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Efficient SAT Encodings for Hierarchical Planning

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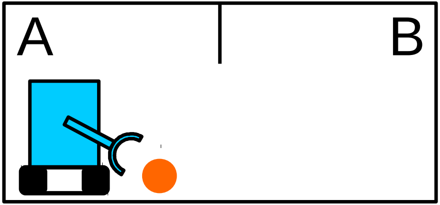
```
                (tag t3 (serve_shot ?sh ?c))
            )
        :constraints(and
                (before (and (ontable ?sh) (clean ?sh) (handempty ?h)) t1)
            )
    )

    (:method do_cocktail_in_shot2
        :parameters (?sh - shot ?i - ingredient)
        :expansion  (
                (tag t1 (do_fill_shot ?sh ?i ?h))
                (tag t2 (leave ?h ?sh))
            )
        :constraints(and
                (before (and (dispenses ?d ?i)) t1)
            )
)
```

Outline

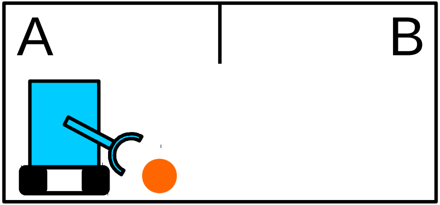
- Background: Planning, Hierarchical Planning, SAT Planning
- Related Work
- Contributions: GCT Encoding, SMS Encoding
- Evaluation
- Conclusion

Automated Planning



Find a valid sequence of actions from some initial world state to a desired goal state.

Automated Planning



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- (World) State: Consistent set of boolean atoms; e.g. `at(ball,A)`, `at(robot,B)`

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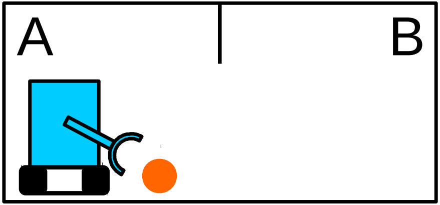
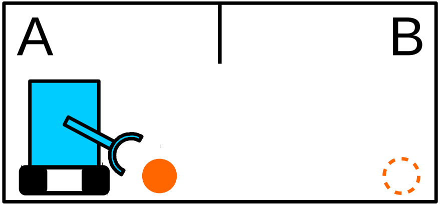


Find a valid *sequence of actions* *from some* *initial world state* *to a* *desired goal state*.

- Action *a*: Has boolean preconditions and effects;
  e.g. action `move(robot,A,B)` requires `at(robot,A)`, deletes `at(robot,A)`, adds `at(robot,B)`

Automated Planning



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- Goal g: Subset of possible states, e.g. `at(ball,B)` must hold

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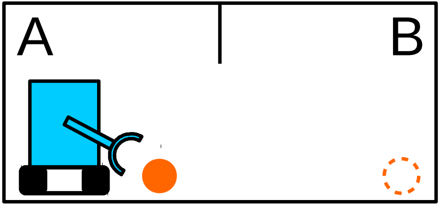

Find a valid sequence of actions from some initial world state to a desired goal state.

- Plan π: Action sequence transforming an initial state to a goal state
  e.g. $\pi =$

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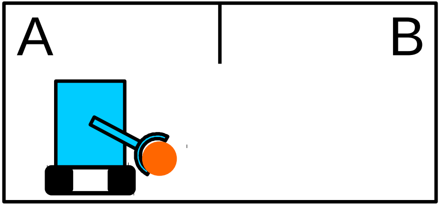

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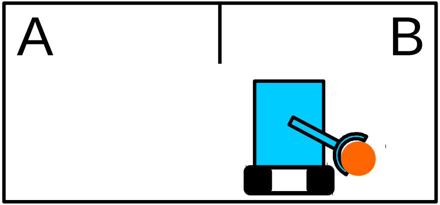

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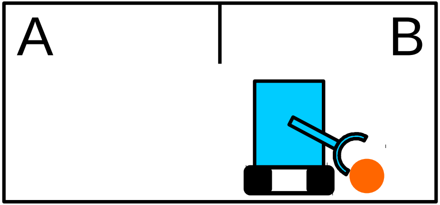

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  e.g. $\pi = \langle$ `pickup(robot,ball,A)`, `move(robot,A,B)`, `drop(robot,ball,B)` $\rangle$

