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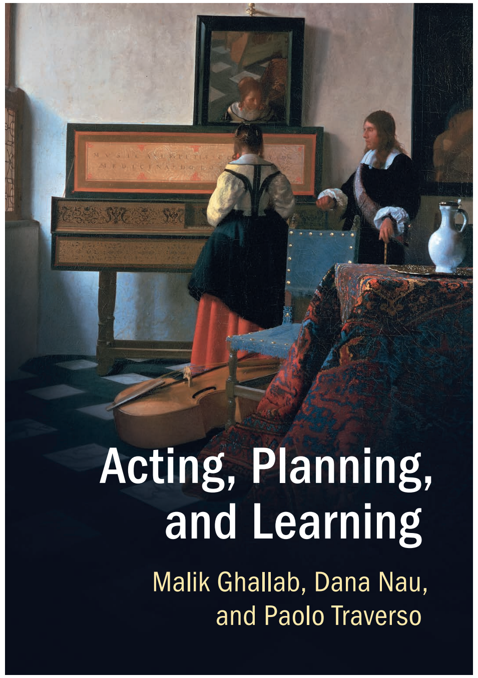

Chapter 6
Acting with HTNs

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Acting, Planning, and Learning

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Using HTN Domain Models for Acting

- Unlike an HTN domain model, the actor’s environment is not necessarily deterministic or static
  - Exogenous events, unanticipated action outcomes ⇒ current state may be different from what an HTN model would predict
- Actor can’t backtrack to a previous state; prior actions are in the past

- HTN domain models still are very useful for providing *operational* models to the actor
  - How to carry out “standard operating procedures”
  - How to perform complex tasks without searching through a large state space
  - How to avoid situations where unanticipated events are likely to cause bad outcomes
  - How to recover when unanticipated events occur

Reactive HTN Actor

- Like TO-HTN-Forward but executes each action
  - Can similarly modify other Chapter 5 algorithms

Line

0 Return success or failure, not a plan

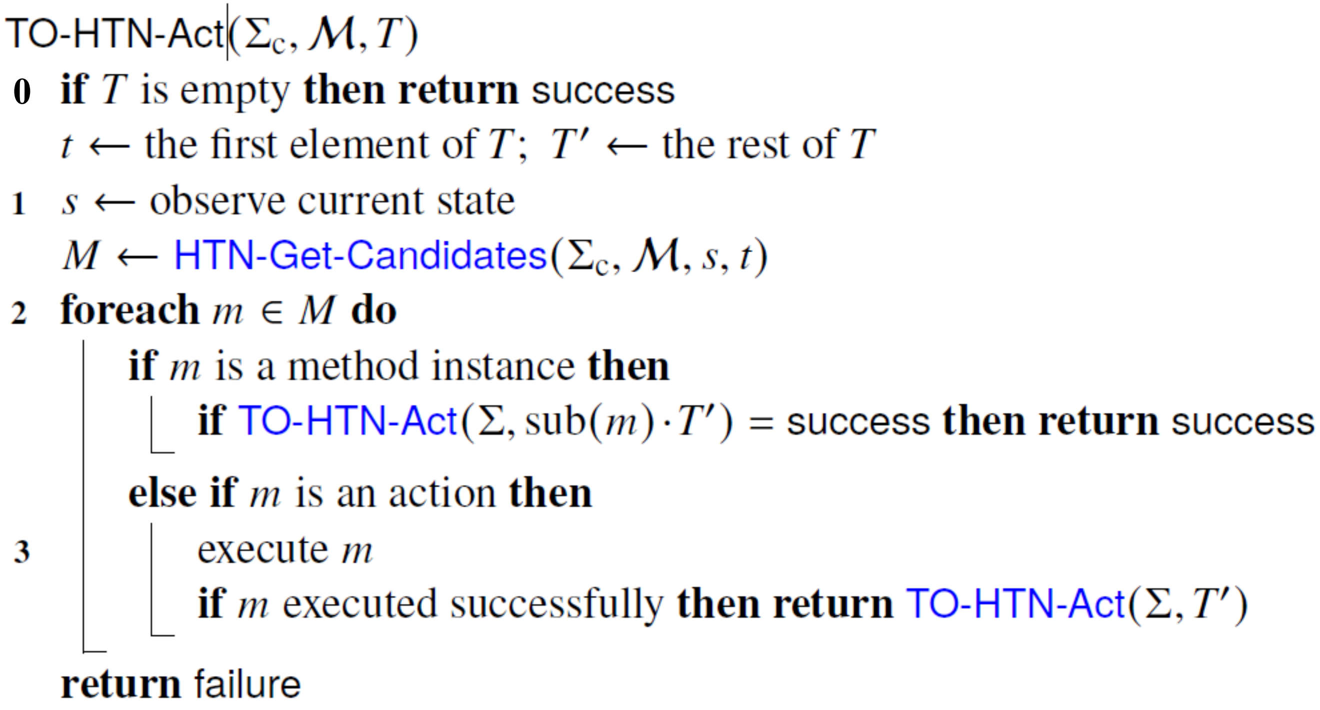
1 *s* isn't an argument, observe it instead

