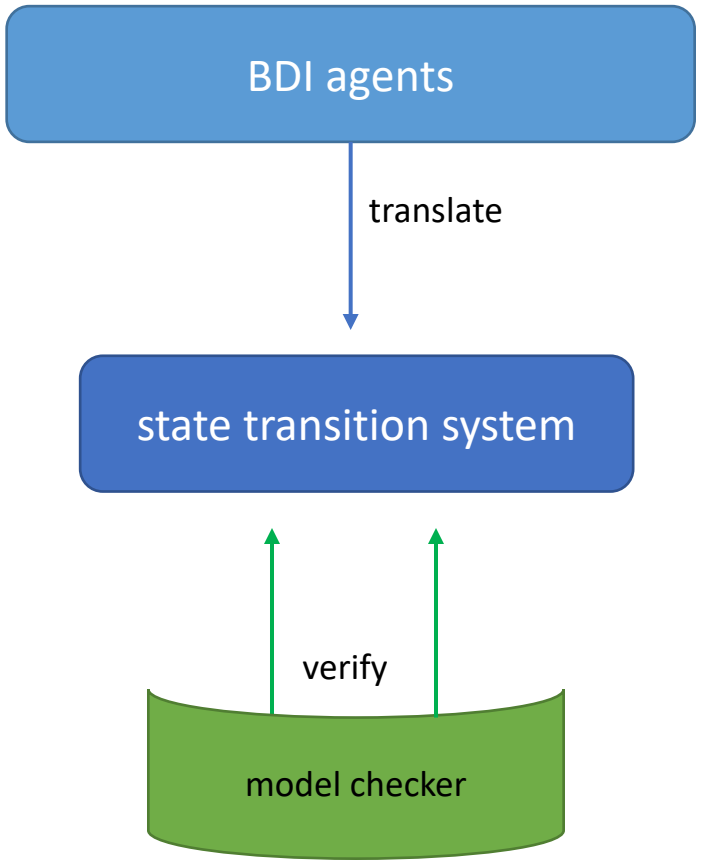
Building Trustworthy BDI Agents

Solution



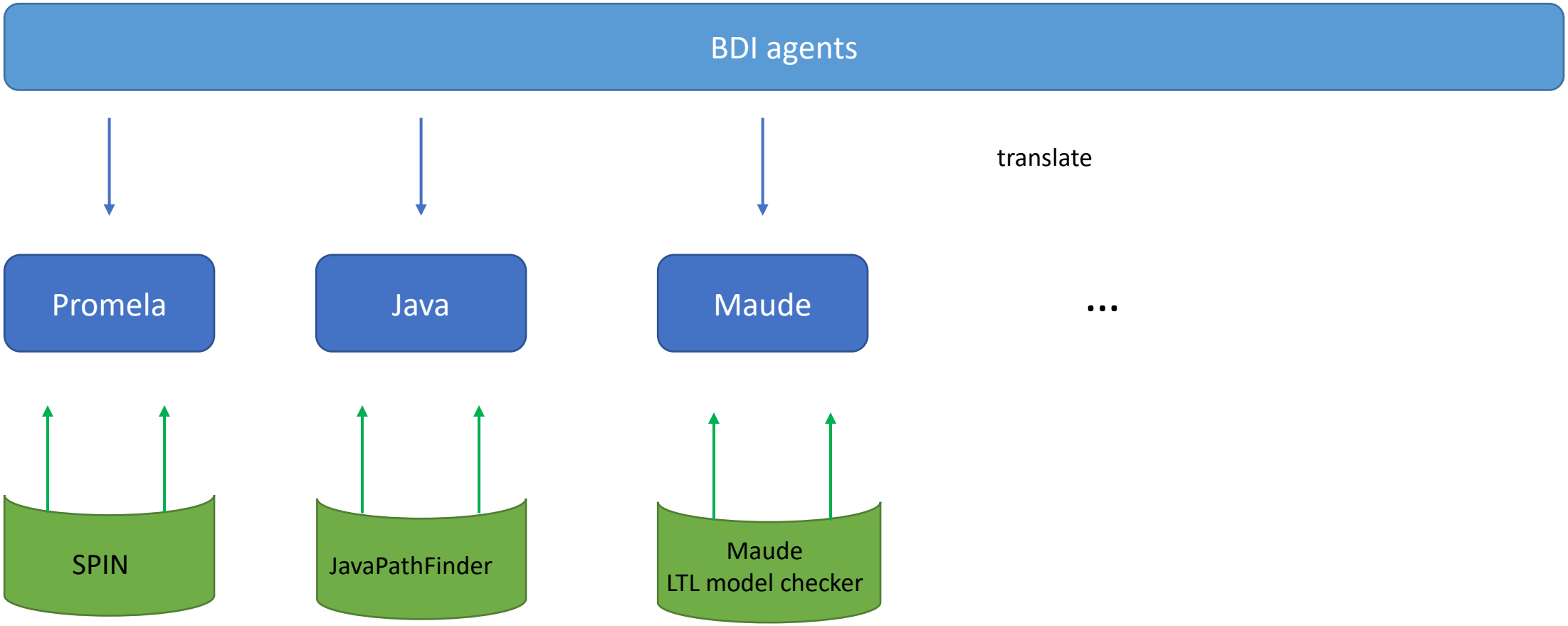
Building Trustworthy BDI Agents

Solution



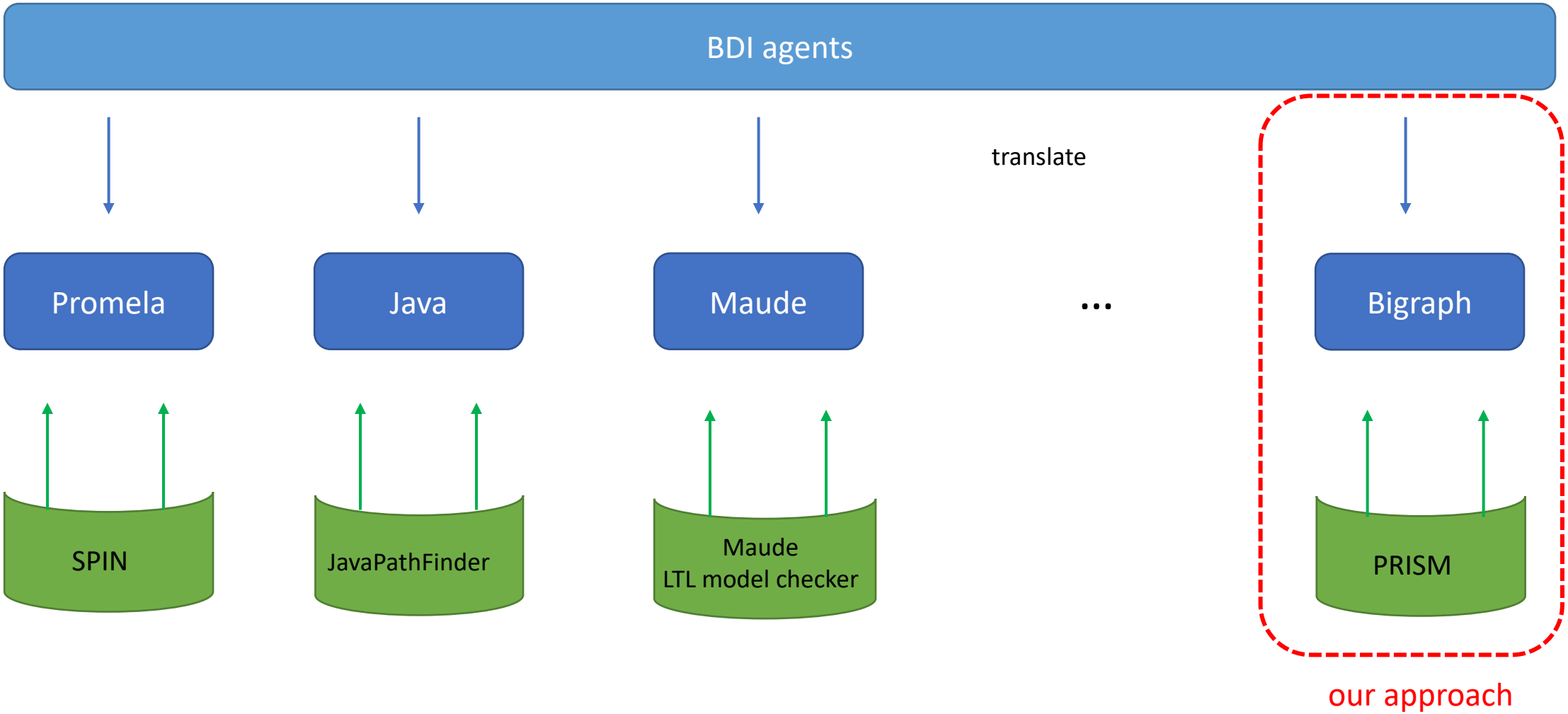
Building Trustworthy BDI Agents

Summary



Building Trustworthy BDI Agents

Summary

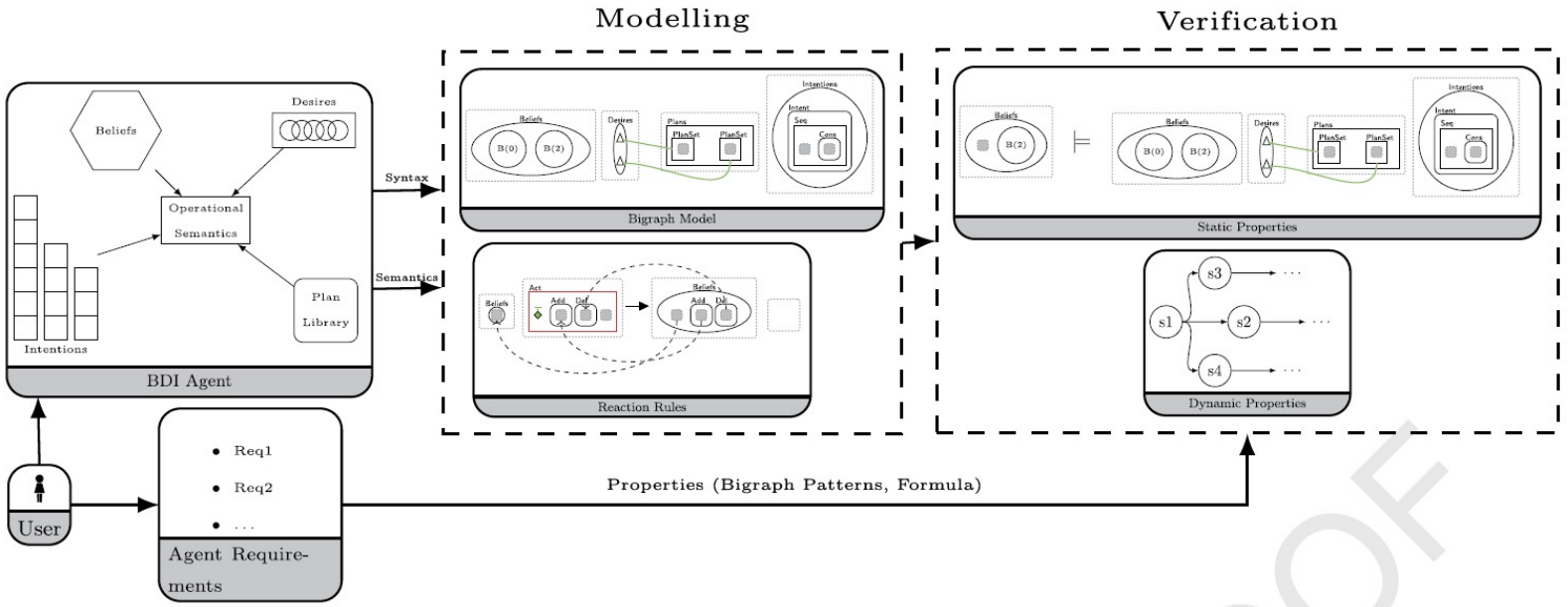


Building Trustworthy BDI Agents

Summary

BDI agents