Hierarchical Planning

Main idea: *Share domain-specific expert knowledge with your planner.*

- Which tasks need to be achieved
- How to directly achieve simple tasks
- How to break down complex tasks into simpler ones

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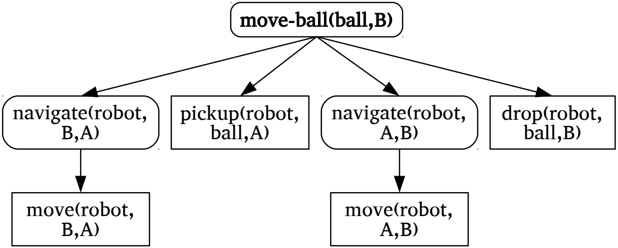
Most popular: Hierarchical Task Network (HTN) Planning [Erol et al., 1994]

- Extension of classical planning (same states, actions, plans)
- More expressive than classical planning
- More focused search, enables more efficient planning

Hierarchical Task Networks



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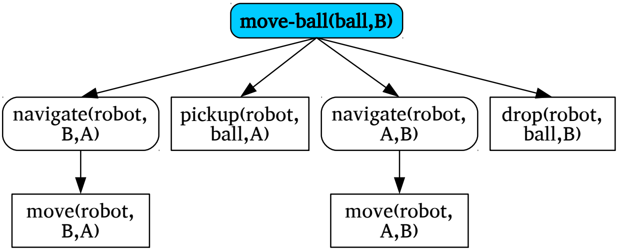
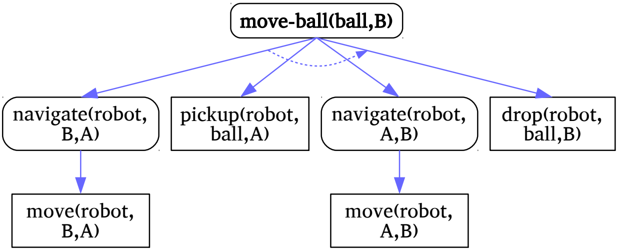


Root(s): Initial task(s), part of problem input

- Abstract notion of what needs to be achieved

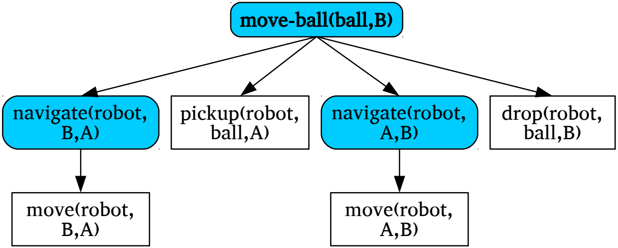
Hierarchical Task Networks



Directed edges: Subtask relationships

- Here: totally ordered
- Span a tree of tasks

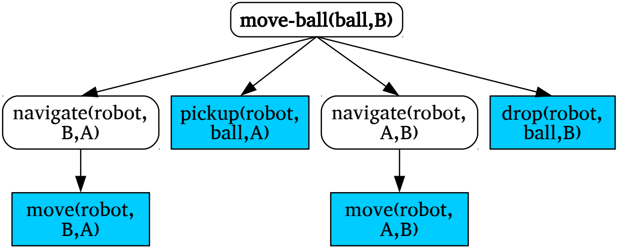
Hierarchical Task Networks



Inner nodes: Compound tasks

- Can be achieved by choosing a method and achieving each subtask
- Example: method `move-ball(ball, to, r, x, y)`
  Preconditions { `at(ball,x)`, `at(r,y)` },
  Subtasks ⟨ (1) `navigate(r,y,x)`, (2) `pickup(r,ball,x)`,
  (3) `navigate(r,x,to)`, (4) `drop(r,ball,to)` ⟩

Hierarchical Task Networks

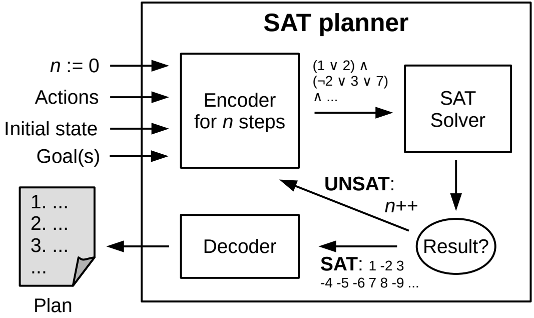


Leaf nodes: Primitive tasks

- Directly correspond to applying a certain action
- In-order traversal of all leaves $\Rightarrow$ Plan!

