Lecture *Hierarchical Planning*

Chapter:
Solving Hierarchical Problems via Search

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Overview:

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  - Local search (not covered).

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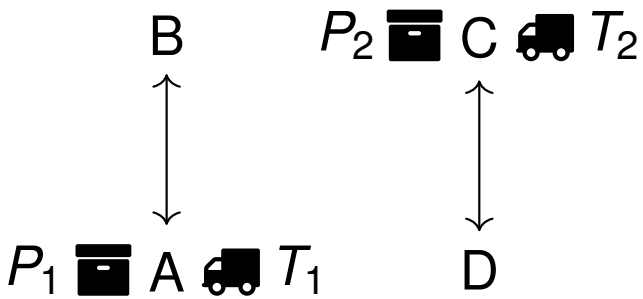

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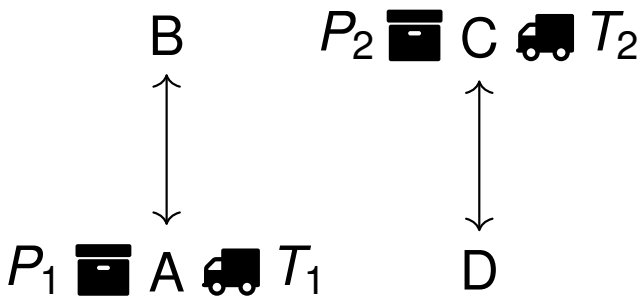
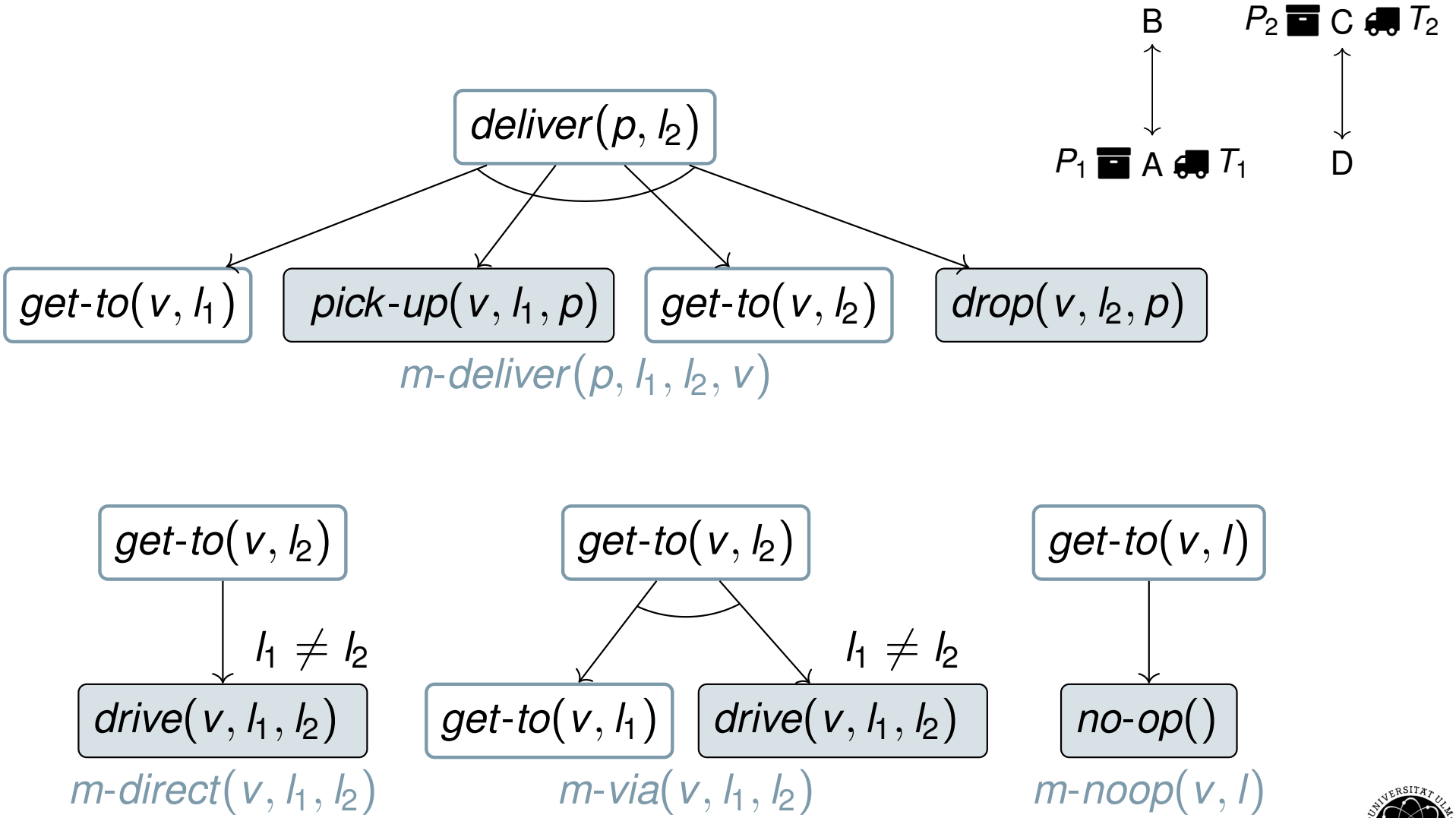
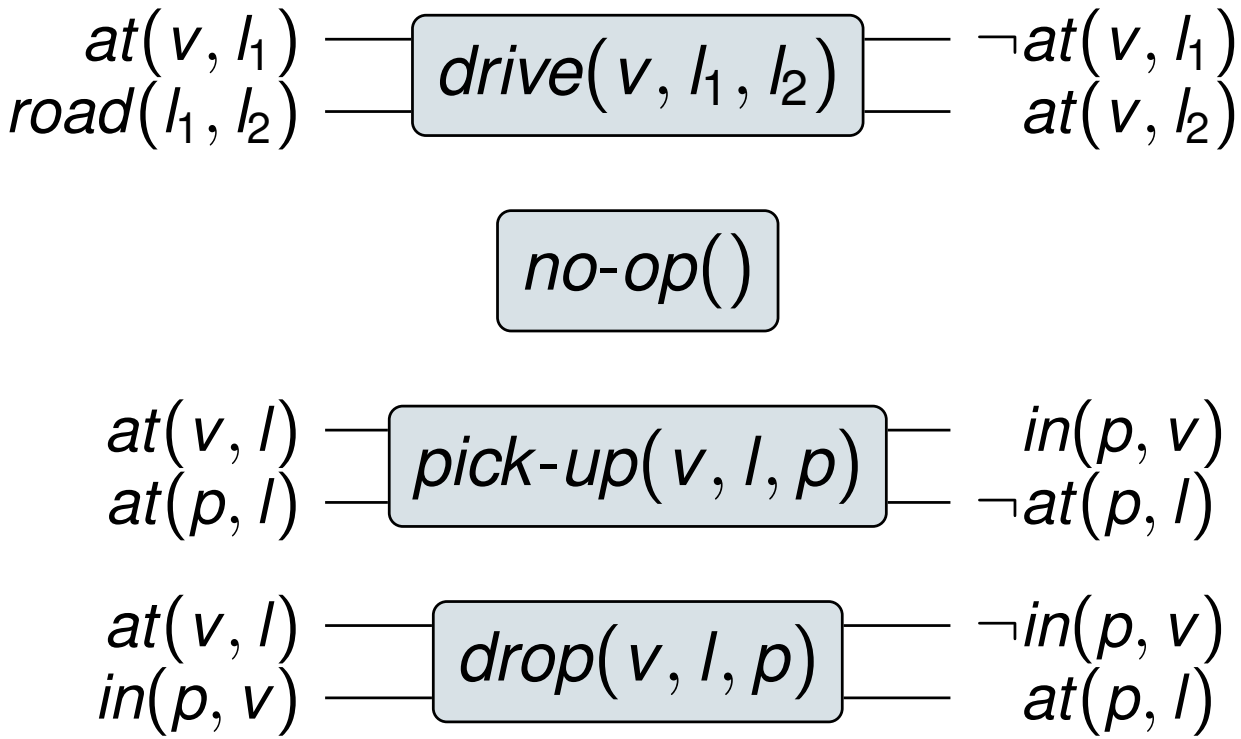


- We model the respective domain and problem as an HTN problem.

Graphical Illustration of Domain Model



Formal Action Model



Assume the following sorts/types: v – *vehicle*, l, l_1, l_2 – *location*, and p – *package*. Further assume that constants of the respective sorts/types are provided.

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- Note: The standard progression algorithm, SHOP2, relies on *preconditions of methods*. (We only discuss this briefly here.)

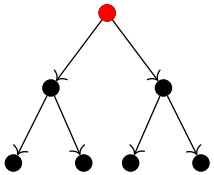
HTN Progression, Pseudo Code

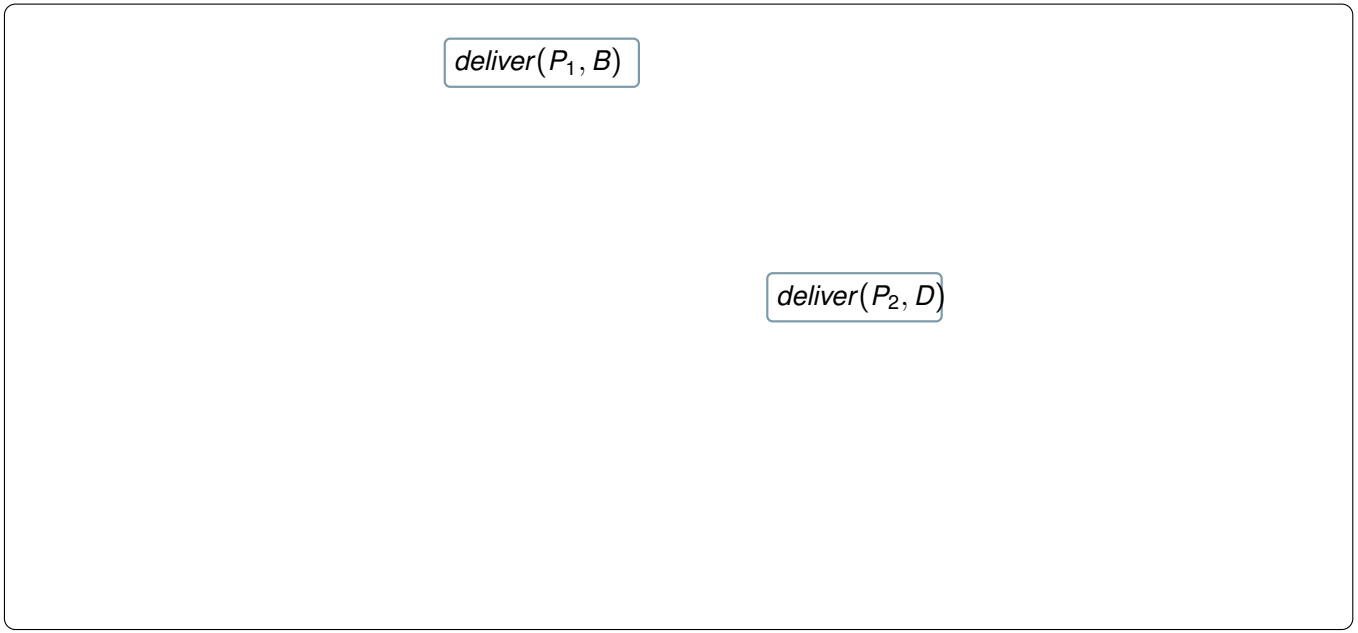
Algorithm: HTN Progression Search

Input: An HTN problem $\mathcal{P} = (V, P, \delta, C, M, s_I, tn_I)$
Output: A solution $\bar{a}$ or ***fail*** if none exists

```
1  fringe ← {(s_I, tn_I, ε)}
2  while fringe ≠ ∅ do
3      n = (s, tn, ā) ← nodeSelectAndRemove(fringe)
4      if tn is empty then
5          return ā
6      else
7          U ← detectUnconstrainedSteps(tn)
8          for t ∈ U do
9              if isPrimitive(t) and pre(t) ⊆ s then
10                 fringe ← fringe ∪ {n.apply(t)}
11             else if isCompound(t) then
12                 fringe ← fringe ∪ {n.decompose(t, m) |
                                      m ∈ M with m = (α(t), tn_m)}
13 return fail
```

HTN Progression, Example





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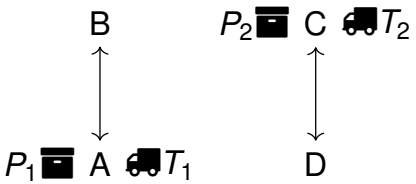

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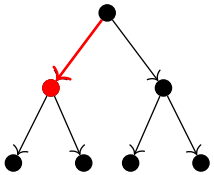

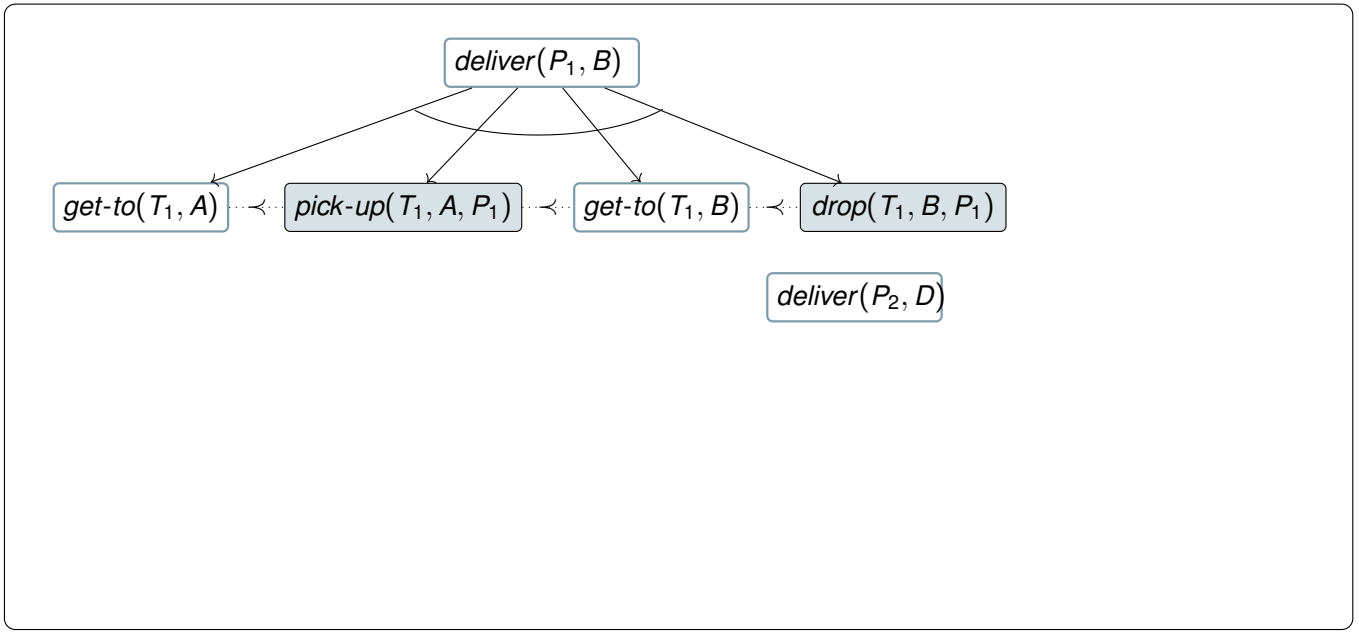

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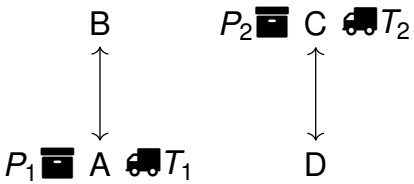

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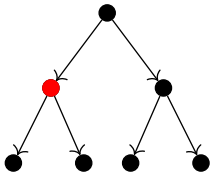

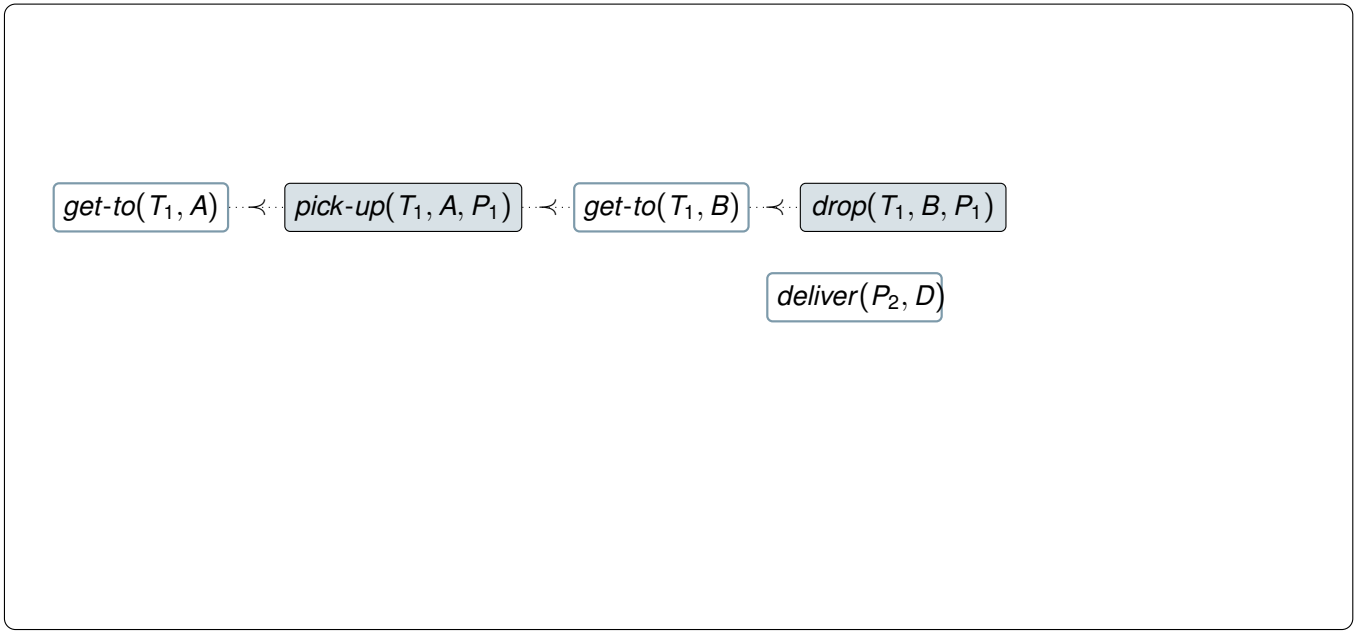

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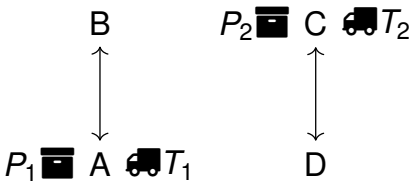

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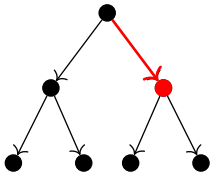

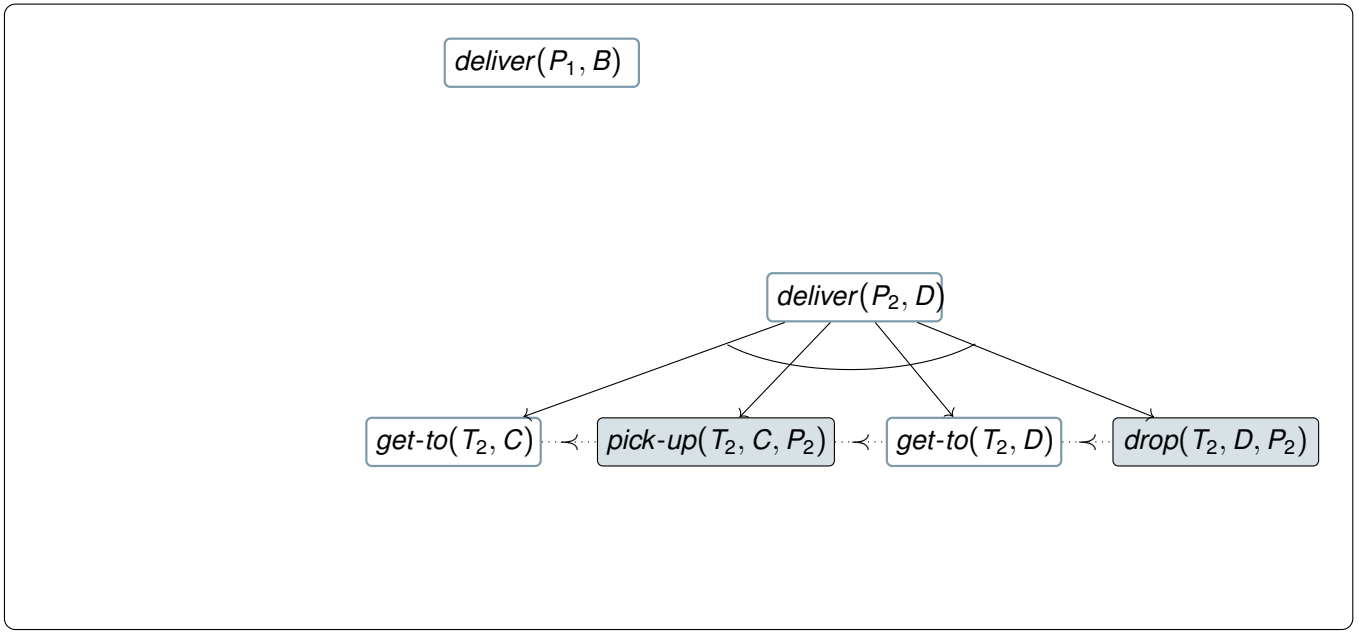

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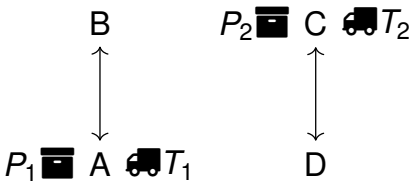

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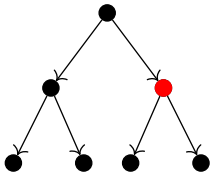

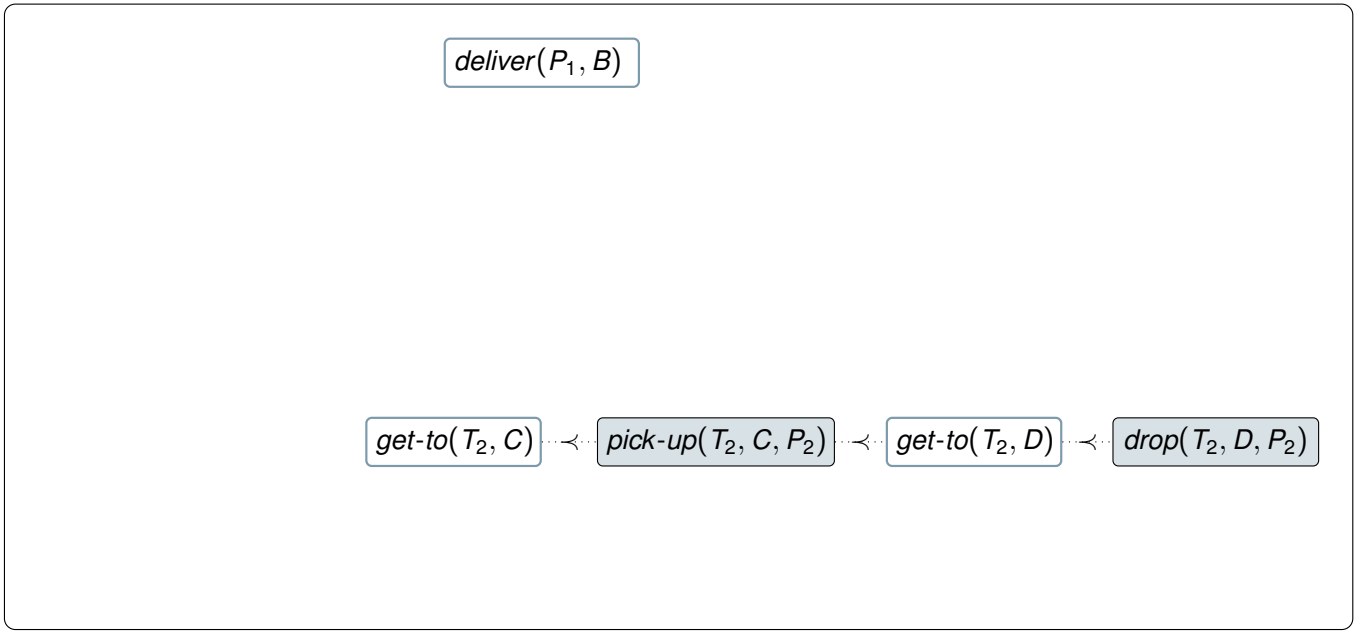

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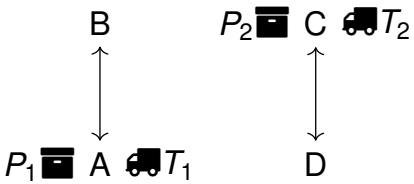

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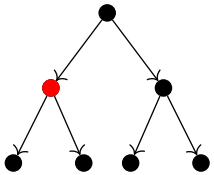

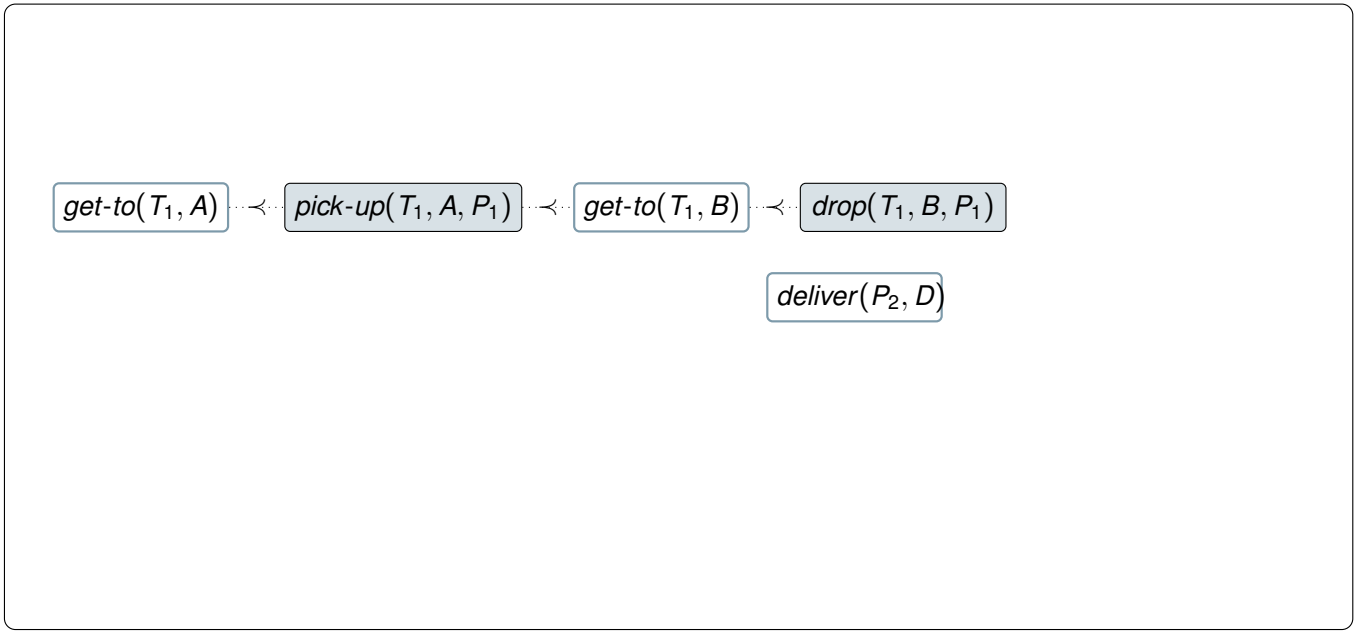

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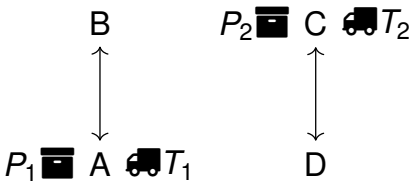

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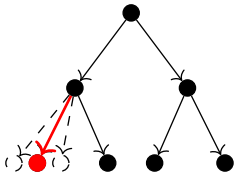

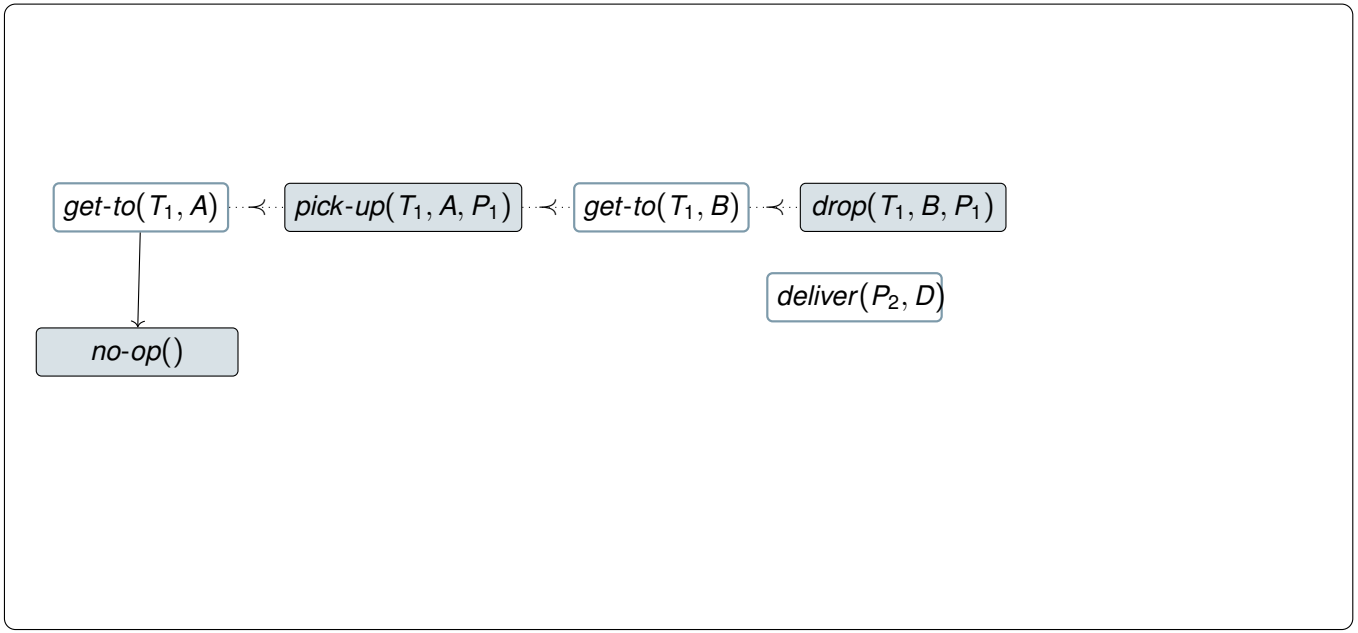

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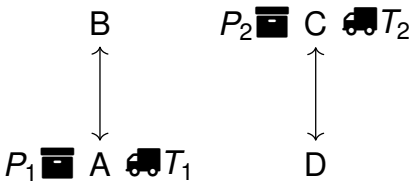

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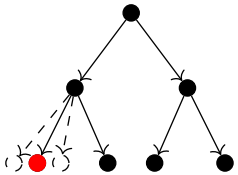

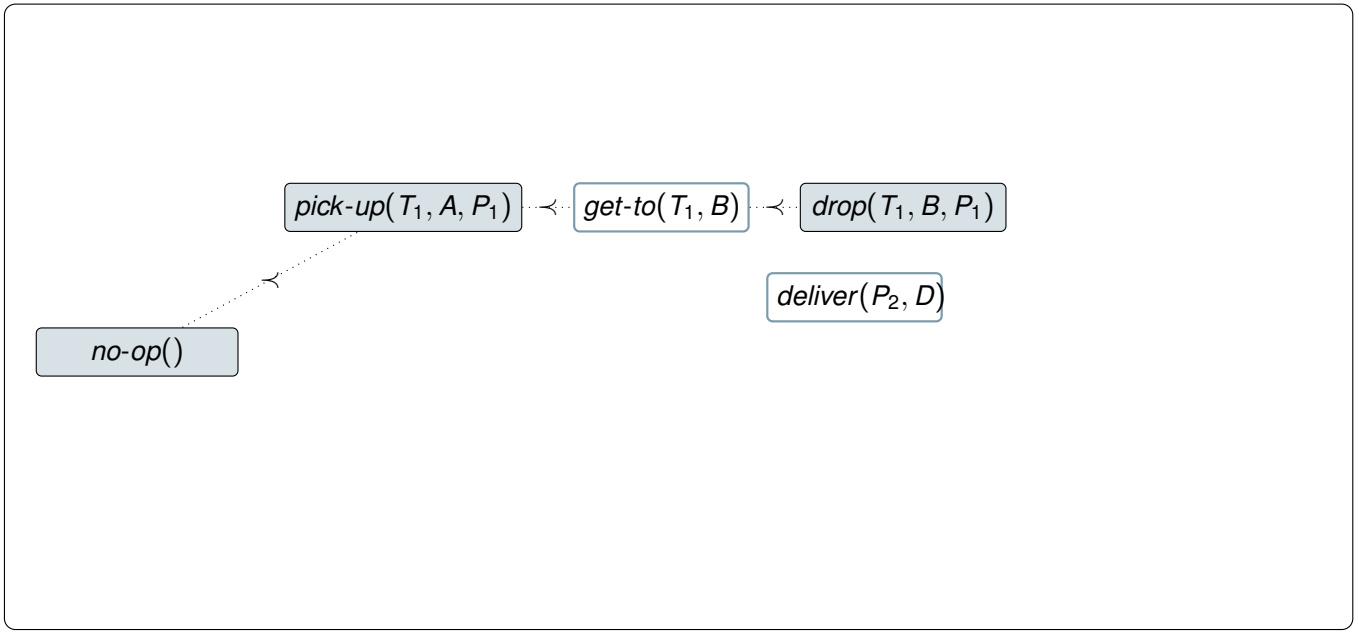

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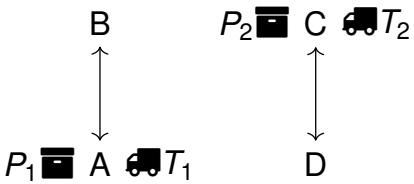

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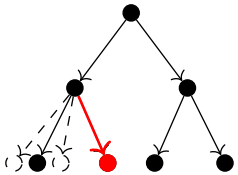

