Multiagent epistemic planning

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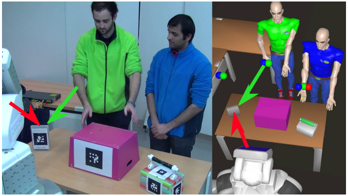
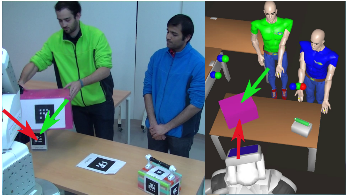
The importance of reasoning about knowledge and belief

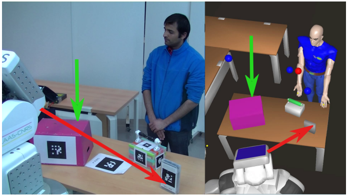
- S. Baron Cohen's False-belief-tasks (Sally-Ann Test, ...)
  [S. Baron Cohen 1985]
  - `https://www.youtube.com/watch?v=jbL34F81Rz0`
  - `https://www.youtube.com/watch?v=N6ylH-LYjOM`
- typically fail the test:
  - children under 3
  - autistic children
- hypothesis: specific human capacity of reasoning about other agents' beliefs ('mind reading', *'theory of mind'*)
  - relevant for any interaction with a human being
  - specifically: planning future actions involving others
- epistemic reasoning = reasoning about knowledge and belief (large sense)

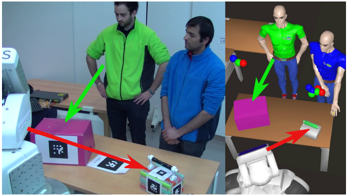
Challenge: robots with theory of mind [Milliez et al. 2014]

- at step 3, GREEN's beliefs 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
   - initial situation

     first-order: *I don't know whether p.*
     second-order: *I don't know whether you know that p.*
     I know that you don't know whether p.
     ...
   - goal

     first-order: *I want to know whether p.*
     second-order: *I want to know whether you know that p.*
     I want you to know that q.
     third-order: ...
   - actions
     - have epistemic effects: sensing, communication

Problems, problems

- representation problems:
  - 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?
  - higher-order belief revision?
  - simple integrations of epistemic and spatial reasoning?

  $\Rightarrow$ to be solved in any application!
- reasoning problems:
  - epistemic reasoning is difficult
    - at least PSPACE (just as classical planning)
    - EXPTIME complete if common knowledge/belief involved
  - no ‘epistemic planning’s blocksworld’ (yet)
  - no good benchmarks (yet)

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Outline

What's in a planning problem?

planning problem = $\langle \texttt{init}, \texttt{goal}, \texttt{actionLaws} \rangle$

1. logical form of `init`: proposition
   - proposition = set of states ('possible worlds')
   - can be described in various logical languages:
     - propositional logic
     - epistemic logic
     - ...
   - classical planning:

     initial state = a single possible world
     = a valuation of propositional logic
     = complete proposition
2. logical form of `goal`: proposition
3. logical form of `actionLaws`: action type
   - action type: *arm-raising*
   - action token: *Paulo's raising of his right arm in room 7 of building 007 on Oct. 1, 2018 at 11:55:55*

What's in an action?

- "something that has precondition and effects" [AI folklore]

$$\boxed{\text{action} = \langle \texttt{precond}, \texttt{effect} \rangle}$$

  - $\texttt{precond}$ = proposition
  - $\texttt{effect}$ = ?

What's in an action effect?

- STRIPS actions: `effect` = conjunction of literals
- however: an action type is instantiated in different circumstances ⇒ effects typically depend on these circumstances
- conditional effects:

$$\texttt{effect} = \Big\{\langle \mathit{condition}_1, L_{1,1} \wedge \cdots \wedge L_{1,m_1}\rangle, \ldots, \langle \mathit{condition}_n, L_{n,1} \wedge \cdots \wedge L_{n,m_1}\rangle\Big\}$$

  - example: agent *i*'s action of flipping a switch

$$\texttt{precond}(\mathit{flip}_i) = \mathit{AtSwitch}_i$$
$$\texttt{effect}(\mathit{flip}_i) = \{\langle \neg On, On\rangle, \langle On, \neg On\rangle\}$$

- what about epistemic effects?

Outline

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*:

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

- second-order attitudes:

$K_i p \wedge K_i K_j p$	$K_i \neg p \wedge K_i K_j \neg p$	$(\neg K_i p \wedge \neg K_i \neg p) \wedge K_i(\neg K_j p \wedge \neg K_j \neg p)$
$K_i p \wedge K_i(\neg K_j p \wedge \neg K_j \neg p)$	...	$(\neg K_i p \wedge \neg K_i \neg p) \wedge K_i(K_j p \vee K_j \neg p)$
$K_i p \wedge (\neg K_i K_j p \wedge \neg K_i \neg K_j p)$	...	$\emptyset$

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

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

  $R_i(w)$ = "set of worlds i cannot distinguish from w"
  = "set of worlds compatible with i's knowledge"
- truth conditions:

  $M, w \Vdash p$ iff $p \in V(w)$

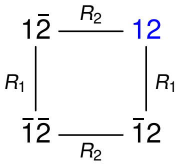
  $M, w \Vdash \neg\varphi$ iff ...

