Dynamic Epistemic Logic and Epistemic Planning

Andreas Herzig

CNRS, IRIT, Univ. Toulouse, France

KR 2020, Rhodes and AoE, Sept. 14, 2020

Intelligent agents plan and act for goals

- reactive agent: doesn't act if environment is static
  (e.g. thermostat; simple controllers)
- proactive agent: actively pursues goals
  - there exist other proactive attitudes (not covered here):
    preferences, desires, intentions, personal obligations
  - which goals should be selected?
    - balance importance and feasibility
- plans for goals
- actions required to achieve goals

> "Our goals can only be reached
> through a vehicle of a plan,
> in which we must fervently believe,
> and upon which we must vigorously act.
> There is no other route to success."
> [Pablo Picasso]

Planning and acting with others

1. classical planning: ‘solipsistic’
    - there are no other agents but the planning agent
    - environment static
2. multiagent strategic reasoning
    - several agents act
    - focus: strategic reasoning
        - “agent can achieve his goal whatever others do”
        - Coalition Logic CL, Alternating-time Temporal Logic ATL, Seeing-To-It-That logic STIT,. . .
        - reasoning: often undecidable
    - typical hypothesis: no uncertainty
        - no consensus about epistemic extensions
3. epistemic planning
    - active field since ∼10 years
    - based on/inspired by dynamic epistemic logic (DEL)
    - large sense: epistemic = knowledge + belief

Aims of tutorial

1. revisit the basic ingredients of planning problems
    - simplifying hypotheses of classical planning
    - several of them to be abandoned in epistemic planning
2. why is epistemic planning so important?
3. where do the epistemic effects come from?
4. complexity of reasoning
    - undecidability threatens

Outline

Problem descriptions

- `Init` = how the world is (according to agent)
- `Goal` = how the world should be (according to agent)

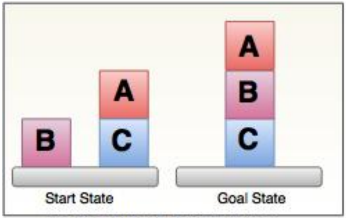


Fig: Blocks-World Planning Problem

Description of `Init`

- logical form of `Init`: proposition
  - can be described in various logical languages
    - propositional logic: boolean formulas

$$\varphi \ ::= \ p \mid \neg\varphi \mid \varphi \wedge \varphi \mid \varphi \vee \varphi \qquad \text{where } p \text{ ranges over } \textbf{Prp}$$

    - epistemic logic (v.i.)
    - probabilities
    - ...
- proposition $\triangleq$ set of states ('possible worlds')
- description of `Init` in classical planning:

initial state = a single valuation of propositional logic
= a single possible world
= a complete proposition

⇒ will get more complex (at least: multiple initial states)

What is a goal? [Cohen&Levesque, AIJ 1991]

1. achievement goals (should be true one day) vs. maintenance goals (should always be true)
    - generalisation: temporally extended goals
2. achievement goal should be realistic
    - agent believes it can be achieved
3. agent should be committed to goal
    - will not be abandoned out of the blue
    - reasons for abandoning:
        - agent learns that it cannot be achieved (“no fanatism”)
        - subgoal of a superior goal that is abandoned
        - subgoal of a superior goal that obtains unexpectedly
    - cf. “Intention is choice with commitment” [Cohen&Levesque, AIJ 1991]
4. goal should be achievable by agent’s actions
    - no ‘sunshine goals’
    - identified with intentions by [Cohen&Levesque, AIJ 1991]
    - formal definition not easy: how define ‘contributes to goal’?
        - causality; logic of ‘seeing-to-it-that’ (stit); . . .

Goals in classical planning

- logical form of `Goal`: proposition
  - proposition $\triangleq$ set of states ('possible worlds')
- w.r.t. Cohen&Levesque's hierarchy:
  1. achievement goals only
  2. focus on realism: is there a plan achieving `Goal`?
  3. commitment to goal is implicit
     - gets relevant in online planning and re-planning
  4. causation of goal is implicit
     - only planning agent acts

  ⇒ should become relevant when there is more than one agent
- more realistic planning will have to deal with all aspects

Actions: basic vs. complex

- basic (primitive) actions: cannot be decomposed further; can be directly executed
  - *raise-arm*, *pull-trigger*, *shift-gear*
- complex actions: cannot be executed directly
  - *build-house*, *travel-to-Paris*, *get-PhD*
- classical planning: no high-level actions (all actions basic)
  - to be abandoned for more realistic, resource-bounded agents
  - cf. Bratman's 'planning theory of intention' [Bratman 1987]

Actions: type vs. token

- action type ('operator'): *arm-raising*
- action token ('instance'): *Renata's raising of her right arm on Sept. 14, 2020 at 13:55:55*
- action token instantiates action type
- hypothesis: determined by start- and end-states of all possible action executions (neglects intermediate states)
    - action instance $\triangleq$ a couple of states (s, s')
    - action type $\triangleq$ a relation on states $\{(s_1, s'_1), (s_2, s'_2), \ldots\}$

Describing action types in classical planning

- how represent action type a?
  - too big: list all couples $(s_1, s_1'), (s_2, s_2'), \ldots$ in relation R_a
- classical planning: STRIPS hypothesis [Fikes&Nilsson, AIJ 1971]
  - STanford Research Institute Problem Solver
  - supposes R_a can be described by $(\texttt{pre}(a), \texttt{effect}(a))$ where
    - $\texttt{pre}(a)$ = boolean formula
    - $\texttt{effect}(a)$ = conjunction of literals $\triangleq \langle \texttt{eff}^+(a), \texttt{eff}^-(a) \rangle$
  - relation R_a can be defined from $(\texttt{pre}(a), \texttt{effect}(a))$:

$$R_a = \left\{(s, s') \ : \ s \models \texttt{pre}(a) \text{ and } s' = (s \setminus \texttt{eff}^-(a)) \cup \texttt{eff}^+(a)\right\}$$

  - restrictions:
    - every action is deterministic
    - no conditional effects

Action types: beyond classical planning

- nondeterministic actions
  - R_a need not be a function

$$R_{\texttt{tossCoin}} = \{(s, \text{“}s{+}\texttt{Heads}\text{”})\} \cup \{(s, \text{“}s{+}\texttt{Tails}\text{”})\}$$

“$s{+}\texttt{Heads}$” = update of s by making $\texttt{Heads}$ true

- actions with conditional effects
  - effect may depend on state

$$\begin{aligned} R_{\texttt{toggleSwitch}} = {} & \{(s, \text{“}s{+}\texttt{On}\text{”}) \ : \ s \models \neg\texttt{On}\} \cup \\ & \{(s, \text{“}s{-}\texttt{On}\text{”}) \ : \ s \models \texttt{On}\} \end{aligned}$$

- actions with epistemic effects ...

