Automatic Reductions from PH into STRIPS
or
How to Generate Short Problems with Very Long Solutions

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Recap from ICAPS-2011

Introduced a software tool that maps instances of an NP decision problem expressed in SO$\exists$ into a STRIPS problem such that

1) instance is a positive instance iff the STRIPS problem has a plan

2) translation runs in polynomial time

3) STRIPS problem is decidable in non-deterministic polytime (NP)

4) plan, when exists, encodes the solution to input instance

Software Tool

$$\xrightarrow[\sigma,\,\Phi,\,\mathcal{A}]{\text{DCT}} \boxed{\text{tool}} \xrightarrow[\text{dom \& ins}]{\text{PDDL}}$$

Input:

- signature σ that contains relational symbols
- SO$\exists$ formula Φ that encodes NP problem
- finite structure $\mathcal{A}$ that encodes instance

Output:

- PDDLs for a fragment of STRIPS that is decidable in NP

Guarantees:

- runs in polytime for fixed σ and Φ
- output is no harder that input (complexity wise)

Contributions

- Extend tool to target Polynomial Time Hierarchy (PH) instead of only NP
- Generated problems are general STRIPS problems
- Translator runs in polynomial time
- Experimental evaluation over (somewhat) difficult instances

Use:

- Leverage current (planning) technology to NP problems
- Design new benchmarks for planning and test planners and heuristics

Descriptive Complexity Theory (DCT)

Studies complexity theory from a logical perspective without commitments to any model of computation

Major complexity classes had been characterized using different fragments of logic:

- NL is captured by SO$\exists$-Krom (CNF with ≤ 2 literals per clause)
- P is captured by SO$\exists$-Horn (CNF with ≤ 1 positive literal)
- NP is captured by SO$\exists$
- PH is captured by SO
- PSPACE is captured by SO+TC (SO $+$ transitive-closure syntactic construct)

Polynomial Time Hierarchy (PH)

Infinite hierarchy of classes that contains P, NP, $\mathsf{NP}^{\mathsf{NP}}$, $\mathsf{NP}^{\mathsf{NP}^{\mathsf{NP}}}$, etc.

Defined as PH $= \bigcup_{k \geq 0} \Sigma_k^P$ where (using oracles):

- $\Sigma_0^P = \mathsf{P}$
- $\Sigma_1^P = \mathsf{NP}^{\Sigma_0^P} = \mathsf{NP}^{\mathsf{P}} = \mathsf{NP}$
- $\ldots$
- $\Sigma_{k+1}^P = \mathsf{NP}^{\Sigma_k^P}$

PH $=$ Co-PH and hence Co-NP and $\Pi_k^P \in$ PH for every $k \geq 0$

It is believed that PH $\neq$ PSPACE; otherwise PSPACE $= \Sigma_k^P$ from some k

Cannonical problem in Σ_k^P is to decide validity of $\exists \bar{x}_1 \forall \bar{x}_2 \exists \bar{x}_3 \cdots \mathcal{Q} \bar{x}_k . \varphi$

Results 1/3

Random formulas of type $\exists\bar{x}\forall\bar{y}\exists\bar{z}.\varphi(\bar{x},\bar{y},\bar{z})$ in Σ_3^P

$\exists\forall\exists$ #$\exists$	#$\forall$	#$\exists$	n	$+$	$-$	time	len	PDDL in KB
10	2	30	5	—	5	4,199.2	—	17.5
	2	50	5	—	5	2,313.9	—	18.4
30	2	30	5	—	5	3,210.7	—	18.5
	2	50	5	—	5	3,166.3	—	19.4
50	2	30	5	—	1	3,313.4	—	19.4
	2	50	5	3	2	3,450.9	640	20.4

- Random $\exists\forall\exists$ problems with 150 clauses each
- Solved with Rintanen's SAT-based planner M
- LAMA'11 does not perform well on this type of problems

