HTN Problem Spaces: Structure, Algorithms, Termination

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Unsolvable problems

HTN planning is semi-decidable.

- If your planner always returns if the problem is solvable, then there exist unsolvable problems for which it will never return.

Why care about unsolvable problems?

- Debugging/developing a domain
- Plan may not exist (Problem: make me a millionaire)
- Techniques that require failure:
  - NDP: uses a deterministic planner for FOND domains
  - Verification tasks

Classical Planning: $D = (S, O, \gamma)$, $P = (D, s_0, G)$

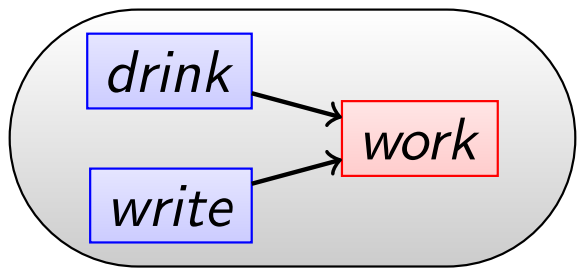
A classical planning problem consists of:

- A domain, D, with:
  - S: A finite set of states
  - O: A finite set of actions
  - $\gamma : S \times O \to S$: A partial function to transition between states
- s_0: An initial state
- G: A set of goal states
- An action a is *executable* in a state if $\gamma(s, a)$ is defined.
- A sequence of actions $\langle a_1, \ldots, a_n \rangle$ is executable in a state if the actions are executable in turn.
  - $\gamma(s_0, a_1) = s_1$
  - $\gamma(s_1, a_2) = s_2$
  - $\ldots$
  - $\gamma(s_{n-1}, a_n) = s_n$
- Objective: Find a plan (an executable sequence) that take us to a goal state.

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

All about the process, not the goal.

- Same S, O, γ, and s_0.
- An initial *task network*, tn_0, which is a DAG of *tasks* to accomplish:
  - Edges represent ordering constraints
  - Nodes either labelled with action names from O (say, $\{drink, write\}$)
  - Or non-primitive with labels from C (say, $\{work\}$)

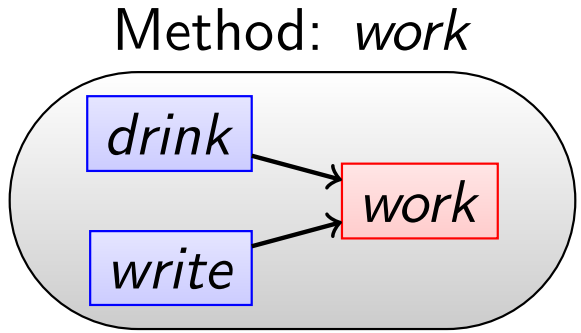


- M, a set of methods to *decompose* non-primitive tasks

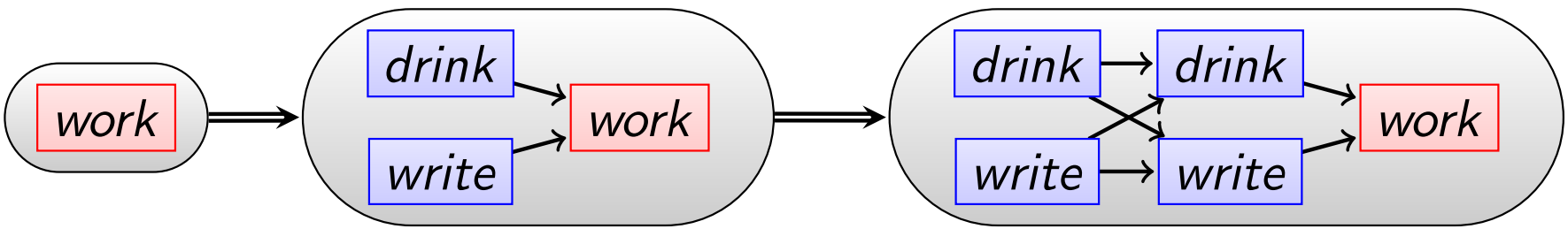
HTN Planning: $D = (S, \mathbf{C}, O, \mathbf{M}, \gamma)$, $P = (D, s_0, \mathbf{tn}_0)$

Example domain and decomposition

- A method is a non-primitive name paired with a task network.



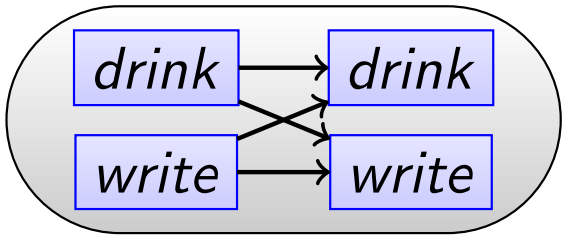
- We *decompose* a task by replacing its node in the network with its method's network.



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

Primitive task networks:

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

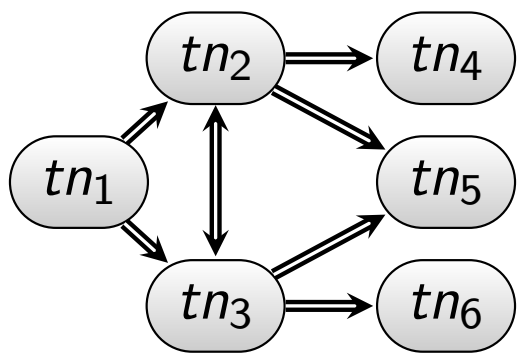


- All names are actions $\Rightarrow$ network is *primitive*
- It is *executable* in a state if there exists a consistent total order (sequence) which is executable.
  - Four possible orderings
  - All executable in both *thirsty* and $\neg thirsty$
  - Could end in either state.
- Objective: Decompose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

Decomposition spaces for HTN planning

Decomposition as a graph

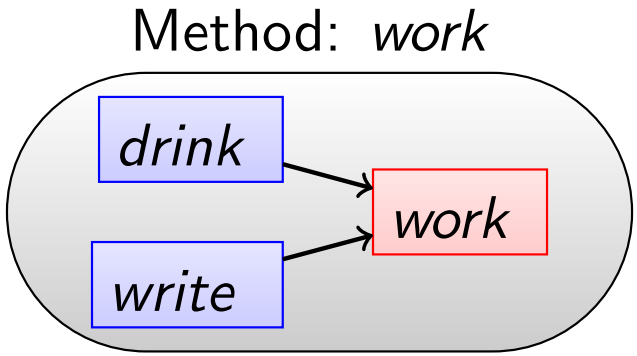
- Decomposition: Choose some non-primitive task and some method to decompose it
- Choices form a graph of task networks reachable via decomposition.
- Call this the *decomposition space* of a problem.
- Plan by searching graph (not always finite)
- Used by UMCP (Erol 94), Landmark-aware HTN planner (Elkawkagy 2011)



Decomposition spaces for HTN planning

Finiteness: $\leq_1$-stratification

- A domain is $\leq_1$-*stratifiable* if we can stratify its task names such that:
  - $(t, tn) \in M$ and $|tn| > 1 \Rightarrow$ every task in tn is on a lower stratum (acyclic decomposition).
  - $(t, tn) \in M$ and $|tn| = 1 \Rightarrow$ tn's task is on an equal or lower stratum (trivially recursive decomposition).
- Existence of a $\leq_1$-stratification implies decomposition either:
  - Replaces task with a single task (no change in size)
  - Replaces task with tasks from lower strata.



