Planning and Scheduling: Hierarchical Task Network Planning

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  by Dana Nau, Gerhard Wickler, Hai Hoang, José Luis Ambite

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Motivation

- We may already have an idea
  how to go about solving problems in a planning domain
- E.g.: travel to a destination that's far away:
  - Domain-independent planner:
    - many combinations of vehicles and routes
  - Experienced human: small number of "recipes", e.g. for flying:
    - buy ticket from local airport to remote airport
    - travel to local airport
    - fly to remote airport
    - travel to final destination
- How to enable planning systems to make use of such recipes?

Two Approaches

- Control rules (Chapter 10 in the book):
  - Write rules to prune every action that does not fit the recipe

- Hierarchical Task Network (HTN) planning:
  - Describe the actions and subtasks that do fit the recipe

Control Rules v HTN Planning

- Control rules (Chapter 10):
  - Write rules to prune every action that does not fit the recipe
- Hierarchical Task Network (HTN) planning:
  - Describe the actions and subtasks that do fit the recipe
- Objective of HTN planning: perform a given set of tasks
- Inputs include:
  - Operators: can directly perform a primitive task
  - Methods: recipes for decomposing a complex/non-primitive task into simpler non-primitive or primitive subtasks
- Planning process:
  - Decompose non-primitive tasks recursively until primitive tasks are reached

Hierarchical Decomposition & Problem Reduction

- To get to a conference in ?x, get to the airport, take a plane to ?x, then go to the conference hotel
  - To get to the airport, either drive or take a cab
  - If you have money for the taxi fare:
  - Enter the cab, say "I want to go to ?y", wait until you are at ?y, pay the fare, then exit the taxi"

- Idea is to capture the hierarchical structure of a planning domain
  - assuming it contains complex tasks and schemas for reducing them.

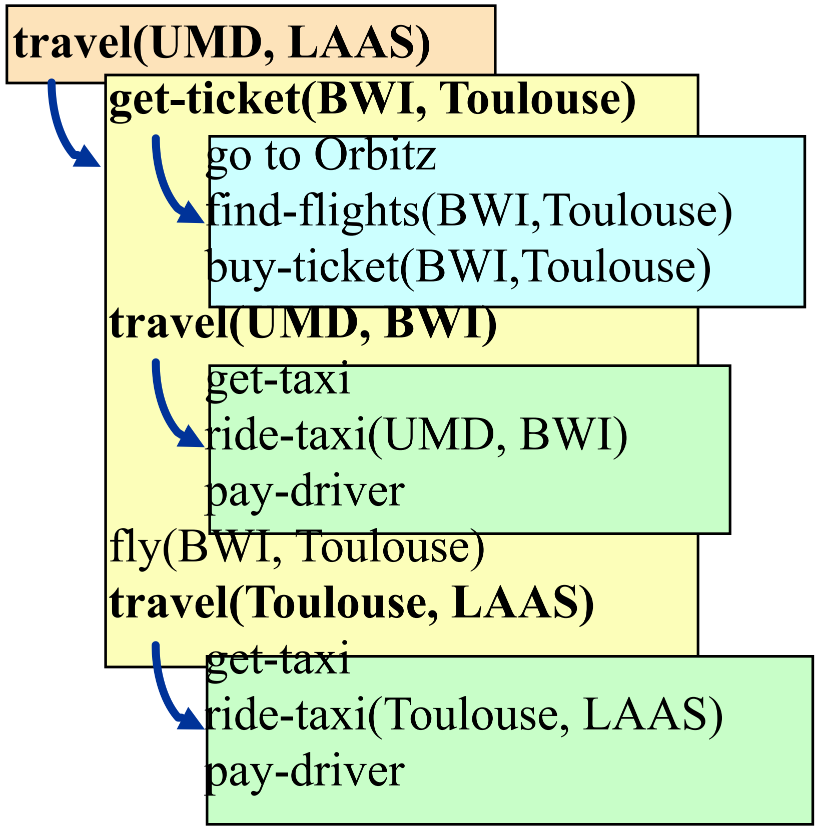
- Reduction schemas:
  - given by the designer
  - express preferred ways to accomplish a task

Outline

- Main idea behind HTN planning
- STNs: Representation and planning algorithms
  - Total order
  - Partial order
- Generalizing the formalism and algorithm to HTN
- Expressivity: comparison to classical planning and control rules
- Experimental Results

HTN Planning

- A type of problem reduction
- Decompose tasks into subtasks
- Handle constraints (e.g., taxi not good for long distances)
- Resolve interactions (e.g., take taxi early enough to catch plane)
- If necessary, backtrack and try other decompositions



travel(UMD, LAAS)

get-ticket(BWI, Toulouse)

go to Orbitz
find-flights(BWI,Toulouse)
buy-ticket(BWI,Toulouse)

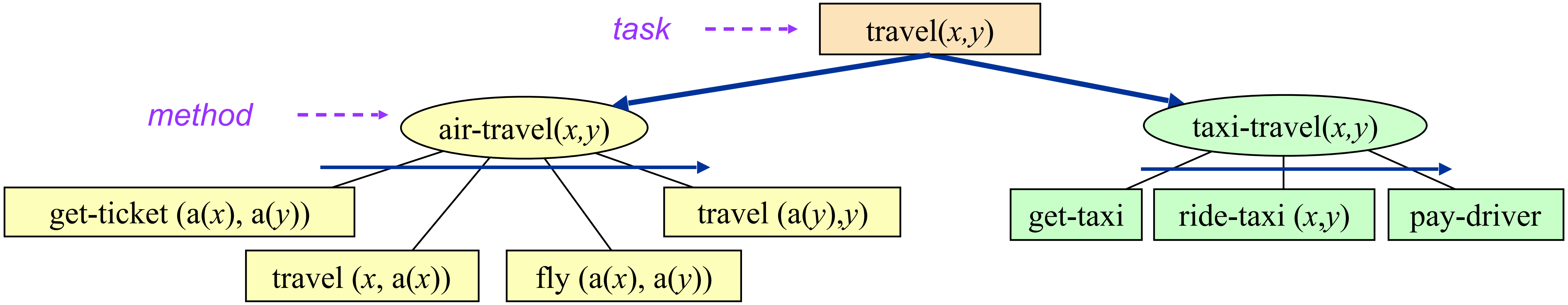
travel(UMD, BWI)

get-taxi
ride-taxi(UMD, BWI)
pay-driver

fly(BWI, Toulouse)

travel(Toulouse, LAAS)

get-taxi
ride-taxi(Toulouse, LAAS)
pay-driver

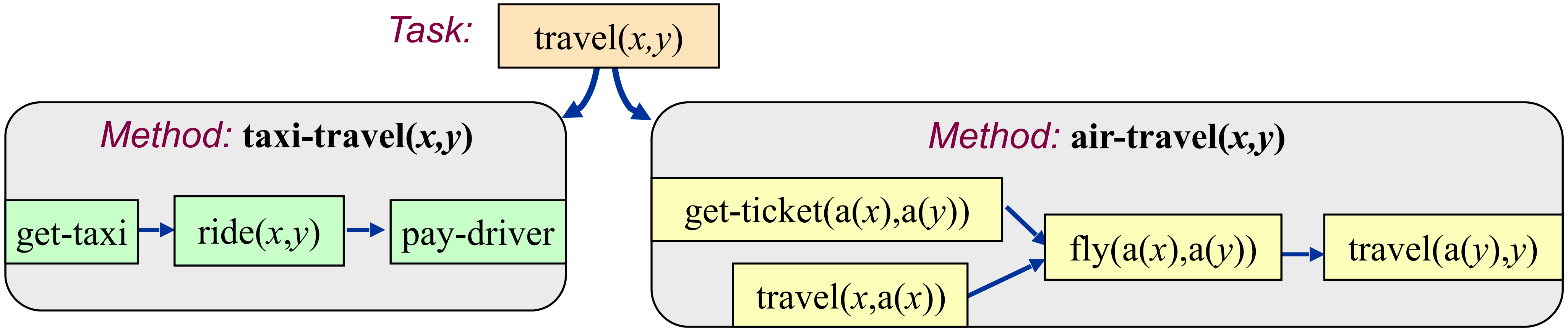


Tasks are in rectangle and methods in ovals

HTN Planning

- HTN planners may be domain-specific
  - e.g., see Chapters 20 (robotics) and 23 (bridge)

