Foundations of Planning for LTL_f and LDL_f Goals

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Outline

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Introduction and background

Reasoning about Actions and Planning community well aware of temporal logics since a long time:

- Temporally extended goals [BacchusKabanza96] - infinite/finite
- Temporal constraints on trajectories [GereviniHaslumLongSaettiDimopoulos09 - PDDL3.0 2009] - finite
- Declarative control knowledge on trajectories [BaierMcIlraith06] - finite
- Procedural control knowledge on trajectories [BaierFrizMcIlraith07] - finite
- Temporal specification in planning domains [CalvaneseDeGiacomoVardi02] - infinite
- Planning via model checking - infinite
  - Branching time (CTL) [CimattiGiunchigliaGiunchigliaTraverso97]
  - Linear time (LTL) [DeGiacomoVardi99]

Foundations for temporal extended goals and constraints

We borrow foundations from temporal logics studied in CS, in particular:
Linear Temporal Logic (LTL) [Pnueli77].

However

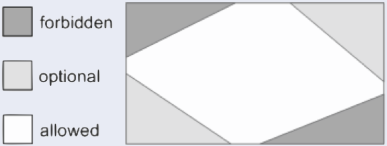
- Often, we interpret temporal logic on **finite trajectories/traces**.
- Often, we blur the distinction interpreting LTL on infinite or on finite traces.

Introduction and background

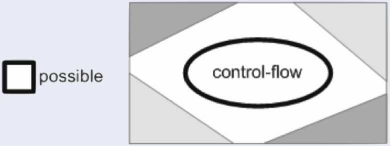
Also BPM (Business Process Management) advocates the use of LTL on finite traces.

Declarative Business Processes

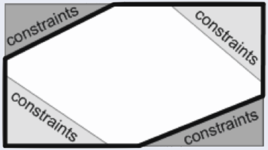
Basic idea: Drop explicit representation of processes, and use LTL **on finite traces** to specify allowed (finite) traces. [VanPesicBovsnavkiDraganVanDerAalst10].



(a) forbidden, optional and allowed in business processes



(b) procedural workflow



(c) declarative workflow

Introduction and background

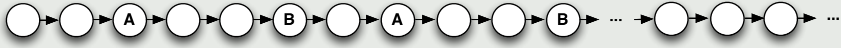
Assuming finite vs. infinite traces has big impact.

Example

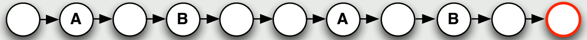
Consider the following formula:

$$\Box(A \supset \Diamond B)$$

- On infinite traces:



- On finite traces:



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Introduction and background

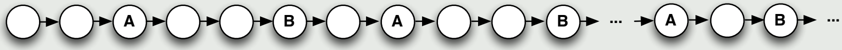
Assuming finite vs. infinite traces has big impact.

Example

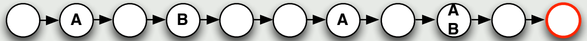
Consider the following formula:

$$\Box(A \supset \Diamond B) \wedge \Box(B \supset \Diamond A)$$

- On infinite traces:



- On finite traces:



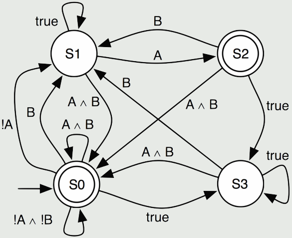
Introduction and background

Assuming finite or infinite traces has big impact.

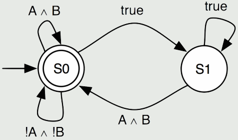
Example

Consider again the formula: $\Box(A \supset \Diamond B) \wedge \Box(B \supset \Diamond A)$

- Buchi automaton accepting its infinite traces:



- NFA accepting its finite traces:



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LTL$_f$: LTL over finite traces

LTL$_f$: the language

$$\varphi ::= A \mid \neg\varphi \mid \varphi_1 \wedge \varphi_2 \mid \circ\varphi \mid \varphi_1 \,\mathcal{U}\, \varphi_2$$

- A: atomic propositions
- $\neg\varphi$, $\varphi_1 \wedge \varphi_2$: boolean connectives
- $\circ\varphi$: "next step exists and at next step (of the trace) φ holds"
- $\varphi_1 \,\mathcal{U}\, \varphi_2$:"eventually φ_2 holds, and φ_1 holds until φ_2 does"
- $\bullet\varphi \doteq \neg\circ\neg\varphi$: "if next step exists then at next step φ holds" *(weak next)*
- $\Diamond\varphi \doteq \mathtt{true}\,\mathcal{U}\,\varphi$: "$\varphi$ will eventually hold"
- $\Box\varphi \doteq \neg\Diamond\neg\varphi$: "from current till last instant φ will always hold"
- $Last \doteq \neg\circ\mathtt{true}$: denotes last instant of trace.

Main formal properties:

- **Expressibility:** FOL over finite sequences or Star-free RE
- **Reasoning:** satisfiability, validity, entailment PSPACE-complete
- **Model Checking:** linear on TS, PSPACE-complete on formula

LTL_f: LTL over finite traces

Some interesting LTL_f formulas:

name of template	*LTL semantics*
$\mathit{responded\ existence}(A, B)$	$\Diamond A \Rightarrow \Diamond B$
$\mathit{co\text{-}existence}(A, B)$	$\Diamond A \Leftrightarrow \Diamond B$
$\mathit{response}(A, B)$	$\Box(A \Rightarrow \Diamond B)$
$\mathit{precedence}(A, B)$	$(\neg B\ U A) \vee \Box(\neg B)$
$\mathit{succession}(A, B)$	$\mathit{response}(A, B) \wedge \mathit{precedence}(A, B)$
$\mathit{alternate\ response}(A, B)$	$\Box(A \Rightarrow \bigcirc(\neg A\ U B))$
$\mathit{alternate\ precedence}(A, B)$	$\mathit{precedence}(A, B) \wedge \Box(B \Rightarrow \bigcirc(\mathit{precedence}(A, B)))$
$\mathit{alternate\ succession}(A, B)$	$\mathit{alternate\ response}(A, B) \wedge \mathit{alternate\ precedence}(A, B)$
$\mathit{chain\ response}(A, B)$	$\Box(A \Rightarrow \bigcirc B)$
$\mathit{chain\ precedence}(A, B)$	$\Box(\bigcirc B \Rightarrow A)$
$\mathit{chain\ succession}(A, B)$	$\Box(A \Leftrightarrow \bigcirc B)$

name of template	*LTL semantics*
$\mathit{not\ co\text{-}existence}(A, B)$	$\neg(\Diamond A \wedge \Diamond B)$
$\mathit{not\ succession}(A, B)$	$\Box(A \Rightarrow \neg(\Diamond B))$
$\mathit{not\ chain\ succession}(A, B)$	$\Box(A \Rightarrow \bigcirc(\neg B))$

name of template	*LTL semantics*
$\mathit{existence}(1, A)$ $\mathit{existence}(2, A)$ ... $\mathit{existence}(n, A)$	$\Diamond A$ $\Diamond(A \wedge \bigcirc(\mathit{existence}(1, A)))$ ... $\Diamond(A \wedge \bigcirc(\mathit{existence}(n-1, A)))$
$\mathit{absence}(A)$	$\neg \mathit{existence}(1, A)$
$\mathit{absence}(2, A)$ $\mathit{absence}(3, A)$ ... $\mathit{absence}(n+1, A)$	$\neg \mathit{existence}(2, A)$ $\neg \mathit{existence}(3, A)$ ... $\neg \mathit{existence}(n+1, A)$
$\mathit{init}(A)$	A