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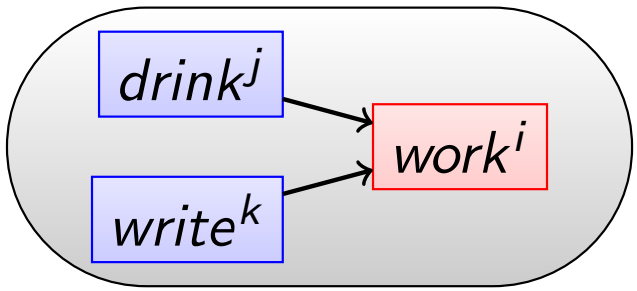
Method: $work^i$



Constraints:

$j < i,\ k < i,\ \ i < i$

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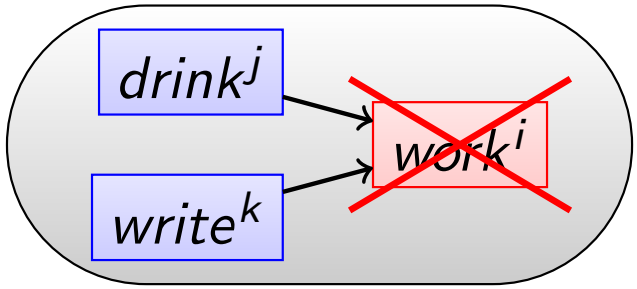


Constraints:

$j < i$, $k < i$, ~~$i < i$~~

2	work
1	drink, write

Decomposition spaces for HTN planning

$\leq_1$-stratification implications

- Exists $\leq_1$-stratification $\Rightarrow$ finite decomposition space (task networks reachable by decomposition)
- No $\leq_1$-stratification $\Rightarrow$ infinite decomposition space
- Dealing with trivial recursion
  - Check for loops during decomposition
  - Compile it away

Progression spaces for HTN planning

For an HTN problem $P = (D, s_0, tn_0)$, if t is a task with no predecessors in tn_0, there are two ways to *progress* it:

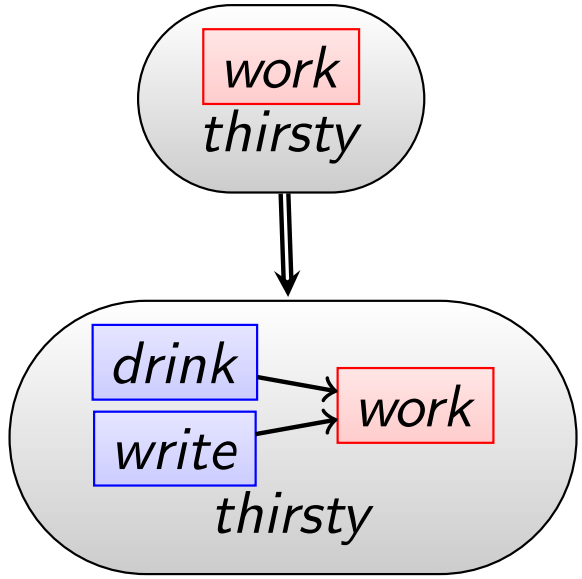
- If t is non-primitive:
  - Let tn' be a decomposition of t in tn_0
  - Then (D, s_0, tn') is a progression of P.
- If t is primitive ($t \in O$) and executable, then:
  - Execute t: $\gamma(s_0, t) = s_1$
  - Remove it from tn_0: $tn' = tn_0 \setminus \{t\}$
  - Then (D, s_1, tn') is a progression of P.
- Progression interleaves decomposition and finding a total order.
- Choices form a graph of problems reachable by progression.