- Or they may be domain-configurable
  - Domain-independent planning engine
  - Domain description defining operators and also methods
  - Problem description
    - domain description, initial state, initial task network



HTN Planning

- HTN planners may be domain-specific
  - e.g., see Chapters 20 (robotics) and 23 (bridge)
- Or they may be domain-configurable
  - Domain-independent planning engine
  - Domain description
    - methods, operators
  - Problem description
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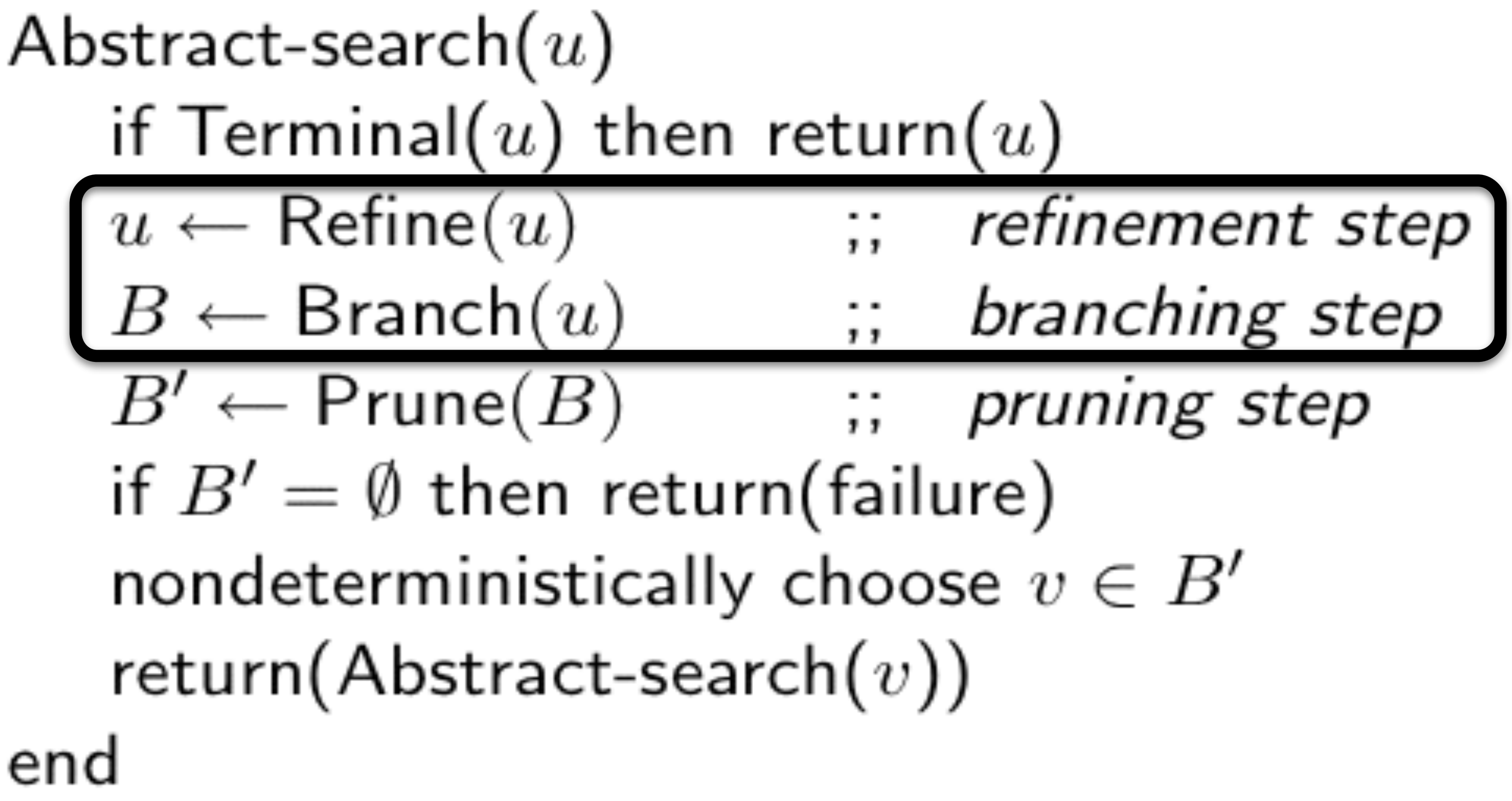
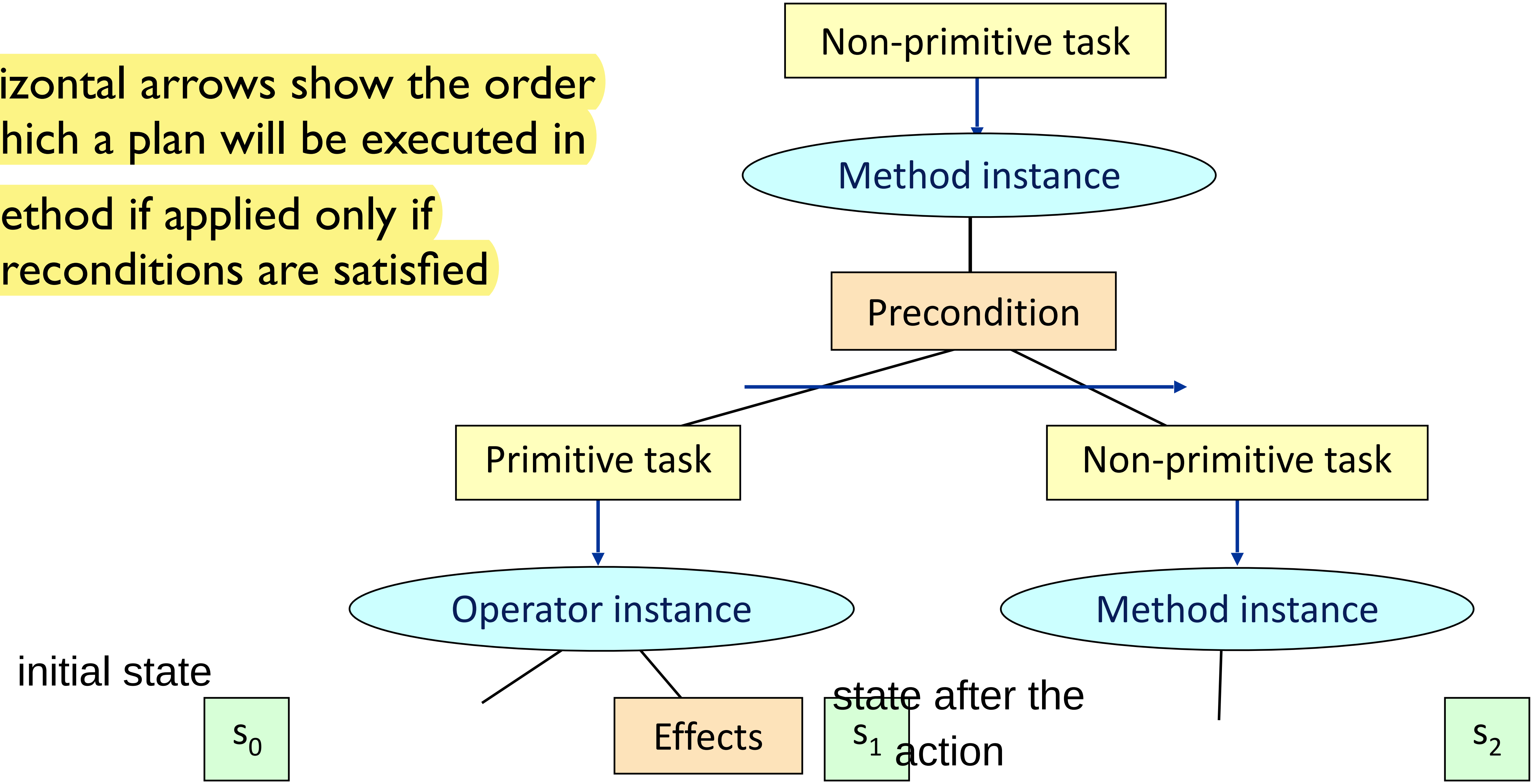


```
Abstract-search($u$)
    if Terminal($u$) then return($u$)
    $u \leftarrow$ Refine($u$)          ;;  refinement step
    $B \leftarrow$ Branch($u$)          ;;  branching step
    $B' \leftarrow$ Prune($B$)          ;;  pruning step
    if $B' = \emptyset$ then return(failure)
    nondeterministically choose $v \in B'$
    return(Abstract-search($v$))
end
```