Bigraphs: a universal graph-based rewriting formalism, developed by Milner as a unifying theory for process algebras such as CCS and π-calculus.



Bigraph

PRISM

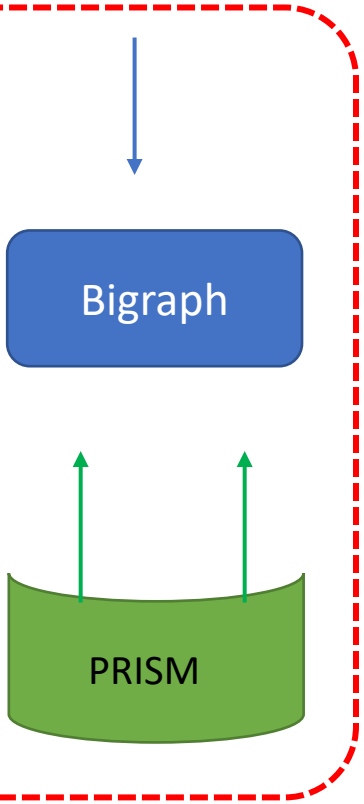
our approach

Building Trustworthy BDI Agents

Summary

BDI agents

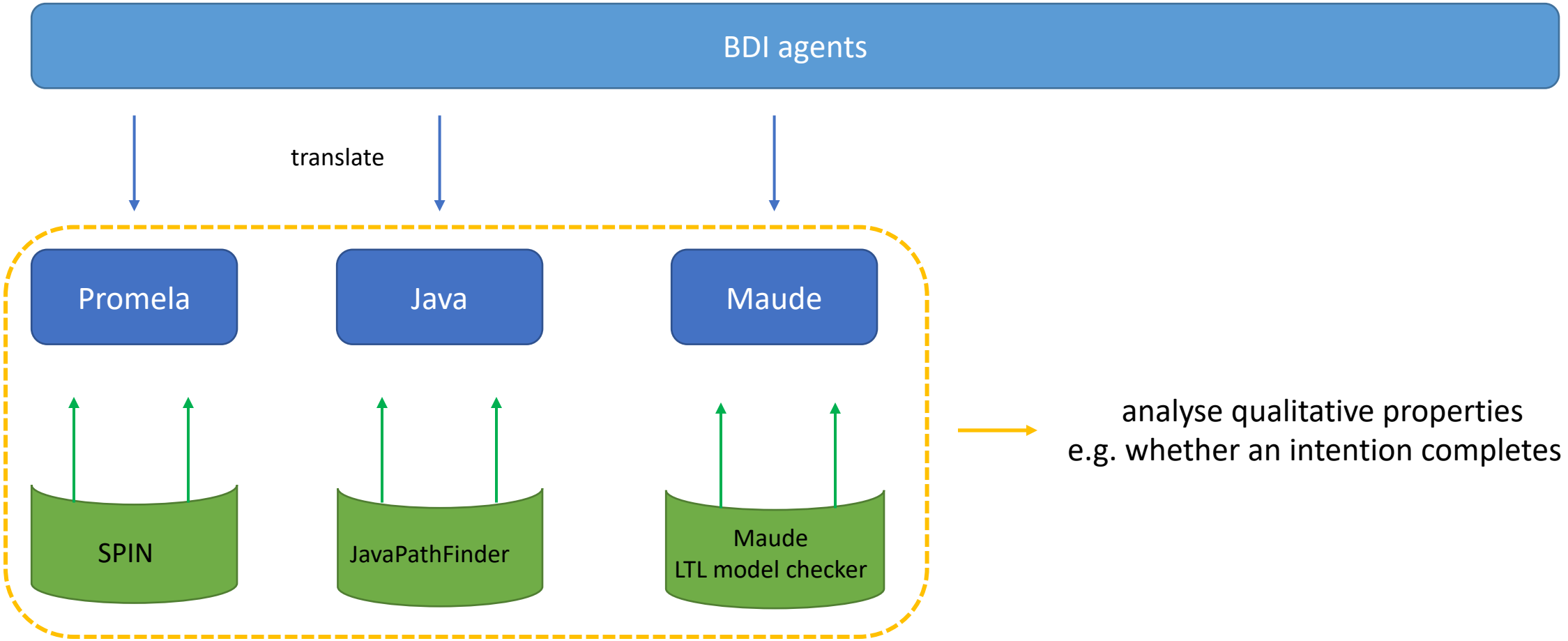
Blair Archibald et al. (2021): Modelling and Verifying BDI Agents with Bigraphs. published Dec 2021 in Science of Computer Programming