What is a plan?

- plan = composition of basic action instances
- kinds of composition: sequential, parallel, conditionals ('if-then-else'), while-loops, . . .
- if actions are nondeterministic:
  - weak plan: there is a execution achieving the goal
    - some `Goal` state reachable from `Init`
  - strong plan: all executions achieve the goal
    + there is at least one possible execution
  - strong cyclic plan: . . .
- in classical planning:
  - sequential plans only
  - each step takes one time unit
  - weak plans

Domain descriptions

- vocabulary
    - names of actions, predicates (with arity), objects (with types)
    - this tutorial: no object types; mainly predicates of arity 0 (propositions)
- action descriptions `ActDescr`
- beyond classical planning:
    - domain axioms (‘domain laws’, ‘static laws’)

$$\mathtt{Clear}(x) \leftrightarrow \neg\mathtt{Holding}(x) \land \forall y \neg\mathtt{On}(y, x)$$

$$\mathtt{Above}(x, y) \leftrightarrow \mathtt{On}(x, y) \lor \exists z(\mathtt{On}(x, z) \land \mathtt{Above}(z, y))$$

    - distinction between basic and high-level actions (‘tasks’), plus hints (‘methods’) how to decompose high-level actions into lower-level actions
        - Hierarchical Task Networks HTN
        - cf. Bratman’s view of intentions as high-level plans [Bratman 1987]

Planning problems

- planning problem = domain description + problem description
  $= (\mathtt{DomDescr}, (\mathtt{Init}, \mathtt{Goal}))$
- solution to a classical planning problem

  $\pi = a_1; \cdots; a_n$ solves $(\mathtt{DomDescr}, (\mathtt{Init}, \mathtt{Goal}))$
  iff there are states $s_0, s_1, \ldots, s_n$ such that
    - $s_0 = \mathtt{Init}$
    - $(s_{k-1}, s_k) \in R_{a_k}$, for $1 \leq k \leq n$
    - $s_n \models \mathtt{Goal}$
- beyond:
  - when `Init` is a set of states: …
  - when actions can be nondeterministic: …
    - ‘conformant planning’
  - when plans can be conditional: …
    - ‘contingent planning’

Reasoning: plan verification

- plan verification problem:

$$\boxed{\text{does } \pi \text{ solve } (\mathtt{DomDescr}, (\mathtt{Init}, \mathtt{Goal}))?}$$

  - formal proof that π solves planning problem
  - logical formalisms: SitCalc, event calculus, fluent calculus, dynamic logic, temporal logic, …

Reasoning: plan existence

- plan existence problem:

$$\boxed{\text{is } (\mathtt{DomDescr}, (\mathtt{Init}, \mathtt{Goal})) \text{ solvable?}}$$

- complexity: from easy to difficult

blocks-world	P (polynomial time)
classical planning with polynomial plan length	NP (nondet. polynomial time)
classical planning	PSPACE (polynomial space)
classical planning under domain laws	EXPTIME (exponential time)
epistemic planing with action models	undecidable

- logical formalisms for deciding plan existence?
  - formal proof *in the logic* that planning problem has a solution ⇒ dynamic logic, temporal logic

Other reasoning about action problems

- prediction
  - given action sequence $a_1; \cdots; a_n$ and $\texttt{Init}$,
  - find $\texttt{Goal}$ such that $a_1; \cdots; a_n$ solves $(\texttt{Init}, \texttt{Goal})$
- postdiction
  - given action sequence $a_1; \cdots; a_n$ and $\texttt{Goal}$,
  - find $\texttt{Init}$ such that $a_1; \cdots; a_n$ solves $(\texttt{Init}, \texttt{Goal})$

Outline

1. Planning: revisiting the main concepts
2. What is epistemic planning?
3. A benchmark proposal: gossip problems
4. Epistemic logic and dynamic epistemic logic
    - States and goals: Epistemic Logic
    - Actions and plans: Dynamic Epistemic Logic
5. Other formalisms
6. Epistemic planning with observability-based knowledge
    - Epistemic planning with conditional effects
    - Embeddings
7. Conclusion

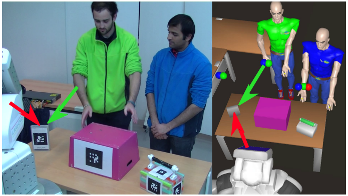
The importance of reasoning about knowledge and belief

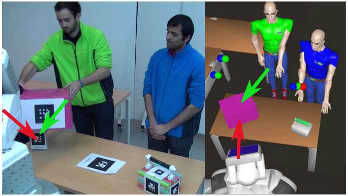
- S. Baron Cohen's False-belief-tasks (Sally-Ann Test, . . .)
  [S. Baron Cohen 1985]

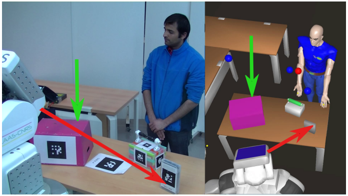
  `https://www.youtube.com/watch?v=jbL34F81Rz0`
- typically fail:
  - persons with autistic disorder
  - children under 3
- hypothesis: specific human capacity of reasoning about other agents' beliefs ('mind reading', *'theory of mind'*)
  - relevant for any interaction with a human being:
    - speech acts (inform, request,. . .)
    - empathy
    - deception, lies
    - planning involving other agents
  - social agents cannot be 'mind-blind'!

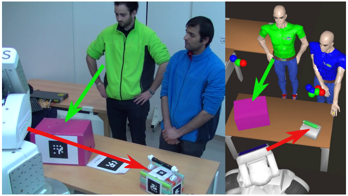
Challenge: robots with theory of mind [Milliez et al. 2014]

- at step 3, beliefs of Sally (here: Mr. Green) become false
    - colored arrows = beliefs about white book position (red = robot)
    - colored spheres = reachability of an object for an agent

1.


2.


3.


4.


Epistemic reasoning in planning

1. single-agent planning
    - uncertainty about initial situation
    - uncertainty about action effects
    - sensing actions (alias knowledge producing actions)

   ⇒ contingent/conformant planning
2. multiagent planning: much more possibilities!
    - initial situation

      1st order: *I know that p.* $K_i p$

      I don't know that p. $\neg K_i p$

      I don't know whether p. $\neg K_i p \land \neg K_i \neg p$

      2nd order: *I don't know whether you know that p.* ...

      I know that you don't know whether p. ...
    - goal

      1st order: *I want to know whether p.* $K_i p \lor K_i \neg p$

      2nd order: *I want to know whether you know that p.* ...

