Generalized Planning with Loops under Strong Fairness Constraints

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KR 2010 - Toronto, May 12, 2010

Nondeterministic Planning Domains

Nondeterministic Planning Domain $\mathcal{D}$:

- A finite set P of *propositions* –whose subsets are called *states*–, capturing all domain's relevant features
- A finite set A of *actions*, to be executed in the domain
- A transition *relation* $\longrightarrow \subseteq 2^P \times A \times 2^P$, representing the (possibly non-deterministic) domain dynamics, subject to action executions

Example (Coin Tossing)

- $P = \{head, tail, holding\}$, $A = \{grab, toss, turn\}$
- $\rho = \{\emptyset \xrightarrow{grab} \{holding\}, \{holding\} \xrightarrow{toss} \{head\}, \{holding\} \xrightarrow{toss} \{tail\}, \{head\} \xrightarrow{turn} \{tail\}, \{tail\} \xrightarrow{turn} \{head\}, \{tail\} \xrightarrow{grab} \{holding\}, \{head\} \xrightarrow{grab} \{holding\}\}$

Conditional Planning Problems

Conditional Planning Under Full Observability

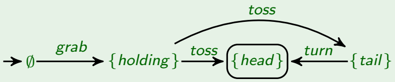
(For now, w/o loops)

- INPUT:
  - a nondeterministic domain $\mathcal{D} = \langle P, A, \rho \rangle$
  - an initial state $S_0 \subseteq P$
  - a propositional goal formula γ over P
- SOLUTION: a *conditional* plan π s.t. all *executions* achieve γ
- COMPLEXITY: EXPTIME-complete (also w/loops)

Example

$\langle S_0 = \emptyset, \gamma = head \rangle$ on *Coin Tossing* solved by plan:

1. *grab*
2. *toss*
3. if($\neg head$) then *turn*

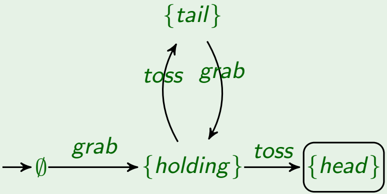


Conditional Planning with Loops

Loops allowed in plans

Example

π = while $(\neg head)$ $\{grab; toss\}$



- Clearly, π does not solve $\langle S_0 = \emptyset, \gamma = head \rangle$...
- ...however, in the real world, everyone would bet it *eventually* does!
- We want to assert non-local constraints!

Conditional Planning with Loops (2)

- Previous work on *Strong Cyclic Planning* [CPRT03] assumes *fair* action executions:
  - All action effects eventually occur
  - Cannot distinguish between fair and unfair action executions (either all or none!)
  - Thus, cannot make decisions based on this

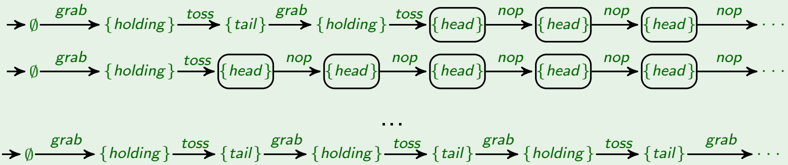
In this work

- We *explicitly* characterize *relevant runs*, through *constraints*
- Capture two different flavours of nondeterminism:
  - Uncertainty: the effect will occurr, but don't know exactly when (e.g., rolling a die)
  - Partial Knowledge: may or may not occur (e.g.: picking cards from a deck with a possibly missing Ace)

Constraints on Runs

Runs: possible evolutions of a domain, generated by executing plans

Example (π executions)



Constraints: LTL formulas built from propositions in $P \cup \bigcup_{a \in A}\{(act = a)\}$

Example (Constraints on $\mathcal{D}$ runs)

Tossing a coin infinitely often yields *head* to occur infinitely often

$$\Box\Diamond(act = toss) \rightarrow \Box\Diamond(head)$$

Constraints on Runs (2)

- *Constraints*: LTL formulas to be evaluated on domain runs
- We use run constraints to *rule out* irrelevant runs
- Only runs satisfying *all* constraints are significant

Semantics of constraints on domain runs

Given:

- a planning domain $\mathcal{D}$ with a finite set $\mathcal{C}$ of constraints on runs
- initial state S_0 and a goal formula γ

A conditional plan π with loops *achieves* γ ($\pi \models \top \mathcal{U} \gamma$) if all of its executions *satisfying* all $\mathcal{C}$ constraints reach a state S s.t. $S \models \gamma$

- LTL is very natural: Conditional Planning focuses on single executions (run-by-run)

Constraints on Runs (3)

We use run constraints to assert non-local domain properties

Example (More realistic Coin Tossing domain)

If we assert the following constraints on Coin Tossing:

- $\Box\Diamond(act = toss) \rightarrow \Box\Diamond(head)$
- $\Box\Diamond(act = toss) \rightarrow \Box\Diamond(tail)$

Then plan $\pi =$ while $(\neg head)$ $\{grab; toss\}$
solves $\langle S_0 = \emptyset, \gamma = head\rangle$