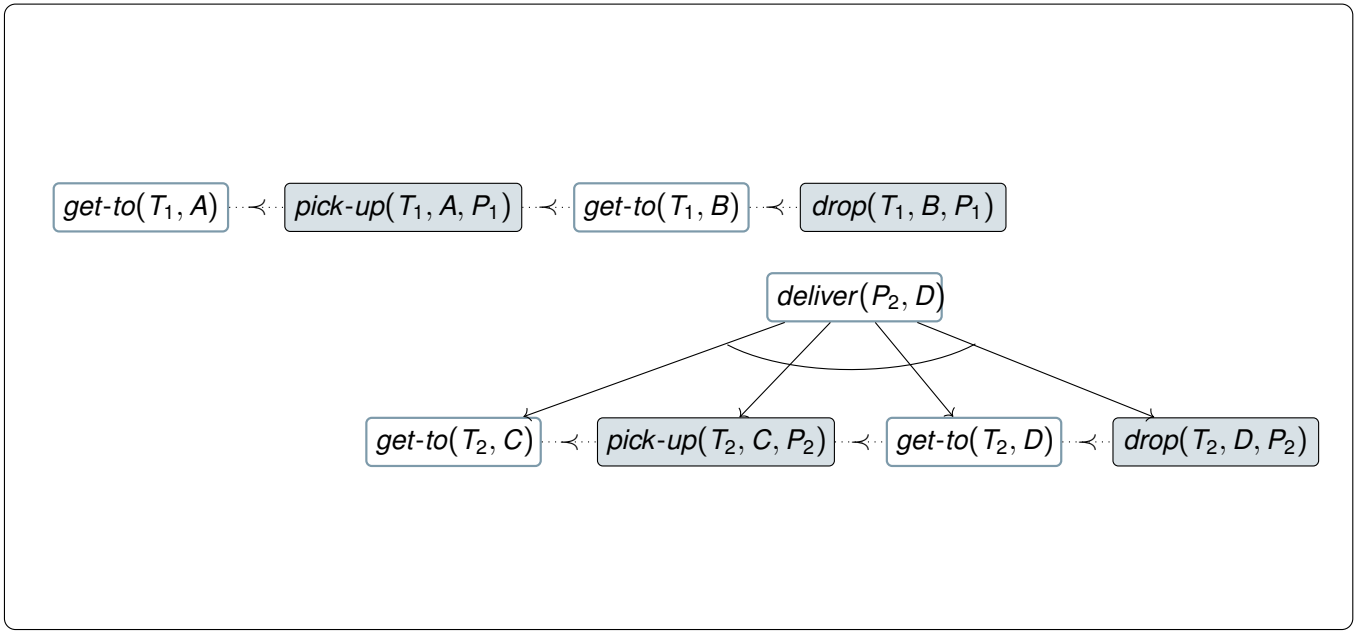

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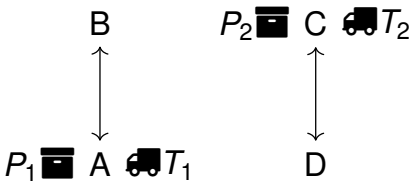

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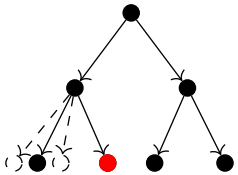

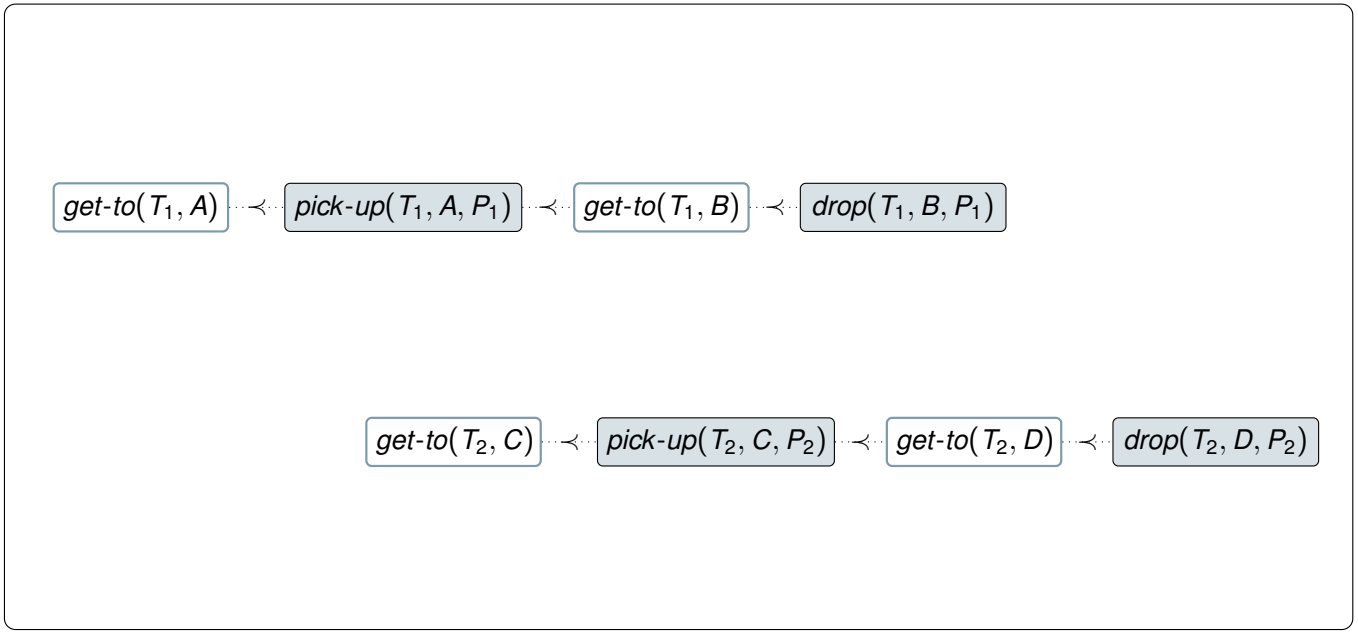

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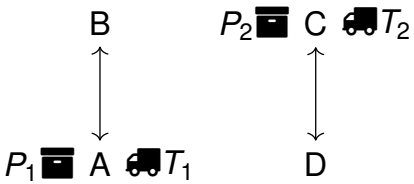

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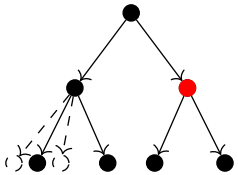

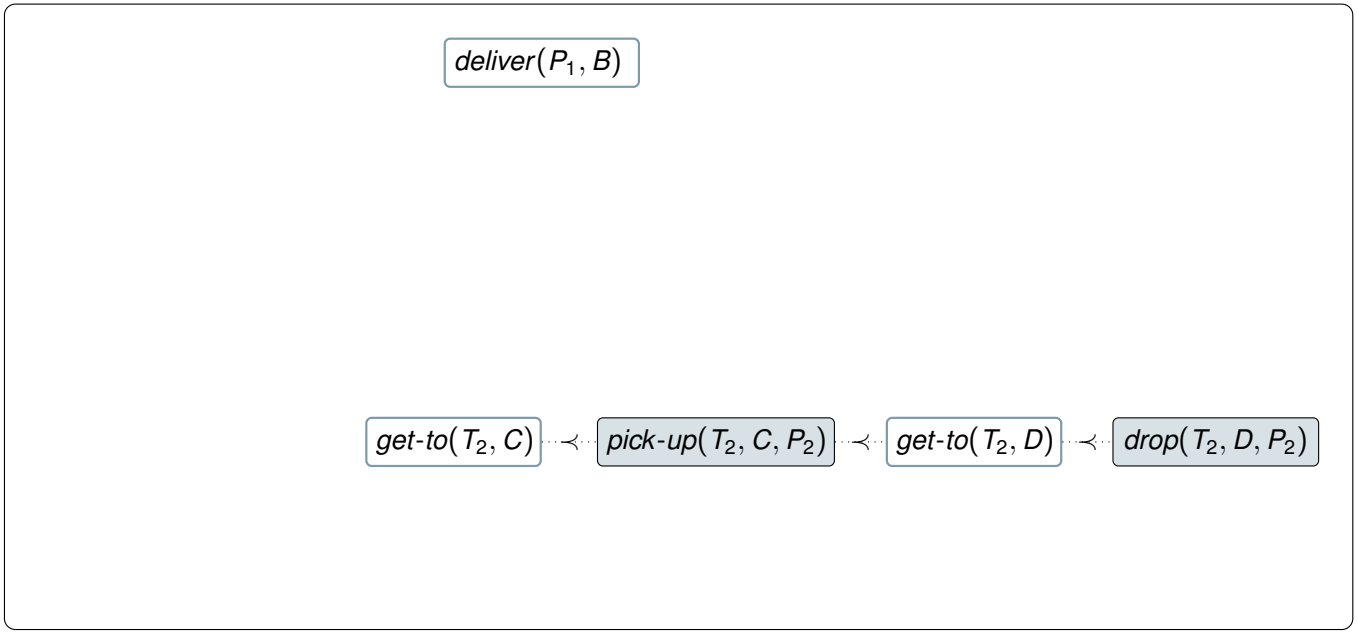

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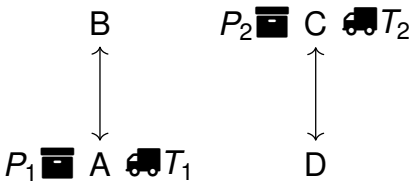

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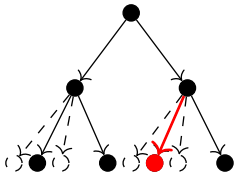

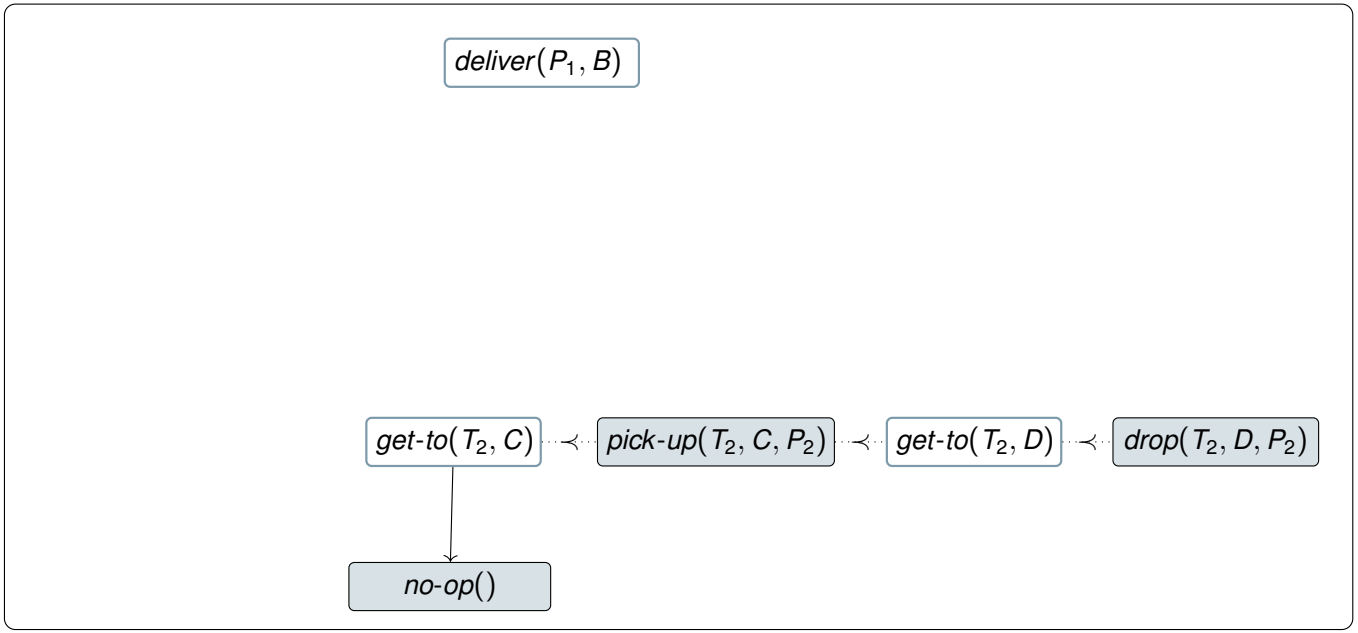

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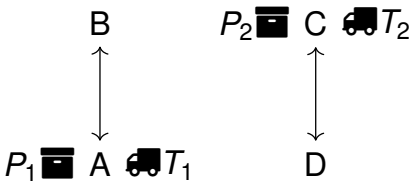

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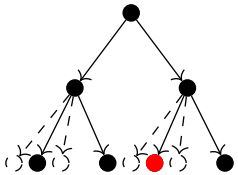

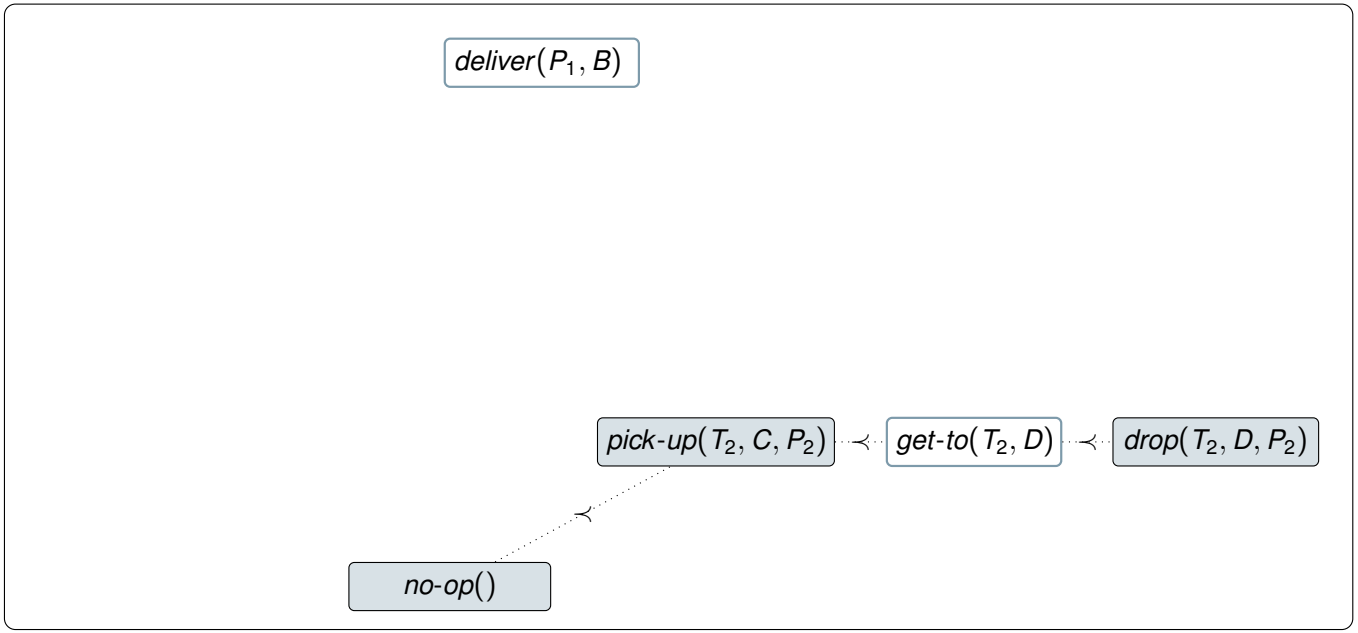

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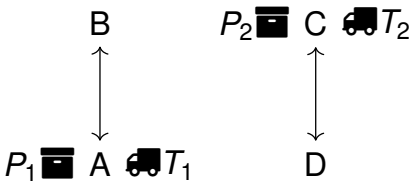
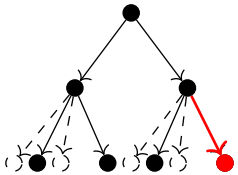
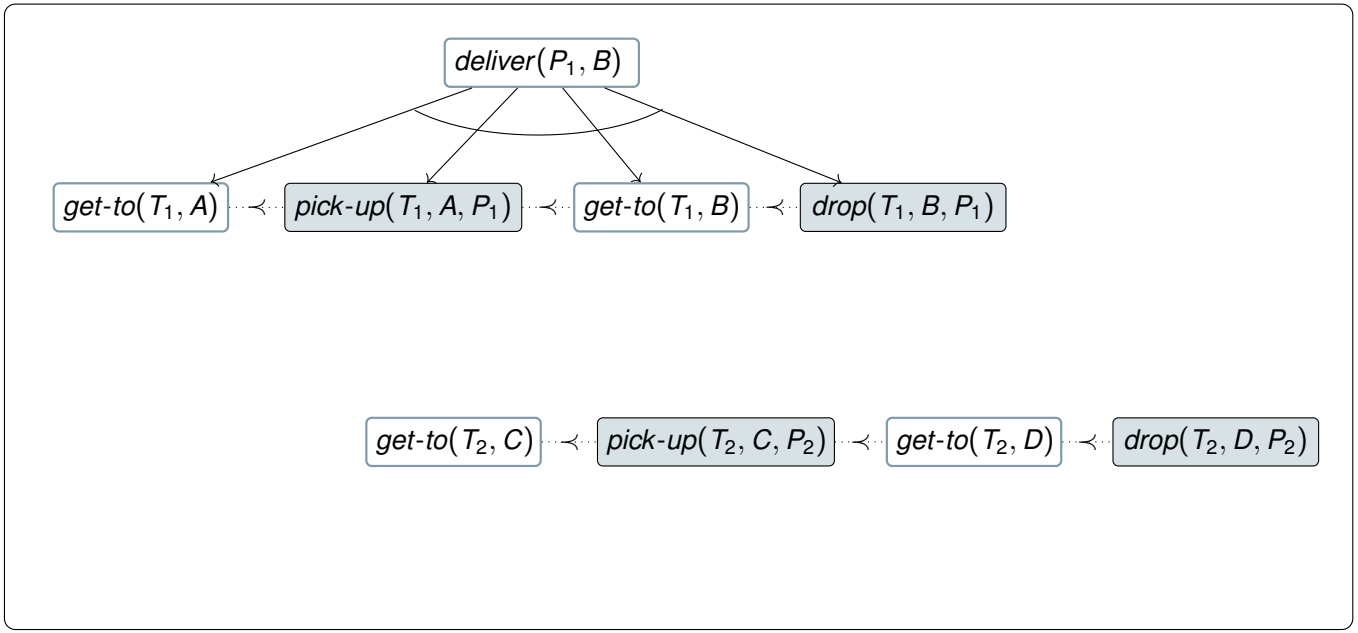


HTN Progression, Example





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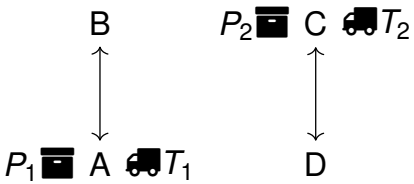
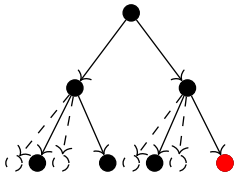
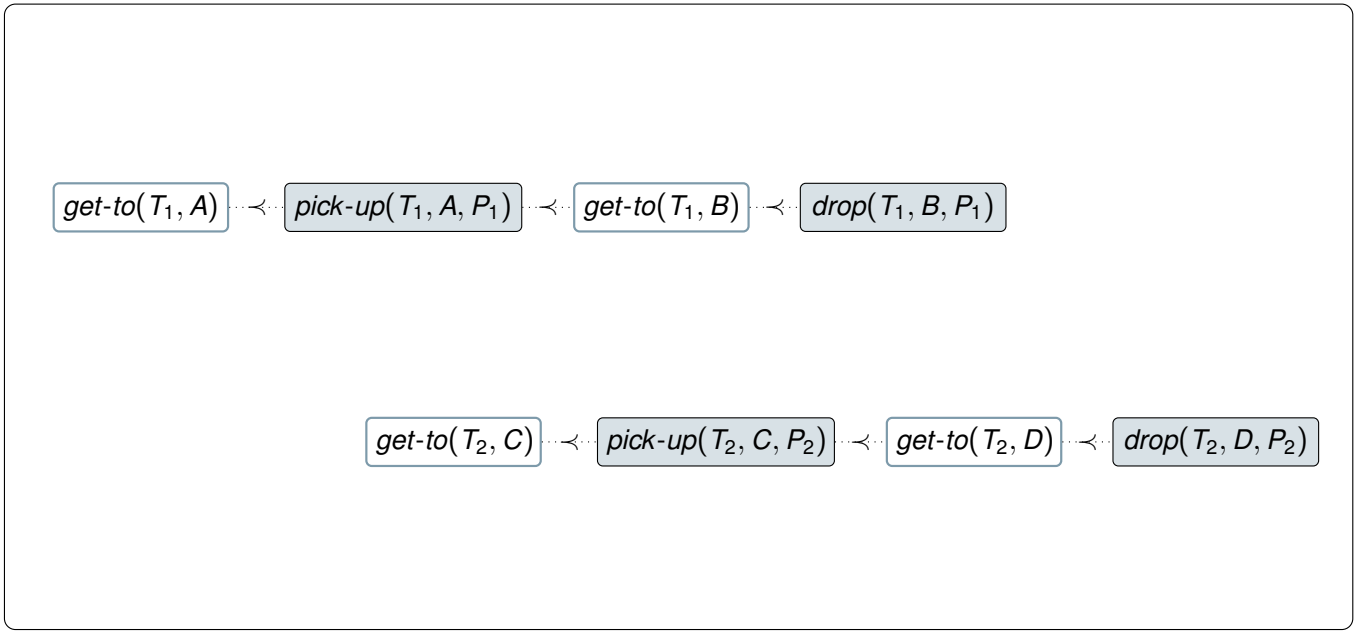


HTN Progression, Example





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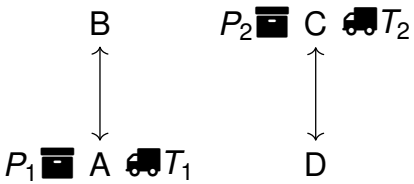
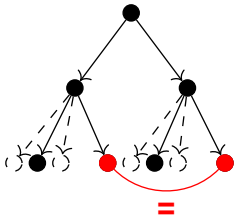
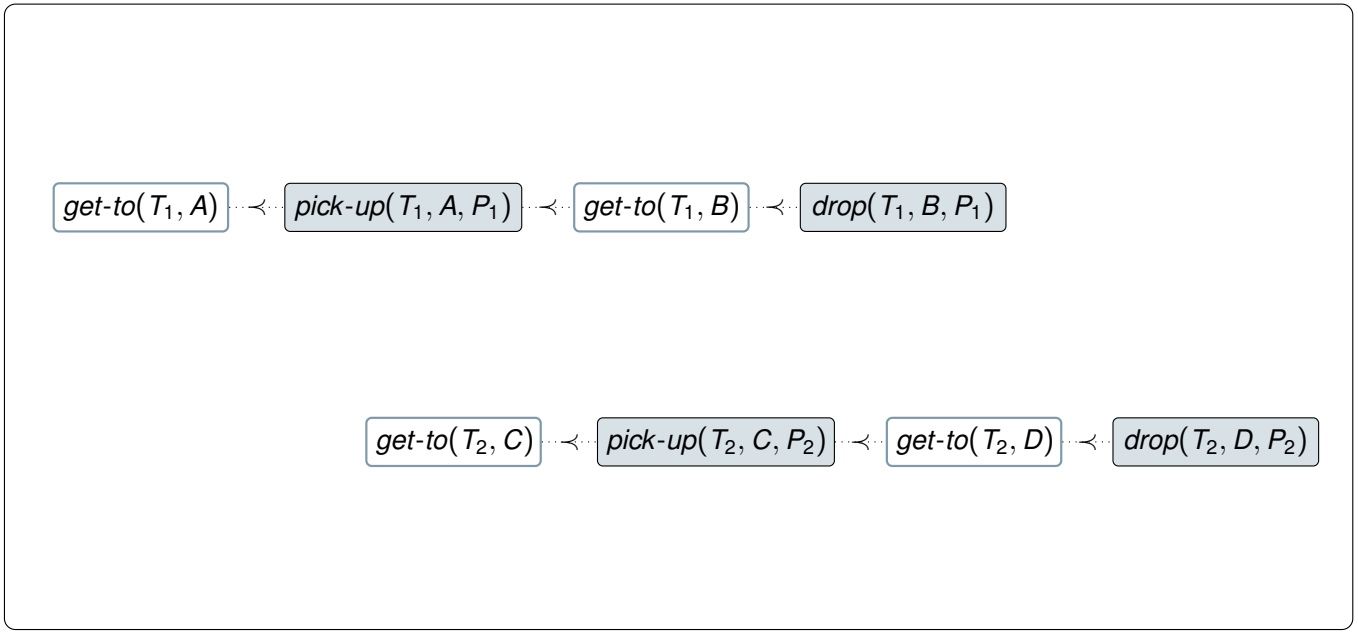


HTN Progression, Example





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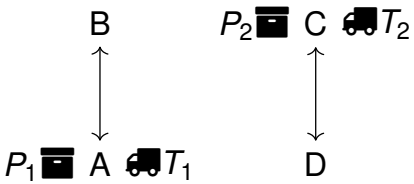
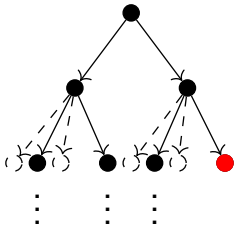
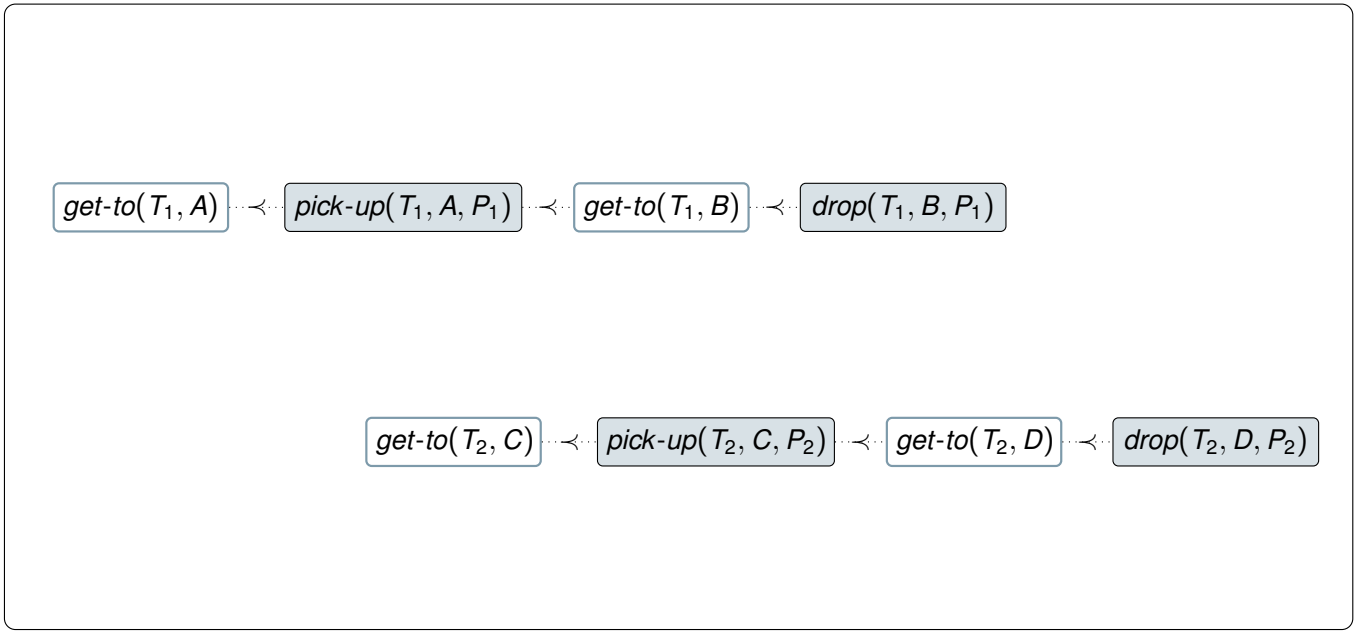


HTN Progression, Example





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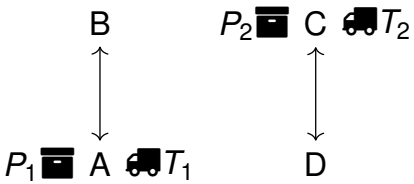
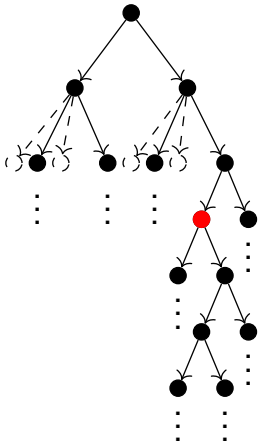
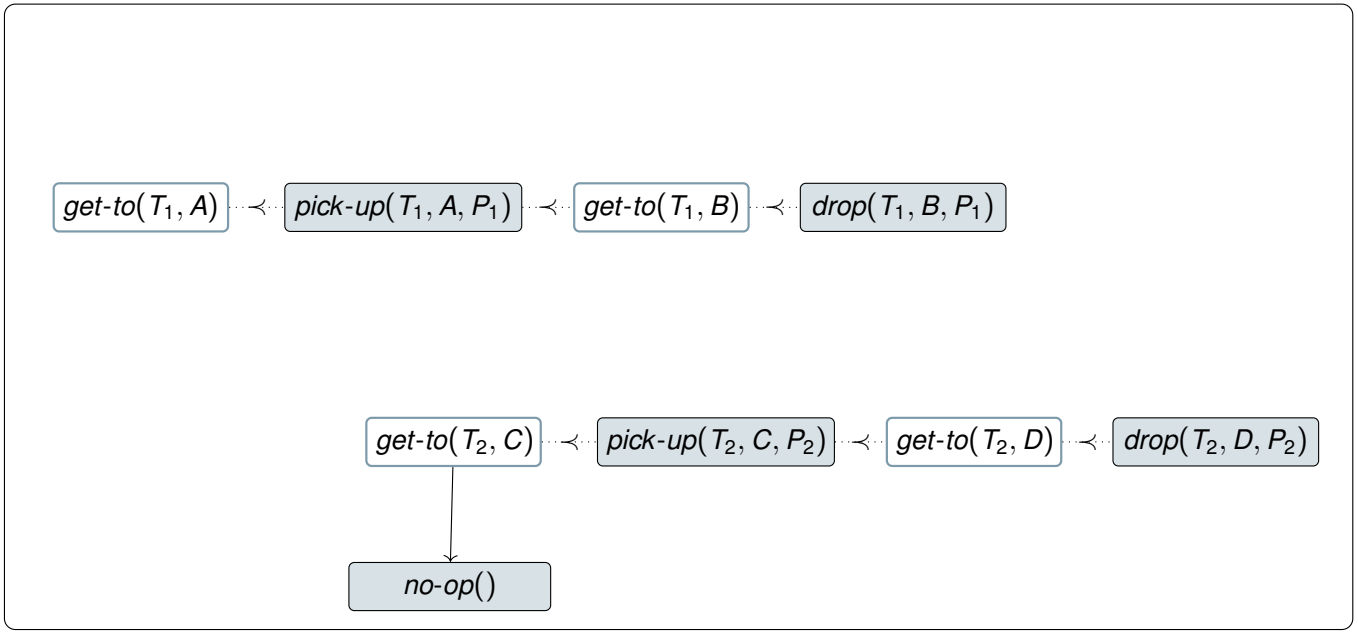


HTN Progression, Example





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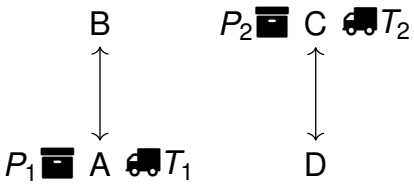
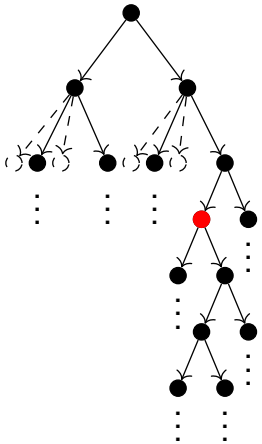
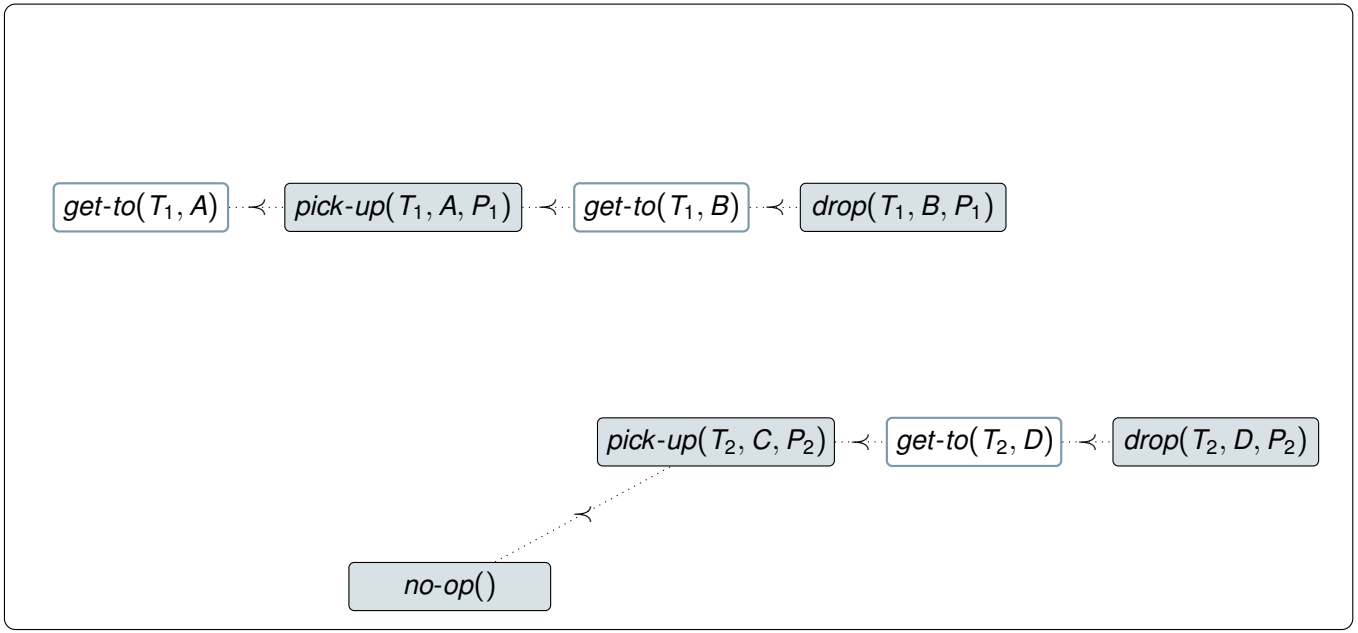