      I want you to know that q. ...
    - actions
        - have epistemic effects: sensing, communication

KR&R problems

- representation problems:
  - how to model epistemic effects of actions?
    - add/delete complex formulas like $K_i(p \vee q)$??
  - higher-order belief revision?
  - simple integration of epistemic and spatial reasoning?
    - social robotics
  - model 'expiry date' for knowledge/belief?
    - light in room x is on at time point T
    - j is in room x (so j believes that the light is on at T)
    - j leaves the room at $T+1$
    - at $T' > T$, does j still believe that the light in x is on?

$\Rightarrow$ to be solved in any 'real' application!

- reasoning problems:
  - 'static' epistemic reasoning is already difficult
    - at least PSPACE (just as classical planning)
    - EXPTIME complete for common knowledge/belief
  - benchmarks? 'epistemic planning's blocksworld'?

KR&R problems

- representation problems:
  - how to model epistemic effects of actions?
    - add/delete complex formulas like $K_i(p \vee q)$??
  - higher-order belief revision?
  - simple integration of epistemic and spatial reasoning?
    - social robotics
  - model ‘expiry date’ for knowledge/belief?
    - light in room x is on at time point T
    - j is in room x (so j believes that the light is on at T)
    - j leaves the room at $T+1$
    - at $T' > T$, does j still believe that the light in x is on?

  ⇒ to be solved in any ‘real’ application!
- reasoning problems:
  - ‘static’ epistemic reasoning is already difficult
    - at least PSPACE (just as classical planning)
    - EXPTIME complete for common knowledge/belief
  - benchmarks? ‘epistemic planning’s blocksworld’?

Outline

1. Planning: revisiting the main concepts
2. What is epistemic planning?
3. A benchmark proposal: gossip problems
4. Epistemic logic and dynamic epistemic logic
   - States and goals: Epistemic Logic
   - Actions and plans: Dynamic Epistemic Logic
5. Other formalisms
6. Epistemic planning with observability-based knowledge
   - Epistemic planning with conditional effects
   - Embeddings
7. Conclusion

The gossip problem

- original problem
  [Baker&Shostak, Discrete Maths 1972]:
    - n friends
    - each friend i has a secret $\mathtt{Sec}_i$
    - two friends can call each other
        - exchange all the secrets they have learned
    - goal: spread all secrets among all friends
- applications:
    - distributed databases
    - social networks
    - disease spreading
    - …

The gossip problem: solution

- initial state: $\left(\bigwedge_{1\leq i\leq n} K_i\, \mathsf{Sec}_i\right) \wedge \left(\bigwedge_{1\leq i,j\leq n, j\neq i} \neg K_i\, \mathsf{Sec}_j\right)$
- goal: shared knowledge ('everybody knows')

$$EK\, \mathit{AllSecrets} = \bigwedge_{1\leq i\leq n} K_i \left(\bigwedge_{1\leq j\leq n} \mathsf{Sec}_j \right)$$

- naive algorithm: $2(n-1)$ calls
- optimal algorithm:

friends	calls
2	1
3	3
4	4
5	6
⋮	⋮
$n \geq 4$	$2(n-2)$

The higher-order gossip problem: attaining higher-order shared knowledge

- attain shared knowledge of level k:

$$\underbrace{EK \cdots EK}_{k \text{ times}} \mathit{AllSecrets}$$

N.B.: impossible to obtain common knowledge (cf. Byzantine Generals)

- calls to attain shared knowledge of order k:

friends	calls for $k{=}1$	calls for $k{=}2$	calls for $k{=}3$	$\dots$
2	1	1		
3	3	4		
4	4	6		
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$n \geq 4$	$2{\times}(n{-}2)$	$3{\times}(n{-}2)$		

- for $n \geq 4$ and $k \geq 1$: $(k{+}1){\times}(n{-}2)$ calls
- for EK^k *AllSecrets*: tell all you know of order $k{-}1$!
- optimal [Cooper et al., ECAI 2016; Discrete Maths 2019]

The higher-order gossip problem: attaining higher-order shared knowledge

- attain shared knowledge of level k:

$$\underbrace{EK \cdots EK}_{k \text{ times}} \, AllSecrets$$

N.B.: impossible to obtain common knowledge (cf. Byzantine Generals)

- calls to attain shared knowledge of order k:

friends	calls for $k{=}1$	calls for $k{=}2$	calls for $k{=}3$	$\ldots$
2	1	1		
3	3	4		
4	4	6		
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$n \geq 4$	$2\times(n{-}2)$	$3\times(n{-}2)$		

- for $n \geq 4$ and $k \geq 1$: $(k{+}1)\times(n{-}2)$ calls
- for $EK^k AllSecrets$: tell all you know of order $k{-}1$!
- optimal [Cooper et al., ECAI 2016; Discrete Maths 2019]

The higher-order gossip problem: attaining higher-order shared knowledge

- attain shared knowledge of level k:

$$\underbrace{EK \cdots EK}_{k \text{ times}} \; AllSecrets$$

N.B.: impossible to obtain common knowledge (cf. Byzantine Generals)

- calls to attain shared knowledge of order k:

friends	calls for $k=1$	calls for $k=2$	calls for $k=3$	...
2	1	1		
3	3	4		
4	4	6		
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$n \geq 4$	$2\times(n-2)$	$3\times(n-2)$		

  - for $n \geq 4$ and $k \geq 1$: $(k+1)\times(n-2)$ calls
  - for $EK^k AllSecrets$: tell all you know of order $k-1$!
  - optimal [Cooper et al., ECAI 2016; Discrete Maths 2019]

Gossip = epistemic planning's blocksworld

- can be viewed as a paradigmatic epistemic planning problem
  - purely epistemic: no physical actions
- experiments: [Cooper et al., KR 2020; forthcoming]
- many possible variations; here:
  - sequential calls
    - parallel: [Cooper et al., KR 2020]
  - centralized protocol
    - distributed: [Apt et al., IJCAI 2017] [Apt&Wojtczak, JAIR 2018]
  - complete graph
    - bipartite, connected, . . . : [Cooper et al., Discrete Maths 2019]
    - dynamic graphs ('learn phone numbers'): [van Ditmarsch et al., J. Applied Logic 2017]

Outline

1. Planning: revisiting the main concepts
2. What is epistemic planning?
3. A benchmark proposal: gossip problems
4. Epistemic logic and dynamic epistemic logic
    - States and goals: Epistemic Logic
    - Actions and plans: Dynamic Epistemic Logic
5. Other formalisms
6. Epistemic planning with observability-based knowledge
    - Epistemic planning with conditional effects
    - Embeddings
7. Conclusion

Which formalism for epistemic planning?