Progression spaces

Example

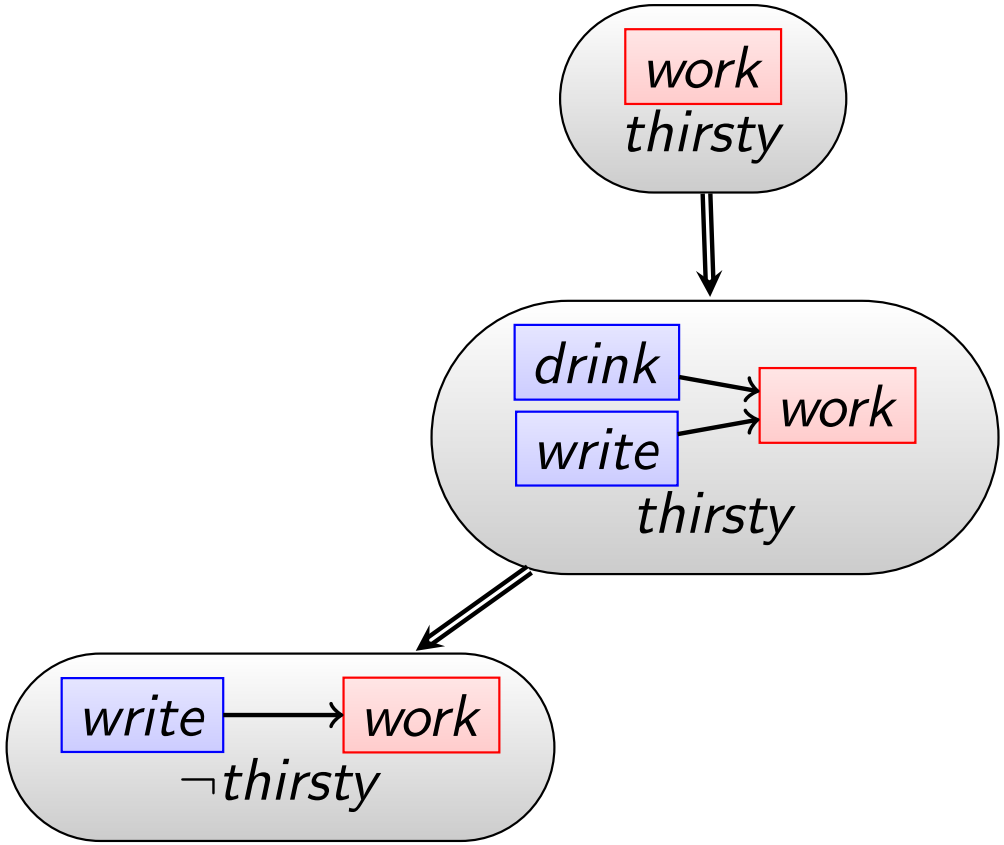
Progression spaces

Example



Progression spaces

Example



Progression spaces

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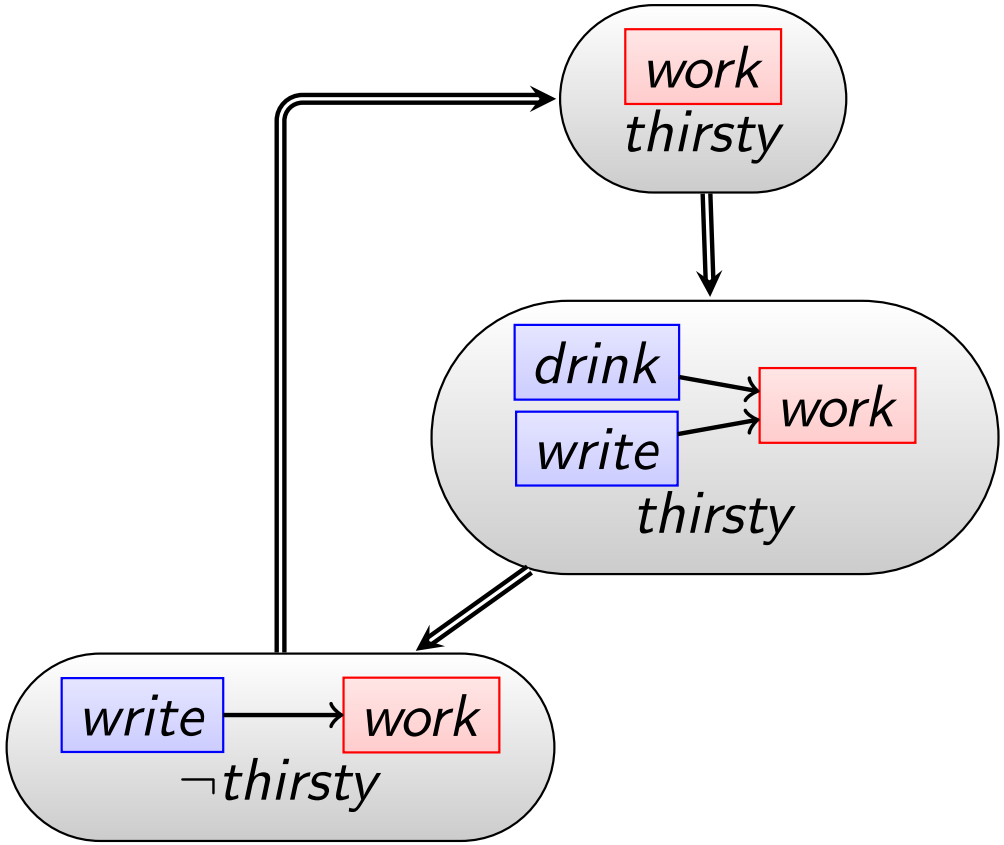

Progression spaces

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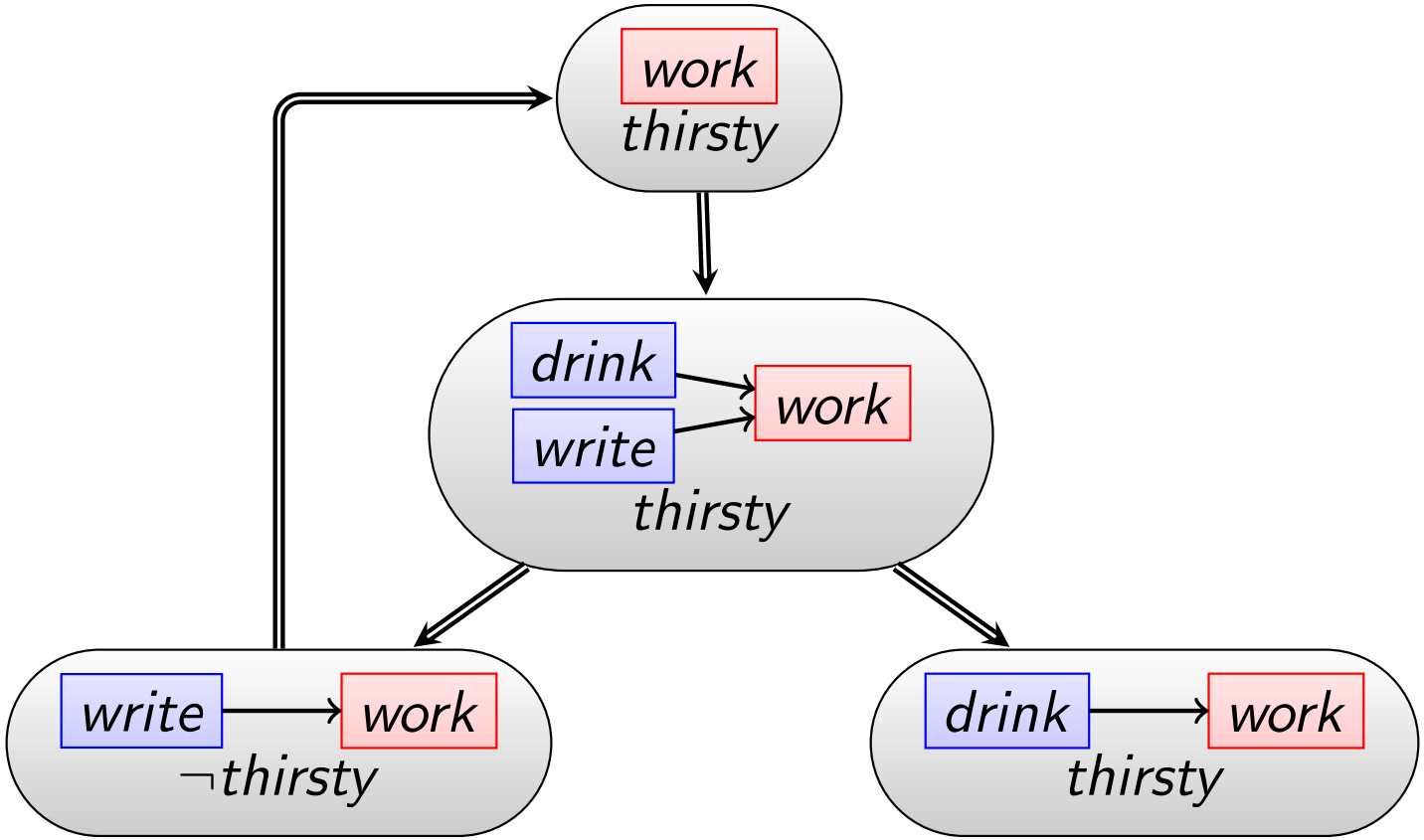
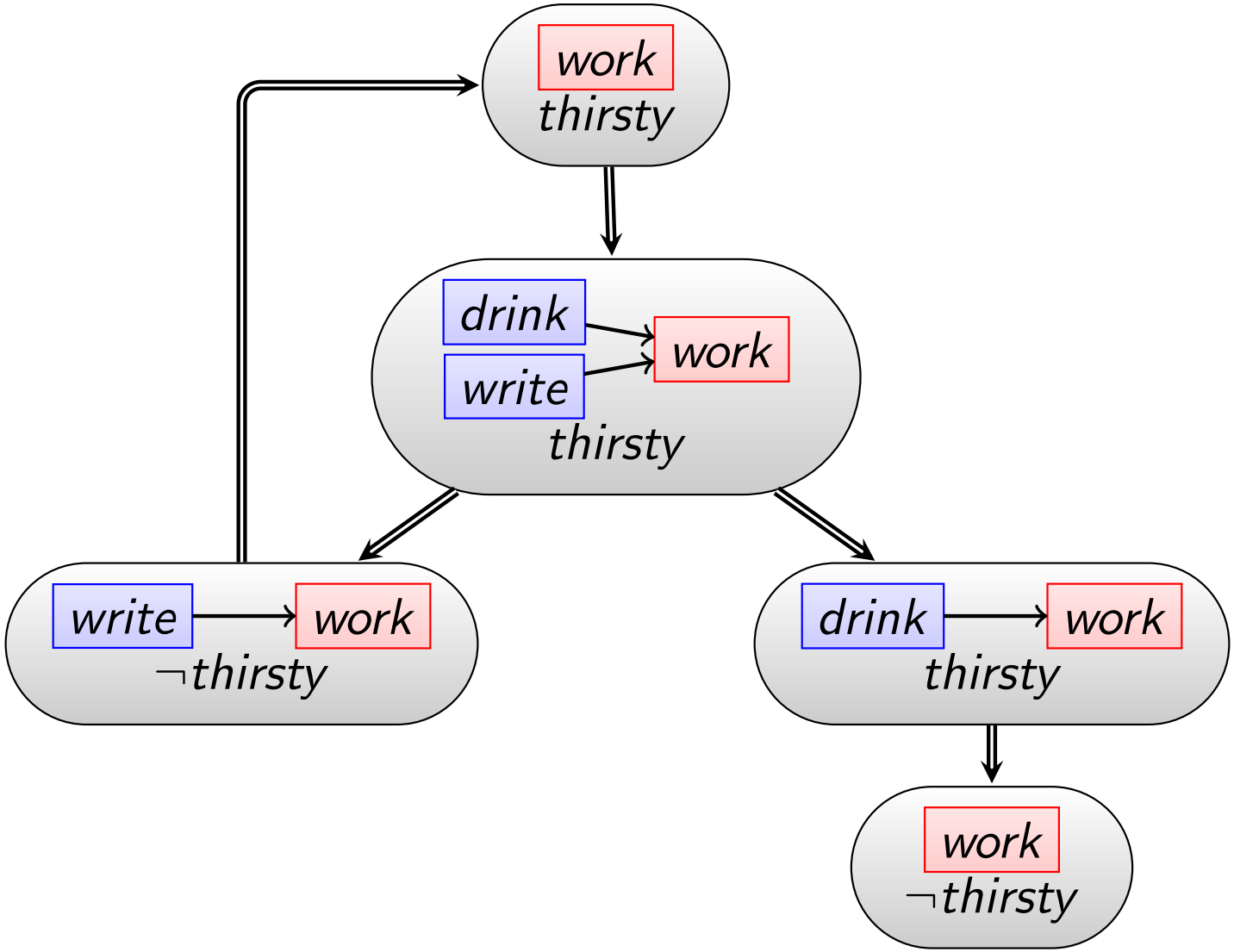