our approach

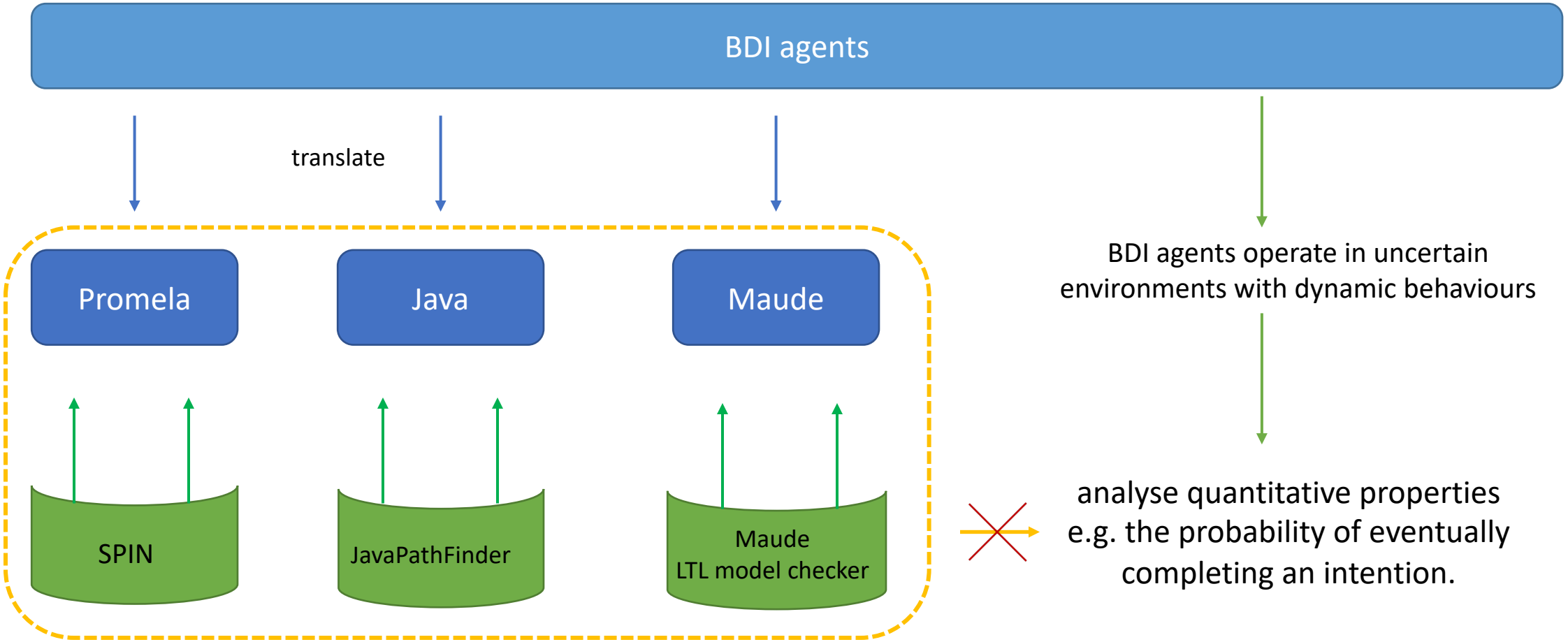
Building Trustworthy BDI Agents

Limitation



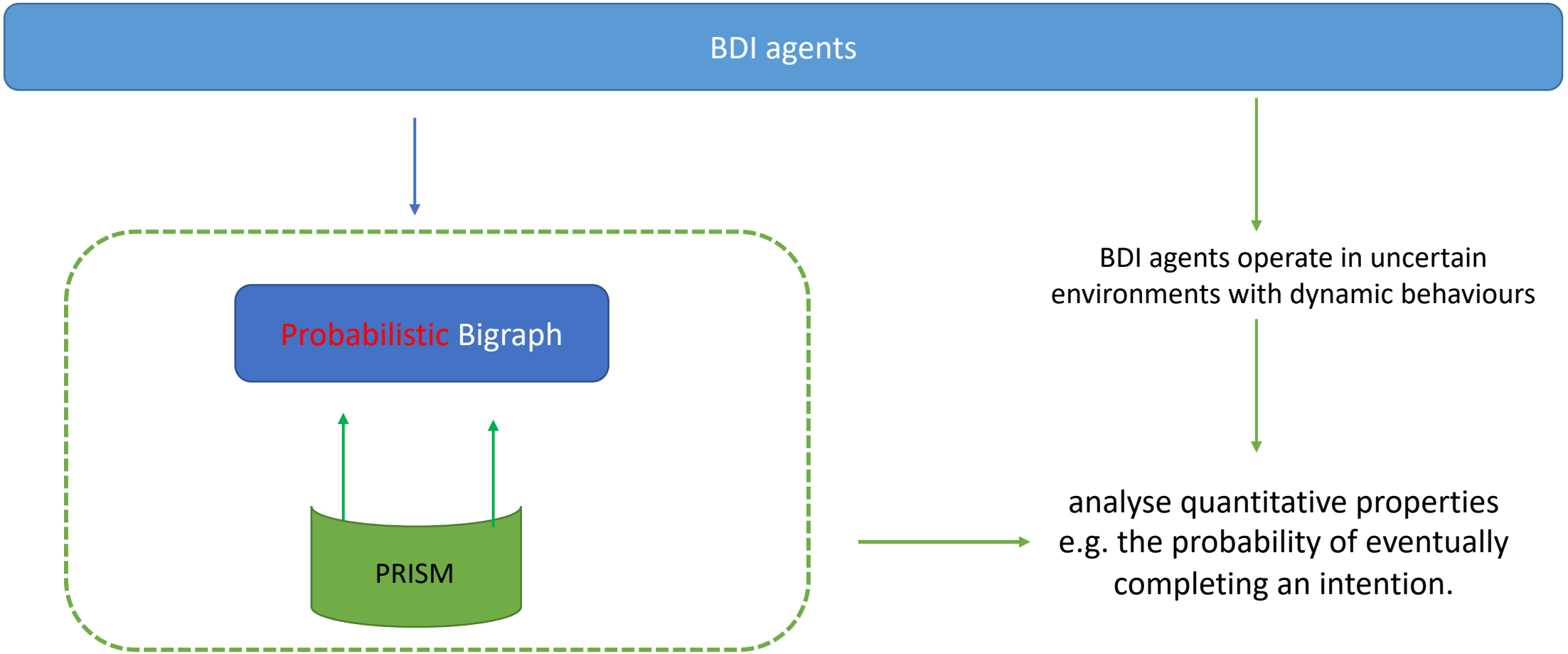
Building Trustworthy BDI Agents

Limitation



Building Trustworthy BDI Agents

Our approach



Building Trustworthy BDI Agents

Our approach

Quantitative properties analysis

actions	probabilistic effects of an action
plans	which plan to select if there is more than one available
intentions	which intention to progress if there is more than one available

Building Trustworthy BDI Agents

Actions

original BDI semantics[1]

$$\frac{act: \varphi \leftarrow \langle \phi^-, \phi^+ \rangle \quad \mathcal{B} \vDash \varphi}{\langle \mathcal{B}, act \rangle \rightarrow \langle (\mathcal{B} \backslash \phi^- \cup \phi^+), nil \rangle} \qquad act$$

probabilistic BDI semantics

$$\frac{act: \varphi \leftarrow \mu \quad \mu(\phi^-, \phi^+) = p \quad \mathcal{B} \vDash \varphi}{\langle \mathcal{B}, act \rangle \rightarrow_p \langle (\mathcal{B} \backslash \phi^- \cup \phi^+), nil \rangle} \qquad act^p$$

$\mu = [(\phi_1^-, \phi_1^+) \mapsto p_1, \cdots, (\phi_n^-, \phi_n^+) \mapsto p_n]$ and $\sum_{i=1}^{n} p_i = 1$.