HTN Progression, Example





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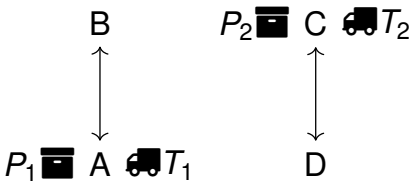
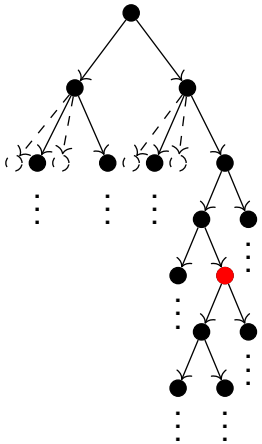
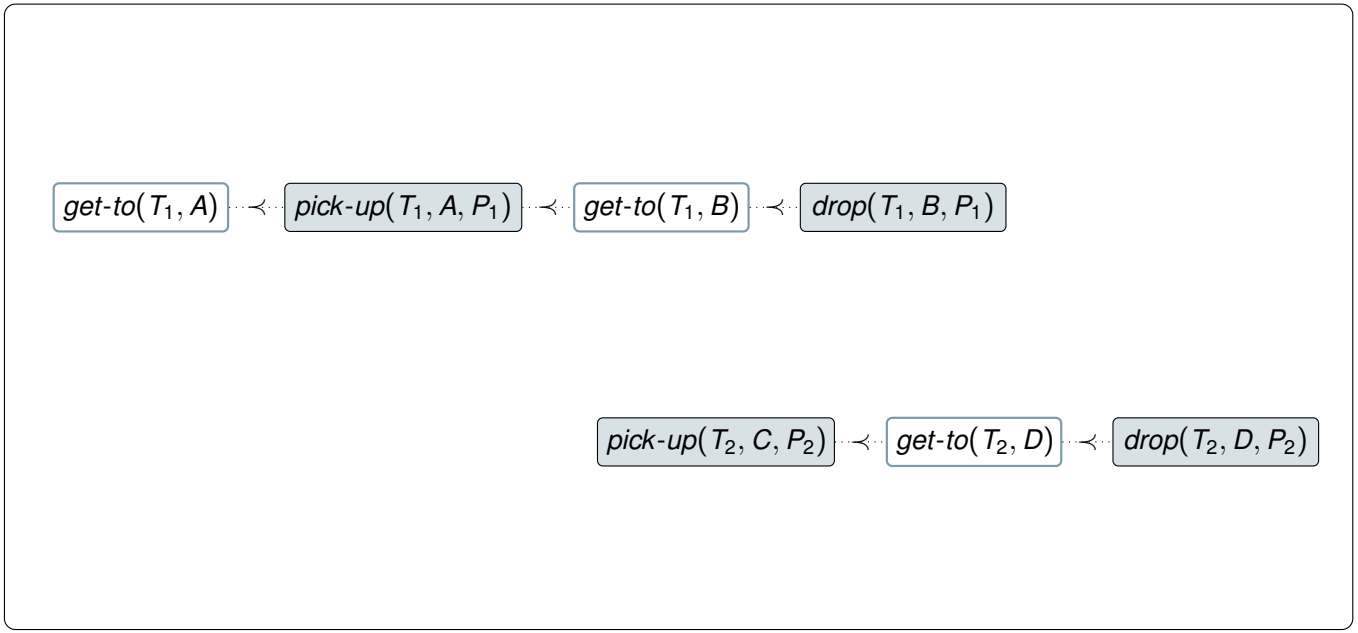
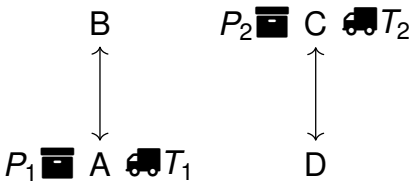


HTN Progression, Example

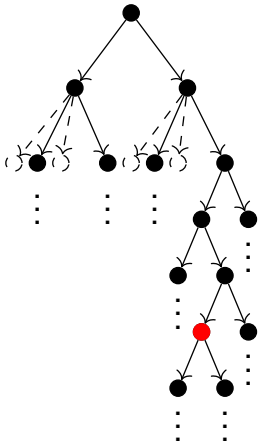


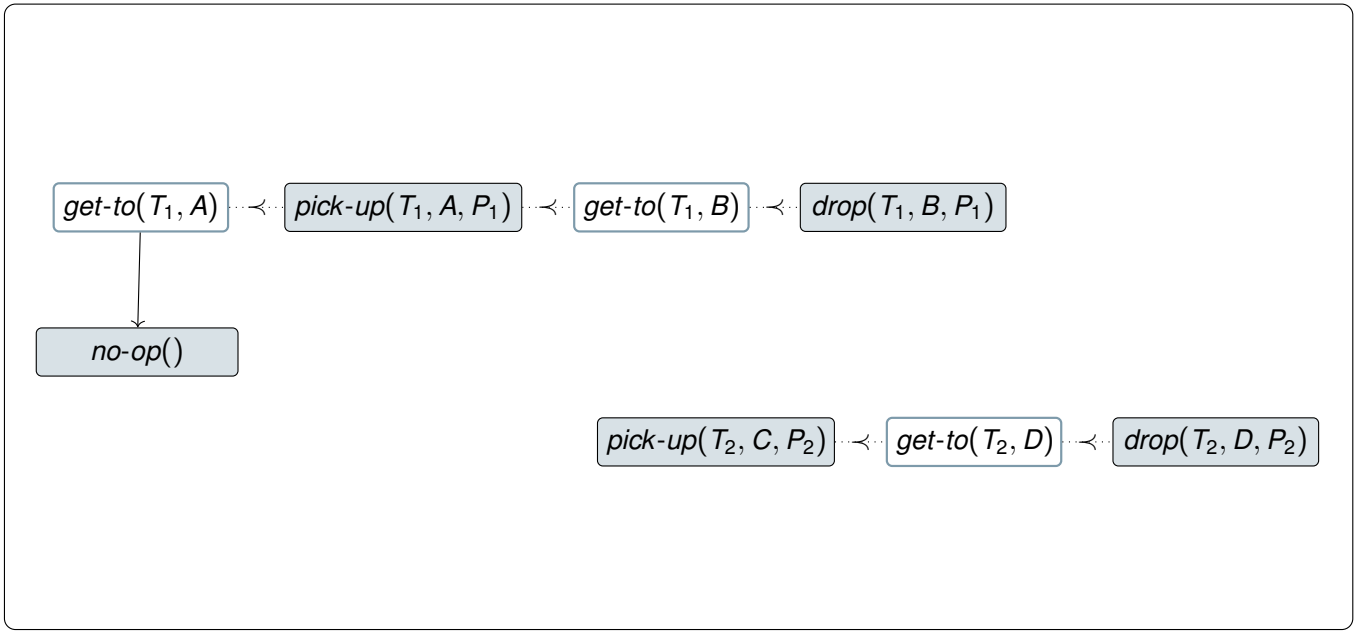


$\pi = (\textit{no-op}())$

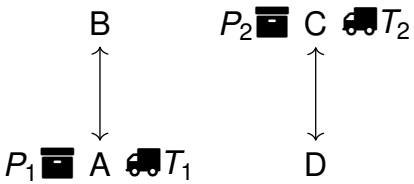


HTN Progression, Example

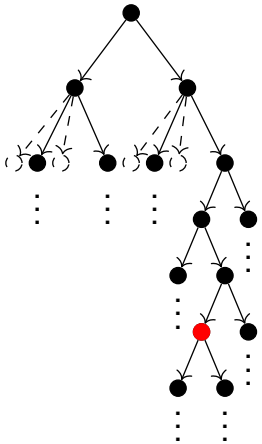


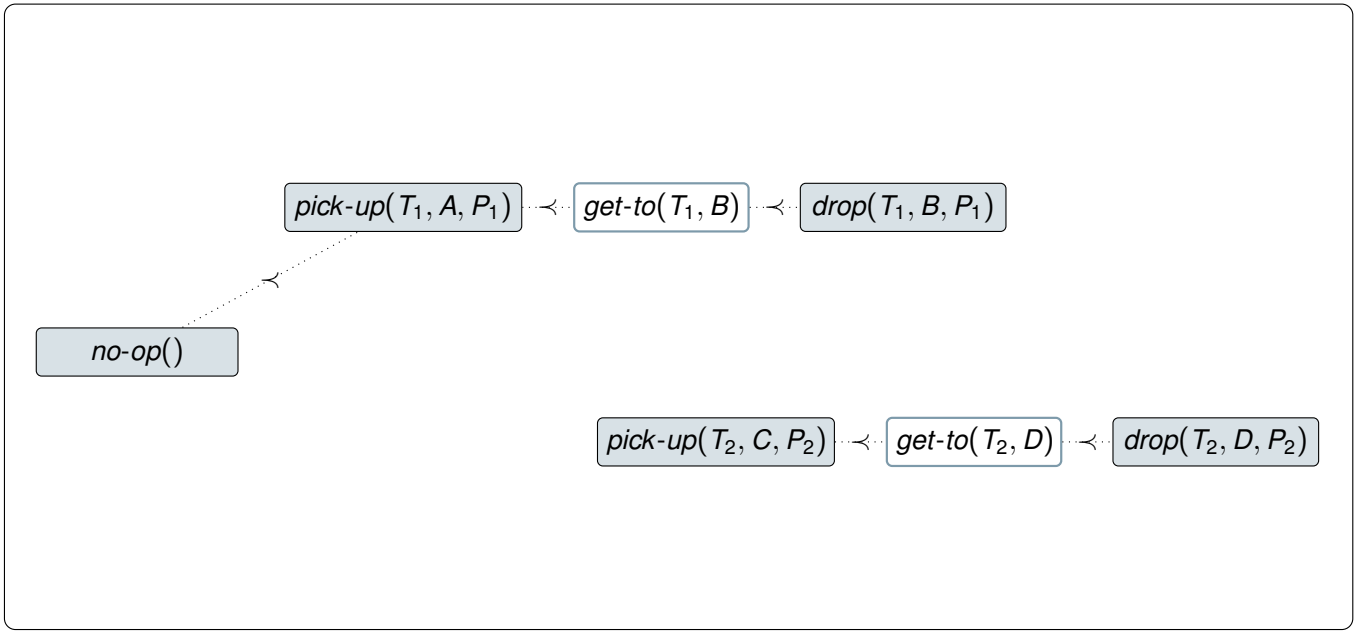


$\pi = (\textit{no-op}())$

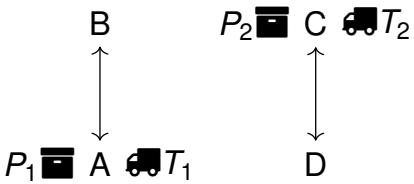


HTN Progression, Example

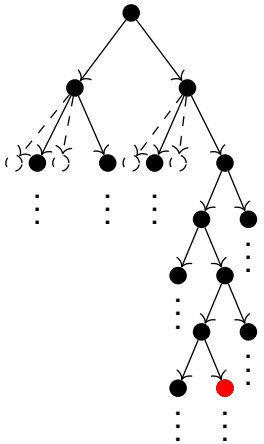


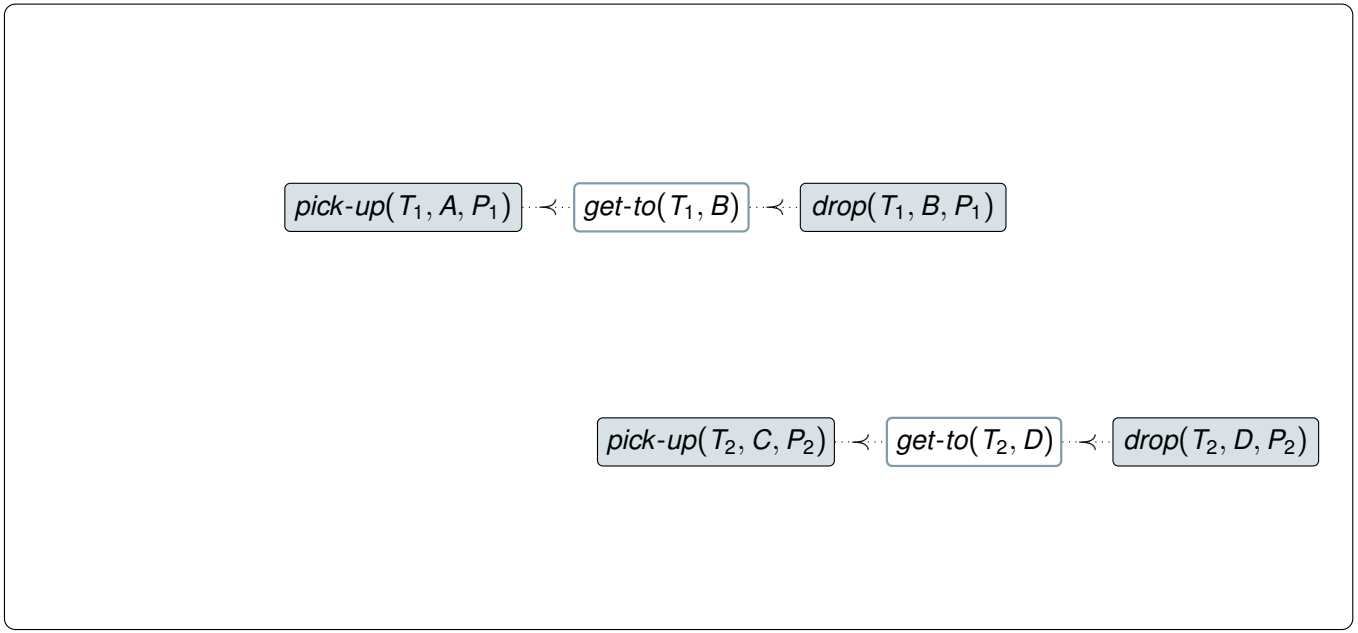


$\pi = (\textit{no-op}())$

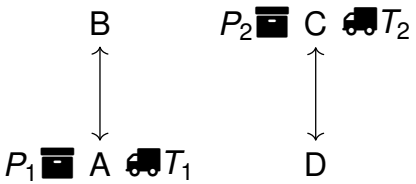


HTN Progression, Example

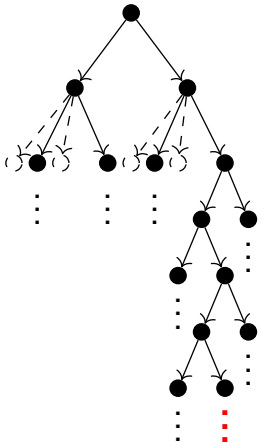


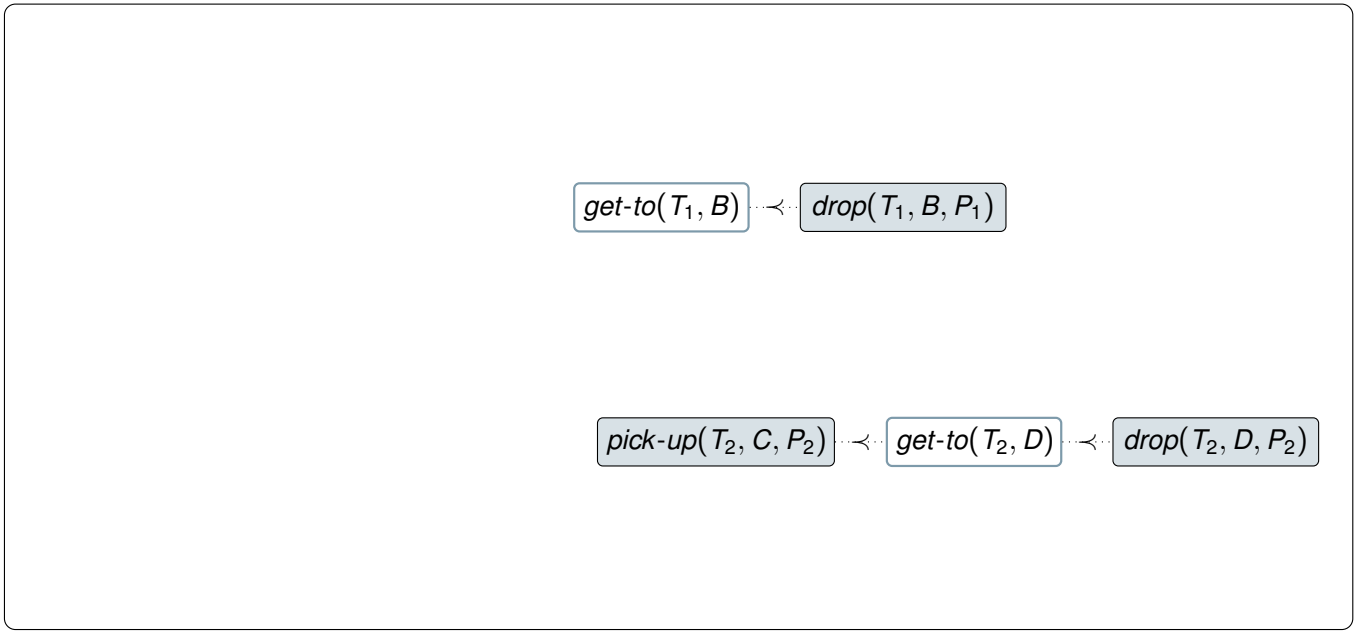


$$\pi = (\textit{no-op}(), \textit{no-op}())$$

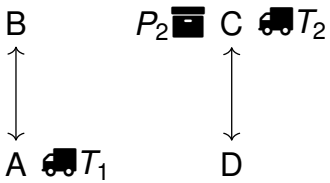


HTN Progression, Example

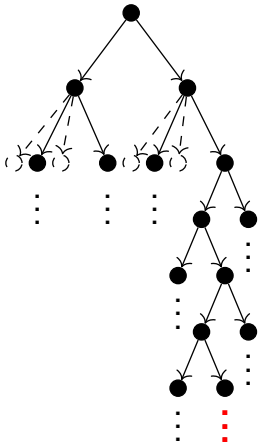


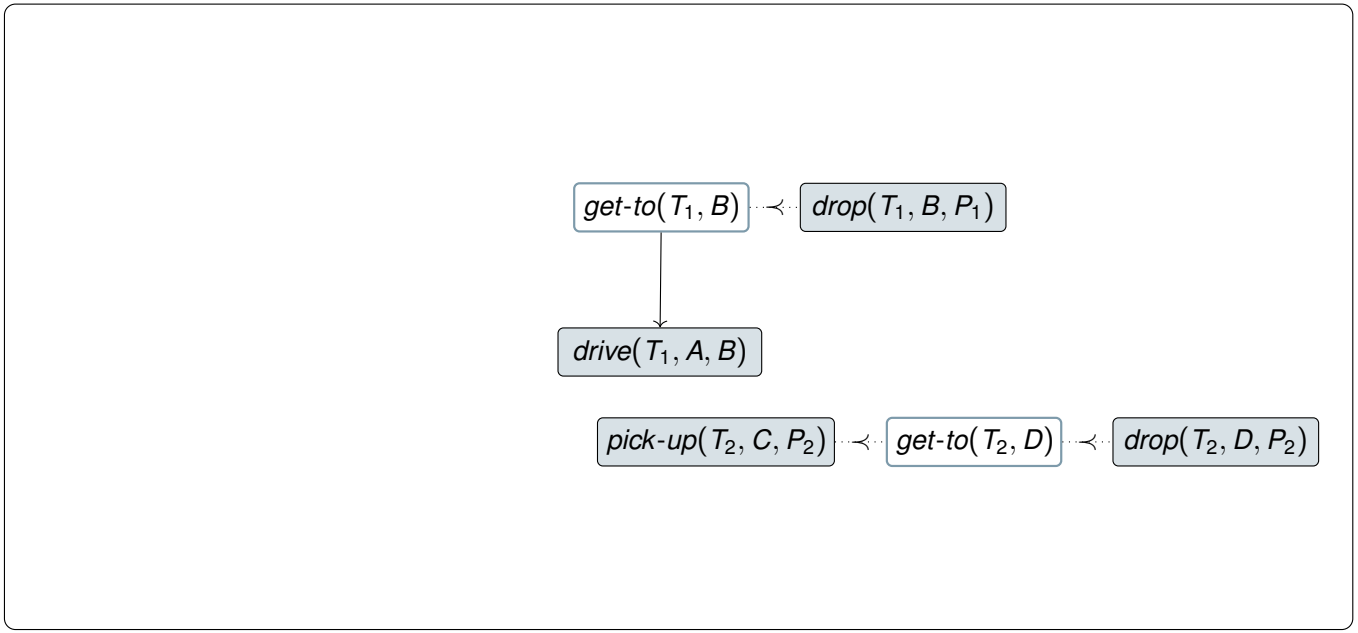


$$\pi = (\textit{no-op}(), \textit{no-op}(), \textit{pick-up}(T_1, A, P_1))$$

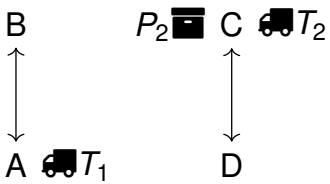


HTN Progression, Example

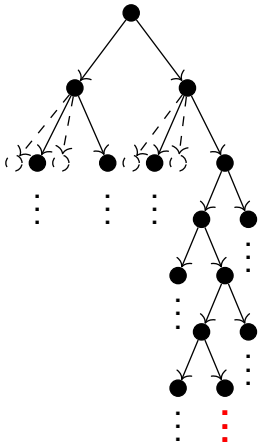


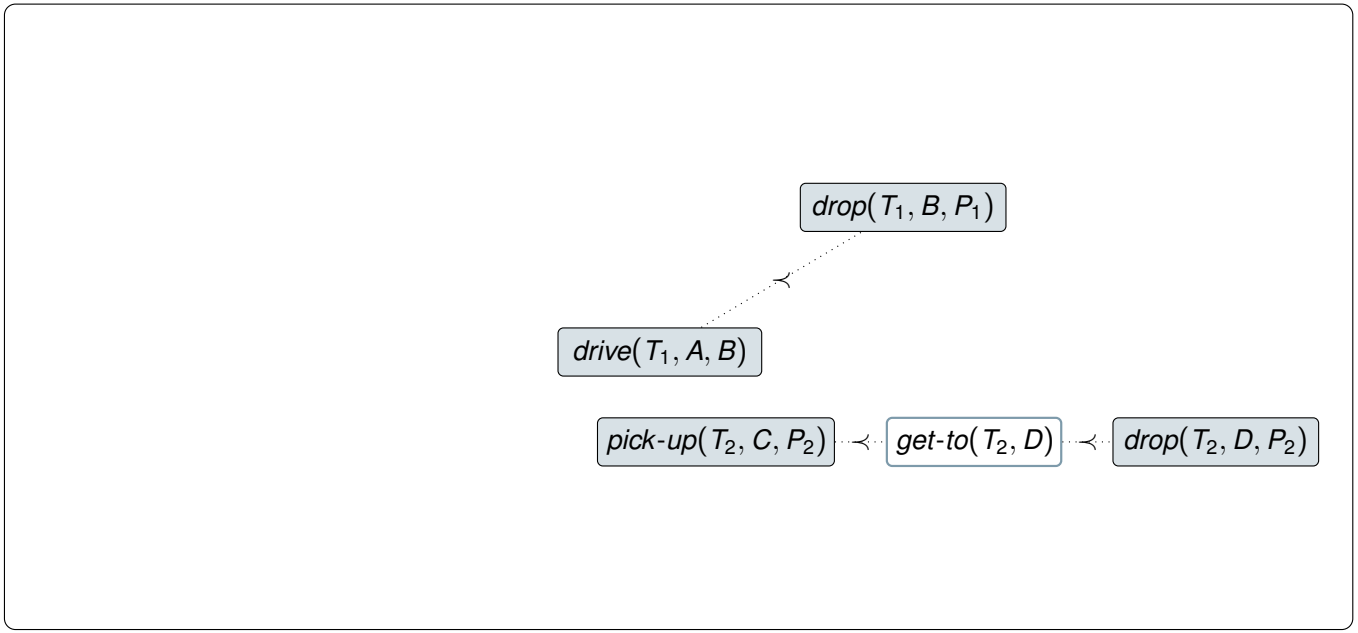


$$\pi = (\textit{no-op}(), \textit{no-op}(), \textit{pick-up}(T_1, A, P_1))$$

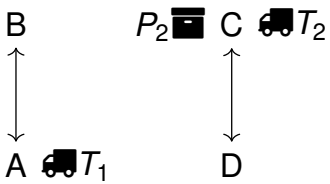


HTN Progression, Example

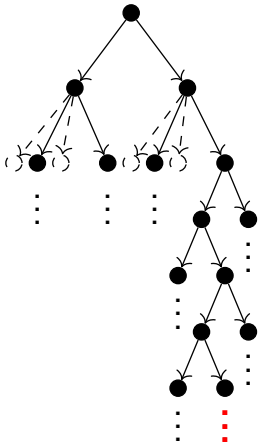


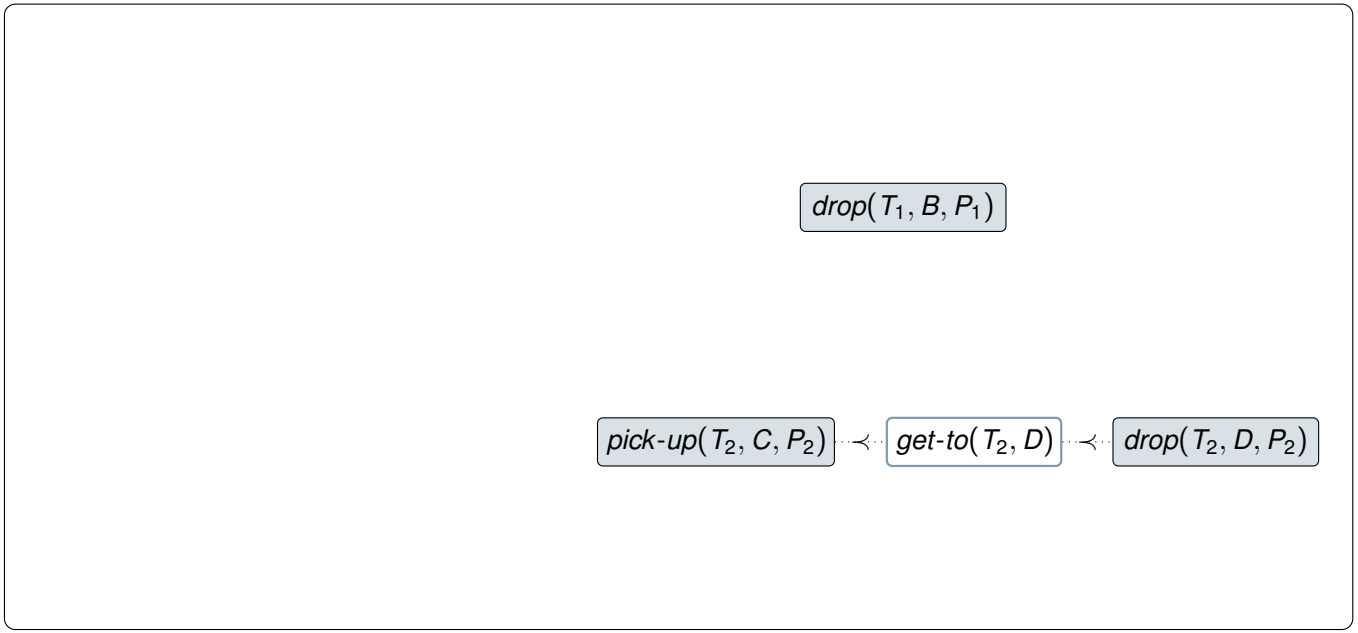


$$\pi = (\textit{no-op}(), \textit{no-op}(), \textit{pick-up}(T_1, A, P_1))$$

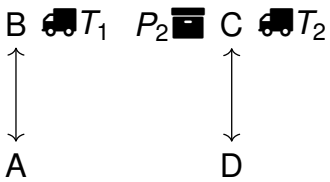


HTN Progression, Example

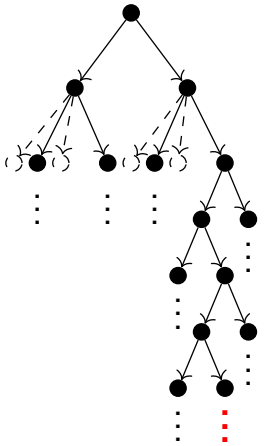


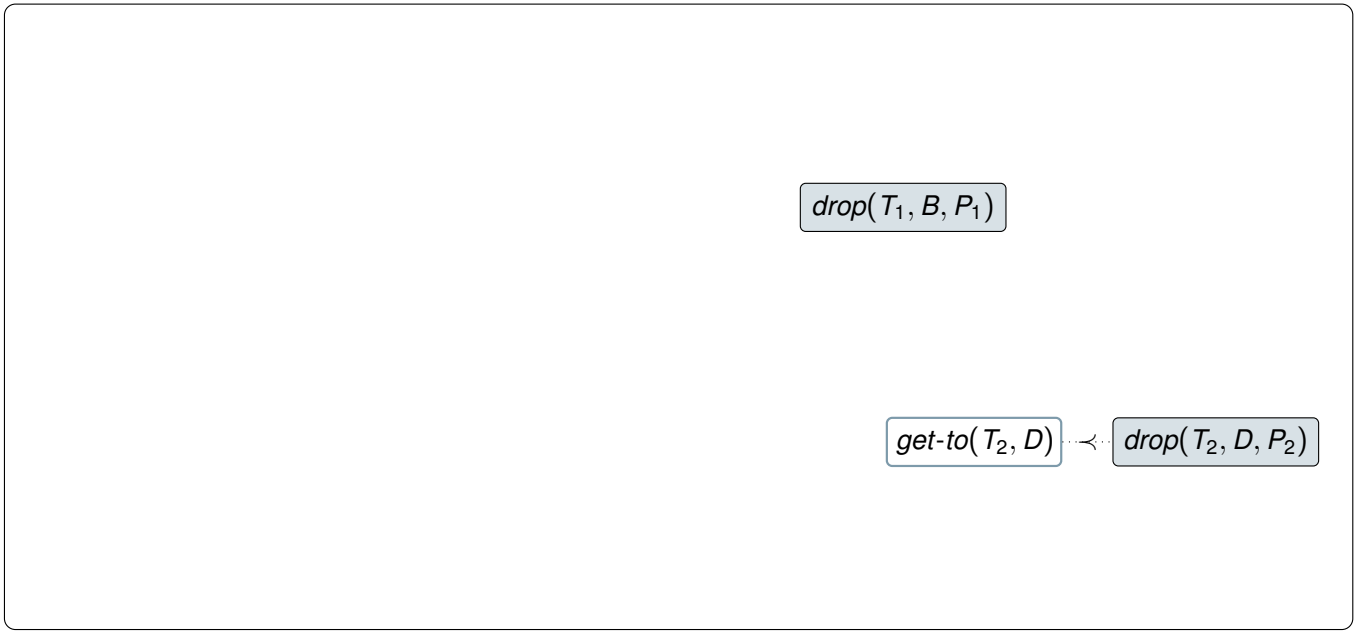


$$\pi = (no\text{-}op(), no\text{-}op(), pick\text{-}up(T_1, A, P_1), drive(T_1, A, B))$$

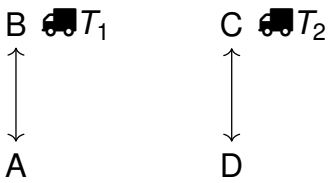


HTN Progression, Example

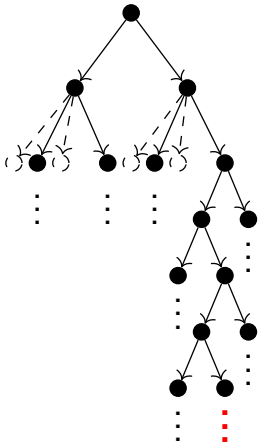


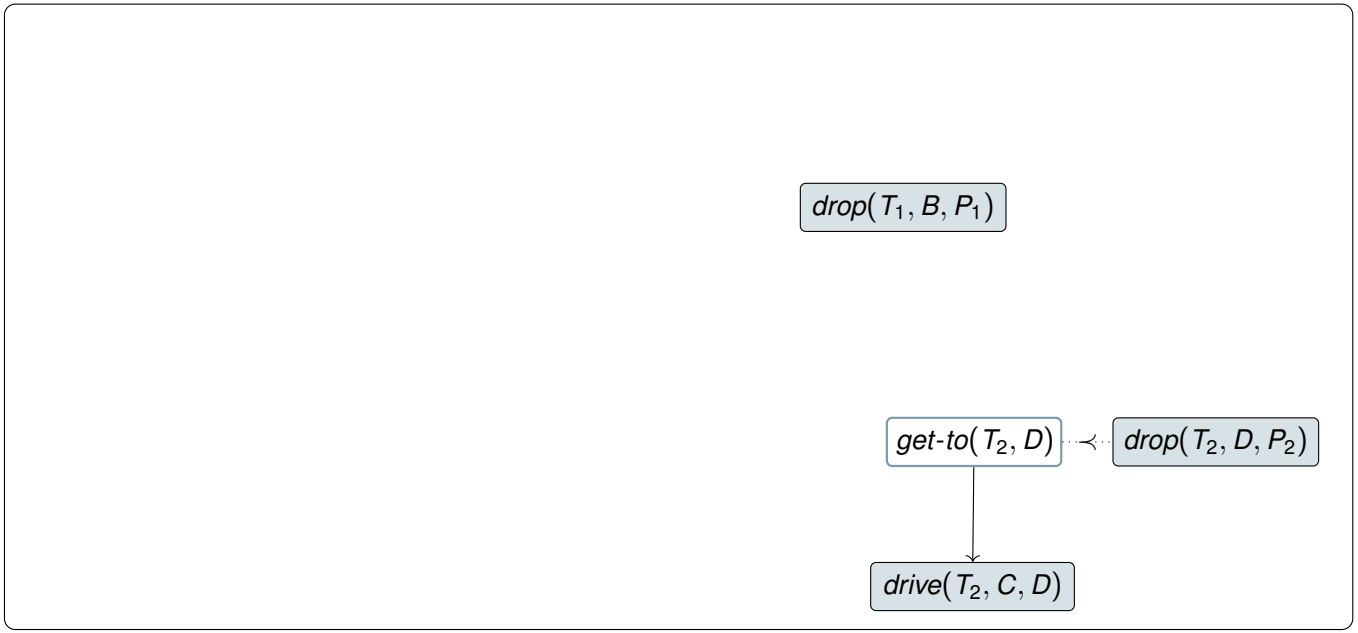


$\pi = (no\text{-}op(), no\text{-}op(), pick\text{-}up(T_1, A, P_1), drive(T_1, A, B), pick\text{-}up(T_2, C, P_2))$

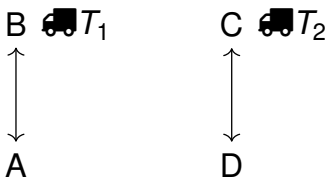


HTN Progression, Example

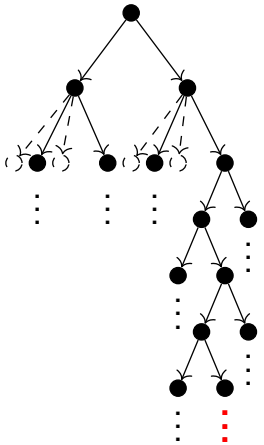


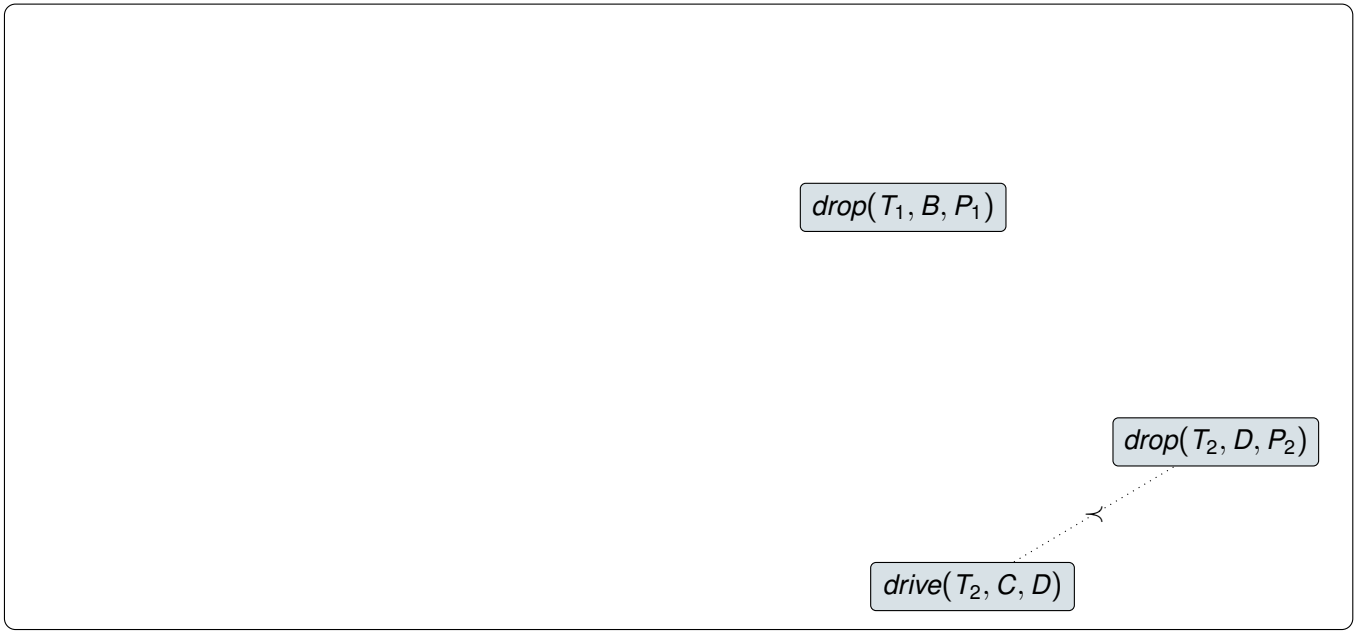


$\pi = (\textit{no-op}(), \textit{no-op}(), \textit{pick-up}(T_1, A, P_1), \textit{drive}(T_1, A, B), \textit{pick-up}(T_2, C, P_2))$

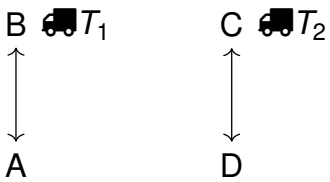


HTN Progression, Example

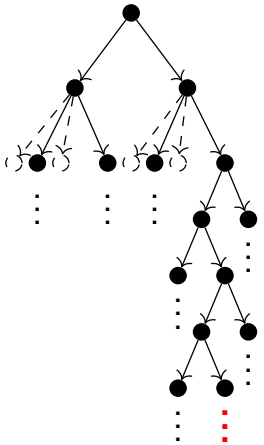




$\pi = (no\text{-}op(), no\text{-}op(), pick\text{-}up(T_1, A, P_1), drive(T_1, A, B), pick\text{-}up(T_2, C, P_2))$



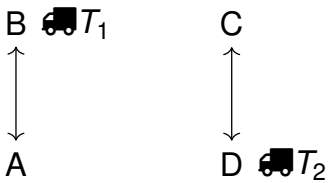
HTN Progression, Example



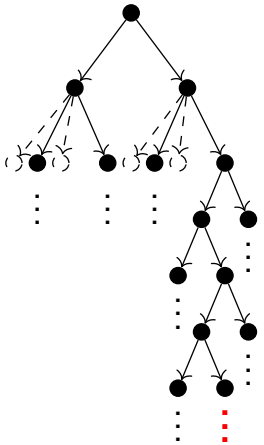
$drop(T_1, B, P_1)$

$drop(T_2, D, P_2)$

$\pi = (no\text{-}op(), no\text{-}op(), pick\text{-}up(T_1, A, P_1), drive(T_1, A, B),$
$pick\text{-}up(T_2, C, P_2), drive(T_2, C, D))$

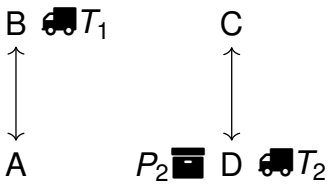


HTN Progression, Example

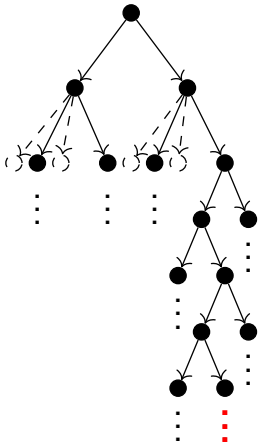


$drop(T_1, B, P_1)$

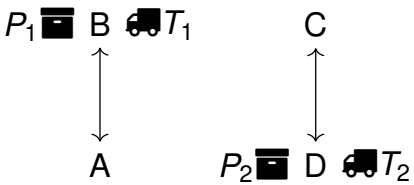
$\pi = (no\text{-}op(), no\text{-}op(), pick\text{-}up(T_1, A, P_1), drive(T_1, A, B),$
$pick\text{-}up(T_2, C, P_2), drive(T_2, C, D), drop(T_2, D, P_2))$



HTN Progression, Example



$\pi = (\textit{no-op}(), \textit{no-op}(), \textit{pick-up}(T_1, A, P_1), \textit{drive}(T_1, A, B),$
$\textit{pick-up}(T_2, C, P_2), \textit{drive}(T_2, C, D), \textit{drop}(T_2, D, P_2), \textit{drop}(T_1, B, P_1))$



Pseudo Code of Standard HTN Progression Search – Can We Do Better?