Progression spaces

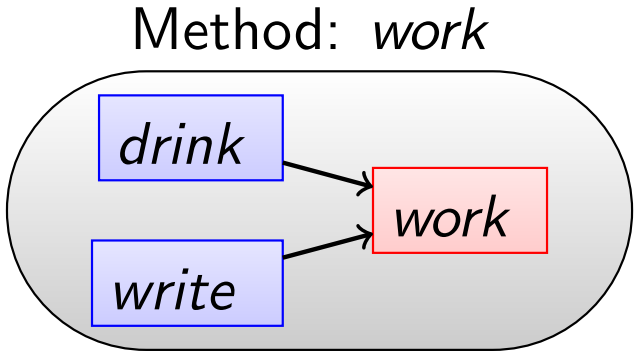
Example



Progression spaces for HTN planning

$\leq_r$-stratification

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



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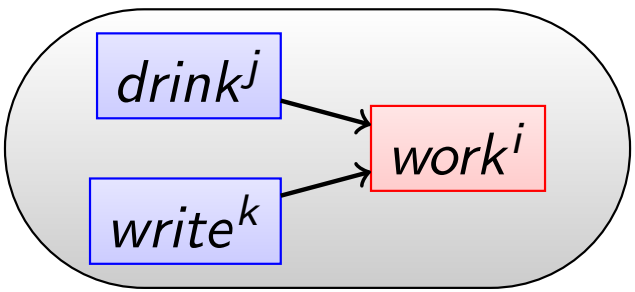


Constraints: $j < i, k < i, i \leq i$

2	work
1	drink, write

Progression spaces for HTN planning

$\leq_r$-stratification implications

- Includes all $\leq_1$-stratifiable problems
- Exists $\leq_r$-stratification $\Rightarrow$
  - Can only decompose to a fixed depth before executing actions.
  - Finite progression space (problems reachable by progression)
- No $\leq_r$-stratification: Progression space might be infinite:
  - γ structure can prune problems from progression space
- Most (all?) SHOP and SHOP2 domains are $\leq_r$-stratifiable
  - Can guarantee termination by adding a loop check

