A Framework for Plan Library Evolution in BDI Agent Systems

Mengwei Xu, Kim Bauters, Kevin McAreavey, Weiru Liu

Extending BDI with FPP

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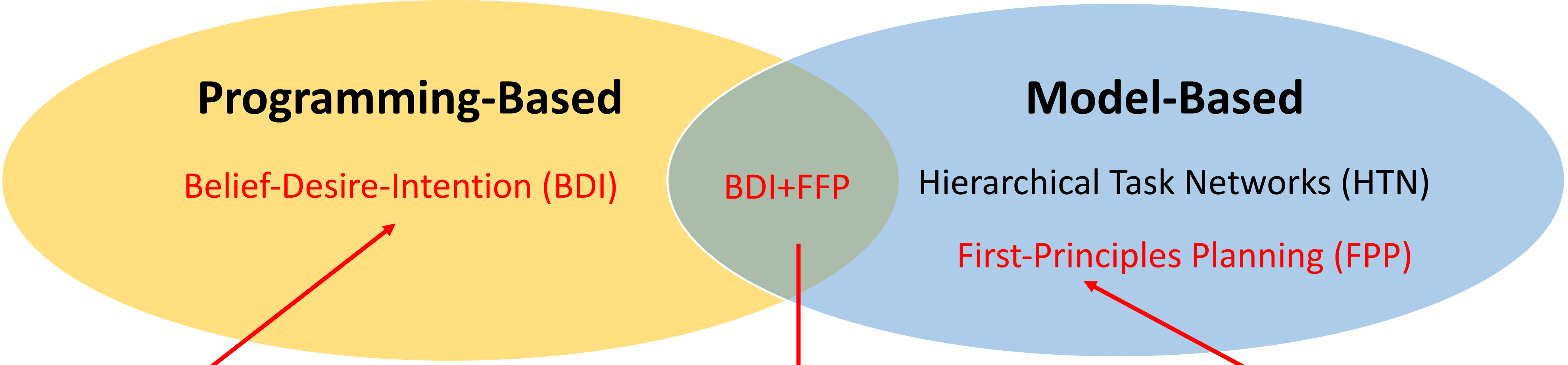