HTN Planning: Task Networks

- Ground/unground
- Primitive/non-primitive
- Partial/total order

- Horizontal arrows show the order in which a plan will be executed in
- A method if applied only if its preconditions are satisfied



HTN v what we've seen so far

- What stays the same:
  - Each state of the world is represented by a set of atoms
  - Each action corresponds to a deterministic state transition
  - Terms, literals, operators, actions, plans have same meaning
  - E.g. (block b1) (block b2) (block b3) (block b4) (on-table b1) (on b2 b1) (clear b2) (on-table b3) (on b4 b3) (clear b4)

- What's new:
  - Perform a set of tasks; not achieve a set of goals
  - Methods describing ways in which tasks can be performed
  - Organized collections of tasks and subtasks called task networks

Simple Task Network (STN) Planning

- A special case of HTN planning

- States and operators
  - The same as in classical planning

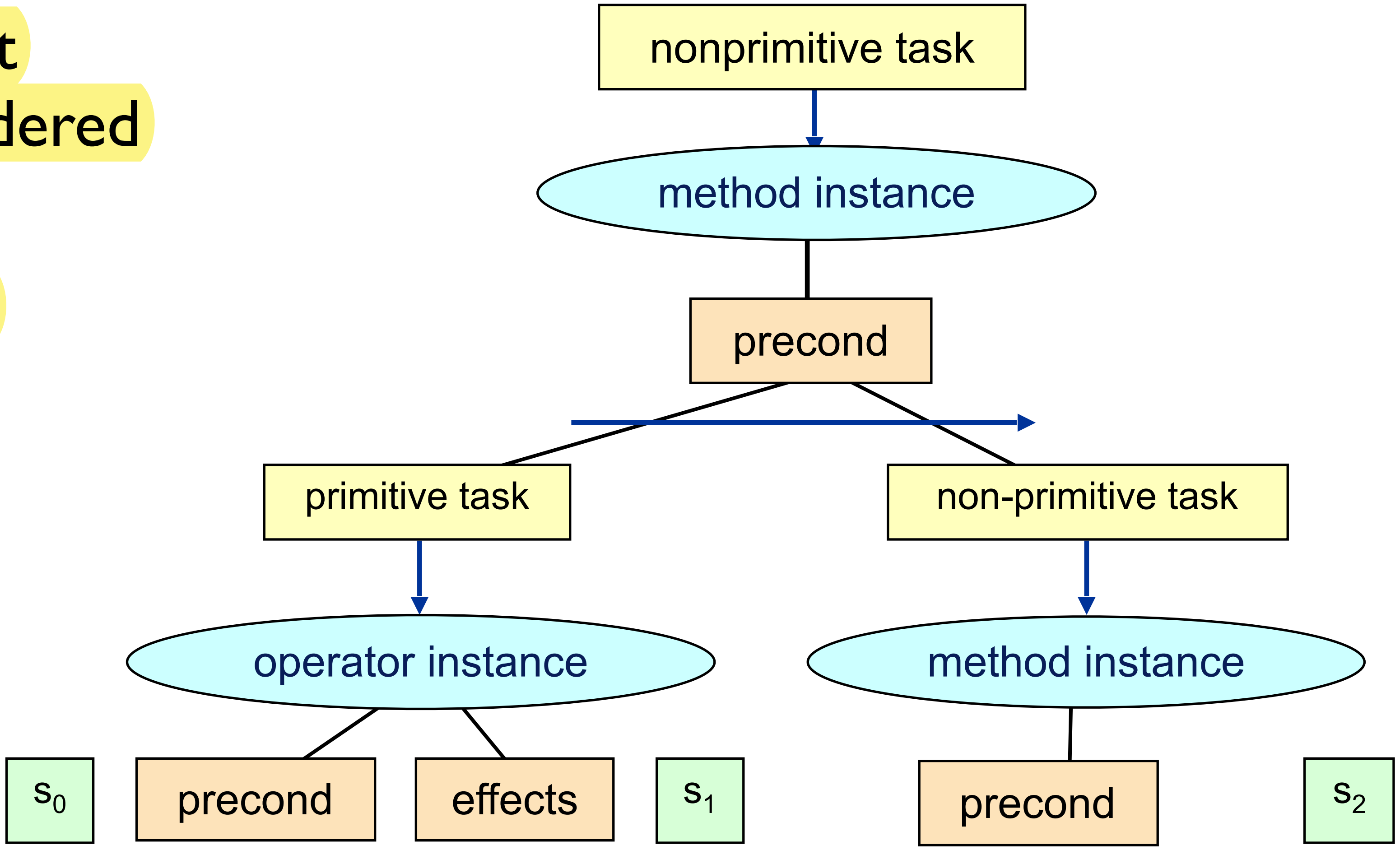
- Task: an expression of the form $t(u_1,\ldots,u_n)$
  - t is a task symbol, and each u_i is a term

- Two kinds of task symbols (and tasks):
  - Primitive: tasks that we know how to execute directly
    - task symbol is an operator name
  - Non-primitive: tasks that must be decomposed into subtasks
    - use methods (next slide)