Algorithm: HTN Progression Search

Input: An HTN problem $\mathcal{P} = (V, P, \delta, C, M, s_I, tn_I)$
Output: A solution $\bar{a}$ or ***fail*** if none exists

```
1  fringe ← {(s_I, tn_I, ε)}
2  while fringe ≠ ∅ do
3      n = (s, tn, ā) ← nodeSelectAndRemove(fringe)
4      if tn is empty then
5          return ā
6      else
7          U ← detectUnconstrainedSteps(tn)
8          for t ∈ U do
9              if isPrimitive(t) and pre(t) ⊆ s then
10                 fringe ← fringe ∪ {n.apply(t)}
11             else if isCompound(t) then
12                 fringe ← fringe ∪ {n.decompose(t, m) |
                                      m ∈ M with m = (α(t), tn_m)}
13 return fail
```

Eliminating Redundancy in Progression Search

- The previous algorithm branches over:

Eliminating Redundancy in Progression Search

- The previous algorithm branches over:
  - All applicable primitive tasks.

Eliminating Redundancy in Progression Search

- The previous algorithm branches over:
  - All applicable primitive tasks.
  - All decomposition methods for all compound tasks.

Eliminating Redundancy in Progression Search

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  - All applicable primitive tasks.
  - All decomposition methods for all compound tasks.
- We have to decompose *all* compound tasks and – in contrast to action application – the order in which they are handled has no influence on the resulting solutions.

Eliminating Redundancy in Progression Search

- The previous algorithm branches over:
  - All applicable primitive tasks.
  - All decomposition methods for all compound tasks.
- We have to decompose *all* compound tasks and – in contrast to action application – the order in which they are handled has no influence on the resulting solutions.

→ It's also correct to *pick* an abstract task!

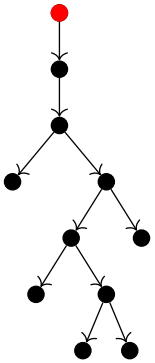
Improved HTN Progression, Pseudo Code

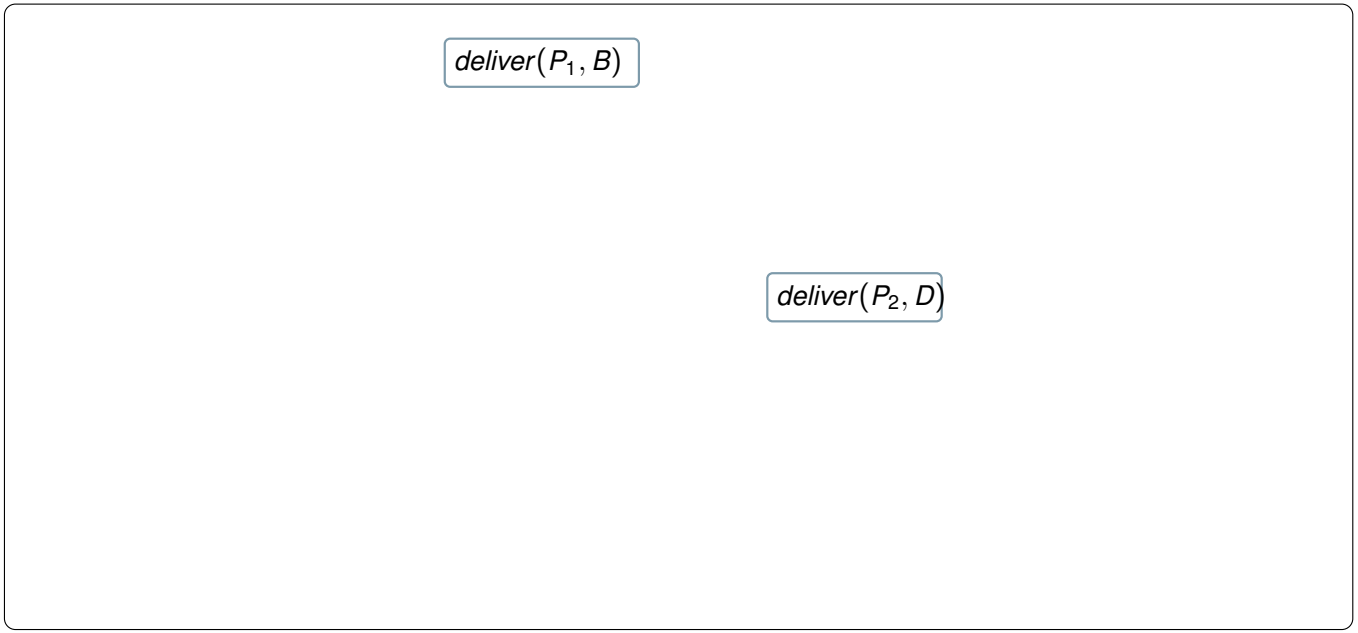
Algorithm: HTN Progression Search

Input: An HTN problem $\mathcal{P} = (V, P, \delta, C, M, s_I, tn_I)$
Output: A solution $\bar{a}$ or ***fail*** if none exists

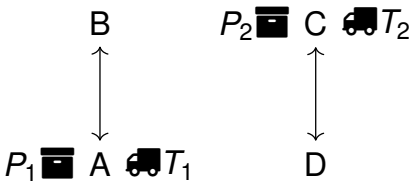
```
1  fringe ← {(s_I, tn_I, ε)}
2  while fringe ≠ ∅ do
3      n = (s, tn, ā) ← nodeSelectAndRemove(fringe)
4      if tn is empty then
5          return ā
6      else
7          (U_P, U_C) ← detectUnconstrainedSteps(tn)
8          for t ∈ U_P do
9              if pre(t) ⊆ s then
10                 fringe ← fringe ∪ {n.apply(t)}
11         t ← compoundTaskSelect(U_C)
12         fringe ← fringe ∪ {n.decompose(t, m) |
                       m ∈ M with m = (α(t), tn_m)}
13 return fail
```