[1]CAN Semantics in [Winikoff et al., 2002]

Building Trustworthy BDI Agents

Plans

original BDI semantics

$$\frac{\varphi{:}\,P \ \in \Delta \quad \mathcal{B} \vDash \varphi}{\langle \mathcal{B}, e{:}\,(|\Delta|)\rangle \rightarrow \langle \mathcal{B}, P \rhd e{:}\,(|\Delta \backslash \{\varphi{:}\,P\}|)\rangle} \quad select$$

probabilistic BDI semantics

$$\frac{\varphi{:}\,P \ \in \Delta \quad \delta^{p}(\mathcal{B}, \Delta) = \mu \quad \mu \neq \bot \quad \mu(\varphi{:}\,P) = p}{\langle \mathcal{B}, e{:}\,(|\Delta|)\rangle \rightarrow_{p} \langle \mathcal{B}, P \rhd e{:}\,(|\Delta \backslash \{\varphi{:}\,P\}|)\rangle} \quad select^{p}$$

probabilistic plan selection function: $\delta^{p}\colon 2^{\mathcal{B}} \times 2^{\Pi} \rightarrow Dist(\Pi) \cup \{\bot\}$

Building Trustworthy BDI Agents

Intentions

original BDI semantics

$$\frac{P \in \Gamma \quad \langle \mathcal{B}, P \rangle \rightarrow \langle \mathcal{B}', P' \rangle}{\langle E^e, \mathcal{B}, \Gamma \rangle \Rightarrow \langle E^e, \mathcal{B}', (\Gamma \backslash \{P\}) \cup \{P'\} \rangle} \quad A_{step}$$

$$\frac{P \in \Gamma \quad \langle \mathcal{B}, P \rangle \nrightarrow}{\langle E^e, \mathcal{B}, \Gamma \rangle \Rightarrow \langle E^e, \mathcal{B}', \Gamma \backslash \{P\} \rangle} \quad A_{update}$$

probabilistic BDI semantics

$$\frac{P \in \Gamma \quad \eta^p(\mathcal{B}, \Gamma) = \mu \quad \mu \neq \bot \quad \mu(P) = p \quad \langle \mathcal{B}, P \rangle \rightarrow_{p'} \langle \mathcal{B}', P' \rangle}{\langle E^e, \mathcal{B}, \Gamma \rangle \Rightarrow_{p \cdot p'} \langle E^e, \mathcal{B}', (\Gamma \backslash \{P\}) \cup \{P'\} \rangle} \quad A^p_{step}$$

$$\frac{P \in \Gamma \quad \eta^p(\mathcal{B}, \Gamma) = \mu \quad \mu \neq \bot \quad \mu(P) = p'' \quad \langle \mathcal{B}, P \rangle \nrightarrow_1}{\langle E^e, \mathcal{B}, \Gamma \rangle \Rightarrow_{p''} \langle E^e, \mathcal{B}, \Gamma \backslash \{P\} \rangle} \quad A^p_{update}$$

probabilistic intention selection function: $\delta^p \colon 2^{\mathcal{B}} \times 2^{\Gamma} \rightarrow Dist(\Gamma) \cup \{\bot\}$ and $\sum_{p''} p'' + \sum_{p,p'} p \cdot p' = 1$

Building Trustworthy BDI Agents

Summary on distribution

Action: $\mu = [(\phi_1^-, \phi_1^+) \mapsto p_1, \cdots, (\phi_n^-, \phi_n^+) \mapsto p_n]$ and $\sum_{i=1}^{n} p_i = 1$.

pre-designed distributions

Building Trustworthy BDI Agents

Summary on distribution

Action: $\mu = [(\phi_1^-, \phi_1^+) \mapsto p_1, \cdots, (\phi_n^-, \phi_n^+) \mapsto p_n]$ and $\sum_{i=1}^{n} p_i = 1$.

pre-designed distributions

Plan: δ^p: $2^{\mathcal{B}} \times 2^{\Pi} \rightarrow Dist(\Pi) \cup \{\bot\}$

situational distributions

Intention: δ^p: $2^{\mathcal{B}} \times 2^{\Gamma} \rightarrow Dist(\Gamma) \cup \{\bot\}$

situational distributions

Building Trustworthy BDI Agents

Summary on distribution

Action: $\mu = [(\phi_1^-, \phi_1^+) \mapsto p_1, \cdots, (\phi_n^-, \phi_n^+) \mapsto p_n]$ and $\sum_{i=1}^{n} p_i = 1$.

pre-designed distributions

Plan: $\delta^p \colon 2^{\mathcal{B}} \times 2^{\Pi} \to Dist(\Pi) \cup \{\bot\}$

situational distributions

Intention: $\delta^p \colon 2^{\mathcal{B}} \times 2^{\Gamma} \to Dist(\Gamma) \cup \{\bot\}$

