Search Complexities for HTN Planning

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Hierarchical Task Network (HTN) planning

HTN planning is the problem of decomposing an initial task to accomplish into a sequence of executable steps:

- Often used to solve classical planning problems faster
- More expressive than classical planning
  - Can express undecidable problems

But...

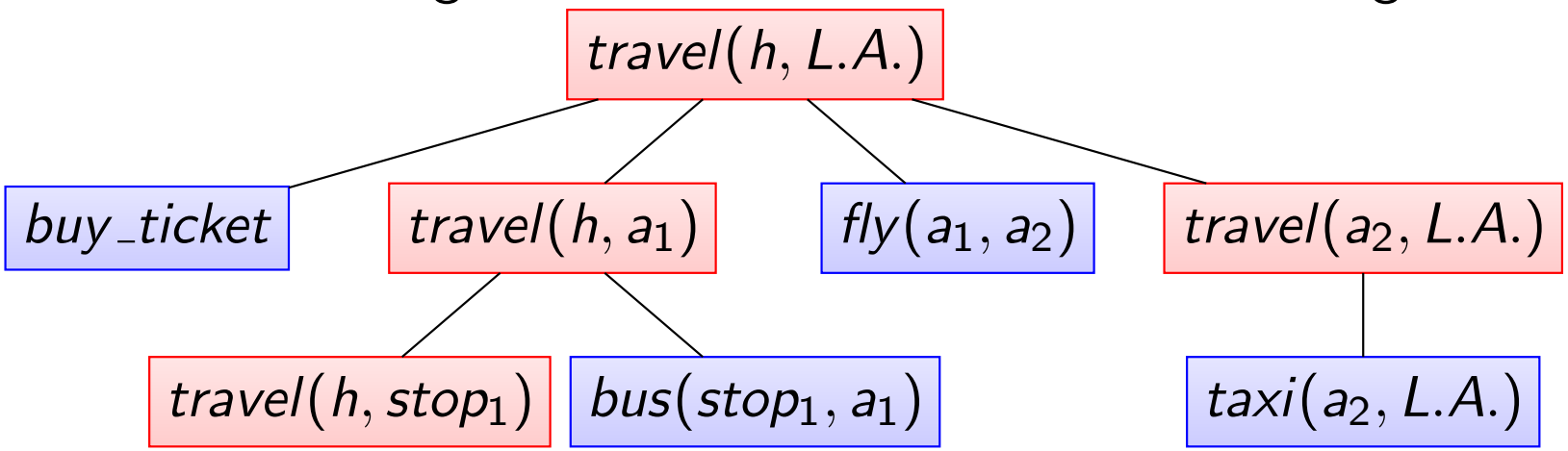
- There are many ways to solve HTN problems
  - Two main algorithms in practice, two new algorithms in thesis
  - What problems are these algorithms guaranteed to solve?
  - How efficient are they?
- Search space is huge
  - Most problems in PSPACE through EXPSPACE
  - What domain independent heuristics can we design for HTN planning?
  - Can these heuristics be effective?

Outline

HTN Planning (overview)

The purpose of HTN planning is to complete a *task*. Tasks are either

- *Primitive*, which corresponds to some concrete action we know how to perform
  - E.g: $walk(room, hall)$, or $drink(coffee)$
- *Non-primitive*, which is an abstract task. E.g. $travel(home, L.A.)$
- Must recursively decompose non-primitive tasks until we get primitive tasks we know how to execute directly
- Given a set of *methods*, which are recipes on how to accomplish abstract tasks. E.g., to travel from *home* to *L.A.*, we might



Planning: Propositional and FOL

- There are two common ways to define HTN classical planning:
  - Over a propositions, and propositional sentences
  - Over a function-free fragment of first-order logic
- My work and this talk are concerned with propositional planning
  - Applies directly to non-propositional planning
  - Complexity results usually go up by an exponential amount

HTN Planning: $D = (\mathbf{O}, M)$, $P = (D, \mathbf{s}_0, tn_0)$

Every HTN problem P contains an *initial state* s_0, which is just a collection of literals, e.g., $\{thirsty, tired\}$.

Actions in our domain work over these states.

Actions have:

- A name (the task)
- A precondition (logical formula over the state)
  - Condition must hold for the action to be executed
- An effect on the state
  - A set of literals to add
  - A set of literals to delete
- Denote execution by a partial function γ:
  - $\gamma(\{thirsty, tired\}, drink) = \{tired\}$

Operator: *sleep*

pre $= tired \wedge \neg thirsty$

eff $= \{\neg tired\}$

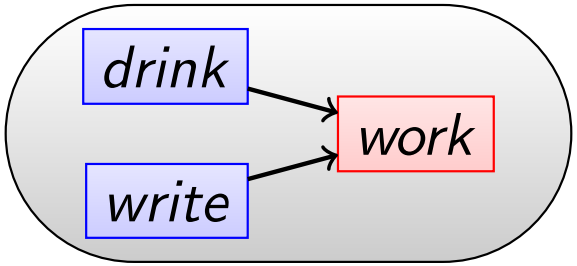
Operator: *drink*

pre $= true$

eff $= \{\neg thirsty\}$

HTN Planning: $D = (O, \mathbf{M})$, $P = (D, s_0, \mathbf{tn}_0)$

- An initial *task network*, tn_0, which is a labeled DAG of *tasks* to accomplish:
  - Edges represent ordering constraints
  - Nodes are labeled with *tasks*, which are either:
    - Primitive tasks (i.e., action names from O: $\{drink, write\}$)
    - Non-primitive tasks (say, $\{work\}$)

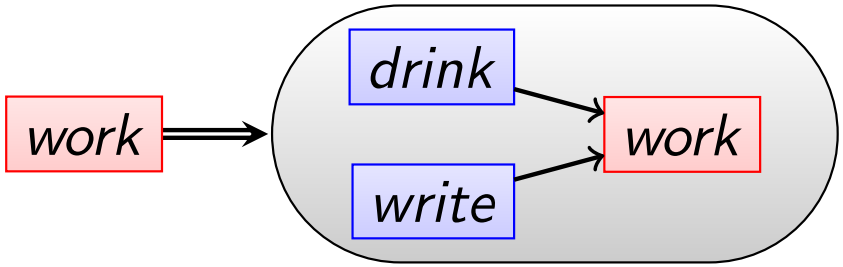


- M, a set of methods to *decompose* non-primitive tasks

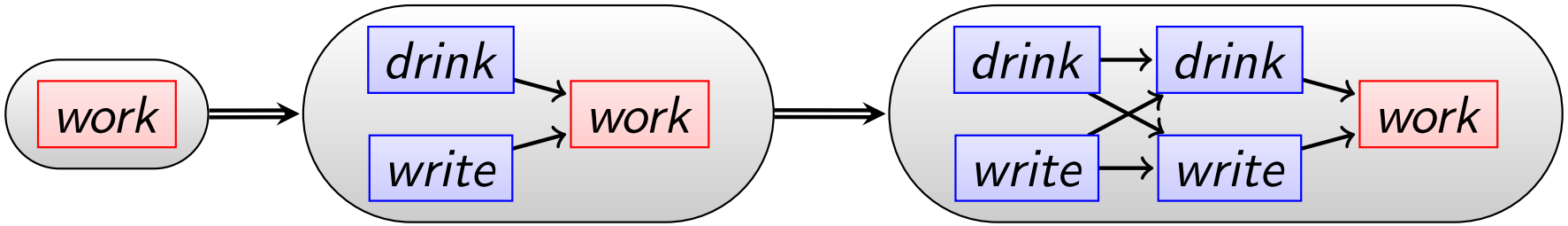
Methods and Decomposition

- A method (t, tn) is a non-primitive task t paired with a network tn

Method:

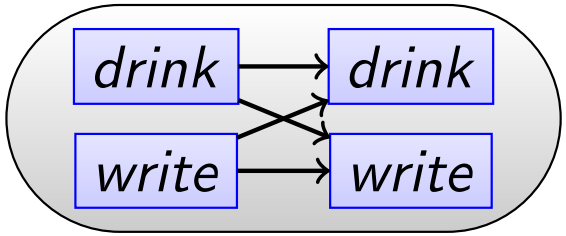


- We *decompose* a task network by replacing a node in the network with a corresponding method's network.



Primitive task networks:

- Two states:
  - $thirsty, \neg thirsty$
- Two actions:
  - $\forall_s \gamma(s, write) = thirsty$
  - $\forall_s \gamma(s, drink) = \neg thirsty$



- All names are actions $\Rightarrow$ network is *primitive*
- It is *executable* in a state if there exists a consistent total order (sequence) which is executable.
  - Four possible orderings
  - All executable in both *thirsty* and $\neg thirsty$
  - Could end in either state.
- Objective: Decompose initial network to a primitive task network that is executable in s_0.

Classical (STRIPS) planning

Differences between HTN and Classical Planning:

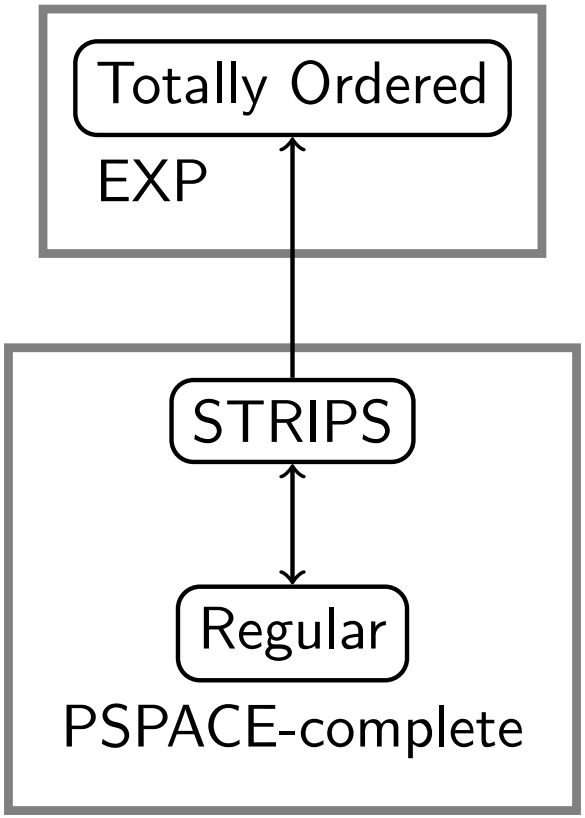
- $P = (O, s_0, G)$
- No methods and no initial task network.
- Objective: Find a plan (any executable sequence) that take us to a goal state.
  - No restriction (other than executability) on when planner can insert an action
- PSPACE-complete for propositional problems

Outline

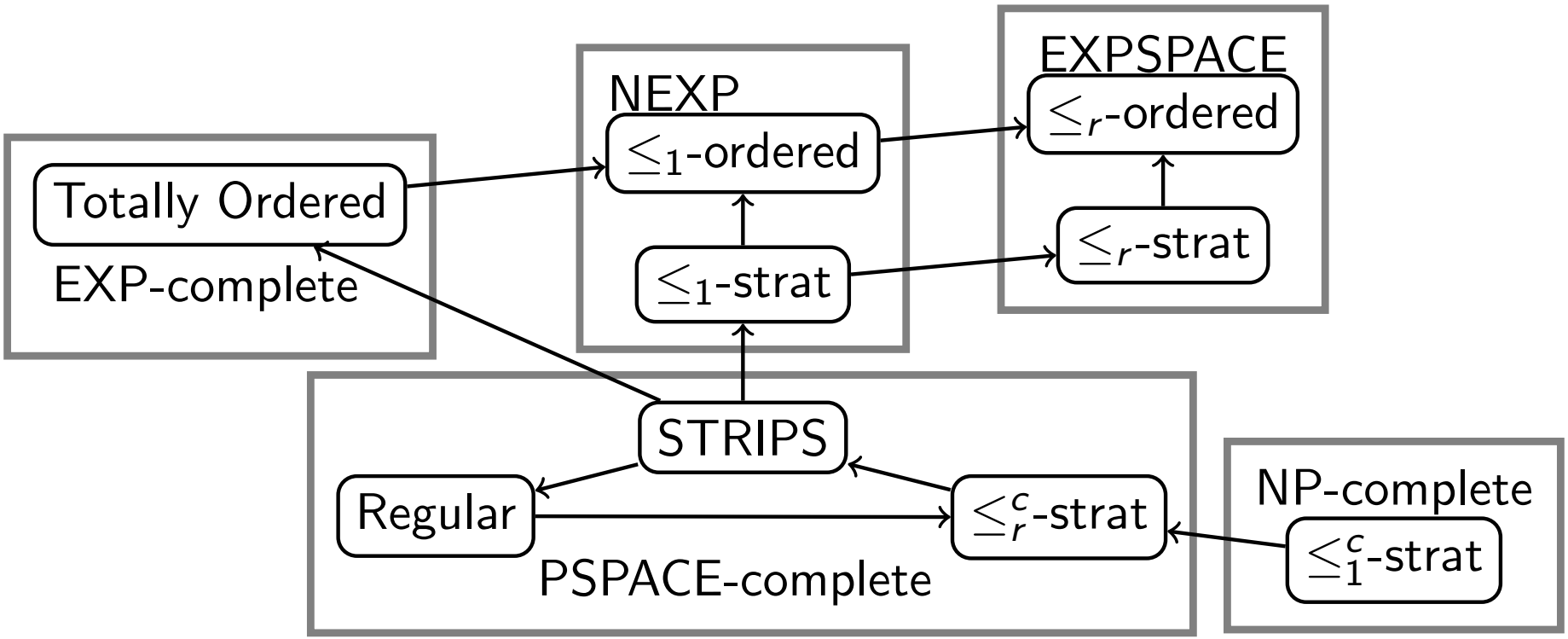
HTN Algorithms and Complexity

- Most HTN planners are sound and complete
  - HTN planning is undecidable
  - There are problems on which any set of planners will never terminate
  - In practice, we observe differences in how well they work. Why?
- General strategy:
  - Identify what problems each HTN algorithm halts on
  - Bound the run-time of the planner on those problems
- Given these problem classes, we can propose new HTN algorithms
  - Compare them to current ones on more than just an experimental basis
  - Two new algorithms in thesis

Before thesis



In the thesis



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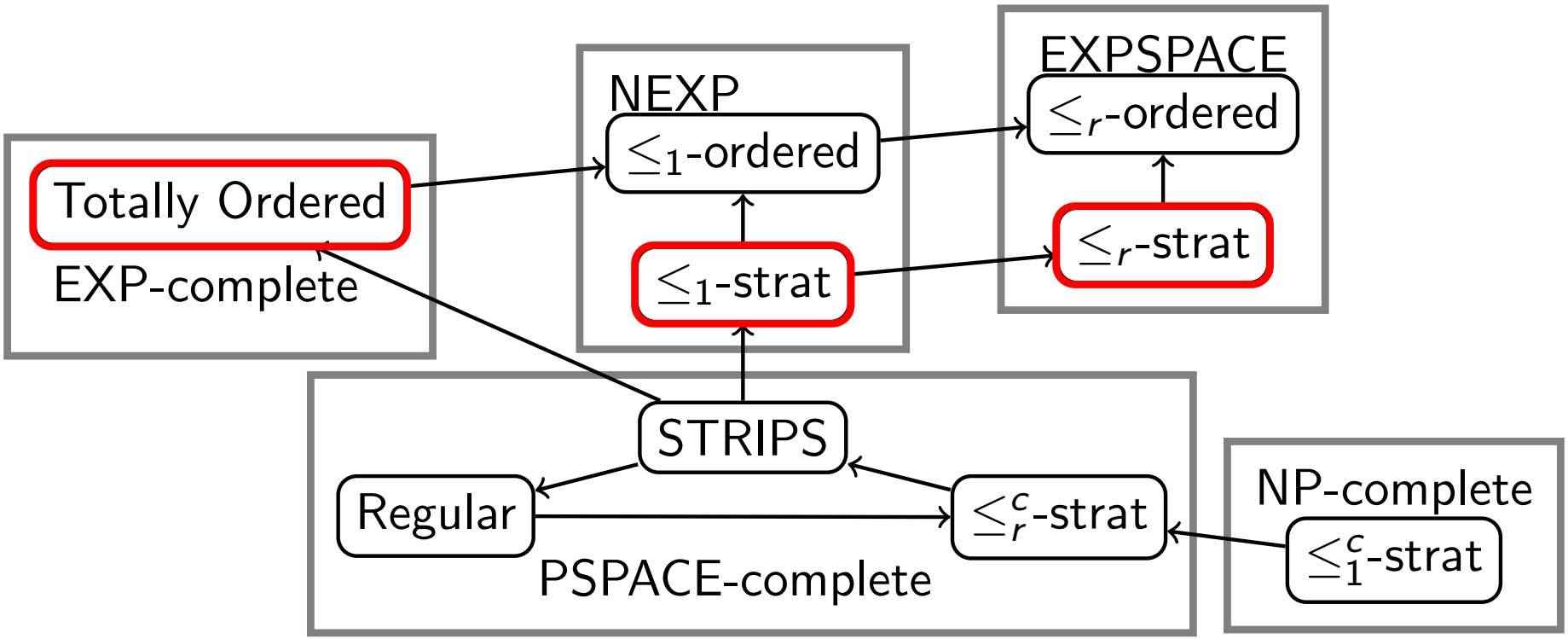
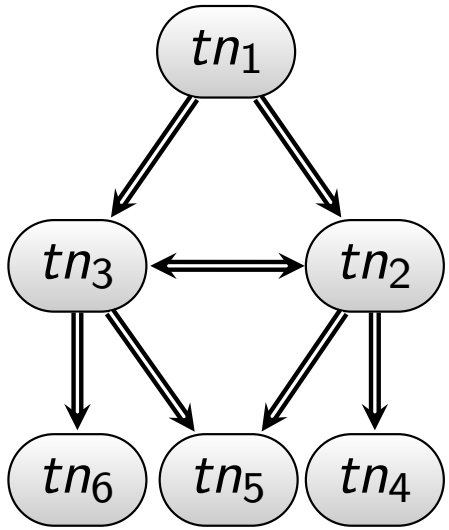


Decomposition as a graph

- UMCP (Erol 94), Landmark-aware HTN planner (Elkawkagy 2012) directly use the definition of decomposition to find solutions
- Starting at the initial task network, the choices form a graph:
  - Each vertex is a task network reachable via decomposition
  - Each edge is a decomposition
- Call this the *decomposition space* of a problem
- Plan by searching graph (not always finite)



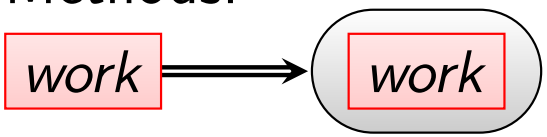
Decomposition-decided problems: $\leq_1$-stratification

- A domain is $\leq_1$-*stratifiable* if we can stratify its task names such that for every method $(t, tn) \in M$:
  - If tn has only one task, then tn's task is on an equal or lower stratum than t (trivially recursive decomposition)
  - Otherwise, every task in tn is on a lower stratum than t (acyclic decomposition)

Constraints:

- $strat(work) \leq strat(work)$

Methods:



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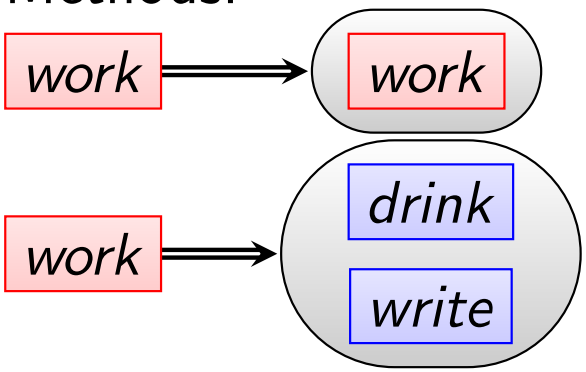

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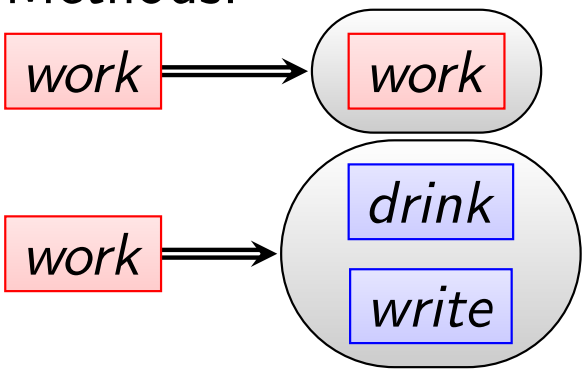

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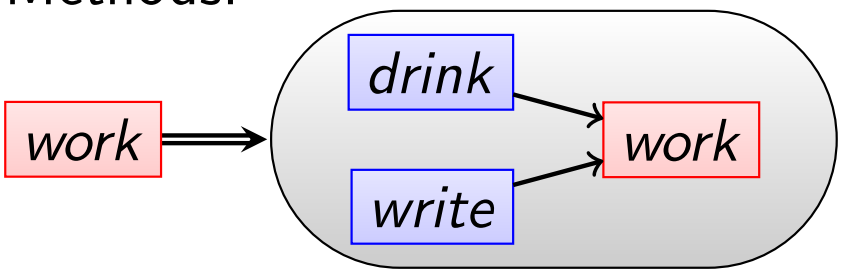