STN: Domains, Planning Problems, Solutions

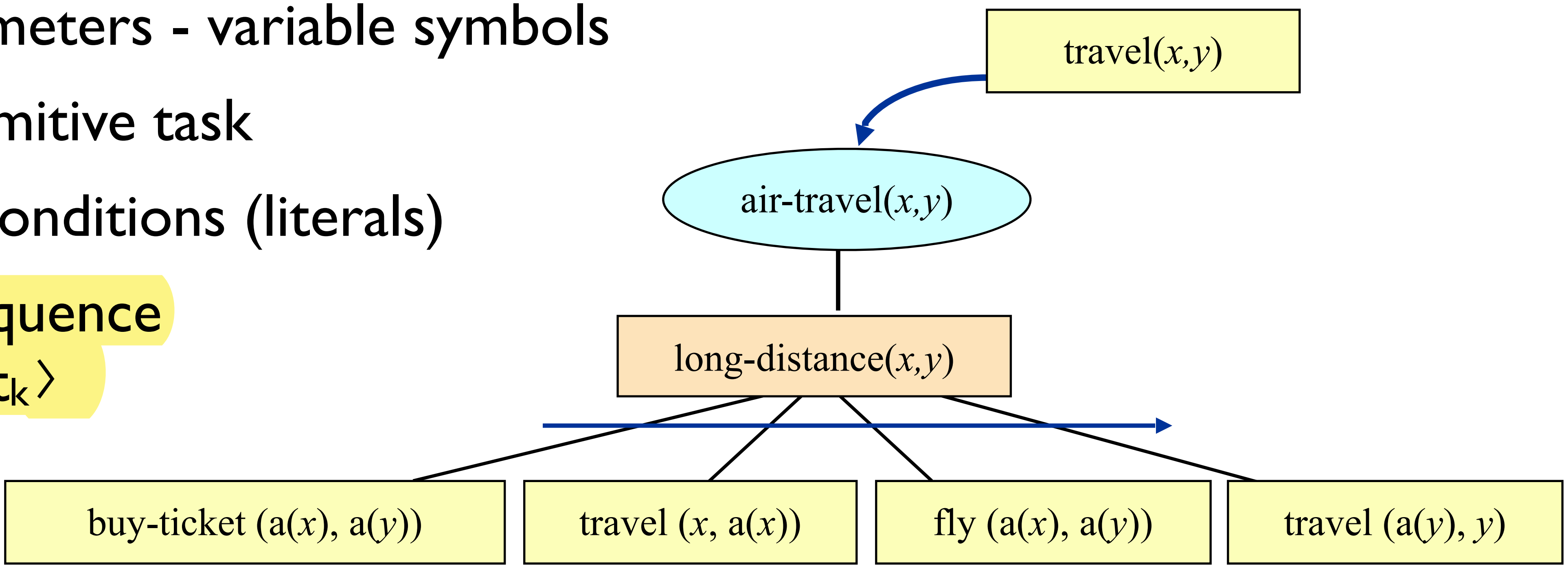
initial task network: our goal plan which consists of primitive tasks that can satisfy our goal

- Domain: methods, operators: $D=(O,M)$
- Problem: initial state, initial task network, operators, methods: $P=(S_0,w_j,O,M)$
- Total-order STN domain and problem:
  - Same as above except that all methods are totally ordered
- Solution: any executable plan that can be generated by recursively applying
  - methods to non-primitive tasks
  - operators to primitive tasks



STN: Methods (totally-ordered)

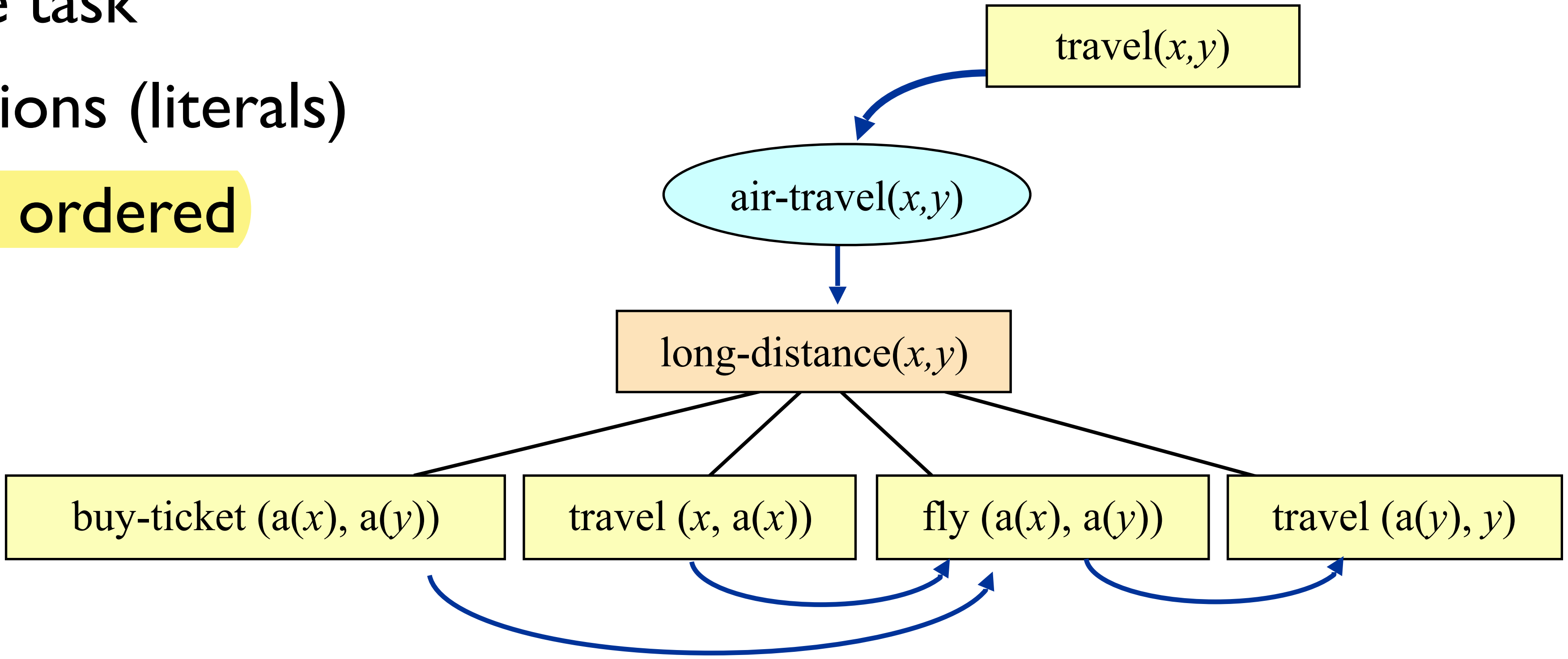
- Totally-ordered method: a 4-tuple
  m = (name(m), task(m), precond(m), subtasks(m))
  - name(m): an expression of the form $n(x_1,\ldots,x_n)$
  - $x_1,\ldots,x_n$ are parameters - variable symbols
  - task(m): a nonprimitive task
  - precond(m): preconditions (literals)
  - subtasks(m): a sequence of tasks $\langle t_1, \ldots, t_k \rangle$



- air-travel(x,y)
  - task: travel(x,y)
  - precond: long-distance(x,y)
  - subtasks: ⟨buy-ticket(a(x),a(y)), travel(x,a(x)), fly(a(x),a(y)), travel(a(y),y)⟩

STN: Methods (partially-ordered)