situational distributions

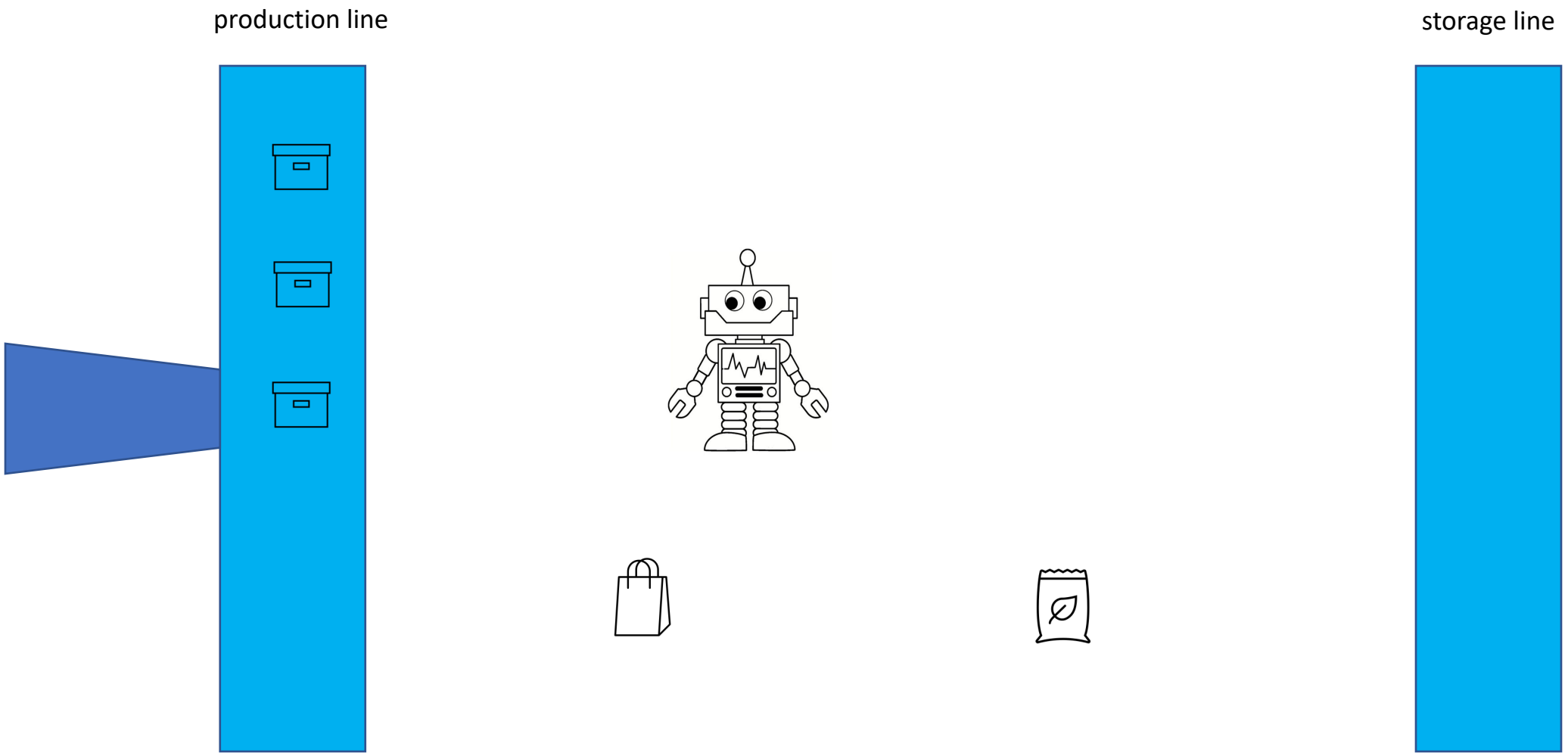
situation value description

$$\langle d_0, \{(\varphi_1, d_1), \cdots, (\varphi_n, d_n)\}, f \rangle$$

default value d_0, if φ_i holds, it will be aggregated according to the function f