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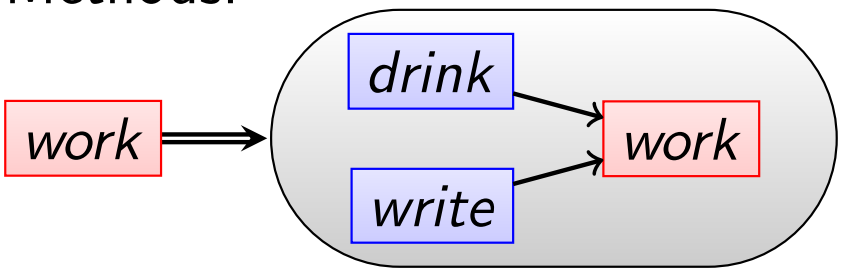

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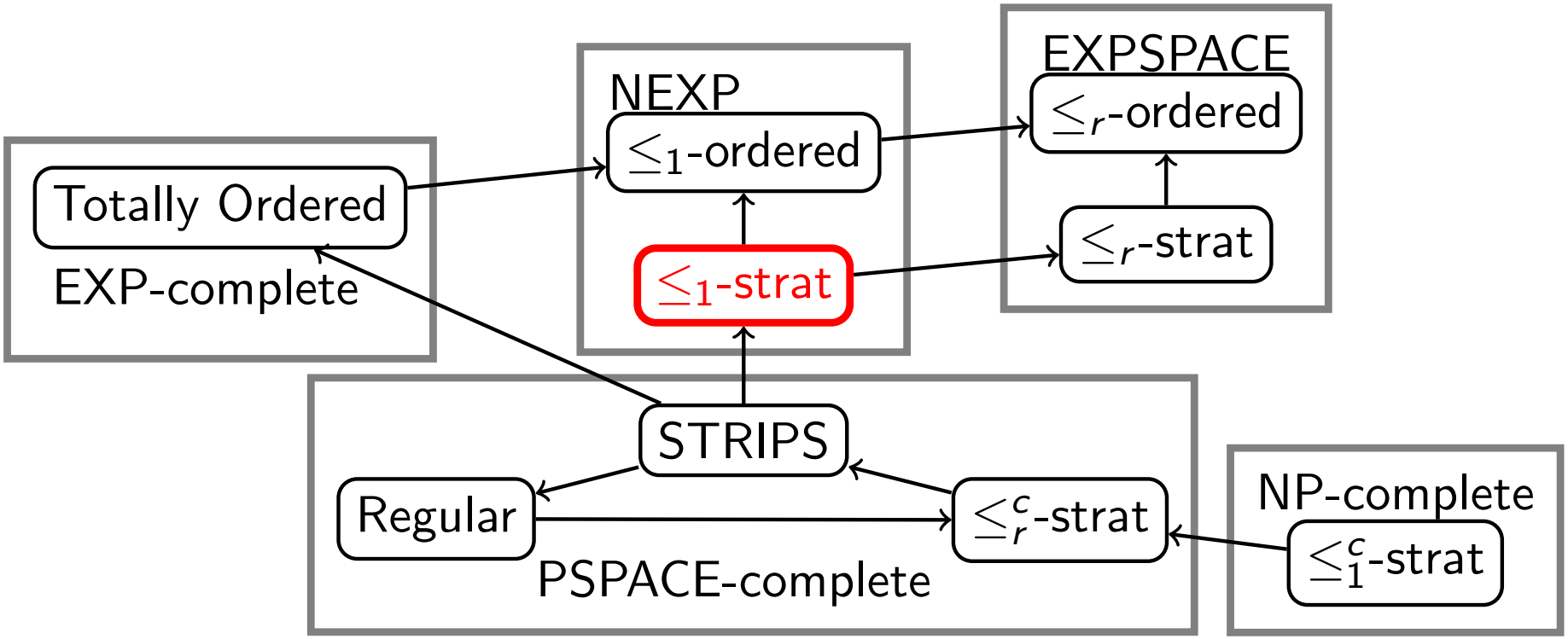
No stratification!

Decomposition spaces and $\leq_1$-stratifiable problems



From the thesis (but not in this talk):

- Theorem: Decomposition decides $\leq_1$-stratifiable problems and nothing else
- Plan existence is in NEXP for $\leq_1$-stratifiable problems
  - Can preprocess $\leq_1$-stratifiable problems into acyclic problems.

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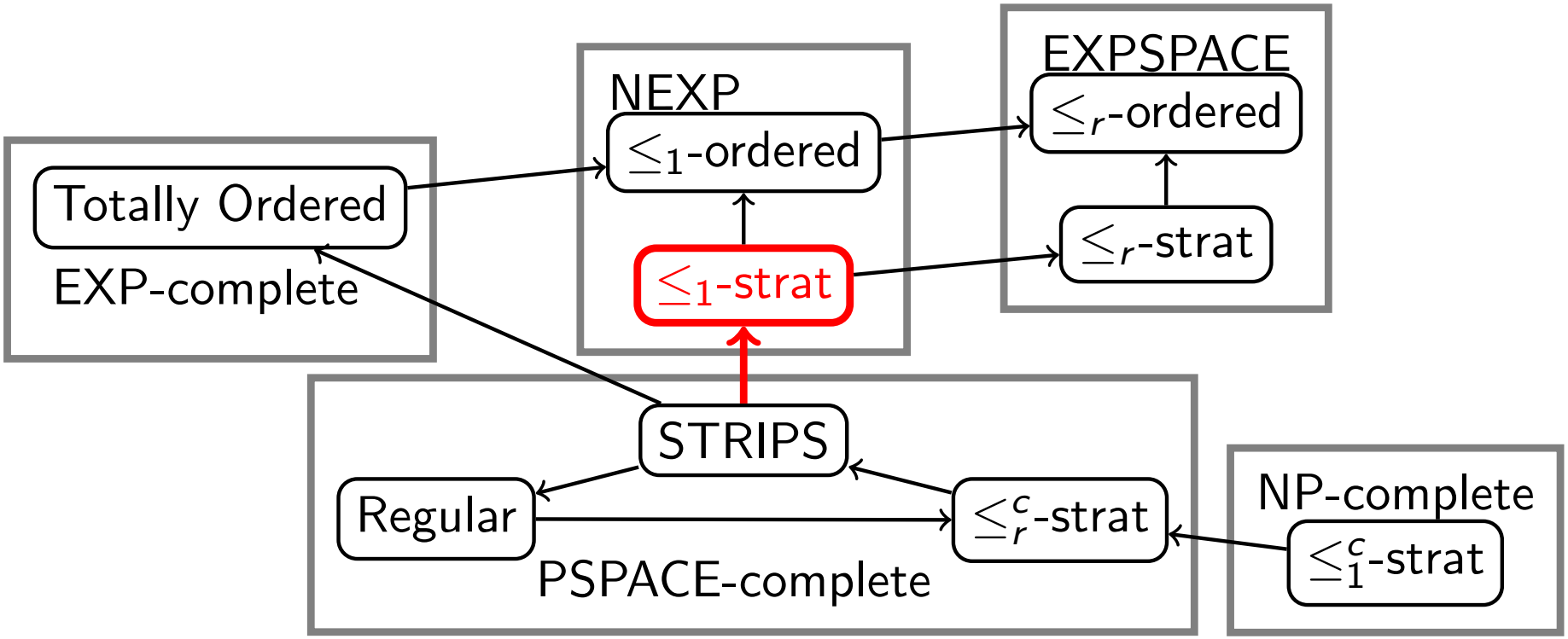

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- Plan existence is in NEXP for $\leq_1$-stratifiable problems
  - Can preprocess $\leq_1$-stratifiable problems into acyclic problems.
- But how hard is $\leq_1$-stratifiable planning?

$\leq_1$-stratifiable HTN planning is PSPACE-hard

Propositional classical planning (Propositional STRIPS)

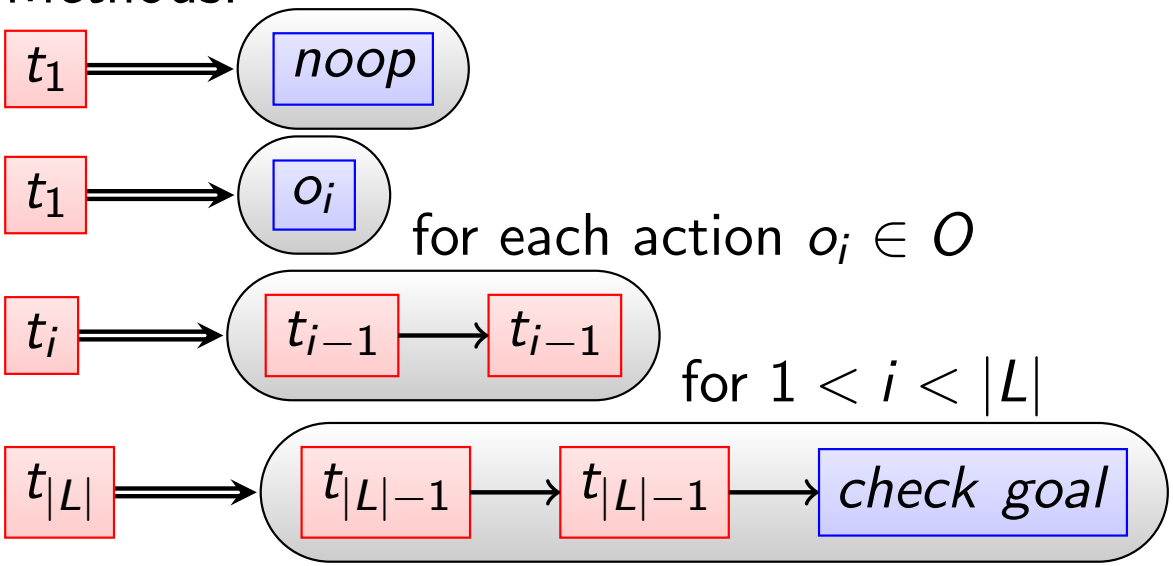
- Similar to HTN planning, but no methods
- Use any sequence of operators to obtain a given goal
- Plan-existence is PSPACE-complete (Erol et. al.)
- Shortest solution is always $< 2^{|L|}$, where L is the set of propositions in the language.

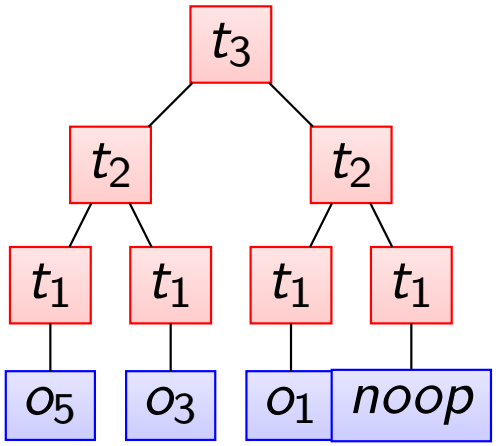
$\leq_1$-stratifiable HTN planning is PSPACE-hard

Encoding STRIPS in $\leq_1$-strat HTNs

Given a propositional STRIPS problem $(L, O, s, goal)$, create an HTN domain D with O, L, the tasks $t_1, \ldots, t_{|L|}$, and the following methods:

Methods:





Translated HTN Problem: $\left(D, s_0, t_{|L|}\right)$

Progression spaces for HTN planning

A number of HTN planners (SHOP, SHOP2, etc) plan for tasks in the order that they are to be executed. This is called *progression*.
For an HTN problem $P = (D, s_0, tn_0)$, we *progress* P by picking a task t in tn_0 with no predecessors. Then:

- If t is non-primitive:
  - Decompose t in tn_0, let tn' be the result
  - Then (D, s_0, tn') is a progression of P.
- If t is primitive ($t \in O$) and executable, then:
  - Apply t: $\gamma(s_0, t) = s_1$
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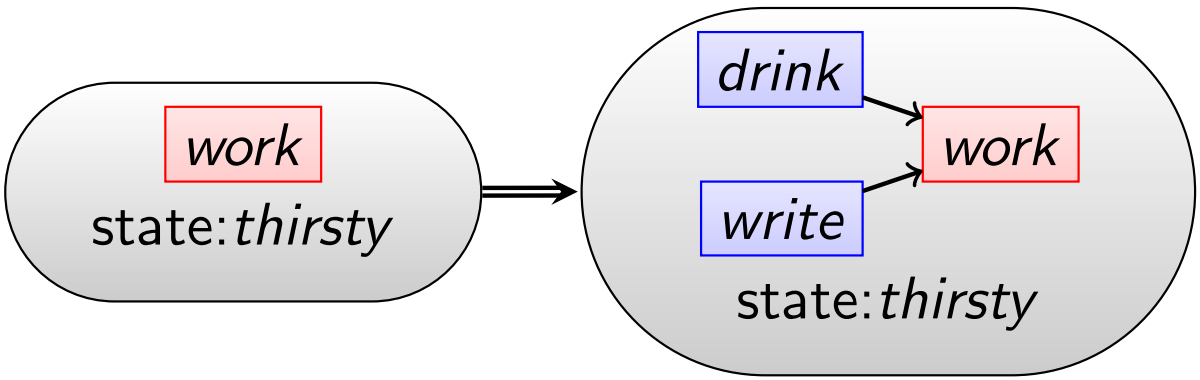

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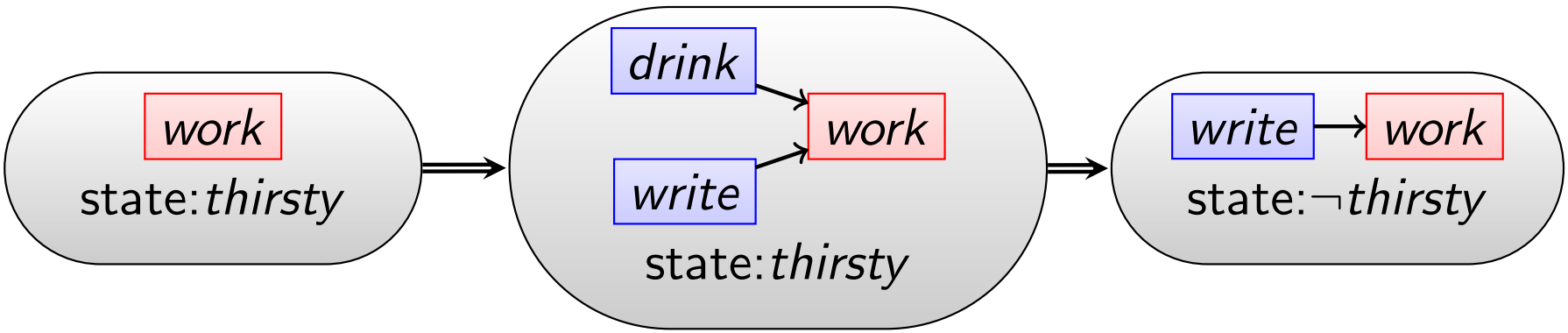
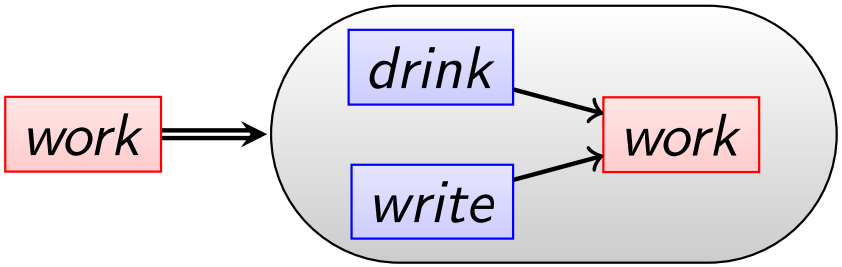


Progression-decided problems: $\leq_r$-stratification

- A $\leq_r$-stratification of task names: For every method (t, tn),
  - **Last task** on equal or lower stratum (tail recursion).
  - Every other task of tn must be on lower strata.

Methods:



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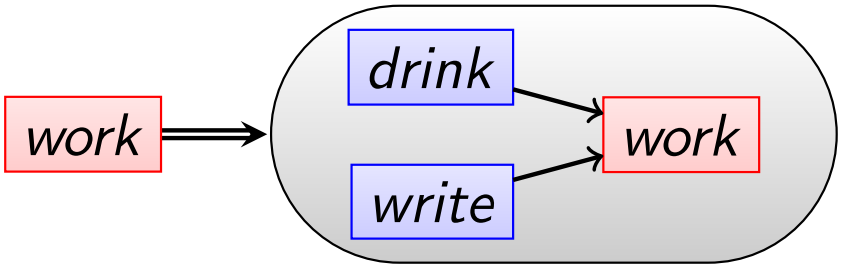

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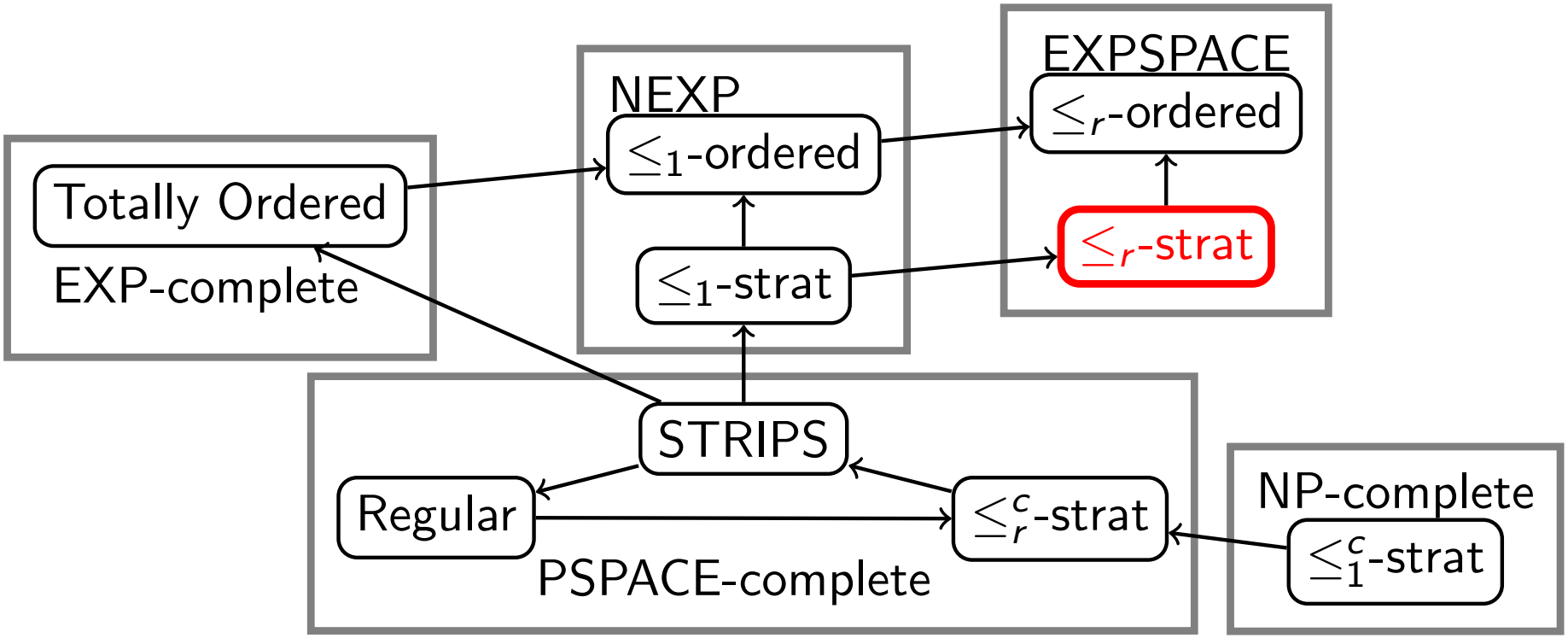
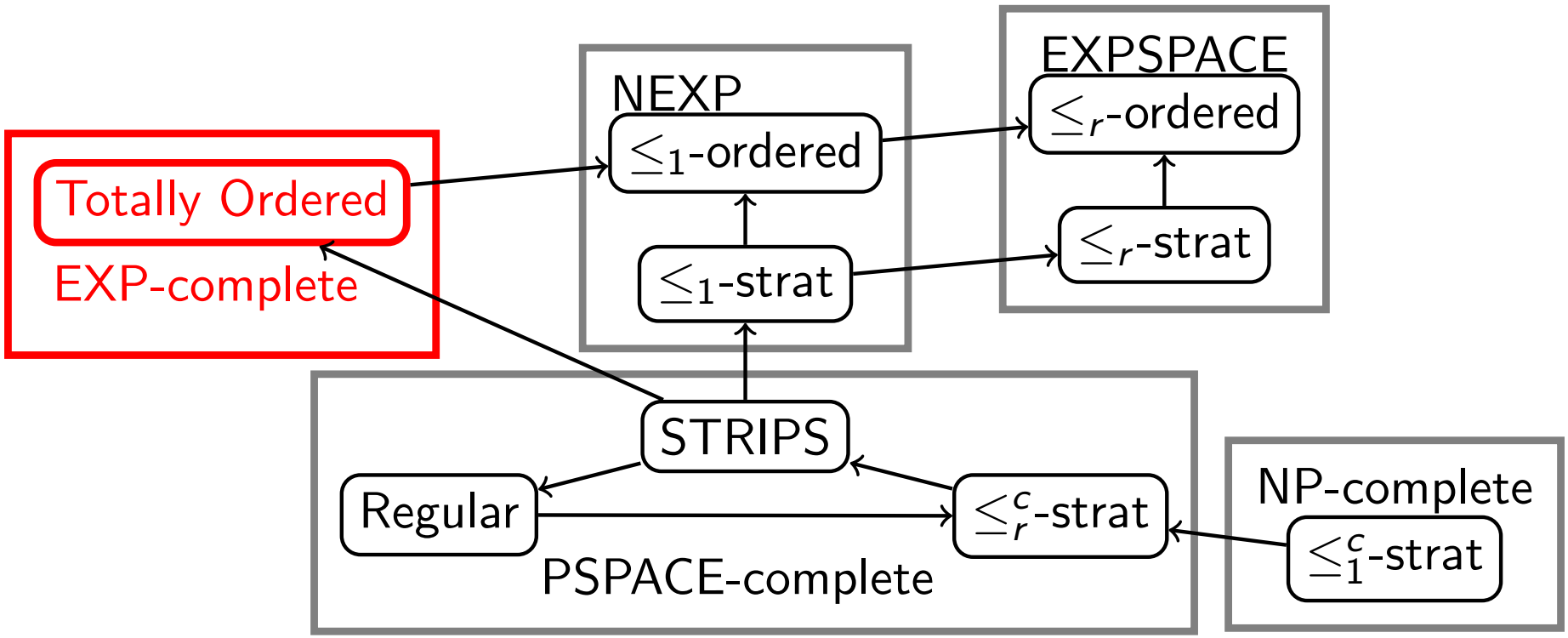


