Temporal Planning with Clock-Based SMT Encodings

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Temporal Planning

- classical planning = choose action sequence to reach a goal
- temporal planning = choose actions + schedule (with concurrency)
- pioneering work by Shin & Davis (2005)
  - complex modeling language
  - effective representation in SAT modulo Theories (SMT) framework
  - SMT before used for classical planning with numeric variables (Wolfman & Weld 1999)
- Few follow-ups to Shin&Davis 2005: room for improvement

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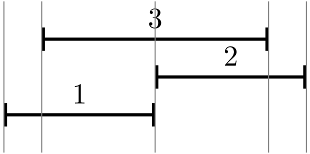
Temporal Planning by Constraints / Logic / SAT / SMT

- Starting point: Shin & Davis 2005 (PDDL 2.1 $\rightarrow$ SMT)
  - Issue 1: ϵ-semantics of PDDL 2.1 $\rightarrow$ far too many steps
  - Issue 2: discretization to integer time not available

  $\Rightarrow$ Poor scalability
- Rintanen (IJCAI 2015): eliminate ϵ semantics; NDL instead of PDDL
  - Advantage 1: Number of steps often halved! Big performance gains.
  - Advantage 2: Reasoning about action dependencies easier
- Rintanen (AAAI 2015): general discretization method
  - Advantage 1: Simpler encodings (often)
  - Advantage 2: Use SAT instead of SMT (many cases)
  - Advantage 3: Optimal makespan practical (when actions "short")
- This work:
  1. Summarized steps: peformance gains through even fewer steps,
  2. Clock-based delays: O(n) size vs. O(n^2) by Shin&Davis 2005

Step-Based Encodings

- Steps part of Kautz&Selman original work (1992)
  - Execution of a plan represented by states/steps $s_0, \ldots, s_n$
  - Encoding expresses transitions $s_i \Rightarrow s_{i+1}$ for all $i \in \{0, \ldots, n-1\}$
- Shin&Davis (2005): steps have a real-valued time



- A step is needed for
  - every action starting point
  - every (discrete) change by action or other event

Variables needed in SMT encodings of Temporal Planning

Let $0, \ldots, N$ be the steps. Following variables needed.

$x@i$	Boolean state variable x is true	$i \in \{0, \ldots, N\}$
$a@i$	action a is taken	$i \in \{0, \ldots, N\}$
$\tau@i$	absolute time at step i	$i \in \{0, \ldots, N\}$
$\Delta@i$	$= \tau@i - \tau@(i-1)$	$i \in \{1, \ldots, N\}$

Constraint: $\Delta@i > 0$

Precondition axioms

If ϕ is the precondition of action a, we have the formula

$$a@i \rightarrow \phi@i \quad (1)$$

where $\phi@i$ is the formula obtained from ϕ by replacing each x by $x@i$.

Effect Axioms and Frame Axioms

causes$(l)@i$ $=$ disjunction of all triggers for l becoming true

Effect axioms

$$\text{causes}(x)@i \rightarrow x@i \tag{2}$$
$$\text{causes}(\neg x)@i \rightarrow \neg x@i \tag{3}$$

Frame axioms

$$(x@i \wedge \neg x@(i-1)) \rightarrow \text{causes}(x)@i \tag{4}$$
$$(\neg x@i \wedge x@(i-1)) \rightarrow \text{causes}(\neg x)@i \tag{5}$$

Shin&Davis-style encoding of causes$(x)@i$

Effect triggers in the Shin & Davis encodings

Trigger for action a and effect x at $t > 0$ in causes$(x)@i$:

$$\bigvee_{j=0}^{i-1} (a@j \wedge ((\tau@i - \tau@j) = t)) \tag{6}$$

This is $\mathcal{O}(n^2)$ size where n is the number of steps.

Step must exist

If action a has an effect at t, a step at relative time t must exist:

$$a@i \rightarrow \bigvee_{j=i+1}^{N} (\tau@j - \tau@i = t). \tag{7}$$

Clock-based encodings (Rintanen 2015)

Idea: every action has its own clock

Encoding

Let action a have effect x at t.

