A Formal Approach to Embedding First-Principles Planning in BDI Agent Systems

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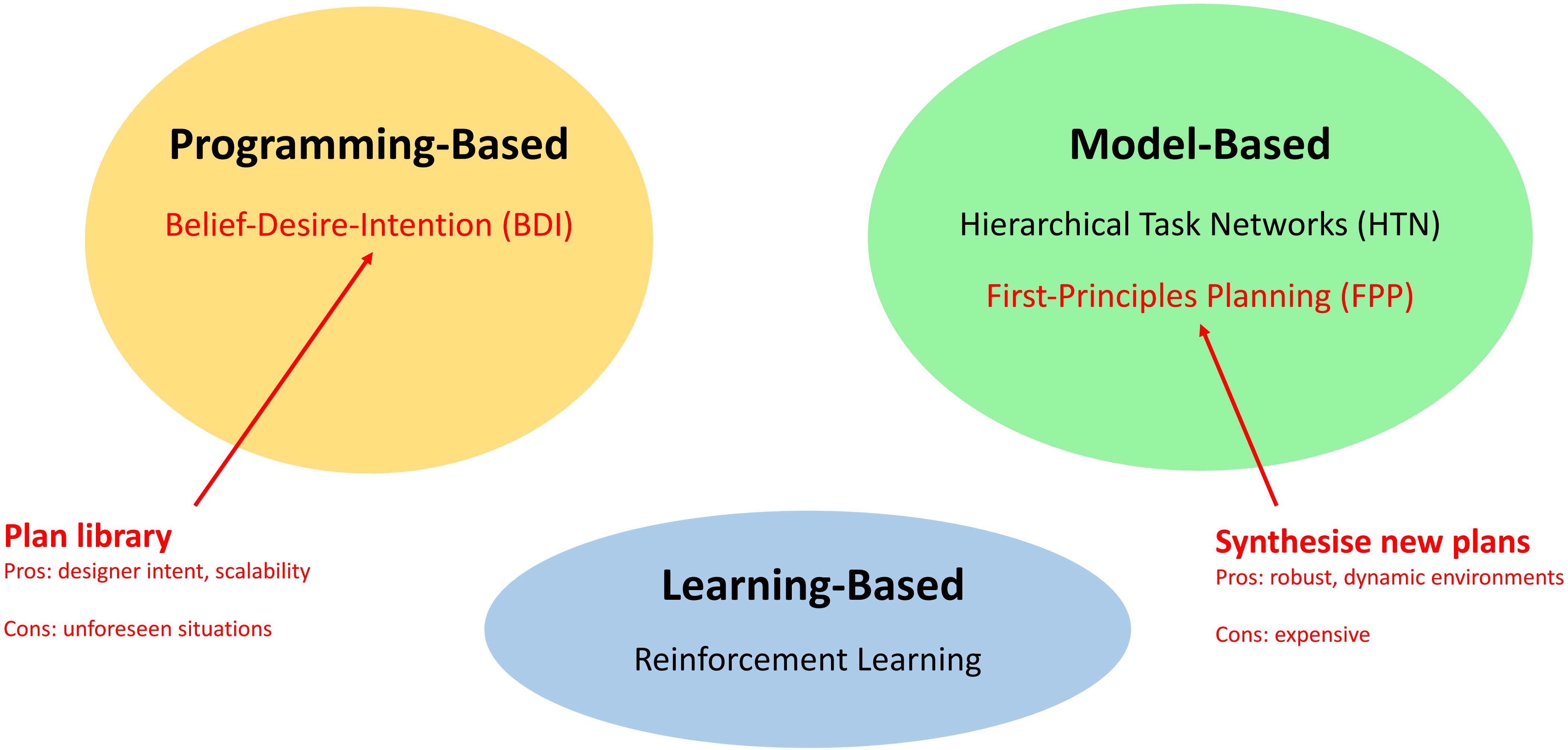
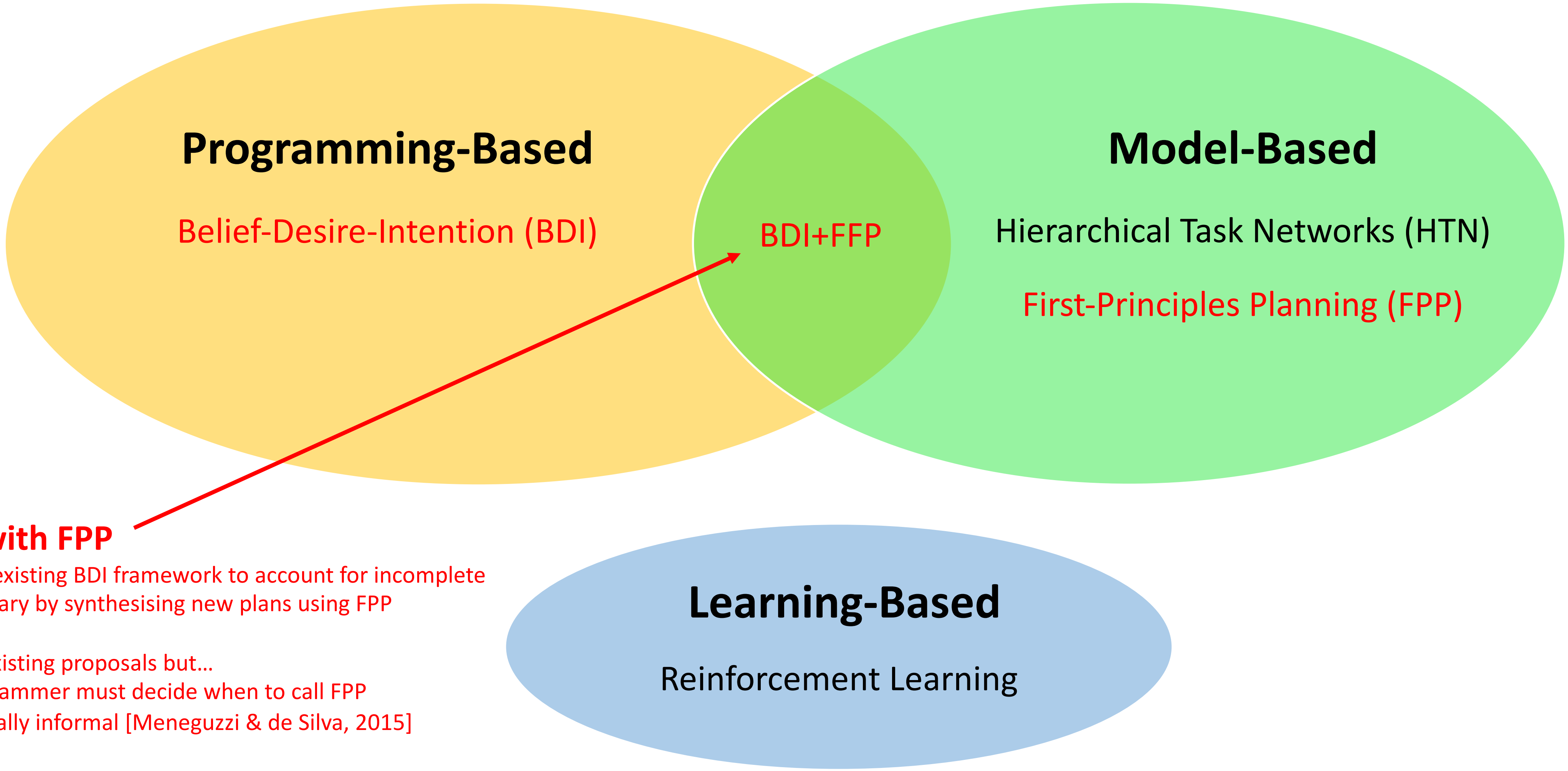
Agent Frameworks