From the thesis (but not in this talk):

- Property: Every $\leq_1$-stratifiable problem is $\leq_r$-stratifiable
- Theorems: Progression decides $\leq_r$-stratifiable domains
  - No larger set of progression-decided problems identifiable from methods only
  - Plan-existence in EXPSPACE for $\leq_r$-stratifiable since it's unclear what the bound is for length of a solution

Totally-Ordered Planning is EXP-time complete



- Totally-Ordered HTN Problems: Initial task network and all method networks are totally ordered.
- Known to be in EXP-time (Erol et. al., TOPHTN from thesis)

Totally-Ordered Planning is EXP-time complete

Totally Ordered Planning:

- Good at Palindromes! The following methods always return to the same state the task '*check*' starts in:

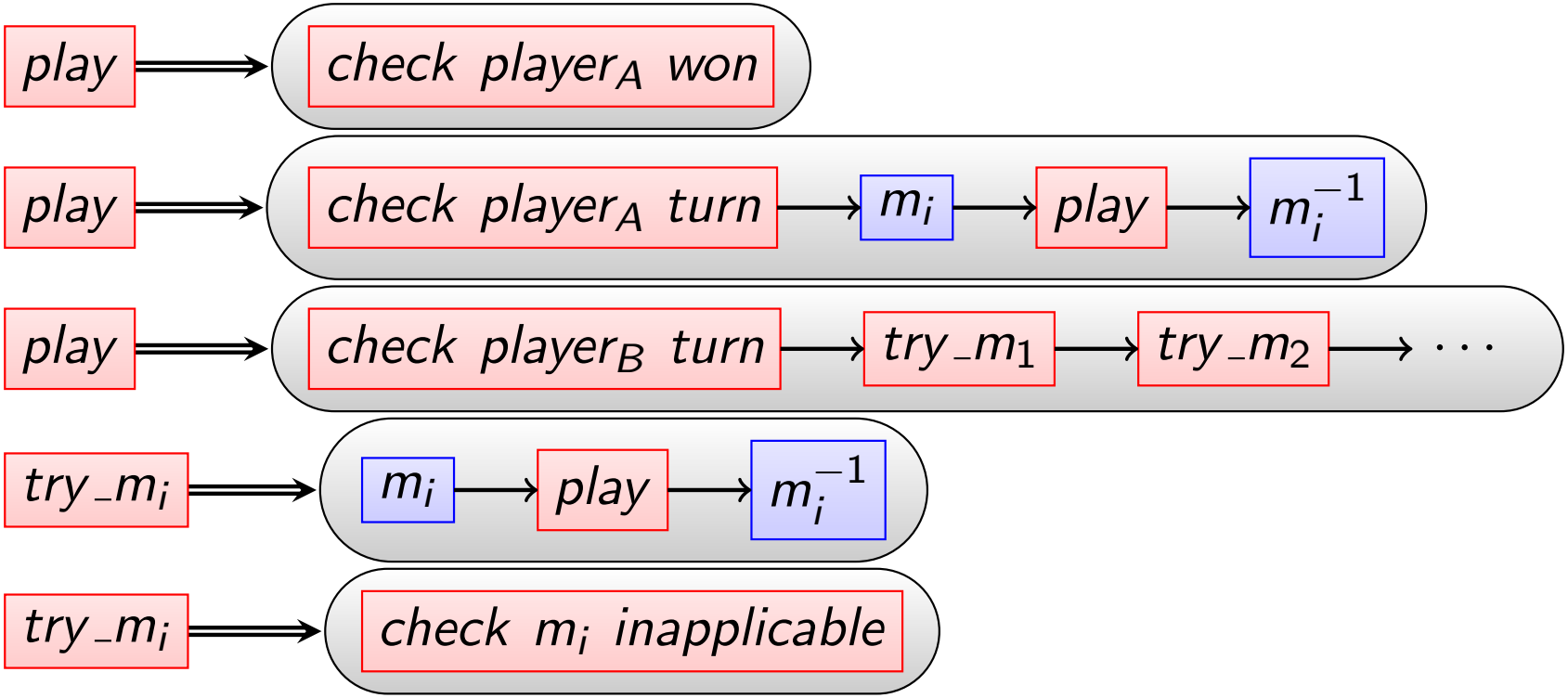
Methods:

- Generalized checkers, chess, versions of Go are all EXP-complete
- We can use palindrome like methods to encode position evaluation as an HTN problem

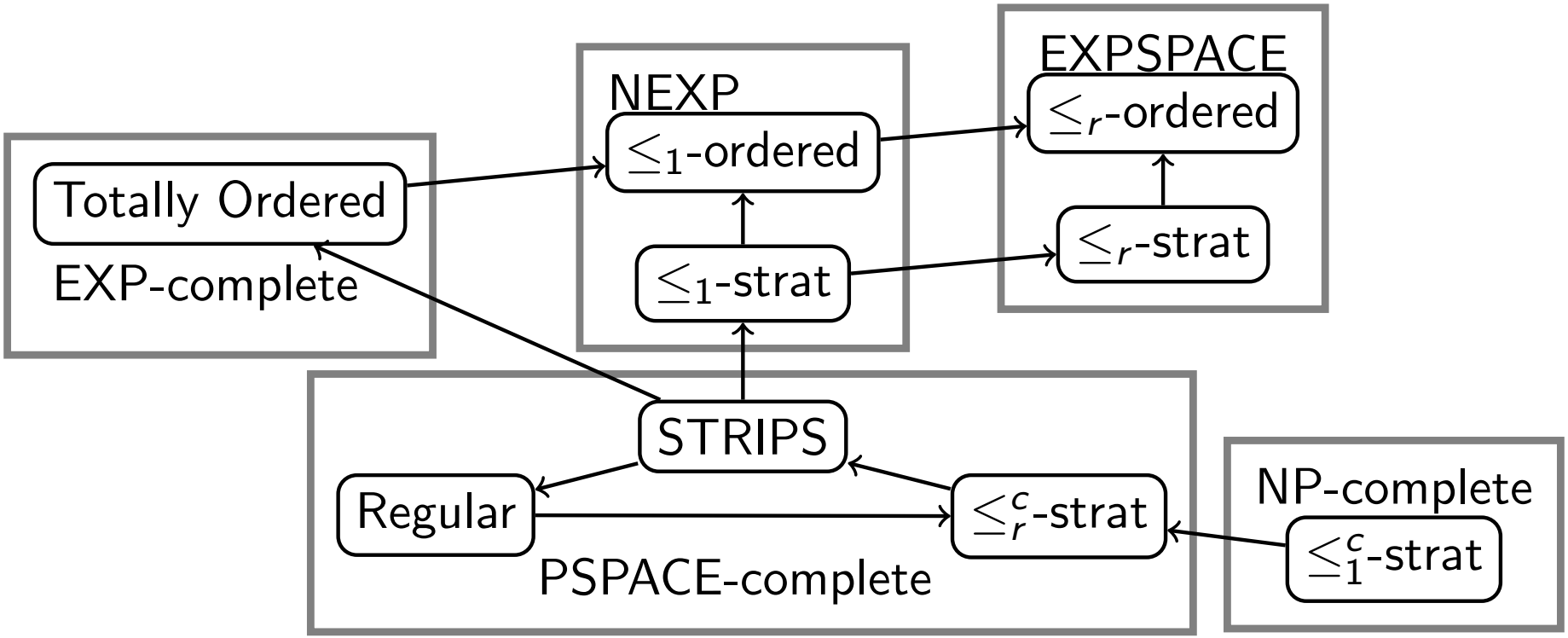
Encoding game tree search

Encoding game tree search: Can $player_A$ force a win?

Methods:



Summary



Characterized four different problem spaces for HTN problems:

- Provided terminating HTN planning algorithms for each space.
- Provided syntactic checks for finiteness for each space.
- Provided expressivity and running-times for syntactically identifiable problems

Outline

Heuristics

Domain independent heuristics in search:

- Problem spaces are still intractably large to search
- A heuristic underestimates the distance to nearest solution, or we pretend it does
- Usually based on solving a *relaxed problem*
  - Should take low-order polynomial time to solve
  - Solution to full problem implies solution to relaxed problem (but not vice versa)

Delete-Free Planning

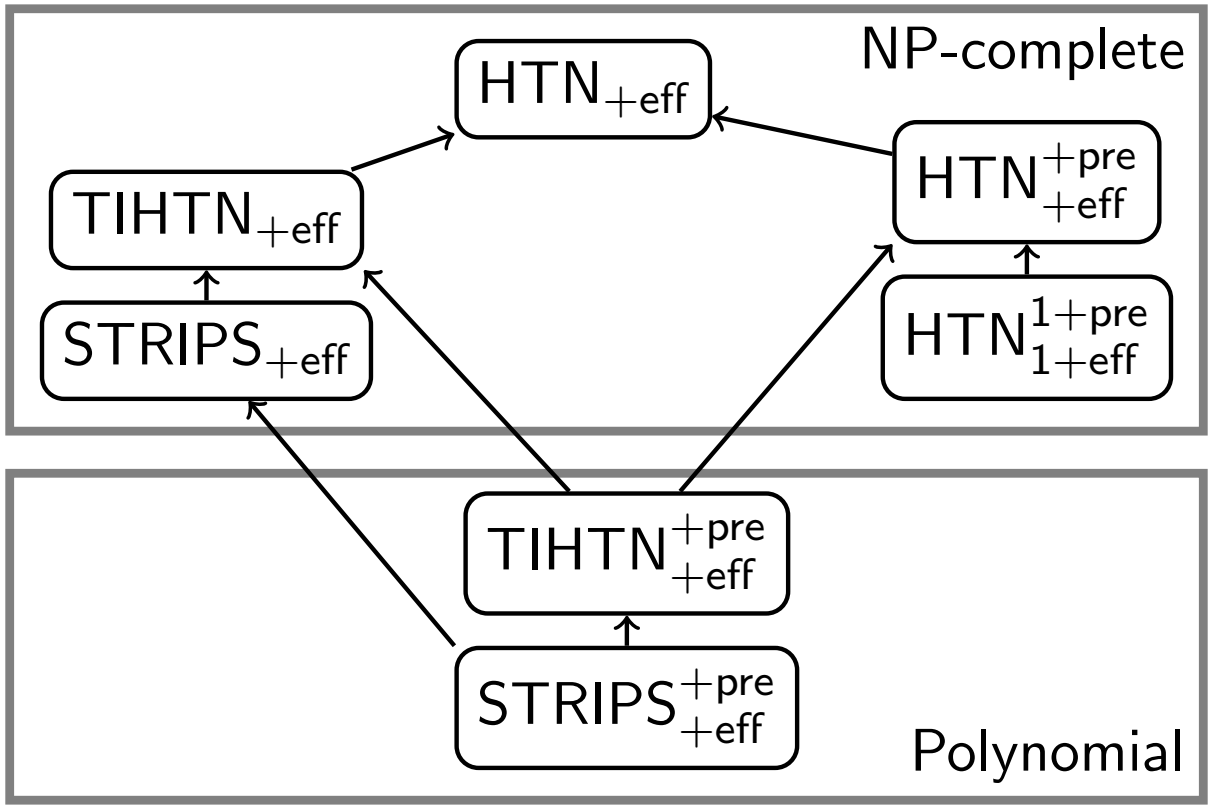
Delete-Free Planning In STRIPS:

- All operators have positive preconditions and effects; positive goal
- Poly-time to find a plan: just apply operators until a fixed point is reached
- NP-hard to find optimal plan
- Basis for the most influential classical planning heuristics

Delete-Free HTN Planning:

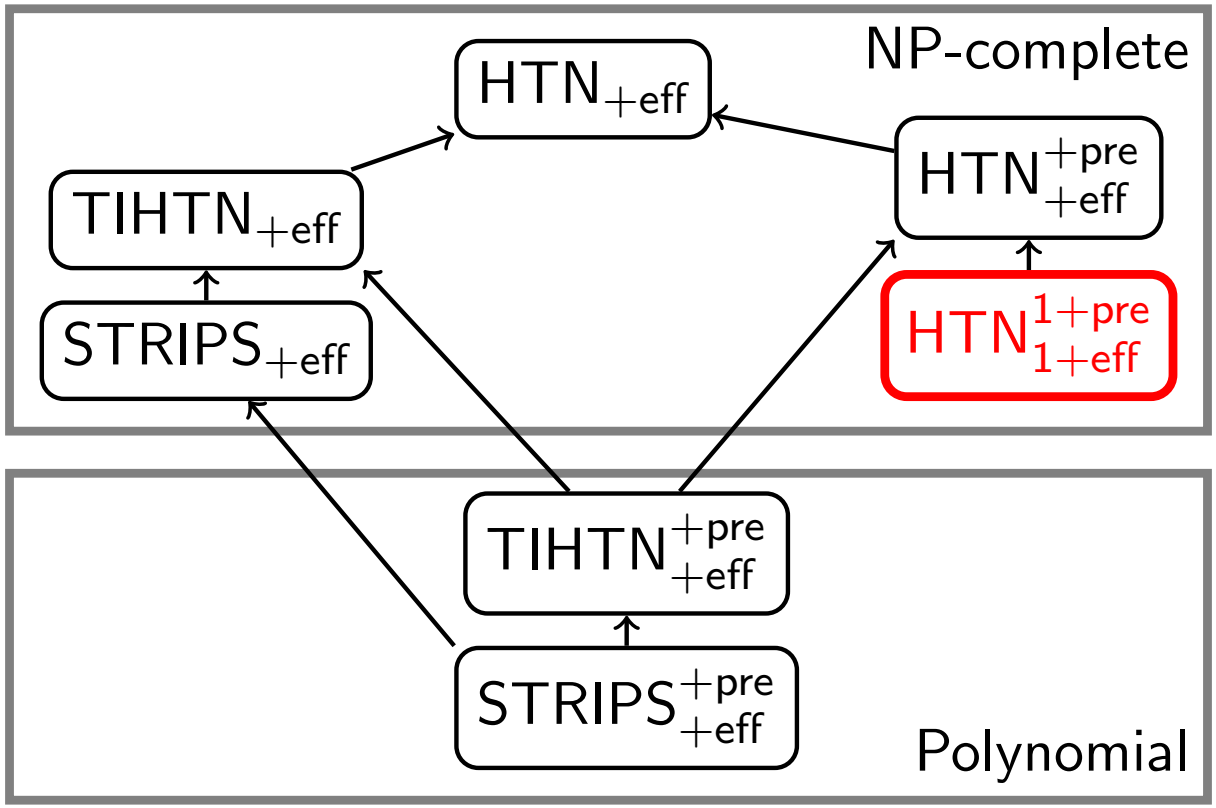
- Positive preconditions and effects
- Decidability and complexity previously unknown

Delete-free HTN planning is NP-complete



- Complexity of plan-existence for propositional delete-free STRIPS and HTN planning with various restrictions. Arrows represent subclass relationships
- The STRIPS results are from Bylander; the other results are new

Delete-free HTN planning is NP-complete



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Delete-Free HTN planning is NP-hard

CNF-SAT: $(V_1 \vee \neg V_3 \vee V_4) \wedge (V_2 \vee V_3 \vee \neg V_4) \wedge \cdots$

Translation of setting variables to delete-free HTN planning:

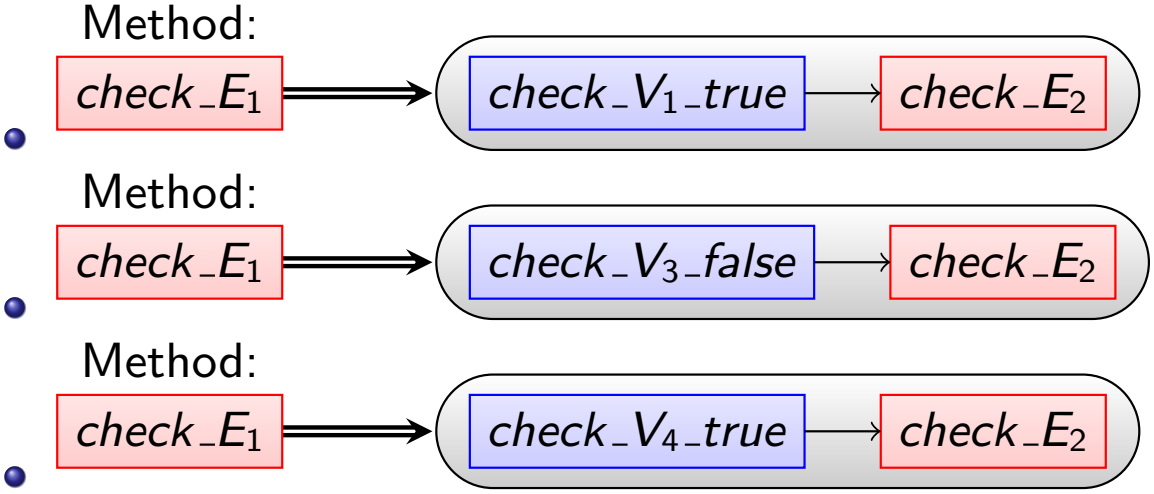
- For each variable V_i:
  - Two propositions: V_i_true, V_i_false
  - Two test operators: $check\_V_i\_true$, $check\_V_i\_false$
  - Two set operators: $set\_V_i\_true$, $set\_V_i\_false$
  - Two methods:
    - Method: set_V_i ⟹ $set\_V_i\_true$ → set_V_{i+1}
    - Method: set_V_i ⟹ $set\_V_i\_false$ → set_V_{i+1}
  - For last variable, replace last task with $check\_E_1$, instead

Delete-Free HTN planning is NP-hard

CNF-SAT: $(V_1 \vee \neg V_3 \vee V_4) \wedge (V_2 \vee V_3 \vee \neg V_4) \wedge \cdots$

Translation of testing the clauses to delete-free HTN planning:

- For disjunctive clause E_i:
  - A method for each literal



  - For last clause, drop the final *check* task

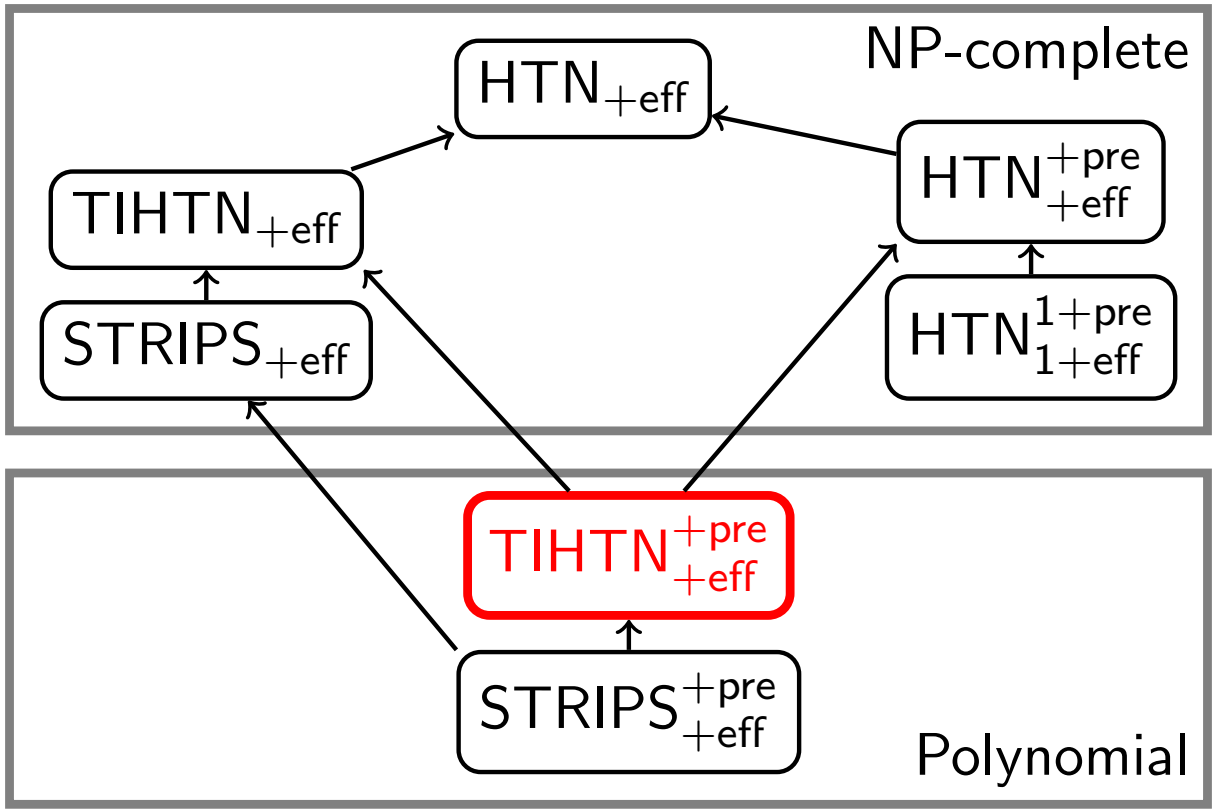
Delete-Free HTN planning is NP-complete

- Polynomial encoding of CNF-SAT means delete-free HTN planning is NP-hard.
- We can also show delete-free HTN planning is in NP(in thesis), so it is NP-complete.
- So we need to relax the semantics of HTN planning to find a poly-time heuristic.