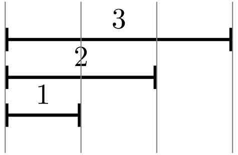
Clock is reset	$a@i \rightarrow c_a@i = 0$
Clock progresses	$\neg a@i \rightarrow c_a@i = c_a@(i-1) + \Delta@i$
Must stop at t	$(c_a@(i-1) < t) \rightarrow (c_a@i \leq t)$
Effect trigger	$c_a@i = t$

Encoding has a linear size. But, far too many real-valued variables. Slow!

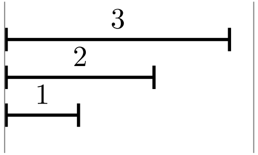
Contribution 1: Summarized Effects

Summarize discrete changes from multiple time points in a single step

Shin & Davis AIJ'05



Rintanen IJCAI'17



Fewer steps $\Rightarrow$ significant performance gain

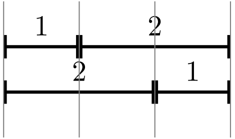
Contribution 1: Implementation

1. No need for axioms requesting a step a specific time!!!
2. Trigger $c_a@i = t$ for effects at relative time t becomes:

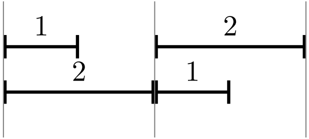
$$(c_a@(i-1) < t) \wedge (c_a@i \geq t) \tag{10}$$

Trade-offs: makespan vs. number of steps

4 steps, makespan 3



3 steps, makespan 4



Sometimes: shorter makespan $\Rightarrow$ more steps

(*Makespan – number of steps* trade-off in all encodings when one long action interchangeable with two short ones)

Contribution 2: Practical Encodings with Clocks

- Rintanen AAAI'15: clock for every action $\Rightarrow$ too many clocks $\Rightarrow$ slow
- New encodings: clocks shared by multiple actions

Idea:

- associate clocks with a resources
- resources represent exclusions of actions $\Rightarrow$ same clock can represent delays of exclusive actions

Why is this good?

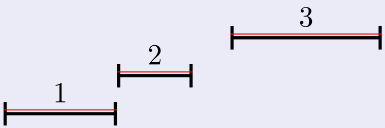
- Number of resources typically low (e.g. 30 resources vs. 1000 actions)
- Number of clocks low $\Rightarrow$ number of real variables low $\Rightarrow$ fast

Contribution 2: Practical Encodings with Clocks

Common easy case

All actions a with resource R:

1. allocation from 0 to d_a
2. last effects at d_a



Clock c_R for resource R can be used for all delays

1. action a can be taken if $c_R \geq 0$
2. action a sets $c_R := -d_a$
3. effect at t triggered when $d_a - c_R = t$

See paper: very general condition for the sufficiency of one clock
See paper: examples where one clock not enough

Contribution 2: Qualitative Clocks for Shared Clocks

A shared clock does not indicate which action is currently active.
Need qualitative (Boolean) clocks for every action.

- The "clock" distinguishes between "qualitative" values:
  1. start of action (action variable is true)
  2. time points where action *active* but no effects
  3. time points where action's effects take place
- Encode rules for transitions from one value to the next
- Connect qualitative clock variables to real-valued clock variables

Experiments

1. SD – encoding of delays/steps as proposed by Shin&Davis
2. C – our new clock encoding
3. R – our new clock encoding + relaxed/summarized steps
4. ITSAT – leading temporal planner (Rankooh & Ghassem-Sani 2013, AIJ'15)
    - Reduction to untimed/classical planning
    - Solved with efficient classical SAT encodings (Rintanen et al. 2006)
    - If solution schedulable to correct plan, done.
    - Otherwise add constraints and try again.

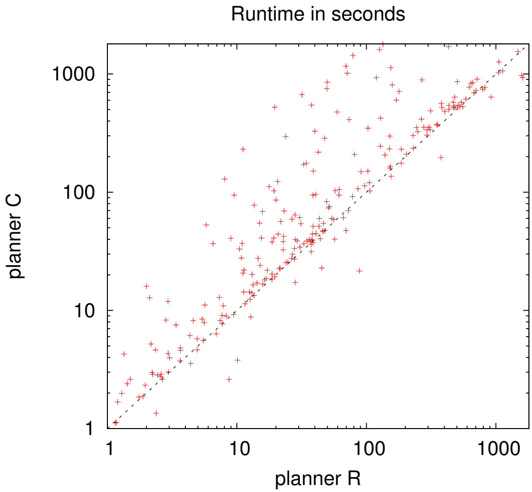
SAT solver ignores metric time: scalability (often) good, plans not!

