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# A4M33MAS - Multiagent Systems

# Belief-Desire-Intention (BDI) Architecture & Social Commitments

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In parts based on Michal Pechoucek: Multi-Agent Systems, Lecture course at State University of New York, University at Binghamton

# Towards Architectures for IA

01

- Reactive Architectures
- Deliberative Architectures

# Models of Practical Reasoning: BDI

*process of figuring out what to do -- practical reasoning is a matter of weighing conflicting considerations for and against competing options, where the relevant considerations are provided by what the agent desires/values/cares about and what the agent believes (Bratman)*

- computational model of human decision process oriented towards an action, based on models of existing mental models of the agents

- human practical reasoning consists of two activities:
  - deliberation: deciding what state of affairs we want to achieve and
  - means-ends reasoning (planning): deciding how to achieve these states

- the outputs of deliberation process are intentions

# BDI Architecture



- BELIEFS
  - collection of information that the agents has about its the status of the environment, peer agents, self
- DESIRES
  - set of long term goals the agent wants to achieve
- INTENTIONS
  - agents immediate commitment to executing an action, either high-level or low level (depends on agents planning horizon)

- BDI architecture connects: (i) reactive (ii) planning & (iii) logical representation. BDI architecture does not count on theorem proving

$$\text{if } \varphi \in \mathcal{L}_{agent} \text{ then } \varphi, (\text{Bel } A\ \varphi), (\text{Des } A\ \varphi), (\text{Int } A\ \varphi) \in \mathcal{L}_{bdi}$$

# BDI Inference Algorithm



- Basic algorithm:

1. initial beliefs → Bel
2. while true do
3. Read(get_next_percept) → in
4. Belief-revision(Bel, in) → Bel
5. Deliberate(Bel, Des) → Int
6. Plan(Bel, Int) →π
7. Execute(π)
8. end while

# BDI Modal Properties



- BELIEFS
  - KD45 system, modal logic where the B relation is serial, transitive and euclidean: satisfies K axioms, positive introspection axiom (4 axiom), negative introspection axiom (5 axiom), beliefs consistency axiom (D axiom).

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$$(\text{Des } A\ \varphi) \rightarrow \neg(\text{Des } \neg\ \varphi)$$

- INTENTIONS
  - KD system, modal logic requiring intentions not to contradict (D axiom).

$$(\text{Int } A\ \varphi) \rightarrow \neg(\text{Int } A\ \neg\ \varphi)$$

# Properties of Intentions

01

- Intention persistency:
  - agents track the success of their intentions, and are inclined to try again if their attempts fail

$$(\mathsf{Int}\ A\ \varphi) \curvearrowleft \varphi$$

- Intention satisfiability:
  - agents believe their intentions are possible; that is, they believe there is at least some way that the intentions could be brought about.

$$(\mathsf{Int}\ A\ \varphi) \Rightarrow \mathsf{EF}\varphi$$

# Properties of Intentions



- Intention-belief inconsistency:
  - agents do not believe they will not bring about their intentions; it would be irrational of agents to adopt an intention if believed was not possible

$$(\mathsf{Int}\ A\ \varphi) \wedge (\mathsf{Bel}\ A \neg \mathsf{EF} \varphi)$$

- Intention-belief incompleteness:
  - agent do not believe that their intention is possible to be achieved, may be understood as rational behavior

$$(\mathsf{Int}\ A\ \varphi) \wedge (\neg \mathsf{Bel}\ A \mathsf{EF} \varphi)$$

  - agents admit that their intentions may not be implemented.

$$(\mathsf{Int}\ A\ \varphi) \wedge (\mathsf{Bel}\ A\ \mathsf{EF} \neg \varphi)$$

# Properties of Intentions



- Intention side-effects:
  - Agents need not intend all the expected side effects of their intentions. Intentions are not closed under implication.

$$(\mathsf{Bel}\ A\ \psi \Rightarrow \varphi) \wedge (\mathsf{Int}\ A\ \psi) \wedge \neg(\mathsf{Int}\ A\ \varphi)$$

    - ✳ *is thus classified as fully rational behavior*

  - Example: I may believe that going to the dentist involves pain, and I may also intend to go to the dentist - but this does not imply that I intend to suffer pain!