- logics:
  - EL = epistemic logic (static) [Hintikka 1962]
  - DEL = dynamic epistemic logic
  - DEL-PAO = DEL of Propositional Assignment and Observation

Epistemic logic: language

- $K_i\varphi$ = "agent *i* knows that φ"
- grammar:

$$\varphi \ ::= \ p \mid \neg\varphi \mid \varphi \wedge \varphi \mid K_i\varphi$$

where *p* ranges over **Prp** and *i* over **Agt**

- first-order epistemic attitudes w.r.t. *p*:

K_ip	$K_i\neg p$	$\neg K_ip \wedge \neg K_i\neg p$

- second-order attitudes:

$K_ip \wedge K_iK_jp$	$K_i\neg p \wedge K_iK_j\neg p$	$(\neg K_ip\wedge\neg K_i\neg p) \wedge K_i(\neg K_jp\wedge\neg K_j\neg p)$
$K_ip \wedge K_i(\neg K_jp \wedge \neg K_j\neg p)$	. . .	$(\neg K_ip\wedge\neg K_i\neg p) \wedge K_i(K_jp\vee K_j\neg p)$
$K_ip \wedge (\neg K_iK_jp \wedge \neg K_i\neg K_jp)$	. . .	$(\neg K_ip \wedge \neg K_i\neg p) \wedge \neg K_i(K_jp \vee K_j\neg p) \wedge \neg K_i(\neg K_jp \vee \neg K_j\neg p)$

Epistemic logic: possible worlds semantics

- knowledge explained in terms of possible worlds [Hintikka 1962]:

“agent *i* knows that φ” = φ true in every world that is possible for *i*

- world model $M = (W, \{R_i\}_{i \in \textbf{Agt}}, V)$ with
  - W non-empty set of possible worlds
  - $R_i \subseteq W \times W$ accessibility relations
  - $V : W \longrightarrow 2^{\textbf{Prp}}$ valuation
- R_i is an equivalence relation (indistinguishability)

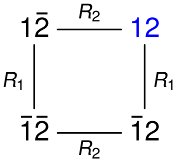
$$\begin{aligned} R_i(w) &= \text{“set of worlds } i \text{ cannot distinguish from } w\text{”} \\ &= \text{“set of worlds compatible with } i\text{'s knowledge”} \end{aligned}$$

- truth conditions:

$$\begin{array}{lll} M, w \Vdash p & \text{iff} & p \in V(w) \\ M, w \Vdash \neg\varphi & \text{iff} & \ldots \\ M, w \Vdash \varphi \wedge \psi & \text{iff} & \ldots \\ M, w \Vdash K_i\varphi & \text{iff} & M, w' \Vdash \varphi \text{ for all } w' \in R_i(w) \end{array}$$

Epistemic logic: possible worlds semantics

- a standard example: the muddy children puzzle



(reflexive arrows omitted)

$$M, 12 \Vdash m_1 \wedge m_2 \wedge K_1 m_2 \wedge \neg K_1 m_1 \wedge \neg K_1 \neg m_1$$

Epistemic logic for epistemic planning?

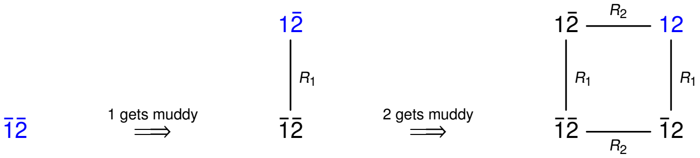
- can be expressed:
  - `Init` = world model / formula of epistemic logic
  - `Goal` = formula of epistemic logic
- cannot be expressed:
  - `actionLaws`

⇒ Dynamic Epistemic Logic DEL

[Baltag,Moss&Solecki, TARK 1998; Baltag&Moss, Synthese 2004]

Muddy children: Episode 1

1. initially, common knowledge that nobody is muddy
2. 1 gets muddy but isn't sure; 2 watches
3. 2 gets muddy but isn't sure; 1 watches



Dynamic epistemic logic DEL

- idea: model uncertainty about *current event* by introducing *possible events*

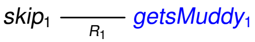
uncertainty about world	uncertainty about event
possible worlds	possible events
indistinguishability of worlds	indistinguishability of events

  ⇒ ‘possible event models’

- distinguish agents who observe from agents who don’t

  N.B.: an agent typically observes only very few events

- muddy children:
  event model where 1 plays, 2 watches



$$skip_1 \underset{R_1}{\text{———}} getsMuddy_1$$

(reflexive arrows omitted)

DEL: event models

- $EM = (E, \{S_i\}_{i \in \mathbf{Agt}}, \mathtt{pre}, \mathtt{effect})$ event model, where
  - E is a nonempty set of events
  - $S_i \subseteq E \times E$
    - every S_i is an equivalence relation
    - eS_if = “i perceives occurrence of e as occurrence of f”
  - $\mathtt{pre} : E \longrightarrow \mathit{Fmls}$
  - $\mathtt{effect} : E \longrightarrow \mathit{Fmls}$ s.th. $\mathtt{effect}(e)$ conjunction of literals

    (just as in STRIPS)

DEL: product construction

- update world model $WM = (W, R, V)$ by event model EM

$$WM \otimes EM = WM'$$

where

$$\begin{array}{rcl} W' & = & \{(w,e) \in W \times E \ : \ M, w \Vdash \texttt{pre}(e)\} \\ (w,e)R'_i(v,f) & \text{iff} & wR_iv \text{ and } eS_if \\ V'((w,e)) & = & (V(w) \setminus \{p \ : \ p \text{ negative in } \texttt{effect}(e)\}) \\ & & \quad \cup \{p \ : \ p \text{ positive in } \texttt{effect}(e)\} \end{array}$$

DEL for epistemic planning?

- explored since ~10 years [Bolander&Anderson 2011]; [Löwe, Pacuit&Witzel 2011]; [Aucher, Maubert&Pinchinat 2014]; ...
- knowledge representation:
  - `Init` = multipointed model/formula of multiagent epistemic logic
  - `Goal` = formula of multiagent epistemic logic
  - action type = agent + event model
  - compact representations ⇒ draw from symbolic model checking [Gattinger, PhD 2018]
- reasoning: difficult [Bolander&Anderson, JANCL 2011]; [Aucher&Bolander, IJCAI 2013]; [Yu, Wen&Liu 2013]; [Bolander et al., IJCAI 2015]; [Yu, Li&Wang 2015]; [Charrier et al., IJCAI 2016]; [Lê Cong et al., IJCAI 2018, Bolander et al., AIJ 2020],...
  - plan existence undecidable in general
  - decidable fragments: heavily restricted (public actions only)
  - world models typically grow exponentially when updated

DEL for epistemic planning: representation problems

- event models rather describe action tokens
  - ☹ `actionLaws` describe types, not tokens
- epistemic effects are typically conditional
  - for each agent, list all possible cases of perception of the actual event
  - conditional effects of $getMuddy(i)$:

$$
\begin{gathered}
(\top, m_i) \\
(inGarden_j, K_j m_i) \\
(K_i inGarden_j, K_i(K_j m_i \vee K_j \neg m_i)) \\
(K_j K_i inGarden_j, \quad \ldots \quad) \\
\vdots \\
(CK_{i,j} inGarden_j, CK_{i,j}(K_j m_i \vee K_j \neg m_i))
\end{gathered}
$$

⇒ event model with an infinite number of points!