Extending BDI with FPP



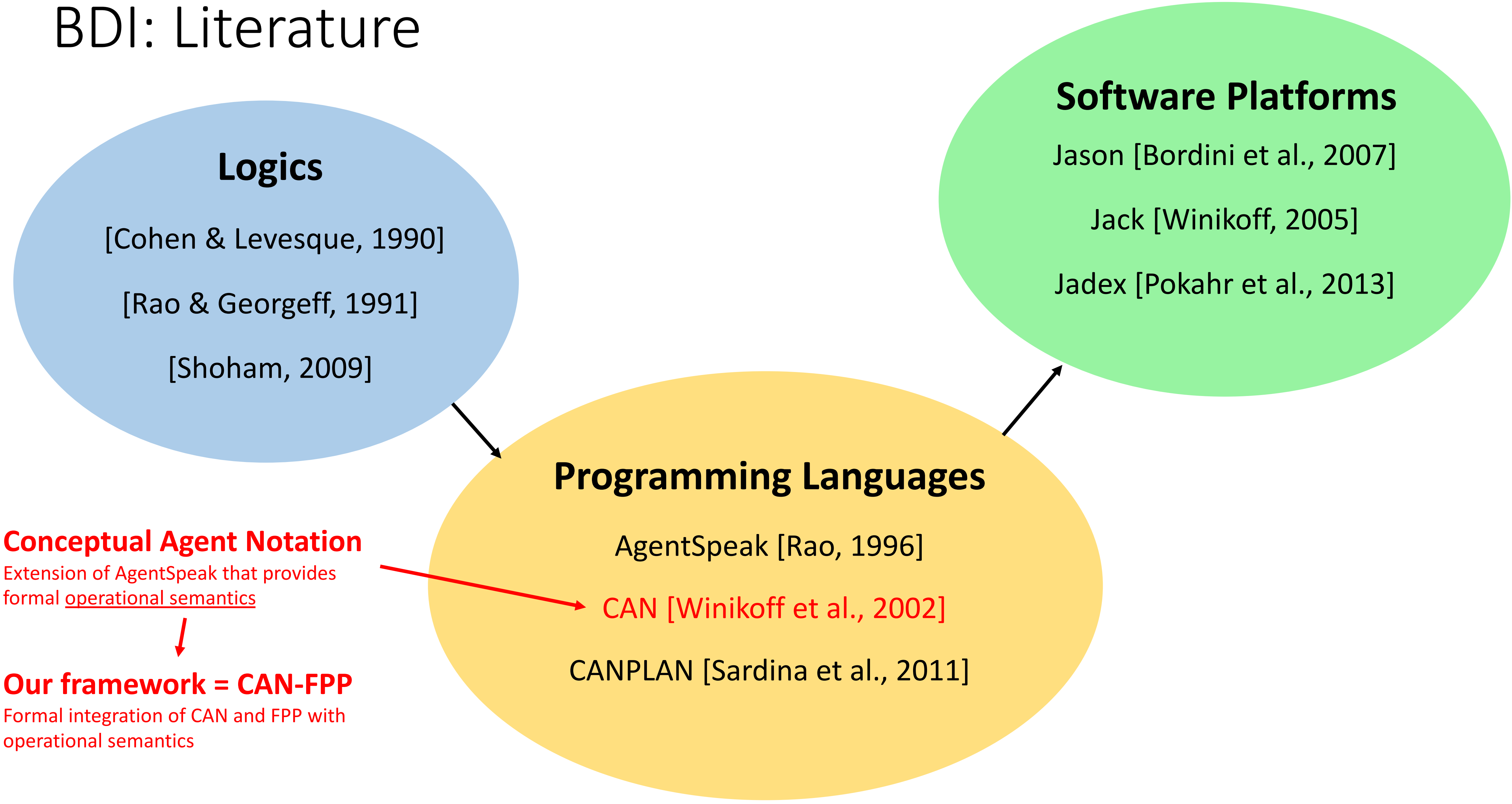
BDI with FPP

Extend existing BDI framework to account for incomplete plan library by synthesising new plans using FPP

Some existing proposals but…

- Programmer must decide when to call FPP
- Typically informal [Meneguzzi & de Silva, 2015]

BDI: Literature



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

Initial belief base

Belief base specifying agent's initial beliefs

Plan library

Set of plan rules

Action description library

Set of STRIPS-style action descriptions

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 $\mathrm{act} : \varphi \leftarrow \mathcal{B}^- ; \mathcal{B}^+$

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) $P ::= \mathrm{nil} \mid \mathrm{act} \mid ?\varphi \mid +b \mid -b \mid !e \mid P_1 ; P_2 \mid P_1 \rhd P_2 \mid P_1 \parallel P_2 \mid (\!| \varphi_1 : P_1, \ldots, \varphi_n : P_n |\!) \mid \mathrm{goal}(\varphi_s, P, \varphi_f)$