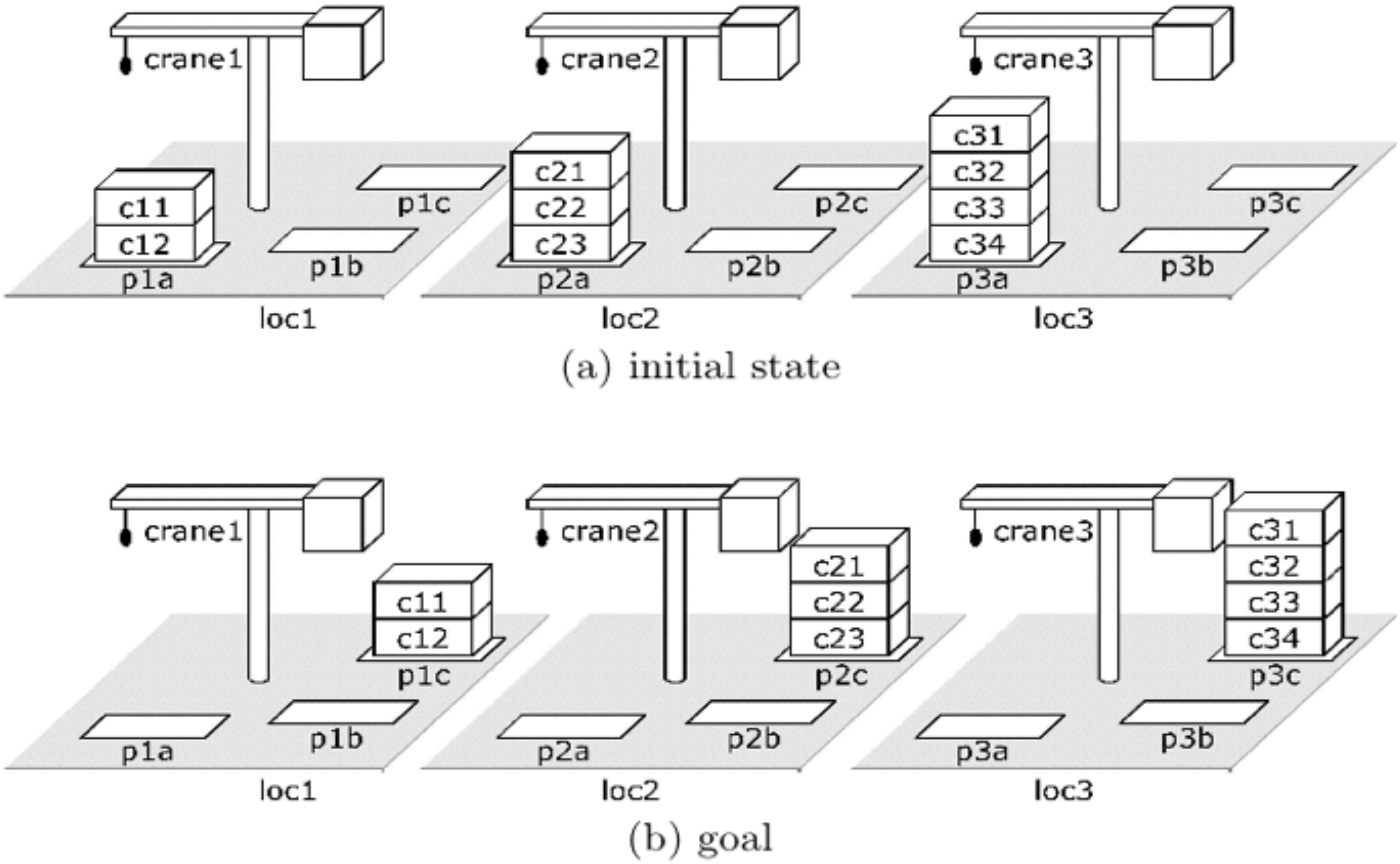
- Partially-ordered method: a 4-tuple
  m = (name(m), task(m), precond(m), subtasks(m))
  - name(m): an expression of the form $n(x_1,\ldots,x_n)$
  - $x_1,\ldots,x_n$ are parameters - variable symbols
  - task(m): a nonprimitive task
  - precond(m): preconditions (literals)
  - subtasks(m): a partially ordered set of tasks $\{t_1, \ldots, t_k\}$



- air-travel(x,y)
  - task: travel(x,y)
  - precond: long-distance(x,y)
  - network: u1=buy-ticket(a(x),a(y)), u2= travel(x,a(x)), u3= fly(a(x),a(y)),
    u4= travel(a(y),y), {(u1,u3), (u2,u3), (u3 ,u4)}

Example: DWR

- Task:
  - Move three stacks of containers in a way that preserves the order of the containers
- One way to move each stack:
  - First move the containers from p to an intermediate pile r
  - Then move them from r to q