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LDL_f: LDL over finite traces

LDL_f: the language

$$\varphi ::= \phi \mid \neg\varphi \mid \varphi_1 \wedge \varphi_2 \mid \langle\rho\rangle\varphi \mid [\rho]\varphi \qquad \rho ::= \phi \mid \varphi? \mid \rho_1 + \rho_2 \mid \rho_1 ; \rho_2 \mid \rho^*$$

- ϕ: propositional formula on current state/instant
- $\neg\varphi$, $\varphi_1 \wedge \varphi_2$: boolean connectives
- ρ is a regular expression on propositional formulas
- $\langle\rho\rangle\varphi$: exists an "execution" of RE ρ that ends with φ holding
- $[\rho]\varphi$: all "executions" of RE ρ (along the trace!) end with φ holding

In the infinite trace setting, such enhancement strongly advocated by industrial model checking [ForSpec, PSL].

Main formal properties:

- **Expressibility:** MSO over finite sequences: adds the power of recursion (as RE)
- **Reasoning:** satisfiability, validity, entailment PSPACE-complete
- **Model Checking:** linear on TS, PSPACE-complete on formula

LDL_f: Linear Dynamic Logic on finite traces

Example

- All coffee requests from person p will eventually be served:

$$[\mathtt{true}^*](request_p \supset \langle \mathtt{true}^* \rangle coffee_p)$$

- Every time the robot opens door d it closes it immediately after:

$$[\mathtt{true}^*]([openDoor_d] closeDoor_d)$$

- Before entering restricted area a the robot must have permission for a:

$$\langle (\neg inArea_a{}^*; getPermission_a; \neg inArea_a{}^*; inArea_a)^*; \neg inArea_a{}^* \rangle end$$

Note that the first two properties (not the third one) can be expressed also in LTL_f:

$$\Box(request_p \supset \Diamond coffee_p) \qquad \Box(openDoor_d \supset \circ closeDoor_d)$$

LDL_f: Linear Dynamic Logic on finite traces

LDL_f, not LTL_f, is able to easily express procedural constraints [BaierFritzMcIlraith07].

Let's introduce a sort of propositional variant of GOLOG

$$\delta ::= A \mid \varphi? \mid \delta_1 + \delta_2 \mid \delta_1 ; \delta_2 \mid \delta^* \mid \textbf{if } \phi \textbf{ then } \delta_1 \textbf{ else } \delta_2 \mid \textbf{while } \phi \textbf{ do } \delta$$

where **if** and **while** can be seen as abbreviations for LDL_f path expression, namely:

$$\textbf{if } \phi \textbf{ then } \delta_1 \textbf{else } \delta_2 \doteq (\phi?; \delta_1) + (\neg\phi?; \delta_2) \qquad \textbf{while } \phi \textbf{ do } \delta \doteq (\phi?; \delta)^*; \neg\phi?$$

Example (LDL_f procedural constraints)

- "At every point, if it is hot then, if the air-conditioning system is off, turn it on, else don't turn it off":

$$[\texttt{true}^*]\langle \textbf{if } (\mathit{hot}) \textbf{ then } \textbf{if } (\neg \mathit{airOn}) \textbf{ then } \mathit{turnOnAir} \textbf{ else } \neg \mathit{turnOffAir} \rangle \mathit{true}$$

- "alternate till the end the following two instractions: (1) while is hot if the air-conditioning system is off turn it on, else don't turn it off; (2) do something for one step"

$$\langle (\textbf{while } (\mathit{hot}) \textbf{ do } \textbf{if } (\neg \mathit{airOn}) \textbf{ then } \mathit{turnOnAir} \textbf{ else } \neg \mathit{turnOffAir}; \texttt{true})^* \rangle \mathit{end}$$

LDL_f: Linear Dynamic Logic on finite traces

Example (LDL_f captures finite domain variant of GOLOG in SitCalc)

GOLOG – finite domain variant

$$\delta \quad ::= \quad A \mid \varphi? \mid \delta_1 + \delta_2 \mid \delta_1 ; \delta_2 \mid \delta^* \mid \pi x.\delta(x) \mid \textbf{if } \phi \textbf{ then } \delta_1 \textbf{else } \delta_2 \mid \textbf{while } \phi \textbf{do } \ \delta$$

- $\pi x.\delta(x)$ **stands for** $\Sigma_{o \in Obj}\ \delta(o)$
- **if** ϕ **then** δ_1**else** δ_2 stands for $(\phi?; \delta_1) + (\neg\phi?; \delta_2)$
- **while** ϕ **do** δ stands for $(\phi?; \delta)^* \neg\phi?$

- $\langle\delta\rangle\phi$ in LDL_f captures SitCalc formula $\exists s'.Do(\delta, s, s') \wedge s \leq s' \leq last \wedge \phi(s')$.
- $[\delta]\phi$ in LDL_f captures SitCalc formula $\forall s'.Do(\delta, s, s') \wedge s \leq s' \leq last \supset \phi(s')$.

($\phi(s)$ "uniform" in s.)

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$\mathrm{LTL}_f/\mathrm{LDL}$ and automata

Key point

$\mathrm{LTL}_f/\mathrm{LDL}_f$ formulas can be translated into nondeterministic finite state automata (NFA).

$$t \models \varphi \text{ iff } t \in \mathcal{L}(\mathcal{A}_\varphi)$$

where $\mathcal{A}_\varphi$ is the NFA φ is translated into.

We can compile reasoning into automata based procedures!

$\mathrm{LTL}_f/\mathrm{LDL}_f$ and automata

Both LTL_f and LDL_f formulas can be translated in exponential time to nondetermiistic automata on finite words (NFA).