Empty program

Primitive action

Entailment

Belief addition

Belief deletion

New (sub)goal

Sequencing

Conditional

Concurrency

Relevant plans

CAN declarative goal

CAN: Operational Semantics

Static entities that will be omitted

Basic configuration $(\mathcal{B}, \Lambda, \Pi, \mathcal{A}, P)$

Current belief base
Belief base specifying agent's current beliefs

Current intention
Remainder of a plan body to execute

Execution history $\mathcal{A} = (\mathrm{act}_1, \mathrm{act}_2, \ldots, \mathrm{act}_n)$
Sequence of primitive actions executed so far

Current intention set
Set of (partially executed) plan bodies

Agent configuration $(\mathcal{B}, \Lambda, \Pi, \mathcal{A}, \Gamma)$

CAN: Operational Semantics (Cont.)

Transition $\mathcal{C} \longrightarrow \mathcal{C}'$

Transition between (basic or agent) configurations

Derivation Rule $\dfrac{p_1 \quad p_2 \quad \dots \quad p_n}{c}\ l$

Specifies when/how an agent transitions to new configuration

$$\frac{}{(\mathcal{B}, \mathcal{A}, +b) \longrightarrow (\mathcal{B} \cup \{b\}, \mathcal{A}, \text{nil})}\ +b$$

$$\frac{(a : \varphi \leftarrow \mathcal{B}^- ;\ \mathcal{B}^+) \in \Lambda \quad a\theta = \text{act} \quad \mathcal{B} \vDash \varphi\theta}{(\mathcal{B}, \mathcal{A}, \text{act}) \longrightarrow ([\mathcal{B} \setminus \mathcal{B}^-\theta] \cup \mathcal{B}^+\theta, \mathcal{A} \cdot \text{act}, \text{nil})}\ \text{act}$$

Substitution $\varphi\theta$

Substitution of variables in φ with values from unifier θ

Our Framework: CAN-FPP

1. Adds notion of “pure” declarative goals, in addition to “CAN” declarative goals
    - “Active” vs. “inactive” pure declarative goals
    - ”Procedural” vs. “declarative” intention sets

2. Adds instrinsic support for automatic calls to FPP
    - Direct call (i.e. programmer specified)
    - Belief-driven call (via motivation library)
    - Recover-aid call (i.e. following plan failure)

3. Extends operational semantics
    - Adopting pure declarative goals
    - Planning for pure declarative goals
    - Managing (dropping, reactivating) pure declarative goals

FPP Problem $(\Lambda, \mathcal{B}, \varphi_g)$

Action description library

Set of STRIPS-style action descriptions

Initial state

Set of atoms $\mathcal{B} \subseteq \mathcal{L}$

Goal

Formula from $\varphi_g \in \mathcal{L}$

Offline solution $\mathrm{sol}^{off}(\Lambda, \mathcal{B}, \varphi_g) = \mathrm{act}_1 \, ; \mathrm{act}_2 \, ; \ldots ; \mathrm{act}_n$

Sequence of actions from Λ that is guaranteed to reach state $\mathcal{B}'$ from $\mathcal{B}$ such that $\mathcal{B}' \vDash \varphi_g$

Online solution $\mathrm{sol}^{on}(\Lambda, \mathcal{B}, \varphi_g) = \mathrm{act}_1$

Next best action from Λ so as to reach state $\mathcal{B}'$ from $\mathcal{B}'$ such that $\mathcal{B} \vDash \varphi_g$

<u>Assumes classical planning</u>

Could be extended to e.g. conformant planning

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

Extended plan library
Set of extended plan rules

Motivation library
Set of motivation rules [à la van Riemsdijk, 2004]

Motivation rule $\varphi \rightsquigarrow \text{goal}(\varphi_s, \varphi_f)$

Triggering condition $\varphi \in \mathcal{L}$

Pure declarative goal

Extended plan rule $e : \varphi \leftarrow P'$

Extended body (program) $P' ::= P \mid \text{goal}(\varphi_s, \varphi_f) \mid \text{activate}\left(\text{goal}(\varphi_s, \varphi_f)\right)$