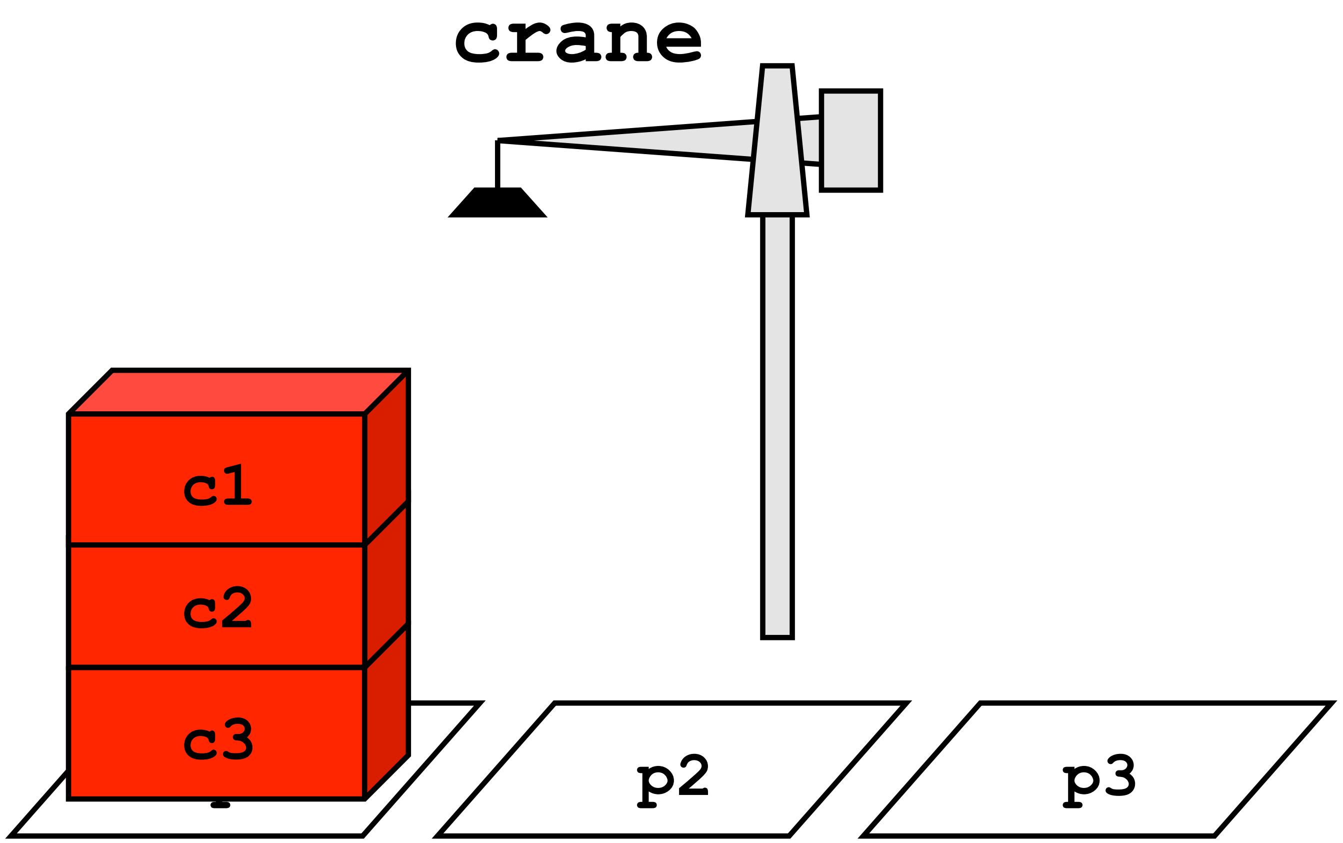


(a) initial state

(b) goal

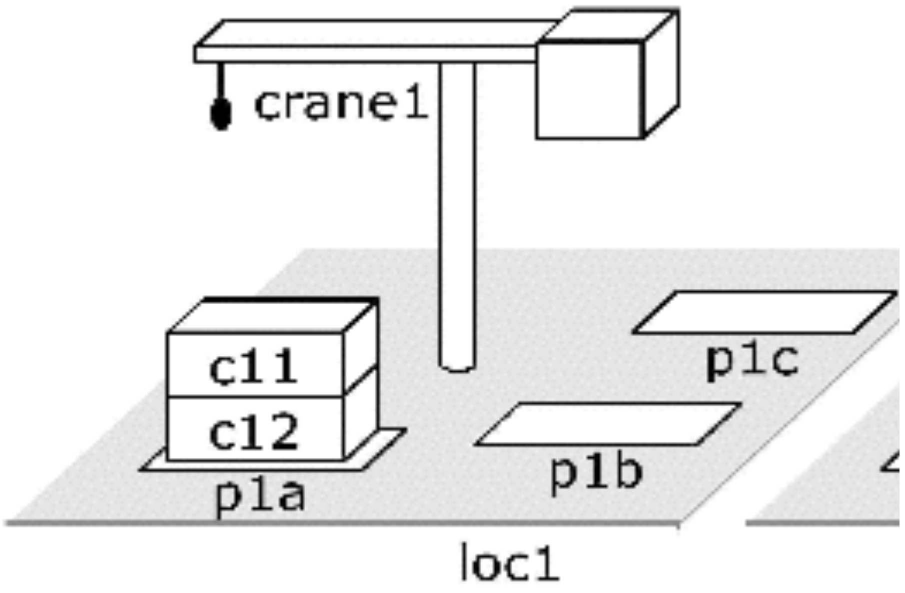
Example: DWR

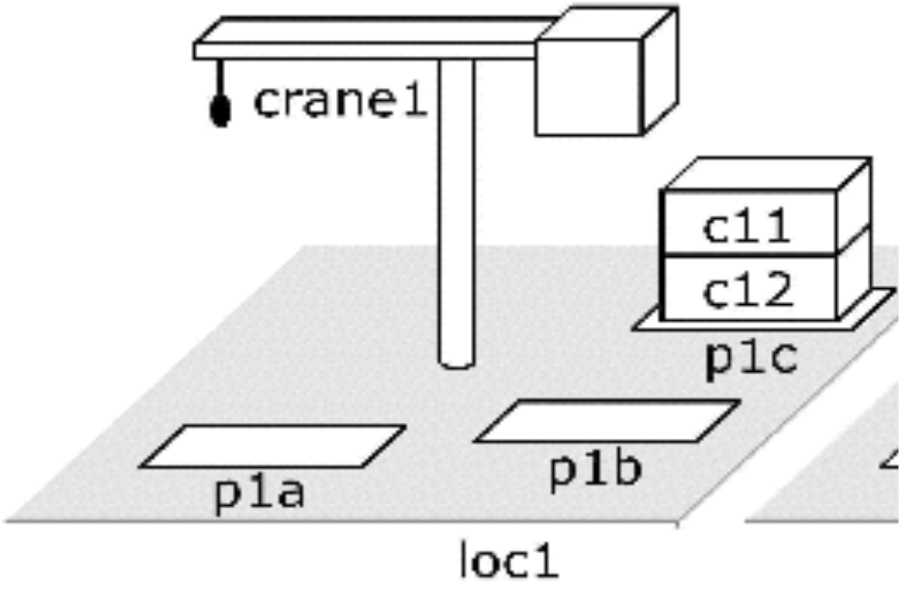
- Methods (informal):
  - move each stack twice:
    - move stack to intermediate pile (reversing order) and then to final destination (reversing order again)
  - move stack:
    - repeatedly/recursively move the topmost container until the stack is empty
  - move top-most:
    - take followed by put action



Example: DWR Total-Order Formulation

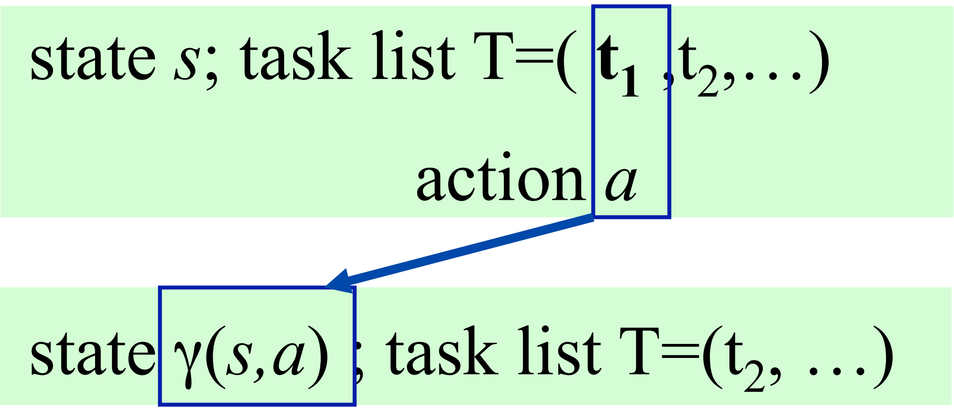
```
take-and-put($c, k, l_1, l_2, p_1, p_2, x_1, x_2$):
    task:      move-topmost-container($p_1, p_2$)
    precond:   top($c, p_1$), on($c, x_1$),          ; true if $p_1$ is not empty
               attached($p_1, l_1$), belong($k, l_1$),   ; bind $l_1$ and $k$
               attached($p_2, l_2$), top($x_2, p_2$)     ; bind $l_2$ and $x_2$
    subtasks:  ⟨take($k, l_1, c, x_1, p_1$), put($k, l_2, c, x_2, p_2$)⟩

recursive-move($p, q, c, x$):
    task:      move-stack($p, q$)
    precond:   top($c, p$), on($c, x$)     ; true if $p$ is not empty
    subtasks:  ⟨move-topmost-container($p, q$), move-stack($p, q$)⟩
               ;; the second subtask recursively moves the rest of the stack

do-nothing($p, q$)
    task:      move-stack($p, q$)
    precond:   top($pallet, p$)     ; true if $p$ is empty
    subtasks:  ⟨⟩    ; no subtasks, because we are done

move-each-twice()
    task:      move-all-stacks()
    precond:     ; no preconditions
    subtasks:    ; move each stack twice:
               ⟨move-stack(p1a,p1b), move-stack(p1b,p1c),
                move-stack(p2a,p2b), move-stack(p2b,p2c),
                move-stack(p3a,p3b), move-stack(p3b,p3c)⟩
```





STN: Solving Total-Order Planning Problems

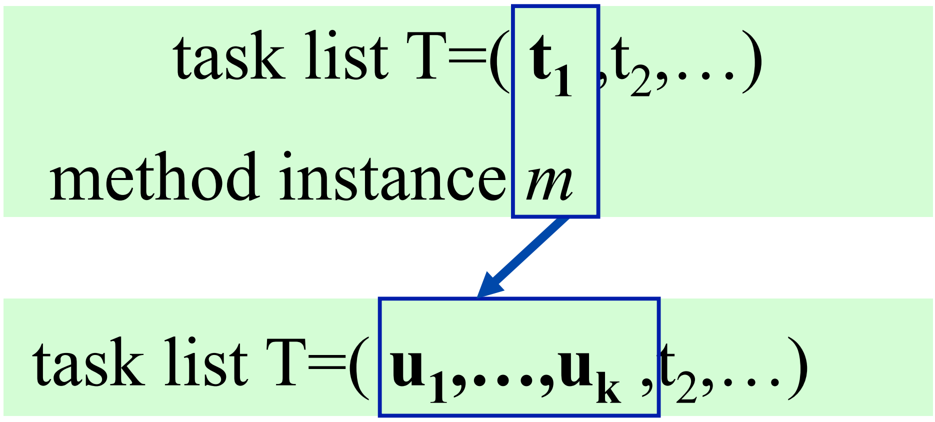
```
TFD($s$, $\langle t_1, \ldots, t_k \rangle$, $O$, $M$)
    if $k = 0$ then return $\langle\rangle$ (i.e., the empty plan)
    if $t_1$ is primitive then
        $active \leftarrow \{(a, \sigma) \mid a$ is a ground instance of an operator in $O$,
                        $\sigma$ is a substitution such that $a$ is relevant for $\sigma(t_1)$,
                        and $a$ is applicable to $s\}$
        if $active = \emptyset$ then return failure
        nondeterministically choose any $(a, \sigma) \in active$
        $\pi \leftarrow$ TFD($\gamma(s, a)$, $\sigma(\langle t_2, \ldots, t_k \rangle)$, $O$, $M$)
        if $\pi$ = failure then return failure
        else return $a.\pi$
    else if $t_1$ is nonprimitive then
        $active \leftarrow \{m \mid m$ is a ground instance of a method in $M$,
                        $\sigma$ is a substitution such that $m$ is relevant for $\sigma(t_1)$,
                        and $m$ is applicable to $s\}$
        if $active = \emptyset$ then return failure
        nondeterministically choose any $(m, \sigma) \in active$
        $w \leftarrow$ subtasks($m$).$\sigma(\langle t_2, \ldots, t_k \rangle)$
        return TFD($s$, $w$, $O$, $M$)
```



state s; task list T=($\mathbf{t_1}$,t_2,…)

action a

state $\gamma(s,a)$; task list T=(t_2, …)