Improved HTN Progression, Example

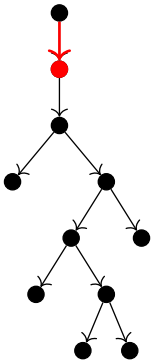


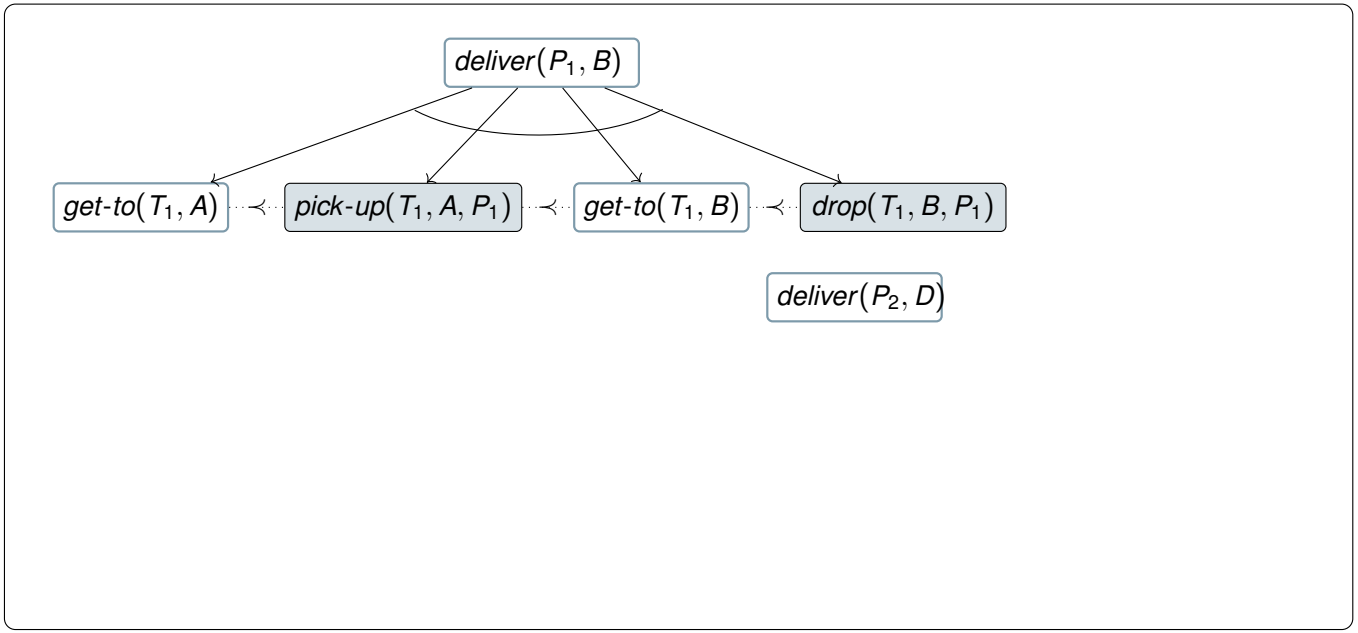


$\pi = ()$

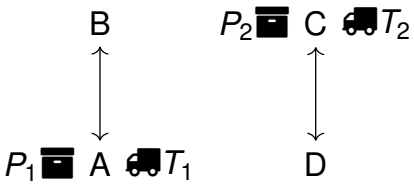


Improved HTN Progression, Example

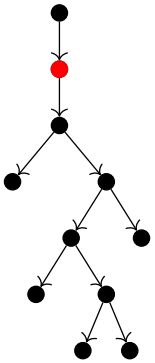


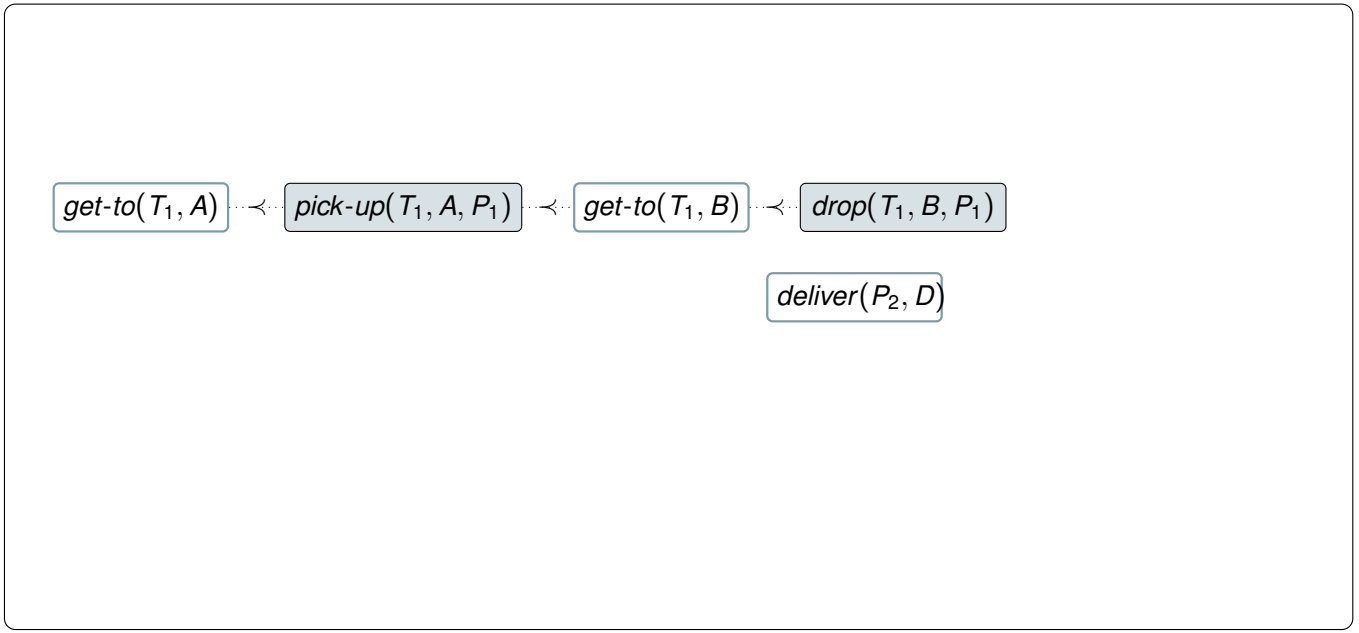


$\pi = ()$

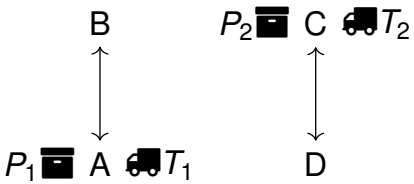


Improved HTN Progression, Example

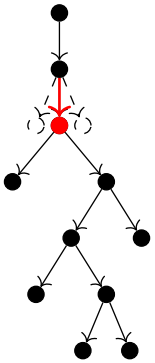


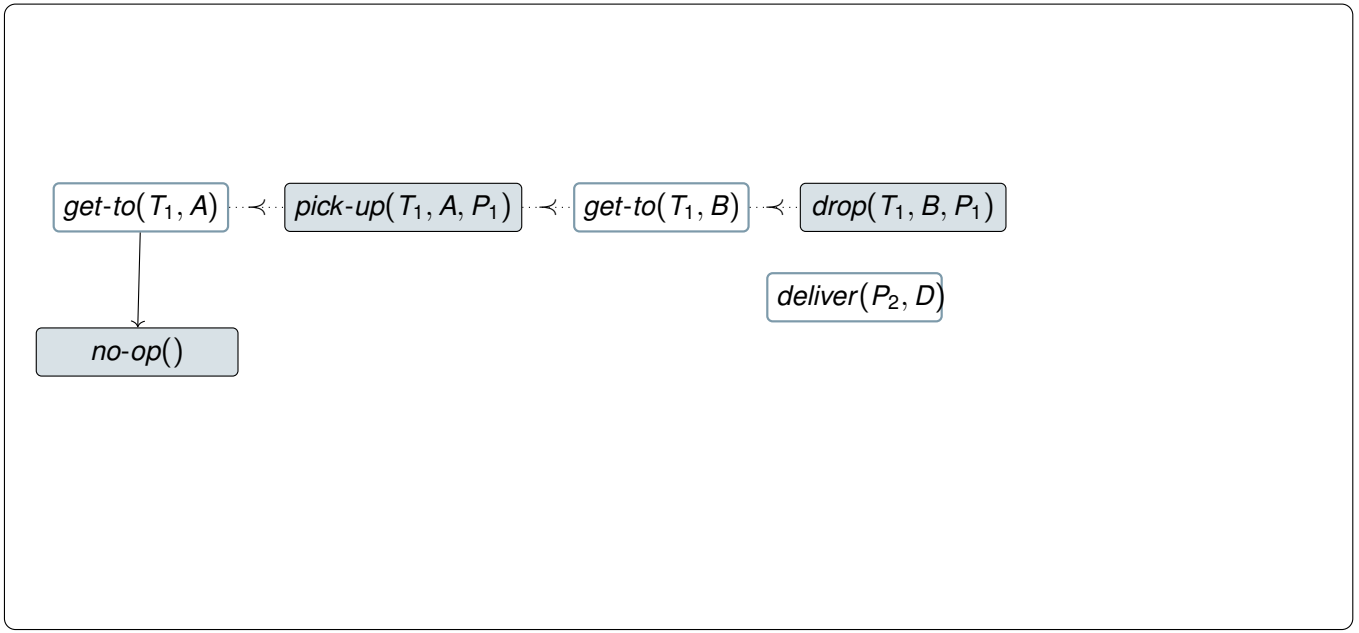


$\pi = ()$

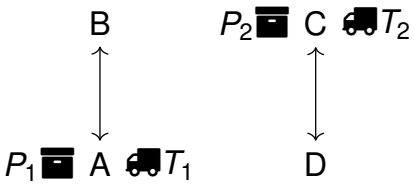


Improved HTN Progression, Example

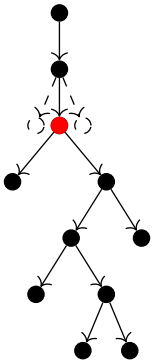


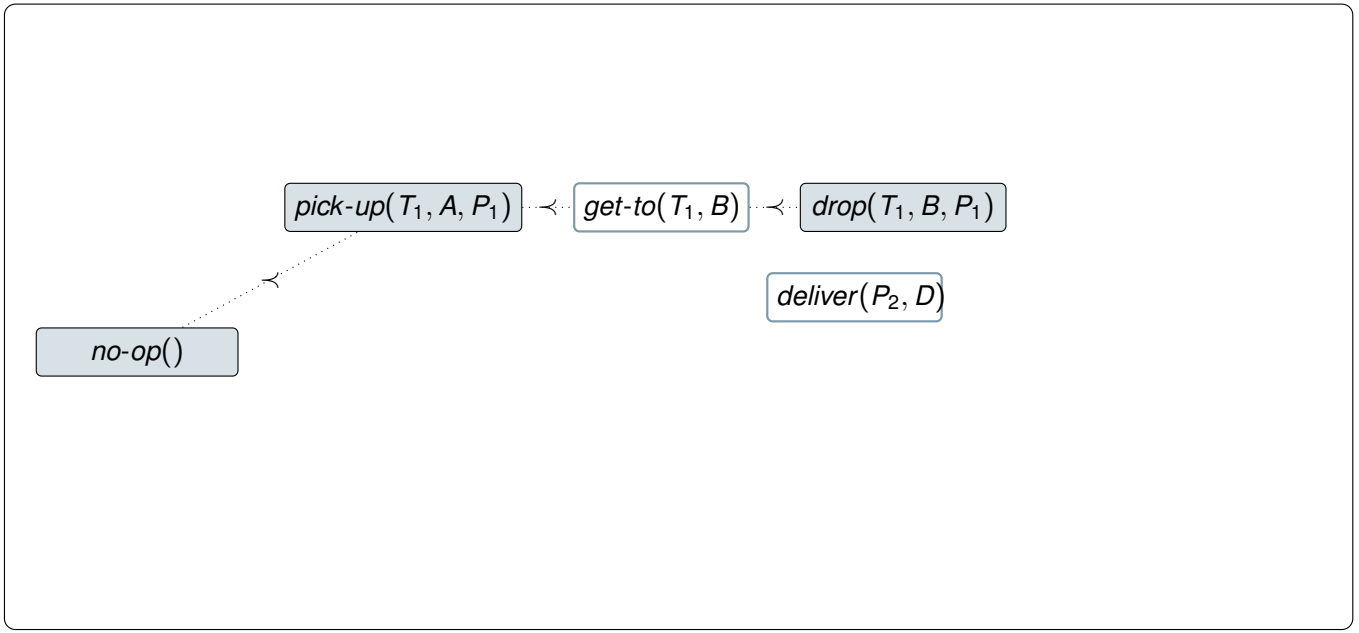


$\pi = ()$

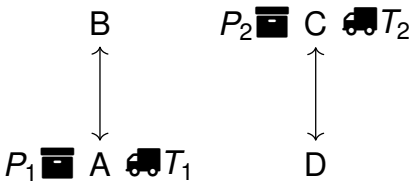


Improved HTN Progression, Example

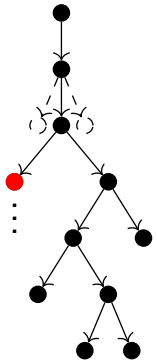


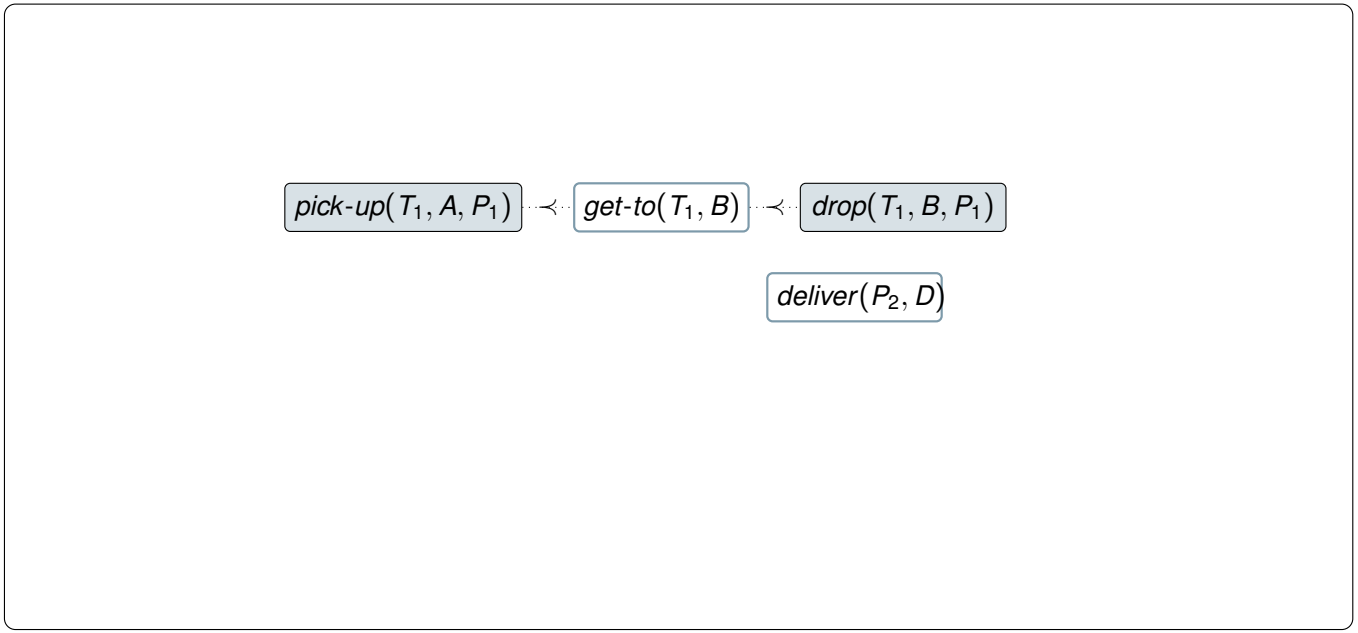


$\pi = ()$

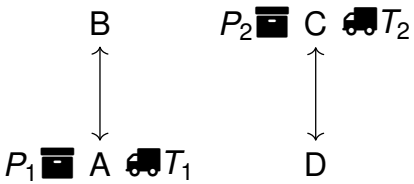


Improved HTN Progression, Example

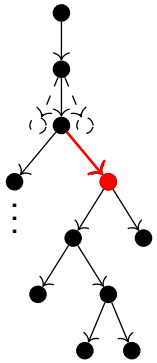


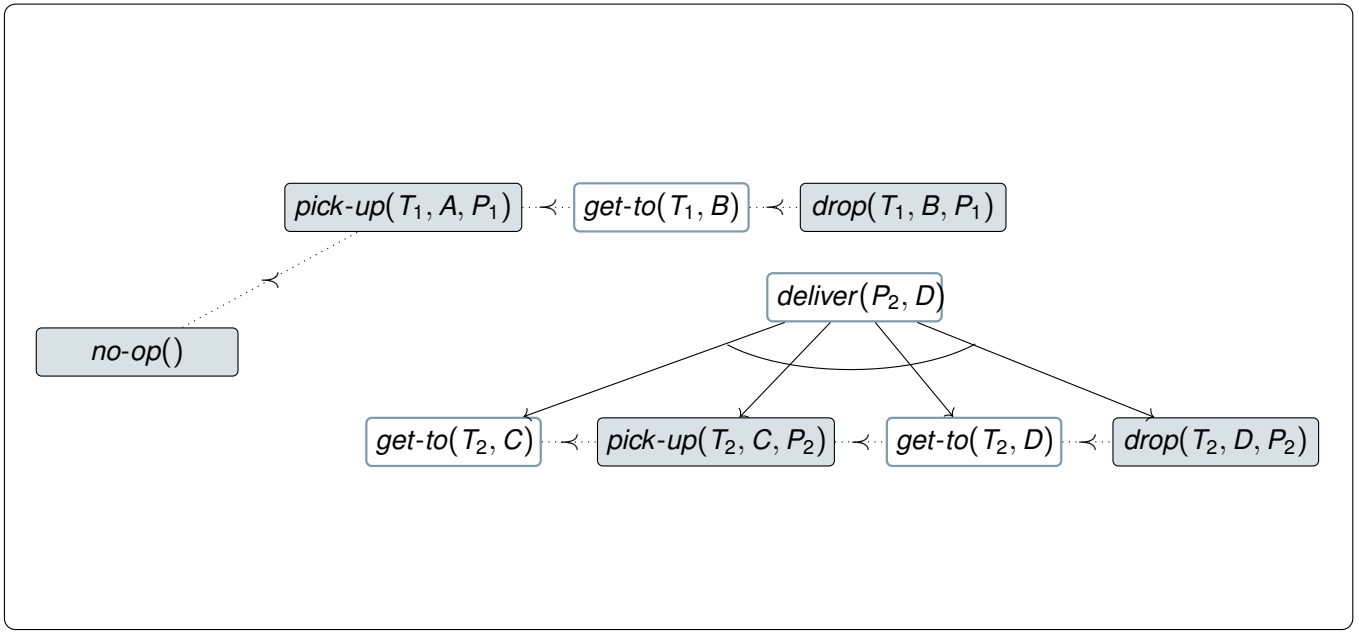


$\pi = (\textit{no-op}())$

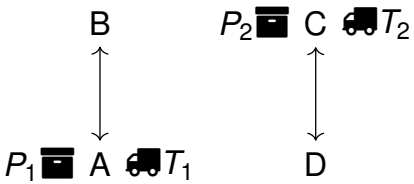


Improved HTN Progression, Example

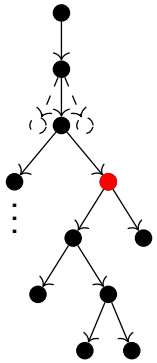


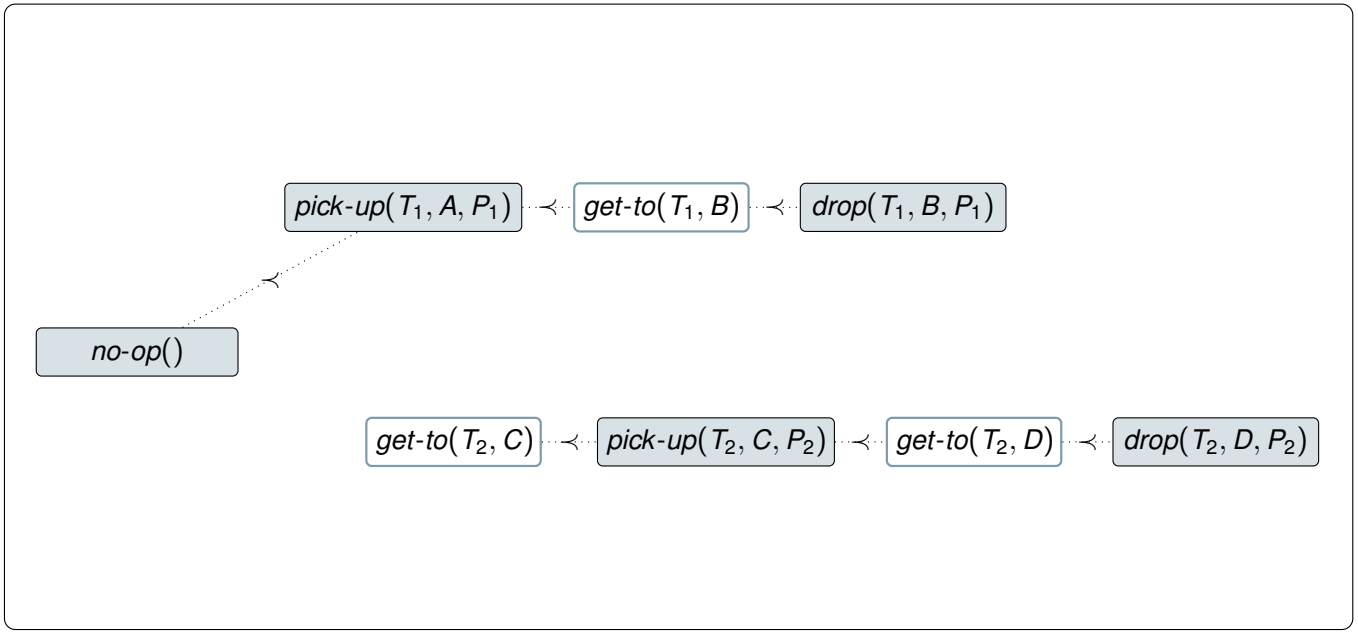


$\pi = ()$

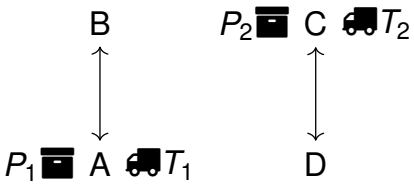


Improved HTN Progression, Example

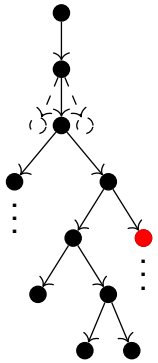


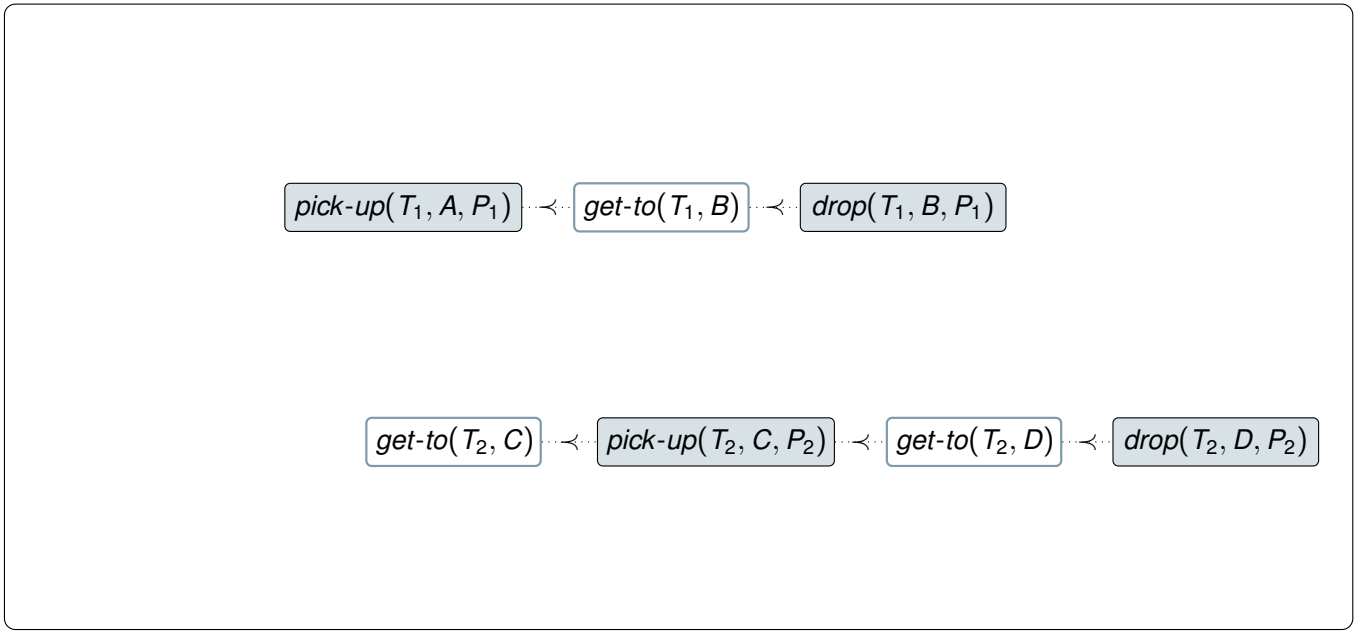


$\pi = ()$

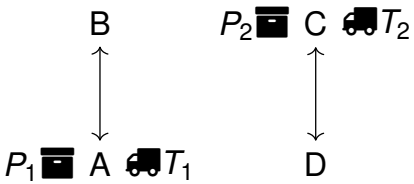


Improved HTN Progression, Example

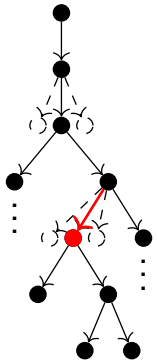


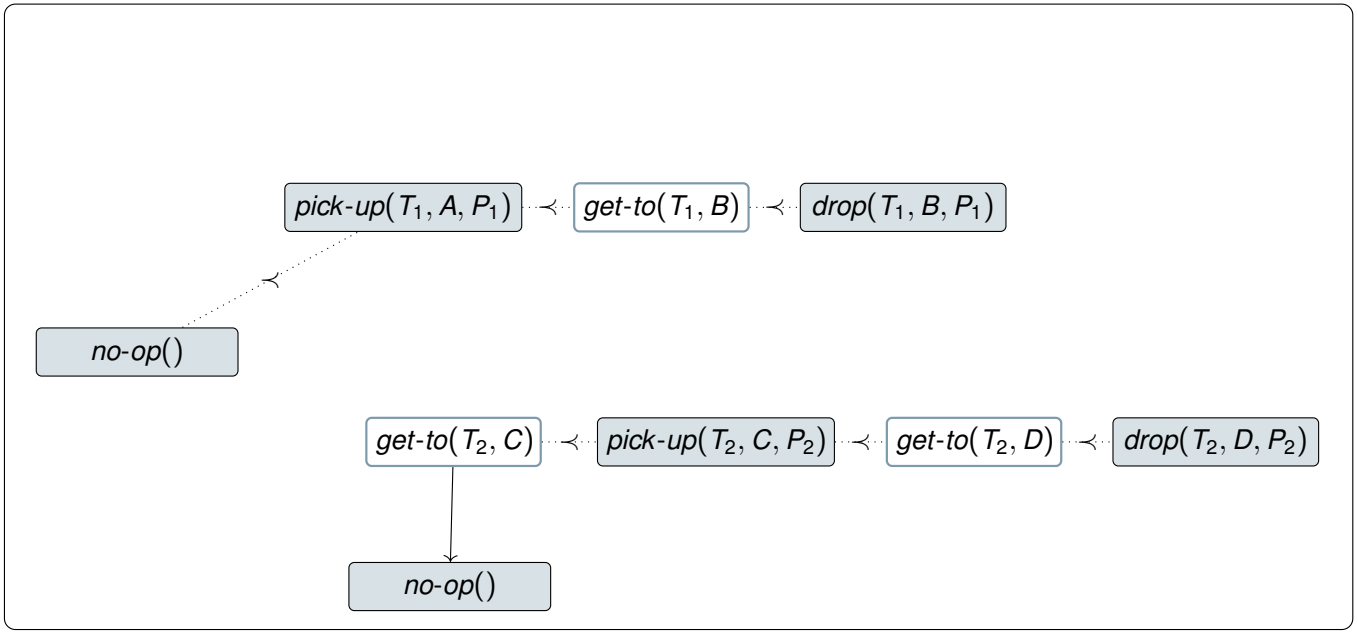


$\pi = (\textit{no-op}())$

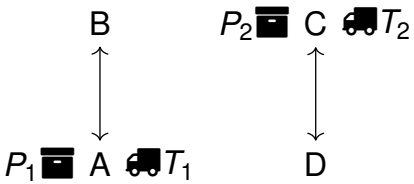


Improved HTN Progression, Example

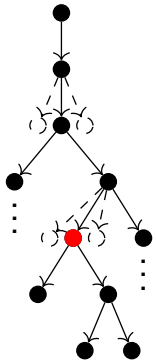


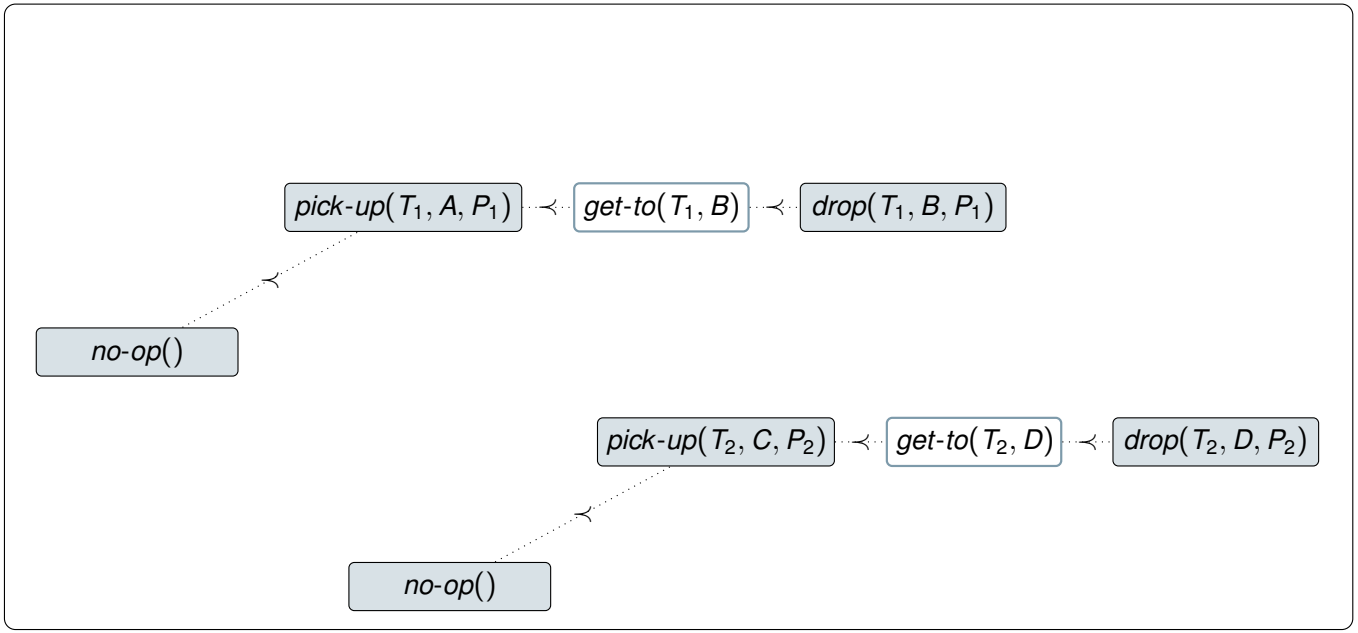


$\pi = ()$

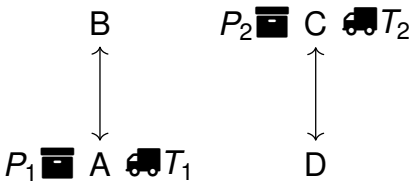


Improved HTN Progression, Example

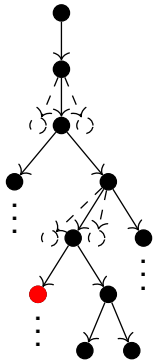


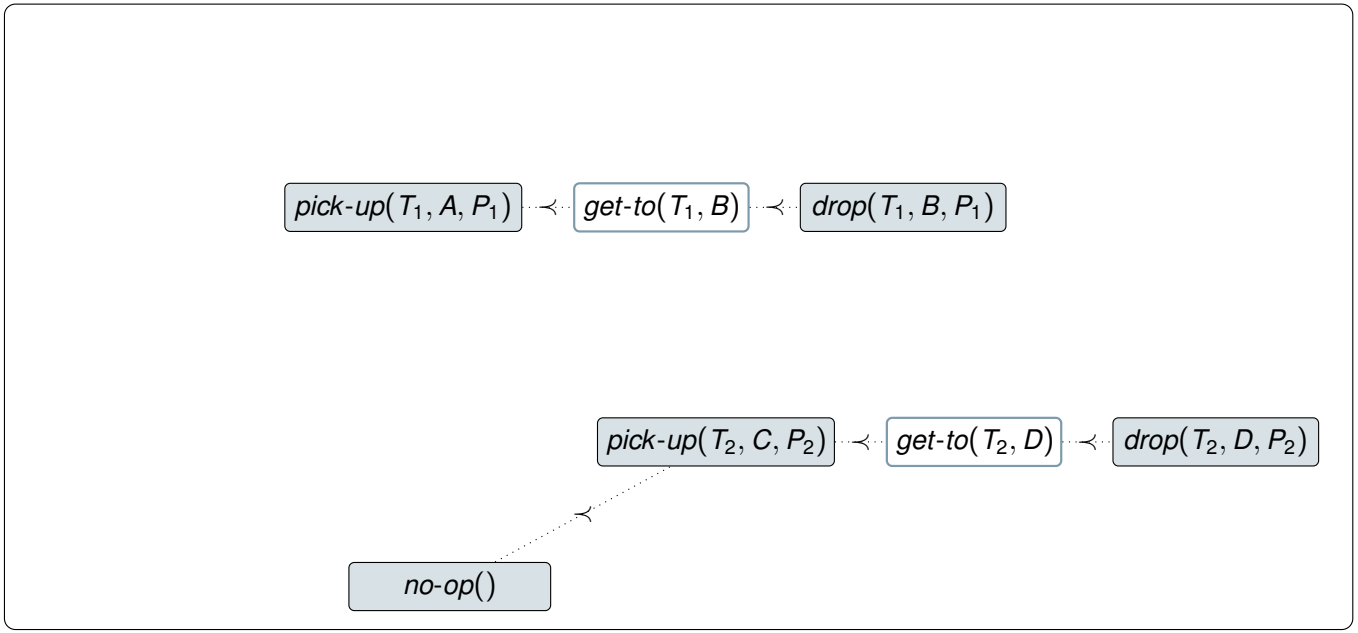


$\pi = ()$

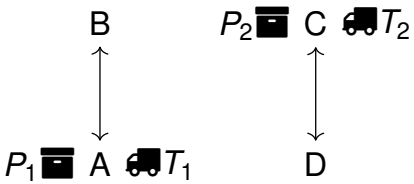


Improved HTN Progression, Example

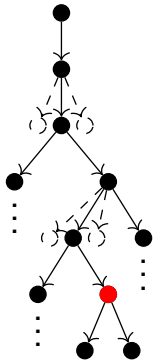


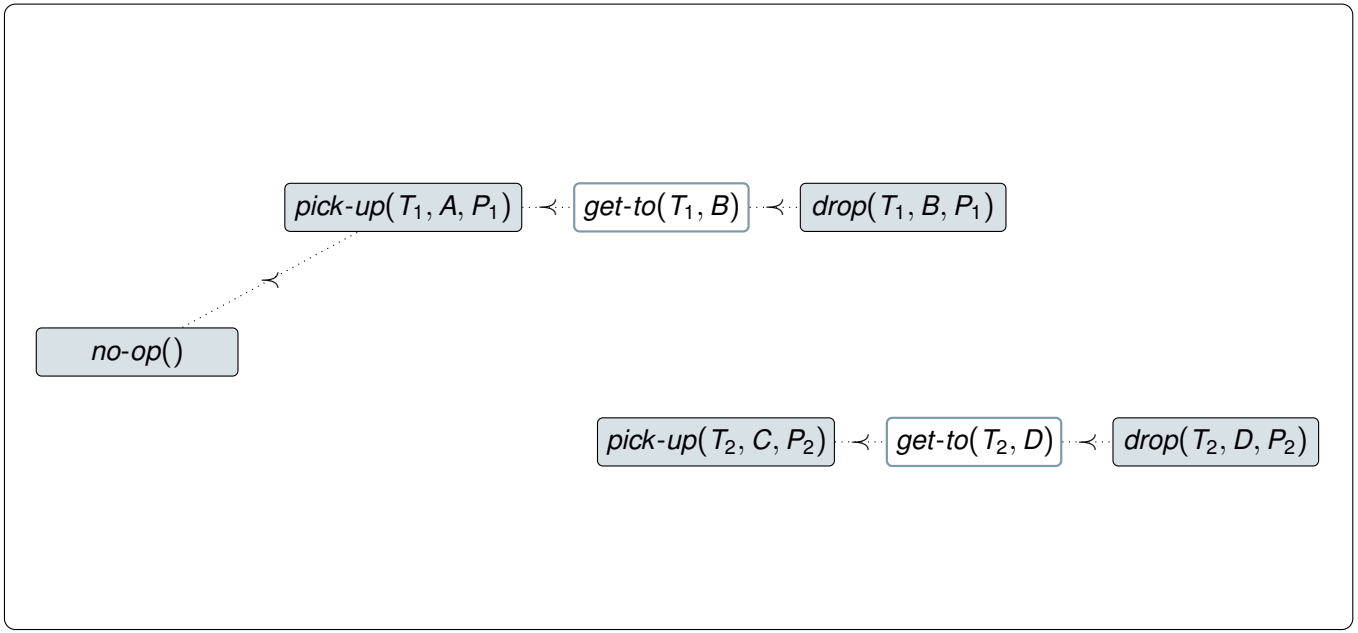


$\pi = (\textit{no-op}())$

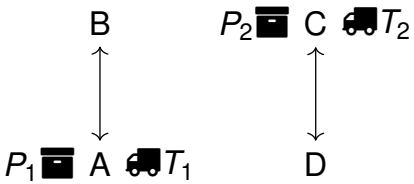


Improved HTN Progression, Example

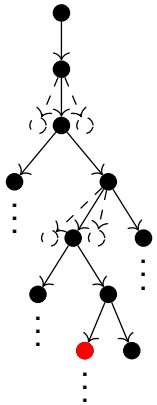


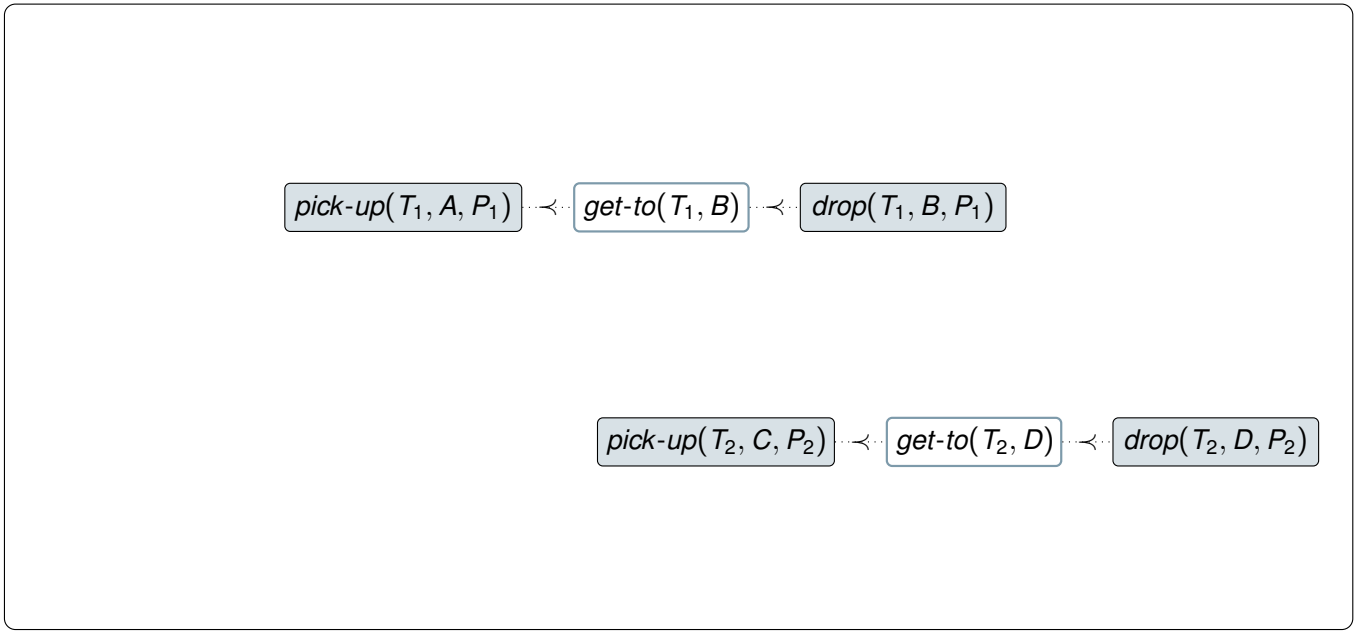


$\pi = (\textit{no-op}())$

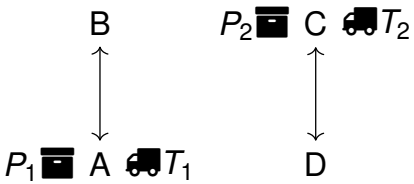


Improved HTN Progression, Example

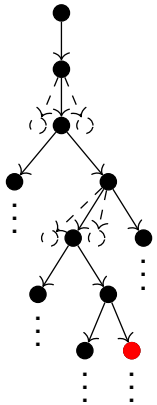


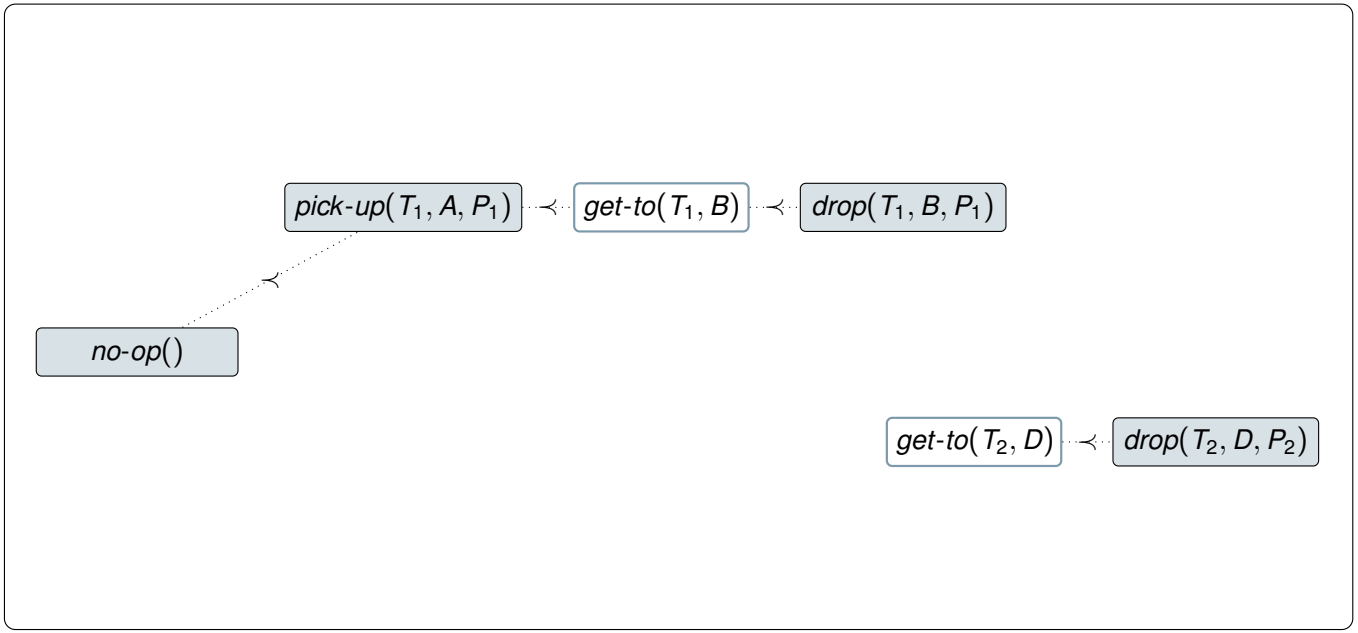


$\pi = (\textit{no-op}(), \textit{no-op}())$



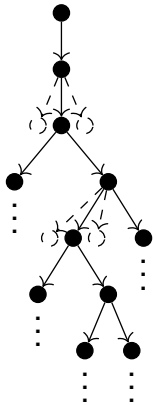
Improved HTN Progression, Example

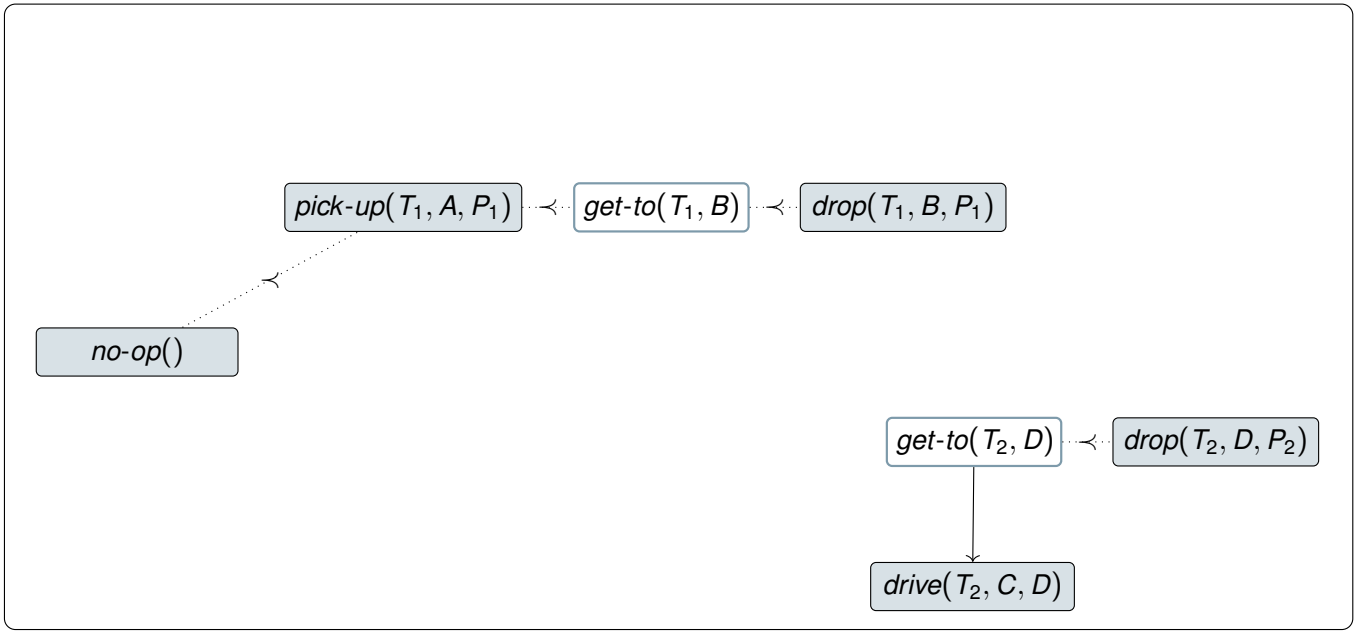




$$\pi = (\textit{no-op}(), \textit{pick-up}(T_2, C, P_2))$$

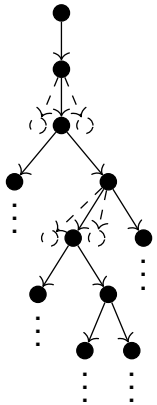
Improved HTN Progression, Example

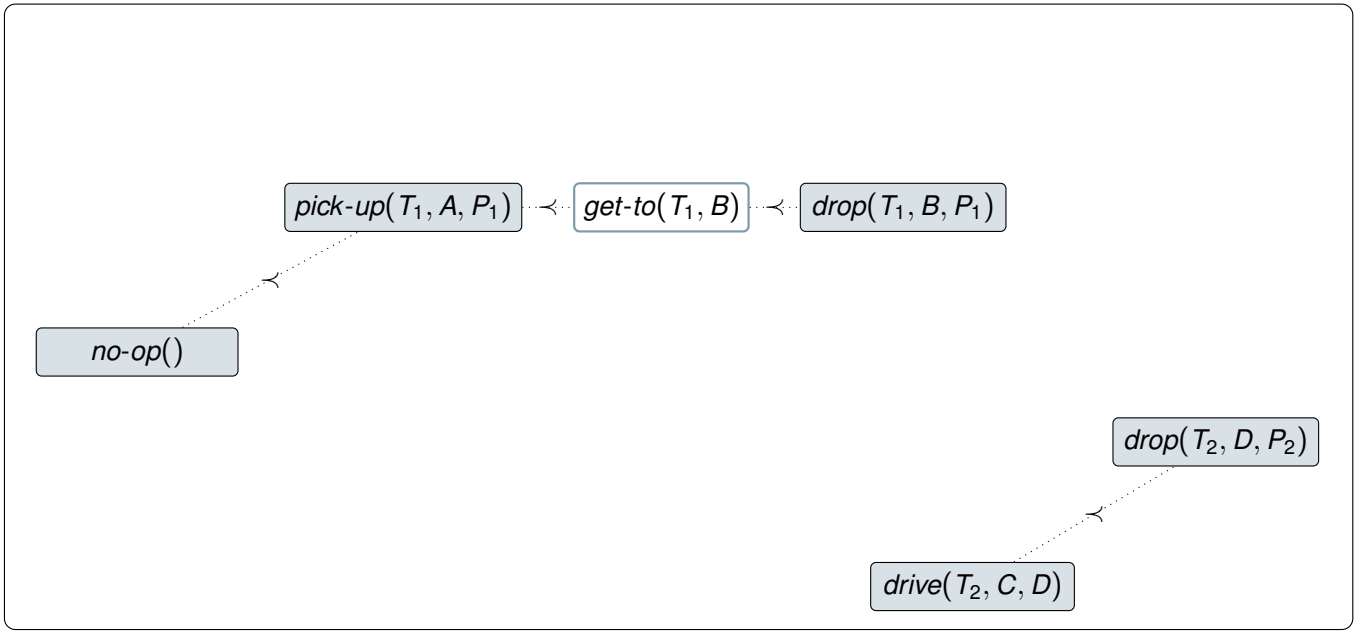




$$\pi = (\textit{no-op}(), \textit{pick-up}(T_2, C, P_2))$$

Improved HTN Progression, Example





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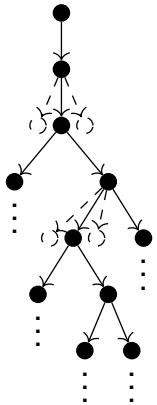

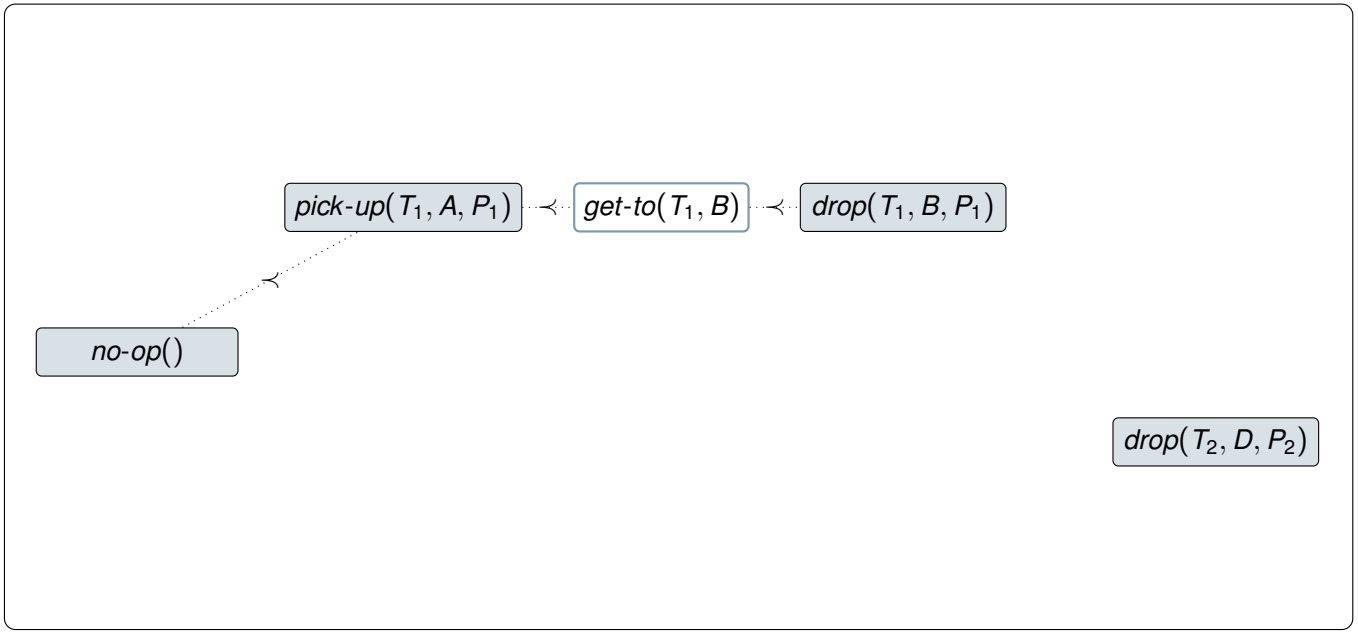

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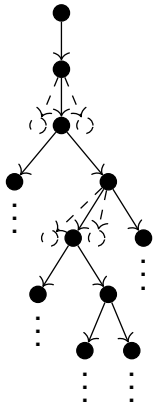

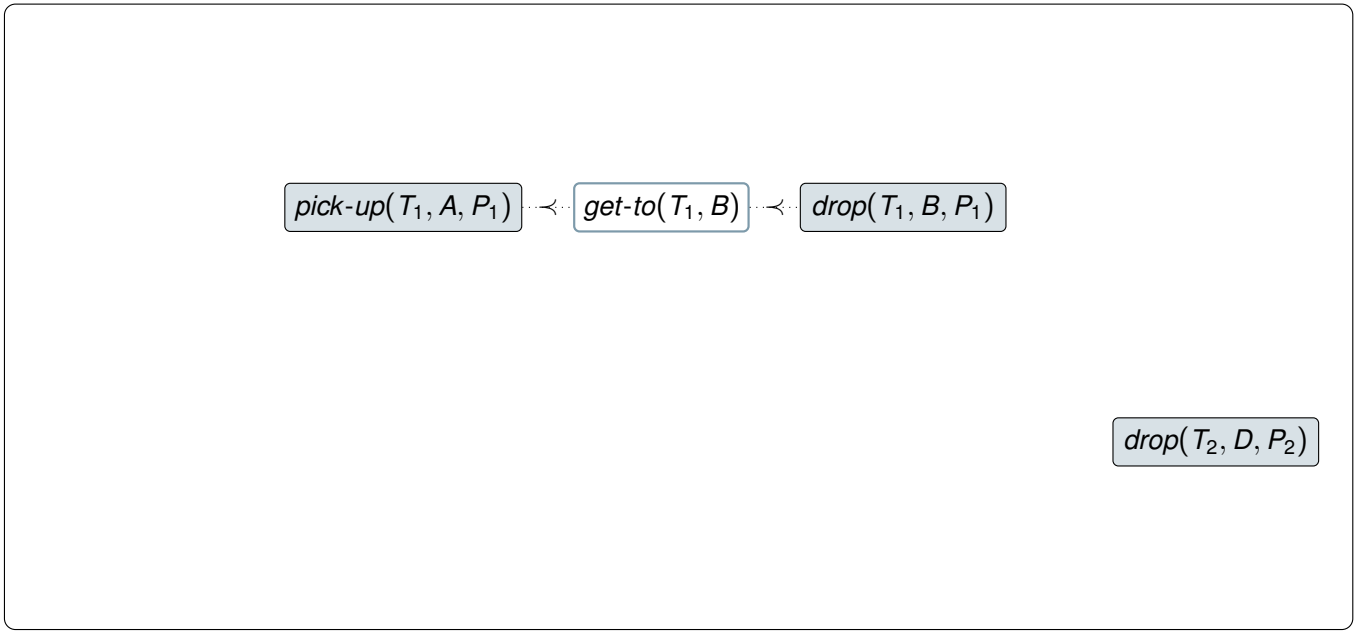

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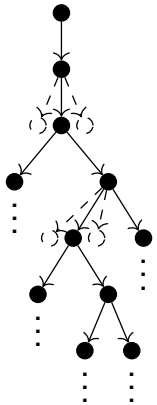

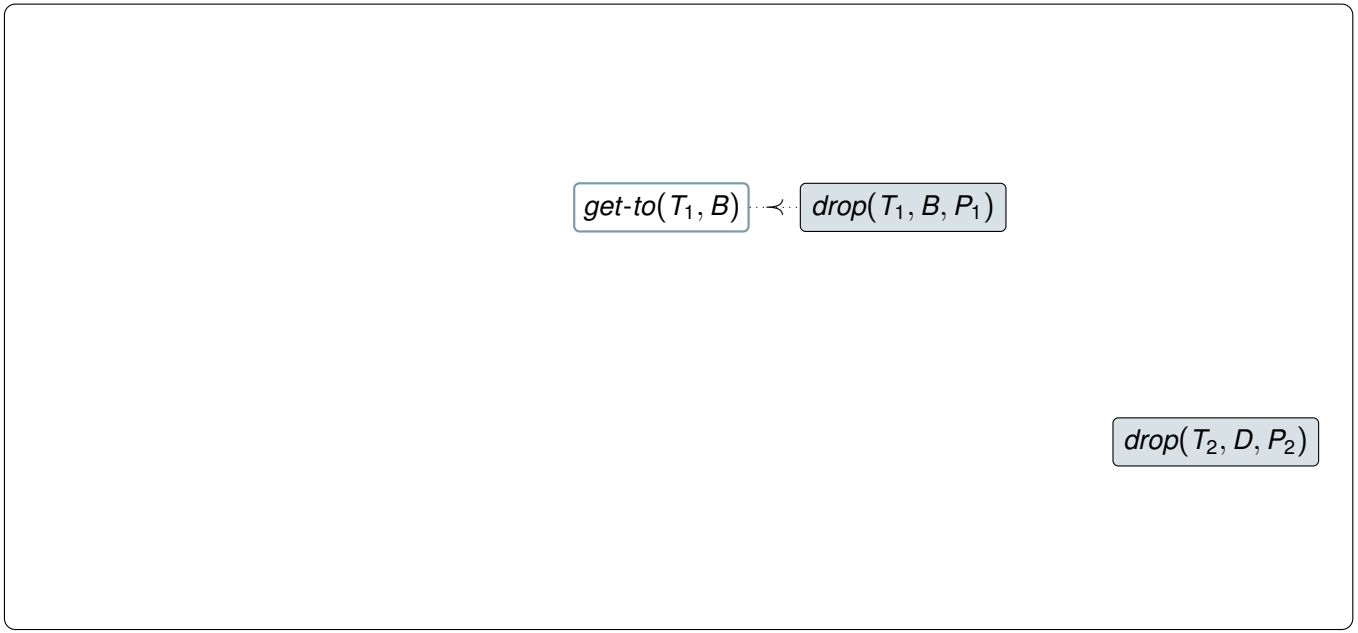

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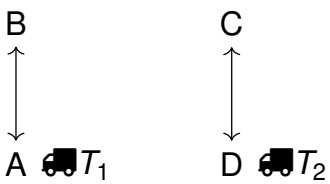

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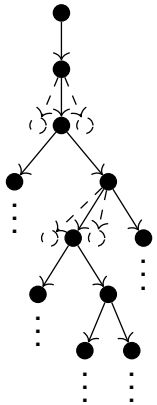