Pure declarative goal

Reactivation program

CAN-FPP: Agent Configuration $(\mathcal{B}, \Pi, \Lambda, \mathcal{M}, \mathcal{A}, \Gamma)$

Motivation library $\mathcal{M}$ is a static entity and will be omitted

Extended intention set $\Gamma = \Gamma_{pr} \cup \Gamma_{de}^{+} \cup \Gamma_{de}^{-}$

$\Gamma_{pr} \cap (\Gamma_{de}^{+} \cup \Gamma_{de}^{-}) = \emptyset$

$\Gamma_{de}^{+} \cap \Gamma_{de}^{-} = \emptyset$

Procedural intention set Γ_{pr}

Standard CAN intention set

Active declarative intention set Γ_{de}^{+}

Set of “active” pure declarative goals

Inactive declarative intention set Γ_{de}^{-}

Set of “inactive” pure declarative goals

Declarative intention set $\Gamma_{de} = \Gamma_{de}^{+} \cup \Gamma_{de}^{-}$

Set of all pure declarative goals

CAN-FPP: Adopting Pure Declarative Goals

$$\frac{P \in \Gamma_{pr} \quad P = \text{goal}(\varphi_s, \text{nil}, \varphi_f) \quad P^{\uparrow} = \text{goal}(\varphi_s, \varphi_f)}{(\mathcal{B}, \mathcal{A}, \Gamma) \xrightarrow{goal} (\mathcal{B}, \mathcal{A}, [\Gamma_{pr} \setminus \{P\}, \Gamma_{de}^{+} \cup \{P^{\uparrow}\}])} A_{goal}^{1}$$

Direct

Translate a CAN declarative goal to a pure declarative goal if it has no procedure

$$\frac{(\varphi \rightsquigarrow P^{\uparrow}) \in \mathcal{M} \quad \mathcal{B} \vDash \varphi\theta \quad P^{\uparrow} = \text{goal}(\varphi_s, \varphi_f)}{(\mathcal{B}, \mathcal{A}, \Gamma) \xrightarrow{goal} (\mathcal{B}, \mathcal{A}, \Gamma_{de}^{+} \cup \{P^{\uparrow}\theta\})} A_{goal}^{2}$$

Belief-driven

Trigger a motivation rule

$$\frac{P \in \Gamma_{pr} \quad P = \text{goal}(\varphi_s, P', \varphi_f) \quad \mathcal{B} \vDash \varphi_f \quad P^{\uparrow} = \text{goal}(\varphi_s, \varphi_f)}{(\mathcal{B}, \mathcal{A}, \Gamma) \xrightarrow{goal} (\mathcal{B}, \mathcal{A}, [\Gamma_{pr} \setminus \{P\}, \Gamma_{de}^{+} \cup \{P^{\uparrow}\}])} A_{goal}^{3}$$

Recovery-aid

Translate a CAN declarative goal to a pure declarative goal if the procedure is blocked

CAN-FPP: Planning for Pure Declarative Goals

$$\frac{P^{\uparrow} \in \Gamma_{de}^{+} \quad P^{\uparrow} = \text{goal}(\varphi_s, \varphi_f) \quad \text{sol}^{off}(\Lambda, \mathcal{B}, \varphi_s) = P \quad P = \text{act}_1 ; \ldots ; \text{act}_n}{(\mathcal{B}, \mathcal{A}, \Gamma) \xrightarrow{bdi} (\mathcal{B}, \mathcal{A}, [\Gamma_{de} \setminus \{P^{\uparrow}\}, \Gamma_{pr} \cup \{\text{goal}(\varphi_s, P, \varphi_f)\}])} P_{\mathcal{F}^{off}}$$

Offline planning

Generate plan for an active declarative goal and add plan to procedural intention set

$$\frac{P^{\uparrow} \in \Gamma_{de}^{+} \quad P^{\uparrow} = \text{goal}(\varphi_s, \varphi_f) \quad \text{sol}^{on}(\Lambda, \mathcal{B}, \varphi_s) = \text{act} \quad P = \text{act} ; \text{activate}(P^{\uparrow})}{(\mathcal{B}, \mathcal{A}, \Gamma) \xrightarrow{bdi} (\mathcal{B}, \mathcal{A}, [\Gamma_{de}^{-} \cup \{P^{\uparrow}\}, \Gamma_{pr} \cup \{\text{goal}(\varphi_s, P, \varphi_f)\}])} P_{\mathcal{F}^{on}}$$