NFA $\mathcal{A}_\varphi$ associated with an LTL_f formula φ (in NNF)

Auxiliary rules

$$
\begin{array}{rcl}
\delta(a, \Pi) & = & \texttt{true if } a \in \Pi \\
\delta(a, \Pi) & = & \texttt{false if } a \notin \Pi \\
\delta(\neg a, \Pi) & = & \texttt{false if } a \in \Pi \\
\delta(\neg a, \Pi) & = & \texttt{true if } a \notin \Pi \\
\delta(\varphi_1 \wedge \varphi_2, \Pi) & = & \delta(\varphi_1, \Pi) \wedge \delta(\varphi_2, \Pi) \\
\delta(\varphi_1 \vee \varphi_2, \Pi) & = & \delta(\varphi_1, \Pi) \vee \delta(\varphi_2, \Pi) \\
\delta(\bigcirc \varphi, \Pi) & = & \begin{cases} \varphi & \text{if } Last \notin \Pi \\ \texttt{false} & \text{if } Last \in \Pi \end{cases} \\
\delta(\Diamond \varphi, \Pi) & = & \delta(\varphi, \Pi) \vee \delta(\bigcirc \Diamond \varphi, \Pi) \\
\delta(\varphi_1 \,\mathcal{U}\, \varphi_2, \Pi) & = & \delta(\varphi_2, \Pi) \vee \\
 & & (\delta(\varphi_1, \Pi) \wedge \delta(\bigcirc(\varphi_1 \,\mathcal{U}\, \varphi_2), \Pi)) \\
\delta(\bullet \varphi, \Pi) & = & \begin{cases} \varphi & \text{if } Last \notin \Pi \\ \texttt{true} & \text{if } Last \in \Pi \end{cases} \\
\delta(\Box \varphi, \Pi) & = & \delta(\varphi, \Pi) \wedge \delta(\bullet \Box \varphi, \Pi) \\
\delta(\varphi_1 \,\mathcal{R}\, \varphi_2, \Pi) & = & \delta(\varphi_2, \Pi) \wedge (\delta(\varphi_1, \Pi) \vee \\
 & & \delta(\bullet(\varphi_1 \,\mathcal{R}\, \varphi_2), \Pi))
\end{array}
$$

($\varepsilon(\varphi)$ replaces in φ all occurrences of tt_ψ and ff_ψ by $\varepsilon(\psi)$)

Algorithm

algorithm LDL_f2NFA
input LTL_f formula φ
output NFA $A_\varphi = (2^{\mathcal{P}}, \mathcal{S}, \{s_0\}, \varrho, \{s_f\})$
$s_0 \leftarrow \{\varphi\}$ ▷ single initial state
$s_f \leftarrow \emptyset$ ▷ single final state
$\mathcal{S} \leftarrow \{s_0, s_f\}$, $\varrho \leftarrow \emptyset$
while ($\mathcal{S}$ or ϱ change) **do**

  if($q \in \mathcal{S}$ and $q' \models \bigwedge_{(\psi \in q)} \delta(\psi, \Pi)$)
    $\mathcal{S} \leftarrow \mathcal{S} \cup \{q'\}$ ▷ update set of states
    $\varrho \leftarrow \varrho \cup \{(q, \Pi, q')\}$ ▷ update transition relation

LTL$_f$/LDL$_f$ and automata

NFA $\mathcal{A}_\varphi$ associated with an LDL$_f$ formula φ (in NNF)

Auxiliary rules

$$
\begin{array}{lcl}
\delta(A,\Pi) & = & \texttt{true} \text{ if } A \in \Pi \\
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\delta(\langle\phi\rangle\varphi,\Pi) & = & \left\{\begin{array}{ll} \texttt{false} & \text{if } \Pi \not\models \phi \text{ or } \mathit{Last} \in \Pi \\ \varepsilon(\varphi) & \text{o/w} \quad (\phi \text{ propositional}) \end{array}\right. \\
\delta(\langle\psi?\rangle\varphi,\Pi) & = & \delta(\psi,\Pi) \wedge \delta(\varphi,\Pi) \\
\delta(\langle\rho_1+\rho_2\rangle\varphi,\Pi) & = & \delta(\langle\rho_1\rangle\varphi,\Pi) \vee \delta(\langle\rho_2\rangle\varphi,\Pi) \\
\delta(\langle\rho_1;\rho_2\rangle\varphi,\Pi) & = & \delta(\langle\rho_1\rangle\langle\rho_2\rangle\varphi,\Pi) \\
\delta(\langle\rho^*\rangle\varphi,\Pi) & = & \delta(\varphi,\Pi) \vee \delta(\langle\rho\rangle \textit{ff}_{\langle\rho^*\rangle\varphi},\Pi) \\
\delta([\phi]\varphi,\Pi) & = & \left\{\begin{array}{ll} \texttt{true} & \text{if } \Pi \not\models \phi \text{ or } \mathit{Last} \in \Pi \\ \varepsilon(\varphi) & \text{o/w} \quad (\phi \text{ propositional}) \end{array}\right. \\
\delta([\psi?]\varphi,\Pi) & = & \delta(\mathit{nnf}(\neg\psi),\Pi) \vee \delta(\varphi,\Pi) \\
\delta([\rho_1+\rho_2]\varphi,\Pi) & = & \delta([\rho_1]\varphi,\Pi) \wedge \delta([\rho_2]\varphi,\Pi) \\
\delta([\rho_1;\rho_2]\varphi,\Pi) & = & \delta([\rho_1][\rho_2]\varphi,\Pi) \\
\delta([\rho^*]\varphi,\Pi) & = & \delta(\varphi,\Pi) \wedge \delta([\rho] \textit{tt}_{[\rho^*]\varphi},\Pi) \\
\delta(\textit{ff}_\psi,\Pi) & = & \texttt{false} \\
\delta(\textit{tt}_\psi,\Pi) & = & \texttt{true}
\end{array}
$$

($\varepsilon(\varphi)$ replaces in φ all occurrences of $\textit{tt}_\psi$ and $\textit{ff}_\psi$ by $\varepsilon(\psi)$)

Algorithm

algorithm LDL$_f$2NFA
input LTL$_f$ formula φ
output NFA $A_\varphi = (2^{\mathcal{P}}, \mathcal{S}, \{s_0\}, \varrho, \{s_f\})$
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    $\varrho \leftarrow \varrho \cup \{(q,\Pi,q')\}$ ▷ update transition relation

$\text{LTL}_f/\text{LDL}_f$ reasoning

$\text{LTL}_f/\text{LDL}_f$ satisfiability (φ SAT)

1: Given $\text{LTL}_f/\text{LDL}_f$ formula φ
2: Compute NFA for φ *(exponential)*
3: Check NFA for nonemptiness *(NLOGSPACE)*
4: Return result of check

$\text{LTL}_f/\text{LDL}_f$ validity (φ VAL)

1: Given $\text{LTL}_f/\text{LDL}_f$ formula φ
2: Compute NFA for $\neg\varphi$ *(exponential)*
3: Check NFA for nonemptiness *(NLOGSPACE)*
4: Return complemented result of check

$\text{LTL}_f/\text{LDL}_f$ logical implication ($\Gamma \models \varphi$)

1: Given $\text{LTL}_f/\text{LDL}_f$ formulas Γ and φ
2: Compute NFA for $\Gamma \wedge \neg\varphi$ *(exponential)*
3: Check NFA for nonemptiness *(NLOGSPACE)*
4: Return complemented result of check

Thm:[IJCAI13] All above reasoning tasks are PSPACE-complete. *(As for infinite traces.)*
(Construction of NFA can be done while checking nonemptiness.)