  $M, w \Vdash \varphi \wedge \psi$ iff ...

  $M, w \Vdash K_i\varphi$ iff $M, w' \Vdash \varphi$ for all $w' \in R_i(w)$

Epistemic logic: possible worlds semantics

- muddy children puzzle, initial situation



(reflexive arrows omitted)

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

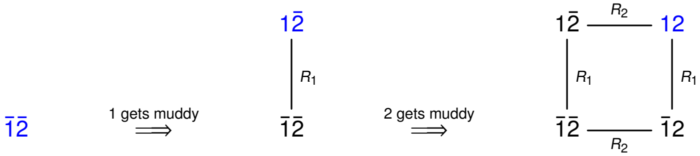
Epistemic logic for epistemic planning?

- can be modeled:
  - `init` = formula of epistemic logic
  - `goal` = formula of epistemic logic
- cannot be expressed:
  - `actionLaws`

Outline

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

$\Rightarrow$ '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

$$\mathit{skip}_1 \;\frac{\quad\quad}{R_1}\; \mathit{getsMuddy}_1$$

(reflexive arrows omitted)

DEL: event models

- $EM = (E, \{S_i\}_{i \in \mathbf{Agt}}, \mathtt{precond}, \mathtt{effect})$ 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"
  - $\mathtt{precond} : E \longrightarrow \mathit{Fmls}$
  - $\mathtt{effect} : E \longrightarrow \mathit{Fmls}$ 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

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

DEL for epistemic planning?

- explored since >5 years [Bolander&Anderson 2011]; [Löwe, Pacuit&Witzel 2011]; [Aucher, Maubert&Pinchinat 2014]; [Yu, Li&Wang 2015],. . .
  - `init` = formula of multiagent epistemic logic
  - `goal` = formula of multiagent epistemic logic
  - action type = agent + event model
- reasoning: not so easy
  - plan existence undecidable in general [Bolander&Anderson 2011]; [Aucher&Bolander 2013]; [Charrier, Maubert&Schwarzentruber 2016]
  - decidable fragments: heavily restricted [Yu, Wen&Liu 2013]; [Bolander et al. 2015],. . .
  - world models typically grow exponentially when updated
- representation: some problems that seemingly went unnoticed. . .

DEL for epistemic planning: problems

- event models rather describe action tokens
- `actionLaws` describe types, not tokens
- how to describe conditional effects?
  - list all possible cases of perception of the actual event
  - infinitely many conditional effects needed
- conditional effects of *getMuddy*(i):

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

$\Rightarrow$ event model with an infinite number of points!

- even when finite, event models have to be big

Outline

The gossip problem

- [Baker&Shostak, Discrete Mathematics 1972]
- *n* friends
- each friend *i* has a secret Σ_i
- two friends can call each other to exchange all the secrets they know
- how many calls to spread all secrets among all friends?

The gossip problem

- relevant for distributed database, social networks, disease spreading, . . .
- hot topic in the DEL community
- different kinds of protocols; here:
    - complete graph
        - other graphs: [Cooper et al., Discrete Maths, to appear]
    - centralized protocol
        - distributed variants: [Apt et al., TARK 2016; IJCAI 2017] [van Ditmarsch et al., LOFT 2016]
- paradigmatic epistemic planning problem?
    - ‘multiagent planning’s blocksworld’

The gossip problem: solution

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

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

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

friends	calls
2	1
3	3
4	4
5	6
6	8
⋮	⋮
$n \geq 4$	$2(n-2)$

The 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)

- algorithm with calls to attain shared knowledge of order k

[Herzig&Maffre, AI Commun. 2017]

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

- for $n \geq 4$ and $k \geq 1$: $(k+1)\times(n-2)$ calls
- optimal [Cooper et al., ECAI 2016; Discrete Maths, to appear]

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Outline

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:

$$R_i = \{(s, s') : s(p) = s'(p) \text{ for every } p \in PVar \text{ observed by } i\}$$

- interpret epistemic operator in Kripke 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

i observes p iff $K_i p \lor K_i \neg p$ true

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

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

  - ☹ who observes what is common knowledge:

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

$\Rightarrow$ not appropriate for gossipping!