3 Instead of computing γ, execute action

2 Failure recovery: if *m* fails, try next one

- if they all fail, return failure to next higher level in the recursion stack, to try other methods there

- At Line 2, a bad method instance can lead to non-optimal solution or failure
  - Can use a heuristic function
  - Can call an HTN planner – but other ways have less computational overhead



```
TO-HTN-Act($\Sigma_c, \mathcal{M}, T$)
0  if $T$ is empty then return success
   $t \leftarrow$ the first element of $T$;  $T' \leftarrow$ the rest of $T$
1  $s \leftarrow$ observe current state
   $M \leftarrow$ HTN-Get-Candidates($\Sigma_c, \mathcal{M}, s, t$)
2  foreach $m \in M$ do
       if $m$ is a method instance then
           if TO-HTN-Act($\Sigma$, sub($m$)$\cdot T'$) = success then return success
       else if $m$ is an action then
3          execute $m$
           if $m$ executed successfully then return TO-HTN-Act($\Sigma, T'$)
   return failure
```

Poll 1. Is line doing backtracking?

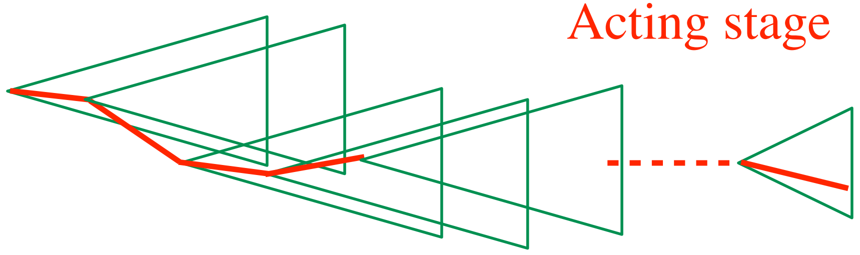
A. Yes B. No C. Unsure

Run-HLookahead

```
HTN-Run-Lookahead($\Sigma$, $T$)
    while True do:
        $s \leftarrow$ observed current state
        $\pi$ = Lookahead($\Sigma$, $s$, $T$)
        if $\pi$ = failure then return failure
        if $\pi = \langle\,\rangle$ then return success
        $a \leftarrow$ pop($\pi$)
        trigger execution of $a$
```

- Here, *Lookahead* is an HTN planner
- Goal formula may not exist
  - Cannot rely on $s \vDash g$
  - Need *Lookahead* to return $\langle\,\rangle$ iff no actions are needed to accomplish T

- Call *Lookahead*, get π, perform 1st action, call *HLookahead* again …
- Useful when unexpected things are likely to happen
  - Replans immediately
- *Lookahead* needs to return quickly
  - Otherwise, HTN-Run-Lookahead may pause repeatedly waiting for *Lookahead* to return
  - May want *Lookahead* to look a limited distance or horizon ahead



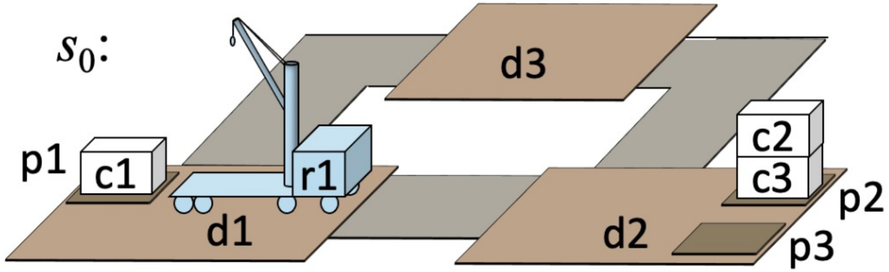
Planning stage

Acting stage

Run-HLookahead (Example 1)

```
HTN-Run-Lookahead(Σ, $\mathcal{T}$)
    while True do:
        $s \leftarrow$ observed current state
        $\pi$ = Lookahead(Σ, $s$, $\mathcal{T}$)
        if $\pi$ = failure then return failure
        if $\pi = \langle\ \rangle$ then return success
        $a \leftarrow \text{pop}(\pi)$
        trigger execution of $a$
```

s_0:



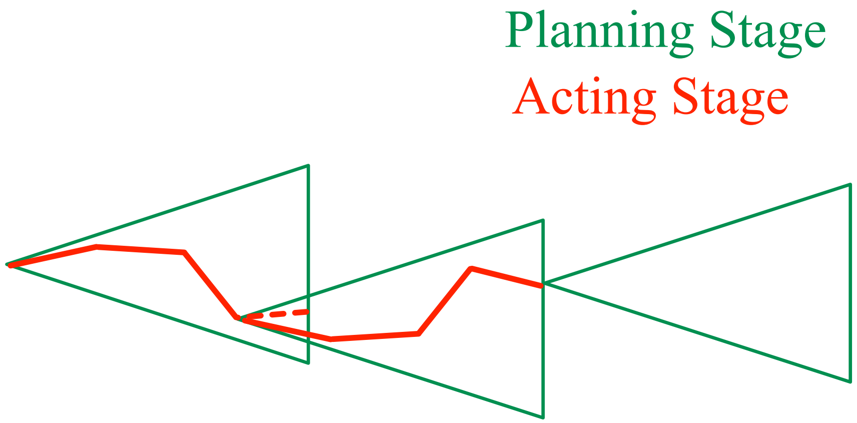
- Call HTN-Run-Lookahead with *Lookahead* = TO-HTN-Forward (THF)
  - Σ = the TOHTN domain in Example 5.8
  - P = (Σ, s_0, T = ⟨{pile(c1)=p2}⟩)
- If nothing unexpected happens:
  - Call TO-HTN-Forward(Σ, s_0, $\mathcal{T}$)
    - π = ⟨take(r1,c1,c2,p1,d1), move(r1,d1,d2), put(r1,c1,c3,p2,d2)⟩
  - Execute take(r1,c1,c2,p1,d1)
  - Call THF(..), get π = ⟨move(r1,d1,d2), put(r1,c1,c3,p2,d2)⟩
  - execute move(r1,d1,d2),
  - call THF(..), get π = ⟨put(r1,c1,c3,p2,d2)⟩
  - execute put(r1,c1,c3,p2,d2),
  - Call THF(..), get π = ⟨ ⟩, return success
- If something unexpected happens but the problem is still solvable:
  - Call THF(..) with latest observed state, it returns a new plan
  - This could fail if there is no applicable method for the new state!

Run-Lazy-HLookahead

```
HTN-Run-Lazy-Lookahead($\Sigma$, $\mathcal{T}$)
    $\pi \leftarrow \langle\,\rangle$; $a \leftarrow$ nil
    while True do:
        if $\pi = \langle\,\rangle$ or execution of $a$ failed then
            $s \leftarrow$ observed state
            $\pi$ = Lookahead($\Sigma$, $s$, $\mathcal{T}$)
            if $\pi$ = failure then return failure
            if $\pi = \langle\,\rangle$ then return success
        $a \leftarrow$ pop($\pi$)
        trigger execution of $a$
```

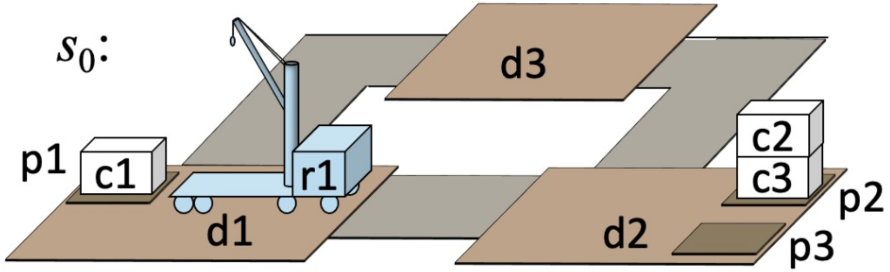
- Two different tests for ⟨ ⟩
  - If we've exhausted the current plan, call *Lookahead*
  - If *Lookahead* returns ⟨ ⟩, return success
- Requires *Lookahead* to return ⟨ ⟩ iff no actions are needed to accomplish $\mathcal{T}$