  - even when finite, event models will be huge

Outline

SitCalc

- SitCalc = Situation Calculus
  [McCarthy 1963, Reiter 1991, Reiter 2001]
  - language of predicate logic
  - terms of type either object or situation
  - predicates have a situation argument
    - $\mathtt{On}(1, 2, s_0)$
  - function $\mathrm{do}(a, s)$, of situation type

$$\mathrm{do}((a_1; a_2), s) = \mathrm{do}(a_2, \mathrm{do}(a_1, s))$$

$$\mathtt{Poss}((a_1; a_2), s) = \mathtt{Poss}(a_1, s) \land \mathtt{Poss}(a_2, \mathrm{do}(a_1, s))$$

  - foundational axioms
    - tree-like situation space

$$\forall a_1 \forall a_2 \forall s \left(\mathrm{do}(a_1, s) {=} \mathrm{do}(a_2, s) \to a_1 {=} a_2\right)$$

$$\ldots$$

    - induction axiom (second-order!)

$$\forall P \left((P(s_0) \land \forall a \forall s (P(s) \to P(\mathrm{do}(a, s)))) \to \forall s P(s)\right)$$

Describing actions in the SitCalc

- description of preconditions:
  - special predicate $\mathtt{Poss}(a, s)$

$$\forall s \forall x \left(\mathtt{Poss}(\mathtt{unstack}(x), s) \leftrightarrow (\ \mathtt{Clear}(x, s) \wedge \neg\mathtt{Holding}(x, s)\ )\right)$$

- description of effects:
  - naively:

$$\forall s \forall x \forall y \left(\mathtt{On}(x, y, s) \rightarrow (\ \mathtt{Holding}(x, \mathtt{do}(\mathtt{unstack}(x), s)) \wedge \mathtt{Clear}(y, \mathtt{do}(\mathtt{unstack}(x), s))\ )\right)$$

Plan verification in the SitCalc

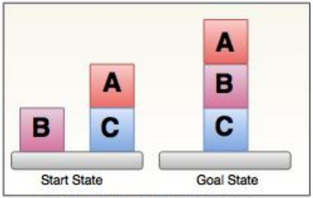


Fig: Blocks-World Planning Problem

- given:

$$\texttt{Init} = \left\{ \texttt{On}(A, C, s_0), \dots \right\}$$

$$\texttt{ActDescr} = \left\{ \forall s \forall x \left(\texttt{Poss}(\texttt{unstack}(x), s) \leftrightarrow \cdots \right), \dots, \right.$$

$$\left. \forall s \forall x \forall y \left(\texttt{On}(x, y, s) \rightarrow \texttt{Holding}(x, \texttt{do}(\texttt{unstack}(x), s))\right), \dots \right\}$$

$$\pi = \texttt{unstack}(A); \texttt{putdown}(A); \texttt{stack}(B, C); \dots$$

- prove:

$$\models_{\mathit{SitCalc}} (\texttt{ActDescr} \wedge \texttt{Init}) \rightarrow$$

$$(\texttt{Poss}(\pi, s_0) \wedge \texttt{On}(A, B, \pi(s_0)) \wedge \texttt{On}(B, C, \pi(s_0)))$$

The frame problem

- problem [McCarthy&Hayes 1969]:

$$\not\models_{\mathit{SitCalc}} (\mathtt{ActDescr} \land \mathtt{Init}) \to \mathtt{On}(B, C, \pi(s_0))$$

- reason:

$$\not\models_{\mathit{SitCalc}} \mathtt{ActDescr} \to (\mathtt{On}(C, D, s) \to \mathtt{On}(C, D, \mathtt{do}(\mathtt{stack}(A, B), s))$$

- solution: add formula to `ActDescr`
  - but unwanted: “there will be a vast number of such axioms because only relatively few actions will affect the value of a given fluent” [Reiter 2001]
- solutions:
  - generic ‘default persistence’ axiom [Reiter]
  - circumscription [McCarthy 1980, Lifschitz]
  - Yale shooting problem
  - Reiter’s successor state axioms

The frame problem: Reiter's solution

- action laws = successor state axioms:

$$\forall a \forall s \forall x \forall y \left(\mathtt{On}(x,y,\mathtt{do}(a,s)) \leftrightarrow \right.$$
$$\left. \left(\left(\mathtt{On}(x,y,s) \wedge a \neq \mathtt{unstack}(x)\right) \vee a = \mathtt{stack}(x,y)\right) \right)$$

  - one axiom per predicate P ('explanation closure')
  - no $\mathtt{do}(a,s)$ on the right
  - each axiom can be expected to be short
- reasoning by regression
  - replace left-hand-side by right-hand-side
  - result: static formula (no more $\mathtt{do}(a,s)$)
    - 'propositional' case (only state and action variables): decidable
  - use any FOL theorem prover
- suboptimal: regressed formula may be exponentially longer

The frame problem: Reiter’s solution (ctd.)

- implementation: GOLOG
  - implementation of planning (breadth-first, depth-first)
- extensions:
  - nondeterministic actions, actions with duration, concurrent actions (ConGolog), ‘natural actions’, continuous time, . . .
  - epistemic extension [Scherl&Levesque, AIJ 2003; McIllraith et col.]

The ramification problem

- problem: difficult to describe all effects of an action
    - already for an action instance
        - effects of shooting Kennedy: $\neg\mathtt{Alive}(\mathtt{Kennedy}), \mathtt{President}(\mathtt{Johnson}), \ldots$
    - even harder for action types
        - think of conditional effects
        - think of epistemic effects
- solution:
    - distinguish primitive and derived predicates
    - define derived predicates by means of logic programs ⇒ action languages B and C, v.i.