Plan library

Pros: designer intent, scalability, reactive

Cons: unforeseen situations, inadequacy

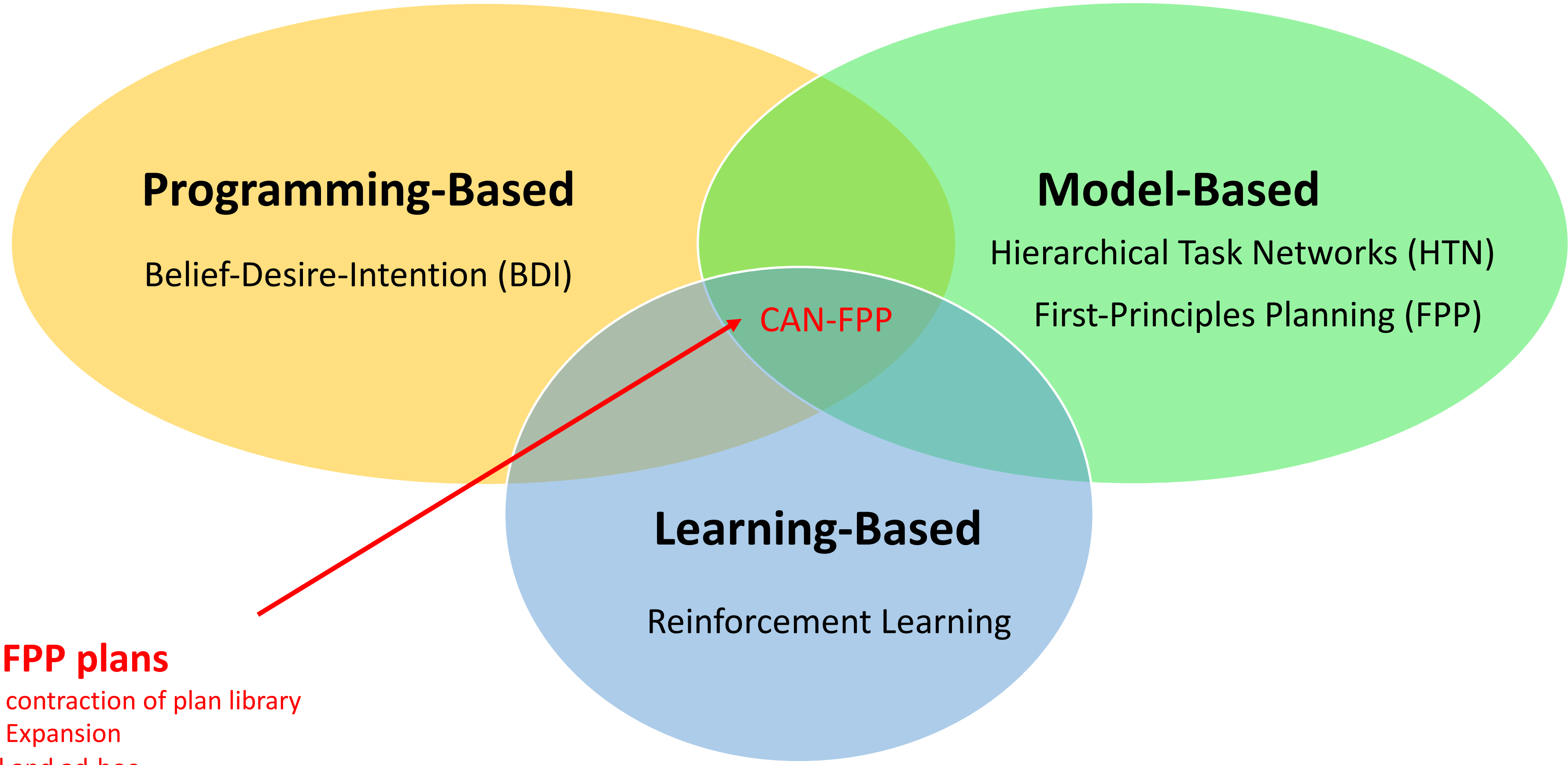
Synthesise new plans

Pros: robust, dynamic environments

Cons: expensive

Extend existing BDI to account for **incomplete** plan library by synthesising new plans using FPP at runtime