- Could also add a *Simulate* program as in Run-Lazy-Lookahead



Run-Lazy-HLookahead (Example 1)

```
HTN-Run-Lazy-Lookahead($\Sigma$, $\mathcal{T}$)
    $\pi \leftarrow \langle\,\rangle$; $a \leftarrow$ nil
    while True do:
        if $\pi = \langle\,\rangle$ or execution of $a$ failed then
            $s \leftarrow$ observed state
            $\pi$ = Lookahead($\Sigma$, $s$, $\mathcal{T}$)
            if $\pi$ = failure then return failure
            if $\pi = \langle\,\rangle$ then return success
        $a \leftarrow$ pop($\pi$)
        trigger execution of $a$
```



- Call HTN-Run-Lazy-Lookahead with *Lookahead* = TO-HTN-Forward (THF)
  - Σ = TOHTN domain in Example 5.8
  - initial state s_0, $\mathcal{T} = \langle$\{pile(c1)=p2\}$\rangle$
- If nothing unexpected happens:
  - Call THF(Σ, s_0, $\mathcal{T}$)
    - $\pi = \langle$take(r1,c1,c2,p1,d1), move(r1,d1,d2), put(r1,c1,c3,p2,d2)$\rangle$
  - Pop actions from π and execute them, until $\pi = \langle\,\rangle$
  - Call THF again, get $\pi = \langle\,\rangle$, return success
- If something unexpected happens but the problem is still solvable:
  - Eventually, either $\pi = \langle\,\rangle$ or a has failed
  - Call THF with observed state, it returns a new plan
- HTN-Run-Lookahead is similar but it calls *Lookahead* before each action is executed

Example 2

- POHTN planning domain
  - Cranes at loading docks, not on the robots
- Actions:
  - The usual move action, and these:

$\mathsf{unstack}(k, c, c', p, d)$ *// take container c from pile p*
  pre: $\mathsf{at}(k, d), \mathsf{at}(p, d), \mathsf{holding}(k) = \mathsf{nil}, \mathsf{pos}(c) = c', \mathsf{top}(p) = c$
  eff: $\mathsf{holding}(k) \leftarrow c, \mathsf{pos}(c) \leftarrow k, \mathsf{pile}(c) \leftarrow \mathsf{nil}, \mathsf{top}(p) \leftarrow c'$

$\mathsf{stack}(k, c, c', p, d)$ *// put container c onto pile p*
  pre: $\mathsf{at}(k, d), \mathsf{at}(p, d), \mathsf{holding}(k) = c, \mathsf{top}(p) \leftarrow c'$
  eff: $\mathsf{holding}(k) \leftarrow \mathsf{nil}, \mathsf{pos}(c) = c', \mathsf{pile}(c) \leftarrow p, \mathsf{top}(p) = c$

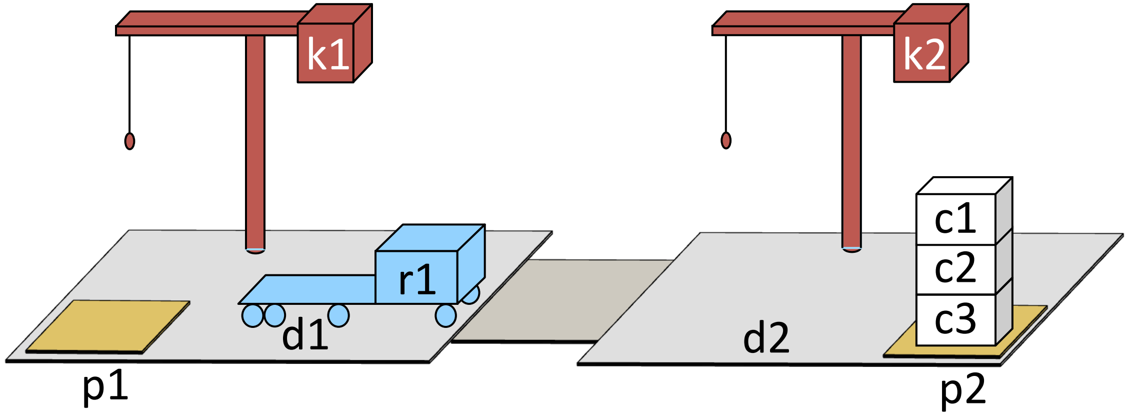
$\mathsf{unload}(k, c, r, d)$ *// take container c from robot r*
  pre: $\mathsf{at}(k, d), \mathsf{holding}(k) = c, \mathsf{loc}(r) = d$
  eff: $\mathsf{cargo}(r) \leftarrow c, \mathsf{pos}(c) \leftarrow r, \mathsf{holding}(k) \leftarrow \mathsf{nil}$