Relationship to Classical Planning

Let Ψ_{domain} describe action domain (LTL_f formula), ϕ_{init} initial state (prop. formula), and G goal (prop. formula). Classical planning amounts to LTL_f satisfiability of:

$$\phi_{init} \wedge \Psi_{domain} \ \wedge \ \Diamond G$$

Complexity: PSPACE-complete.

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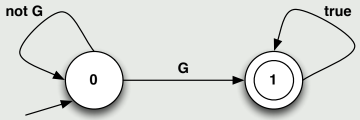
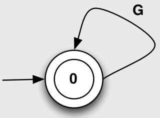
Automata for some LTL_f formulas

Example (Automata for some LTL_f formulas)

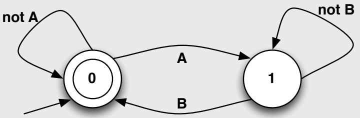
- $\Diamond G$:



- $\Box G$



- $\Box(A \supset \circ\Diamond B)$



Observe all of these automata are DFAs!

Outline

Planning in deterministic domain

Deterministic domain (including initial state)

$\mathcal{D} = (2^{\mathcal{F}}, \mathcal{A}, s_0, \delta, \alpha)$ where:

- $\mathcal{F}$ **fluents** (atomic propositions)
- $\mathcal{A}$ **actions** (atomic symbols)
- $2^{\mathcal{F}}$ set of states
- s_0 initial state (initial assignment to fluents)
- $\alpha(s) \subseteq \mathcal{A}$ represents **action preconditions**
- $\delta(s, a) = s'$ with $a \in \alpha(s)$ represents **action effects (including frame)**.

Traces

A **trace** for $\mathcal{D}$ is a finite sequence:

$$s_0, a_1, s_1, \cdots, a_n, s_n$$

where s_0 is the initial state, and $a_i \in \alpha(s_i)$ and $s_{i+1} = \delta(s_i, a_{i+1})$ for each i.

Goals, planning, and plans

Goal $=$ propositional formula G on fluents
Planning $=$ find a trace $s_0, a_1, s_1, \cdots, a_n, s_n$ such that $s_n \models G$. (PSPACE-complete)
Plan $=$ project traces on actions, i.e., return $a_1, \cdots, a_n$.

Deterministic planning domains as automata

Let's transform the planning domain $\mathcal{D} = (2^{\mathcal{F}}, \mathcal{A}, s_0, \delta, \alpha)$ into a DFA recognizing all its traces.

DFA A_D for $\mathcal{D}$

$A_{\mathcal{D}} = (2^{\mathcal{F} \cup \mathcal{A}}, (2^{\mathcal{F}} \cup \{s_{init}\}), s_{init}, \varrho, F)$ where:

- $2^{\mathcal{F} \cup \mathcal{A}}$ alphabet (actions $\mathcal{A}$ include dummy *start* action)
- $2^{\mathcal{F}} \cup \{s_{init}\}$ set of states
- s_{init} dummy initial state
- $F = 2^{\mathcal{F}}$ (all states of the domain are final)
- $\rho(s, [a, s']) = s'$ **with** $a \in \alpha(s)$, **and** $\delta(s, a) = s'$
  $\rho(s_{init}, [start, s_0]) = s_0$

(notation: $[a, s']$ stands for $\{a\} \cup s'$)

Traces

Each trace $s_0, a_1, s_1, \cdots, a_n, s_n$ of the domain $\mathcal{D}$ becomes a finite sequence:

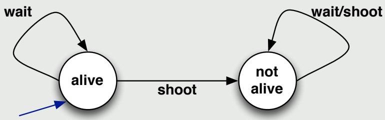
$$[start, s_0], [a_1, s_1], \cdots, [a_n, s_n]$$

recognized by the DFA $A_{\mathcal{D}}$.

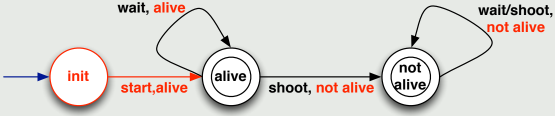
Deterministic planning domains as automata

Example (Simplified Yale shooting domain)

- Domain $\mathcal{D}$:



- DFA $A_{\mathcal{D}}$:



Deterministic planning domains as automata

Planning in deterministic domains

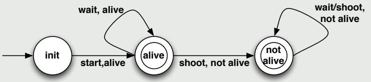
Planning = find a trace of DFA $A_{\mathcal{D}}$ for deterministic domain $\mathcal{D}$ such that is also a trace for the DFA for $\Diamond G$ where G is the goal. That is:

CHECK for nonemptiness $A_{\mathcal{D}} \cap A_{\Diamond G}$*: extract plan from witness.*

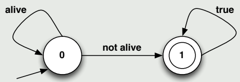
(Computable on-the-fly, PSPACE in $\mathcal{D}$, constant in G. i.e., optimal)

Example (Simplified Yale shooting domain)

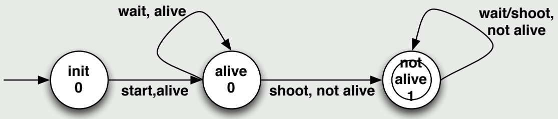
$A_{\mathcal{D}}$



$A_{\Diamond \neg alive}$



$A_{\mathcal{D}} \cap A_{\Diamond G}$:



Generalization: planning for $\text{LTL}_f/\text{LDL}_f$ goals in deterministic domains

Planning in deterministic domains for $\text{LTL}_f/\text{LDL}_f$ goals

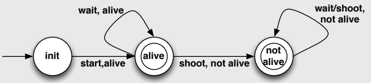
Planning = find a trace of DFA $A_{\mathcal{D}}$ for deterministic domain $\mathcal{D}$ such that is also a accepted by NFA A_φ for the $\text{LTL}_f/\text{LDL}_f$ formula φ. That is:

CHECK for nonemptiness $A_{\mathcal{D}} \cap A_\varphi$: extract plan from witness.