Extending BDI with Evolving Plan Library

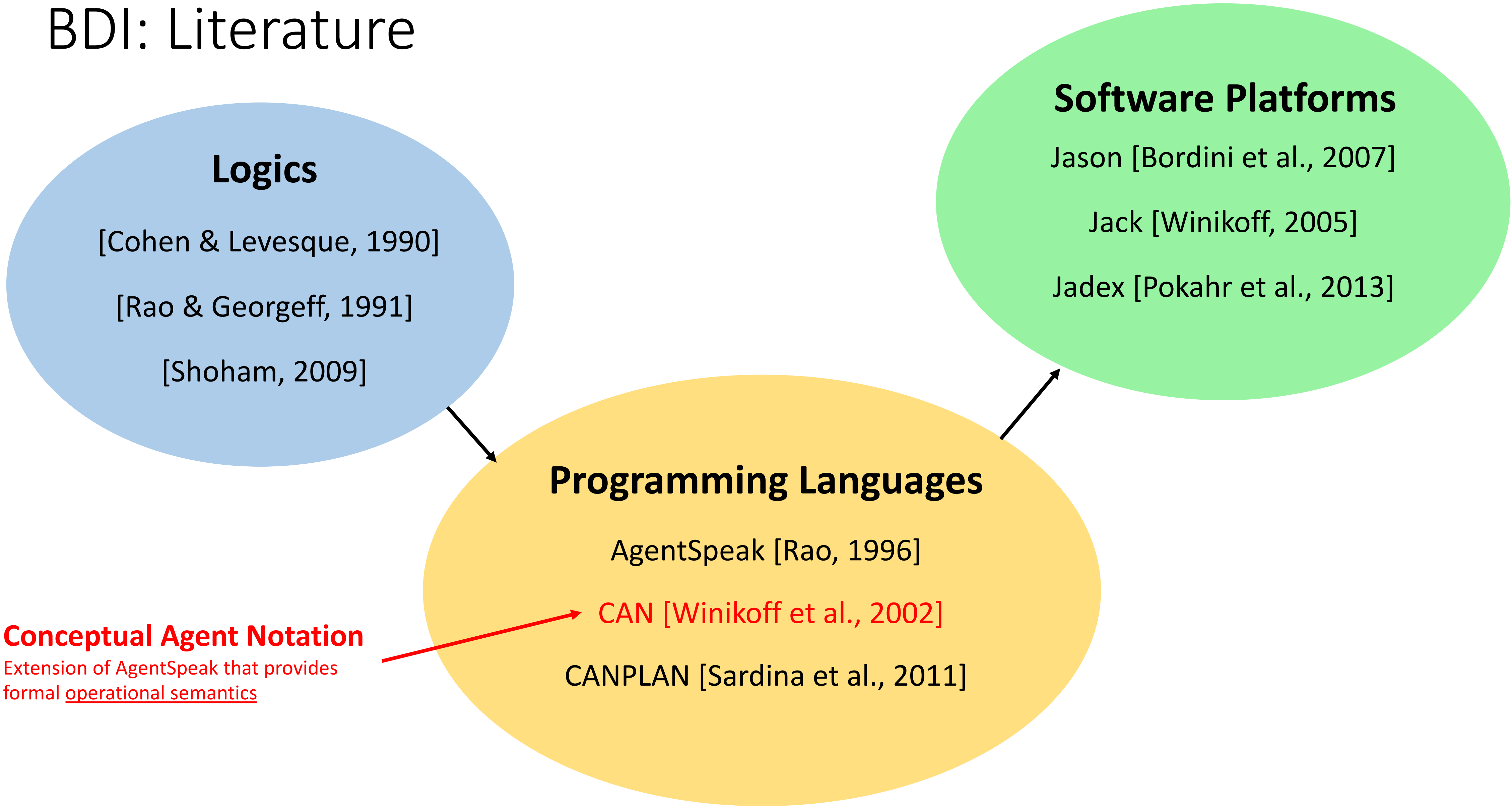


Reusable FPP plans

Expansion and contraction of plan library

- Plan Library Expansion
  -- Syntactical and ad-hoc
- No works on Plan Library Contraction

BDI: Literature



CAN: Agent $(\mathcal{B}, \Lambda, \Pi)$

Initial belief base

Belief base specifying agent's initial beliefs

Action description library

Set of STRIPS-style action descriptions

Plan library

Set of plan rules

CAN: Agent $(\mathcal{B}, \Lambda, \Pi)$

Initial belief base

Belief base specifying agent's initial beliefs

Belief base $\mathcal{B} \subseteq \mathcal{L}$

Set of formulas from **logical language** $\mathcal{L}$

$\mathcal{B}$ must support:

- $\mathcal{B} \vDash \varphi$ (Entailment)
- $\mathcal{B} \cup \{\varphi\}$ (Addition)
- $\mathcal{B} \setminus \{\varphi\}$ (Deletion)

<u>Assume $\mathcal{B}$ is a set of atoms</u>

CAN: Agent $(\mathcal{B}, \Lambda, \Pi)$

Action description library

Set of STRIPS-style action descriptions

Action description $\text{act} : \varphi \leftarrow \mathcal{B}^- \,;\, \mathcal{B}^+$

Primitive action symbol

Precondition $\varphi \in \mathcal{L}$

Set of "delete" atoms $\mathcal{B}^- \subseteq \mathcal{L}$

Set of "add" atoms $\mathcal{B}^+ \subseteq \mathcal{L}$

CAN: Agent $(\mathcal{B}, \Lambda, \Pi)$

Plan library

Set of plan rules

Triggering event e

e.g. belief update, new (sub)goal

Context $\varphi \in \mathcal{L}$

Formula from $\mathcal{L}$

Plan rule $e : \varphi \leftarrow P$

Body (program) $P ::= nil \mid act \mid ?\varphi \mid +b \mid -b \mid !e \mid P_1 ; P_2 \mid P_1 \rhd P_2 \mid P_1 \parallel P_2 \mid goal(\varphi_s, P, \varphi_f) \mid goal(\varphi_s, \varphi_f)$

- Empty program
- Primitive action
- Entailment
- Belief addition
- Belief deletion
- New (sub)goal
- Sequencing
- Conditional
- Concurrency
- CAN declarative goal
- Pure declarative goal

CAN: Operational Mechanism Sketch

Triggering event e —*select*→ **Relevant Plans** —*select*→ **Applicable Plans**

e.g. belief update, new (sub)goal

Relevant Plans:

$$\begin{array}{l} e : \varphi_1 \leftarrow P_1 \\ e : \varphi_2 \leftarrow P_2 \\ e : \varphi_3 \leftarrow P_3 \\ \vdots \\ e : \varphi_n \leftarrow P_n \end{array}$$