Delete-Free Task-Insertion HTN Planning

- Need to relax HTN semantics to find poly-time heuristic
- Task-Insertion HTN (TIHTN) Planning:
  - Allows insertion of arbitrary operators into task network
- Delete-free TIHTN planning is poly-time:
  - Insert operators until you reach a fixpoint
  - Test to see if tasks are executable in the fixpoint state (similar to testing if a CFG is empty).

Relaxed-semantics HTN heuristics exist



- So there exist poly-time heuristics for HTN planning. But if they deviate significantly from HTN semantics, will they still be useful?

Outline

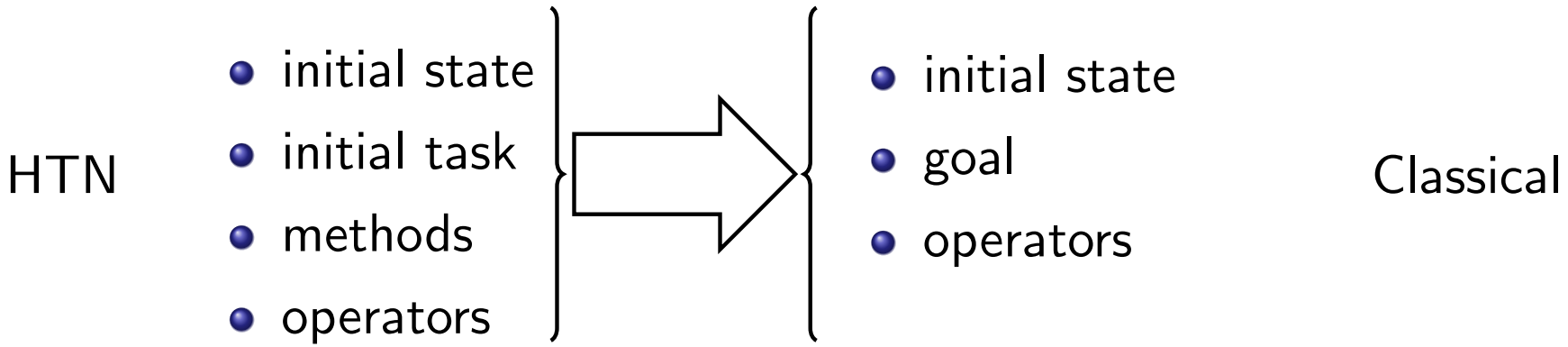
Translating to Classical Planning:

Motivation

- Variety of domain independent heuristics
- Highly tuned search implementations
- Want to make use of these for HTN planning!

HTN Planning via translation to Classical Planning

- Both STRIPS and totally-ordered $\leq_r$-stratifiable planning are PSPACE-complete
- We can translate any totally-ordered $\leq_r$-stratifiable HTN problem into a classical planning problem.
- To do this, we translate the progression space of an HTN planner into the state space of a classical planner:

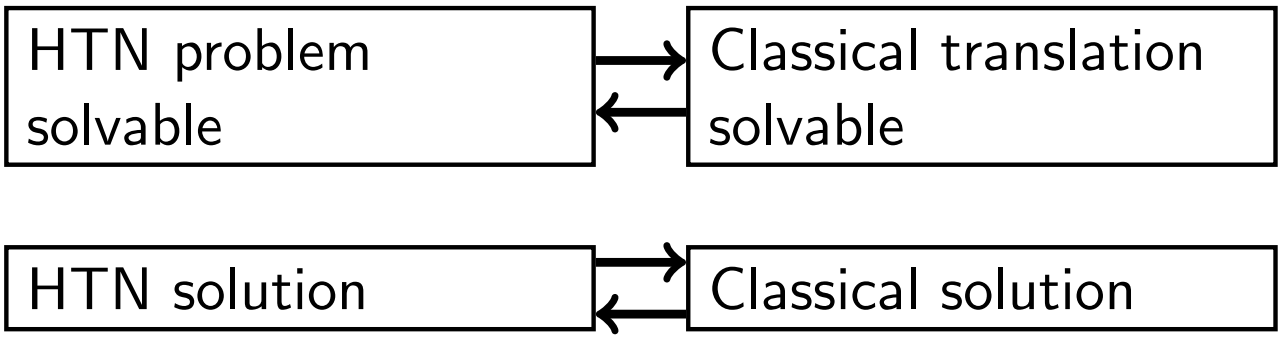


- (detail in the thesis)

Formal Properties

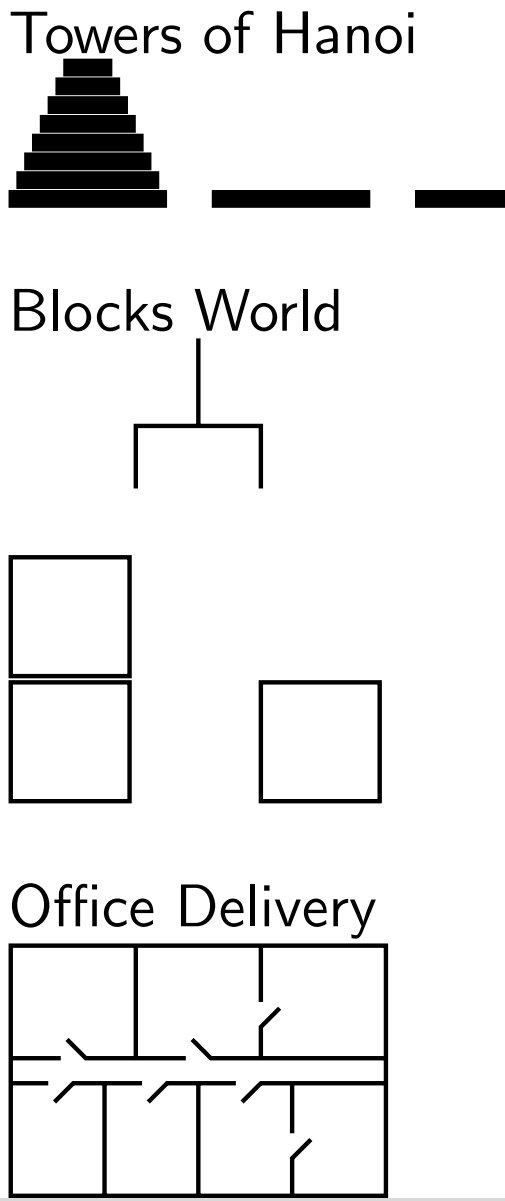
Given an $\leq_r$-stratifiable problem:

- A solution to the translated problem $\iff$ a solution to the HTN problem
- Any classical planner is now an HTN planner (free heuristic function to guide the search and often guaranteed termination).



Experiments

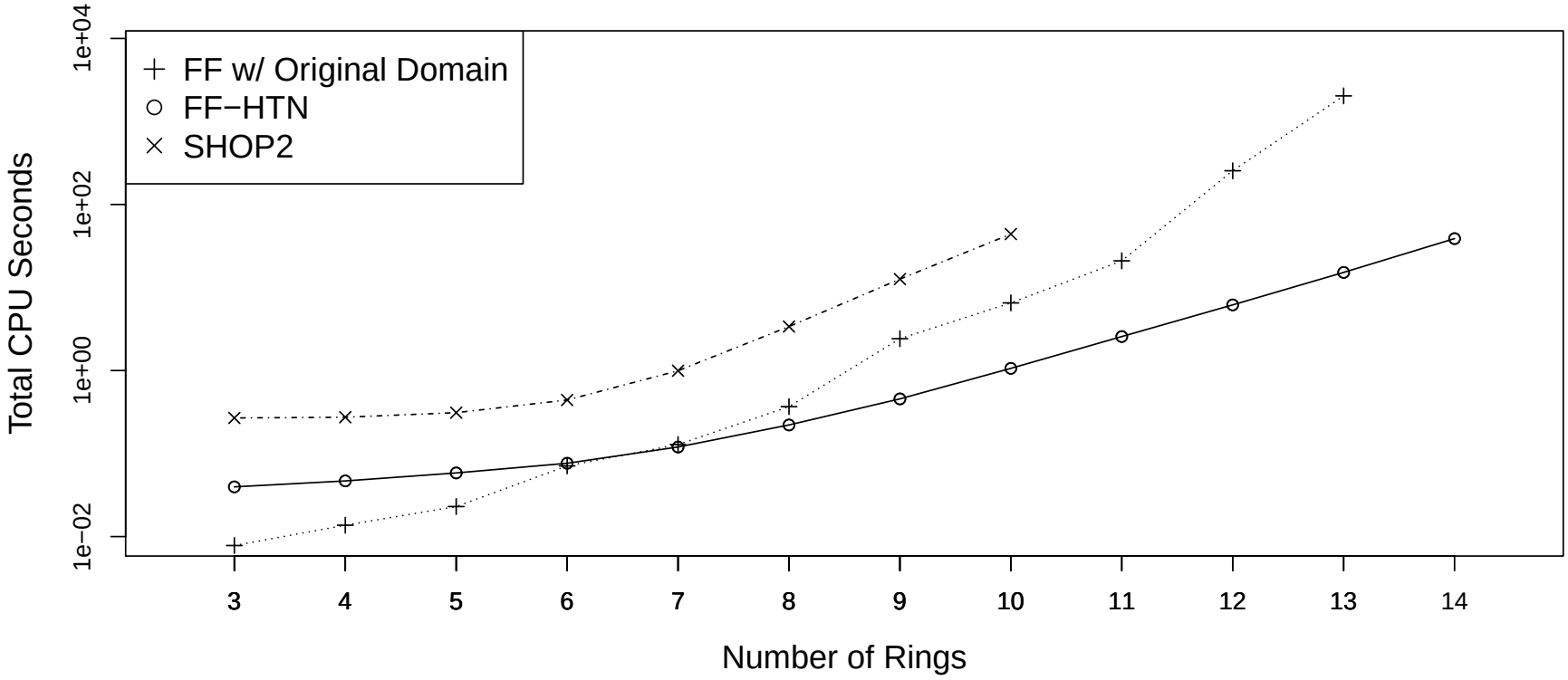
- Took FastForward (FF) [Hoffmann and Nebel, 2001]
  - FF is a well known classical planner
  - Investigated how well FF did on its own
  - Investigated how FF did with a translated HTN
- Compared against SHOP2 [Nau et al., 2003]
  - SHOP2 is an influential HTN planner
  - Used here with depth-first search
- 3 domains, about 5000 experiments:
  - Towers of Hanoi
  - Blocks World
  - An office delivery domain



Results: Towers of Hanoi

- Exponentially long plans
- No branching in the HTN domain
- Average of 100 runs / point

- FF with the translated HTNs runs exponentially faster
- SHOP2 timed out after 10 rings
  - Most likely a performance bug

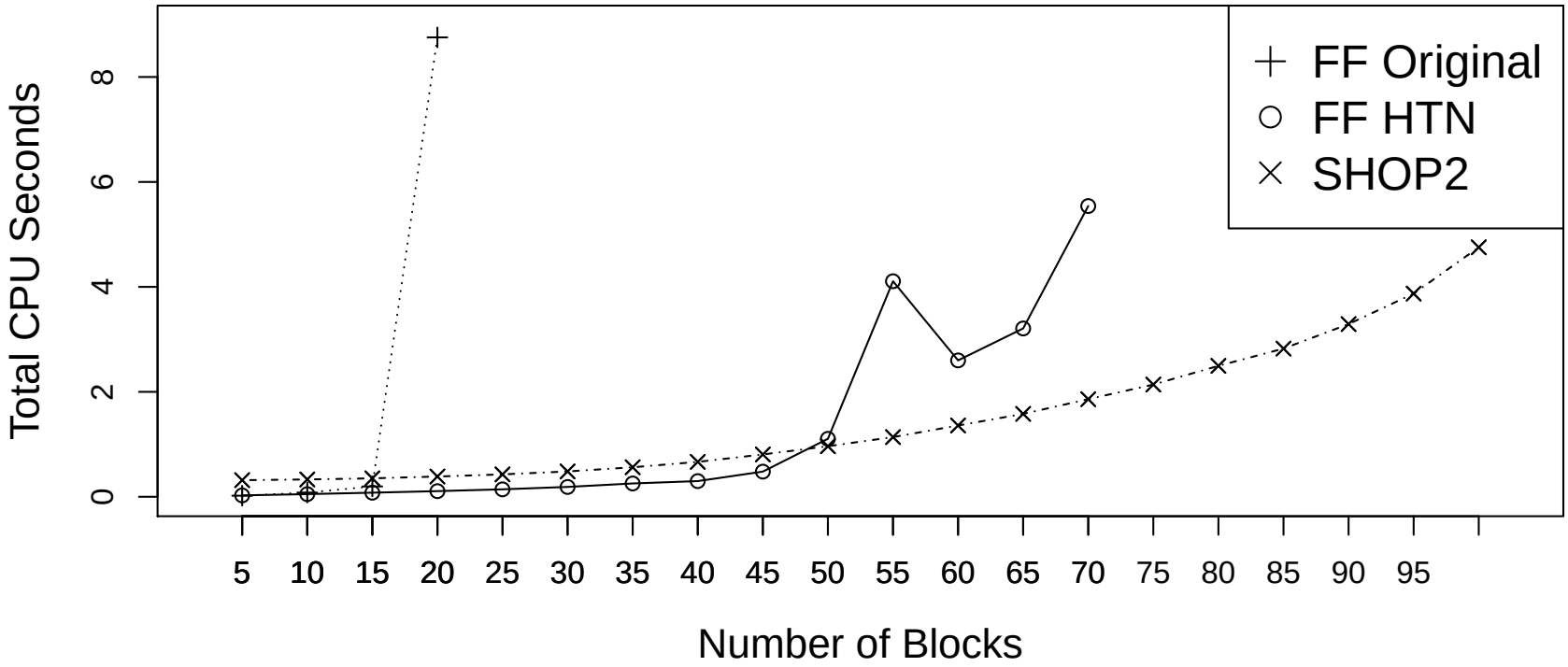


Results: Blocks World Time

HTN description

- Forces a polynomial length plan
- Does not enforce optimal solution

- FF's heuristic is known poor at blocks world
- FF with translated HTNs can solve problems up to 70 blocks in size
- SHOP2 scaled better after 50 blocks.

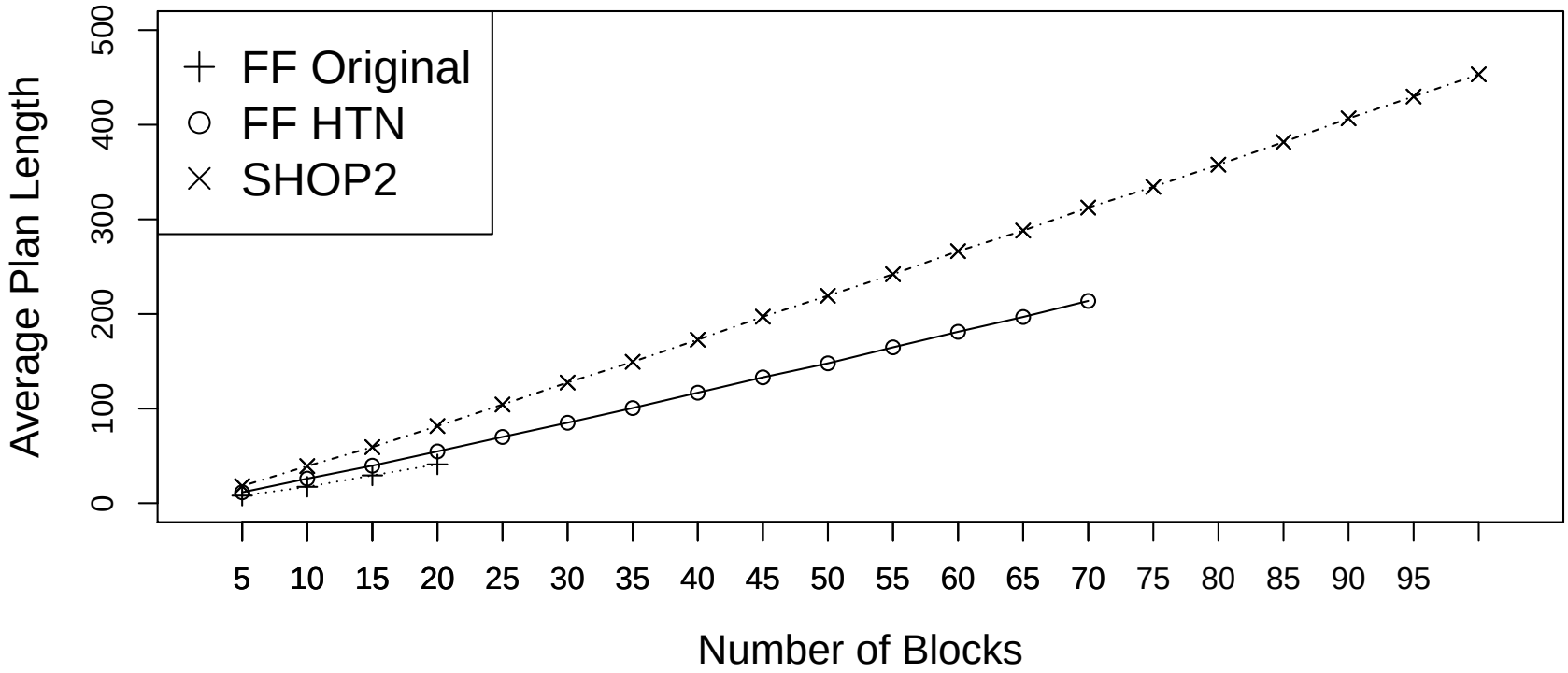


Results: Blocks World Plan Length

HTN description

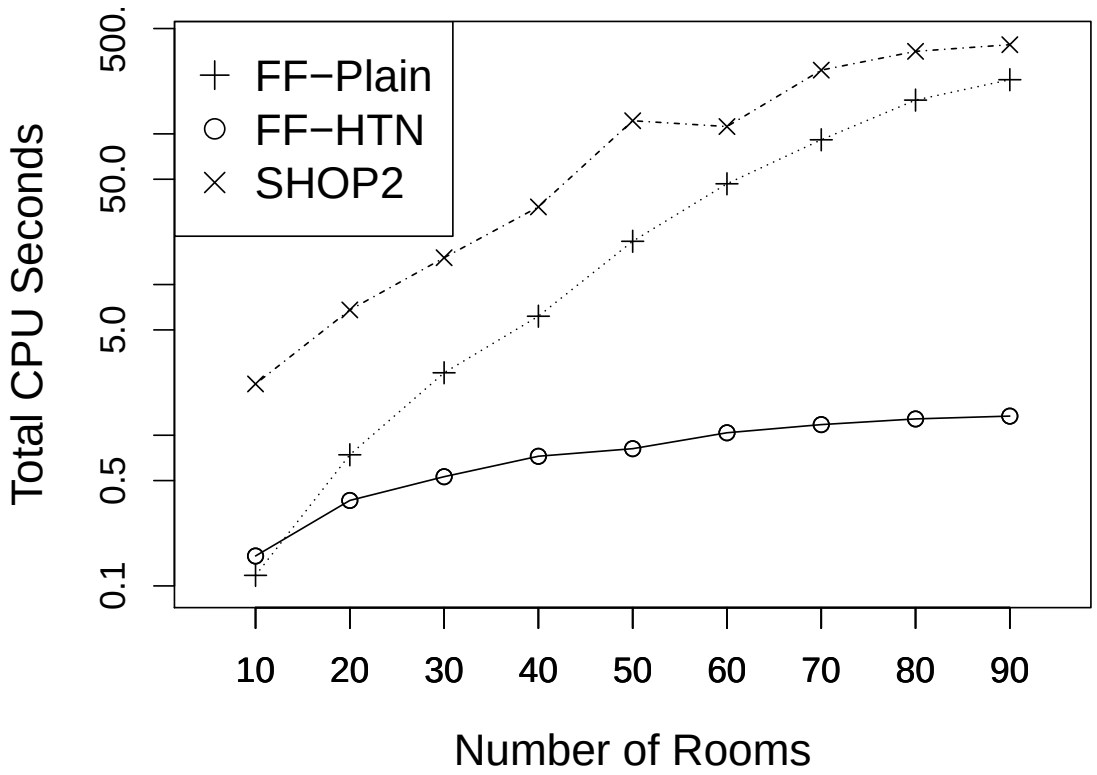
- Forces a polynomial length plan
- Does not enforce optimal solution

- FF with HTNs produced better plans than SHOP2
- HTNs forbid some optimal solutions, hence the plans were not the shortest possible



Results: An Office Delivery Domain

- Office delivery: Pick up packages, deliver to another room.
- HTNs orders 'pickup'/'putdown' actions
- No guidance on what room to move to.