The qualification problem

- problem: difficult to describe preconditions

$$\begin{aligned}\mathtt{Poss}(\mathtt{startCar}, s) \leftrightarrow\ & \mathtt{HasKey}(s) \land \\ & \neg\mathtt{TankEmpty}(s) \land \\ & \neg\mathtt{BatteryEmpty}(s) \land \\ & \cdots \land \\ & \neg\mathtt{PotatoInTailpipe}(s)\end{aligned}$$

- solution: integrate default reasoning
  - when $\not\models KB \to \mathtt{BatteryEmpty}(s)$ then infer $\models KB \to \neg\mathtt{BatteryEmpty}(s)$

Action language A

- idea: simple and natural language for reasoning about actions
  [Gelfond&Lifschitz, J. Logic Programming 1993]
- extends STRIPS by conditional effects
- action laws:

$$\begin{aligned}\{ & \ \texttt{load causes Loaded}, \\ & \texttt{shoot causes } \neg\texttt{Loaded}, \\ & \texttt{shoot causes } \neg\texttt{Alive if Loaded} \ \}\end{aligned}$$

  - induce deterministic relations on states

$$R_{\texttt{shoot}} = \ldots$$

- initial state: $\texttt{Init} = \{\texttt{initially } \neg\texttt{Loaded}\}$
- define consequence relation:

$$\texttt{ActDescr} \cup \texttt{Init} \models \texttt{Goal after } \pi$$
$$\texttt{ActDescr} \cup \texttt{Init} \models \neg\texttt{Alive after load}; \texttt{shoot}$$

- plan verification: NP complete [Liberatore, ETAI 1997]
- implemented in logic programming (ASP)

Action languages B and C

- extend A by a solution to the ramification problem
  - distinguish primitive and derived predicates
    - $\mathtt{On}(x, y)$ primitive
    - $\mathtt{Clear}(x)$ derived
  - define derived predicates by means of logic programs

$$\begin{aligned} \mathtt{Clear}(x, s) &\leftarrow \neg\exists y \mathtt{On}(y, x, s) \\ \mathtt{Above}(x, y, s) &\leftarrow \mathtt{On}(x, z, s) \vee \exists z(\mathtt{On}(x, z, s) \wedge \mathtt{Above}(z, y, s)) \end{aligned}$$

- fixed-point semantics
  - simpler (and more intuitive) when programs are stratified
  - implemented in logic programming (ASP)
- similar proposal for PDDL [Thiebaux et al., AIJ 2005]
- strictly more succinct (‘expressive’) than without derived predicates [Thiebaux et al., AIJ 2005]
- epistemic extensions inspired by DEL [Baral et al., AAMAS 2010]; [NMR 2012; Le et al., ICAPS 2018; Son&Balduccini, KI 2018]

The Planning Domain Definition Language PDDL

- motivated by planning competition
  `http://www.icaps-conference.org/index.php/Main/Competitions`
- planner input: description of a planning problem in PDDL
  - problem description = $(\mathtt{Init}, \mathtt{Goal})$
  - domain description: actions with conditional effects
- here: PDDL 1.2 [McDermott et al., 1998]
  - various extensions: numbers, plan-metrics; actions with duration; hard&soft constraints on trajectories
    ⇒ PDDL 2.1, 2.2, 3.0, 3.1

Outline

1. Planning: revisiting the main concepts
2. What is epistemic planning?
3. A benchmark proposal: gossip problems
4. Epistemic logic and dynamic epistemic logic
    - States and goals: Epistemic Logic
    - Actions and plans: Dynamic Epistemic Logic
5. Other formalisms
6. Epistemic planning with observability-based knowledge
    - Epistemic planning with conditional effects
    - Embeddings
7. Conclusion

Simplifications of DEL for epistemic planning

- [Baral et al., AAMAS 2010; NMR 2012; Le et al., ICAPS 2018]
  - multiagent extension of action language A with DEL action models
  - syntactical restrictions on `Init`
  - simple language to describe some DEL action models
    - $i\ \texttt{observes}\ \texttt{unstack}(j)\ \texttt{if}\ \texttt{watching}(i,j)$
      $i\ \texttt{aware}-\texttt{of}\ \texttt{unstack}(j)\ \texttt{if}\ \texttt{watching}(i,j)$
  - ASP-based implementation
- [Muise et al., AAAI 2015]
  - epistemic literals only
    $K_i p,\ K_i\neg p,\ \neg K_i\neg p,\ \neg K_i\neg p$
  - no disjunctions
    - express “*i* knows that *j* knows whether *p*”?
  - reduction to classical planning
- [Kominis&Geffner, ICAPS 2015; 2018]
  - public actions only
    - cannot account for gossip (private communication)
  - reduction to classical planning

How should we represent actions in epistemic planning?

- where do the epistemic effects come from?
  1. described together with the action
     - event models of dynamic epistemic logic (DEL)
  2. follow from state descriptions
     - positioning of agents in space [Gasquet et al., J. AAMAS 2016]
     - information about who pays attention [Bolander et al., JoLLI 2016]
     - information about who sees what . . .

Grounding knowledge on propositional observability

agent *i* observes whether propositional variable *p* is true

- originates in model checking distributed systems (MOCHA)
  - logic:
    [v.d.Hoek&Wooldridge, AIJ 2005; v.d.Hoek et al., AAMAS 2011]
- *derive* indistinguishability relation:

  $R_i \ = \{(s,s') : s(p) = s'(p)$ for every $p \in PVar$ observed by $i\}$
- interpret epistemic operator in world model $(2^{PVar}, R, id)$
- compact models
  1. valuations of classical propositional logic
  2. visibility information: subset of **Agt** × **Prp**
- ‘anti-Hintikka’
  - grounded on origins of knowledge (what we know comes from observation + communication)

Propositional observability: properties

$$\boxed{i \text{ observes } p \text{ iff } K_i p \vee K_i \neg p \text{ true}}$$

- all axiom schemas of S5 valid
- plus some more:
  - ☹ distributes over disjunction:

$$K_i(p \vee q) \leftrightarrow (K_i p \vee K_i q)$$

  - ☹ who observes what is common knowledge:

$$(K_i p \vee K_i \neg p) \rightarrow K_j(K_i p \vee K_i \neg p)$$
$$\neg(K_i p \vee K_i \neg p) \rightarrow K_j \neg(K_i p \vee K_i \neg p)$$

⇒ not appropriate for gossipping!