Experiments: Solved Instances

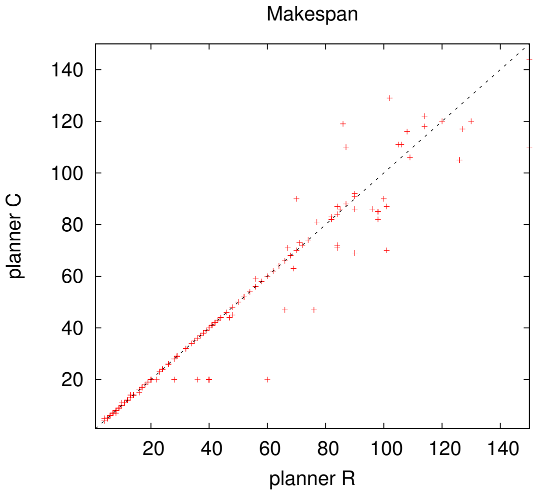
		ITSAT	SD	C	R	
08-crewplanning	30	30	10	14	15	
08-elevators	30	16	4	6	9	
08-elevators-num	30	-	4	8	13	(numeric vars: ITSAT not applicable)
08-openstacks	30	30	4	5	7	
08-pegsol	30	30	30	30	30	
08-sokoban	30	17	17	17	16	
08-transport	30	-	4	6	8	(numeric vars: ITSAT not applicable)
08-woodworking	30	-	16	15	23	(numeric vars: ITSAT not applicable)
08-openstacks-adl	30	-	3	5	8	(numeric vars: ITSAT not applicable)
08-openstacks-num-adl	30	-	5	9	18	(numeric vars: ITSAT not applicable)
11-floortile	20	20	20	20	20	
11-matchcellar	10	10	10	10	10	
11-parking	40	9	12	12	12	
11-storage	20	10	0	0	0	
11-tms	20	20	20	20	20	
11-turnandopen	20	20	18	18	18	
14-floortile	20	20	20	20	20	
14-matchcellar	20	20	19	20	19	
14-parking	20	18	19	19	19	
14-tms	20	20	20	20	20	
14-turnandopen	20	9	5	5	5	
14-driverlog	30	4	0	0	0	
total (w/o numeric)	410	303	228	236	240	
total	560	303	260	279	310	

Table: Instances solved in 1800 seconds by domain

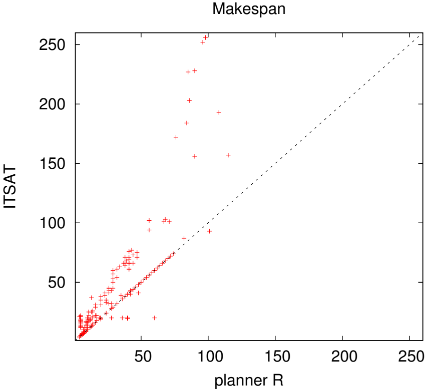
Experiments: Summarization Improves Runtimes



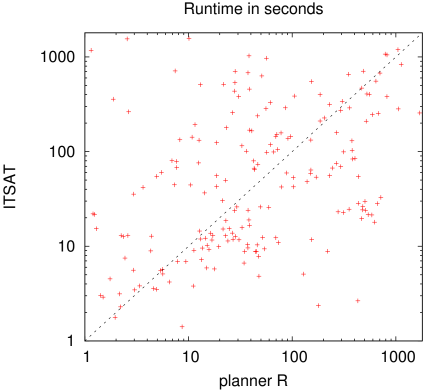
Experiments: Summarization Can Worsen Makespans



Experiments: Far Better Makespans than with ITSAT



Experiments: ITSAT's Runtime Advantage Unsystematic



Conclusion

- First competitive clock-based encodings with clock-sharing and resources
- Summarization reduces number of steps $\Rightarrow$ better scalability
- Comparison to ITSAT:
    - On average, scalability still not as good
    - Often far superior plans (shorter makespan)