$\subseteq \Pi$

Applicable Plans:

$$\begin{array}{l} e : \varphi_{11} \leftarrow P_{11} \\ e : \varphi_{21} \leftarrow P_{21} \\ e : \varphi_{31} \leftarrow P_{31} \\ \vdots \\ e : \varphi_{n1} \leftarrow P_{n1} \end{array}$$

where $\boldsymbol{\mathcal{B}} \vDash \varphi_{\boldsymbol{j1}}, j \in \{1, \cdots, n\}$

Our Plan Library Evolution Framework in BDI

1. Introduce Domain-independent Characteristics of a Plan Library
    - ***Activeness*** (i.e. how often plans are used)
    - ***Success*** (i.e. how well plans have performed)
    - ***Functionality*** (i.e. how many types of triggering events/goals it can respond to)
    - ***Robustness*** (i.e. how easy it is to replace a plan when it does not work)

2. Present Principle Definition of a Plan Library Evolution Framework
    - Postulates of a plan library ***expansion operation***
    - Postulates of a plan library ***contraction operator***
    - None-functionality and robustness decreasing ***theorem to plan library expansion operator***
    - Set operation properties ***theorem to plan library contraction operator***

3. Instantiate Plan Library Contraction Operator
    - ***Employ*** multi-criteria argumentation-based decision making
    - ***Prove*** such specific contraction operator satisfies the postulates

Measuring Performance of Plan

$$\mathcal{S}: \mathcal{P} \times \mathcal{T} \rightarrow \{\top, \bot, \emptyset\}$$

- $\mathcal{S}$: ***Status function***
- $\mathcal{P}$: ***plans***
- $\mathcal{T}$: ***timestamps***
- $\top$: ***success***
- $\bot$: ***failure***
- $\emptyset$: ***undefined (e.g. still under execution)***

Execution frequency: $\Delta(P, t_1, t_2) = |\{\mathcal{S}(P, t_i) \neq \emptyset \cdot i = 1, 2, \cdots, n\}|$

- t_1: starting point
- t_2: ending point

→

1. overall execution frequency
2. latest execution frequency

Success rate: $$\Phi(P, t_1, t_2) = \frac{\Delta^s(P, t_1, t_2)}{\Delta(P, t_1, t_2)}$$

where $\Delta^s(P, t_1, t_2) = |\{\mathcal{S}(P, t_i) \neq \top \cdot i = 1, 2, \cdots, n\}|$

Relationships between Plans

Recall: $\mathcal{P}$ is a set of plans and e^P = $\begin{matrix} e : \varphi_1 \leftarrow P_1 \\ e : \varphi_2 \leftarrow P_2 \\ e : \varphi_3 \leftarrow P_3 \\ \vdots \\ e : \varphi_n \leftarrow P_n \end{matrix}$ is a set of relevant plans to respond to triggering event e

Relevancy: $\Upsilon_{\mathcal{P}}(P) = |e^P| - 1$

Replaceability: $\Gamma_{\mathcal{P}}(P) = |S \cdot P \rhd_{mr} S|$

where $P \rhd_r S = \{P_1, P_2, \cdots, P_n\}$

iff. 1. overlapping possible world $\mathcal{O}(P, P_1, P_2, \cdots, P_n) \neq 0$

2. post-effects subsuming holds $post(P, P_1, P_2, \cdots, P_n) \vDash post(P)$

where $P \rhd_{mr} S = \{P_1, P_2, \cdots, P_n\}$

iff. 1. $P \rhd_r S$

2. $P \not\rhd_r S \setminus P'$ for $\forall P' \in S$

Summary Information for a Plan Library

Execution frequency:

$$\Delta(\Pi, t_1, t_2) = \frac{\sum_{P \in \Pi} \Delta(P, t_1, t_2)}{|\Pi|}$$

Success rate:

$$\Phi(\Pi, t_1, t_2) = \frac{\sum_{P \in \Pi} \Delta^S(P, t_1, t_2)}{|\Pi|}$$

Functionality:

$$\mathcal{F}(\Pi) = |\{e \cdot e^P \sqsubseteq \Pi\}|$$

Relevancy:

$\Upsilon_{\mathcal{P}}(P)$ where $\mathcal{P} = \Pi$

Replaceability:

$\Gamma_{\mathcal{P}}(P)$ where $\mathcal{P} = \Pi$

Domain-independent Characteristics Orderings

$$\langle \succcurlyeq_{activeness}, \succcurlyeq_{success}, \succcurlyeq_{functionality}, \succcurlyeq_{robustness} \rangle$$

- $\Pi \succcurlyeq_{activeness} \Pi'$ iff $\Delta(\Pi, t_1, t_2) \geq \Delta(\Pi', t_1, t_2)$
- $\Pi \succcurlyeq_{success} \Pi'$ iff $\Phi(\Pi, t_1, t_2) \geq \Phi(\Pi', t_1, t_2)$
- $\Pi \succcurlyeq_{functionality} \Pi'$ iff $\mathcal{F}(\Pi) \geq \mathcal{F}(\Pi')$
- $\Pi \succcurlyeq_{robustness} \Pi'$ iff $\nexists P \in \Pi$ s.t. $P \in \Pi', \Upsilon_{\Pi}(P) \leq \Upsilon_{\Pi'}(P), \Gamma_{\Pi}(P) \leq \Gamma_{\Pi'}(P)$

Plan Library Expansion

Plan Library Expansion Operator

Given a plan library Π and a plan P, $\Pi \circ P$ denotes the expansion of Π by P with $\circ$ if and only if it satisfies the following postulates:

EO1 $\Pi \circ P$ is a plan libray.
EO2 $P \in \Pi \circ P$ and $\Pi \subseteq \Pi \circ P$.
EO3 if $P \in \Pi$, then $\Pi \circ P = \Pi$.
E04 $(\Pi \circ P) \circ P' = (\Pi \circ P') \circ P$.

Proposition: $\Pi \circ \{P, P'\} = (\Pi \circ P) \circ P' = (\Pi \circ P') \circ P$

Theorem: $\Pi \circ P \succcurlyeq_{functionality} \Pi$ and $\Pi \circ P \succcurlyeq_{robustness} \Pi$

the number of types of triggering event (functionality)

relevancy and replaceability (robustness)

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the number of types of triggering event

relevancy and replaceability

Union ∪

$e : \varphi' \leftarrow P'$ ∪

$e : \varphi_1 \leftarrow P_1$
$e : \varphi_2 \leftarrow P_2$
$e : \varphi_3 \leftarrow P_3$
$\vdots$
$e : \varphi_n \leftarrow P_n$

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$e : \varphi_n \leftarrow P_n$
$e : \varphi' \leftarrow P'$

?CONFLICT

Plan Library Contraction (Cont.)

Plan Library Contraction Operator

Given a plan library Π, $\nabla(\Pi)$ denotes the contraction of Π by ∇ iff it satisfies the following postulates:

CO1 $\nabla(\Pi)$ is a plan libray.
CO2 $\nabla(\Pi) \subseteq \Pi$.
CO3 if $\mathcal{P} \subseteq \Pi \setminus \nabla(\Pi)$ and $\mathcal{P} \subseteq \Pi' \subseteq \Pi$, then $\mathcal{P} \subseteq \Pi' \setminus \nabla(\Pi')$.
C04 $\nabla(\Pi) \succcurlyeq \Pi$ where $\succcurlyeq \in \{\succcurlyeq_{activeness}, \succcurlyeq_{success}\}$.
CO5 $\forall P \in \Pi \setminus \nabla(\Pi)$, then $\Gamma_{\nabla(\Pi)}(P) > 0$.

Set Properties of contraction operator ∇

1. $\nabla(\Pi') \subseteq \nabla(\Pi)$if $\Pi' \subseteq \Pi$. ordered set inclusion
2. $\nabla(\Pi \cap \Pi') \subseteq \nabla(\Pi) \cap \nabla(\Pi')$. intersection set inclusion
3. $\nabla(\Pi \setminus \Pi') \subseteq \nabla(\Pi) \setminus \nabla(\Pi')$. difference set inclusion
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Plan Library Contraction (Cont.)