- SHOP2 has no heuristic to guide navigation
- FF without HTNs is poor at package management
- FF with HTNs returns plans exponentially faster than either of the above.

Summary

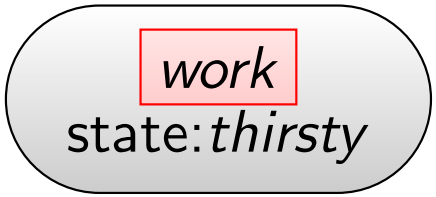
- Four problems spaces for HTN planning
  - Syntactic checks for when those spaces must be finite
  - Algorithms to search these spaces (unimplemented)
  - Expressivity and running times for identified spaces
- Theoretical results impacting HTN heuristics:
  - Delete-free HTN planning is NP-complete
  - Poly-time relaxed-semantics variants exist
- An HTN-to-Classical translation for any totally-ordered $\leq_r$-stratifiable problem

Contributions

Provided:

- Theoretical background to compare HTN planning search algorithms
- Theoretical limits on fidelity of HTN heuristics
- Evidence that heuristic search is effective for HTN planning

Progression Example (over problems, not task networks)



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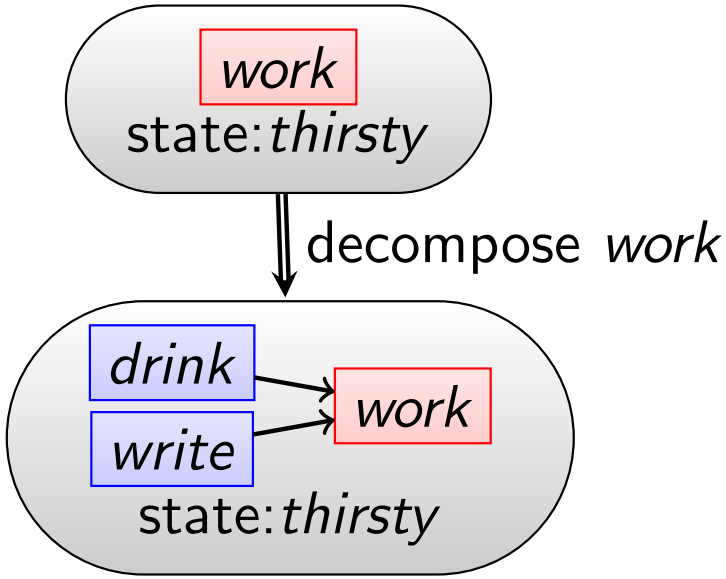

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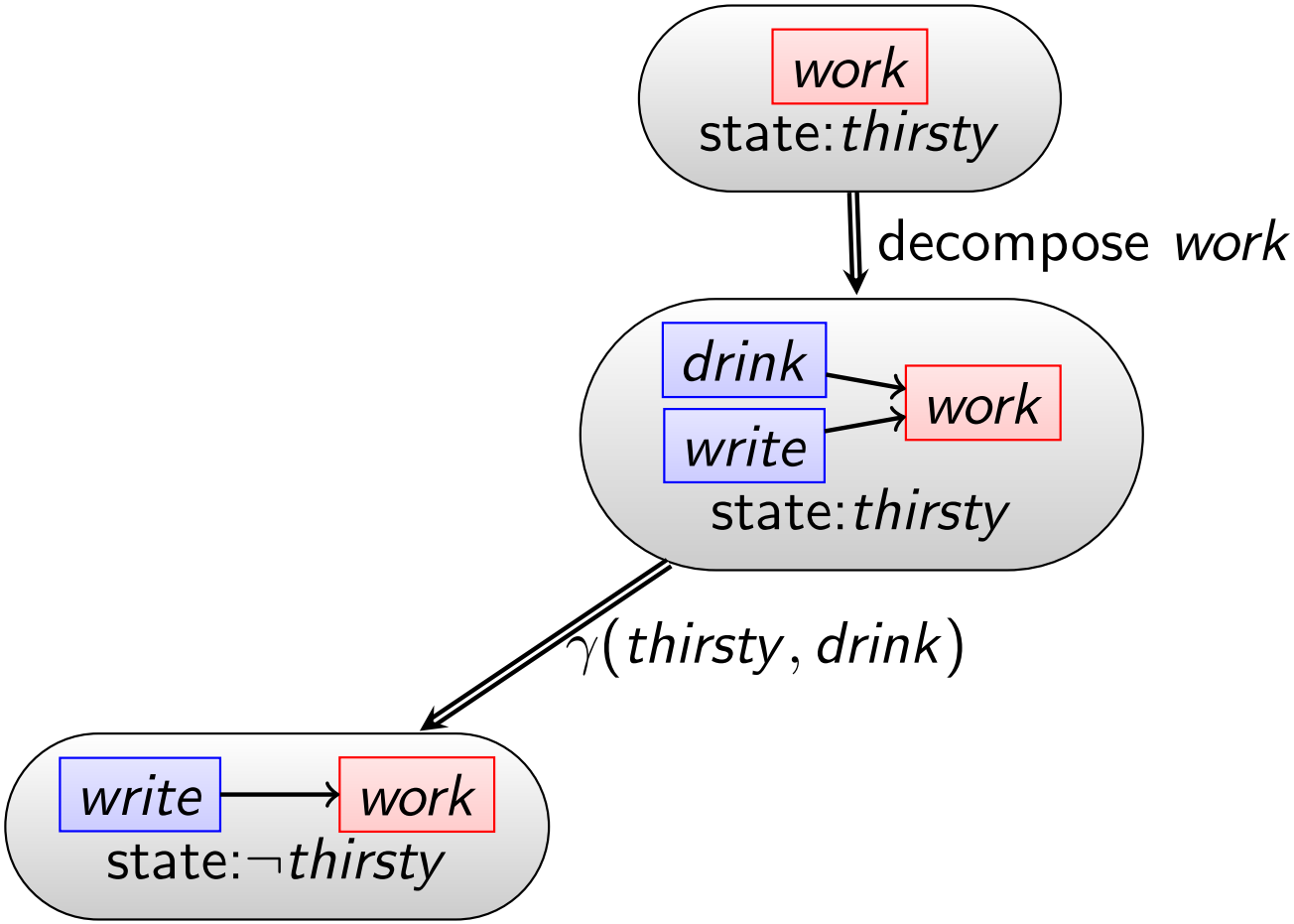

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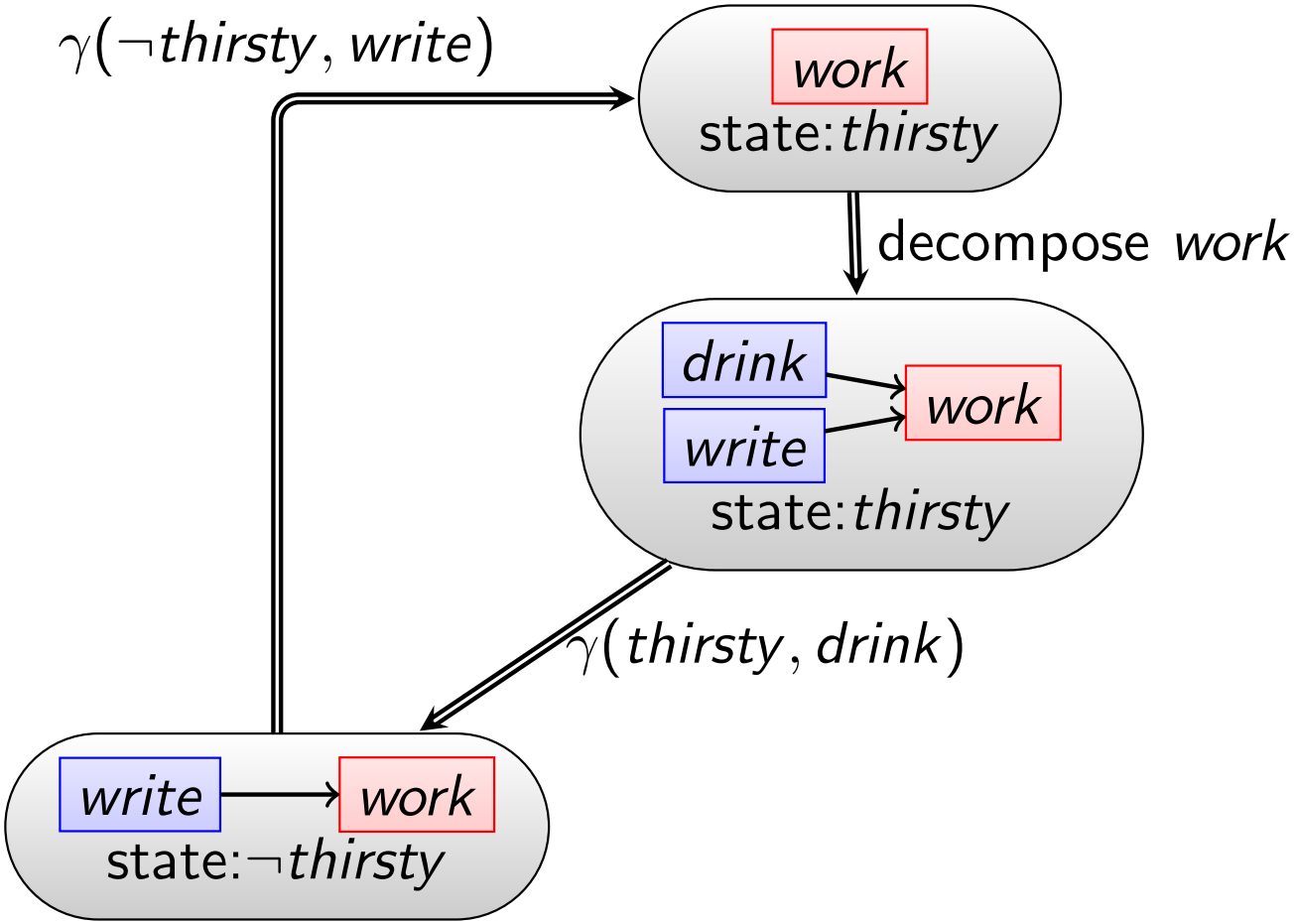

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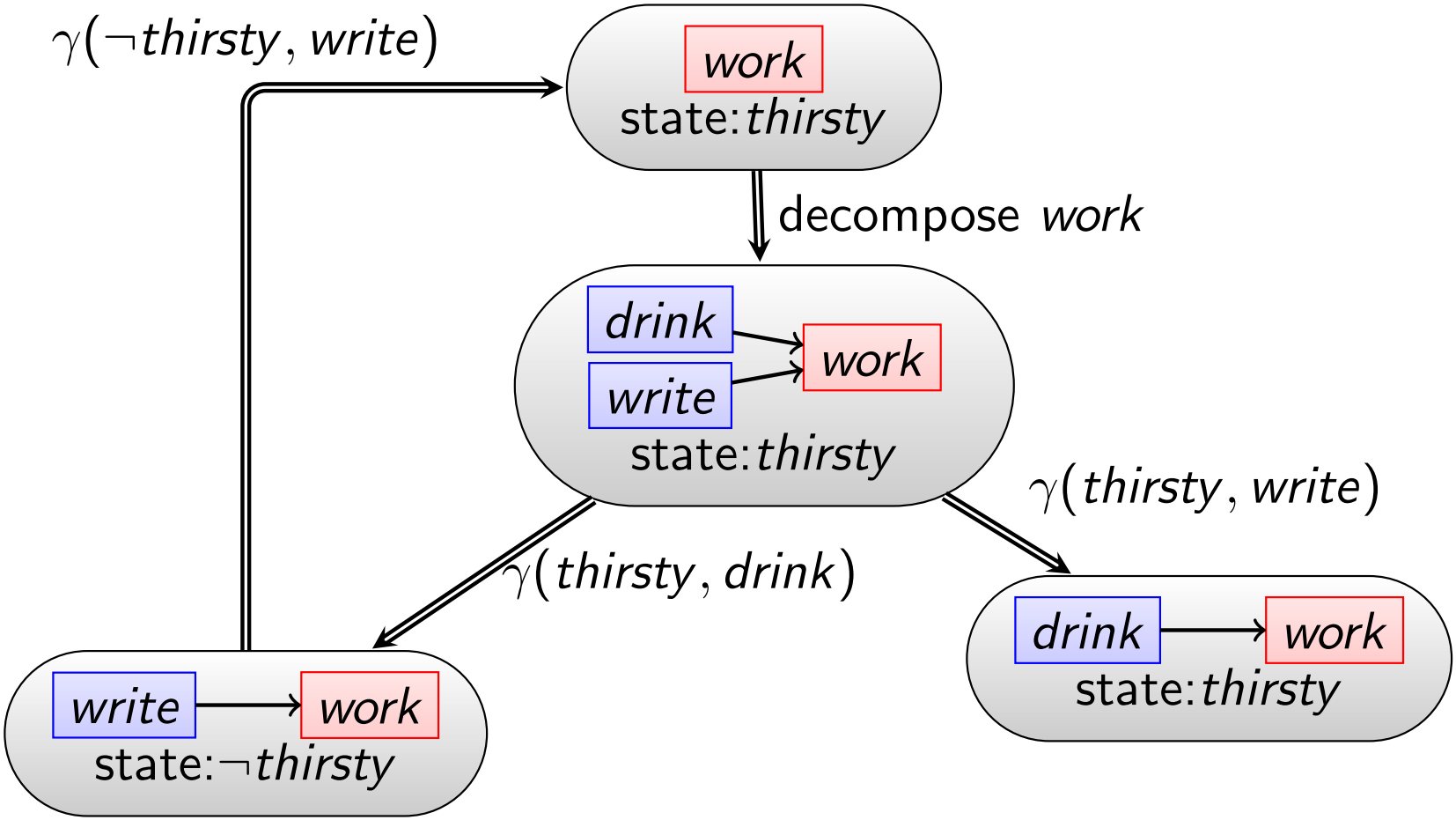

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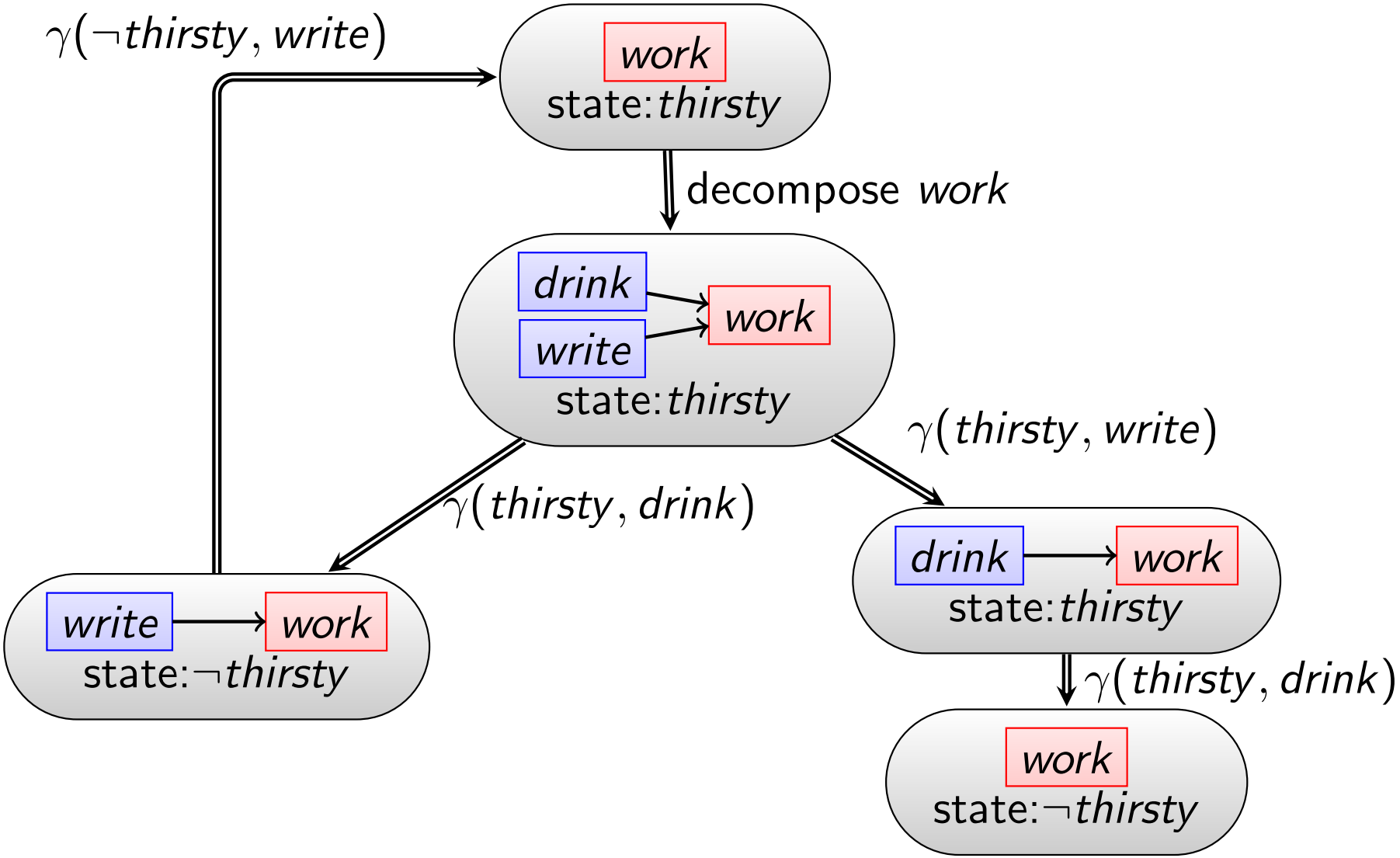


Totally-Ordered $\leq_r$-stratifiable problems

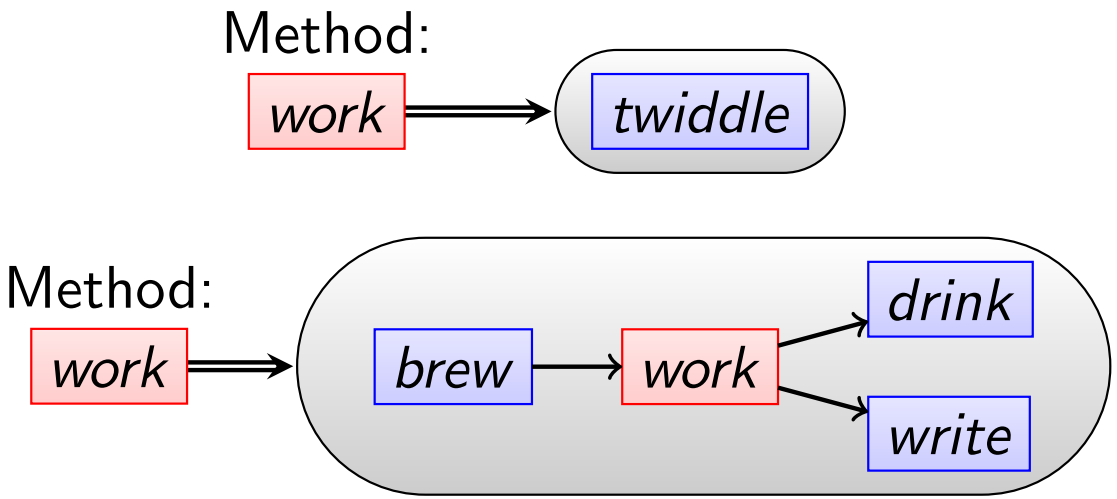
- Totally-Ordered HTN Problems: Initial task network and all method networks are totally ordered.
- Theorem: Totally-ordered $\leq_r$-stratifiable planning is PSPACE-complete. Proof:
  - Hardness: Contains *regular* HTN planning (Erol et. al.)
  - Progression space contains only totally-ordered problems
  - Progression can only add lower stratum tasks to the beginning of the task network
  - So $\langle 4, 4, 5, 5 \rangle \rightarrow \langle 3, 3, 3, 4, 4, 5, 5 \rangle$
  - Max network size: $m \cdot h$, where m size of largest method, h height of stratification.
- Contains totally-ordered $\leq_1$-stratifiable planning. Searching progression space is optimal, searching decomposition space is not.

Motivating Example: Morning coffee

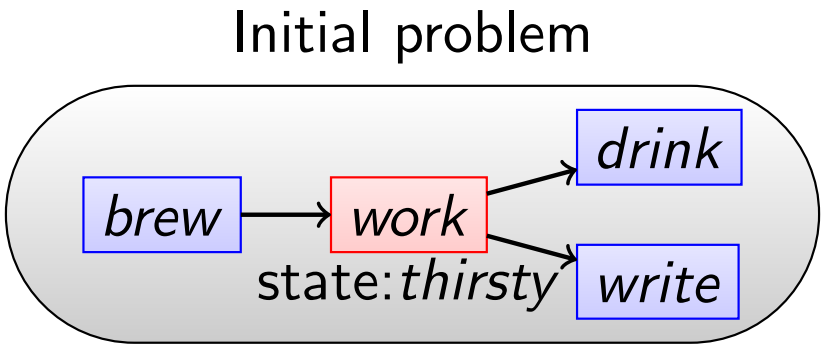
- Brew as much coffee in the morning as you need throughout the day.
- Not $\leq_r$-stratifiable ('*work*' now in the middle)
  - '*work*' is a subtask of itself, but not the last task.