SAT-based Planning

- Encode planning problem into propositional logic up to a certain number of steps [Kautz and Selman, 1992]
- Use Satisfiability (SAT) Solver to find satisfying assignment
- Decode assignment back into a plan



Related Work

Introduction of incremental SAT solving to planning [Gocht and Balyo, 2017]

- Maintain and iteratively extend a single logical formula
- Remember logical conflicts from previous iterations

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SAT-based HTN planning: Few research before 2018
[Mali and Kambhampati, 1998]

- Previous encodings do not address recursive task relationships (fixed maximum amount of actions for each task)
- Complexity of clauses and variables cubic in amount of steps
- In practice, infeasible for today's problem instances

Encoding: Grammar-Constrained Tasks

Enhancement of previous *bottom-up linear forward* encoding [Mali and Kambhampati, 1998]

- Focused on totally ordered HTN planning
- Fully supporting recursive subtask relationships
- Resulting in smaller encoding size (quadratic in #steps, #tasks)

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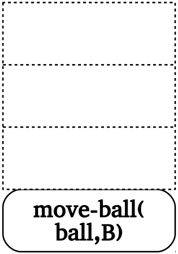
Observation: HTN is like enforcing a grammar on valid plans

- Totally ordered HTN corresponds to context-free grammar
- Finding a plan equivalent to deriving a word from the grammar

Encoding: Stack Machine Simulation (1)

Based on idea of context-free grammar:

- Encode stack of tasks at each step of future plan
- Add transition rules (**pop**, **push**) to process tasks until stack is empty



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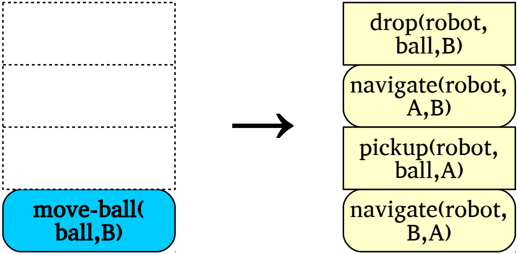

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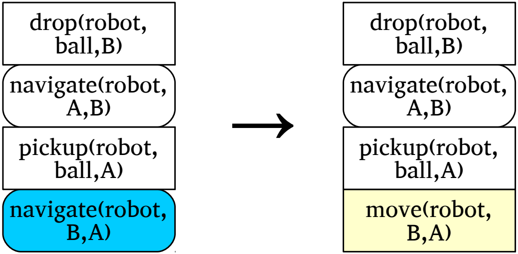

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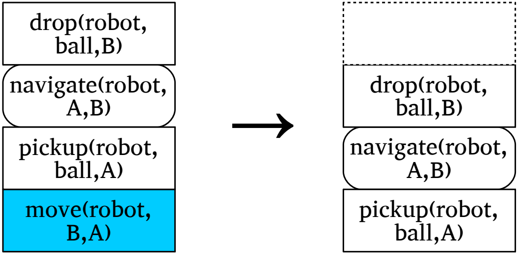

Plan: $\langle$ `move(robot,room2,room1)` $\rangle$

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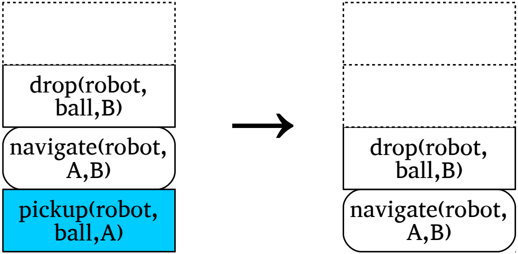

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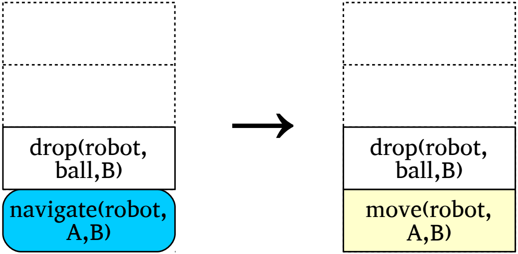