# Rationality of Inevitables & Options

1. **inevitables:**

$$(\mathsf{Int}\ A\ \mathsf{AG}\varphi) \Rightarrow (\mathsf{Des}\ A\ \mathsf{AG}\varphi) \qquad (\mathsf{Des}\ A\ \mathsf{AG}\varphi) \Rightarrow (\mathsf{Bel}\ A\ \mathsf{AG}\varphi)$$
$$(\mathsf{Des}\ A\ \mathsf{AG}\varphi) \Rightarrow (\mathsf{Int}\ A\ \mathsf{AG}\varphi) \qquad (\mathsf{Int}\ A\ \mathsf{AG}\varphi) \Rightarrow (\mathsf{Bel}\ A\ \mathsf{AG}\varphi)$$
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2. **options:**

$$(\mathsf{Int}\ A\ \mathsf{EF}\varphi) \Rightarrow (\mathsf{Des}\ A\ \mathsf{EF}\varphi) \qquad (\mathsf{Des}\ A\ \mathsf{EF}\varphi) \Rightarrow (\mathsf{Bel}\ A\ \mathsf{EF}\varphi)$$
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# Example: Model Checking AgentSpeak

- AgentSpeak(L) is a BDI programming language introduced by Rao.
- A simple but powerful programming language for building rational agents. Based on Prolog.
- Jason:
  - implementation of AgentSpeak in Java
  - A development environment for AgentSpeak systems

# Example: Model Checking AgentSpeak



- AgentSpeak(L) is a BDI programming language introduced by Rao.
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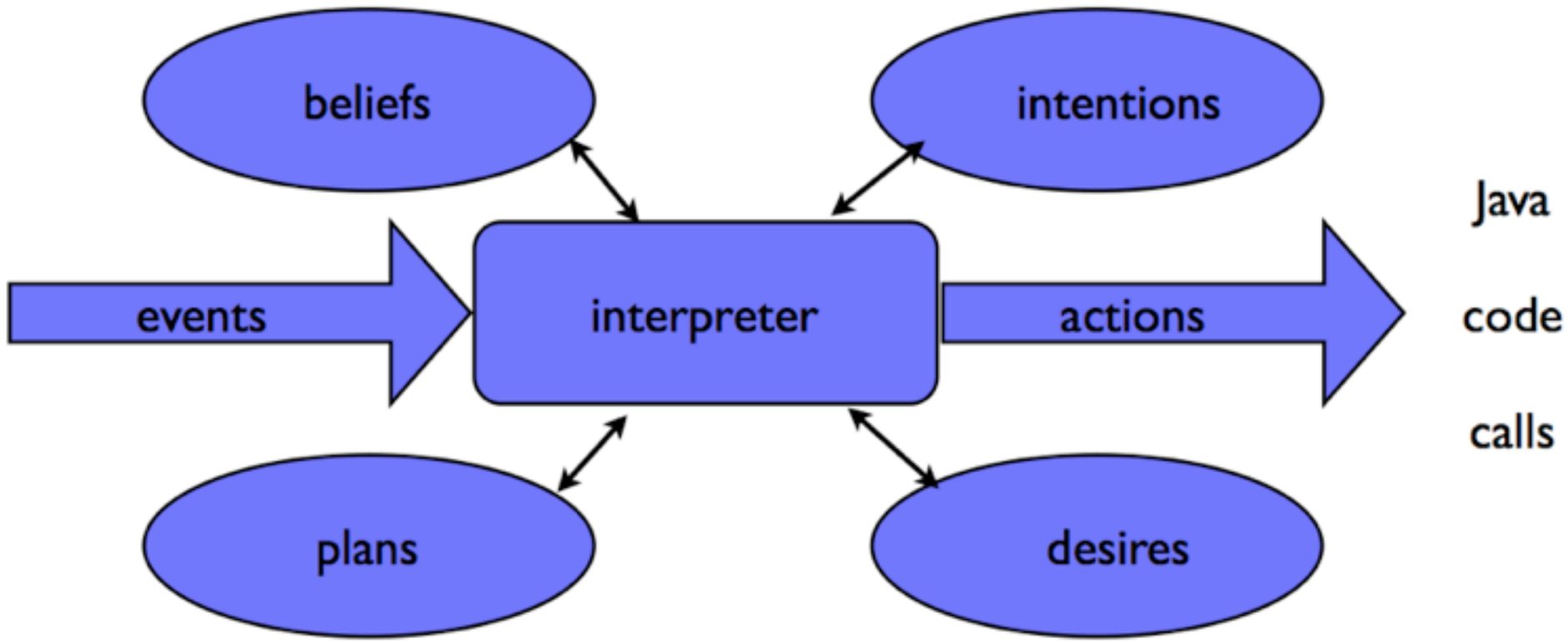