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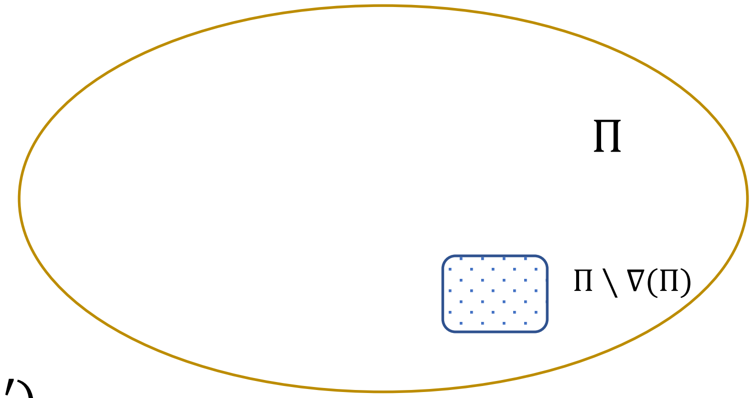

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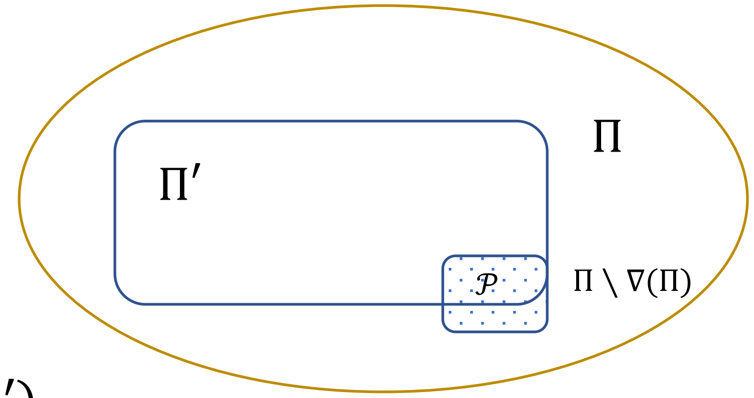

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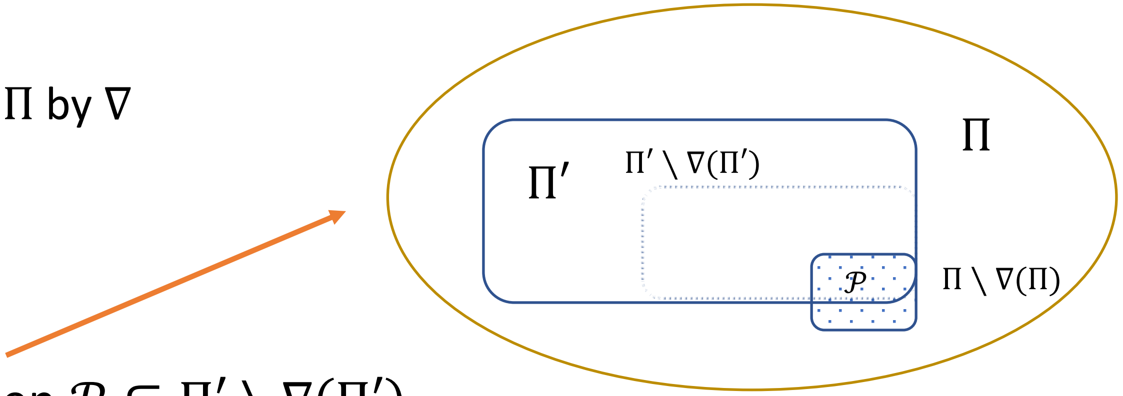