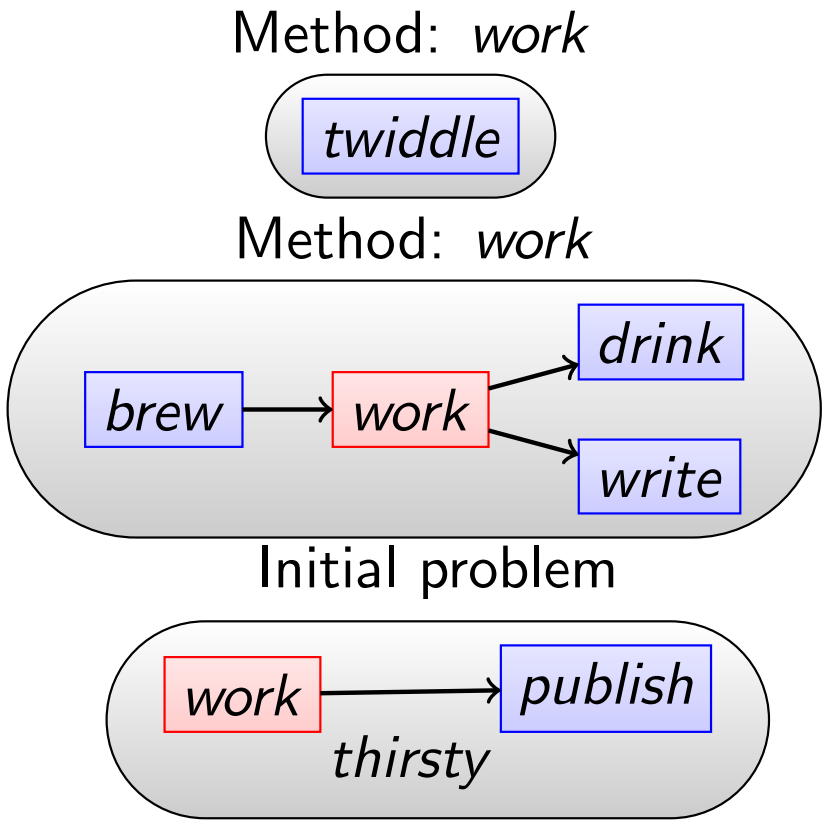
Total Order Partition spaces

Motivating Example: Morning coffee

- Brew as much coffee in the morning as you need throughout the day.
- Easy to express as HTN
  - Difficult in classical planning (artificially limit coffee?)
  - Not $\leq_r$-stratifiable ('work' now in the middle)

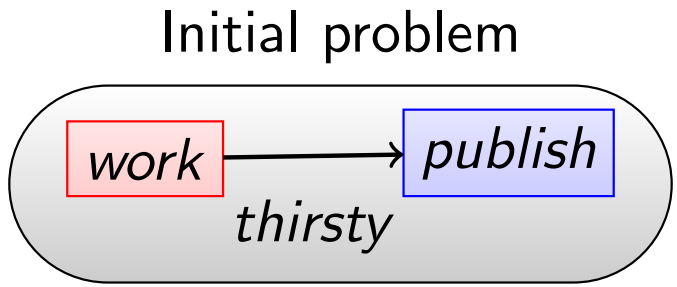
New actions:

- $\gamma(s, \mathit{brew}) = s$
- $\gamma(s, \mathit{twiddle}) = s$
- $\gamma(s, \mathit{publish}) = \emptyset$



Total Order Partition spaces

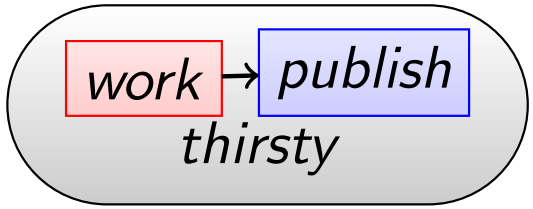
Serialization



- Plan by splitting into smaller parts
- 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

Total Order Partition spaces

Example



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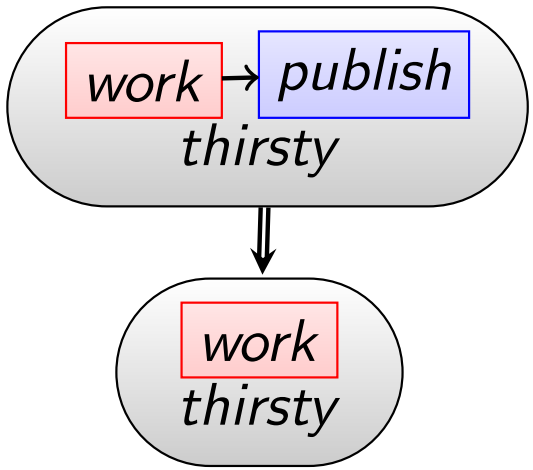

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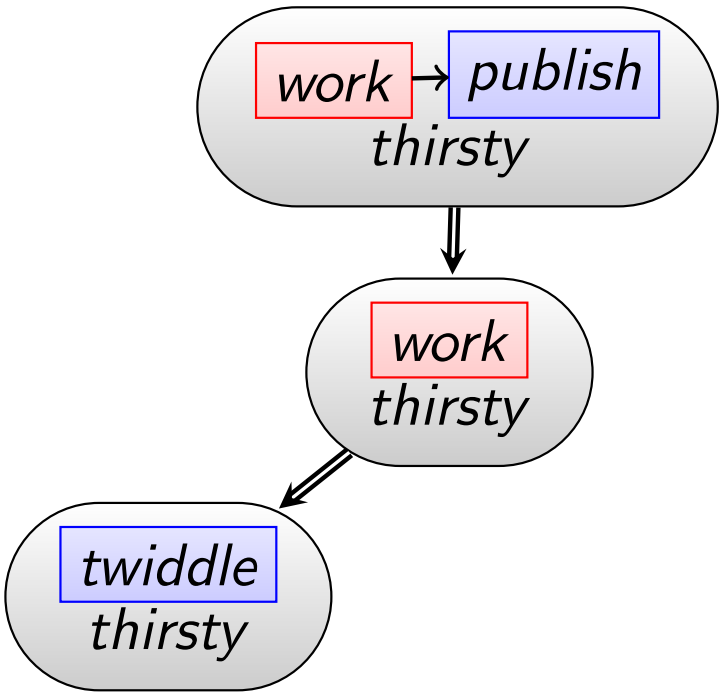

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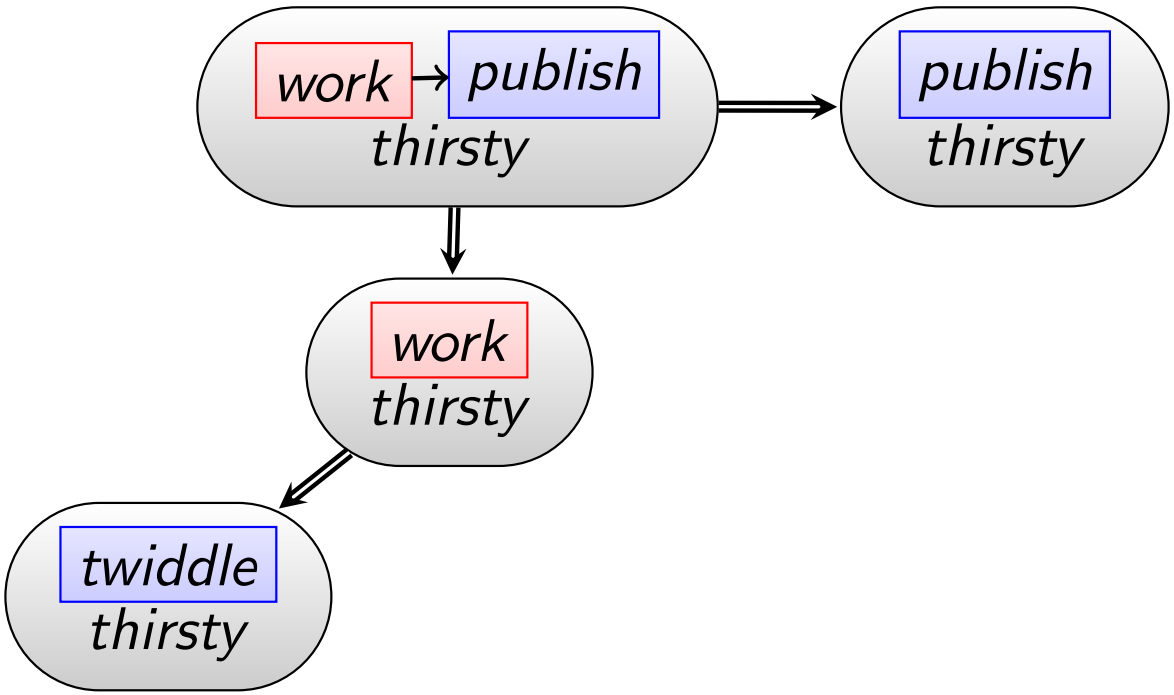