$\mathsf{load}(k, c, r, d)$ *// put container c onto robot r*
  pre: $\mathsf{at}(k, d), \mathsf{holding}(k) = \mathsf{nil}, \mathsf{loc}(r) = d, \mathsf{cargo}(r) = c$
  eff: $\mathsf{pos}(c) \leftarrow k, \mathsf{holding}(k) \leftarrow c, \mathsf{cargo}(r) \leftarrow \mathsf{nil}$

- Methods

$\mathsf{m1\text{-}put\text{-}on\text{-}robot}(k, c, c', r, d, p)$
  task: $\mathsf{put\text{-}on\text{-}robot}(c, r)$
  pre: $\mathsf{cargo}(r) = \mathsf{nil}, \mathsf{top}(p) = c, \mathsf{at}(p, d),$
    $\mathsf{attached}(k, d), \mathsf{holding}(k) = \mathsf{nil}$
  sub: $(\mathsf{t1}, \mathsf{navigate}(r, d)),$ *// compound task*
    $(\mathsf{t2}, \mathsf{unstack}(k, c, c', p, d)),$ *// action*
    $(\mathsf{t3}, \mathsf{load}(k, c, r, d))$ *// action*
  $\prec$: $\mathsf{t1} \prec \mathsf{t3},\ \mathsf{t2} \prec \mathsf{t3}$

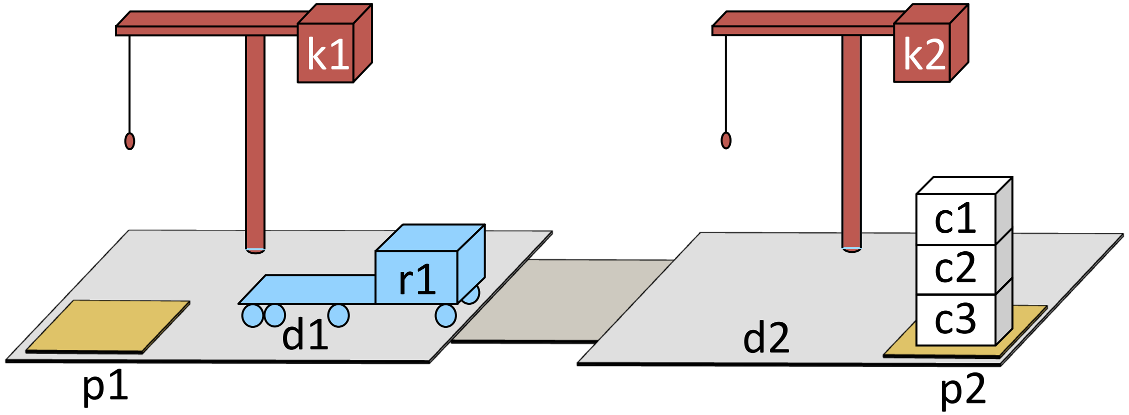
- The usual navigate methods



Example 2

- Call HTN-Run-Lazy-Lookahead with *Lookahead* = POHTN-Forward
  - Σ = POHTN domain on previous page
  - initial state s_0, the only task in $\mathcal{T}$ is put-on-robot(c1,r1)
- If nothing unexpected happens:
  - Call POTHN-Forward(Σ, s_0, $\mathcal{T}$)
    - Two solution plans, suppose it returns this one:
    - π_2 = ⟨unstack(k2,c1,c2,p2,d2), move(r1,d1,d2), load(k2,c1,r1,d2)⟩
  - Pop actions from π and execute them, until π = ⟨ ⟩
  - Call POHTN-Forward again, get π = ⟨ ⟩, return success
- Suppose move fails without changing the current state:
  - Call POHTN-Forward(Σ, s_0, $\mathcal{T}$)
    - failure: no applicable methods when k2 is holding c1
- Run-Lookahead
  - Call POHTN-Forward, get plan, execute unstack, call PPlan, PPlan fails

```
Run-Lazy-HLookahead($\Sigma$, $\mathcal{T}$)
    $\pi \leftarrow \langle\,\rangle$; $a \leftarrow$ nil
    while True do:
        if $\pi = \langle\,\rangle$ or execution of $a$ failed then
            $s \leftarrow$ observed state
            $\pi$ = HTN-Lookahead($\Sigma$, $s$, $\mathcal{T}$)
            if $\pi$ = failure then return failure
            if $\pi = \langle\,\rangle$ then return success
        $a \leftarrow$ pop($\pi$)
        trigger execution of $a$
```