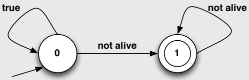
(Computable on-the-fly, PSPACE in $\mathcal{D}$, PSPACE also in φ i.e., optimal)
(We can use NFA directly since we are checking for ***existence*** *of a trace satisfying φ)*

Example (Simplified Yale shooting domain)

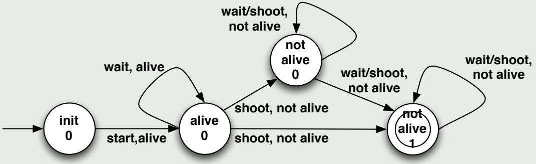
$A_{\mathcal{D}}$



$A_{\Diamond\Box\neg alive}$



$A_{\mathcal{D}} \cap A_{\Diamond\Box\neg alive}$:



Generalization: planning for $\mathrm{LTL}_f/\mathrm{LDL}_f$ goals in deterministic domains

Planning for $\mathrm{LTL}_f/\mathrm{LDL}_f$ goals

Algorithm: Planning for $\mathrm{LDL}_f/\mathrm{LTL}_f$ goals

1: Given $\mathrm{LTL}_f/\mathrm{LDL}_f$ domain $\mathcal{D}$ and goal φ
2: Compute corresponding NFA (exponential)
3: Compute intersection with DFA of $\mathcal{D}$ (polynomial)
5: Check nonemptiness of resulting NFA (NLOGSPACE)
6: Return plan

Theorem

Planning for $\mathrm{LTL}_f/\mathrm{LDL}_f$ goals is:

- *PSPACE-complete in the domain;*
- *PSPACE-complete in the goal.*

Outline

FOND_{sp}: strong planning in nondeterministic domains

Nondeterministic domain (including initial state)

$\mathcal{D} = (2^{\mathcal{F}}, \mathcal{A}, s_0, \delta, \alpha)$ where:

- $\mathcal{F}$ **fluents** (atomic propositions)
- $\mathcal{A}$ **actions** (atomic symbols)
- $2^{\mathcal{F}}$ set of states
- s_0 initial state (initial assignment to fluents)
- $\alpha(s) \subseteq \mathcal{A}$ represents **action preconditions**
- $\delta(s, a, s')$ with $a \in \alpha(s)$ represents **action effects (including frame)**.

Who controls what?

Fluents controlled by **environment**

Actions controlled by **agent**

Observe: $\delta(s, a, s')$

Goals, planning, and plans

Goal = propositional formula G on fluents
Planning = **game** between two players:

> **agent** *tries to force eventually reaching* G *no matter how other* **environment** *behave.*

Plan = **strategy** to **win** the game.

(FOND_{sp} *is EXPTIME-complete*)

Nondeterministic domains as automata

Let's transform the nondeterministic domain $\mathcal{D} = (2^{\mathcal{F}}, \mathcal{A}, s_0, \delta, \alpha)$ into an automaton recognizing all its traces.

Automaton A_D for $\mathcal{D}$ is a DFA!!!

$A_{\mathcal{D}} = (2^{\mathcal{F} \cup \mathcal{A}}, (2^{\mathcal{F}} \cup \{s_{init}\}), s_{init}, \varrho, F)$ where:

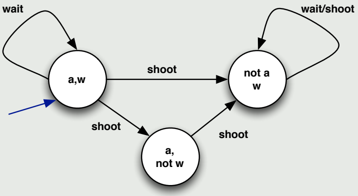
- $2^{\mathcal{F} \cup \mathcal{A}}$ alphabet (actions $\mathcal{A}$ include dummy $start$ action)
- $2^{\mathcal{F}} \cup \{s_{init}\}$ set of states
- s_{init} dummy initial state
- $F = 2^{\mathcal{F}}$ (all states of the domain are final)
- $\rho(s, [a, s']) = s'$ **with** $a \in \alpha(s)$**, and** $\delta(s, a, s')$
  $\rho(s_{init}, [start, s_0]) = s_0$

(notation: $[a, s']$ stands for $\{a\} \cup s'$)

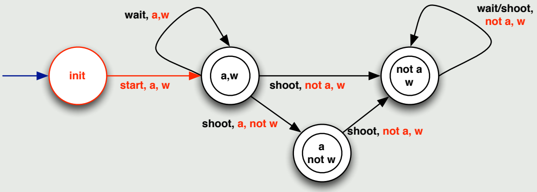
Nondeterministic domains as automata

Example (Simplified Yale shooting domain variant)

- Domain $\mathcal{D}$:



- DFA $A_{\mathcal{D}}$:



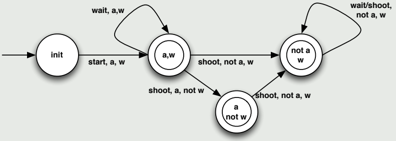
Nondeterministic domains as automata

FOND_{sp}: strong planning in nondeterministic domains

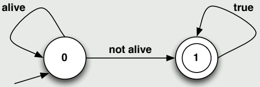
- Set the **arena** formed by all traces that satisfy both the DFA $A_{\mathcal{D}}$ for $\mathcal{D}$ and the DFA for $\Diamond G$ where G is the goal.
- Compute a **winning strategy**. *(EXPTIME-complete in $\mathcal{D}$, constant in G)*

Example (Simplified Yale shooting domain)

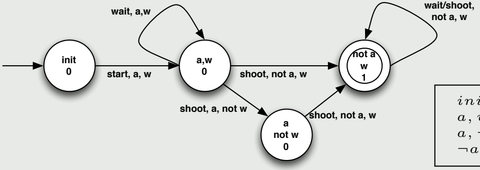
$A_{\mathcal{D}}$



$A_{\Diamond\neg a}$



$A_{\mathcal{D}} \cap A_{\Diamond\neg a}$:

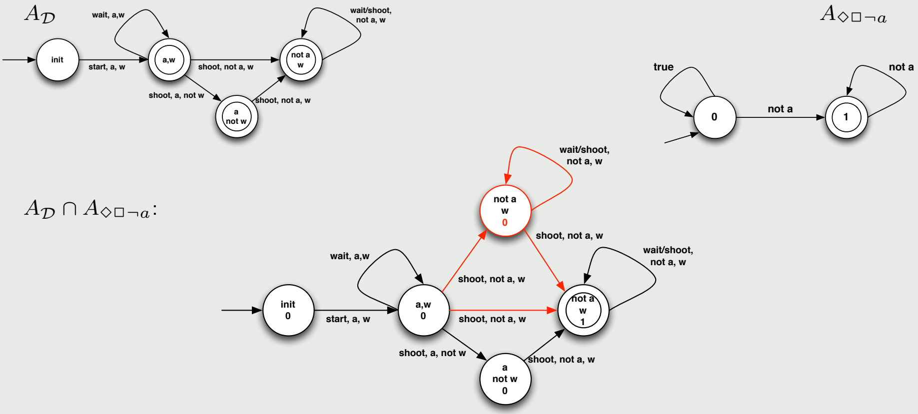


strategy

$init, 0$	$\rightarrow$	$start$
$a, w, 0$	$\rightarrow$	$shoot$
$a, \neg w, 0$	$\rightarrow$	$shoot$
$\neg a, w, 1$	$\rightarrow$	`win!`

Generalization: FOND_{sp} for $\text{LTL}_f/\text{LDL}_f$ goals

Example (Simplified Yale shooting domain)



Can we use directly NFA's?