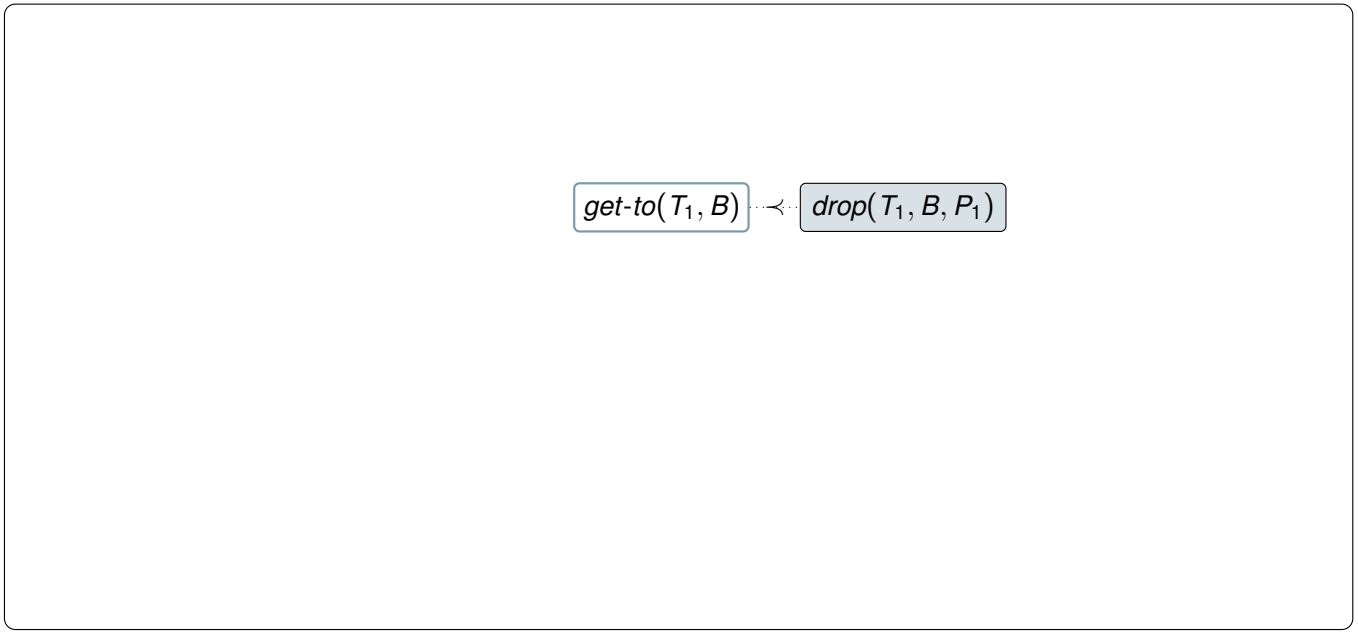

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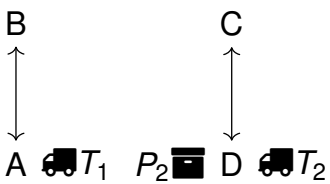

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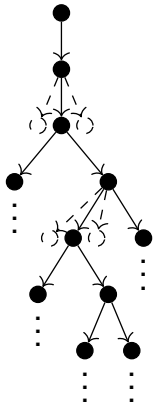

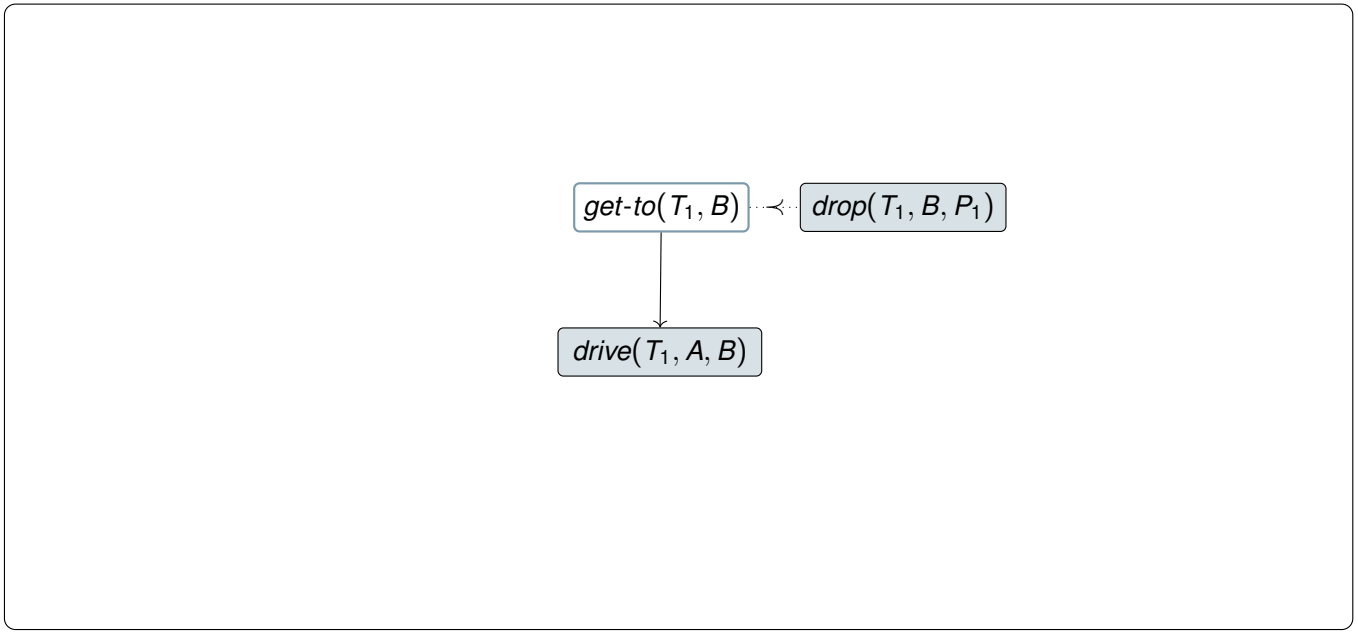

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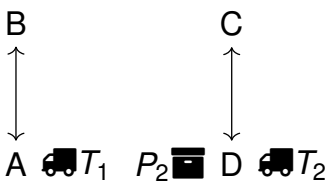

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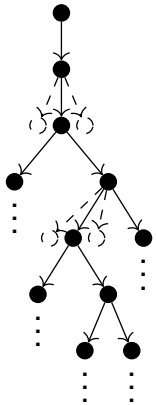

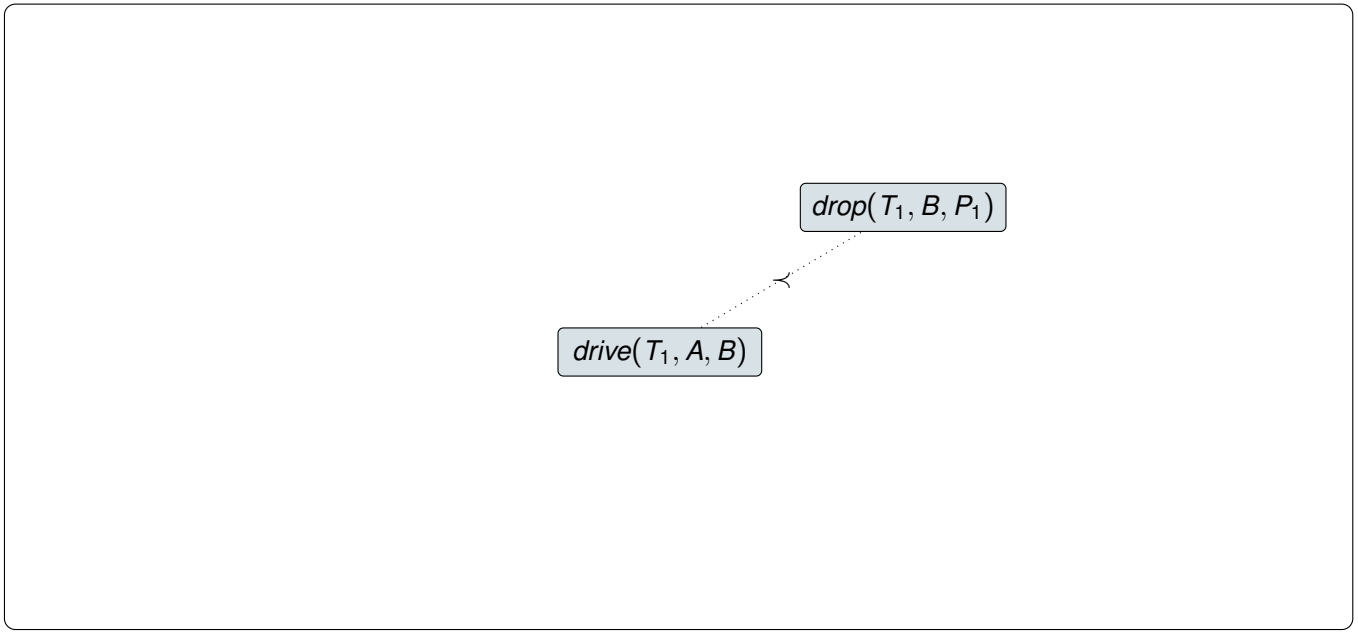

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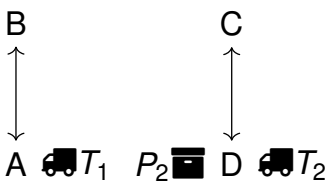

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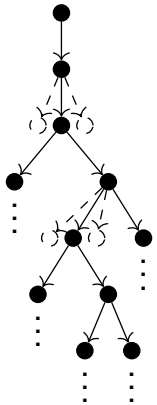

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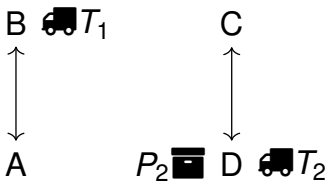

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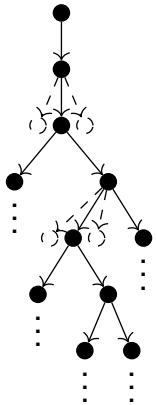

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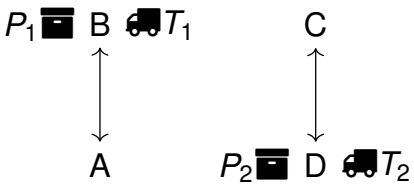

Properties

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Proof:
Follows from the properties of the underlying search algorithm.
However:

- Be aware that the transition system is not finite!
- We need to argue why the restricted algorithm is still complete although not branching over all choices.

SHOP/SHOP2 and Method Preconditions

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  - Note: these valuations can be arbitrary program calls.
- Note the semantical difference of method preconditions in total-order HTN probelms (i.e., SHOP) versus partial-order HTN problems (i.e, SHOP2).

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- State constraints: They can simply be tracked as well (and removed as soon as satisfied) in accordance to the definition given in the lecture.

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Terminology:

- In the remainder, we will fuse the terminologies from POCL planning with those from HTN planning.
- Rather than talking about *task networks*, we refer to them as *partial plans*.

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  - Producer *could be added* via decomposing a compound task: decompose with the respective methods (more details later).

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Let $(PS, \prec, CL, \alpha)$ be a partial plan (where a plan step $ps \in PS$ can also contain compound tasks, $\alpha(ps) \in P \cup C$).

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- Let the planning problem be acyclic. Then, we can offer *one modification* for each producer for (v, ps). Note that this might include applying methods over several levels of abstraction at once.

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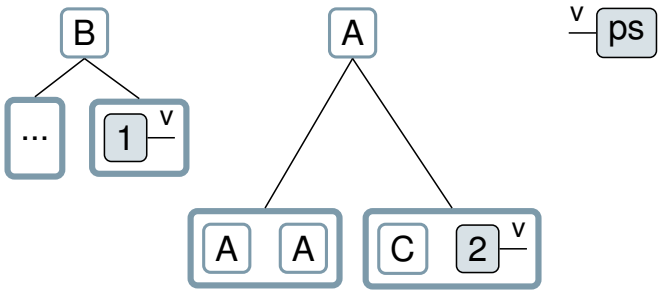
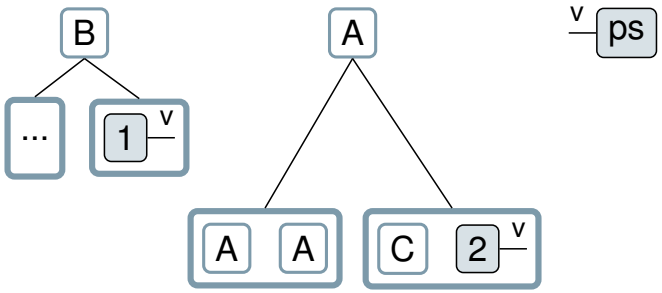


$\rightarrow$ Only offering two modifications (one for A and one for B) will wrongly prevent the planner from inserting C arbitrarily often.

Alterations to POCL Planning, Open Preconditions, cont'd II

Let $ps \in PS$ be (primitive), $ps' \in PS$ (compound), and (v, ps) (open condition) as before.

- Let the planning problem be cyclic. With the previous strategy, there might be *infinitely many* modifications. Otherwise, we might become incomplete:



$\rightarrow$ Only offering two modifications (one for A and one for B) will wrongly prevent the planner from inserting C arbitrarily often.

- Solution (in such cyclic cases): We just decompose A, but without resolving the open precondition flaw. So, how many modifications do we get here?

Alterations to POCL Planning, Open Preconditions, cont'd II

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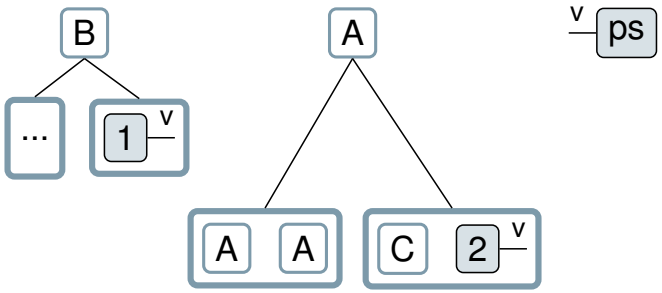

$\rightarrow$ Only offering two modifications (one for A and one for B) will wrongly prevent the planner from inserting C arbitrarily often.

- Solution (in such cyclic cases): We just decompose A, but without resolving the open precondition flaw. So, how many modifications do we get here?
- Three! Two of them do insert a link and hence resolve the flaw.

Alterations to POCL Planning, Causal Threats

Let $ps, ps' \in PS$ be primitive tasks sharing a causal link (ps, v, ps').
When does a further step $ps'' \in PS$ threaten that causal link?

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- Decomposition: Could we just choose decompositions that prevent deleting v?

Alterations to POCL Planning, Causal Threats

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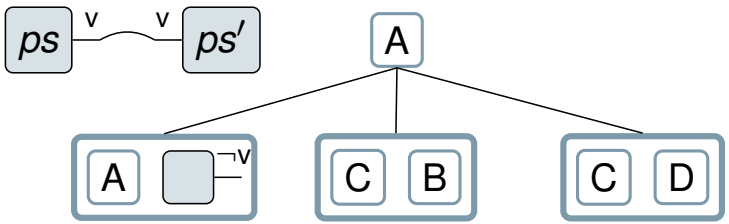
Modifications if ps'' is compound:

- Promotion and Demotion: Doing this is correct and resolves the flaw, but introduces non-systematicity and violates least commitment. Why? Because it orders all sub tasks rather than just those required for eliminating the treatening step.
- Decomposition: Could we just choose decompositions that prevent deleting v? No!



Plan Space-based HTN Planning, Pseudo Code

Algorithm: Plan space-based HTN Search

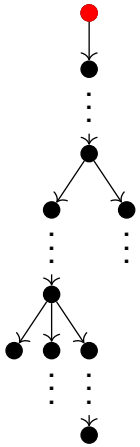
Input: An HTN problem $\mathcal{P} = (V, P, \delta, C, M, s_I, tn_I)$

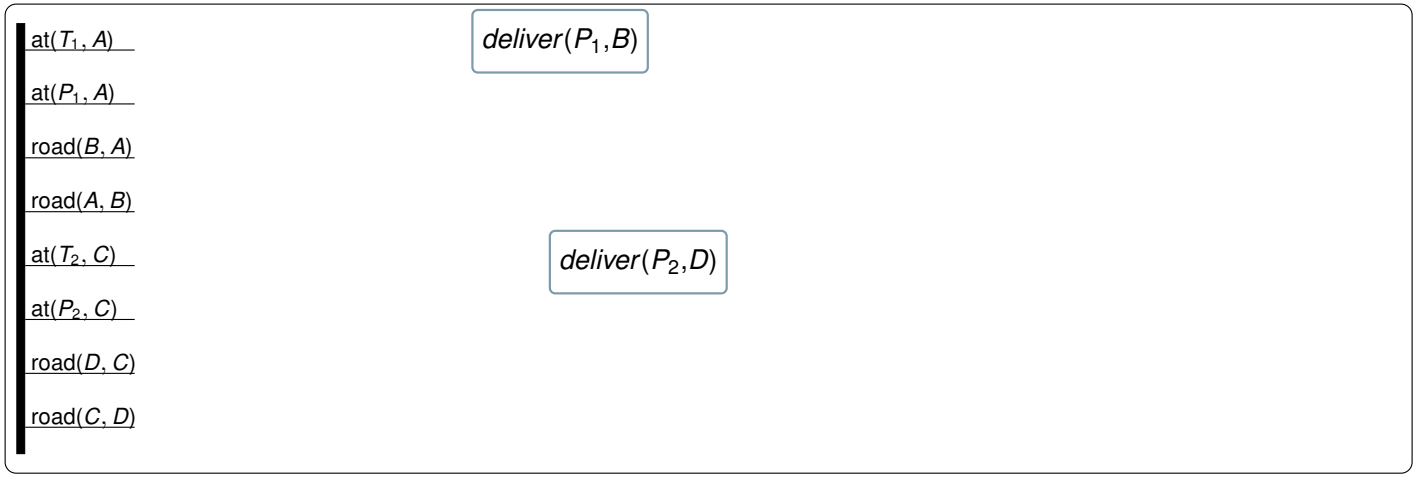
Output: A solution plan or ***fail***.

```
1 fringe = {P_I} // Created from tn_I as seen in first lecture.
2 while fringe ≠ ∅ do
3     P := nodeSelectAndRemove(()fringe)
4     F := flawDetection(P)
5     if F = ∅ then return P
6     f := flawSelection(F)
7     fringe := {applyModification(m, f) | m is a modification for f}
8 return fail
```

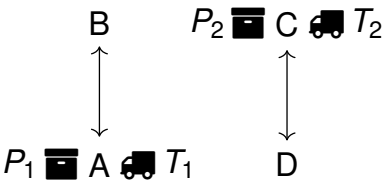
Note: Syntactically, this algorithm looks *exactly* like the POCL algorithm, but with flaws/modifications altered accordingly.

Plan Space-based HTN Planning, Example

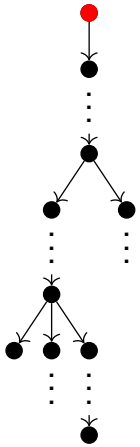


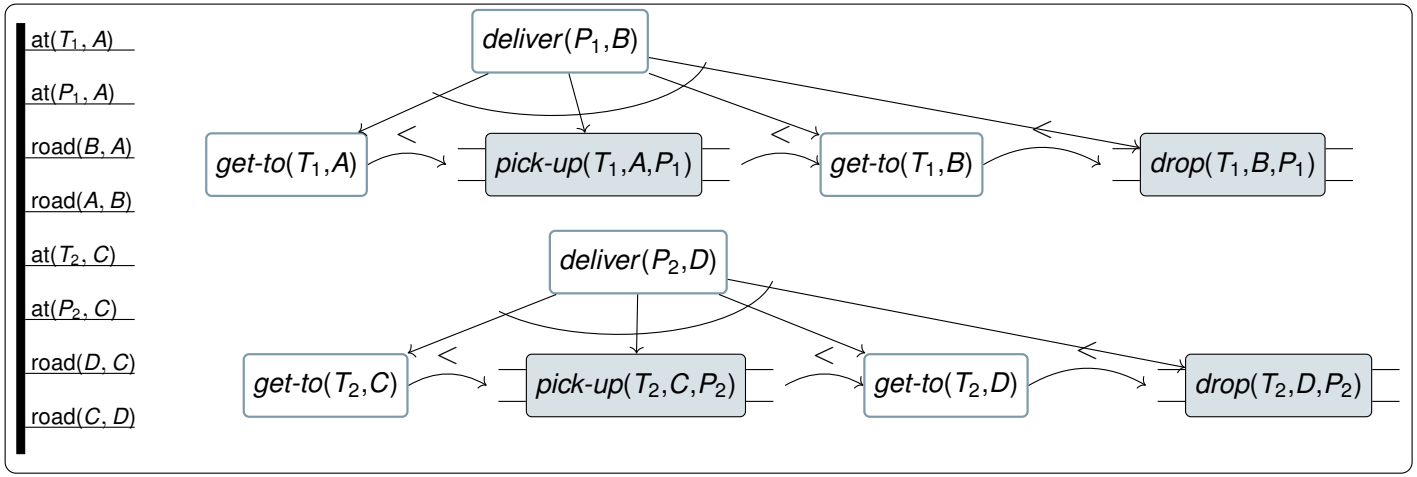


Flaws **Modifications**

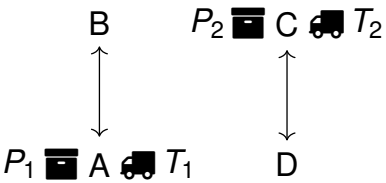


Plan Space-based HTN Planning, Example





Flaws	**Modifications**
compound task: deliver(P_1, B)	decompose with *m-deliver(P_1, A, B, T_1)*
compound task: deliver(P_2, D)	decompose with *m-deliver(P_2, C, D, T_2)*



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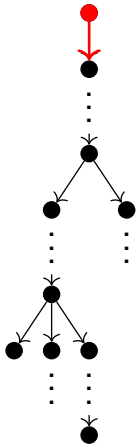

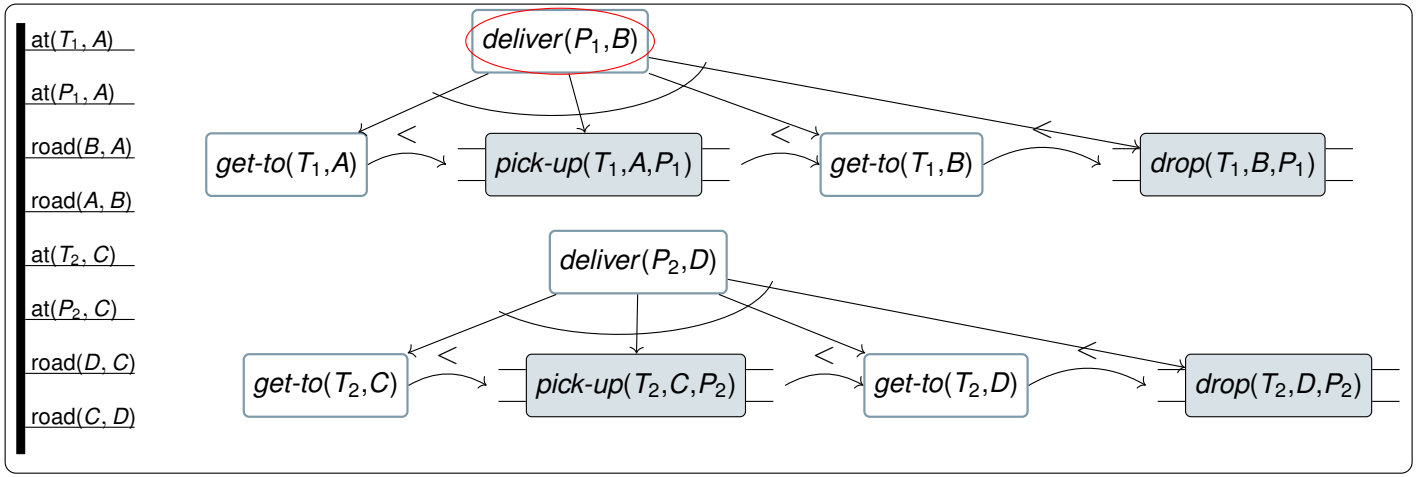

Flaws	**Modifications**
compound task: deliver(P_1, B)	**decompose with *m-deliver(P_1, A, B, T_1)***
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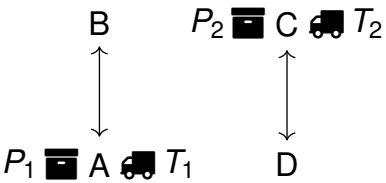

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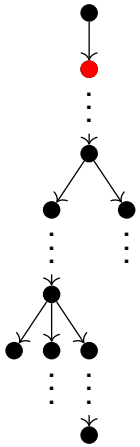

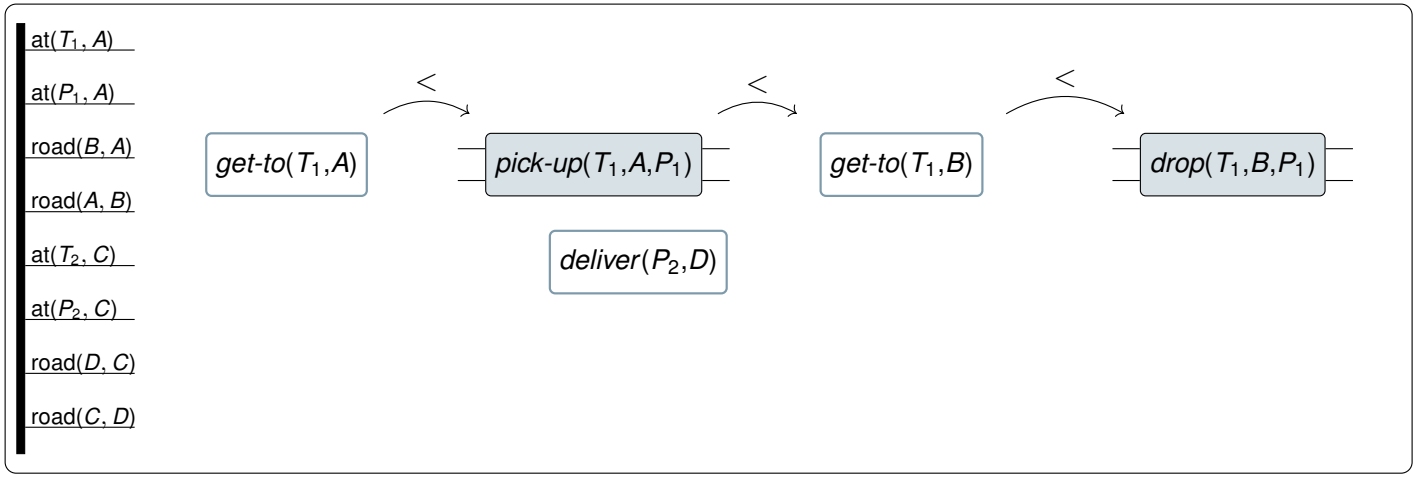

Flaws	**Modifications**
compound task: deliver(P_2, D)	decompose with *m-deliver(P_2, C, D, T_2)*
compound task: get-to(T_1, A)	decompose with *m-direct(T_1, B, A)* decompose with *m-via(T_1, B, A)* decompose with *m-noop(T_1, A)*
open prec.: at(T_1, A) of *pick-up(T_1, A, P_1)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
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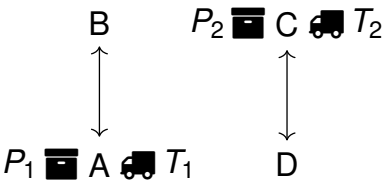
compound task: get-to(T_1, B)	decompose with *m-direct(T_1, A, B)* decompose with *m-via(T_1, A, B)* decompose with *m-noop(T_1, B)*
open prec.: at(T_1, B) of *drop(T_1, B, P_1)*	decompose *get-to(T_1, B)* with *m-direct(T_1, A, B)* decompose *get-to(T_1, B)* with *m-via(T_1, A, B)*
open prec.: in(P_1, T_1) of *drop(T_1, B, P_1)*	insert causal link from *pickup($T1$, A, $P1$)*



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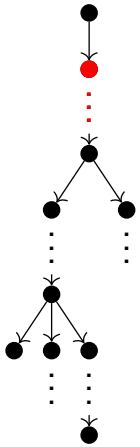

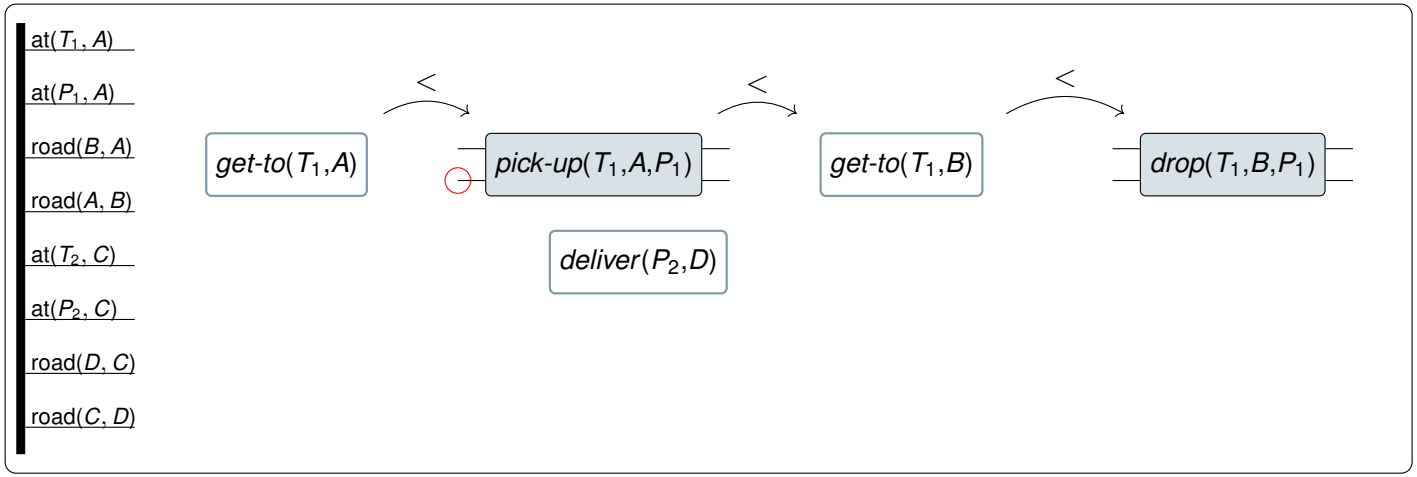

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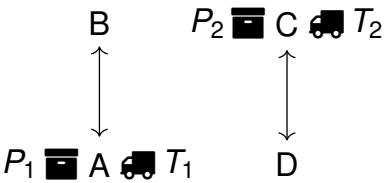

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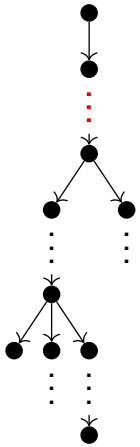

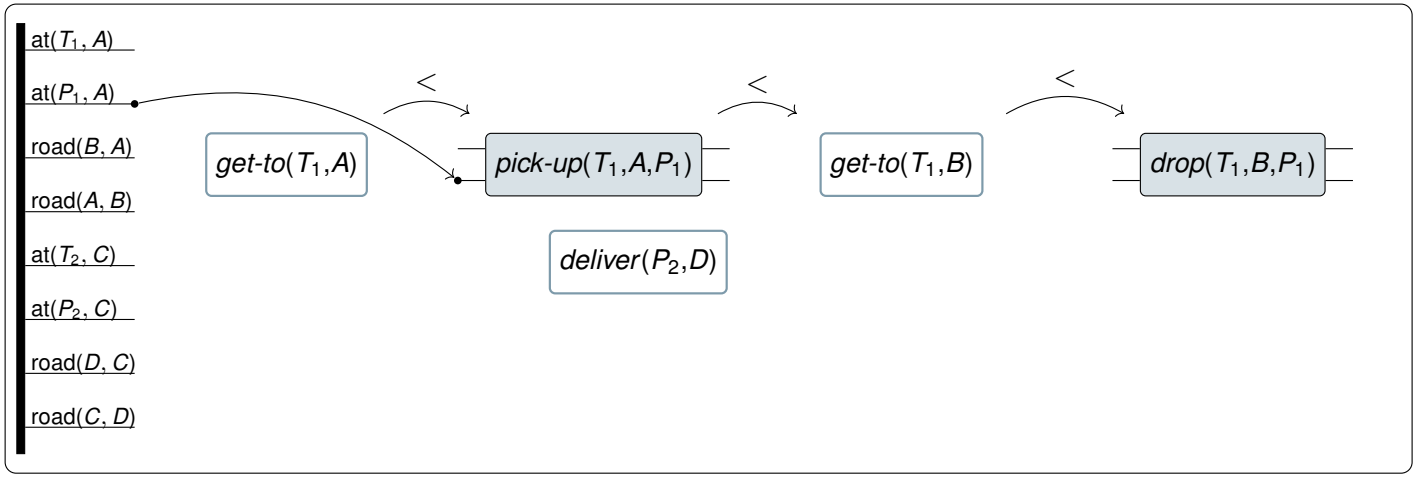

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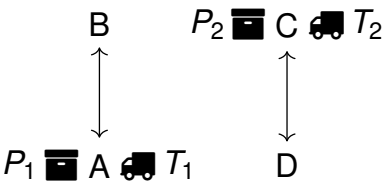
open prec.: at(T_1, B) of *drop(T_1, B, P_1)*	decompose *get-to(T_1, B)* with *m-direct(T_1, A, B)* decompose *get-to(T_1, B)* with *m-via(T_1, A, B)*
open prec.: in(P_1, T_1) of *drop(T_1, B, P_1)*	insert causal link from *pickup($T1$, A, $P1$)*



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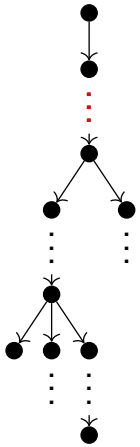

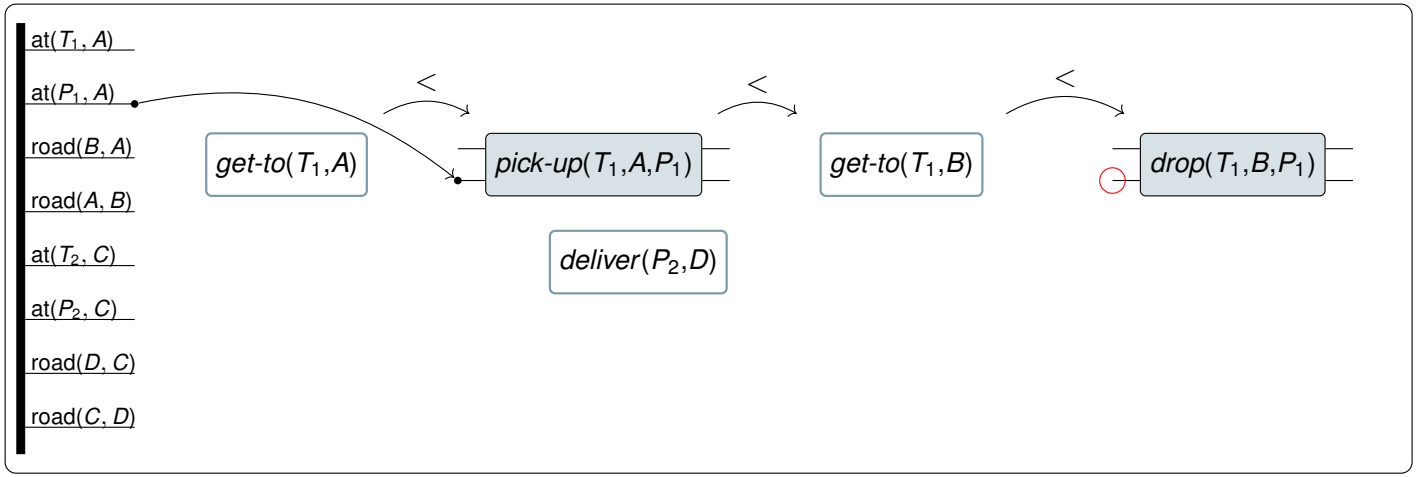

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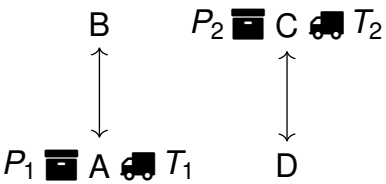
open prec.: at(T_1, B) of *drop(T_1, B, P_1)*	decompose *get-to(T_1, B)* with *m-direct(T_1, A, B)* decompose *get-to(T_1, B)* with *m-via(T_1, A, B)*
open prec.:* in(P_1, T_1) of *drop(T_1, B, P_1)	**insert causal link from *pickup($T1$, A, $P1$)***