# AgentSpeak Control Loop

01

1. agent receives events, which are either
   - external (from the environment, from perceptual data)
   - internally generated
2. tries to handle events by looking for plans that match the event and lead to the goal → desires (options)
3. chooses one plan from its desires to execute: becomes committed to it → intention
4. as it executes a plan may generate new events that require handling

# AgentSpeak: BDI primitives



- Beliefs: Symbolically represented (ground atoms or FOL formulas)

$$ag = \langle bs, ps \rangle\text{: } \mathrm{BEL}_{\langle ag, C \rangle}(\varphi) \equiv \varphi \in bs.$$

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agent beliefs plans

(Bel $A$ $\varphi$)

context

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- Manipulating beliefs:

  +B adding new belief

  −B dropping belief

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- Beliefs: Symbolically represented (ground atoms or FOL formulas)

$$ag = \langle bs, ps \rangle\text{: } \mathrm{BEL}_{\langle ag, C \rangle}(\varphi) \equiv \varphi \in bs.$$

- Manipulating beliefs:

  +B adding new belief

  −B dropping belief

- Manipulating goals/intentions:

  +!D adding new desire

  −!D dropping desire

- Plans:

```
triggerCondition :
        context <-
        body.
```

# AgentSpeak: Example

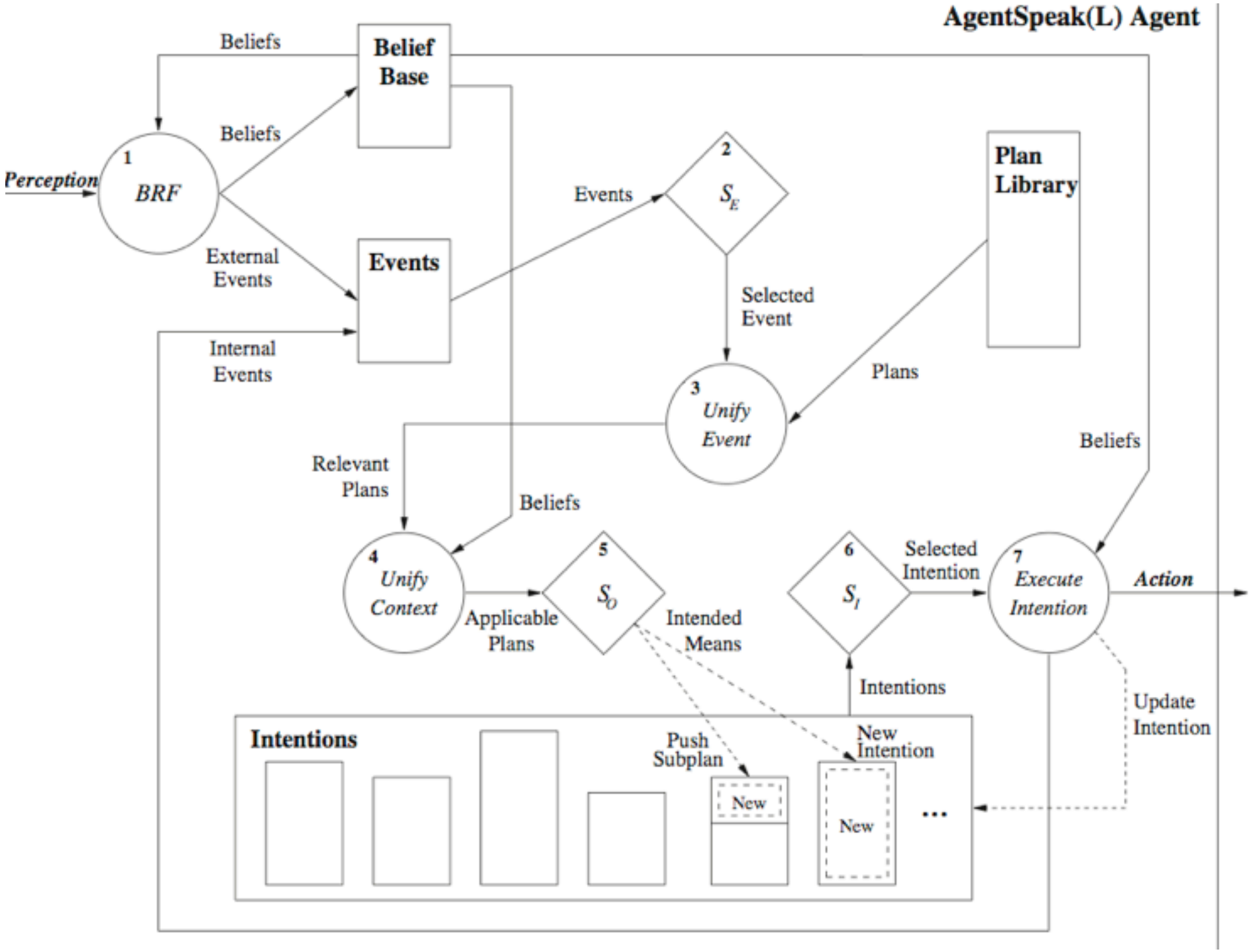


```
+green_patch(Rock)
    : not battery_charge(low)
      <- ?location(Rock,Coordinates);
         !traverse(Coordinates);
         !examine(Rock).

+!traverse(Coords)
    : safe_path(Coords)
      <- move_towards(Coords).

+!traverse(Coords) :
    : not safe_path(Coords)
      <- ...
```