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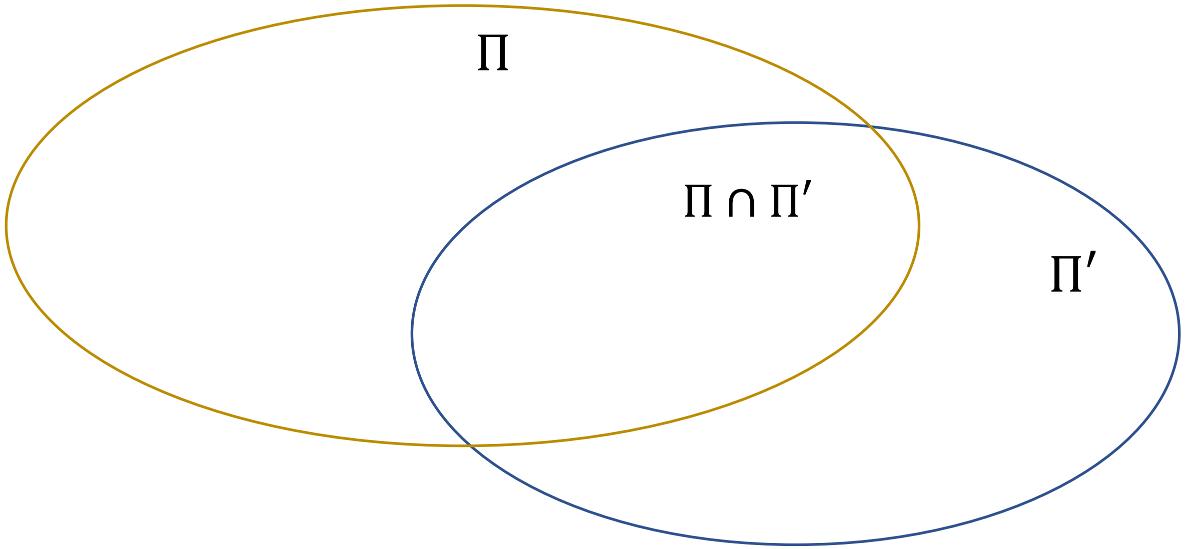

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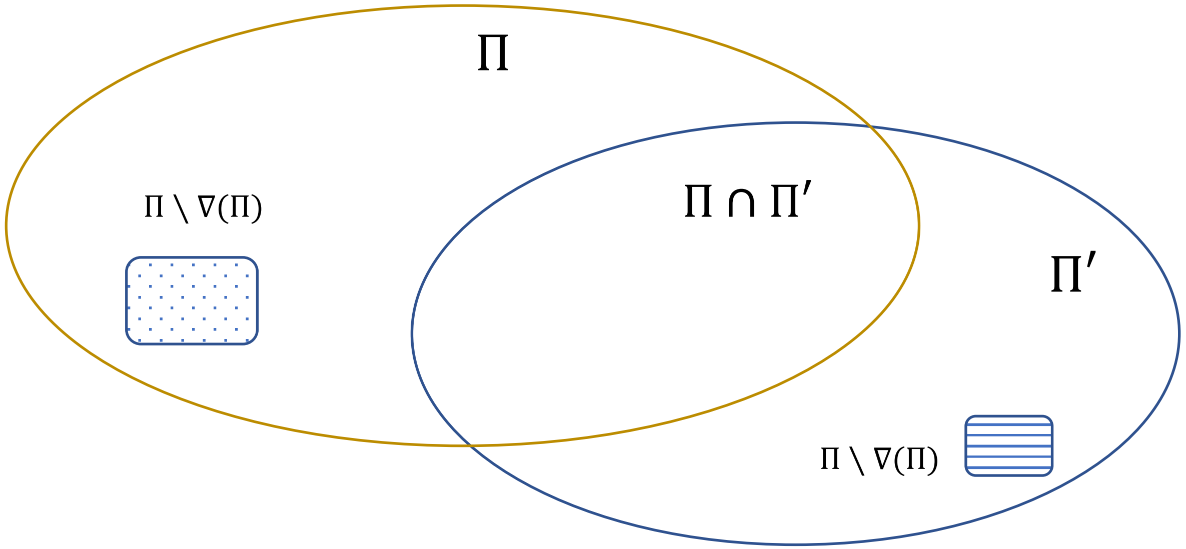