Higher-order observability

- idea: introduce higher-order visibility atoms

  [Herzig et al., LORI 2015]; [Herzig&Maffre, AI Comm. 2017]; [Cooper et al., ECAI 2016]

  $\mathrm{S}_i\, p$ = "*i* sees the value of *p*"

  $\mathrm{S}_i\, \mathrm{S}_j\, p$ = "*i* sees *whether* *j* sees the value of *p*"

  $\mathrm{S}_i\, \mathrm{S}_j\, \mathrm{S}_k\, p$ = "…"
- intuitively:

$$
\begin{aligned}
K_i p &\leftrightarrow p \land \mathrm{S}_i\, p \\
K_i \neg p &\leftrightarrow \neg p \land \mathrm{S}_i\, p \\
K_i K_j p &\leftrightarrow K_i(p \land \mathrm{S}_j\, p) \\
&\leftrightarrow K_i p \land K_i \mathrm{S}_j\, p \\
&\leftrightarrow p \land \mathrm{S}_i\, p \land \mathrm{S}_j\, p \land \mathrm{S}_i\, \mathrm{S}_j\, p
\end{aligned}
$$

Language

- grammar:

$$\varphi ::= \sigma p \mid \neg\varphi \mid \varphi \wedge \varphi \mid K_i\varphi$$

  where σp is a *visibility atom*
  - σ = sequence of visibility operators S_i
  - p = propositional variable
- propositional variables are special cases: σ empty

States

- state s = set of visibility atoms
    - initial gossip state (supposing all secrets are true)

$$s_0 = \{\mathsf{Sec}_1, \ldots, \mathsf{Sec}_n\} \cup \{\mathsf{S}_1\,\mathsf{Sec}_1, \ldots, \mathsf{S}_n\,\mathsf{Sec}_n\}$$

- define indistinguishability relations as before:

$$sR_is' \text{iff} \quad \forall\alpha, \text{ if } \mathsf{S}_i\,\alpha \in s \text{ then } s(\alpha) = s'(\alpha)$$

- problem: reflexive, but neither transitive nor symmetric
    - $\emptyset R_i s$ for every s
    - not($sR_i\emptyset$) as soon as $p \in s$ and $\mathsf{S}_i\,p \in s$
- s must be introspective
    - contains all observability atoms of form $\sigma\mathsf{S}_i\,\mathsf{S}_i\,\sigma' p$, for all i
- properties of introspective states:
    - R_i equivalence relations
    - who observes what no longer common knowledge
        - $\mathsf{S}_i\,p \to \mathsf{S}_j\,\mathsf{S}_i\,p$ invalid
        - $\mathsf{S}_i\,p \to K_j\mathsf{S}_i\,p$ invalid
        - $(K_ip \vee K_i\neg p) \to K_j(K_ip \vee K_i\neg p)$ invalid
- normal form: replace $\sigma\mathsf{S}_i\,\mathsf{S}_i\,\sigma' p$ by $\top$ (introspectively valid)

States

- state s = set of visibility atoms
    - initial gossip state (supposing all secrets are true)

$$s_0 = \{\mathsf{Sec}_1, \ldots, \mathsf{Sec}_n\} \cup \{\mathsf{S}_1\,\mathsf{Sec}_1, \ldots, \mathsf{S}_n\,\mathsf{Sec}_n\}$$

- define indistinguishability relations as before:

$$sR_i s' \text{iff} \quad \forall\alpha,\ \text{if } \mathsf{S}_i\,\alpha \in s \text{ then } s(\alpha) = s'(\alpha)$$

- problem: reflexive, but neither transitive nor symmetric
    - $\emptyset R_i s$ for every s
    - not($sR_i\emptyset$) as soon as $p \in s$ and $\mathsf{S}_i\,p \in s$
- s must be introspective
    - contains all observability atoms of form $\sigma \mathsf{S}_i\,\mathsf{S}_i\,\sigma' p$, for all i
- properties of introspective states:
    - R_i equivalence relations
    - who observes what no longer common knowledge
        - $\mathsf{S}_i\,p \rightarrow \mathsf{S}_j\,\mathsf{S}_i\,p$ invalid
        - $\mathsf{S}_i\,p \rightarrow K_j \mathsf{S}_i\,p$ invalid
        - $(K_i p \vee K_i \neg p) \rightarrow K_j(K_i p \vee K_i \neg p)$ invalid
- normal form: replace $\sigma \mathsf{S}_i\,\mathsf{S}_i\,\sigma' p$ by $\top$ (introspectively valid)

States

- state s = set of visibility atoms
    - initial gossip state (supposing all secrets are true)

$$s_0 = \{\mathsf{Sec}_1, \ldots, \mathsf{Sec}_n\} \cup \{\mathsf{S}_1\,\mathsf{Sec}_1, \ldots, \mathsf{S}_n\,\mathsf{Sec}_n\}$$

- define indistinguishability relations as before:

$$sR_is' \text{iff} \quad \forall\alpha, \text{ if } \mathsf{S}_i\,\alpha \in s \text{ then } s(\alpha) = s'(\alpha)$$

- problem: reflexive, but neither transitive nor symmetric
    - $\emptyset R_i s$ for every s
    - not($sR_i\emptyset$) as soon as $p \in s$ and $\mathsf{S}_i\,p \in s$
- s must be introspective
    - contains all observability atoms of form $\sigma \mathsf{S}_i\,\mathsf{S}_i\,\sigma' p$, for all i
- properties of introspective states:
    - R_i equivalence relations
    - who observes what no longer common knowledge
        - $\mathsf{S}_i\,p \to \mathsf{S}_j\,\mathsf{S}_i\,p$ invalid
        - $\mathsf{S}_i\,p \to K_j \mathsf{S}_i\,p$ invalid
        - $(K_i p \vee K_i \neg p) \to K_j(K_i p \vee K_i \neg p)$ invalid
- normal form: replace $\sigma \mathsf{S}_i\,\mathsf{S}_i\,\sigma' p$ by $\top$ (introspectively valid)

Conditional actions

- *conditional action* $a = (pre(a), eff(a))$ where:
  - $pre(a)$ proposition
  - $eff(a)$ set of conditional effects; in particular:
    - add observability atoms
    - delete observability atoms
- example:

$$\begin{aligned} pre(\mathtt{call}_j^i) &= \top \\ eff(\mathtt{call}_j^i) &= \Big\{ (\mathsf{S}_i\,\mathsf{Sec}_1 \vee \mathsf{S}_j\,\mathsf{Sec}_1, \{\mathsf{S}_i\,\mathsf{Sec}_1, \mathsf{S}_j\,\mathsf{Sec}_1\}, \emptyset), \\ &\qquad \ldots \\ &\qquad (\mathsf{S}_i\,\mathsf{Sec}_n \vee \mathsf{S}_j\,\mathsf{Sec}_n, \{\mathsf{S}_i\,\mathsf{Sec}_n, \mathsf{S}_j\,\mathsf{Sec}_n\}, \emptyset) \Big\} \end{aligned}$$

- conditional action $a \Rightarrow$ transition relation between states R_a

Conditional actions: normal form

- $a = (pre(a), eff(a))$ is in normal form iff
  1. $pre(a)$ in normal form
     - no introspectively valid $\sigma S_i\, S_i\, \sigma' p$
  2. every conditional effect $ce \in eff(a)$ in normal form
  3. no conflicting effects
- every action can be put in normal form