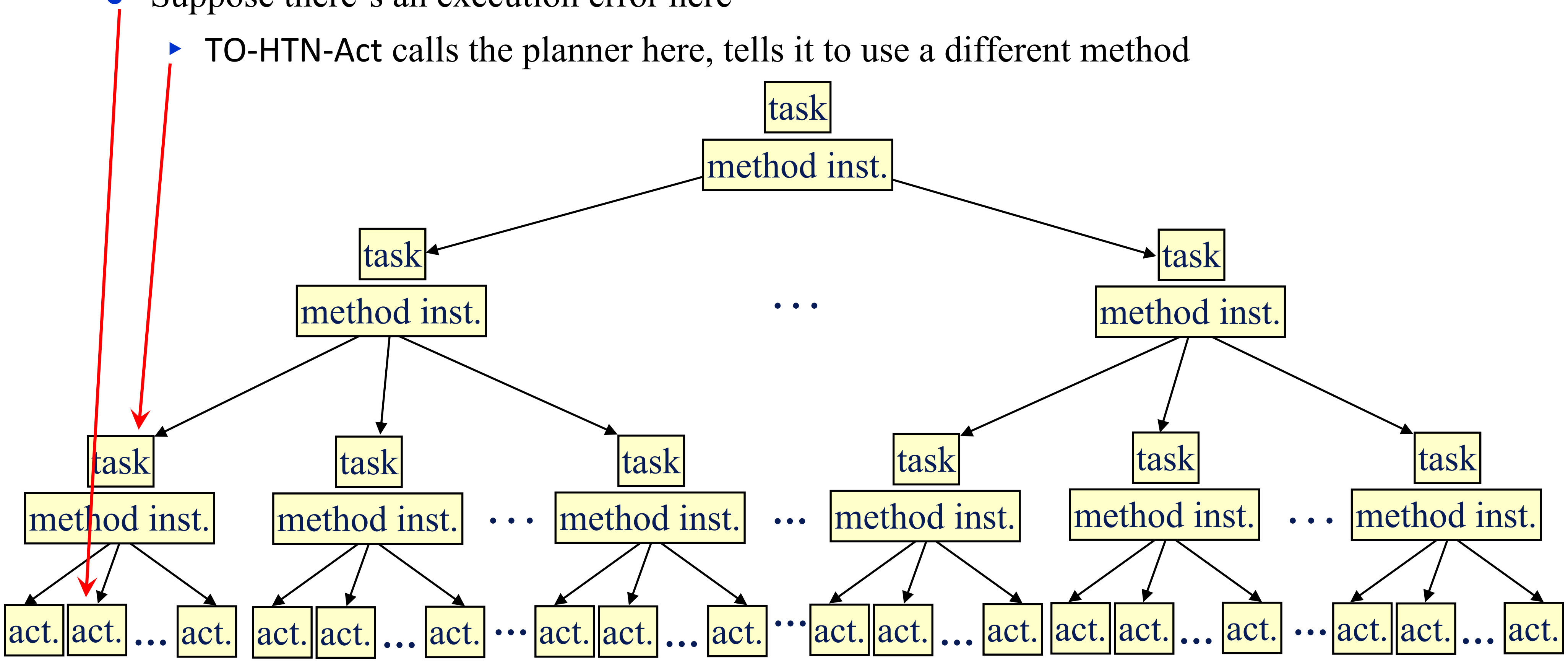
Error Recovery in HTN Domains

- HTN methods require the solution plan to follow a particular trajectory
- Encode requirements that aren't explicit in the classical planning domain
  - Safety requirements:
    - Secure a container onto the robot before starting to move the robot
  - Commitments to other agents
    - Don't use a particular resource, because others may need it
  - A company's standard operating procedures