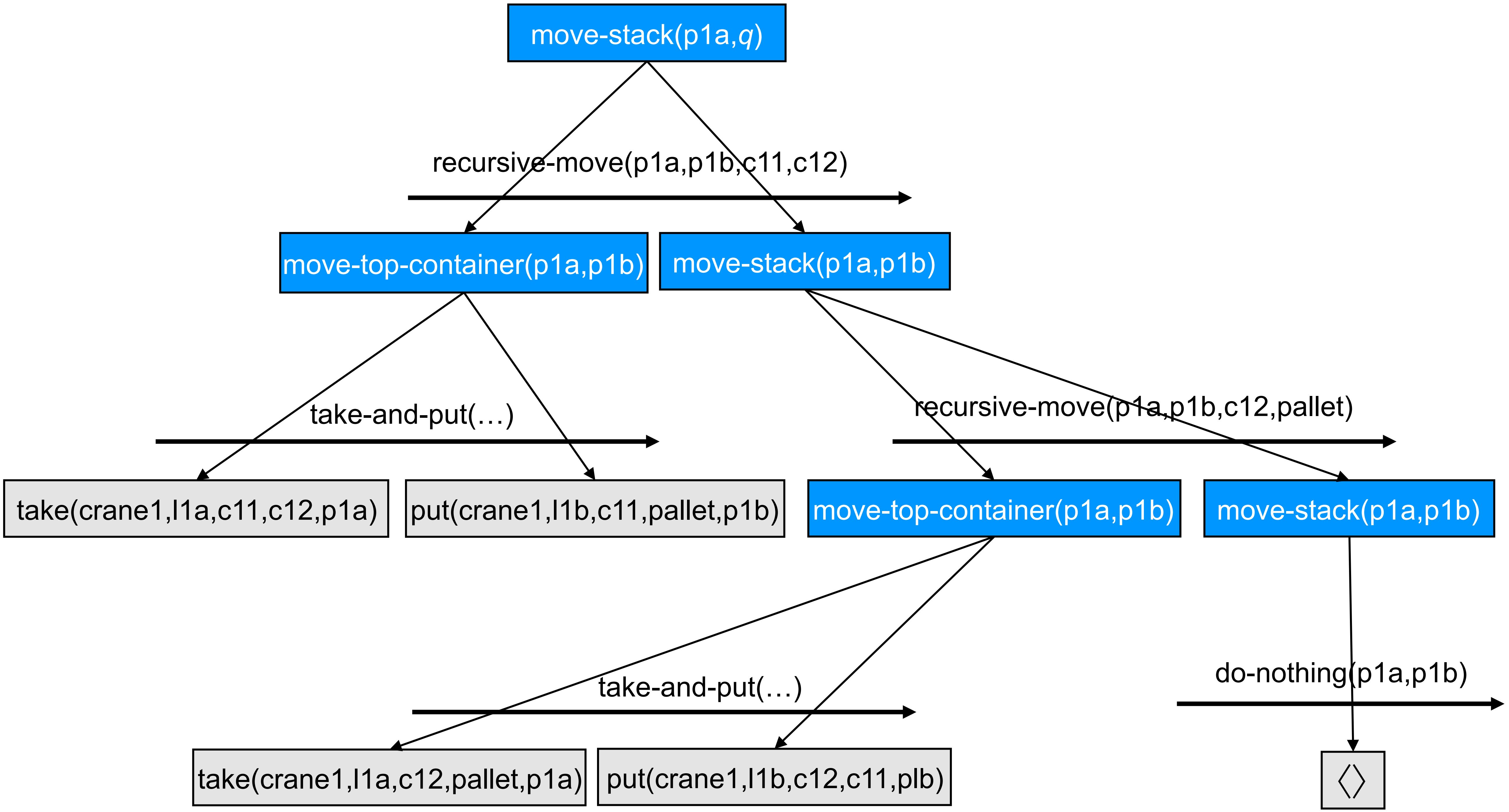


task list T=($\mathbf{t_1}$,t_2,…)

method instance m

task list T=($\mathbf{u_1,\ldots,u_k}$,t_2,…)

Example: DWR Decomposition Tree - TFD



move-stack(p1a,*q*)

recursive-move(p1a,p1b,c11,c12)

move-top-container(p1a,p1b)

move-stack(p1a,p1b)

take-and-put(…)

recursive-move(p1a,p1b,c12,pallet)

take(crane1,l1a,c11,c12,p1a)

put(crane1,l1b,c11,pallet,p1b)

move-top-container(p1a,p1b)

move-stack(p1a,p1b)

take-and-put(…)

do-nothing(p1a,p1b)

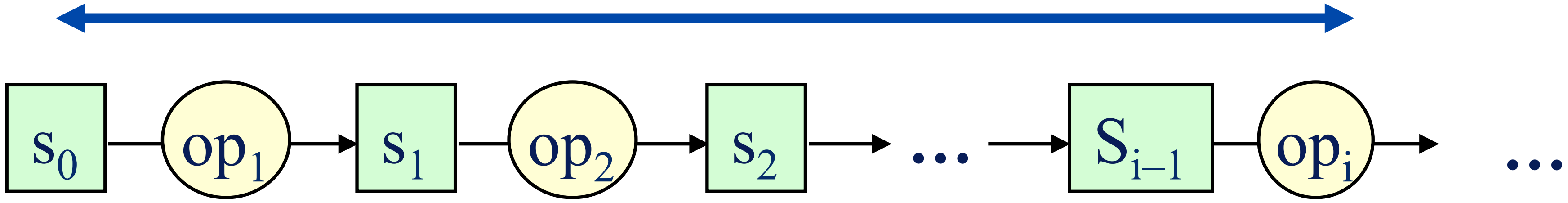
take(crane1,l1a,c12,pallet,p1a)

put(crane1,l1b,c12,c11,plb)