Domain actions:

- $\forall_s \gamma(s, brew) = s$
- $\forall_s \gamma(s, twiddle) = s$
- $\forall_s \gamma(s, write) = thirsty$
- $\forall_s \gamma(s, drink) = \neg thirsty$



Total Order Partition spaces



- Plan by splitting problems into smaller problems
- If there is a total order over chunks of the task network:
  - Serialize network into smaller chunks
  - End state of one is the start state of the next.
  - If last chunk solvable, then the whole problem is solvable
- When no total order, use progression
- Call this the Total Order Progression (TOP) space
  - No existing planner terminates on all problems with a finite TOP space
  - Possible to write an algorithm that does (see thesis for details)

Total Order Partition spaces

$\leq_r$-ordered

- For finiteness, need to consider the structure of networks in the problem.
- A task network tn is $\leq_r$-*ordered* if $\langle tn_1, \ldots, tn_n \rangle$ are the totally ordered chunks of tn and every tn_i is either:
  - singular (only one task)
  - $\leq_r$-stratifiable
- A problem is $\leq_r$-*ordered* if the initial task network and all methods' task networks are $\leq_r$-ordered
- $\leq_1$-ordered is defined similarly over $\leq_1$-stratification

TOP spaces and $\leq_r$-ordered problems

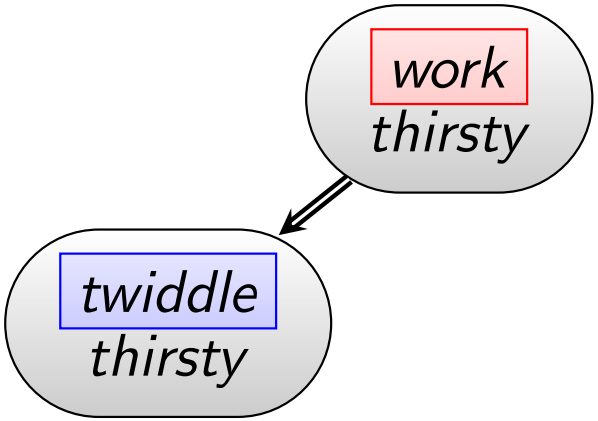
From the thesis (but not in this talk):

- Property: If a problem is $\leq_r$-stratifiable, it is $\leq_r$-ordered
- Property: If a problem is totally ordered, it is $\leq_r$-ordered
- Theorem: If a problem is $\leq_r$-ordered, its TOP space is finite.
  - SHOP and SHOP2 may not terminate on these problems.
  - Possible to implement a planner that does (TOPHTN).
- Plan-existence in EXPSPACE for $\leq_r$ ordered, in NEXP for $\leq_1$-ordered

Example

End states of $(D, thirsty, work)$:

Example



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thirsty

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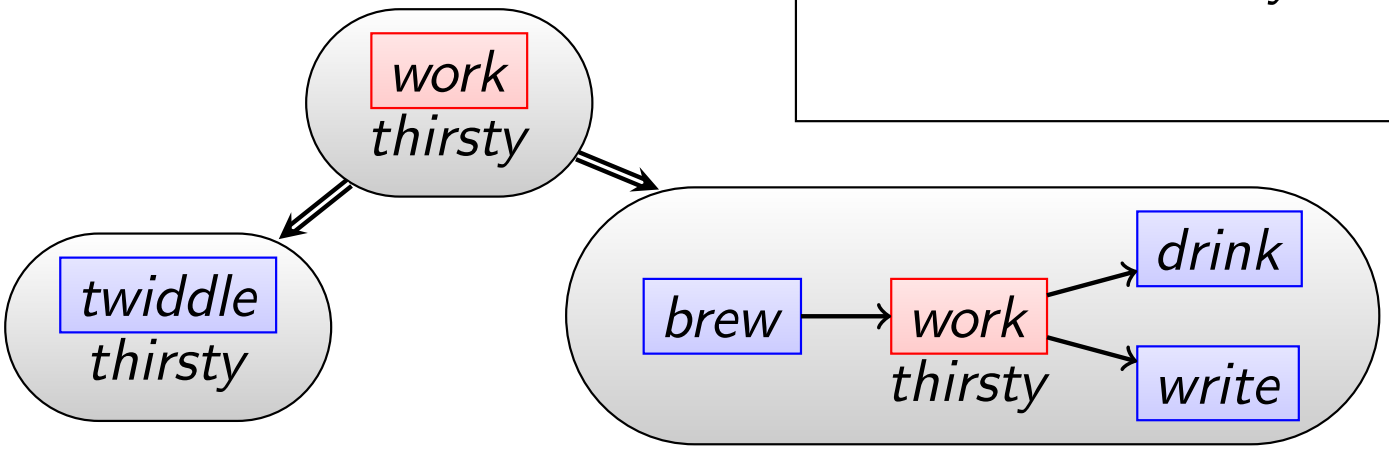

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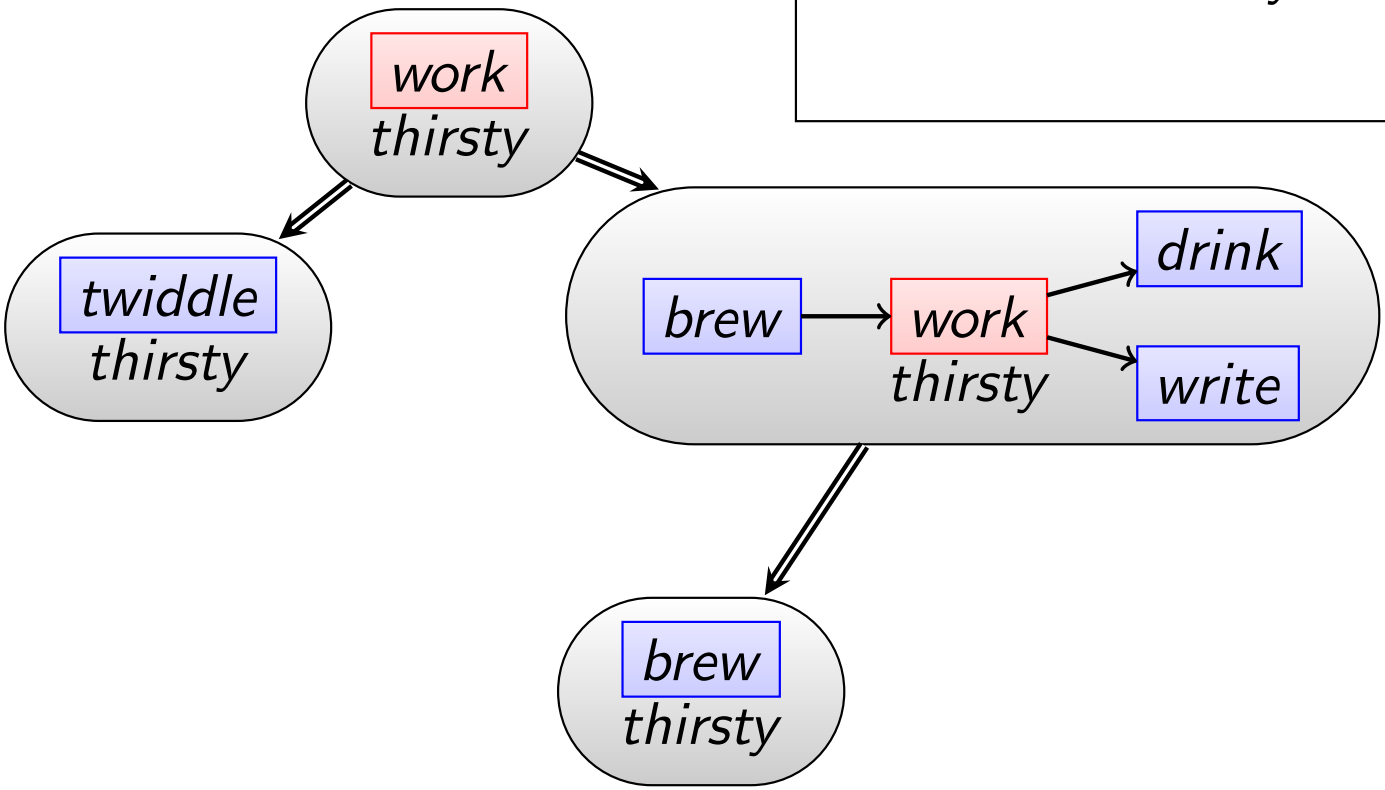

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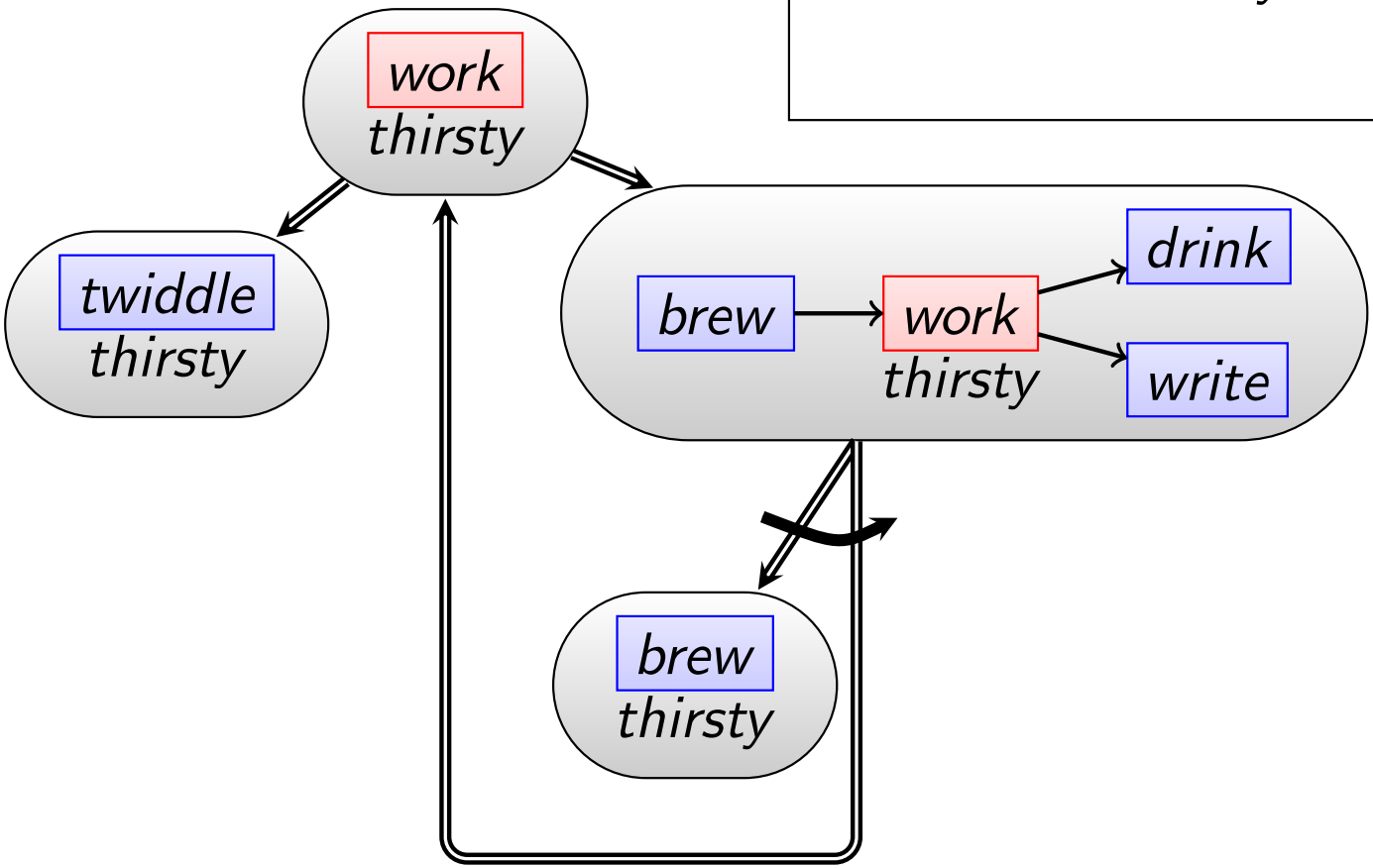

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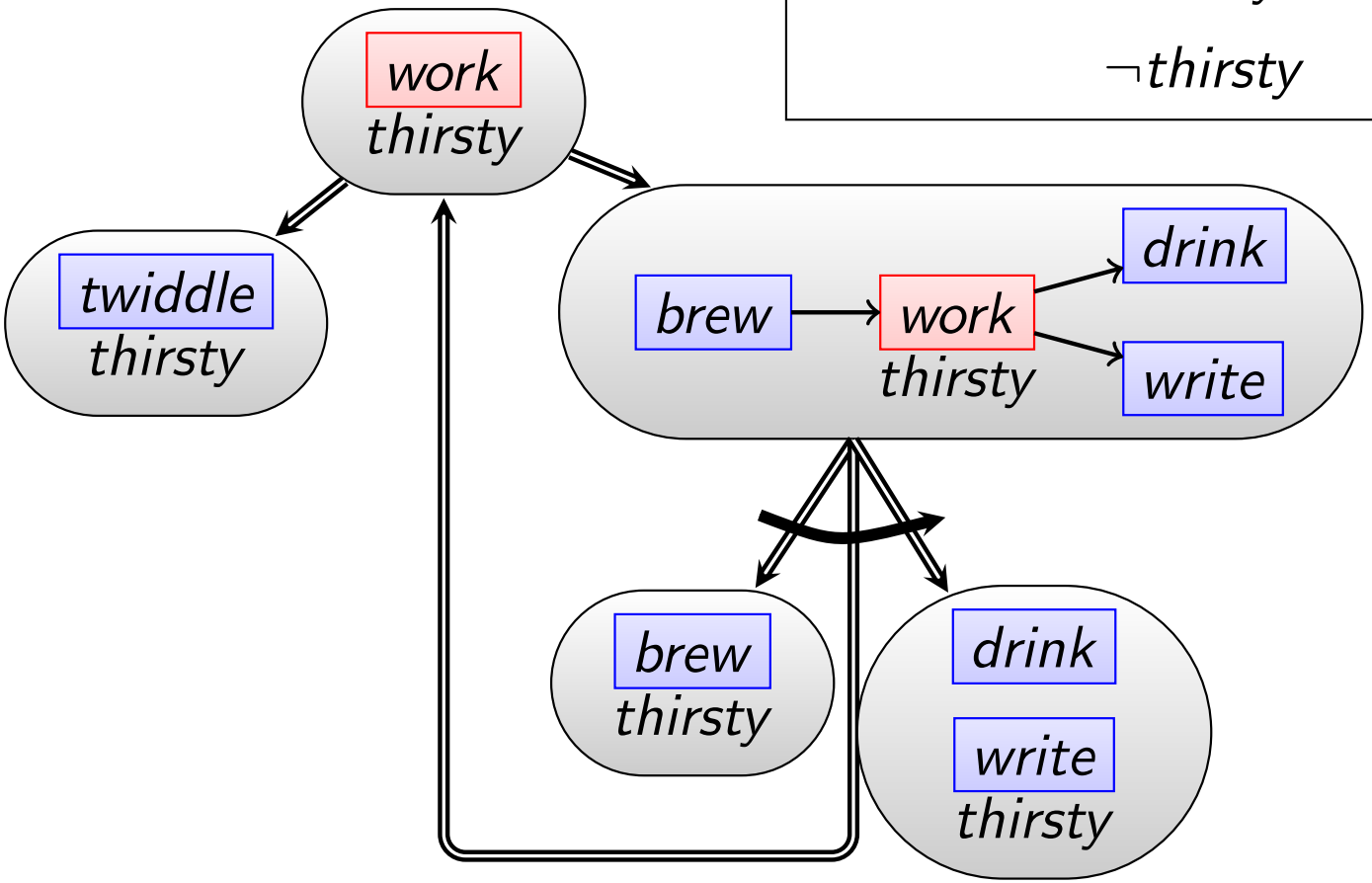
$thirsty$

$\neg thirsty$



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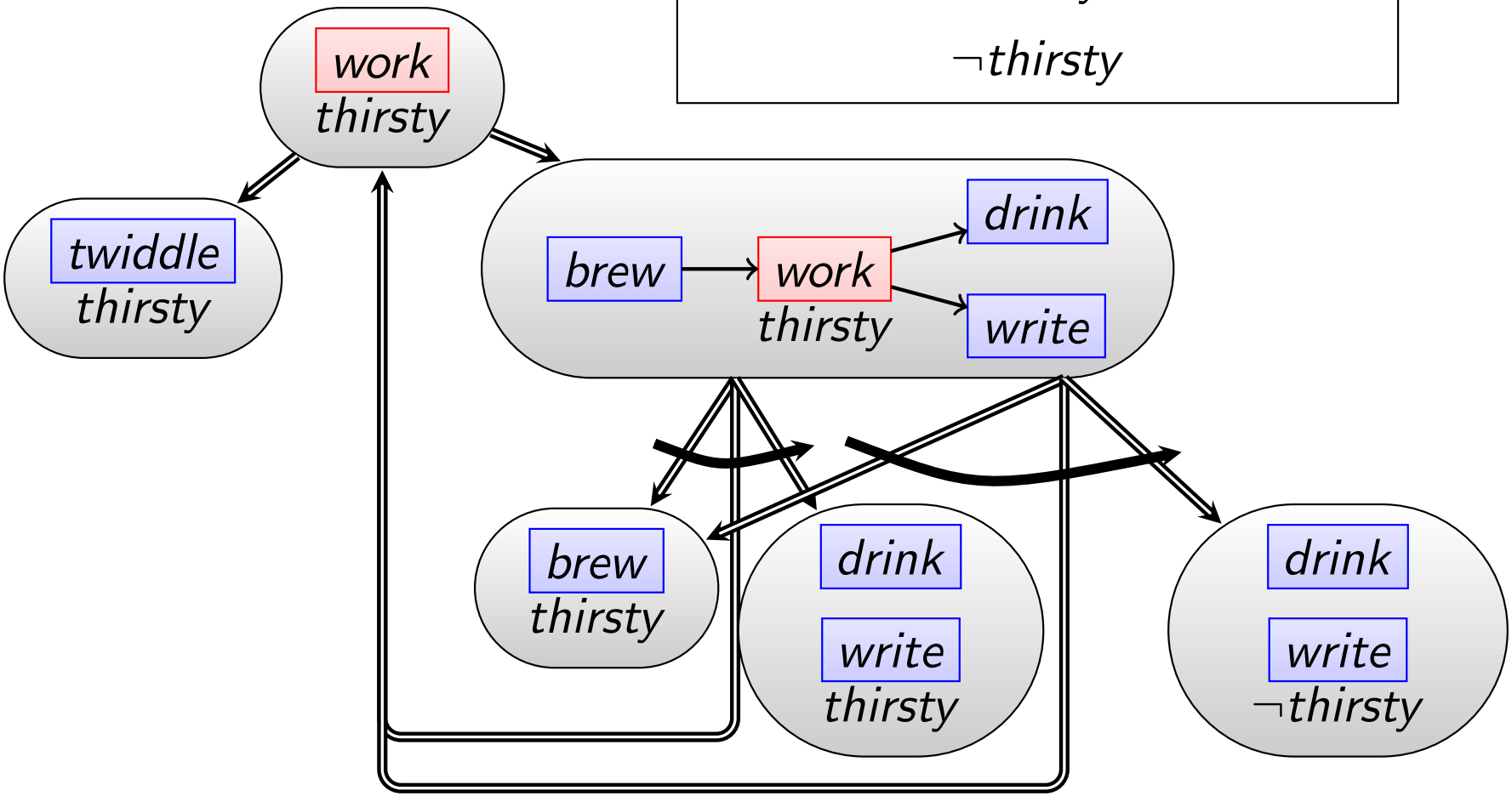
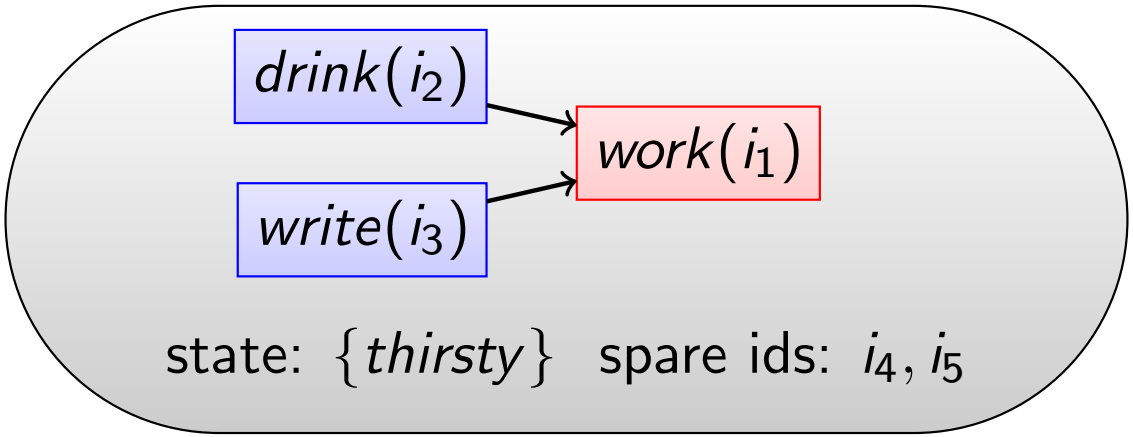
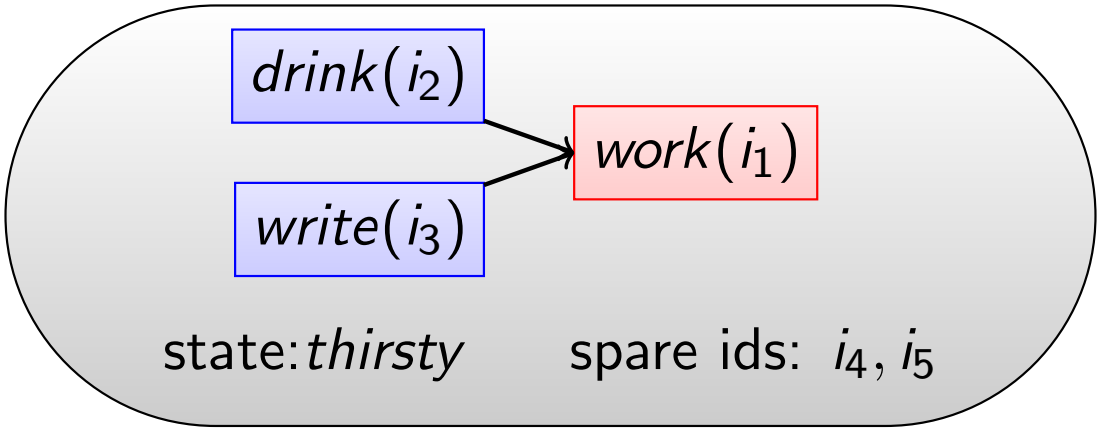