Higher-order observability

- idea: introduce higher-order visibility atoms
  $S_i\, p$ = "*i* sees the value of *p*"
  $S_i\, S_j\, p$ = "*i* sees *whether* *j* sees the value of *p*"
  $S_i\, S_j\, S_k\, p$ = "..."
- intuitively:

$$
\begin{aligned}
K_i p &\leftrightarrow p \land S_i\, p \\
K_i \neg p &\leftrightarrow \neg p \land S_i\, p \\
K_i K_j p &\leftrightarrow K_i(p \land S_j\, p) \\
&\leftrightarrow K_i p \land K_i S_j\, p \\
&\leftrightarrow p \land S_i\, p \land S_j\, p \land S_i\, S_j\, p
\end{aligned}
$$

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)

$$s_0 = \{\Sigma_1, \ldots, \Sigma_n\} \cup \{S_1\, \Sigma_1, \ldots, S_n\, \Sigma_n\}$$

- define indistinguishability relations as before:

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

- 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 $S_i\, p \in s$
- s must be introspective
  - contains all observability atoms of form $\sigma S_i\, S_i\, \sigma' p$, for all i
- properties of introspective states:
  - R_i equivalence relations
  - who observes what no longer common knowledge
    - $S_i\, p \to S_j\, S_i\, p$ invalid
    - $S_i\, p \to K_j S_i\, p$ invalid
    - $(K_i p \vee K_i \neg p) \to K_j(K_i p \vee K_i \neg p)$ invalid
- normal form: replace $\sigma S_i\, S_i\, \sigma' p$ by $\top$ (introspectively valid)

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Outline

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:

$$
\begin{aligned}
pre(\mathtt{call}_j^i) &= \top \\
eff(\mathtt{call}_j^i) &= \{(S_i\,\Sigma_1 \vee S_j\,\Sigma_1, \{S_i\,\Sigma_1, S_j\,\Sigma_1\}, \emptyset), \\
&\qquad \ldots \\
&\qquad (S_i\,\Sigma_n \vee S_j\,\Sigma_n, \{S_i\,\Sigma_n, S_j\,\Sigma_n\}, \emptyset)\}
\end{aligned}
$$

- 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

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Planning tasks

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

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

Outline

Extending the logic by assignment programs

- extend logic of observability-based knowledge by assignment programs

$$\varphi ::= \sigma p \mid \neg\varphi \mid \varphi \wedge \varphi \mid K_i\varphi \mid [\pi]\varphi$$
$$\pi ::= +\sigma p \mid -\sigma p \mid \pi;\pi \mid \pi \sqcup \pi \mid \pi^* \mid \varphi?$$

- call = program:

$$\begin{aligned}\mathtt{call}^i_j = &\Big((K_i\Sigma_1 \vee K_j\Sigma_1?; +\mathrm{S}_i\,\Sigma_1; +\mathrm{S}_j\,\Sigma_1) \sqcup \neg(K_i\Sigma_1 \vee K_j\Sigma_1)?\Big);\\ &\cdots;\\ &\Big((K_i\Sigma_n \vee K_j\Sigma_n?; +\mathrm{S}_i\,\Sigma_n; +\mathrm{S}_j\,\Sigma_n) \sqcup \neg(K_i\Sigma_n \vee K_j\Sigma_n)?\Big)\end{aligned}$$

- For initial gossip state s_0:

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

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

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

Embedding and complexity

Theorem

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

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

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

Encoding into PDDL

- formulas:

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

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

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

- conditional effects of actions:

$$\texttt{(when } tr_{PDDL}(cnd(ce))$$
$$\texttt{(and } tr_{PDDL}(\alpha_1)\ \ldots\ tr_{PDDL}(\alpha_m)$$
$$\texttt{(not } tr_{PDDL}(\beta_1)\texttt{)}\ \ldots\ \texttt{(not } tr_{PDDL}(\beta_\ell)\texttt{)))}$$

- experiments with FDSS-2014

  [Röger et al., Int. Planning Competition 2014]
  - variants of the gossip problem
    - shared knowledge of order k; negative goals
  - exam problem
    - teacher has prepared exam and keeps printout in his office
    - student's goal: $S_{student}\, ex \land \neg S_{teacher}\, S_{student}\, ex$

Conclusion (1)

- knowledge representation with DEL event models:
  - art rather than craft
  - practical problems
  - conceptual problems (type vs. token)
- the other agents' observation should be based on information from the possible worlds model, not from the possible event model
  - edge-conditioned event models [Bolander, 2015]
  - special propositional variable "agent *i* is watching" [Bolander et al., JoLLI 2016]
    - part of the state, not part of the action!

Conclusion (2)

- a simple epistemic planning problem: gossip
- a simple dynamic epistemic logic based on visibility
  - captures epistemic planning problems
  - in PSPACE (even with common knowledge)
  - can be mapped to classical planning
- related work
  - public actions only
    [Kominis&Geffner, ICAPS 2015; 2018]
  - public announcements
    [v.Benthem et al., LORI 2015],
    [Charrier et al., KR 2016]
  - boolean games [H. et al., IJCAI 2016]
- future work
  - from knowledge to belief?