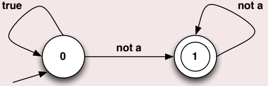
No, because of a basic mismatch

- NFA have perfect **foresight**, or **clairvoyance** *(angelic nondeterminism)*
- Strategies must be runnable: **depend only on past**, not future *(devilish nondeterminism)*

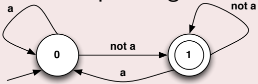
Generalization: FOND_{sp} for $\mathrm{LTL}_f/\mathrm{LDL}_f$ goals

We need first to determinize the NFA for $\mathrm{LTL}_f/\mathrm{LDL}_f$ formula

NFA for $\Diamond\Box\neg a$



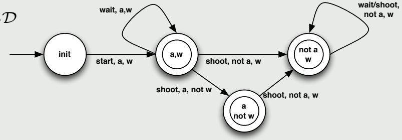
corresponding DFA



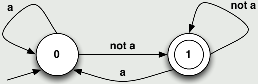
(DFA can be exponential in NFA in general)

Example (Simplified Yale shooting domain)

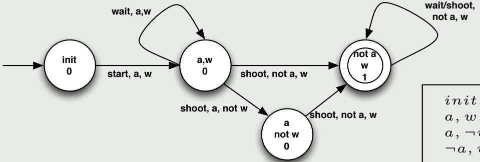
$A_{\mathcal{D}}$



$A_{\Diamond\Box\neg a}$



$A_{\mathcal{D}} \cap A_{\Diamond\Box\neg a}$:



strategy

$init, 0$	$\rightarrow$	$start$
$a, w, 0$	$\rightarrow$	$shoot$
$a, \neg w, 0$	$\rightarrow$	$shoot$
$\neg a, w, 1$	$\rightarrow$	win!

Generalization: DFA Games

DFA games

A DFA **game** $\mathcal{G} = (2^{\mathcal{F}\cup\mathcal{A}}, S, s_{init}, \varrho, F)$, is such that:

- $\mathcal{F}$ controlled by environment; $\mathcal{A}$ controlled by agent;
- $2^{\mathcal{F}\cup\mathcal{A}}$, alphabet of game;
- S, states of game;
- s_{init}, initial state of game;
- $\varrho : S \times 2^{\mathcal{F}\cup\mathcal{A}} \to S$, transition function of the game: given current state s and a choice of action a and resulting fluents values E the resulting state of game is $\varrho(s, [a, E]) = s'$;
- F, final states of game, where game can be considered terminated.

Winning Strategy:

- A play is **winning** for the agent if such a play leads from the initial to a final state.
- A **strategy** for the agent is a function $f : (2^{\mathcal{F}})^* \to \mathcal{A}$ that, given a **history of choices from the environment**, decides which action $\mathcal{A}$ to do next.
- A **winning strategy** is a strategy $f : (2^{\mathcal{F}})^* \to \mathcal{A}$ such that for all traces π with $a_i = f(\pi_{\mathcal{F}}|_i)$ we have that π leads to a final state of $\mathcal{G}$.

Generalization: DFA Games

Winning condition for DFA games

Let

$$PreC(\mathcal{S}) = \{s \in S \mid \exists a \in \mathcal{A}. \forall E \in 2^{\mathcal{F}}. \varrho(s, [a, E]) \in \mathcal{S}\}$$

Compute the set Win of winning states of a DFA game $\mathcal{G}$, i.e., states from which the agent can win the game $\mathcal{G}$, by **least-fixpoint**:

- $Win_0 = F$ (the final states of $\mathcal{G}$)
- $Win_{i+1} = Win_i \cup PreC(Win_i)$
- $Win = \bigcup_i Win_i$

(Computing Win is linear in the number of states in $\mathcal{G}$)

Computing the winning strategy

Let's define $\omega : S \to 2^{\mathcal{A}}$ as:

$$\omega(s) = \{a \mid \text{ if } s \in Win_{i+1} - Win_i \text{ then } \forall E. \varrho(s, [a, E]) \in Win_i\}$$

- **Every way** of restricting $\omega(s)$ to return only one action (chosen arbitrarily) gives a **winning strategy** for $\mathcal{G}$.
- Note s **is a state of the game**! not of the domain only!
  To phrase ω wrt the domain only, we need to return a **stateful transducer** with transitions from the game.

Generalization: FOND_{sp} for $\text{LTL}_f/\text{LDL}_f$ goals

FOND_{sp} for $\text{LTL}_f/\text{LDL}_f$ goals

Algorithm: FOND_{sp} for $\text{LDL}_f/\text{LTL}_f$ goals

1: Given $\text{LTL}_f/\text{LDL}_f$ domain $\mathcal{D}$ and goal φ
2: Compute NFA for φ (exponential)
3: Determinize NFA to DFA (exponential)
4: Compute intersection with DFA of $\mathcal{D}$ (polynomial)
5: Synthesize winning strategy for DFA game (linear)
6: Return strategy

Theorem

FOND_{sp} *for* $\text{LTL}_f/\text{LDL}_f$ *goals is:*

- *EXPTIME-complete in the domain;*
- *2-EXPTIME-complete in the goal.*

Outline

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FOND$_{sc}$: strong cyclic planning in nondeterministic domains

Nondeterministic domain (including initial state)

$\mathcal{D} = (2^{\mathcal{F}}, \mathcal{A}, s_0, \delta, \alpha)$ where:

- $\mathcal{F}$ **fluents** (atomic propositions)
- $\mathcal{A}$ **actions** (atomic symbols)
- $2^{\mathcal{F}}$ set of states
- s_0 initial state (initial assignment to fluents)
- $\alpha(s) \subseteq \mathcal{A}$ represents **action preconditions**
- $\delta(s, a, s')$ with $a \in \alpha(s)$ represents **action effects (including frame)**.

Who controls what?

Fluents controlled by **environment**, though under **fairness assumption**:

(i.e., all effects will eventually happen)

Actions controlled by **agent**

Observe: $\delta(s, a, s')$

Goals, planning, and plans

Goal = propositional formula G on fluents
Planning = **agent**, in spite of the **environment**, stays in an area from where is possible to reach G

(with the cooperation of **environment***! it is not a pure adversarial game!)*

Plan = **strategy** to stay within the good area.

(FOND$_{sc}$ is EXPTIME-complete)

Nondeterministic domains as automata

Let's transform the nondeterministic domain $\mathcal{D} = (2^{\mathcal{F}}, \mathcal{A}, s_0, \delta, \alpha)$ into an automaton recognizing all its traces as before.

Automaton A_D for $\mathcal{D}$ is a DFA!!!