Online planning

Generate a single action for pure declarative goal, deactivate that goal, create plan to first execute that action then to reactive the goal, and add plan to procedural intention set

$$\frac{P^{\uparrow} \in \Gamma_{de}^{+} \quad P^{\uparrow} = \text{goal}(\varphi_s, \varphi_f) \quad \text{sol}(\Lambda, \mathcal{B}, \varphi_s) = \bot}{(\mathcal{B}, \mathcal{A}, \Gamma) \xrightarrow{bdi} (\mathcal{B}, \mathcal{A}, \Gamma_{de} \setminus \{P^{\uparrow}\})} P_{\mathcal{F}^{\bot}}$$

Planning failure

Drop pure declarative goal if planning fails (alternatively: add goal to inactive declarative intention set)

CAN-FPP: Managing Pure Declarative Goals

$$\frac{P^{\uparrow} \in \Gamma_{de} \quad P^{\uparrow} = \text{goal}(\varphi_s, \varphi_f) \quad \mathcal{B} \vDash \varphi_s \vee \varphi_f}{(\mathcal{B}, \mathcal{A}, \Gamma) \xrightarrow{drop} (\mathcal{B}, \mathcal{A}, \Gamma_{de} \setminus \{P^{\uparrow}\})} \; G_{drop}$$

Drop pure declarative goal

Drop declarative goal (whether active or inactive) if success or fail condition is met

$$\frac{P \in \Gamma_{pr} \quad P = \text{activate}(P^{\uparrow}) \quad P^{\uparrow} \in \Gamma_{de}^{-}}{(\mathcal{B}, \mathcal{A}, \Gamma) \xrightarrow{goal} (\mathcal{B}, \mathcal{A}, [\Gamma_{pr} \setminus \{P\}, \Gamma_{de}^{+} \cup \{P^{\uparrow}\}])} \; A_{re}$$

Reactivate pure declarative goal

Activate a pure declarative goal that is inactive

CAN-FPP: Theoretical Results

Offline FPP

Goal state

$$\frac{P^{\uparrow} = \mathrm{goal}(\varphi_s, \varphi_f) \quad \mathrm{sol}^{off}(\Lambda, \mathcal{B}, \varphi_s) = P \quad (\mathcal{B}, \mathcal{A}, P) \xrightarrow{bdi} \ldots \xrightarrow{bdi} (\mathcal{B}', \mathcal{A} \cdot P, \mathrm{nil}) \quad \mathcal{B}' \vDash \varphi_s}{(\mathcal{B}, \mathcal{A}, P^{\uparrow}) \xrightarrow{bdi} \ldots \xrightarrow{bdi} (\mathcal{B}', \mathcal{A} \cdot P, \mathrm{nil})} \text{ Theorem 1 (i)}$$