# AgentSpeak Reasoning Lifecycle



# AgentSpeak: Example

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## Agent I

```
+auction(N) : true
    <- place_bid(N,6).
```

# AgentSpeak: Example



## Agent1

```
+auction(N) : true
   <- place_bid(N,6).
```

## Agent2

```
myself(ag2).
bid(ag2,4).
ally(ag3).

+auction(N) : myself(I) & ally(A) & not(alliance(A,I))
   <- ?bid(I,B); place_bid(N,B).

+auction(N) : myself(I) & ally(A) & (alliance(A,I))
   <- place_bid(N,0).

+alliance(A,I) : myself(I) & ally(A)
   <- ?bid(I,B);
      .send(A,tell,bid(I,B));
      .send(A,tell,alliance(A,I)).
```

# AgentSpeak: Example



## Agent3

```
myself(ag3).
bid(ag3,3).
ally(ag2).
threshold(3).
```

```
+auction(N) : threshold(T) & .gte(T,N)
   <- !bid_normally(N).

+auction(N) : myself(I) & winner(I)
                & ally(A) & not(alliance(I,A))
   <- !bid_normally(N).

+auction(N) : myself(I) & not(winner(I))
                & ally(A) & not(alliance(I,A))
   <- !alliance(I,A);
      !bid_normally(N).

+auction(N) : alliance(I,A)
   <- ?bid(I,B); ?bid(A,C);
      .plus(B,C,D); place_bid(N,D).

+!bid_normally(N) : true
   <- ?bid(I,B); place_bid(N,B).

+!alliance(I,A) : not(alliance(I,A))
   <- .send(A,tell,alliance(I,A)).
```

# AgentSpeak: Example

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$$\Box( \quad \neg(\text{Bel ag3 winner(ag3)}) \wedge (\text{Des ag3 alliance(ag3, ag2)}) \Rightarrow \Diamond(\text{Int ag3 alliance(ag3, ag2)}) \quad )$$

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$$\Box( \quad \neg(\text{Bel ag3 winner}(\text{ag3})) \wedge (\text{Des ag3 alliance}(\text{ag3}, \text{ag2})) \Rightarrow \Diamond(\text{Int ag3 alliance}(\text{ag3}, \text{ag2})) \quad )$$

$$\Diamond( \quad (\text{Bel ag2 alliance}(\text{ag3}, \text{ag2})) \wedge (\text{Bel ag3 alliance}(\text{ag3}, \text{ag2})) \quad )$$

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$$\Box(\quad (\text{Bel ag2 alliance(ag3, ag2)}) \wedge (\text{Bel ag3 alliance(ag3, ag2)}) \Rightarrow \Diamond\Box\text{winner(ag3)} \quad)$$

# Social Commitments

# Agents Individual/Social Commitments

01

- Commitments: knowledge structure, declarative programming concept based on intentions (intentions are special kinds of comms).
  - specify relationships among different intentional states of the agents
  - specify social relations among agents, based on their comms to joint actions

*The commitment is an agent's state of 'the mind' where it commits to adopting the single specific intention or a longer term desire.*