Results 2/3

Random instances of $\overline{\text{3Col}}$ in $\Pi_1^P = \text{Co-NP}$

V	n	$+$	$-$	time / $+$	time / $-$	plan len	PDDL
4	5	1	4	0.1	0.8	1,731	0.4
5	5	2	3	0.6	67.9	6,695	0.6
6	5	2	3	3.4	464.9	26,163	0.7
7	5	2	2	74.8	1.6	102,935	0.8
8	5	1	2	624.0	5.9	406,851	1.0
9	5	—	1	—	0.3	—	1.1

- 5 random graphs for each number of vertices (V)
- Solved with LAMA'11 and obtained very long plans!
- M does not perform well on this type of problems
- **How come does LAMA'11 find a plan with $>$ 400k actions?**

Results 3/3

Random instances of $\overline{\text{3Col}}$ in Π_1^P = Co-NP

V	n	$+$	$-$	time / $+$	time / $-$	plan len	PDDL
4	5	1	4	1,850.1	0.1	1,731	0.4
5	5	—	3	—	11.7	—	0.6
6	5	—	3	—	81.9	—	0.7
7	5	—	2	—	0.2	—	0.8
8	5	—	2	—	1.0	—	1.0
9	5	—	1	—	0.0	—	1.1

- The same random instances for $\overline{\text{3Col}}$
- Solved with blind search
- Significantly worse than LAMA'11. Thus, these problems are non-trivial
- **Conjecture:** LAMA'11 solves these instances because of implicit serialization of subgoals enforced by the multiple queues

Example: SAT and UNSAT

Defined over vocabulary $\sigma = \langle P^2, N^2 \rangle$ where:

- $P(x, y)$ tells that variable x appears positive in clause y
- $N(x, y)$ tells that variable x appears negative in clause y

$$\Psi_{\mathsf{SAT}} = \underbrace{(\exists T)}_{\text{s.o. unary relation used to encode guessed assignment}}(\forall y)(\exists x)[(P(x, y) \wedge T(x)) \vee (N(x, y) \wedge \neg T(x))$$

$$\Psi_{\mathsf{UNSAT}} = \underbrace{(\forall T)}_{\text{s.o. unary relation used to encode all assignments}}(\exists y)(\forall x)[(P(x, y) \Rightarrow \neg T(x)) \wedge (N(x, y) \Rightarrow T(x))$$

Example: SAT

$$\Psi_{\mathsf{SAT}} = (\exists T)(\forall y)(\exists x)[(P(x,y) \wedge T(x)) \vee (N(x,y) \wedge \neg T(x))$$

Instance: $\underbrace{(x_0 \vee \neg x_1 \vee x_2)}_{\text{clause 0}} \wedge \underbrace{(\neg x_0 \vee \neg x_2)}_{\text{clause 1}} \wedge \underbrace{(\neg x_0 \vee x_1)}_{\text{clause 2}}$

Instance is satisfiable with model $\{\neg x_0, \neg x_1, \neg x_2\}$

STRIPS plan:

```
(begin-proof)
(end-guess-T)

(prove-and-2 var0 var1)
(prove-or-2 var0 var1)
(prove-exists var0)
(prove-forall-base var0)

(prove-and-2 var1 var0)
(prove-or-2 var1 var0)
(prove-exists var1)
(prove-forall-induc var0 var1)

(prove-and-2 var2 var0)
(prove-or-2 var2 var0)
(prove-exists var2)
(prove-forall-induc var1 var2)

(prove-so-exist-T var2)
(prove-goal)
```

Example: UNSAT

$$\Psi_{\mathsf{UNSAT}} = (\forall T)(\exists y)(\forall x)[(N(x,y) \Rightarrow T(x)) \wedge (P(x,y) \Rightarrow \neg T(x))]$$

Instance: $\underbrace{(x_0)}_{\text{clause 0}} \wedge \underbrace{(\neg x_0 \vee \neg x_1)}_{\text{clause 1}} \wedge \underbrace{(\neg x_0 \vee x_1)}_{\text{clause 2}}$