Conditional actions: normal form

- $a = (pre(a), eff(a))$ is in normal form iff
  1. $pre(a)$ in normal form
     - no introspectively valid $\sigma S_i\, S_i\, \sigma' p$
  2. every conditional effect $ce \in eff(a)$ in normal form
  3. no conflicting effects
- every action can be put in normal form

Planning tasks

- planning task = $(Act, s_0, \mathtt{Goal})$ where
    - Act is a finite set of actions
    - s_0 finite state (the initial state)
    - $\mathtt{Goal} \in Fmls_{bool}$
- is in *normal form* iff

  $\ldots$
- is *solvable* if there is a state s such that
    1. $s_0 \left(\bigcup_{a \in Act} R_a \right)^* s$
    2. $s \models \mathtt{Goal}$

Extending the logic by assignment programs

- extend logic of observability-based knowledge by assignment programs

$$\varphi ::= \sigma p \mid \neg\varphi \mid \varphi \land \varphi \mid K_i\varphi \mid [\pi]\varphi$$

$$\pi ::= +\sigma p \mid -\sigma p \mid \pi;\pi \mid \pi \sqcup \pi \mid \pi^* \mid \varphi?$$

- call = program:

$$\begin{aligned}\mathtt{call}^i_j = {} & \big((K_i\mathsf{Sec}_1 \lor K_j\mathsf{Sec}_1?; +\mathsf{S}_i\,\mathsf{Sec}_1; +\mathsf{S}_j\,\mathsf{Sec}_1) \sqcup \neg(K_i\mathsf{Sec}_1 \lor K_j\mathsf{Sec}_1)?\big);\\ & \cdots;\\ & \big((K_i\mathsf{Sec}_n \lor K_j\mathsf{Sec}_n?; +\mathsf{S}_i\,\mathsf{Sec}_n; +\mathsf{S}_j\,\mathsf{Sec}_n) \sqcup \neg(K_i\mathsf{Sec}_n \lor K_j\mathsf{Sec}_n)?\big)\end{aligned}$$

- For initial gossip state s_0:

$$s_0 \models \big[\mathtt{call}^1_2; \mathtt{call}^3_4; \mathtt{call}^5_6; \mathtt{call}^1_3; \mathtt{call}^4_5; \mathtt{call}^1_6; \mathtt{call}^2_4; \mathtt{call}^3_5\big]\, \mathit{EK\ AllSecrets}$$

$$s_0 \models \Big\langle\Big(\bigsqcup_{1\leq i,j\leq 6} \neg\mathsf{S}_i\,\mathsf{Sec}_j?; \mathtt{call}^i_j\Big)^6\Big\rangle\, \mathit{EK\ AllSecrets}$$

$$s_0 \models \Big[\Big(\bigsqcup_{1\leq i,j\leq 6} \neg\mathsf{S}_i\,\mathsf{Sec}_j?; \mathtt{call}^i_j\Big)^5\Big]\, \neg\mathit{EK\ AllSecrets}$$

Embedding and complexity

Theorem

A planning task $(Act, s_0, \texttt{Goal})$ in normal form is solvable iff

$$s_0 \models \langle \big(\bigsqcup_{a \in Act} execAct(a) \big)^* \rangle \texttt{Goal}$$

where $execAct(a)$ encodes action a as a dynamic logic assignment program

(involves storing values of variables to trigger conditional effects correctly)

- proof of correctness of gossip algorithms in the logic
    - base case and induction step are theorems of the logic

Theorem

Deciding the solvability of an planning task is PSPACE-complete

Embedding into PDDL 1.2

- formulas:

$$tr_{PDDL}(\mathsf{S}_{i_1} \dots \mathsf{S}_{i_m}\, p) = \begin{cases} \texttt{(p)} & \text{if } m = 0 \\ \texttt{(}\mathbf{\texttt{S-m}}\texttt{ i1 ... im p)} & \text{otherwise} \end{cases}$$

$$tr_{PDDL}(\neg\varphi) = \texttt{(not } tr_{PDDL}(\varphi)\texttt{)}$$

$$tr_{PDDL}(\varphi_1 \wedge \varphi_2) = \texttt{(and } tr_{PDDL}(\varphi_1)\ tr_{PDDL}(\varphi_2)\texttt{)}$$

- conditional effects of actions:

$$\begin{array}{l} \texttt{(when } tr_{PDDL}(cnd(ce)) \\ \quad \texttt{(and } tr_{PDDL}(\alpha_1) \ \dots \ tr_{PDDL}(\alpha_m) \\ \qquad \texttt{(not } tr_{PDDL}(\beta_1)\texttt{)} \ \dots \ \texttt{(not } tr_{PDDL}(\beta_\ell)\texttt{))))} \end{array}$$

- experiments with FDSS-2014

  [Röger et al., Int. Planning Competition 2014]
  - variants of the gossip problem
    - shared knowledge of order k; negative goals

Outline

1. Planning: revisiting the main concepts
2. What is epistemic planning?
3. A benchmark proposal: gossip problems
4. Epistemic logic and dynamic epistemic logic
    - States and goals: Epistemic Logic
    - Actions and plans: Dynamic Epistemic Logic
5. Other formalisms
6. Epistemic planning with observability-based knowledge
    - Epistemic planning with conditional effects
    - Embeddings
7. Conclusion

Summary

1. action languages for reasoning about actions
   - STRIPS
   - SitCalc
   - action languages A, B, C
   - PDDL
2. epistemic planning
   - a simple epistemic planning problem: gossip
   - knowledge representation in DEL: practical and conceptual problems (type vs. token)
3. a simple dynamic epistemic logic based on observability
   - captures epistemic planning problems
   - in PSPACE (even with common knowledge)
   - can be mapped to classical planning
   - limitations?

Perspectives

1. observation-based knowledge
    - integrate communication; public announcement of complex formulas [Charrier et al., KR 2016]
    - from knowledge to belief (requires belief revision)
2. parallel actions ⇒ Elise's talk (Thursday)
3. towards cognitive planning
    - logics of goals and intentions (BDI logics)
    - goals, commitments, intentions
    - integrate HTN planning
4. strategic planning
    - epistemic extensions of CL, ATL,. . .

An active domain

- AIJ special issue Epistemic Planning (ongoing; almost ready)
- IJCAI 2020 Workshop on MultiAgent, Flexible, Temporal, Epistemic and Contingent Planning (MAFTEC 2020), Jan. 2021, `https://www.irit.fr/maftec2020/`
- ICAPS 2020 Workshop on Epistemic Planning (EpiP 2020), Oct. 21-23, 2020, `https://icaps20.icaps-conference.org/workshops/epip`
- ICAPS 2020 Tutorial on Epistemic Planning (EpiP 2020), Oct. 19-20, 2020, `https://icaps20.icaps-conference.org/tutorials/epistemic-planning/`