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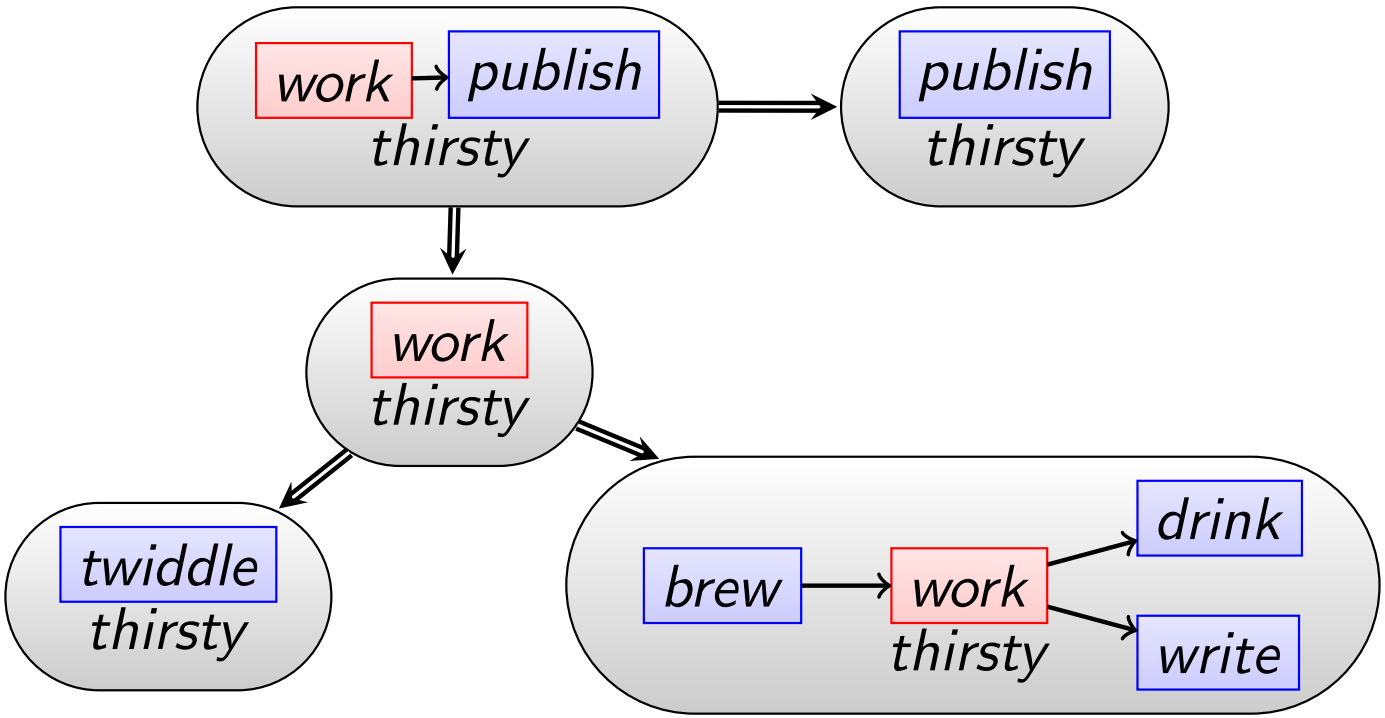

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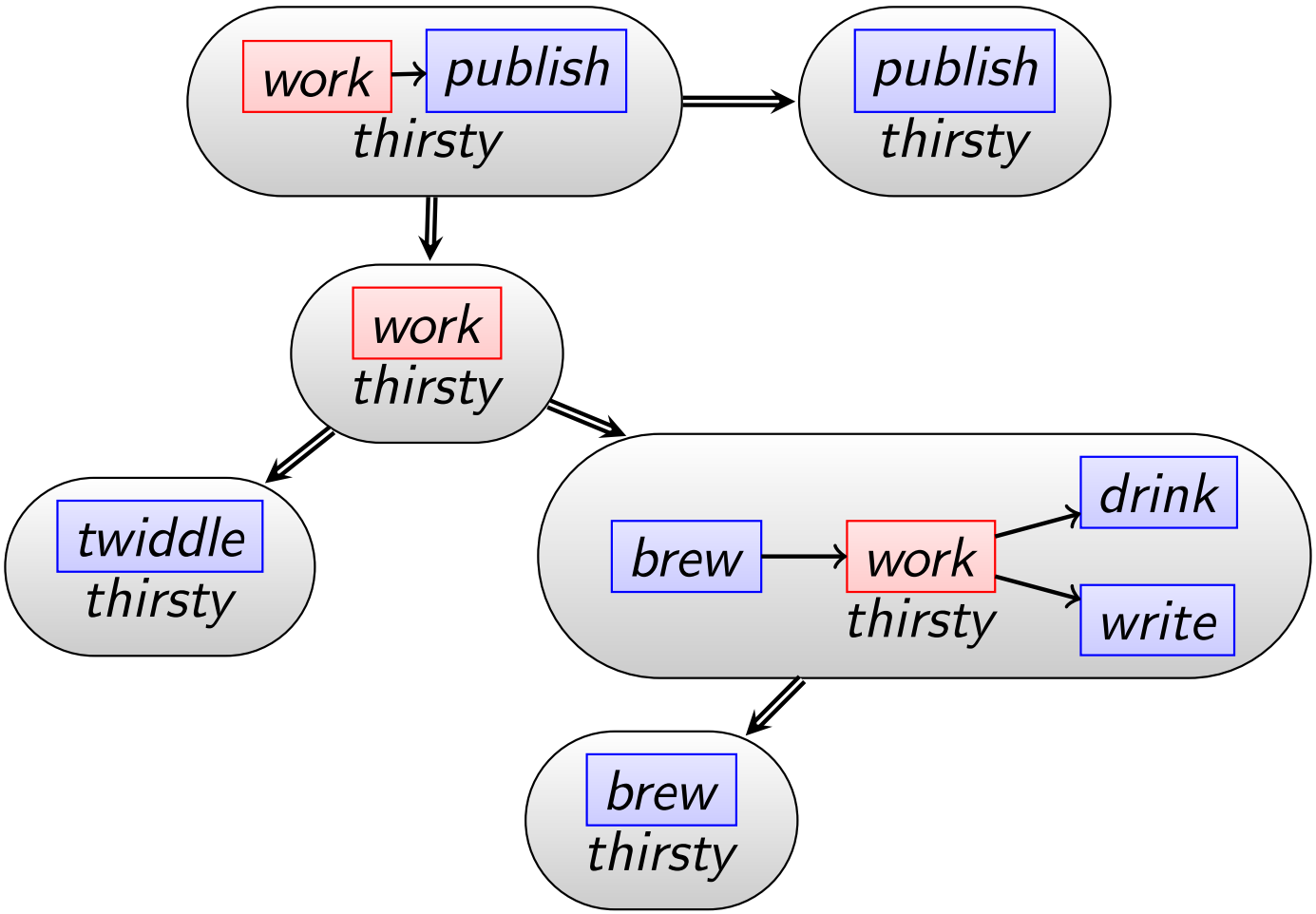