- HTN-Run-Lookahead and HTN-Run-Lazy-Lookahead don't know anything about the trajectory requirements
- That's OK if nothing goes wrong
- If unexpected events occur, need to recover in a way that still satisfies the trajectory requirements
- Three approaches
  1. Modify TO-HTN-Act to call an HTN planner
     - HTN planner returns a method selection
  2. Modify HTN planner to return a solution tree
     - Actor traverses the tree
  3. Actor calls HTN planner to do replanning in a modified domain

TO-HTN-Act (modified) with an HTN Planner

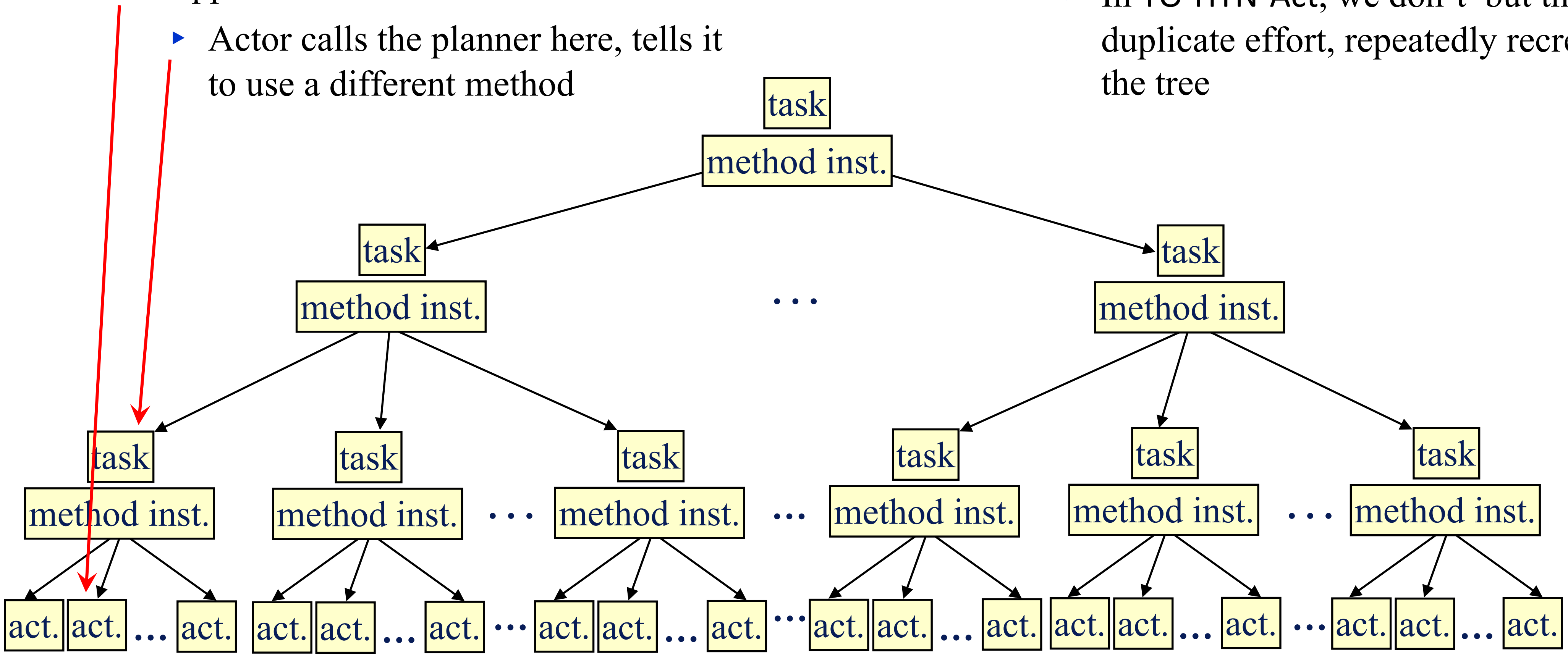
- HTN planner similar to TO-HTN-Forward, but returns the top-level method in its solution tree
- Suppose there's an execution error here
  - TO-HTN-Act calls the planner here, tells it to use a different method



Traversing a Solution Tree

- HTN planner returns a solution tree
- Actor traverses the tree
- Suppose there’s an execution error here
    - Actor calls the planner here, tells it to use a different method