$A_{\mathcal{D}} = (2^{\mathcal{F} \cup \mathcal{A}}, (2^{\mathcal{F}} \cup \{s_{init}\}), s_{init}, \varrho, F)$ where:

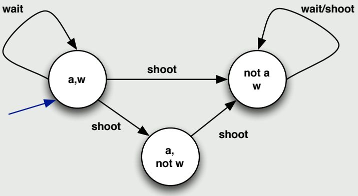
- $2^{\mathcal{F} \cup \mathcal{A}}$ alphabet (actions $\mathcal{A}$ include dummy $start$ action)
- $2^{\mathcal{F}} \cup \{s_{init}\}$ set of states
- s_{init} dummy initial state
- $F = 2^{\mathcal{F}}$ (all states of the domain are final)
- $\rho(s, [a, s']) = s'$ **with** $a \in \alpha(s)$**, and** $\delta(s, a, s')$
  $\rho(s_{init}, [start, s_0]) = s_0$

(notation: $[a, s']$ stands for $\{a\} \cup s'$)

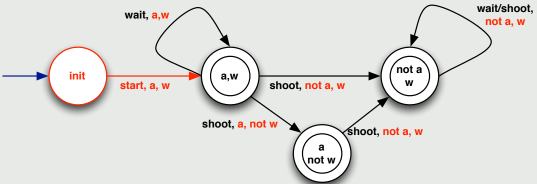
Nondeterministic domains as automata

Example (Simplified Yale shooting domain variant)

- Domain $\mathcal{D}$:



- DFA $A_{\mathcal{D}}$:



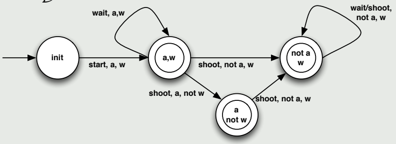
Nondeterministic domains as automata

FOND_{sc}: strong cyclic planning in nondeterministic domains

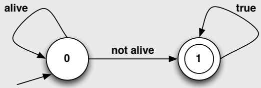
- Set the **arena** formed by all traces that satisfy both the DFA $A_{\mathcal{D}}$ for $\mathcal{D}$ and the DFA for $\Diamond G$ where G is the goal.
- Compute a **winning strategy**. *(EXPTIME-complete in $\mathcal{D}$, constant in G)*

Example (Simplified Yale shooting domain)

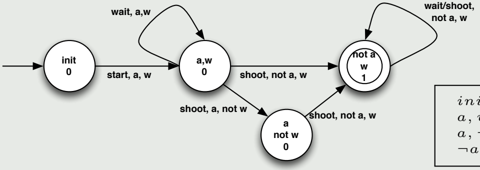
$A_{\mathcal{D}}$



$A_{\Diamond\neg a}$



$A_{\mathcal{D}} \cap A_{\Diamond\neg a}$:



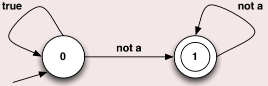
strategy

$init, 0$	$\rightarrow$	$start$
$a, w, 0$	$\rightarrow$	$shoot$
$a, \neg w, 0$	$\rightarrow$	$shoot$
$\neg a, w, 1$	$\rightarrow$	win!

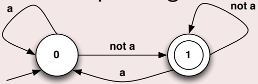
Generalization: FOND_{sc} for $\text{LTL}_f/\text{LDL}_f$ goals

We need first to determinize the NFA for $\text{LTL}_f/\text{LDL}_f$ formula

NFA for $\Diamond\Box\neg a$



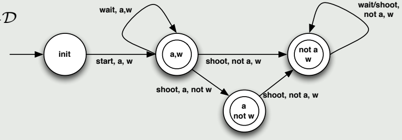
corresponding DFA



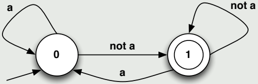
(DFA can be exponential in NFA in general)

Example (Simplified Yale shooting domain)

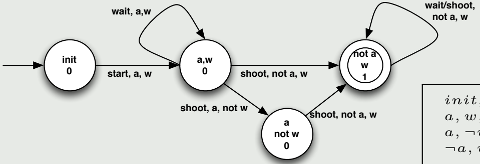
$A_{\mathcal{D}}$



$A_{\Diamond\Box\neg a}$



$A_{\mathcal{D}} \cap A_{\Diamond\Box\neg a}$:



strategy

$init, 0$	$\rightarrow$	$start$
$a, w, 0$	$\rightarrow$	$shoot$
$a, \neg w, 0$	$\rightarrow$	$shoot$
$\neg a, w, 1$	$\rightarrow$	win!

Generalization: Fair DFA Games

Fair DFA games

A **fair** DFA **game** $\mathcal{G} = (2^{\mathcal{F}\cup\mathcal{A}}, S, s_{init}, \varrho, F)$, is such that:

- $\mathcal{F}$ controlled by environment; $\mathcal{A}$ controlled by agent;
- $2^{\mathcal{F}\cup\mathcal{A}}$, alphabet of game;
- S, states of game;
- s_{init}, initial state of game;
- $\varrho : S \times 2^{\mathcal{F}\cup\mathcal{A}} \to S$, transition relation of the game: given current state s and a choice of action a and resulting fluents values E the resulting state of game is $s' = \varrho(s, [a, E])$;
- F, final states of game, where game can be considered terminated.

Winning Strategy:

- A play is **winning** for the agent if from the initial the agent can force to remain in a safe area from which is possible to cooperatively reach the final state.
- A **strategy** for the agent is a function $f : (2^{\mathcal{F}})^* \to \mathcal{A}$ that, given a **history of choices from the environment**, decides which action $\mathcal{A}$ to do next.
- A **winning strategy** is a strategy $f : (2^{\mathcal{F}})^* \to \mathcal{A}$ such that all traces π with $a_i = f(\pi_{\mathcal{F}}|_i)$ are winning for the agent.

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Generalization: Fair DFA Games

Existential and universal preimages wrt the environament

$$\begin{array}{rcl} PreE(a,\mathcal{S}) & = & \{s \in S \mid a \in \mathcal{A}. \exists E \in 2^{\mathcal{F}}. \varrho(s,[a,E]) \in \mathcal{S}\} \\ PreA(a,\mathcal{S}) & = & \{s \in S \mid a \in \mathcal{A}. \forall E \in 2^{\mathcal{F}}. \varrho(s,[a,E]) \in \mathcal{S}\} \end{array}$$

Agent forces that always agent reach a final state if environment cooperates

The winning condition of the game is defined by two nested fixpoints, a **greatest-fixpoint** (for safety) and **least fixpoint** (for reachability):

$$Safe = \nu X.\mu Y.F \cup \bigcup_{a \in \mathcal{A}} (PreA(a,X) \cap PreE(a,Y))$$

This gives rise to the following nested fixpoint computation:

- $X_0 = S$ (all states of $\mathcal{G}$)
- $X_{i+1} = Y_{i+1} = \mu Y.F \cup \bigcup_{a \in \mathcal{A}} (PreA(a,X_i) \cap PreE(a,Y))$
- $Safe = \bigcap_i X_i$

where $\mu Y.F \cup \bigcup_{a \in \mathcal{A}} (PreA(a,X_i) \cap PreE(a,Y))$ is computed as

- $Y_{i,0} = F$ (the final states of $\mathcal{G}$)
- $Y_{i,j+1} = F \cup \bigcup_{a \in \mathcal{A}} (PreA(a,X_i) \cap PreE(a,Y_{i,j}))$
- $Y_i = \bigcup_i Y_{i,j}$

(Computing each Y_i is linear in the number of states in $\mathcal{G}$, hence computing $Safe$ is quadratic.)