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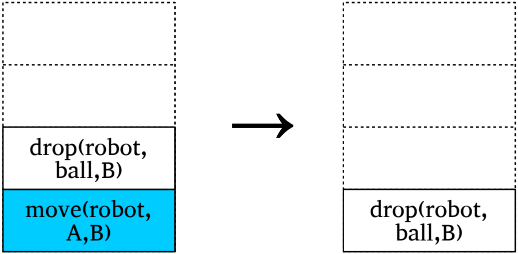

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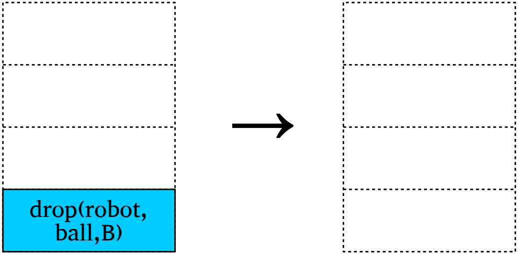

Plan: $\langle$ `move(robot,room2,room1)`, `pickup(robot,ball,room1)`, `move(robot,room1,room2)`, `drop(robot,ball,room2)` $\rangle$

Encoding: Stack Machine Simulation (2)

Realization in propositional logic:

- Boolean variables for each task at each stack position at each step, for each action at each step, for each atom at each step

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Properties

- Handles all special cases (recursive subtasks, no interleaving, etc.)
- Requires parameter σ: Maximum stack size to encode
- $\mathcal{O}(\#\mathit{steps} \cdot (\sigma \cdot \#\mathit{tasks} + \#\mathit{methods} + \#\mathit{actions}))$ clauses

Evaluation

Internal evaluation of approaches

- GCT Encoding
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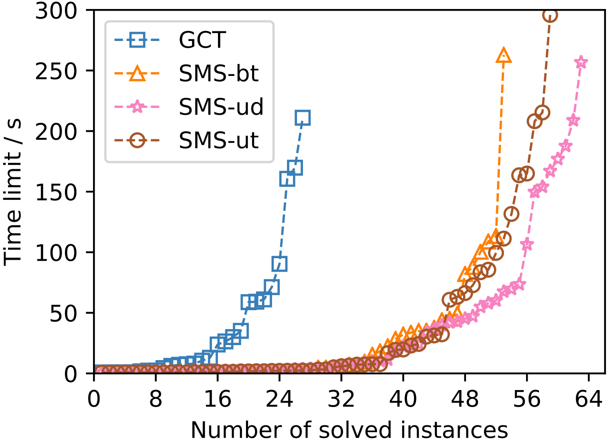
Evaluation environment:

- 120 benchmark instances from six IPC domains
  Barman, Blocksworld, Childsnack, Elevator, Rover, Satellite
- 24 core Intel Xeon CPU E5-2630 @ 2.30 GHz, 264 GB of RAM
- Limits per run: five minutes; 12 GB of RAM

Comparison of Run Times



Run Time Scores per Domain

Domain	GCT	SMS-bt	SMS-ut	SMS-ur
Barman	0.09	1.90	1.96	**4.68**
Blocksworld	0.08	9.22	**10.94**	6.74
Childsnack	0.98	3.90	**9.95**	4.50
Elevator	4.21	**14.86**	13.32	10.29
Rover	0.44	**6.17**	5.40	5.58
Satellite	0.96	7.08	7.17	**16.08**
Total	6.75	43.13	**48.74**	47.88

Score for each instance and competitor: $\frac{T^*}{T} = \frac{\text{best competitor's run time}}{\text{run time}}$

Plan Length Scores per Domain

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Domain	GCT	SMS-bt	SMS-ut	SMS-ur
Barman	0.85	2.72	2.00	**5.00**
Blocksworld	2.00	10.00	**13.00**	11.00
Childsnack	3.00	6.00	**10.00**	8.00
Elevator	13.00	**16.00**	15.00	15.00
Rover	3.86	**6.62**	6.55	**6.62**
Satellite	4.00	9.61	11.79	**16.77**
Total	26.70	50.96	58.33	**62.40**

Score for each instance and competitor: $\frac{T^*}{T} = \frac{\text{best competitor's plan length}}{\text{plan length}}$

Conclusion

- Two new SAT encodings for totally ordered HTN planning
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Future work

- Enhance SMS to expand tasks more rapidly
- Eliminate hyper-parameter σ by changing structure of encoding
- Compare to recent related work [Behnke et al., 2018]

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Thank you for your attention!

References I

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