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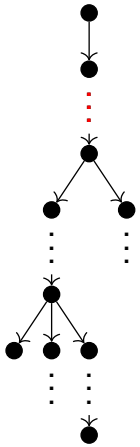

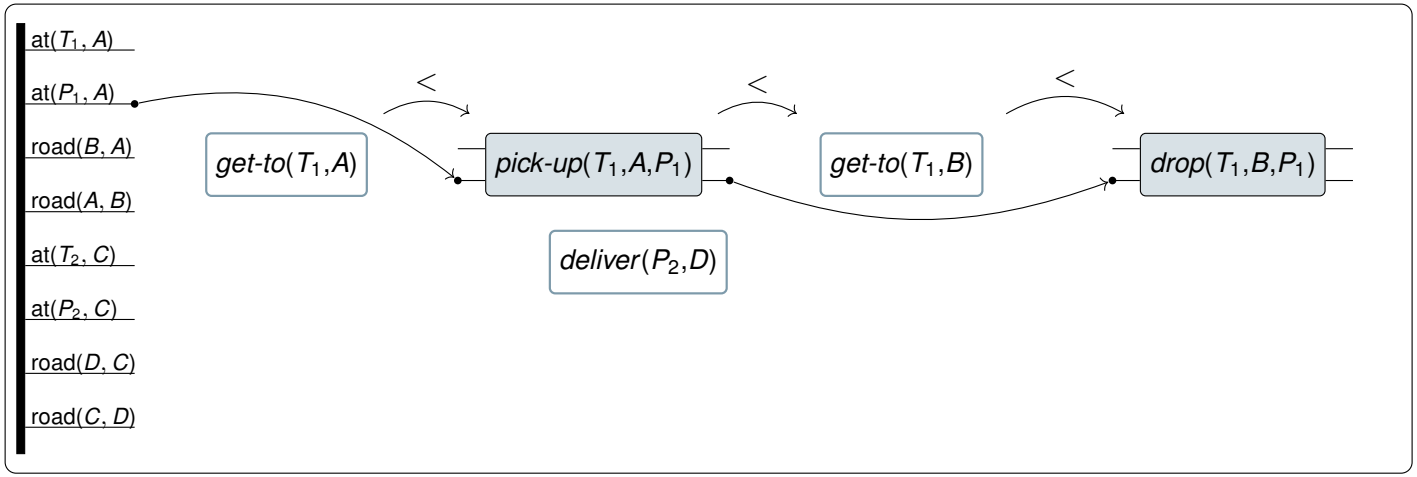

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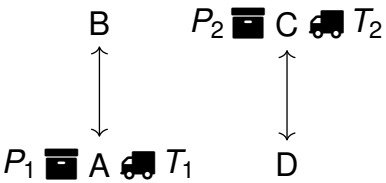
open prec.: at(T_1, B) of *drop(T_1, B, P_1)*	decompose *get-to(T_1, B)* with *m-direct(T_1, A, B)* decompose *get-to(T_1, B)* with *m-via(T_1, A, B)*



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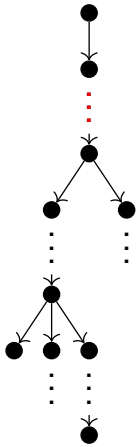

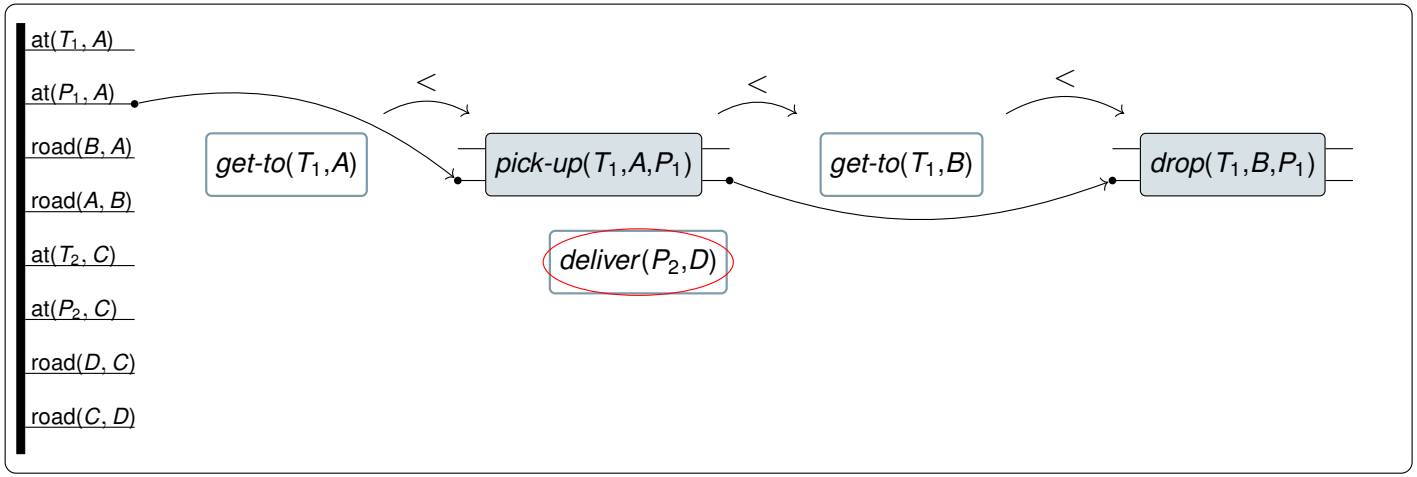

Flaws	**Modifications**
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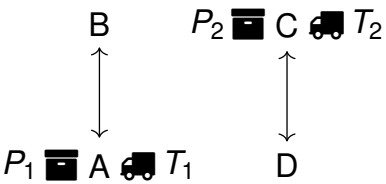
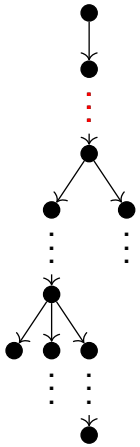
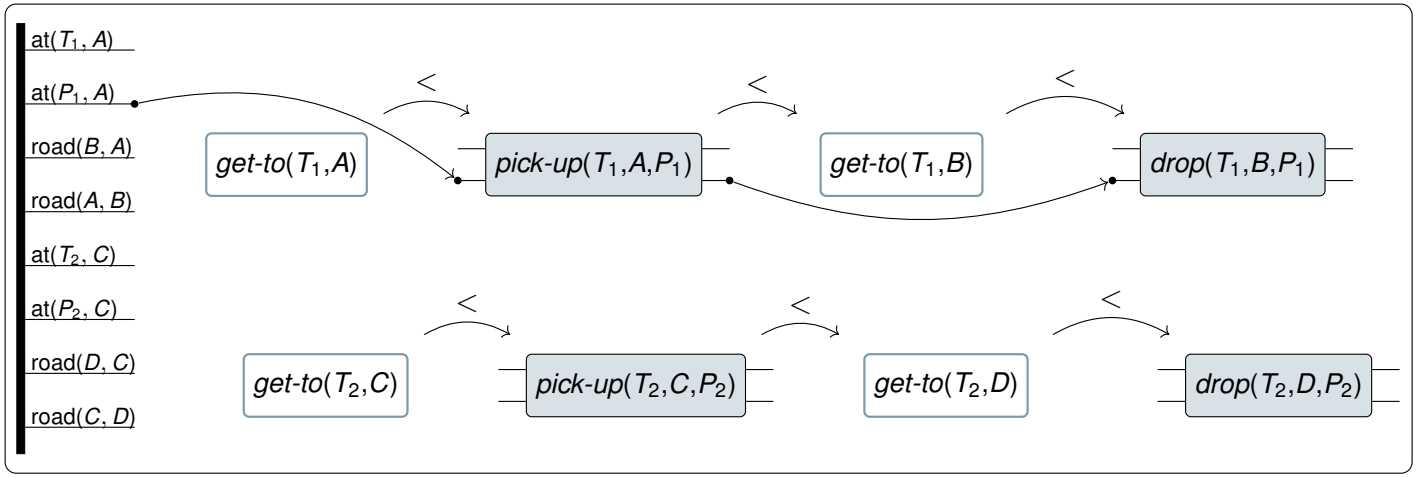
compound task: get-to(T_1, B)	decompose with *m-direct*(T_1, A, B) decompose with *m-via*(T_1, A, B) decompose with *m-noop*(T_1, B)
open prec.: at(T_1, B) of *drop*(T_1, B, P_1)	decompose *get-to*(T_1, B) with *m-direct*(T_1, A, B) decompose *get-to*(T_1, B) with *m-via*(T_1, A, B)

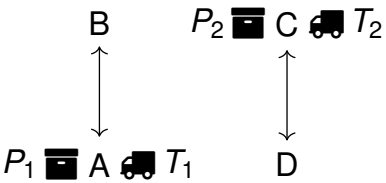


Plan Space-based HTN Planning, Example

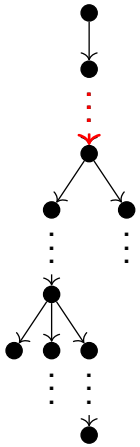


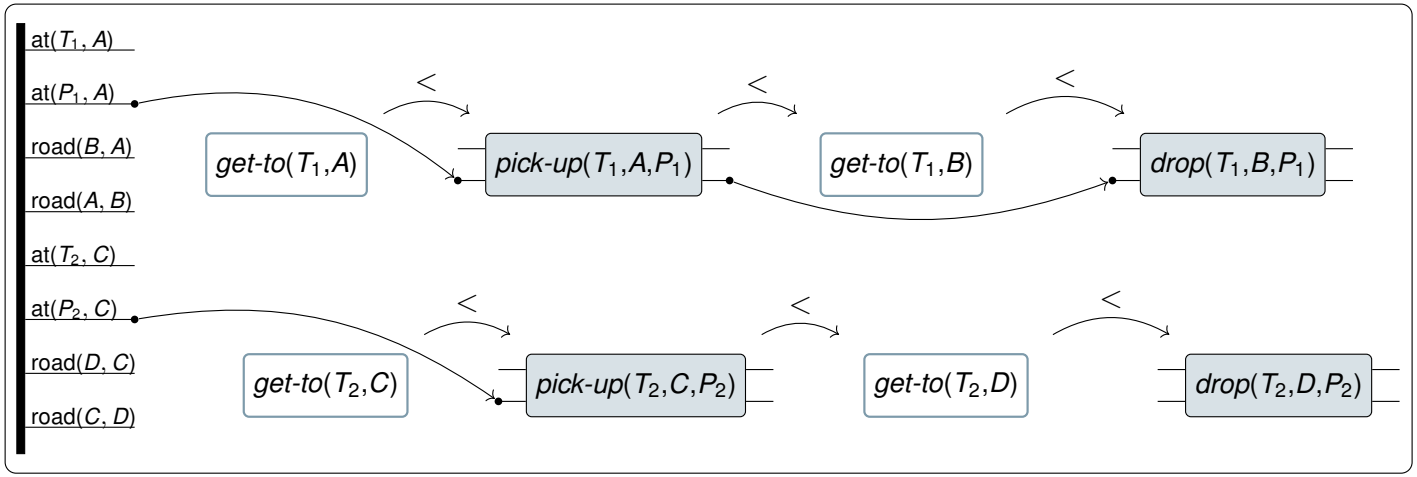


Flaws	**Modifications**
compound task: get-to(T_1, A)	decompose with *m-direct(T_1, B, A)* decompose with *m-via(T_1, B, A)* decompose with *m-noop(T_1, A)*
open prec.: at(T_1, A) of *pick-up(T_1, A, P_1)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
compound task: get-to(T_1, B)	decompose with *m-direct(T_1, A, B)* decompose with *m-via(T_1, A, B)* decompose with *m-noop(T_1, B)*
open prec.: at(T_1, B) of *drop(T_1, B, P_1)*	decompose *get-to(T_1, B)* with *m-direct(T_1, A, B)* decompose *get-to(T_1, B)* with *m-via(T_1, A, B)*
...	...

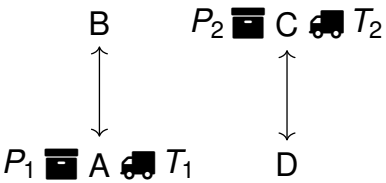


Plan Space-based HTN Planning, Example

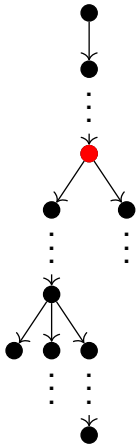


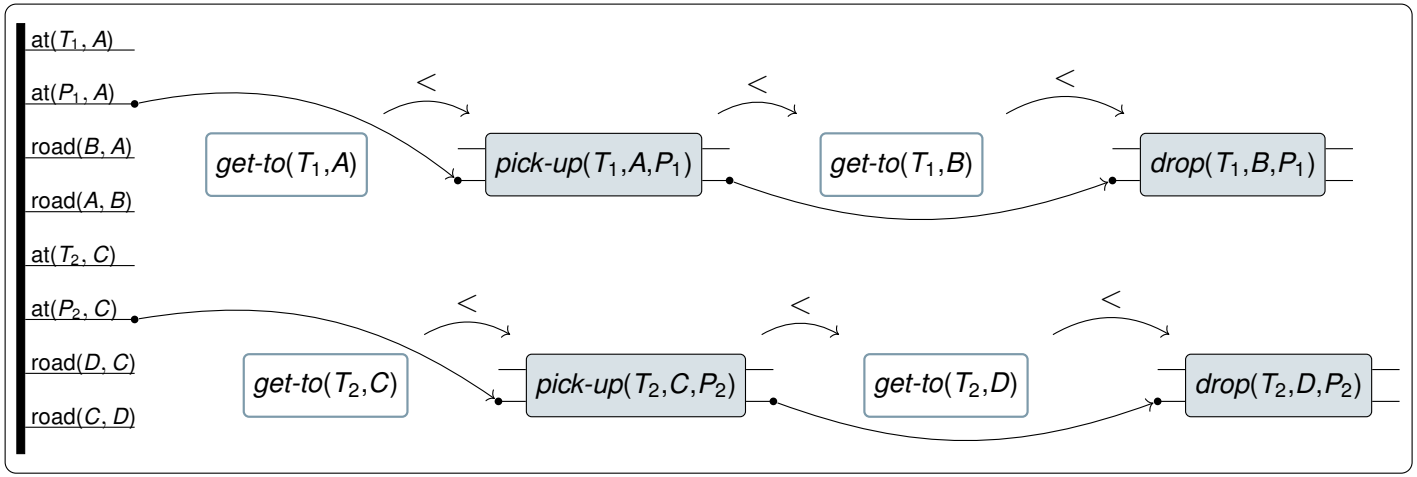


Flaws	**Modifications**
compound task: get-to(T_1, A)	decompose with *m-direct(T_1, B, A)* decompose with *m-via(T_1, B, A)* decompose with *m-noop(T_1, A)*
open prec.: at(T_1, A) of *pick-up(T_1, A, P_1)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
compound task: get-to(T_1, B)	decompose with *m-direct(T_1, A, B)* decompose with *m-via(T_1, A, B)* decompose with *m-noop(T_1, B)*
open prec.: at(T_1, B) of *drop(T_1, B, P_1)*	decompose *get-to(T_1, B)* with *m-direct(T_1, A, B)* decompose *get-to(T_1, B)* with *m-via(T_1, A, B)*
...	...

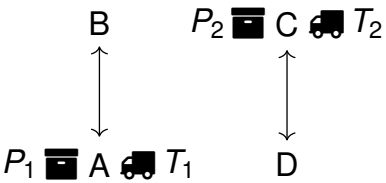


Plan Space-based HTN Planning, Example

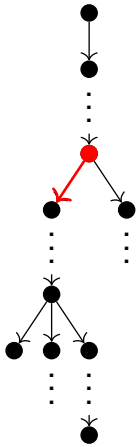


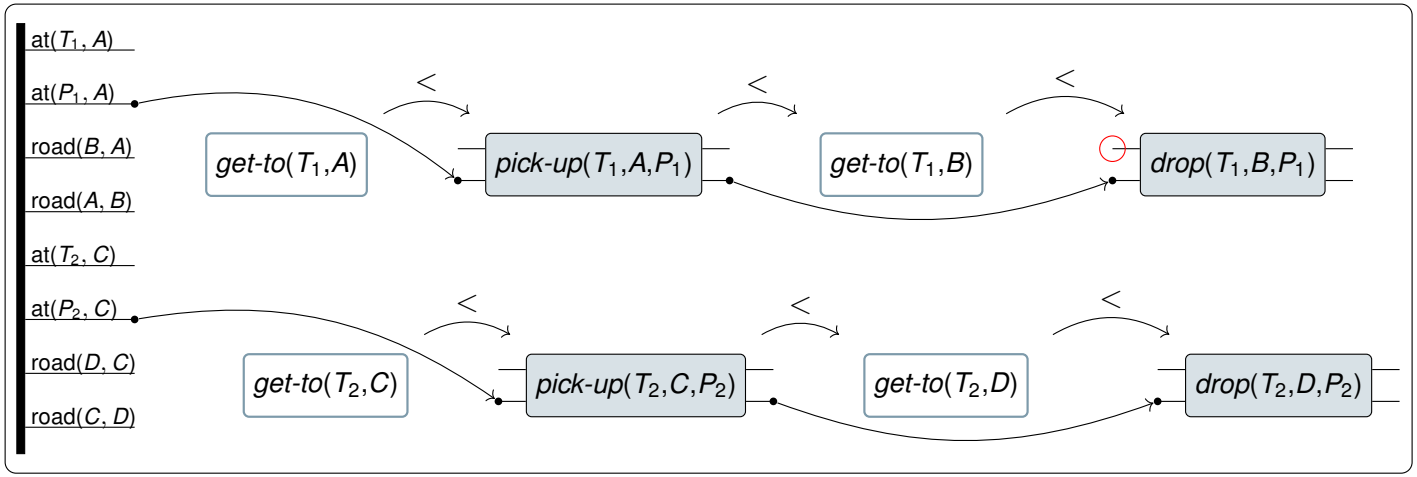


Flaws	**Modifications**
compound task: get-to(T_1, A)	decompose with *m-direct(T_1, B, A)* decompose with *m-via(T_1, B, A)* decompose with *m-noop(T_1, A)*
open prec.: at(T_1, A) of *pick-up(T_1, A, P_1)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
compound task: get-to(T_1, B)	decompose with *m-direct(T_1, A, B)* decompose with *m-via(T_1, A, B)* decompose with *m-noop(T_1, B)*
open prec.: at(T_1, B) of *drop(T_1, B, P_1)*	decompose *get-to(T_1, B)* with *m-direct(T_1, A, B)* decompose *get-to(T_1, B)* with *m-via(T_1, A, B)*
...	...

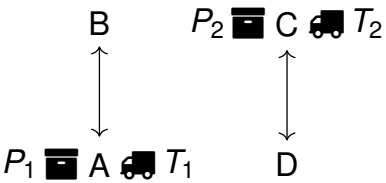


Plan Space-based HTN Planning, Example

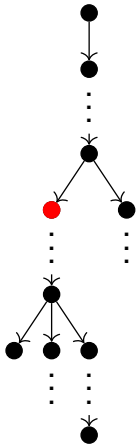


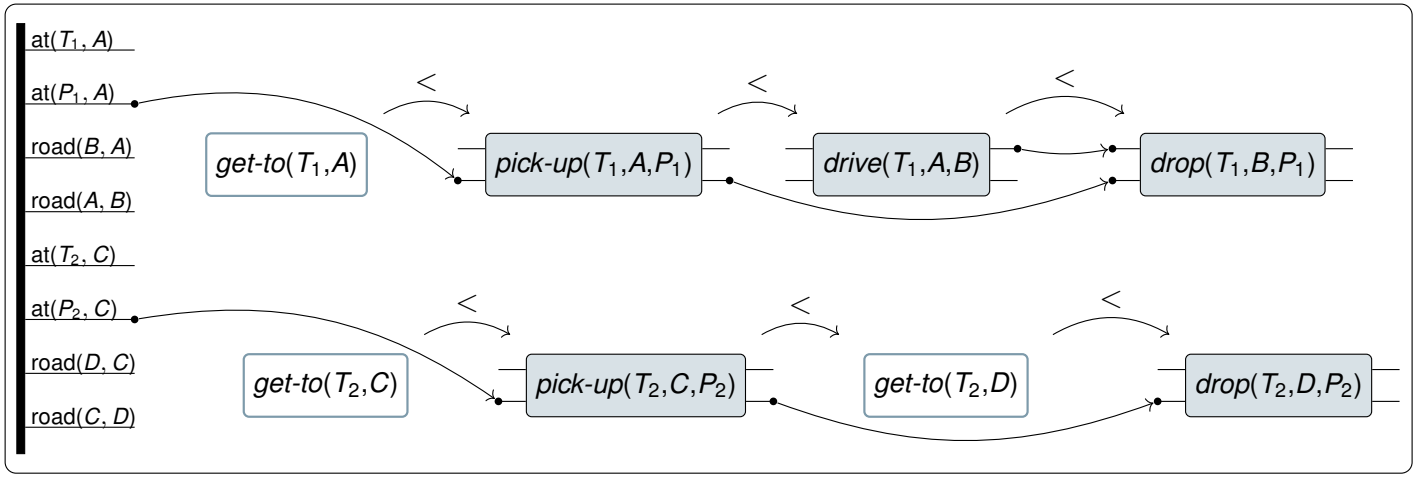


Flaws	**Modifications**
compound task: get-to(T_1, A)	decompose with *m-direct(T_1, B, A)* decompose with *m-via(T_1, B, A)* decompose with *m-noop(T_1, A)*
open prec.: at(T_1, A) of *pick-up(T_1, A, P_1)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
compound task: get-to(T_1, B)	decompose with *m-direct(T_1, A, B)* decompose with *m-via(T_1, A, B)* decompose with *m-noop(T_1, B)*
open prec.:* at(T_1, B) of *drop(T_1, B, P_1)	**decompose *get-to(T_1, B)* with *m-direct(T_1, A, B)*** decompose *get-to(T_1, B)* with *m-via(T_1, A, B)*
...	...

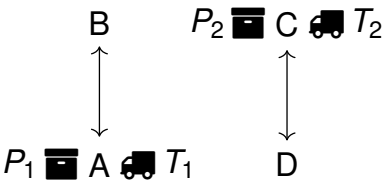


Plan Space-based HTN Planning, Example

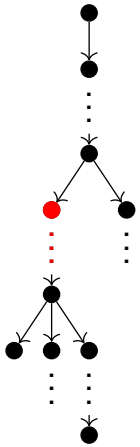


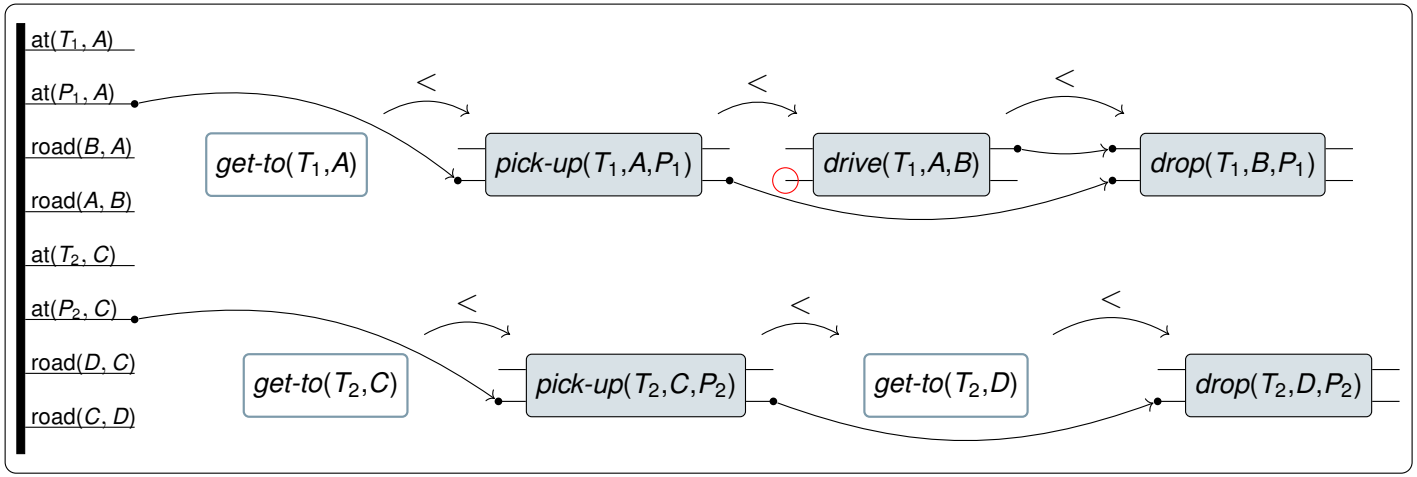


Flaws	**Modifications**
compound task: get-to(T_1, A)	decompose with *m-direct(T_1, B, A)* decompose with *m-via(T_1, B, A)* decompose with *m-noop(T_1, A)*
open prec.: at(T_1, A) of *pick-up(T_1, A, P_1)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
open prec.: at(T_1, A) of *drive(T_1, A, B)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
open prec.: road(A, B) of *drive(T_1, A, B)*	insert causal link from *init*
...	...

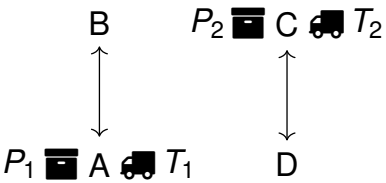


Plan Space-based HTN Planning, Example

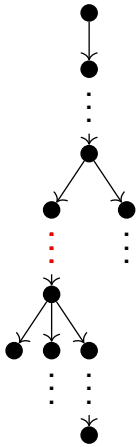


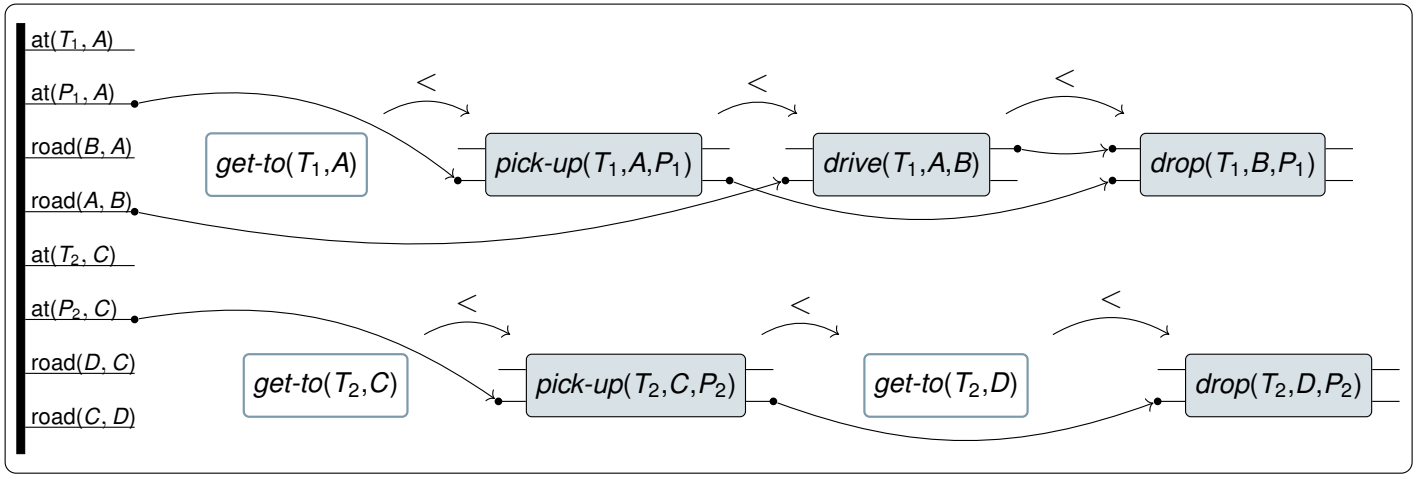


Flaws	**Modifications**
compound task: get-to(T_1, A)	decompose with *m-direct(T_1, B, A)* decompose with *m-via(T_1, B, A)* decompose with *m-noop(T_1, A)*
open prec.: at(T_1, A) of *pick-up(T_1, A, P_1)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
open prec.: at(T_1, A) of *drive(T_1, A, B)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
open prec.:* road(A, B) of *drive(T_1, A, B)	**insert causal link from *init***
...	...

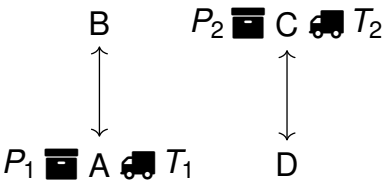


Plan Space-based HTN Planning, Example

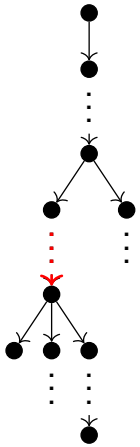


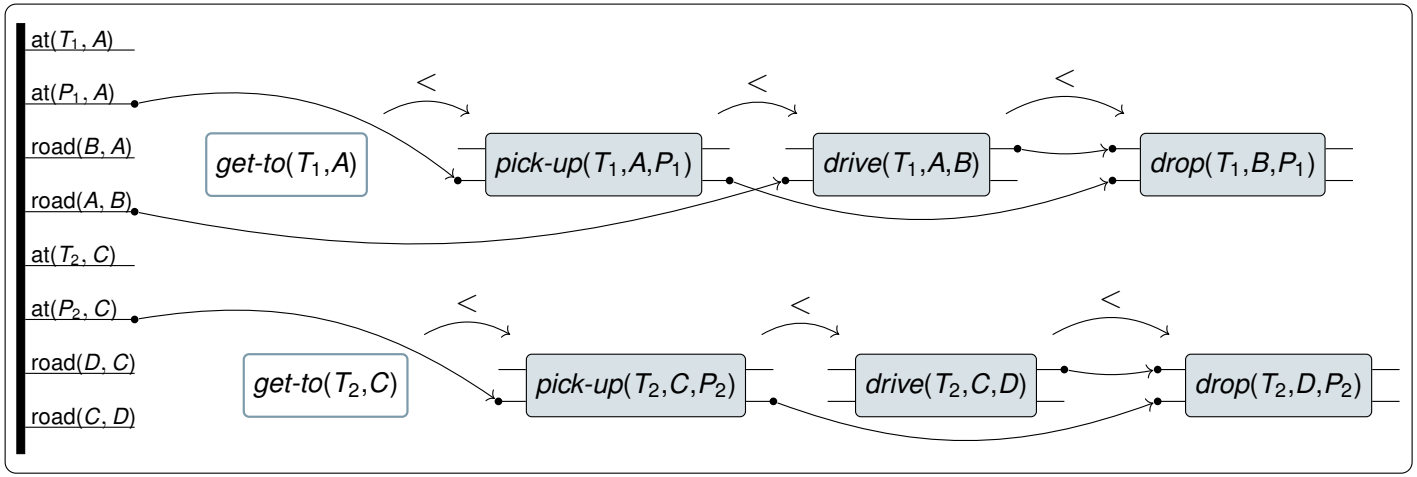


Flaws	**Modifications**
compound task: get-to(T_1, A)	decompose with *m-direct(T_1, B, A)* decompose with *m-via(T_1, B, A)* decompose with *m-noop(T_1, A)*
open prec.: at(T_1, A) of *pick-up(T_1, A, P_1)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
open prec.: at(T_1, A) of *drive(T_1, A, B)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
...	...

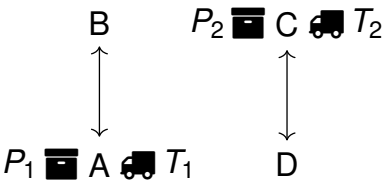


Plan Space-based HTN Planning, Example

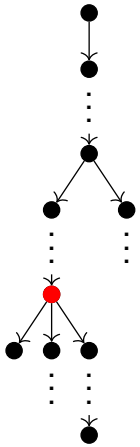


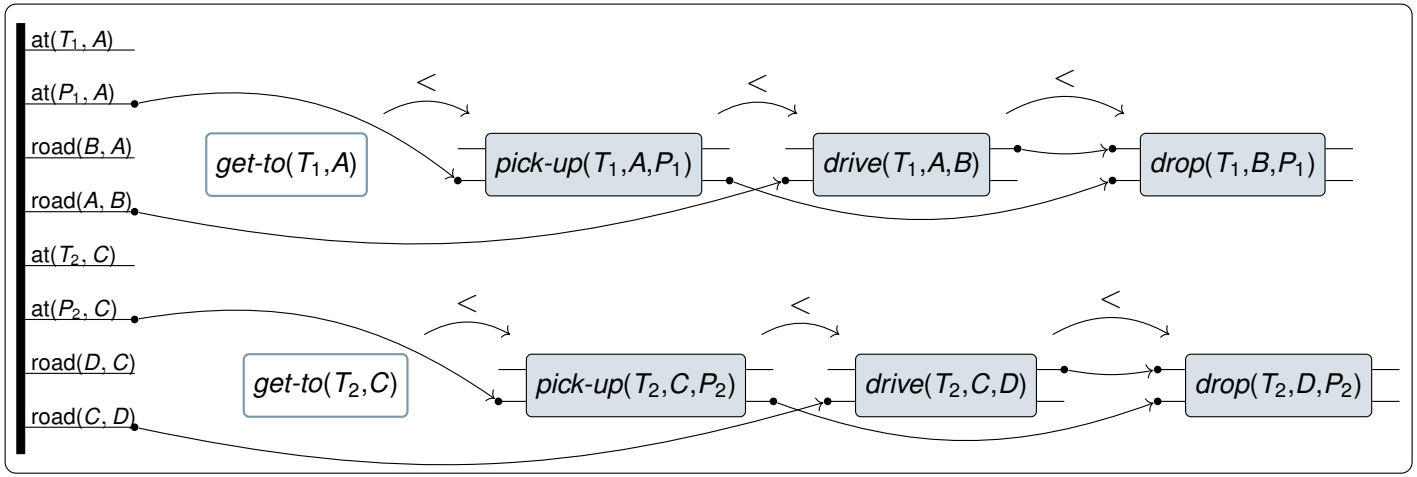


Flaws	**Modifications**
compound task: get-to(T_1, A)	decompose with *m-direct(T_1, B, A)* decompose with *m-via(T_1, B, A)* decompose with *m-noop(T_1, A)*
open prec.: at(T_1, A) of *pick-up(T_1, A, P_1)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
open prec.: at(T_1, A) of *drive(T_1, A, B)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
...	...