- We distinguish between:
  - specific, commonly used commitments — general commitments
  - individual commitments — social commitments

# Individual Commitments



- $A$ can get committed to its intention $\varphi$ in several different ways:
  - blind commitment: also referred to as fanatical commitment, the agent is intending the intention until it believes that it has been achieved (persistent intention)

$$(\text{Commit } A\ \varphi) \equiv \text{AG}((\text{Int } A\ \varphi) \curvearrowleft (\text{Bel } A\ \varphi))$$

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  - single-minded commitment: besides above it intends the intention until it believes that it is no longer possible to achieve the goal

$$(\text{Commit } A\ \varphi) \equiv \text{AG}((\text{Int } A\ \varphi) \curvearrowleft ((\text{Bel } A\ \varphi) \vee (\text{Bel } A\ \neg\text{EF}\varphi))$$

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  - open-minded commitment: besides above it intends the intention as long as it is sure that the intention is achievable

$$(\text{Commit } A\ \varphi) \equiv \text{AG}((\text{Int } A\ \varphi) \curvearrowleft ((\text{Bel } A\ \varphi) \vee \neg(\text{Bel } A\ \text{EF}\varphi))$$

# General Commitments



- Commitment is defined as $(\text{Commit } A\ \varphi\ \psi\ \lambda)$ , where
- Convention is defined as $\lambda = \{\langle \rho_k, \gamma_k \rangle\}_{k \in \{1,\ldots,l\}}$
  - provided $\curvearrowleft$ stands for *until*, A stands for *always in the future*, Int is *agent's intention* and Bel is *agent's belief* then for $\lambda = \langle \rho, \gamma \rangle$ the commitment has the form:

$$(\text{Commit } A\ \varphi\ \psi\ \lambda) \equiv \psi \wedge \mathsf{A}((\text{Int } A\ \varphi) \wedge \textit{decommitment\_rule}\ ) \curvearrowleft \gamma)$$

$$(\text{Commit } A\ \varphi\ \psi\ \lambda) \equiv \psi \wedge \mathsf{A}((\text{Int } A\ \varphi) \wedge ((\text{Bel } A\ \rho) \Rightarrow \mathsf{A}(\text{Int } A\ \gamma)) \curvearrowleft \gamma) \curvearrowleft \gamma)$$

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$$
\begin{aligned}
(\text{Commit } A\ \varphi\ \psi\ \lambda) \quad \equiv \quad & \\
& \psi \wedge \mathsf{A}((\text{Int } A\ \varphi) \wedge \\
& \quad ((\text{Bel } A\ \rho_1) \Rightarrow \mathsf{A}(\text{Int } A\ \gamma_1)) \curvearrowleft \gamma_1) \\
& \quad \ldots \\
& \quad ((\text{Bel } A\ \rho_k) \Rightarrow \mathsf{A}(\text{Int } A\ \gamma_k)) \curvearrowleft \gamma_k) \\
& \curvearrowleft \bigvee_i \gamma_i)
\end{aligned}
$$

# Joint (Social) Commitment



- Form of a commitment that represents how a group of agents is committed to a joint action (goal, intention, ...)

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$$(\text{J-Commit } \Theta\ \varphi\ \psi\ \lambda) \equiv$$

$$\forall A : (A \in \theta) \Rightarrow$$

$$\psi \wedge \mathsf{A}((\text{Int } A\ \varphi) \wedge ((\text{Bel } A\ \rho) \Rightarrow \mathsf{A}(\text{Int } A\ \gamma) \curvearrowleft \gamma) \curvearrowleft \gamma)$$

# Joint (Social) Commitment



- Form of a commitment that represents how a group of agents is committed to a joint action (goal, intention, ...)
  - for a convention in the form of $\lambda = \{\langle \rho_k, \gamma_k \rangle\}_{k \in \{1,\ldots,l\}}$

$$(\text{J-Commit } \Theta\ \varphi\ \psi\ \lambda) \equiv \forall A:\ (A \in \theta) \Rightarrow \psi \wedge \mathsf{A}((\chi_1 \wedge \chi_2) \curvearrowleft \chi_3)$$

where

$$\begin{aligned}
\chi_1 &= (\text{Int } A\ \varphi) \\
\chi_2 &= ((\text{Bel } A\ \rho_1) \Rightarrow \mathsf{A}((\text{Int } A\ \gamma_1) \curvearrowleft \gamma_1)) \wedge ((\text{Bel } A\ \rho_2) \Rightarrow \\
&\quad \mathsf{A}((\text{Int } A\ \gamma_2) \curvearrowleft \gamma_1) \wedge \cdots \wedge ((\text{Bel } A\ \rho_n) \Rightarrow \mathsf{A}((\text{Int } A\ \gamma_n) \curvearrowleft \gamma_n))) \\
\chi_3 &= \gamma_1 \vee \gamma_1 \vee \cdots \vee \gamma_n
\end{aligned}$$