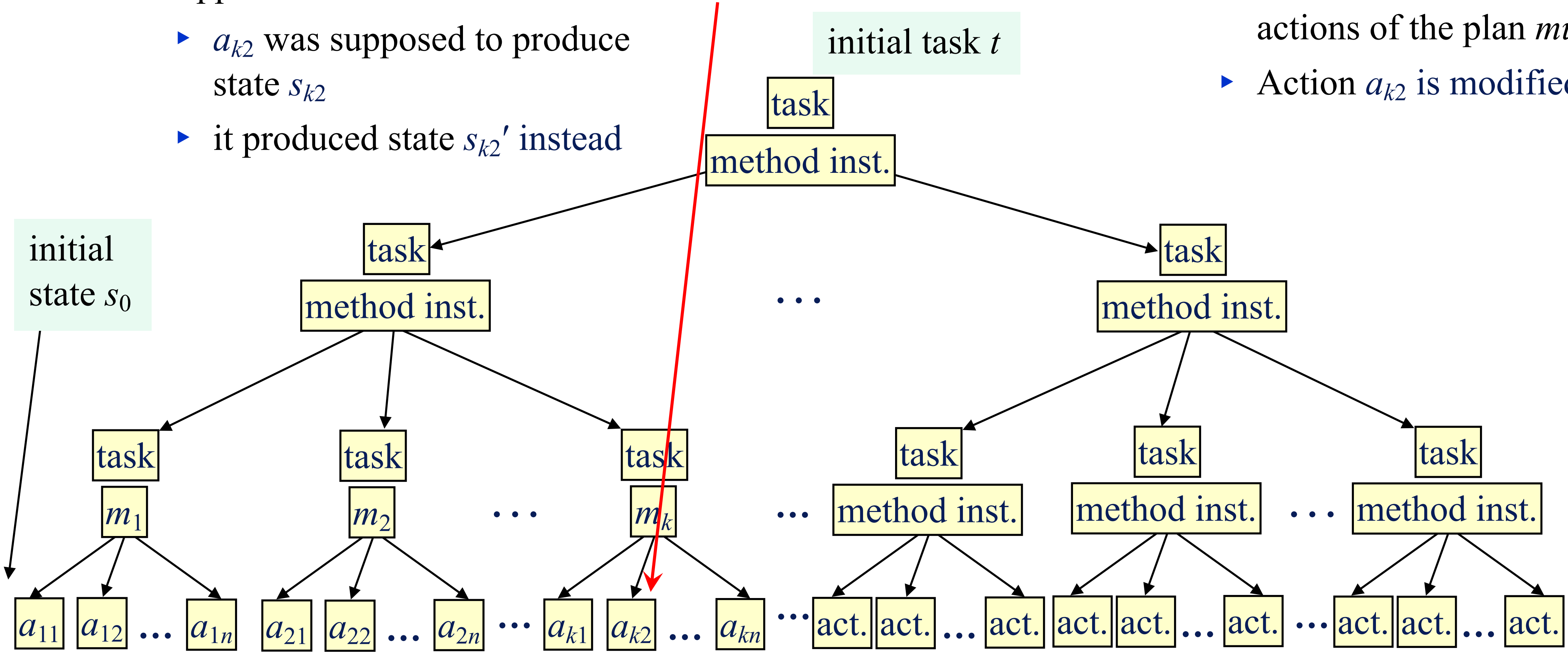
- HTN planner returns a solution tree, actor traverses the tree
- Time vs. space tradeoff
    - Here, we need the entire tree
    - In TO-HTN-Act, we don’t but the actor and planner duplicate effort, repeatedly recreating the current part of the tree



Modifying the Planning Domain

- Modified version of HTN-Run-Lazy-Lookahead
  - Calls TPlan to get a plan
- Suppose there’s an execution error here
  - a_{k2} was supposed to produce state s_{k2}
  - it produced state s_{k2}' instead

- Actor calls TO-HTN-Forward again, with the same initial state s_0 and task t as before
- Modified planning domain
  - Methods are modified so that the initial actions of the plan *must* be $a_{11}, \ldots, a_{kn}$
  - Action a_{k2} is modified so that $\gamma(s_{k1}, a_{k2}) = s_{k2}'$



Summary

- Issues
  - Actor’s environment may not be deterministic or static
  - Actor can’t backtrack to a previous state
- TO-HTN-Act: reactive actor similar to TO-HTN-Forward
- HTN-Run-Lookahead, HTN-Run-Lazy-Lookahead
  - Examples where they work well, where they don’t
- Error recovery in HTN domains
- Three approaches
  - TO-HTN-Act modified to call an HTN planner
  - Actor that traverses a solution tree
  - Actor that re-invokes TO-HTN-Forward on the original problem in a modified planning domain

- Tradeoff: time versus space