Indeed, the only unsuccessful π execution

$$\rightarrow \emptyset \xrightarrow{grab} \{holding\} \xrightarrow{toss} \{tail\} \xrightarrow{grab} \{holding\} \xrightarrow{toss} \{tail\} \xrightarrow{grab} \{holding\} \xrightarrow{toss} \{tail\} \xrightarrow{grab} \cdots$$

is *discarded* by first constraint above

Strong Fairness Constraints

Strong Fairness

If something ϕ_s *happens infinitely often, then something else* ϕ_e *happens infinitely often*

$$\Box\Diamond\phi_s \longrightarrow \Box\Diamond\phi_e$$

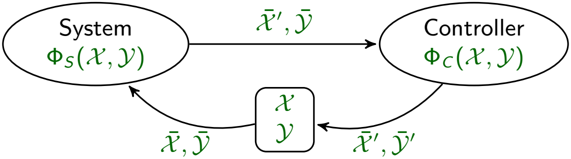
(ϕ_s and ϕ_e essentially propositional, $\bigcirc$ (Next) allowed)

- Strong Fairness captures also:
  - Weak fairness (something ϕ happens infinitely often): $\Box\Diamond\top \longrightarrow \Box\Diamond\phi$
  - Persistence (something ϕ holds from a point on): $\Box\Diamond\neg\phi \longrightarrow \Box\Diamond\bot$
- Not expressible in CTL [CGP99]

- Can phrase typical properties of our interest
- Good computational behavior (wrt Conditional Planning, see below)
- Existing results on LTL synthesis [PPS06, KPP05] apply

Synthesis in LTL

LTL Synthesis Problem:



- Uncontrolled ($\mathcal{X} = \{x_1, \ldots, x_n\}$) and controlled ($\mathcal{Y} = \{y_1, \ldots, y_m\}$) vars
- *System* assigns $\mathcal{X}$ vars (moves first), *Controller* assigns $\mathcal{Y}$ vars
- Both have their own *structural assumptions* (constraints on execution)

Objective:

- Find a controller strategy satisfying an LTL specification φ (Technically, φ combines Φ_C, Φ_S, and desired requirements. In particular, φ requires the strategy to meet Φ_C when interacting with Φ_S)

Synthesis in LTL (2)

Complexity:

- For arbitrary φ, the problem is 2EXPTIME-complete [PR89]
- GR(1) formulas yield an EXPTIME bound [PPS06, KPP05]

Generalized Reactivity (1) Specifications:

$$\varphi = \varphi_a \longrightarrow \varphi_r$$

- φ_a: *System structural assumptions* + possible (weak) fairness constraints
- φ_r: *Controller structural assumptions* + possible (weak) fairness constraints
- Express (desired) requirements of the form

$$\bigwedge_n \Box\Diamond\phi_i \longrightarrow \bigwedge_m \Box\Diamond\psi_j$$

- Expressive enough for our problem!

Conditional Planning w/ Loops under SFC as LTL Synthesis

$$\varphi = \varphi_a \longrightarrow \varphi_r$$

In our case:

1. $\varphi_a = \varphi_a^{init} \wedge \varphi_a^{trans} \wedge \varphi_a^{rc}$, where:
   - φ_a^{init}: initial condition ($\mathcal{D}$ state)
   - φ_a^{trans}: $\mathcal{D}$ transitions and goal achievement
   - φ_a^{rc}: constraints on $\mathcal{D}$ runs (phrased as weak fairness)

2. $\varphi_r = \varphi_r^{trans} \wedge \varphi_r^{goal}$, where:
   - φ_r^{trans}: one executable action at each point (plan structure)
   - φ_r^{goal}: achieve desired goal γ (phrased as weak fairness)

Main Results

Theorem (Soundness & Completeness)

Conditional Planning w/ Loops under Strong Fairness Constraints can be reduced to LTL synthesis for GR(1) formulas

Theorem (Complexity)

Building a conditional plan with loops under strong fairness constraints is EXPTIME-complete

Same complexity class as Conditional Planning w/ Full Observability!

Implementation

- Actual system available: TLV
- Based on (global) Model Checking techniques

Other Results

(See paper)

In general, approach shown effective for:

1. Goals of the form $\varphi = \psi \mathcal{U} \phi$ (achieve ϕ while maintaining ψ)
2. Planning Programs [DPS10], whose atomic instructions are goals $\phi \mathcal{U} \psi$, can be captured and realized
3. Component-based Planning: actions offered by (finite-state) devices, possibly subject to strong fairness constraints

Conclusions and Future Directions

1. Conditional Planning w/ loops, with non-local constraints explicitly asserted
2. More general but not computationally harder than Conditional Planning w/ out Loops
3. Tackled as an LTL synthesis problem, actual system available
4. Suitable for extended scenarios (Planning Programs, Component-based Planning)

1. Performance evaluation to be carried out
2. Plan quality: e.g., avoid loops when not required
3. Planning-oriented techniques and heuristics

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