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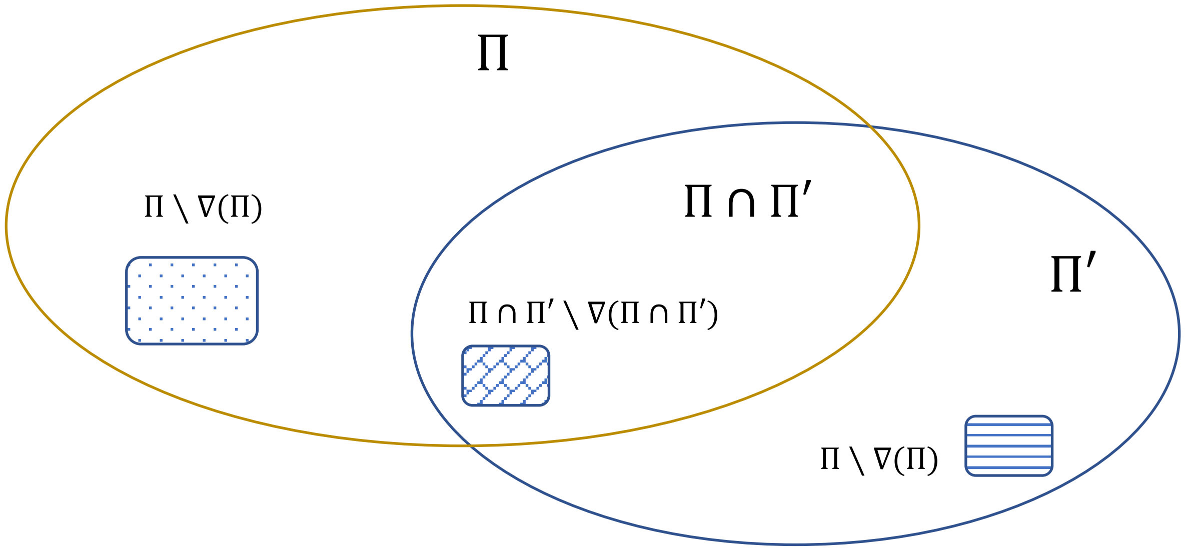

Practical Results: Instantiation of Contraction Operator ∇

$$\nabla^{abm} = \Omega(\langle X, \mathcal{C}, >_{\mathcal{C}}, \mathcal{R} \rangle)$$

Multi-criteria argumentation-based decision making contraction operator

Selected candidates of decision problem

$$X = \{P \in \mathcal{P} \mid \Gamma_{\mathcal{P}}(P) > 0, C_4(P) < \tau\}$$

Replaceability
Filtering to protect the fragility

Latest success rate
Tolerance

$$\mathcal{C} = \{C_1, C_2, C_3, C_4\}$$

Overall execution frequency

Latest execution frequency

Overall success rate

$$>_{\mathcal{C}} = \{(C_4, C_3), (C_2, C_1), (C_4, C_2), (C_3, C_1)\}$$

$$\{W\} \overset{X}{\Leftarrow} \{ws(W, Y)\}, not\ \{ws(Z, W)\}$$

$$\{W, Y\} \overset{X}{\Leftarrow} \{sm(W, Y)\}, not\ \{ws(Z, W)\}$$

Theoretical Results: Satisfiability of Contraction Operator $\boldsymbol{\nabla^{abm}}$

$\nabla^{abm} = \Omega(\langle X, \mathcal{C}, >_{\mathcal{C}}, \mathcal{R}\rangle$ is indeed a contraction operator satisfying **CO1– CO5**

CO1 $\nabla(\Pi)$ is a plan libray. **HOLDS**

CO2 $\nabla(\Pi) \subseteq \Pi$. **HOLDS**

CO3 if $\mathcal{P} \subseteq \Pi \setminus \nabla(\Pi)$ and $\mathcal{P} \subseteq \Pi' \subseteq \Pi$, then $\mathcal{P} \subseteq \Pi' \setminus \nabla(\Pi')$. **HOLDS**

C04 $\nabla(\Pi) \succcurlyeq \Pi$ where $\succcurlyeq \in \{\succcurlyeq_{activeness}, \succcurlyeq_{success}\}$. **HOLDS**

CO5 $\forall P \in \Pi \setminus \nabla(\Pi)$, then $\Gamma_{\nabla(\Pi)}(P) > 0$. **HOLDS**

Summary:

1. One of the very first works which challenges the static nature of plan library in BDI agent system.
2. One of works which proposed clear domain-independent characteristics of the plan library and corresponding measures.
    - Useful for Agent Validation Development
    - Useful for Agent Programming Development
    - Useful for Agent Reasoning Development
3. A none-trivial combination of recent techniques (e.g. measuring literature and multi-criteria decision making) based on useful concepts in BDI.
4. The first work which suggests some desirable properties of plans to formalize plan library modifications in BDI agent systems.

Future Work:

Intention Progression In BDI Agent System: A Formal Approach (targeting AAMAS2019)

1. ***Formalise*** intention as decomposition-history graph
2. ***Tackle*** interleaved deliberation of concurrent intentions
3. ***Propose*** quantitative approach i.e. urgency of goals, preference of plans, awards of actions
4. ***Manage*** uncertainty arising from non-determinism (e.g. stochastic effects of actions)
5. ***Support*** anytime manner (i.e. online planning via Monte-Carlo Tree Search)

Questions?

Thank you