Generalization: Fair DFA Games

Computing the winning strategy

We can stratify $Safe$ according to when a state enters the least fixpoint:

- $Reach_1 = F$,
- $Reach_{j+1} = Reach_j \cup PreA(a, Safe) \cap PreE(a, Reach_j)$.

Note that $Safe = \cup_{j \leq |S|} Reach_j$.
Let's define $\omega : S \to 2^{\mathcal{A}}$ as:

$$\omega(s) = \{a \mid \text{ if } s \in Reach_{j+1} - Reach_j \text{ then } \exists E.\varrho(s, [a, E]) \in Reach_j\}$$

- **Every way** of restricting $\omega(s)$ to return only one action (chosen arbitrarily) gives a **winning strategy** for $\mathcal{G}$.
- Note s **is a state of the game**! not of the domain only!
To phrase ω wrt the domain only, we need to return a **stateful transducer** with transitions from the game.

Generalization: FOND_{sc} for $\text{LTL}_f/\text{LDL}_f$ goals

FOND_{sc} for $\text{LTL}_f/\text{LDL}_f$ goals

Algorithm: FOND_{sc} for $\text{LDL}_f/\text{LTL}_f$ goals

1: Given $\text{LTL}_f/\text{LDL}_f$ domain $\mathcal{D}$ and goal φ
2: Compute NFA for φ (exponential)
3: Determinize NFA to DFA (exponential)
4: Compute intersection with DFA of $\mathcal{D}$ (polynomial)
5: Synthesize winning strategy for resulting fairDFA game (quadratic)
6: Return strategy

Theorem

FOND_{sc} *for* $\text{LTL}_f/\text{LDL}_f$ *goals is:*

- *EXPTIME-complete in the domain;*
- *2-EXPTIME-complete in the goal.*

Outline

POND_{sp}: strong planning in nondeter. domain with partial observability

Nondeterministic partially observable domain (including initial state)

$\mathcal{D} = (2^{\mathcal{F}}, \mathcal{A}, Obs, s_0, \delta, \alpha, obs)$ where:

- $\mathcal{F}$ **fluents** (atomic propositions)
- $Obs \subseteq \mathcal{F}$ **observable fluents**
- $\mathcal{A}$ **actions** (atomic symbols)
- $2^{\mathcal{F}}$ set of states
- s_0 initial state (initial assignment to fluents)
- $\alpha(s) \subseteq \mathcal{A}$ represents **action preconditions**
- $\delta(s, a, s')$ with $a \in \alpha(s)$ represents **action effects (including frame)**
- $obs(s) \subseteq Obs$ project s on the **observable fluents only**.

Goals, planning, and plans

Goal = propositional formula G on fluents
Planning = **game** between two players:

> **agent** *tries to force eventually reaching G no matter how other* **environment** *behave and in spite of seeing only observable fluents.*

Plan = **strategy** (depending on observable fluens only) to **win** the game.

> *Strategies $f : (2^{Obs})^* \to \mathcal{A}$ such that for all generated traces π with E_i compatible with observations O_i and $a_i = f(\pi_{Obs}|_i)$, we have that π satisfies eventually $\mathcal{G}$.*

(POND, strong plans, 2-EXPTIME-complete)

Does Belief-State Construction for POND_{sp} work for $\mathrm{LTL}_f/\mathrm{LDL}_f$? Yes ...

Belief-states DFA game

Given a DFA game $\mathcal{A} = (2^{\mathcal{F}\cup\mathcal{A}}, S, s_{init}, \varrho, F)$ the associated **belief-states** DFA **game** is the following DFA game: $\mathcal{G}_A^{Obs} = (2^{\mathcal{F}\cup\mathcal{A}}, \mathcal{B}, B_{init}, \partial, \mathcal{F})$, where:

- $2^{\mathcal{F}\cup\mathcal{A}}$ is the alphabet which is the same of the original game;
- $\mathcal{B} = 2^S$ are the **belief states**, corresponding to sets of the states of the original game;
- $B_{init} = \{s_{init}\}$ is the initial belief-state, formed by initial state of the original game;
- $\partial : \mathcal{B} \times 2^{\mathcal{F}\cup\mathcal{A}} \to \mathcal{B}$ is the transition function: given the current belief-state B and a choice of action a and propositions E, respectively for the agent and the enviroment:

$$\partial(B, [a, E]) = \{s' \mid \exists s, E'.s \in B \wedge obs(E') = obs(E) \wedge \delta(s, [a, E]) = s'\}$$

- $\mathcal{F} = 2^F$ are the final belief-states, formed only by final states of the original game.

*NB: **belief-states** DFA **game** $\mathcal{G}_A^{Obs}$ is itself a DFA game (with full observability) over the $\mathcal{F}$ and $\mathcal{A}$.*

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… Belief-State Construction is 3EXPTIME in the goal!

Belief-State Algorithm for POND_{sp} for $\mathrm{LDL}_f/\mathrm{LTL}_f$ goals

1: Given domain $\mathcal{D}$ and $\mathrm{LTL}_f/\mathrm{LDL}_f$ formula φ
2: Compute NFA for φ (exponential)
3: Determinize NFA to DFA (exponential)
4: Compute intersection with DFA of $\mathcal{D}$ (polynomial)
5: Compute the belief-state DFA game (exponential)
6: Synthesize winning strategy for resulting DFA game (linear)
7: Return strategy

Cost is 2-EXPTIME in $\mathcal{D}$ and 3-EXPTIME in φ!

Can we do better? **YES!**

Projection-based Construction

POND_{sp} for $\text{LTL}_f/\text{LDL}_f$ goals

Projection-based Algorithm for POND_{sp} for $\text{LDL}_f/\text{LTL}_f$ goals

1: Given domain $\mathcal{D}$ and $\text{LTL}_f/\text{LDL}_f$ formula φ
2: Compute NFA for $\neg\varphi$ (exponential)
4: Compute NFA for union with complement of DFA for $\mathcal{D}$ (polynomial)
3: Project out unobservable props, getting NFA $\overline{A}$ (linear)
(behaves existentially on unobservables)
4: Complement NFA $\overline{A}$ getting DFA A (exponential)
(behaves universally on unobservables)
5: Synthesize winning strategy for resulting DFA game A (linear)
6: Return strategy

(Inspired by [DeGiacomoVardi-IJCAI16])

Theorem

POND_{sp} *for* $\text{LTL}_f/\text{LDL}_f$ *goals is:*

- *2-EXPTIME-complete in the domain;*
- *2-EXPTIME-complete in the goal.*

Outline

What to bring home

- Interpreting temporal constraints/goals on finite traces is different than interpreting them on infinite traces (and much more well-behaved)
- When expressing temporal constraints and temporally extend goals we can add to usual LTL_f more powerful constructs a la LDL_f at no cost (possibly for future versions of PDDL).
- There are very general and effective techniques for reasoning, verification and synthesis in this setting – it's not just theory.
- In perspective, the Planning community may come up with a new generation of performing algorithms to deal with these basic tasks (after all, these are all compilable to reachability in large search spaces).

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