# Blind Social Commitment



- each agent is trying to accomplish the commitment until achieved

$\lambda_{blind} = \{\langle(\text{Bel } A\ \varphi), (\text{M-Bel } \Theta\ \varphi)\rangle\}$
$\psi_{blind} = \neg(\text{Bel } A\ \varphi)$

$$
\begin{aligned}
(\text{J-Commit } \Theta\ \varphi\ \psi\ \lambda) \quad \equiv \quad & \forall A: \ (A \in \Theta) \Rightarrow \\
& (\neg(\text{Bel } A\ \varphi) \wedge (\text{A}((\text{Int } A\ \varphi) \wedge \\
& ((\text{Bel } A\ \varphi) \Rightarrow \text{A}((\text{Int } A\ (\text{M-Bel } \Theta\ \varphi)) \\
& \curvearrowleft (\text{M-Bel } \Theta\ \varphi)))) \\
& \curvearrowleft (\text{M-Bel } \Theta\ \varphi))).
\end{aligned}
$$

# Minimal Social Commitment



- minimal social commitment, also related to as joint persistent goal:
  - initially agents do not believe that goal is true but it is possible
  - every agent has the goal until *termination condition* is true
  - until termination: if agent beliefs that the goal is either *true or impossible* than it will want the goal that it becomes a mutually believed, but keep committed
  - the termination condition is that it is *mutually believed* either goal is true or impossible to be true.

$$\psi_{soc} = \neg(\text{Bel } A\ \varphi) \wedge (\text{Bel } A\ \text{EF}\varphi)$$

$$\lambda_{soc} = \left\{ \begin{array}{l} \langle(\text{Bel } A\ \varphi), (\text{M–Bel } \Theta\ \varphi)\rangle, \\ \langle(\text{Bel } A\ \text{AG}\neg\varphi), (\text{M–Bel } \Theta\ \text{AG}\neg\varphi)\rangle \end{array} \right\}$$

# Minimal Social Commitment



$$(\text{J-Commit}\ \Theta\ \varphi\ \psi_{soc}\ \lambda_{soc}) \equiv$$

$$\forall A,\ A \in \Theta : [\neg(\text{Bel}\ A\ \varphi) \wedge (\text{Bel}\ A\ \text{EF}\varphi)] \wedge$$

$$\text{A}\left[\left(\begin{array}{l}(\text{Int}\ A\ \varphi) \wedge \\ ((\text{Bel}\ A\ \varphi) \Rightarrow \text{A}((\text{Int}\ A(\text{M-Bel}\ \Theta\ \varphi))) \curvearrowleft \chi \wedge \\ ((\text{Bel}\ A\ \text{AG}\neg\varphi) \Rightarrow \text{A}((\text{Int}\ A(\text{M-Bel}\ \Theta\ \text{AG}\neg\varphi))) \curvearrowleft \chi\end{array}\right) \curvearrowleft \chi\right]$$

where $\chi \equiv ((\text{M-Bel}\ \Theta\ \varphi) \vee (\text{M-Bel}\ \Theta\ \text{AG}\neg\varphi)))$

# Mutual Belief ?



Definition 1:

$$(\text{M-Bel}\ \Theta\ \varphi) \equiv \forall A,\ A \in \Theta\ (\text{Bel}\ A\ (\text{M-Bel}\ \Theta\ \varphi))$$

Definition 2:

$$(\text{E-Bel}^{0}\ \Theta\ \varphi) \equiv \forall A,\ A \in \Theta\ (\text{Bel}\ A\ \varphi)$$

$$(\text{E-Bel}^{k}\ \Theta\ \varphi) \equiv \forall A,\ A \in \Theta\ (\text{E-Bel}^{k-1}\ \Theta\ \varphi)$$

$$(\text{M-Bel}\ \Theta\ \varphi) \equiv \forall m \in \mathbb{N}\ (\text{E-Bel}^{m}\ \Theta\ \varphi)$$


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