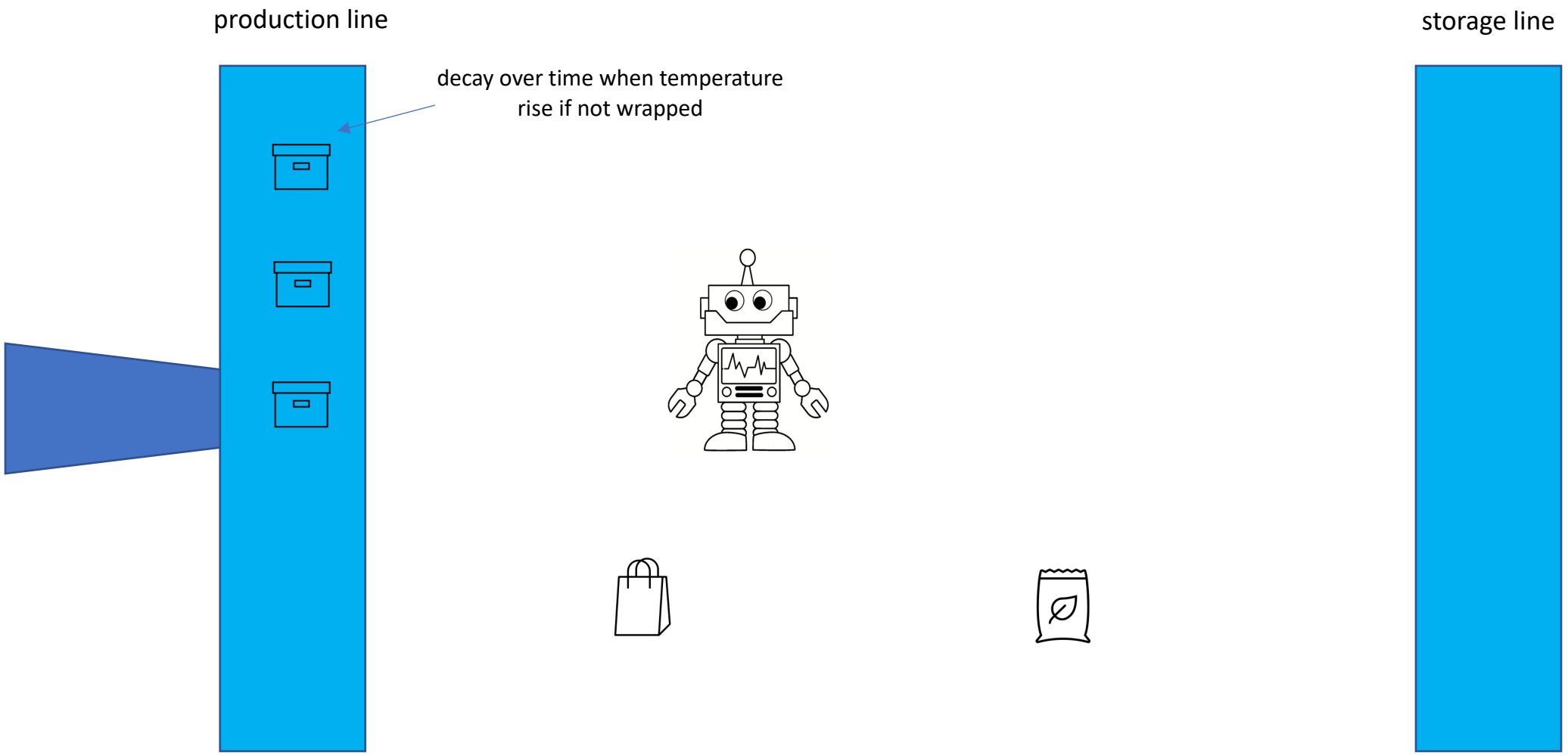
Building Trustworthy BDI Agents

Evaluation



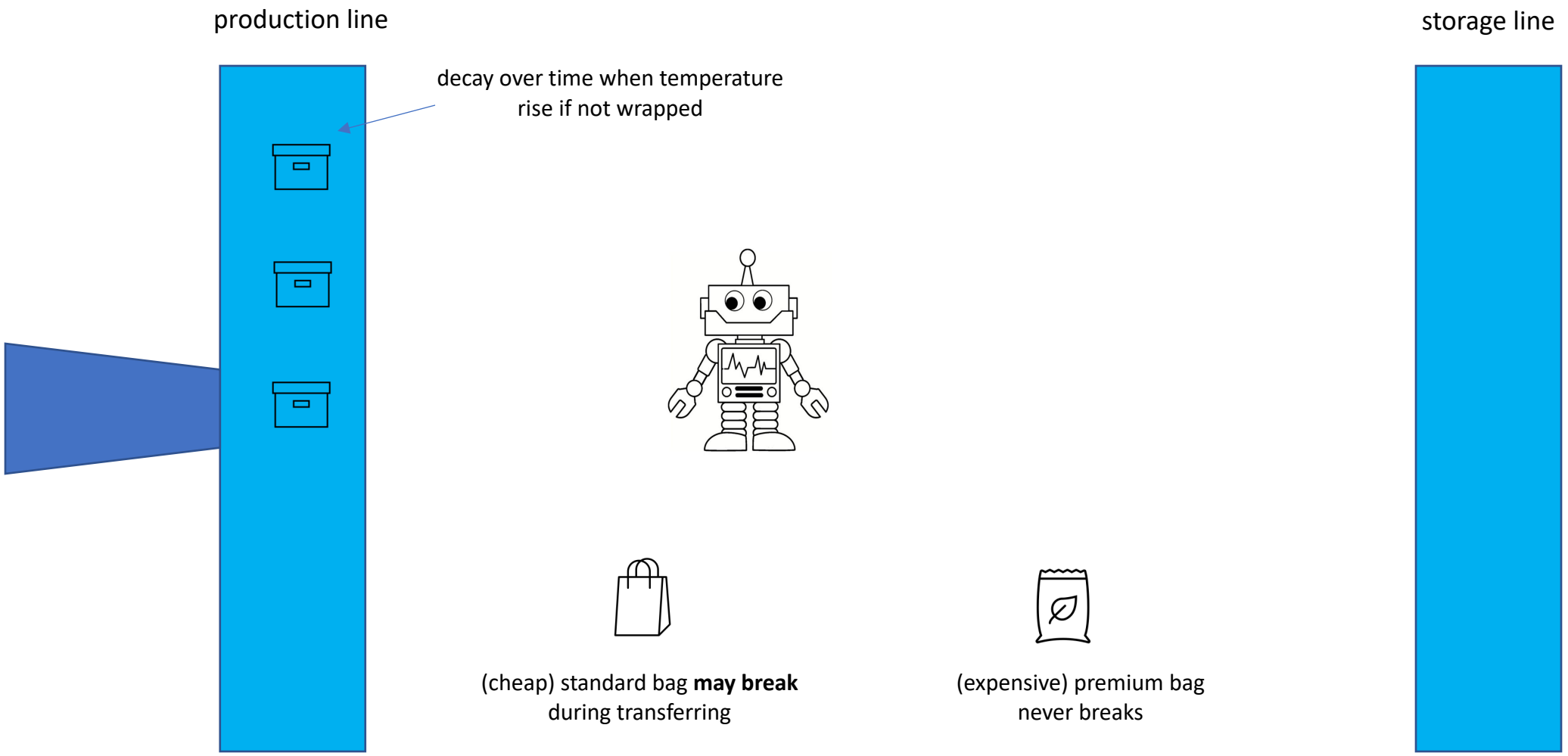
Building Trustworthy BDI Agents

Evaluation



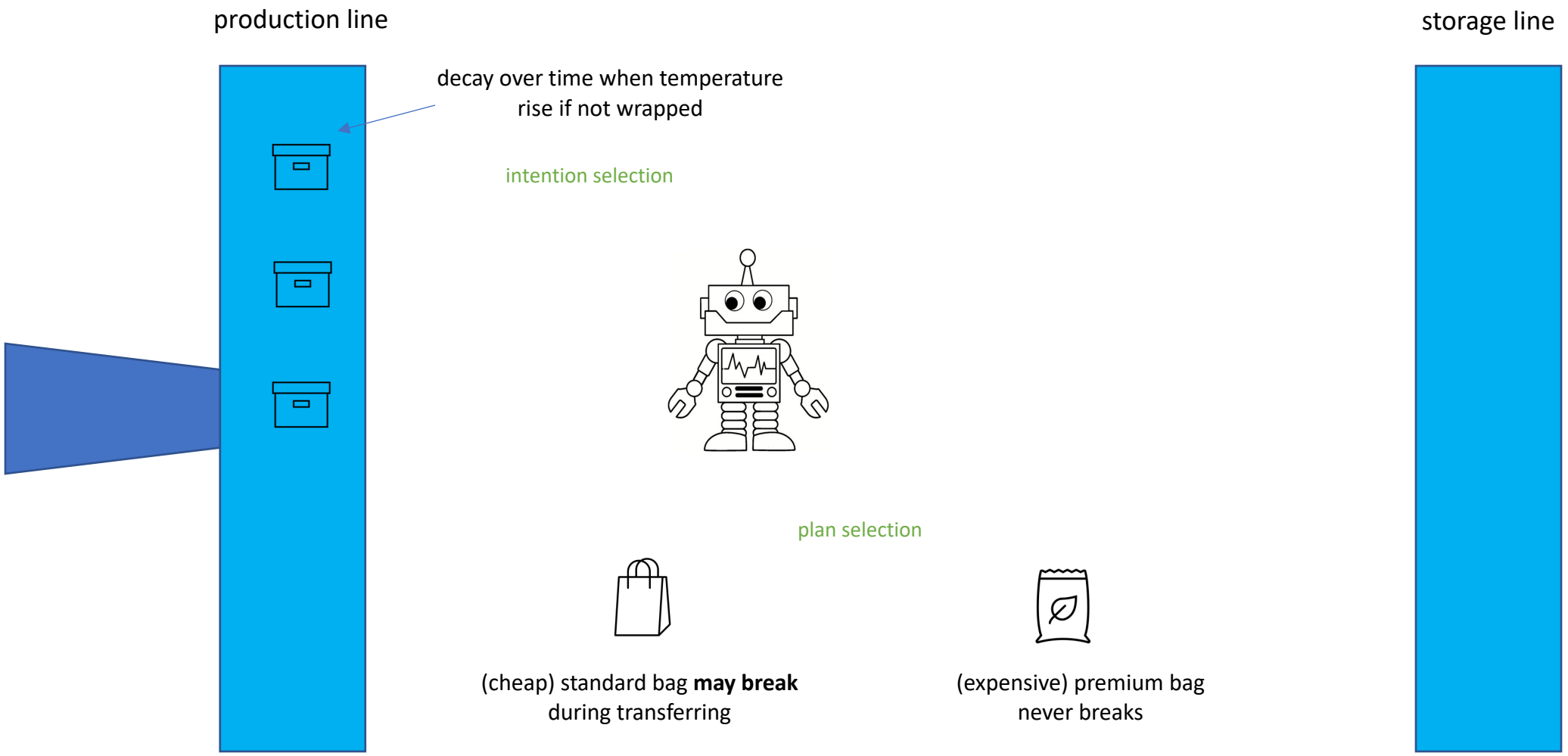
Building Trustworthy BDI Agents

Evaluation



Building Trustworthy BDI Agents

Evaluation



Building Trustworthy BDI Agents

Analysis

production line

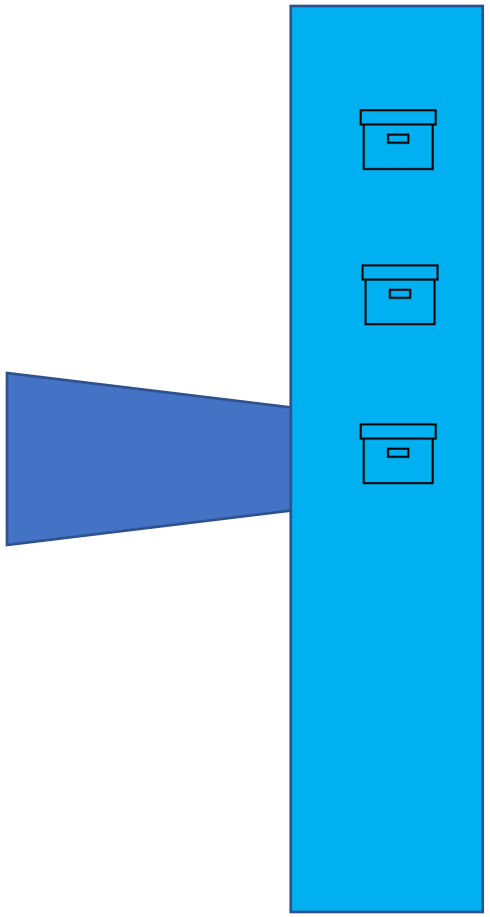
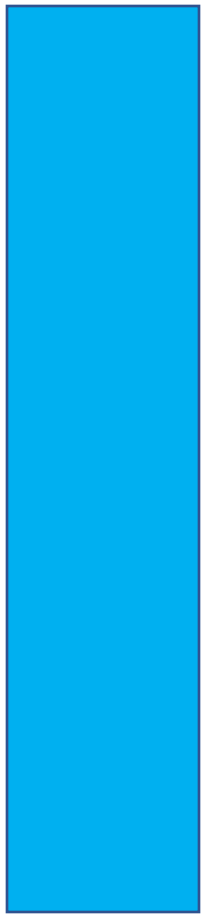


Table 2. Plan and intention selection strategies.