Instance is unsatisfiable

STRIPS plan:

```
(begin-proof)
(init-so-forall-T)

(prove-or_1_1 var0 var0)
(prove-or_2_2 var0 var0)
(prove-and var0 var0)
(prove-forall_base var0 var0)
(prove-or_1_1 var0 var1)
(prove-or_2_2 var0 var1)
(prove-and var0 var1)
(prove-forall_induc var0 var0 var1)
(prove-exists var0 var1)

(change_for_coin_T var0)
(zero_plus_one_T var0)

(prove-or_1_2 var2 var0)
(prove-or_2_1 var2 var0)
(prove-and var2 var0)
(prove-forall_base var2 var0)
(prove-or_1_1 var2 var1)
(prove-or_2_2 var2 var1)
(prove-and var2 var1)
(prove-forall_induc var2 var0 var1)
(prove-exists var2 var1)

(change_for_coin_T var0)
(one_plus_one_0_T var0 var1)
(zero_plus_one_T var1)

(prove-or_1_1 var0 var0)
(prove-or_2_2 var0 var0)
(prove-and var0 var0)
(prove-forall_base var0 var0
(prove-or_1_2 var0 var1)
(prove-or_2_1 var0 var1)
(prove-and var0 var1)
(prove-forall_induc var0 var0 var1)
(prove-exists var0 var1)

(change_for_coin_T var0)
(zero_plus_one_T var0)
(prove-or_1_2 var1 var0)
(prove-or_2_1 var1 var0)
(prove-and var1 var0)
(prove-forall_base var1 var0)
(prove-or_1_2 var1 var1)
(prove-or_2_1 var1 var1)
(prove-and var1 var1)
(prove-forall_induc var1 var0 var1)
(prove-exists var1 var1)

(change_for_coin_T var0)
(one_plus_one_0_T var0 var1)
(one_plus_one_final_T var1)

(prove-goal)
```

Idea of Translation

For FO formulas (from ICAPS-11):

- fluents represent validity of subformulas where parameters stand for free variables
- operators establish validity of formulas (fluents) from validity of subformulas (inductively in structure of formulas)

For SO existential quantifiers (similar to ICAPS-11):

- plan chooses one interpretation of quantified symbol
- plan then moves and proves validity with chosen interpretation

For SO universal quantifiers:

- plan iterates over all interpretations of quantified symbol
- for each such interpretation, plan proves validity

Iteration over All Interpretations

Consider a unary relation T and a universe with n objects

There are 2^n different interpretations of T that can be identified with the 2^n differents binary words of length n:

i-th element belongs to T's interpretation iff i-th bit in word is 1

Iterating over interpretations is done by iterating over such words

The word is treated as a counter that starts at '$00 \cdots 0$' and is incremented until '$11 \cdots 1$' by adding 1

How to Capture PSPACE

PSPACE = SO + TC

$\mathsf{TC}[\Psi](\bar{x}, \bar{y})$ denotes connectivity on a graph defined by the formula $\Psi(\bar{u}, \bar{v})$

If we use the fluent $\mathfrak{F}[\Psi](\bar{u}, \bar{v})$ to denote the validity of $\Psi(\bar{u}, \bar{v})$, then can design actions to prove the validity of $\mathsf{TC}[\Psi](\bar{x}, \bar{y})$

Therefore, implementing $\mathsf{TC}[\Psi]$ in STRIPS is straightforward:

it is just finding a path on a graph whose edges are given by fluents $\mathfrak{F}[\Psi](\bar{u}, \bar{v})$

Summary

– Extended the tool presented in ICAPS-11 so that:

- targets the much bigger complexity class PH
- implements a type system that permits more efficient translations

– Performed experiments and got interesting results for LAMA'11

– Tool can be used to design challenging benchmarks for planners

– Tool can be extended to target whole PSPACE without much work

Thanks. Questions?