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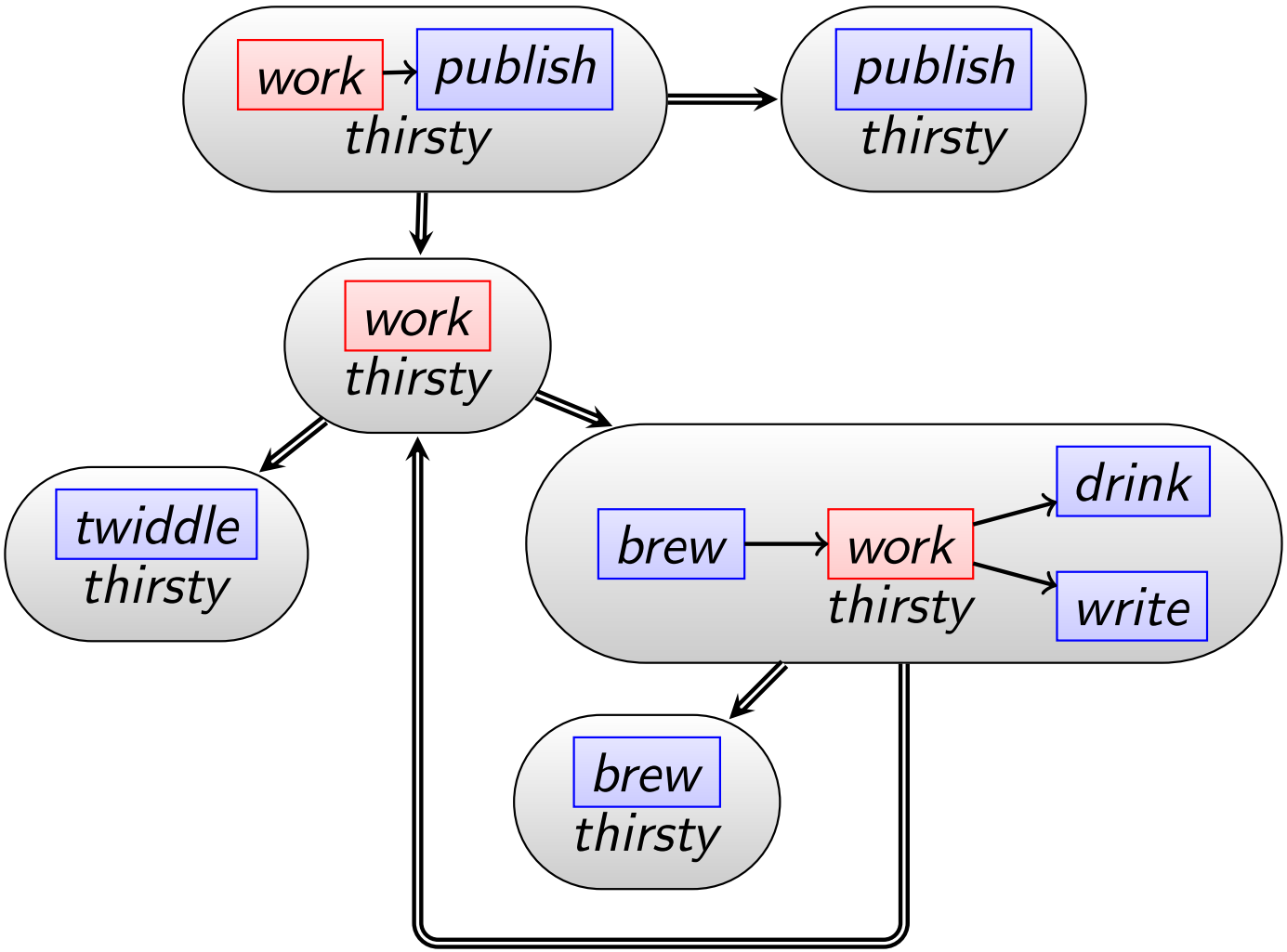

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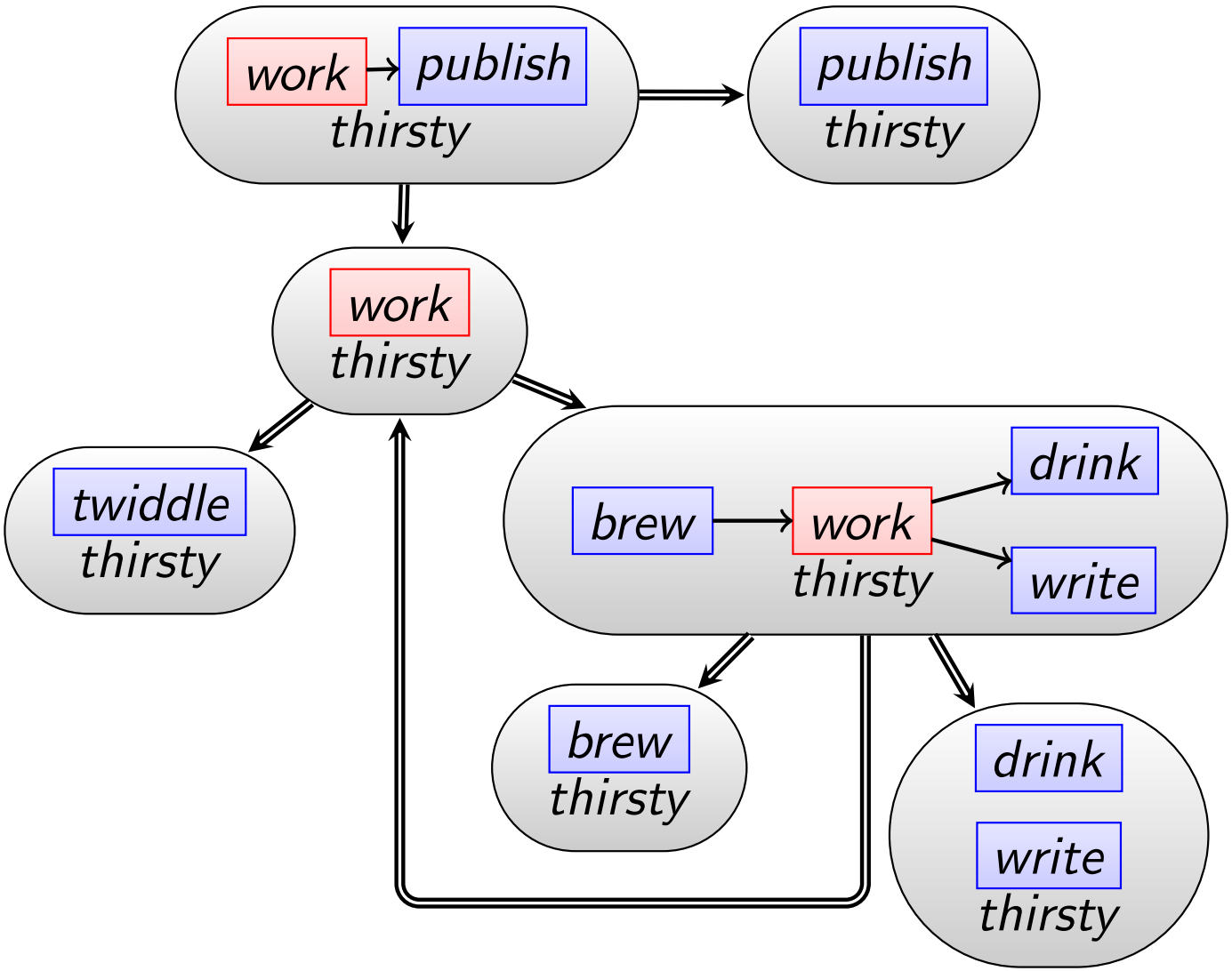