Plan Selection Strategies	Intention Selection Strategies
SMP: Select Most Preferred	**SMU**: Select Most Urgent
PSD: Preference Situational Distribution	**FIFO**: First-In-First-Out
	RR: Round Robin
	PUSD: Pure Urgency Situational Distribution
	LUSD: Layered Urgency Situational Distribution
	OLUSD: Optimised Layered Urgency Situational Distribution

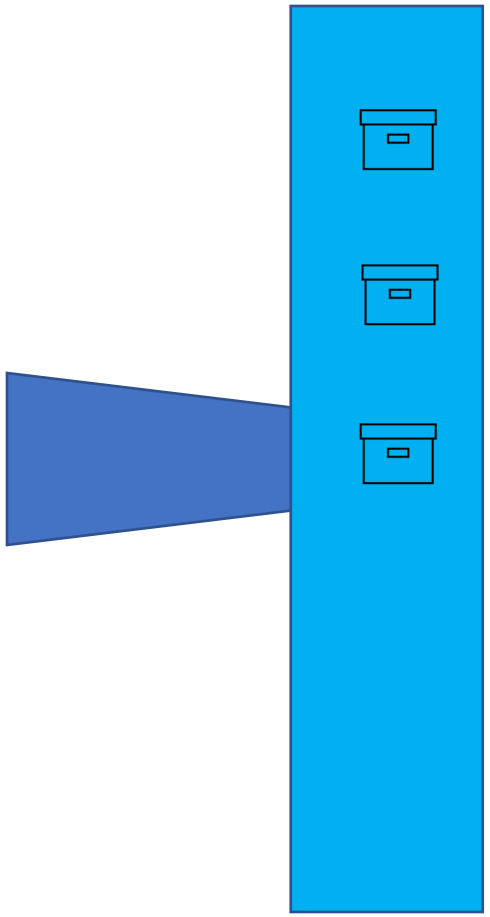
storage line



Building Trustworthy BDI Agents

Analysis

production line



storage line

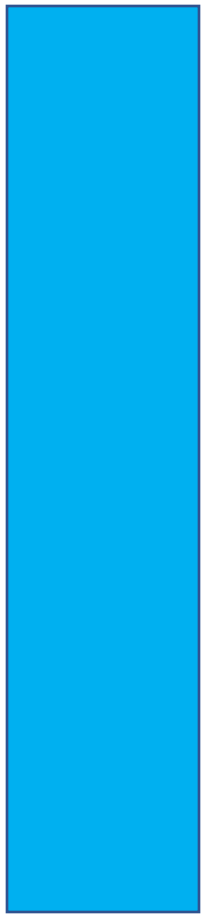


Table 2. Plan and intention selection strategies.

Plan Selection Strategies	Intention Selection Strategies
SMP: Select Most Preferred	**SMU**: Select Most Urgent
PSD: Preference Situational Distribution	**FIFO**: First-In-First-Out
	RR: Round Robin
	PUSD: Pure Urgency Situational Distribution
	LUSD: Layered Urgency Situational Distribution
	OLUSD: Optimised Layered Urgency Situational Distribution

Table 3. Probability of product 1, product 2 for the properties, *e.g.* (S1, S2) with different plan and intention selection strategies listed in Table 2.

		Intention: SMU		FIFO		RR	
Plan	SMP	(S1,S2) 0	(S1,F2) 0.9	(S1,S2) 0	(S1,F2) 0	(S1,S2) 0	(S1,F2) 0
		(F1,S2) 0	(F1, F2) 0.1	(F1,S2) 0.9	(F1,F2) 0.1	(F1,S2) 0	(F1,F2) 1
	PSD	(S1,S2) 0	(S1,F2) 0.93	(S1,S2) 0	(S1,F2) 0	(S1,S2) 0	(S1,F2) 0
		(F1,S2) 0	(F1,F2) 0.07	(F1,S2) 0.93	(F1,F2) 0.07	(F1,S2) 0	(F1,F2) 1
		PUSD		**LUSD**		**OLUSD**	
Plan	SMP	(S1,S2) 0.03	(S1,F2) 0.48	(S1,S2) 0.510	(S1,F2) 0	(S1,S2) 0.97	(S1,F2) 0
		(F1,S2) 0.08	(F1,F2) 0.41	(F1,S2) 0.482	(F1,F2) 0.008	(F1,S2) 0.037	(F1,F2) 0
	PSD	(S1,S2) 0.03	(S1,F2) 0.49	(S1,S2) 0.513	(S1,F2) 0	(S1,S2) 0.98	(S1,F2) 0
		(F1,S2) 0.08	(F1,F2) 0.4	(F1,S2) 0.481	(F1,F2) 0.05	(F1,S2) 0.02	(F1,F2) 0

Building Trustworthy BDI Agents

Analysis

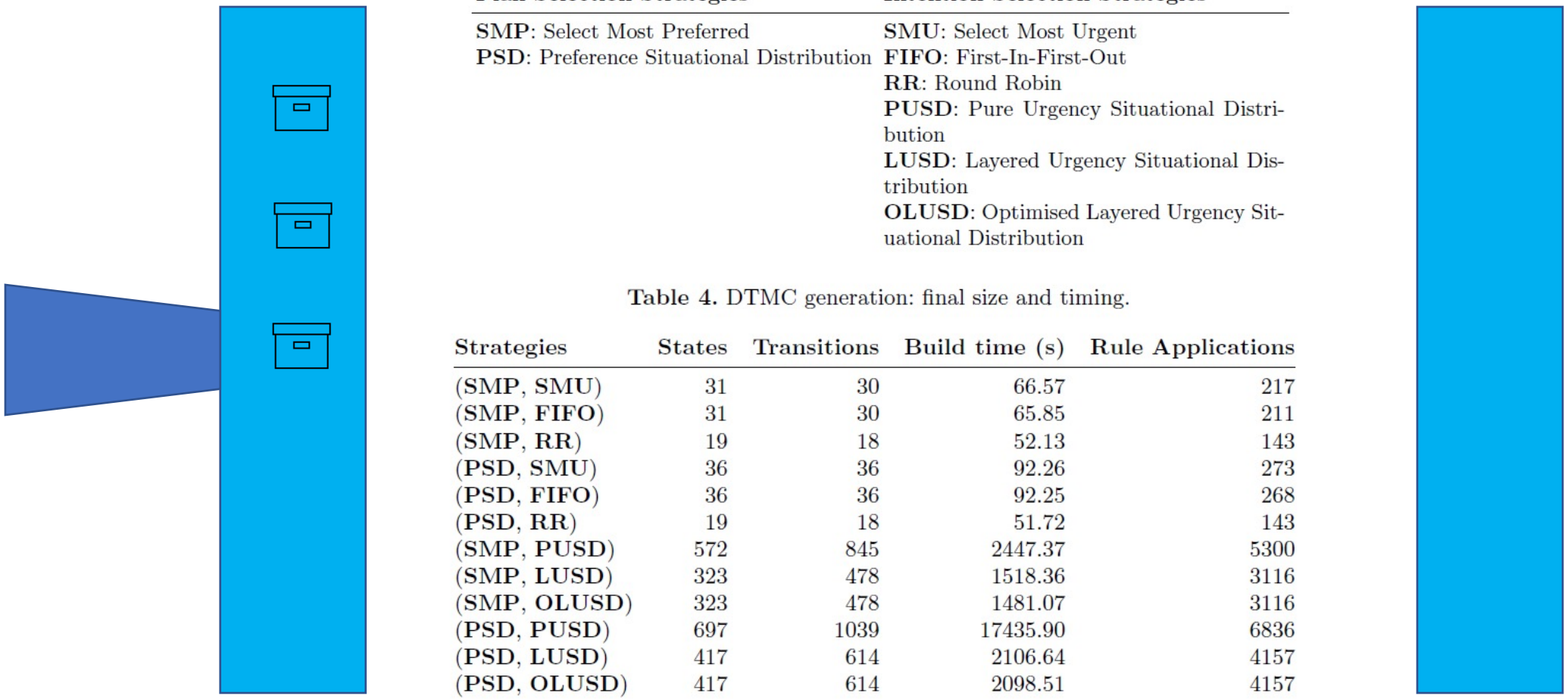


Table 2. Plan and intention selection strategies.