Successful execution

Offline FPP

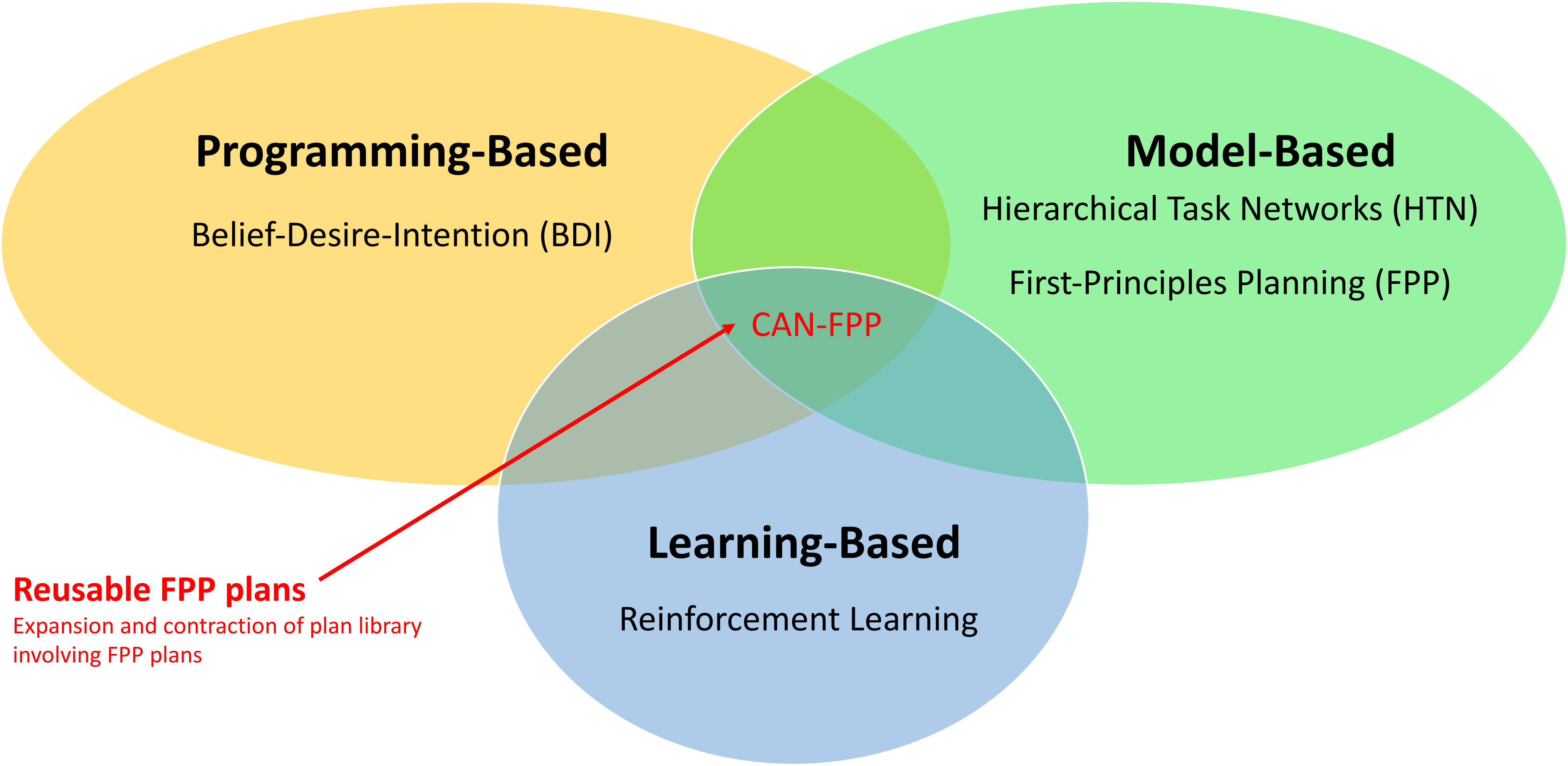
Goal state

$$\frac{\begin{array}{c} P^{\uparrow} = \mathrm{goal}(\varphi_s, \varphi_f) \quad \mathrm{sol}^{on}(\Lambda, \mathcal{B}, \varphi_s) = \mathrm{act}_1 \quad P = \mathrm{act}_1 \,; \mathrm{activate}(P^{\uparrow}) \\ (\mathcal{B}, \mathcal{A}, P) \xrightarrow{bdi} \ldots \xrightarrow{bdi} (\mathcal{B}', \mathcal{A} \cdot \mathrm{act}_1 \cdot \ldots \cdot \mathrm{act}_n, \mathrm{nil}) \quad \mathcal{B}' \vDash \varphi_s \end{array}}{(\mathcal{B}, \mathcal{A}, P^{\uparrow}) \xrightarrow{bdi} \ldots \xrightarrow{bdi} (\mathcal{B}', \mathcal{A} \cdot \mathrm{act}_1 \cdot \ldots \cdot \mathrm{act}_n, \mathrm{nil})} \text{ Theorem 1 (iii)}$$

Successful execution

Future Work

Mengwei Xu, Kim Bauters, Kevin McAreavey, and Weiru Liu. **A framework for plan library evolution in BDI agent systems.** In *Proceedings of ICTAI'18*, to appear.



Reusable FPP plans

Expansion and contraction of plan library involving FPP plans

Questions?

Thank you