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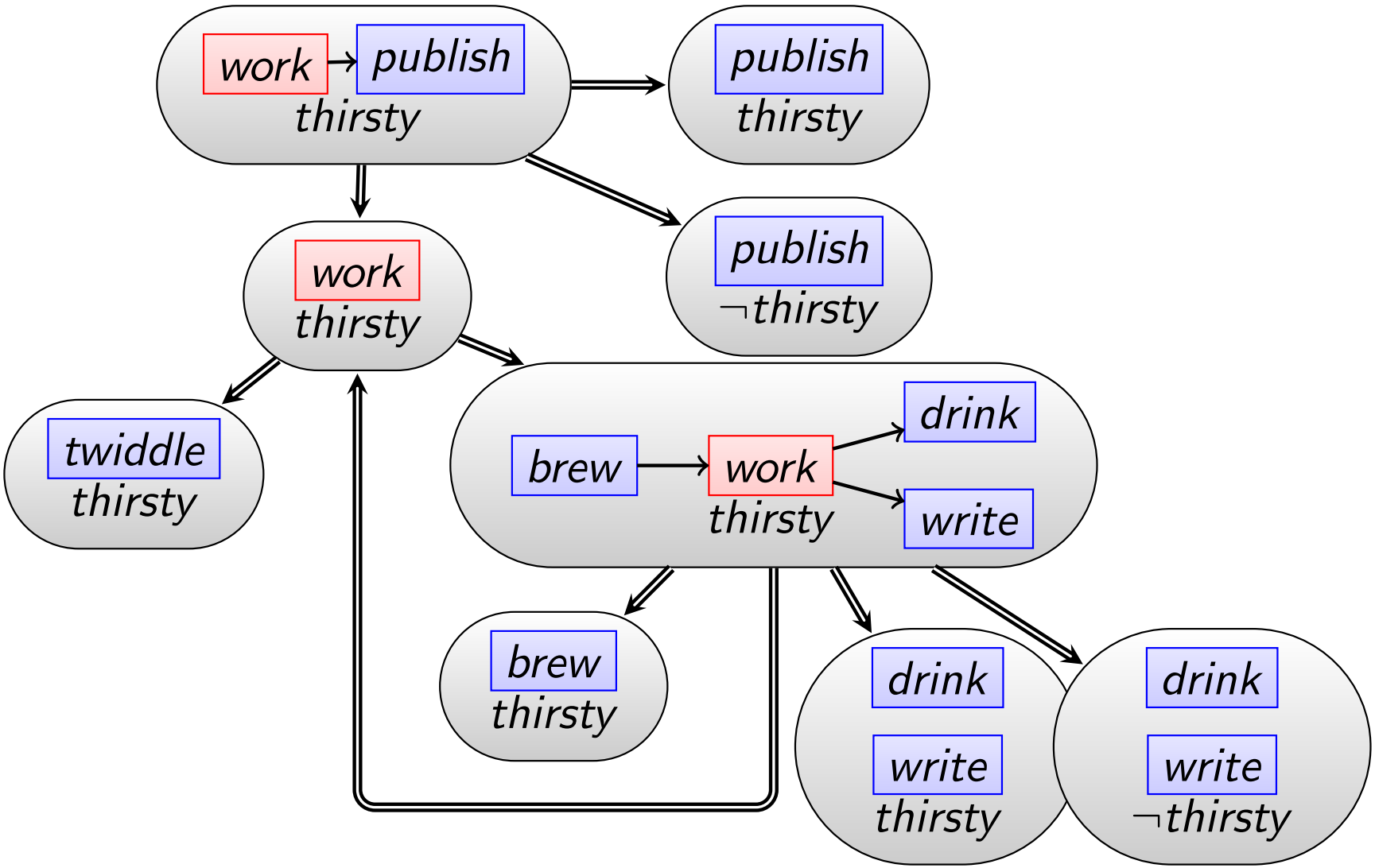

Total Order Partition spaces

$\leq_r$-ordered

- For finiteness, need to consider the structure of networks in the problem.
- Let $\langle tn_1, \ldots, tn_n \rangle$ be the totally ordered chunks of a network tn. tn is $\leq_r$-ordered if every tn_i is either:
  - singular (only one task)
  - $\leq_r$-stratifiable
- Initial task network and all methods $\leq_r$-ordered $\Rightarrow$ problem is $\leq_r$-ordered
- Checks that we never introduce a partial order that can't be solved via progression.

Total Order Partition spaces

$\leq_r$-ordered implications

- Includes $\leq_r$-stratifiable problems
- Includes totally ordered HTN planning.
  - Every finite-state finite-task domain that SHOP can handle.
  - SHOP may not terminate on these
  - Possible to develop a planner that does.
- Heuristic search may be fun:
  - Loops
  - Sequential dependencies between children

Wrap-up

Contributions:

- Characterized three different ways to search for HTN problems (fourth in paper)
- Two ways well implemented, but now we know when we can get them to terminate.
  - Stratification checks may be helpful for domain authors
- A new way to search, which terminates on more problems.

Future work:

- Heuristic search for TOP spaces
- Use $\leq_r$-stratification to find automatic bounds for translation based planning