Translating a Task Network



- Associate each task with a unique identifier: *brew*(i_1), *drink*(i_2), *write*(i_3), *work*(i_4)
- Mark which task nodes have no preceding tasks: *running*(i_1)
- Describe the ordering relationships between the nodes
- Add a pool of spare identifiers

Translating Operators



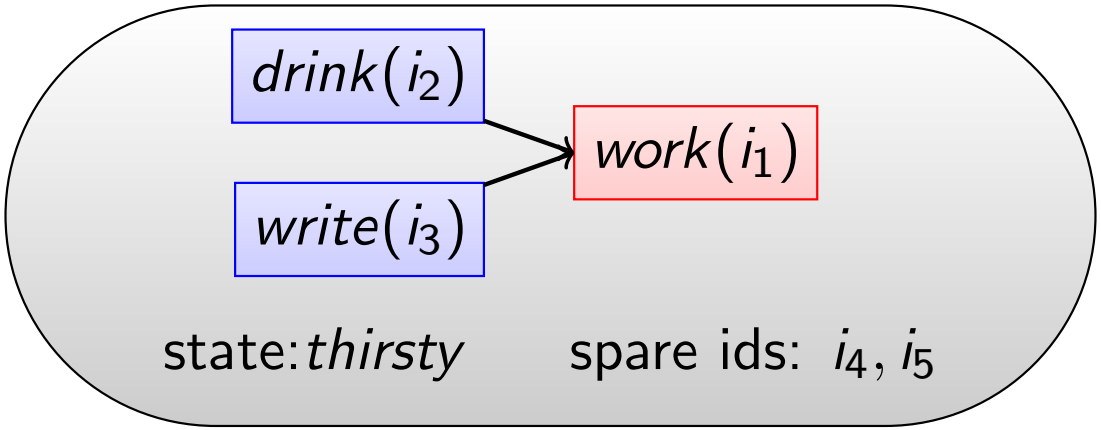
- For operators
  - Syntactically the same in HTN and classical planning
  - Semantically, can only apply an operator when it's in the task network and has no predecessors
  - Add task literal to precondition of operator

Operator: *brew*(i)

pre = {*brew*(i), *running*(i) ...}

eff = {¬*brew*(i), ¬*running*(i), *finished*(i) ...}

Translating Operators



Execute *drink*: $\gamma(thirsty, drink(i_2)) = \neg thirsty$

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Operator: $brew(i)$

$pre = \{brew(i), running(i) \dots\}$

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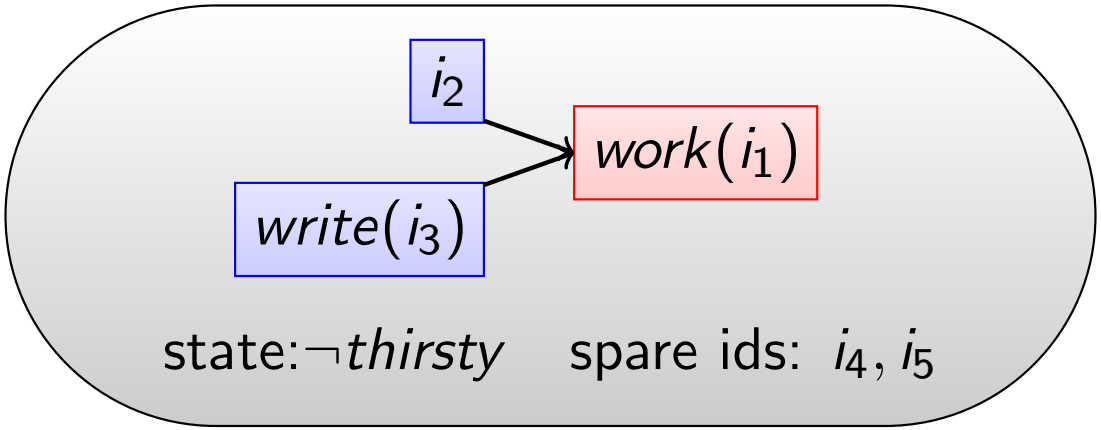
Translating Operators



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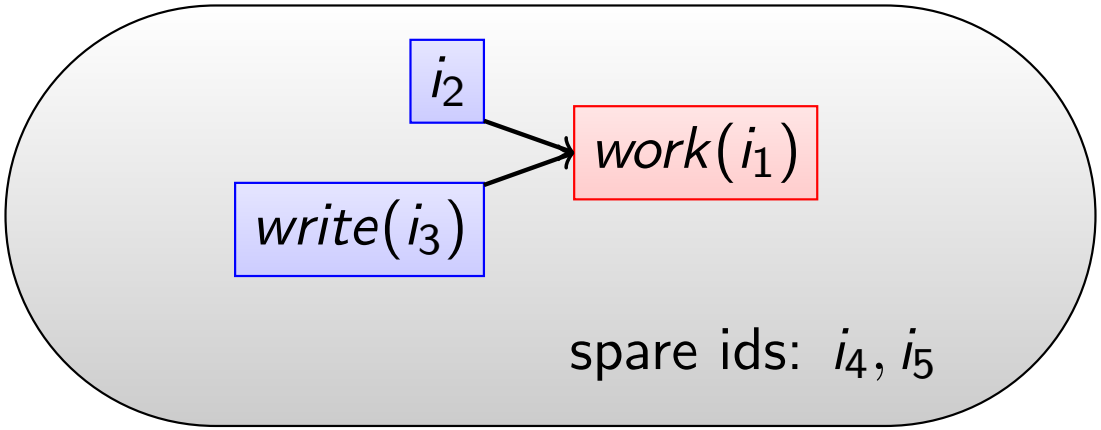

Execute *write*: $\gamma(\neg thirsty, write(i_3)) = thirsty$

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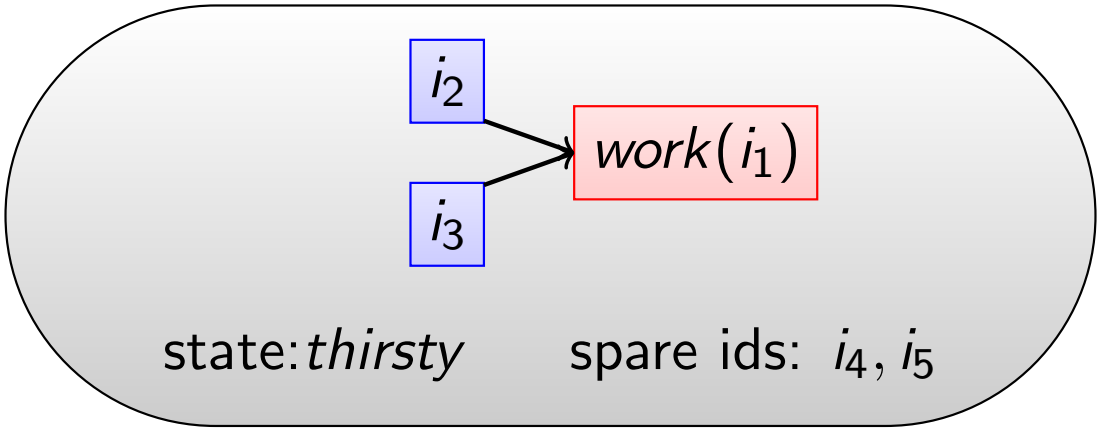

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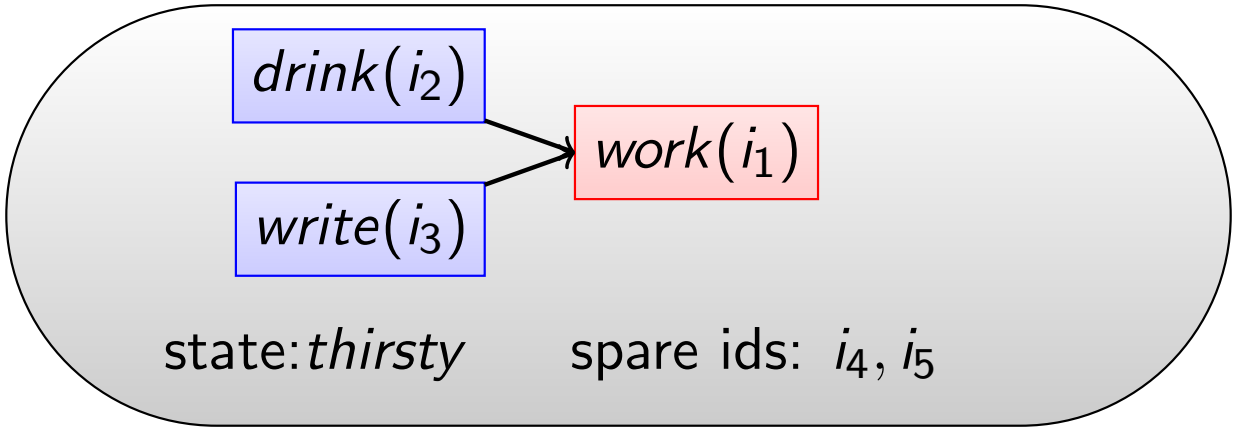
Managing precedence constraints



Manage precedence constraints with operators:

- Wait for tasks to be finished
- Free the identifiers
- Mark task as ready to run

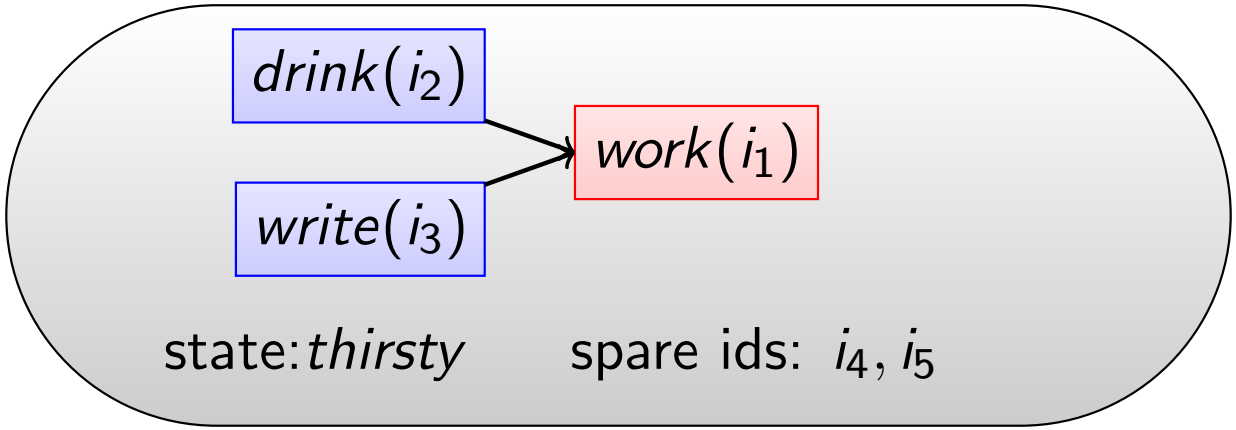
Wait op: $wait_{22}(i_1, i_2, i_3)$

$\text{pre} = \{finished(i_2), finished(i_3), \ldots\}$

$\text{eff} = \{\texttt{free } i_2 \texttt{ and } i_3$

$running(i_1)\}$

Managing precedence constraints



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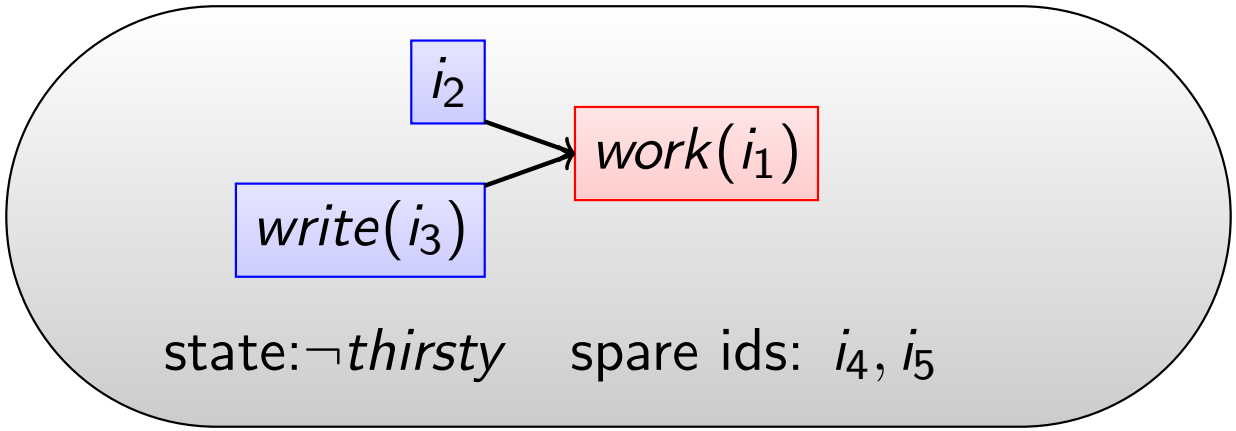

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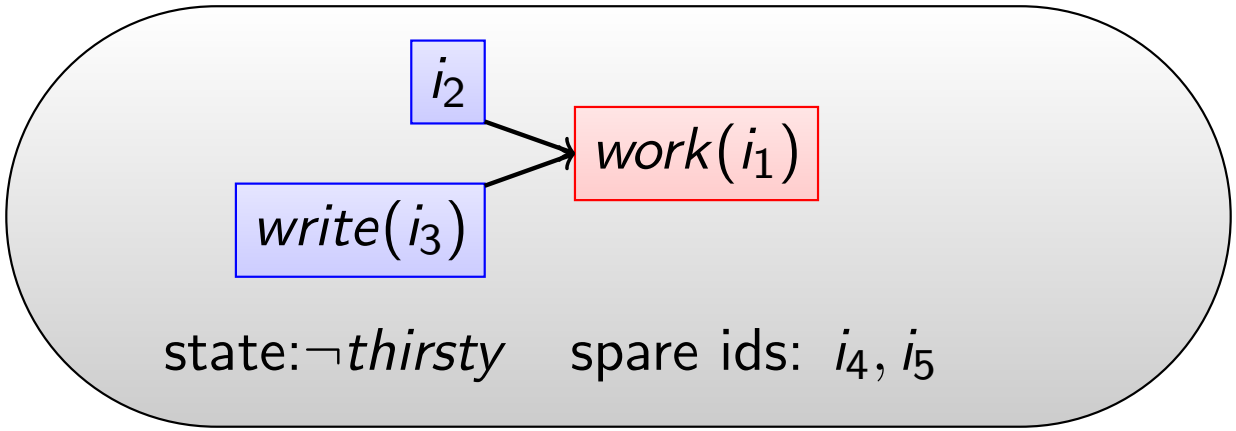

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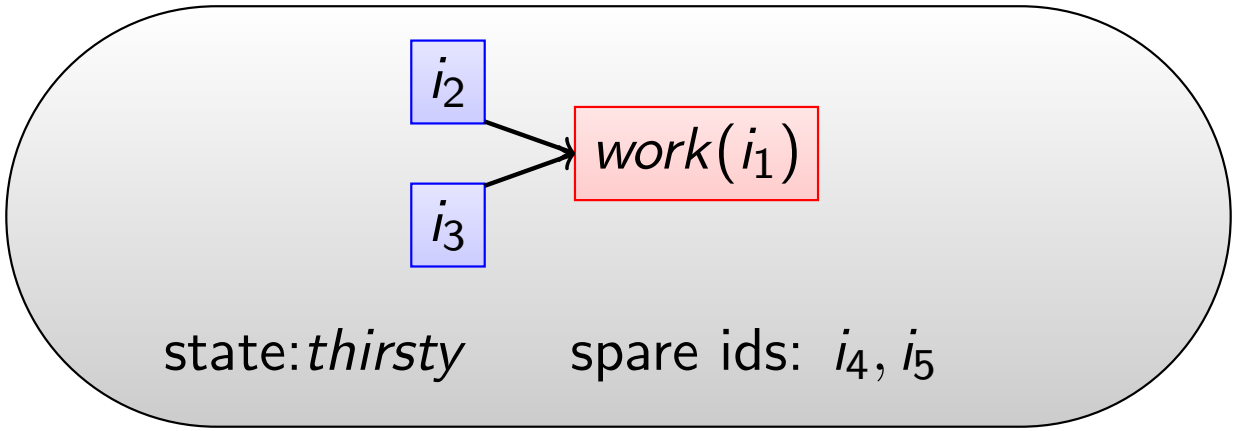

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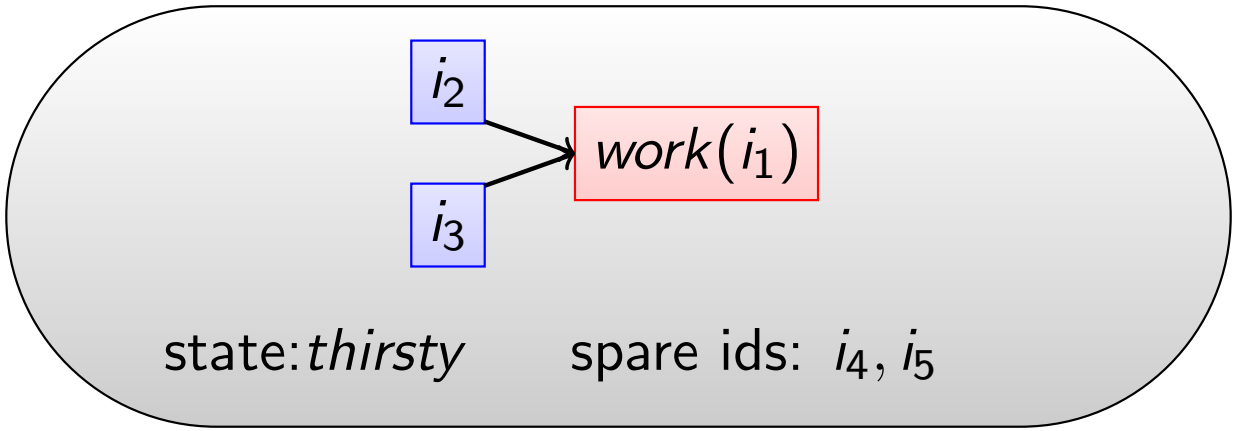
$running(i_1)\}$

Managing precedence constraints



Remove constraints with $wait_{22}(i_1, i_2, i_3)$

Manage precedence constraints with operators:

- Wait for tasks to be finished
- Free the identifiers
- Mark task as ready to run

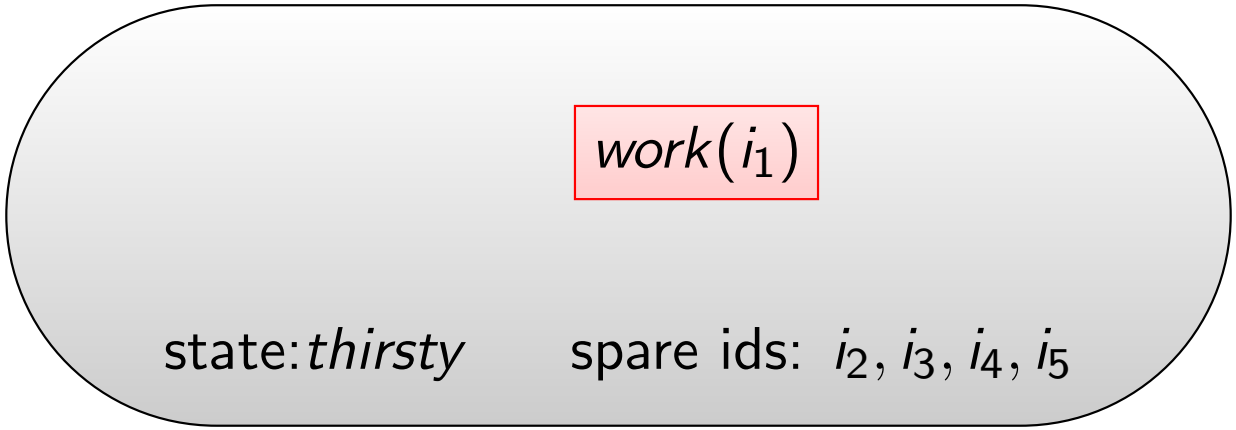
Wait op: $wait_{22}(i_1, i_2, i_3)$

$\text{pre} = \{finished(i_2), finished(i_3), \ldots\}$

$\text{eff} = \{\texttt{free } i_2 \texttt{ and } i_3$

$running(i_1)\}$

Managing precedence constraints



Manage precedence constraints with operators:

- Wait for tasks to be finished
- Free the identifiers
- Mark task as ready to run

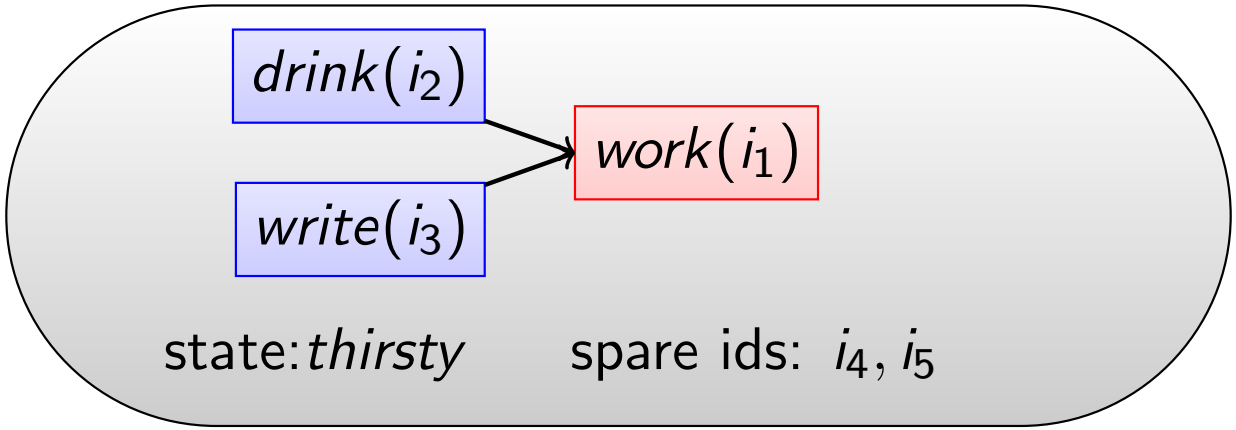
Wait op: $wait_{22}(i_1, i_2, i_3)$

$\text{pre} = \{finished(i_2), finished(i_3), \ldots\}$

$\text{eff} = \{\texttt{free } i_2 \texttt{ and } i_3$

$running(i_1)\}$

Translating Methods: Overview



When translating a method (> 2 tasks):

- Allocate identifiers
- Assert task network into state
  - Reuse task identifier for last task
- Mark first tasks as ready to run

Method op: $work(i_1, i_2, i_3)$

$\text{pre} = \{work(i_1), running(i_1)\}$

$\text{eff} = \{$`allocate` i_1, i_2

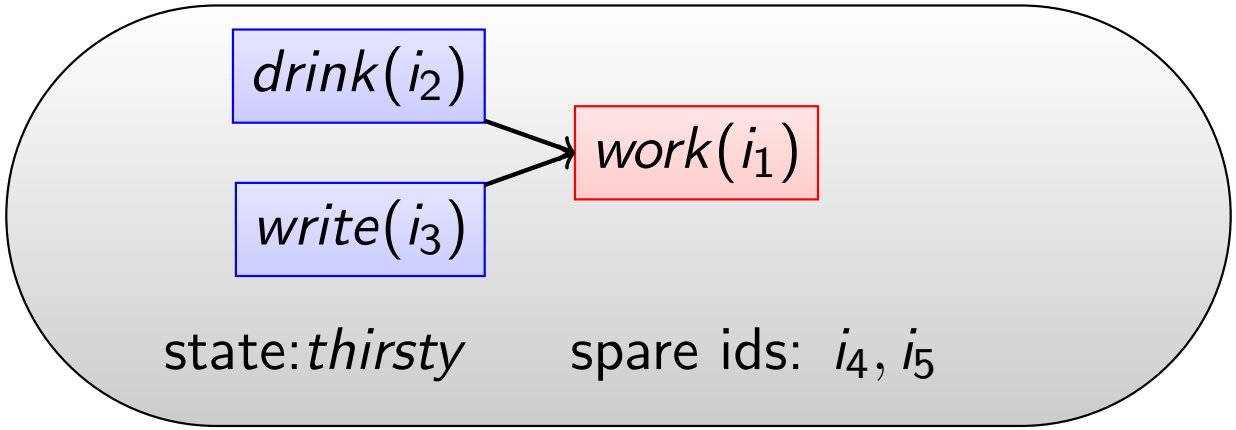
$drink(i_2), brew(i_3), work(i)$

$wait_{22}(i, i_2, i_3)$,

$running(i_2), running(i_3)$

$running(i_\cdot)\}$

Translating Methods: Overview



Execute *drink*(i_2)

When translating a method (> 2 tasks):

- Allocate identifiers
- Assert task network into state
  - Reuse task identifier for last task
- Mark first tasks as ready to run

Method op: *work*(i_1, i_2, i_3)

pre $= \{$*work*(i_1), *running*(i_1)$\}$

eff $= \{$`allocate` i_1, i_2

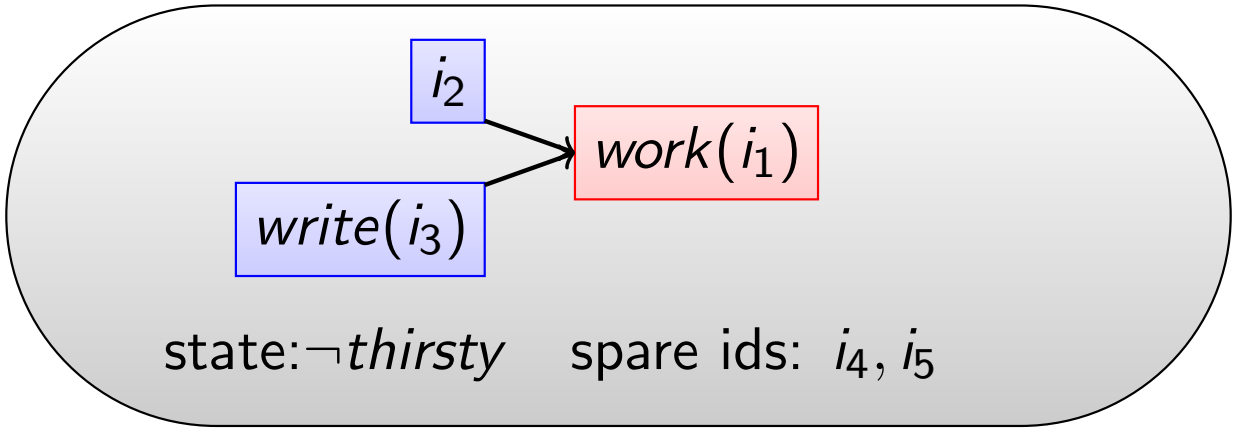
drink(i_2), *brew*(i_3), *work*(i)

wait$_{22}$(i, i_2, i_3),

running(i_2), *running*(i_3)

running(i)$\}$

Translating Methods: Overview



When translating a method (> 2 tasks):

- Allocate identifiers
- Assert task network into state
  - Reuse task identifier for last task
- Mark first tasks as ready to run

Method op: $work(i_1, i_2, i_3)$

pre $= \{work(i_1), running(i_1)\}$

eff $= \{$`allocate` i_1, i_2

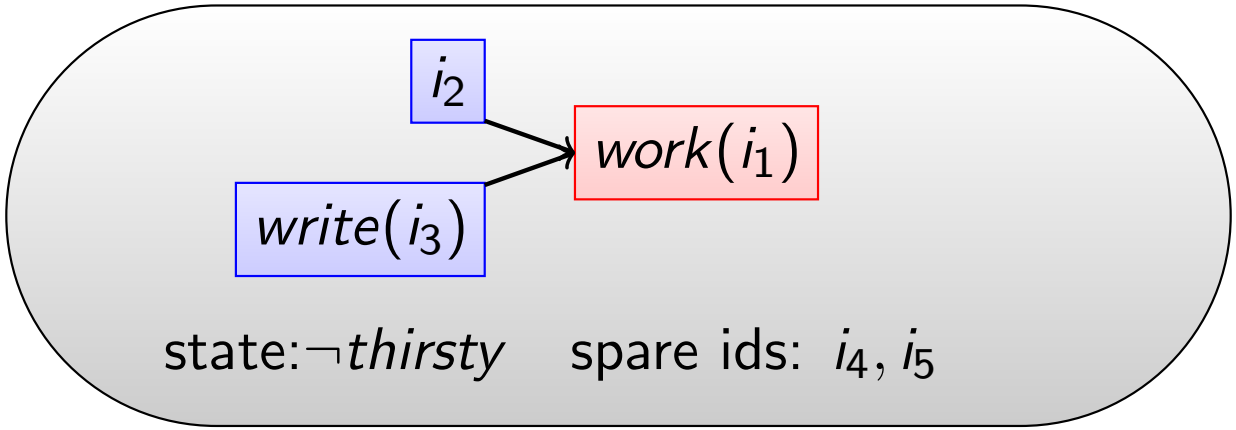
$drink(i_2), brew(i_3), work(i)$

$wait_{22}(i, i_2, i_3)$,

$running(i_2), running(i_3)$

$running(i_4)\}$

Translating Methods: Overview



Execute $write(i_3)$

When translating a method (> 2 tasks):

- Allocate identifiers
- Assert task network into state
  - Reuse task identifier for last task
- Mark first tasks as ready to run

Method op: $work(i_1, i_2, i_3)$

pre $= \{work(i_1), running(i_1)\}$

eff $= \{$`allocate` i_1, i_2

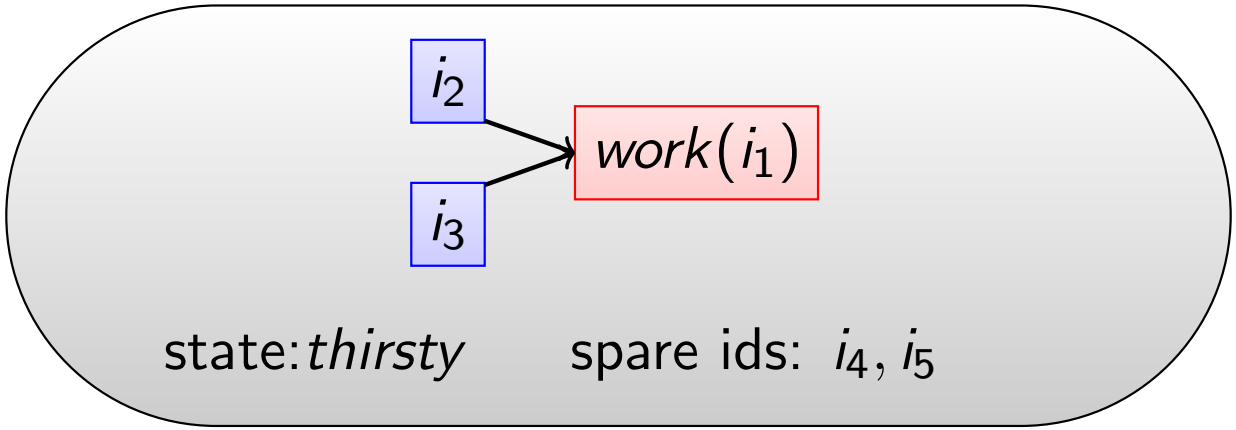
$drink(i_2), brew(i_3), work(i)$

$wait_{22}(i, i_2, i_3)$,

$running(i_2), running(i_3)$

$running(i_1)\}$

Translating Methods: Overview



When translating a method (> 2 tasks):

- Allocate identifiers
- Assert task network into state
  - Reuse task identifier for last task
- Mark first tasks as ready to run

Method op: $work(i_1, i_2, i_3)$

$pre = \{work(i_1), running(i_1)\}$

$eff = \{$`allocate` i_1, i_2

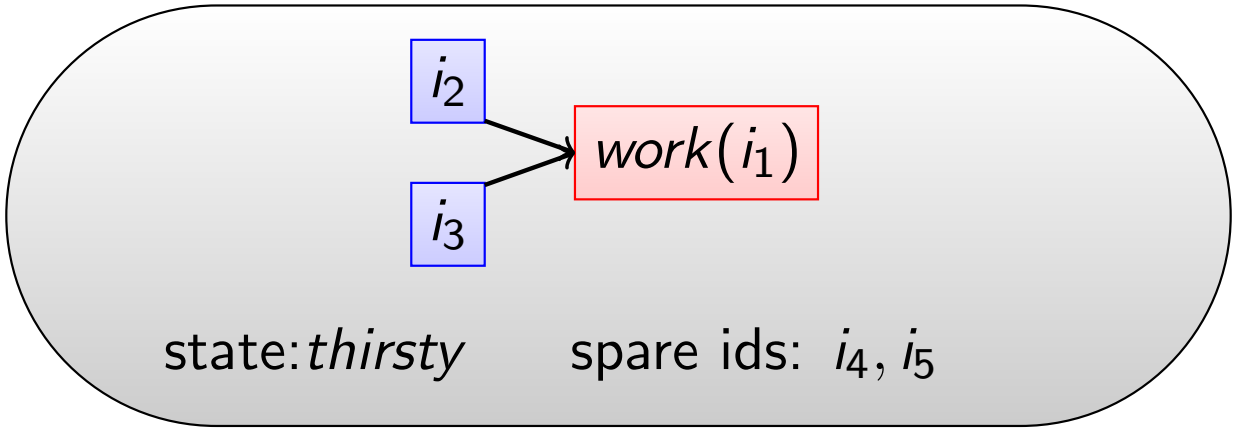
$drink(i_2), brew(i_3), work(i)$

$wait_{22}(i, i_2, i_3),$

$running(i_2), running(i_3)$

$running(i_3)\}$

Translating Methods: Overview



Execute $wait_{22}$

When translating a method (> 2 tasks):

- Allocate identifiers
- Assert task network into state
  - Reuse task identifier for last task
- Mark first tasks as ready to run

Method op: $work(i_1, i_2, i_3)$

$\text{pre} = \{work(i_1), running(i_1)\}$

$\text{eff} = \{\texttt{allocate } i_1, i_2$

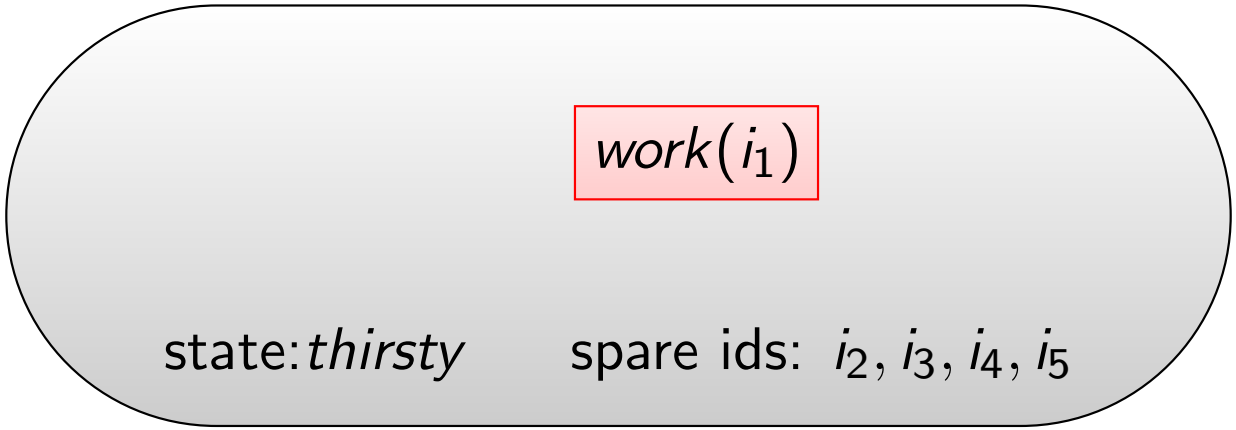
$drink(i_2), brew(i_3), work(i)$

$wait_{22}(i, i_2, i_3),$

$running(i_2), running(i_3)$

$running(i_1)\}$

Translating Methods: Overview



When translating a method (> 2 tasks):

- Allocate identifiers
- Assert task network into state
  - Reuse task identifier for last task
- Mark first tasks as ready to run

Method op: $work(i_1, i_2, i_3)$

$\text{pre} = \{work(i_1), running(i_1)\}$

$\text{eff} = \{\texttt{allocate}\ i_1, i_2$

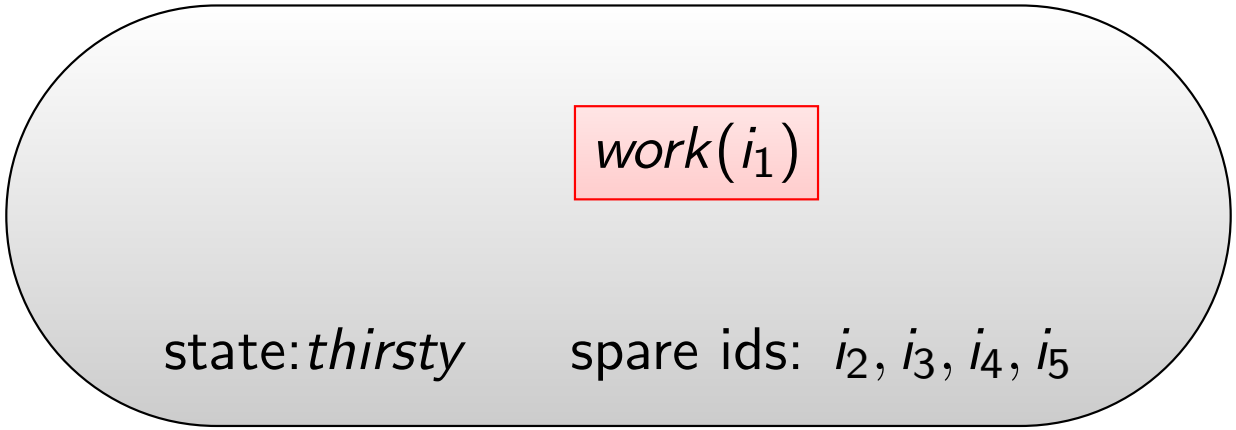
$drink(i_2), brew(i_3), work(i)$

$wait_{22}(i, i_2, i_3),$

$running(i_2), running(i_3)$

$running(i_\cdot)\}$

Translating Methods: Overview



Execute $work(i_1, i_2, i_3)$

When translating a method (> 2 tasks):

- Allocate identifiers
- Assert task network into state
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Method op: $work(i_1, i_2, i_3)$

$\text{pre} = \{work(i_1), running(i_1)\}$

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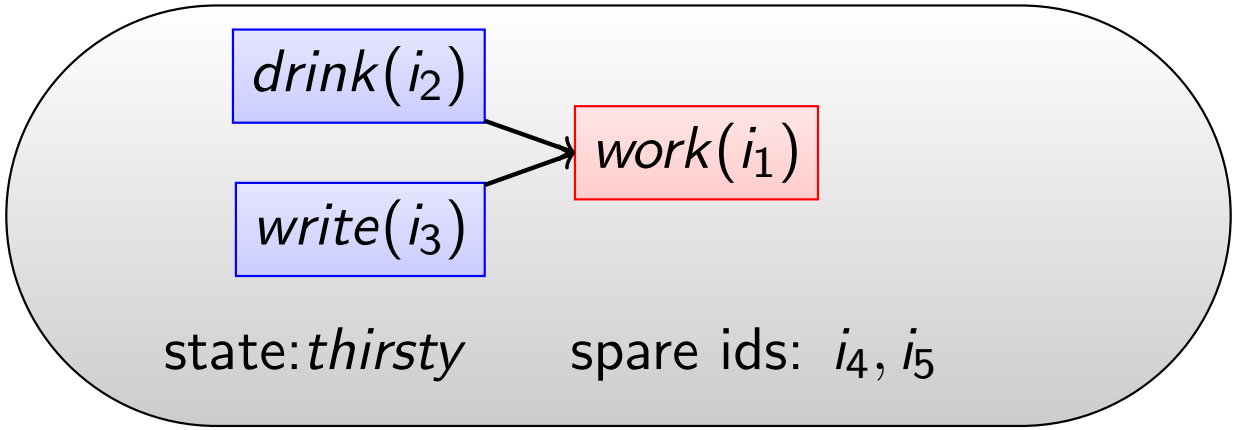
$drink(i_2), brew(i_3), work(i)$

$wait_{22}(i, i_2, i_3),$

$running(i_2), running(i_3)$

Translating Methods: Overview



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$drink(i_2), brew(i_3), work(i)$

$wait_{22}(i, i_2, i_3)$,

$running(i_2), running(i_3)$

$running(i_\cdot)\}$