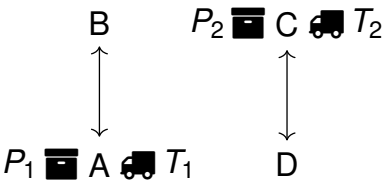


Plan Space-based HTN Planning, Example

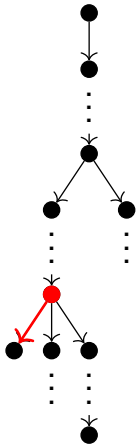


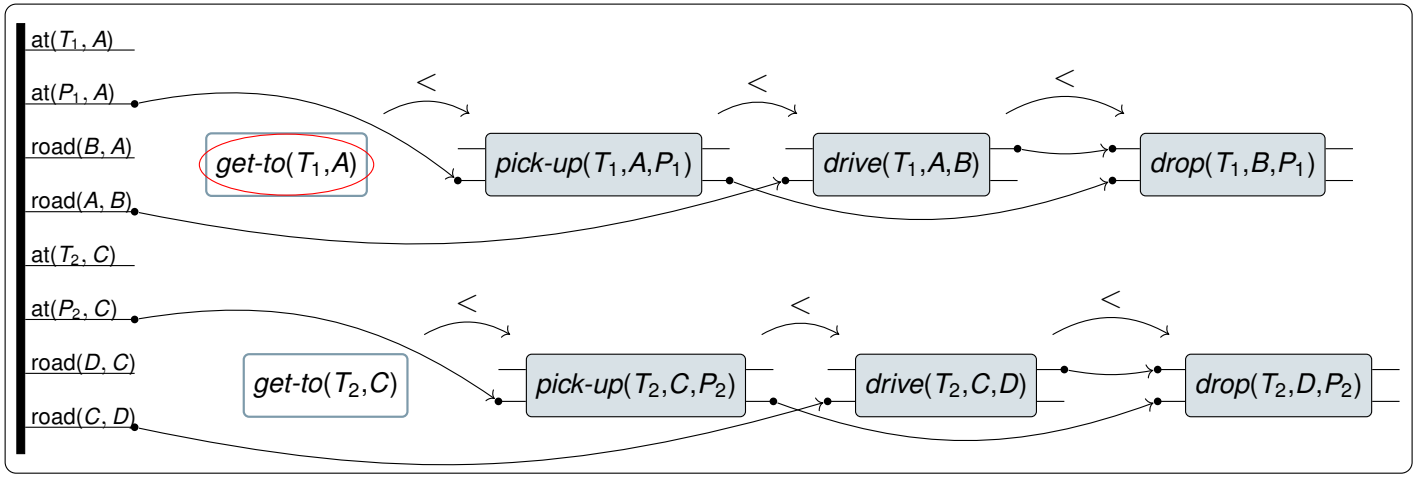


Flaws	**Modifications**
compound task: get-to(T_1, A)	decompose with *m-direct(T_1, B, A)* decompose with *m-via(T_1, B, A)* decompose with *m-noop(T_1, A)*
open prec.: at(T_1, A) of *pick-up(T_1, A, P_1)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
open prec.: at(T_1, A) of *drive(T_1, A, B)*	insert causal link from *init* decompose *get-to(T_1, A)* with *m-direct(T_1, B, A)* decompose *get-to(T_1, A)* with *m-via(T_1, B, A)*
...	...

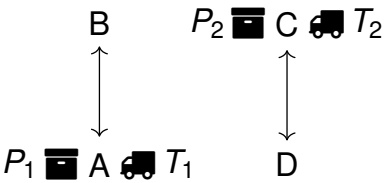


Plan Space-based HTN Planning, Example

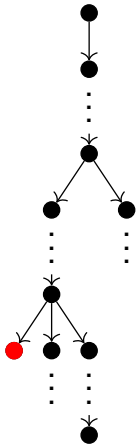


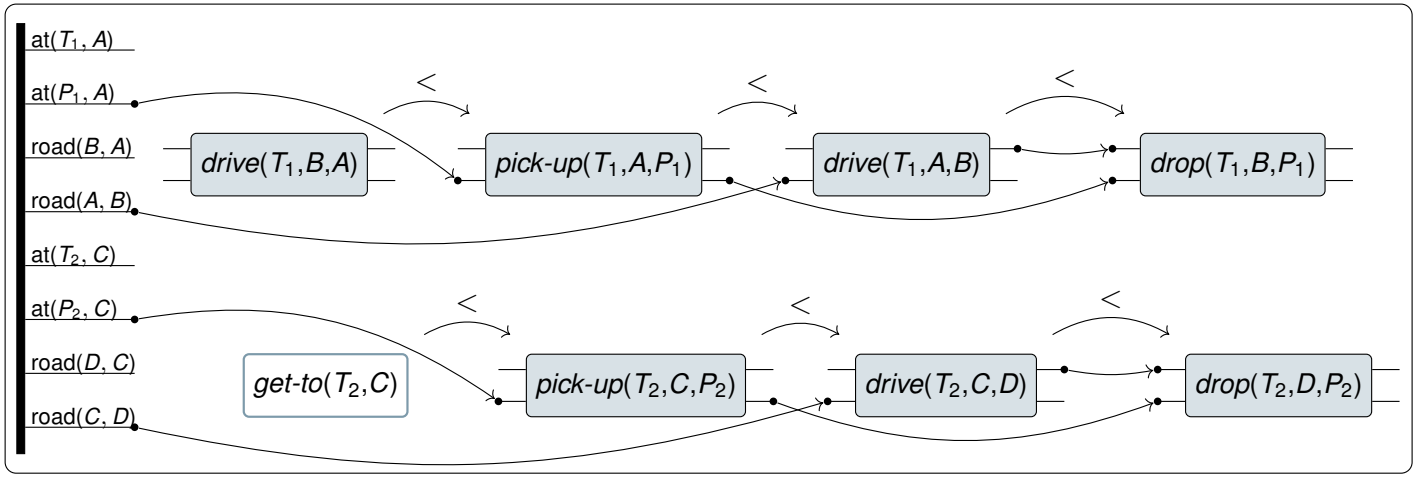


Flaws	**Modifications**
compound task: get-to(T_1, A)	**decompose with *m-direct***(T_1, B, A) decompose with *m-via*(T_1, B, A) decompose with *m-noop*(T_1, A)
open prec.: at(T_1, A) of *pick-up*(T_1, A, P_1)	insert causal link from *init* decompose *get-to*(T_1, A) with *m-direct*(T_1, B, A) decompose *get-to*(T_1, A) with *m-via*(T_1, B, A)
open prec.: at(T_1, A) of *drive*(T_1, A, B)	insert causal link from *init* decompose *get-to*(T_1, A) with *m-direct*(T_1, B, A) decompose *get-to*(T_1, A) with *m-via*(T_1, B, A)
...	...

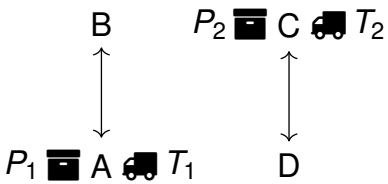


Plan Space-based HTN Planning, Example

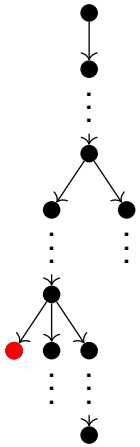


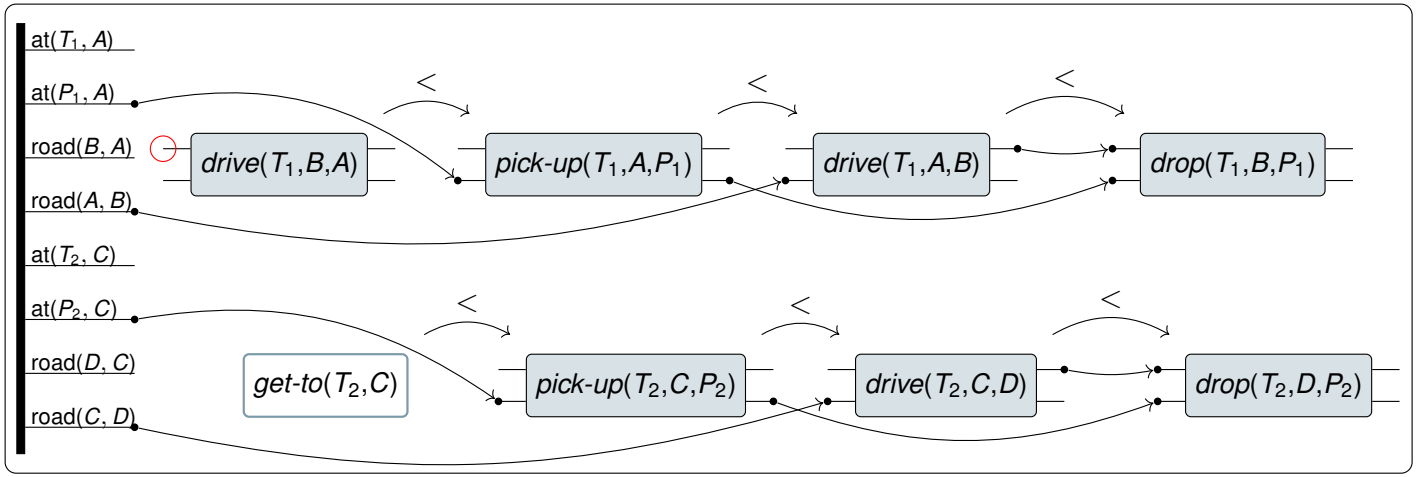


Flaws	**Modifications**
open prec: at(T_1, B) of *drive*(T_1, B, A)	—
open prec.: road(B, A) of *drive*(T_1, B, A)	insert causal link from *init*
open prec.: at(T_1, A) of *pick-up*(T_1, A, P_1)	insert causal link from *init* insert causal link from *drive*(T_1, B, A)
open prec.: at(T_1, A) of *drive*(T_1, A, B)	insert causal link from *init* insert causal link from *drive*(T_1, B, A)
...	...



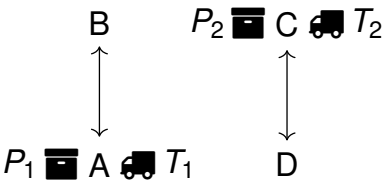
Plan Space-based HTN Planning, Example



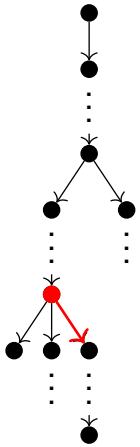


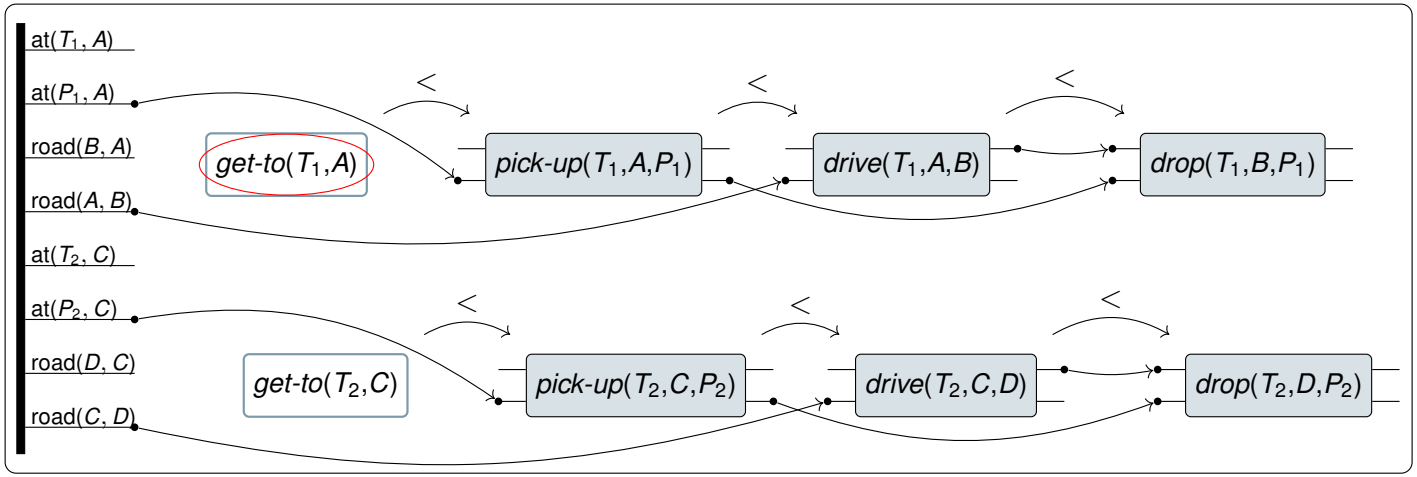
Flaws	**Modifications**
***open prec:* at(T_1, B) of *drive*(T_1, B, A)**	**—**
open prec.: road(B, A) of *drive*(T_1, B, A)	insert causal link from *init*
open prec.: at(T_1, A) of *pick-up*(T_1, A, P_1)	insert causal link from *init* insert causal link from *drive*(T_1, B, A)
open prec.: at(T_1, A) of *drive*(T_1, A, B)	insert causal link from *init* insert causal link from *drive*(T_1, B, A)
...	...

This partial plan can be discarded, because it has a flaw without modifications



Plan Space-based HTN Planning, Example





Flaws	**Modifications**
compound task: get-to(*T_1, A*)	decompose with *m-direct(*T_1, B, A*)* decompose with *m-via(*T_1, B, A*)* **decompose with *m-noop(*T_1, A*)***
open prec.: at(T_1, A) of *pick-up(*T_1, A, P_1*)*	insert causal link from *init* decompose *get-to(*T_1, A*)* with *m-direct(*T_1, B, A*)* decompose *get-to(*T_1, A*)* with *m-via(*T_1, B, A*)*
open prec.: at(T_1, A) of *drive(*T_1, A, B*)*	insert causal link from *init* decompose *get-to(*T_1, A*)* with *m-direct(*T_1, B, A*)* decompose *get-to(*T_1, A*)* with *m-via(*T_1, B, A*)*
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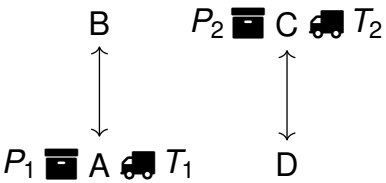

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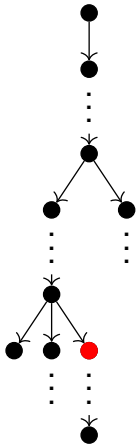

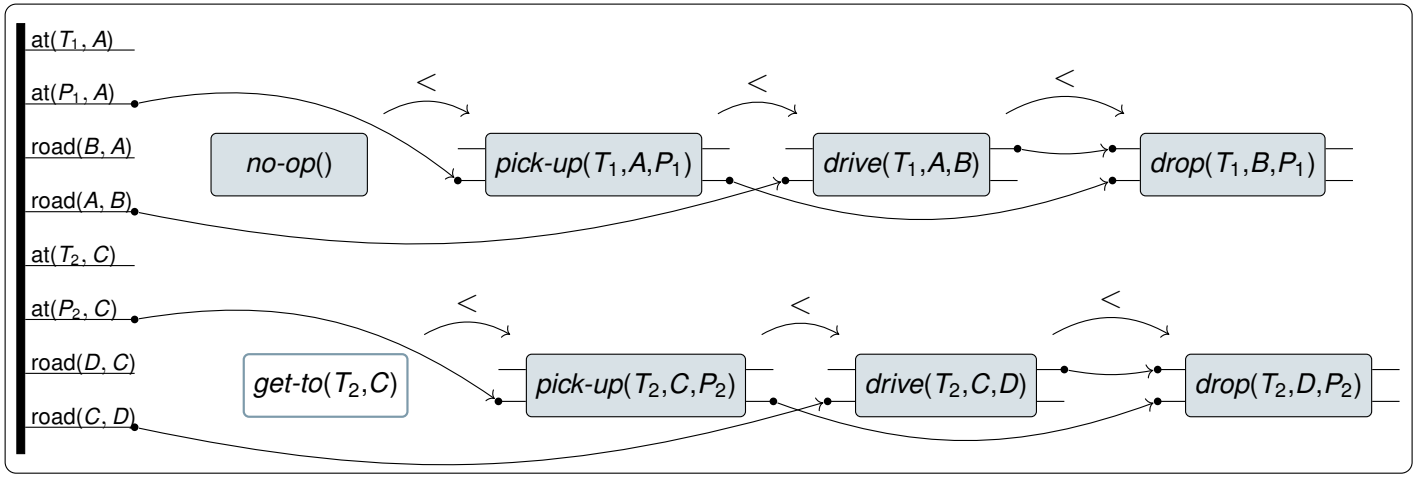

Flaws	**Modifications**
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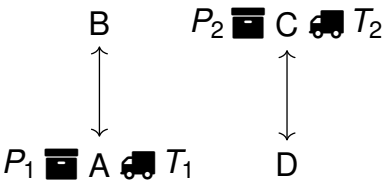

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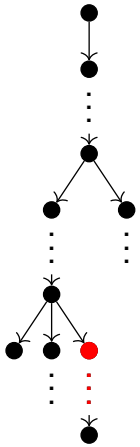

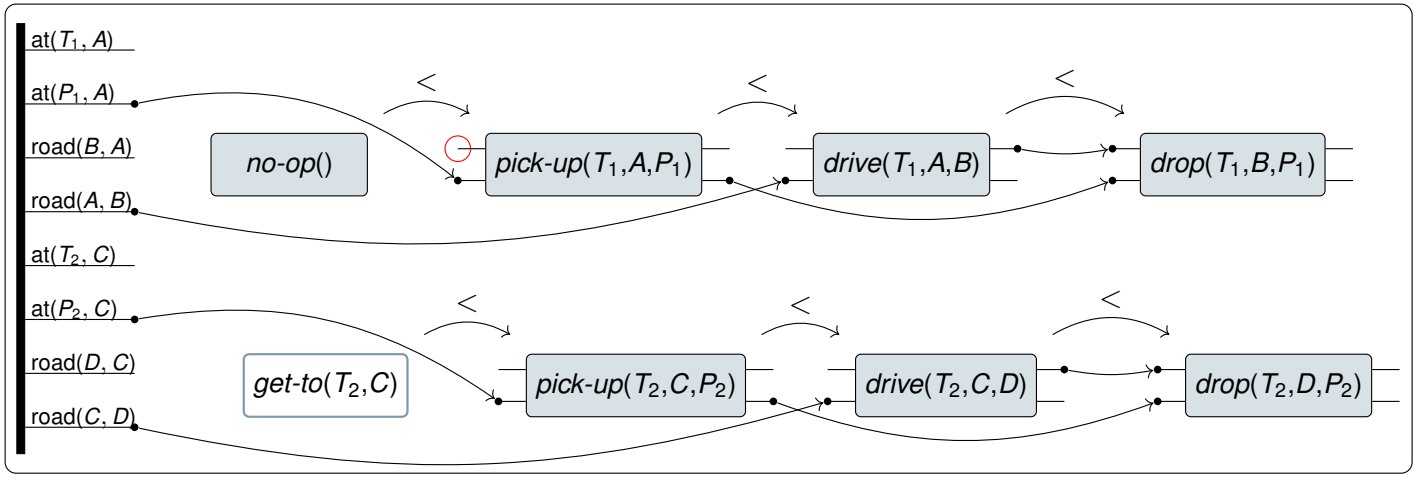

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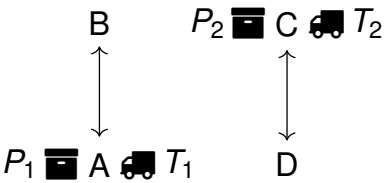

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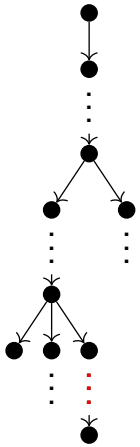

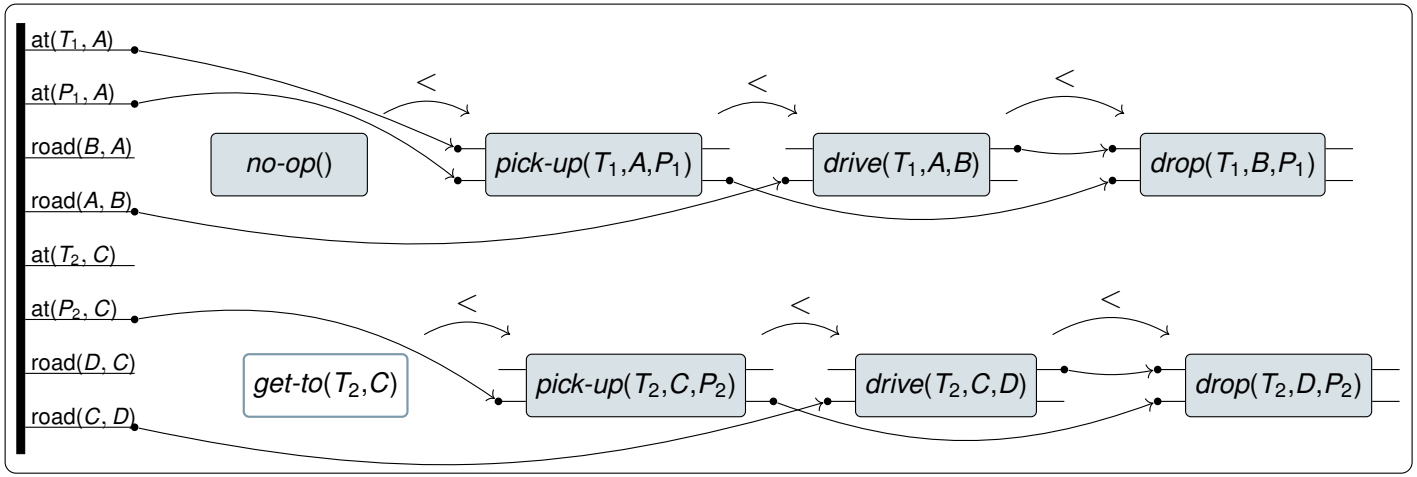

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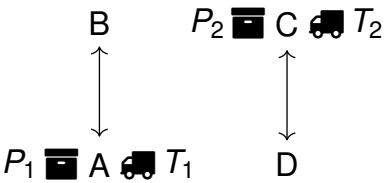

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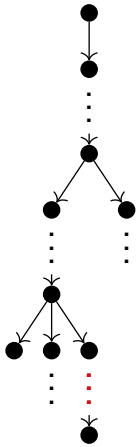

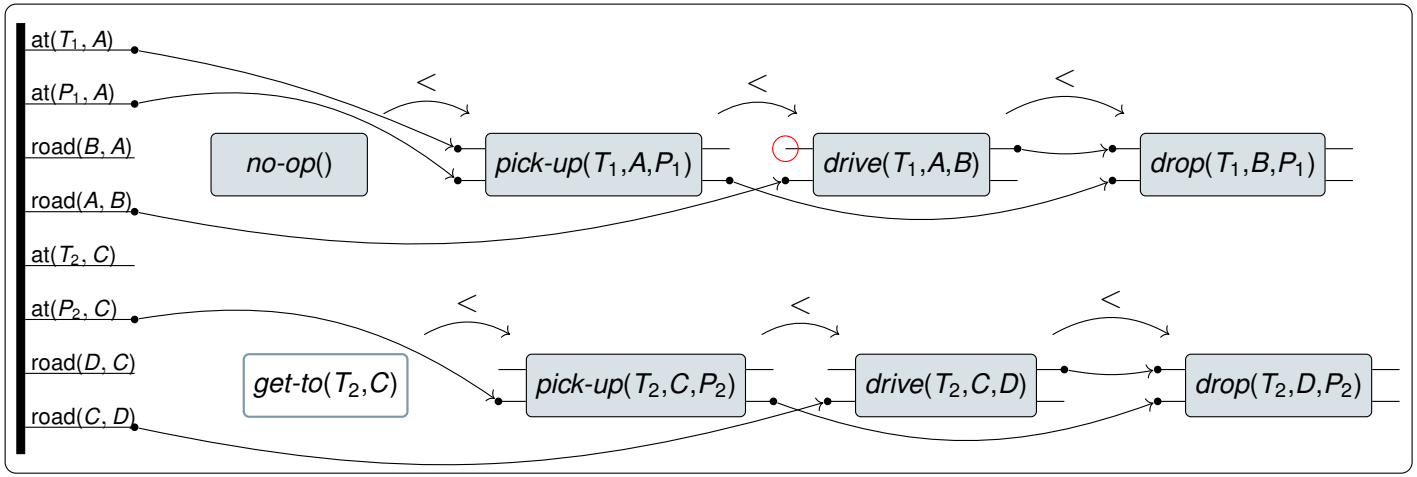

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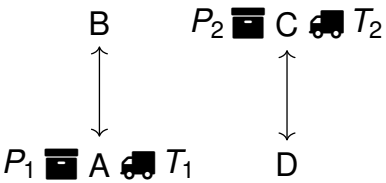

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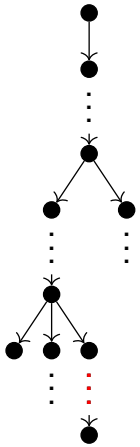

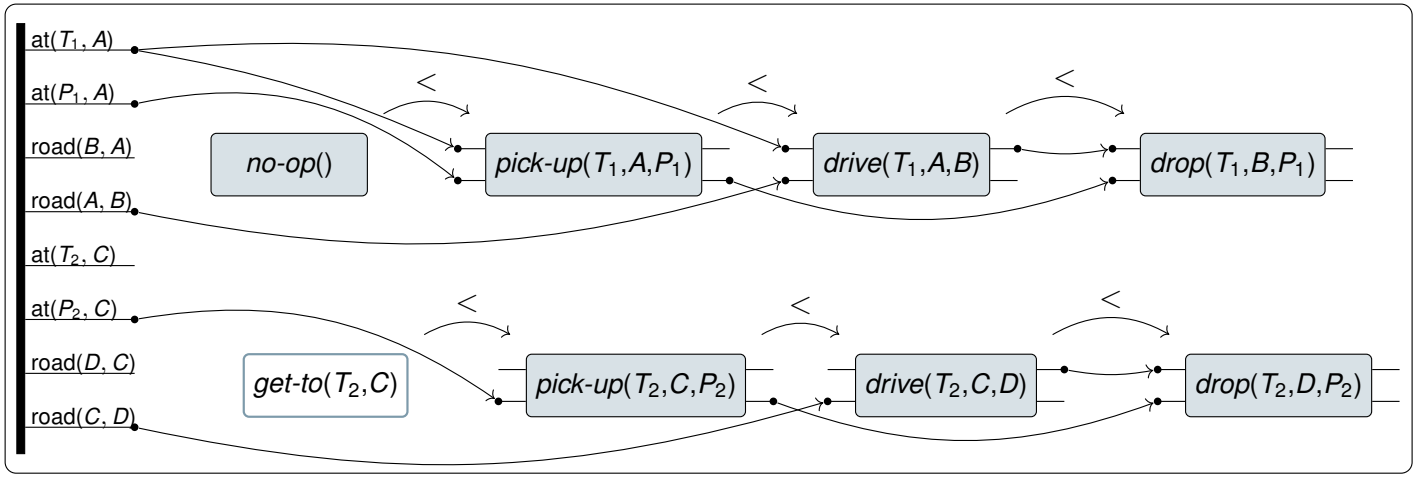

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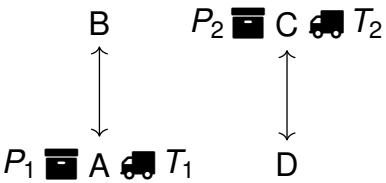

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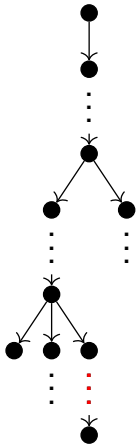

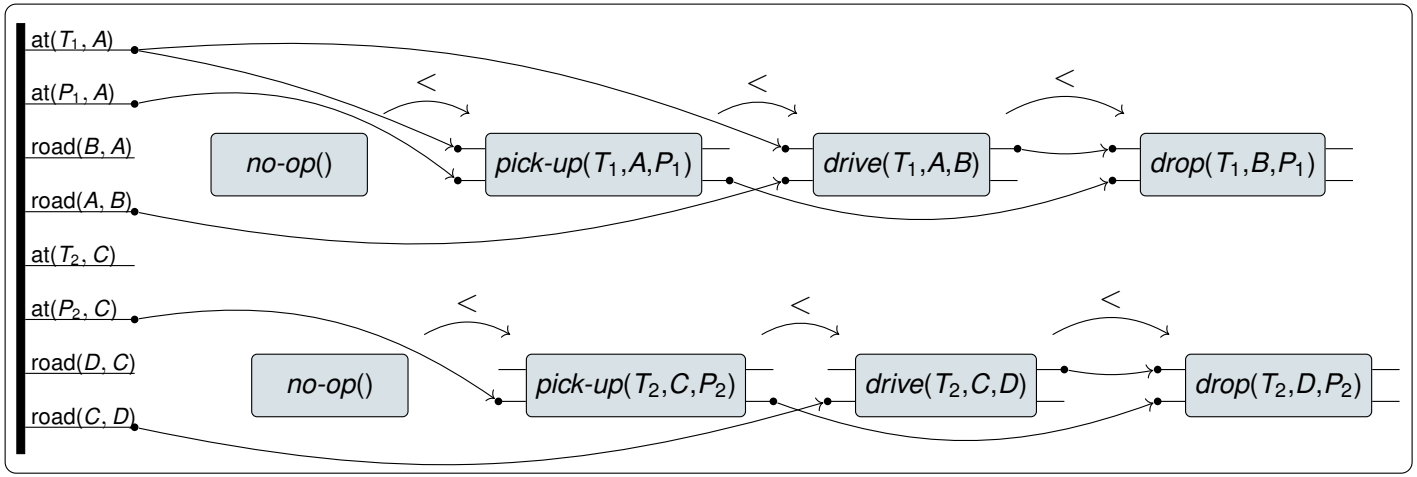

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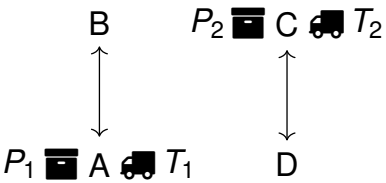

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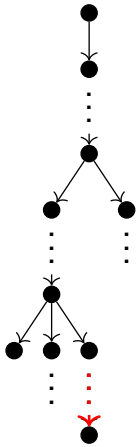

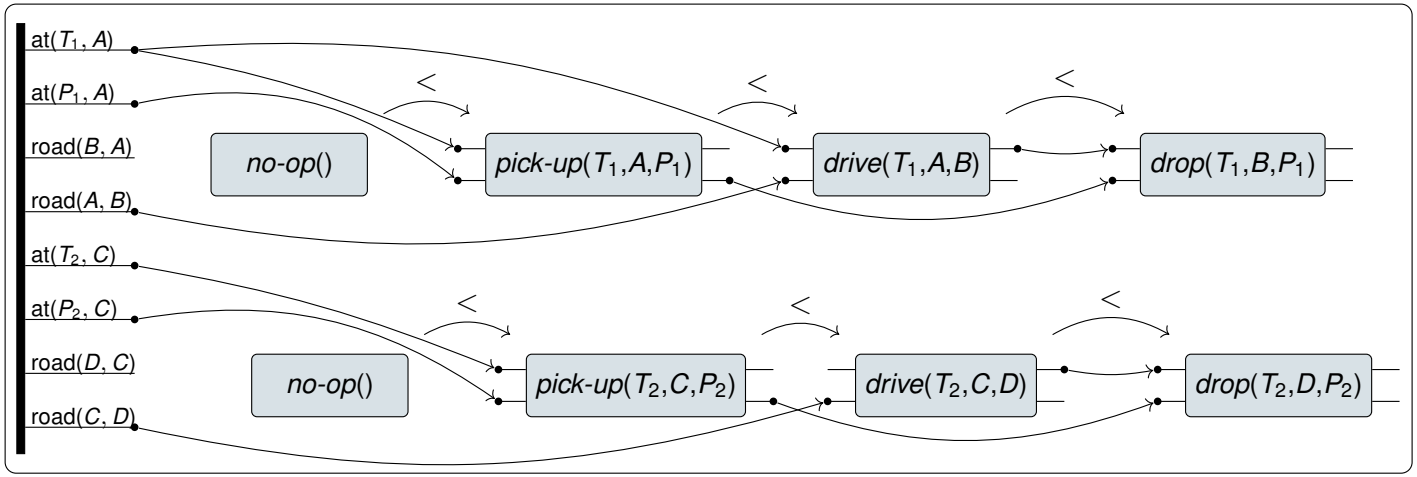

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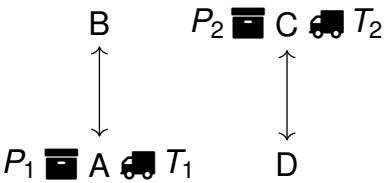

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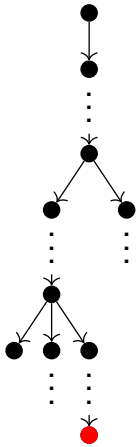
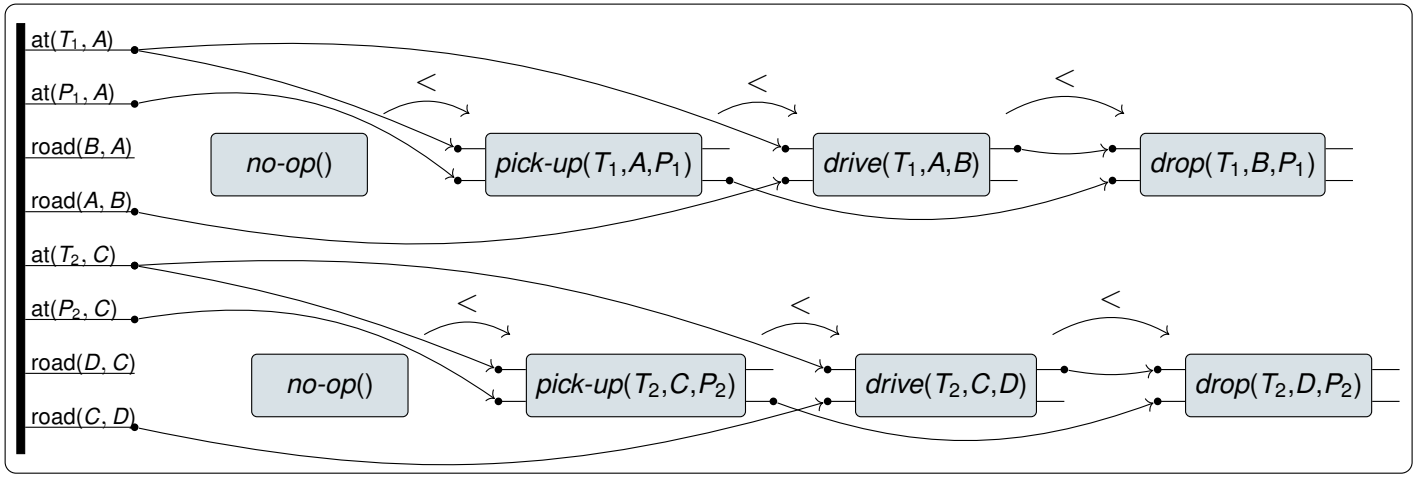
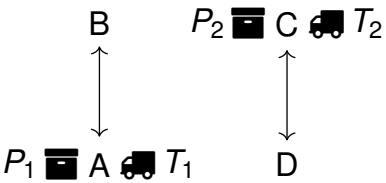




Flaws **Modifications**

This partial plan has no flaws, so it is a solution and returned



Flaw Selection Strategies

- Many of the flaw selection strategies for POCL planning can be reused for plan space-based HTN planning.
- As for POCL planning, one good possibility is LCFR. Further strategies might be discussed in the exercises.

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Theorem

Plan space-based search is sound and complete.

The completeness, however, depends on the deployed search strategy, i.e., the implementation of *nodeSelectAndRemove*().

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Proof:
Follows from the properties of the underlying search algorithm.
However:

- Be aware that the transition system is not finite!
- We had to show that for each flaw, *all* possible ways to resolve it are generated and that no unintended side effects occur such as being overly restrictive thereby unintentionally ruling out solutions.

Extensions

- Method preconditions:

Extensions

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- Extension to hybrid planning, where compound tasks show preconditions and effects as well: Discussed at the end of the lecture if time.

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  - both approaches rely on heuristics to guide search (next lecture).