Plan Selection Strategies	Intention Selection Strategies
SMP: Select Most Preferred	**SMU**: Select Most Urgent
PSD: Preference Situational Distribution	**FIFO**: First-In-First-Out
	RR: Round Robin
	PUSD: Pure Urgency Situational Distribution
	LUSD: Layered Urgency Situational Distribution
	OLUSD: Optimised Layered Urgency Situational Distribution

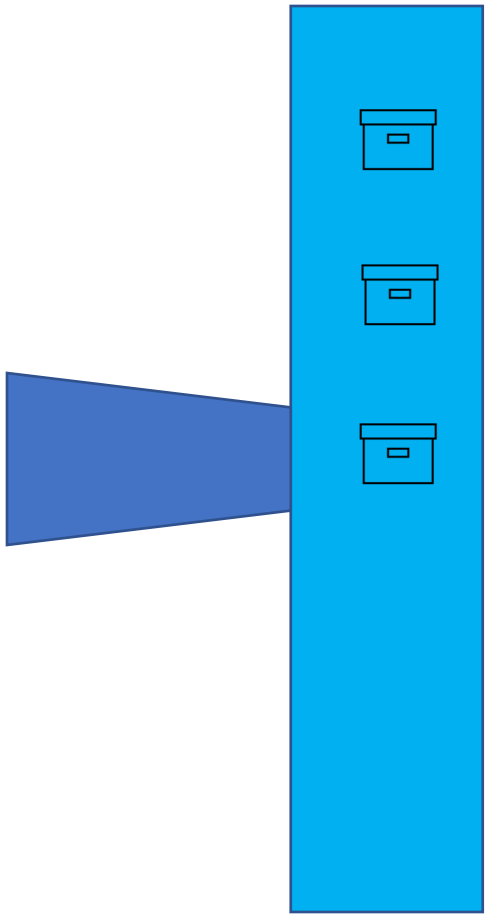
Table 4. DTMC generation: final size and timing.

Strategies	States	Transitions	Build time (s)	Rule Applications
(SMP, SMU)	31	30	66.57	217
(SMP, FIFO)	31	30	65.85	211
(SMP, RR)	19	18	52.13	143
(PSD, SMU)	36	36	92.26	273
(PSD, FIFO)	36	36	92.25	268
(PSD, RR)	19	18	51.72	143
(SMP, PUSD)	572	845	2447.37	5300
(SMP, LUSD)	323	478	1518.36	3116
(SMP, OLUSD)	323	478	1481.07	3116
(PSD, PUSD)	697	1039	17435.90	6836
(PSD, LUSD)	417	614	2106.64	4157
(PSD, OLUSD)	417	614	2098.51	4157

Building Trustworthy BDI Agents

Analysis

production line



storage line

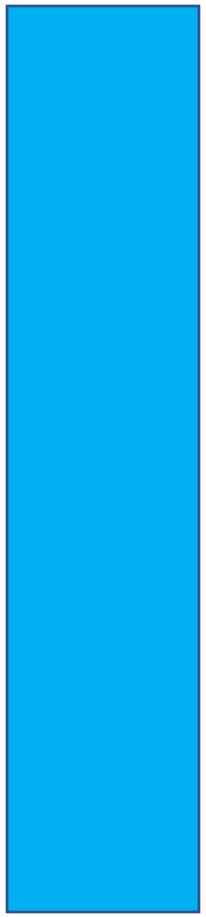


Table 2. Plan and intention selection strategies.

Plan Selection Strategies	Intention Selection Strategies
SMP: Select Most Preferred	**SMU**: Select Most Urgent
PSD: Preference Situational Distribution	**FIFO**: First-In-First-Out
	RR: Round Robin
	PUSD: Pure Urgency Situational Distribution
	LUSD: Layered Urgency Situational Distribution
	OLUSD: Optimised Layered Urgency Situational Distribution

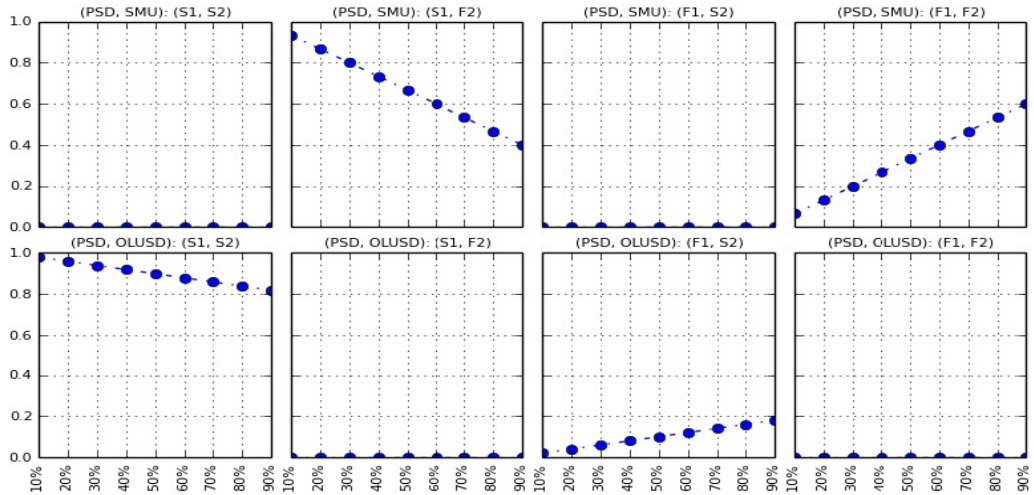


Fig. 2. Probability of reaching the end state (product 1, product 2) with increasing failure probability in (**PSD**, **SMU**) and (**PSD**, **OLUSD**).

Building Trustworthy BDI Agents

Note

In principle, our approach allows users to “run” any example with

1. different external events (e.g. tasks)
2. different plan libraries (e.g. methods)
3. custom situation value descriptions

Building Trustworthy BDI Agents

Note

In principle, our approach allows users to “run” any example with

1. different external events (e.g. tasks)
2. different plan libraries (e.g. methods)
3. custom situation value descriptions

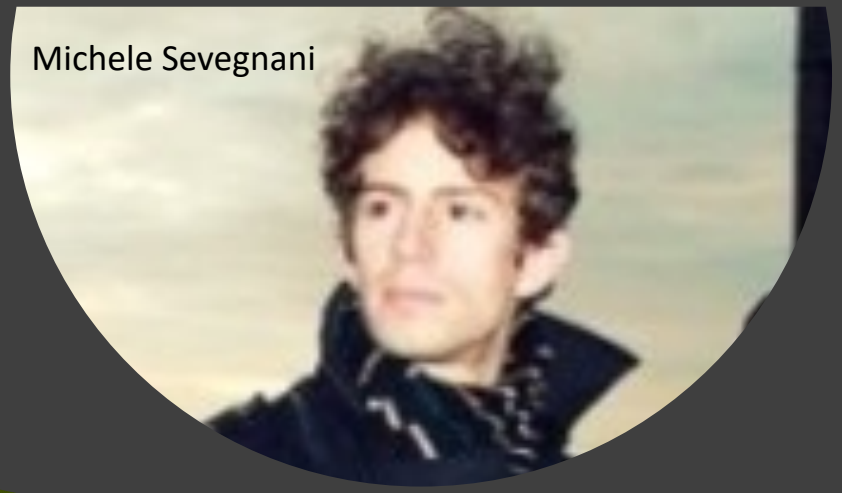
provide probabilistic support
to deliver quantitative assurance of agent behaviours
in more realistic industrial systems prone to failures

Building Trustworthy BDI Agents

Future Work

1. multi-objective analysis: obtaining high success rate while keeping the overall bag cost low

2. dynamic environment: new product being reduced and more robots being employed


Michele Sevegnani


Blair Archibald


Mengwei Xu


Muffy Calder

Many thanks for your attentions

University of Glasgow