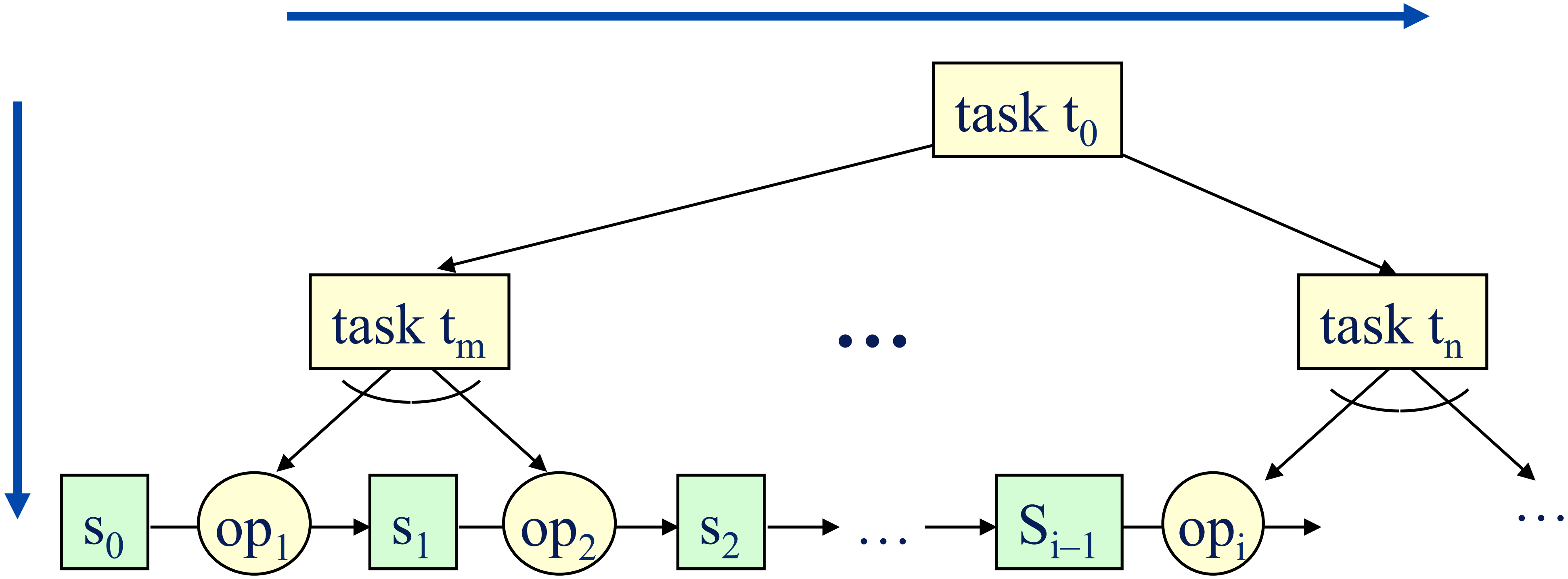
⟨⟩

Comparison to Forward and Backward Search

- In state-space planning, must choose whether to search forward or backward

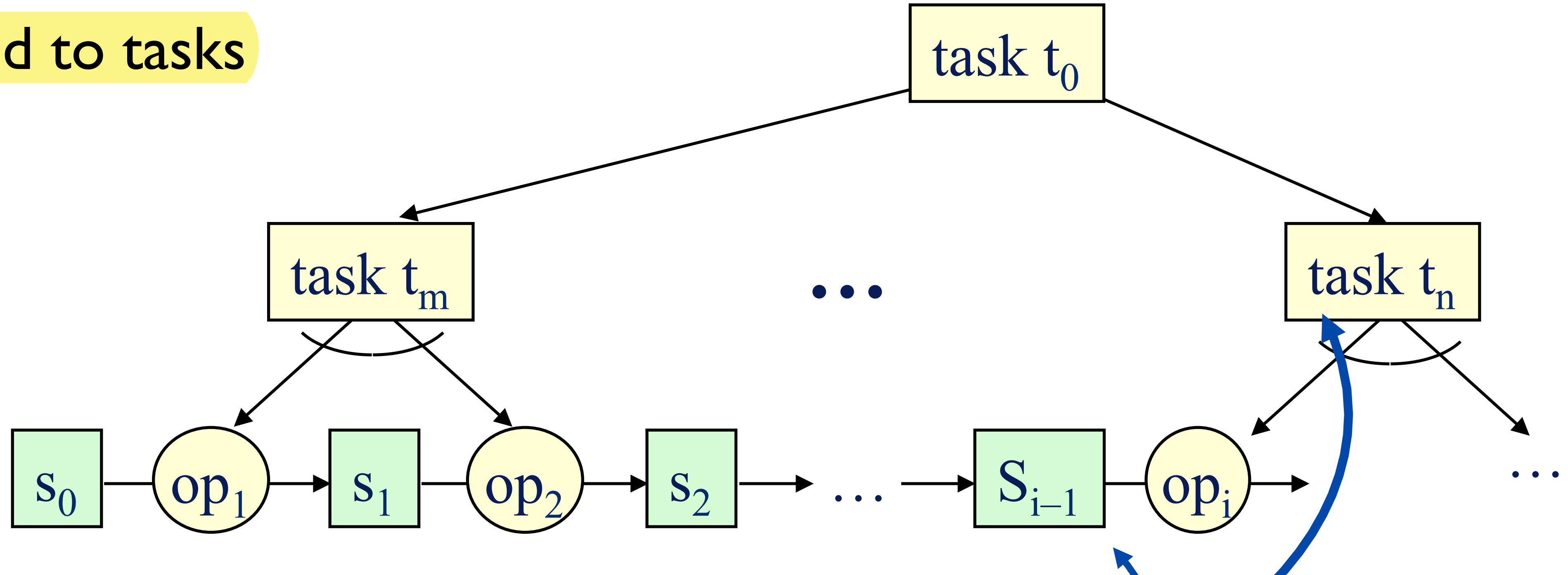


- In HTN planning, there are two choices to make about direction:
  - forward or backward
  - up or down
- TFD goes down and forward



Comparison to Forward and Backward Search

- Like a backward search, TFD is goal-directed
  - Goals correspond to tasks



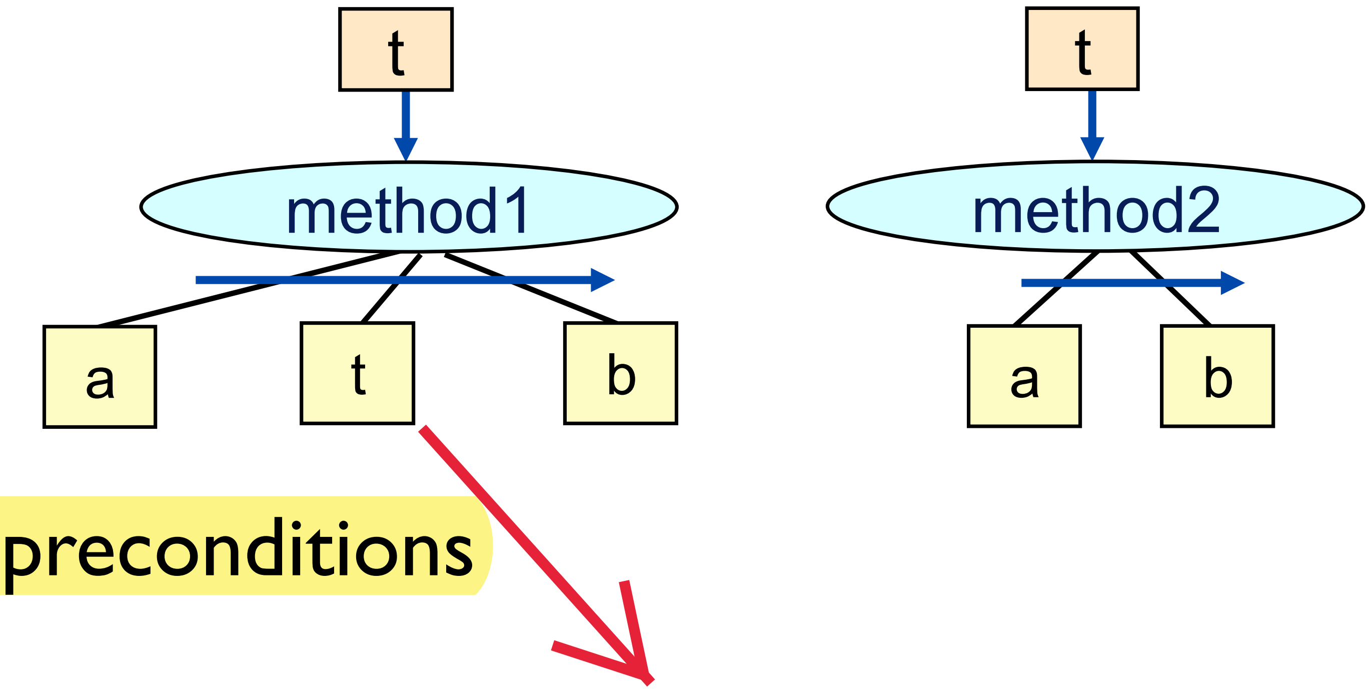
- Like a forward search, it generates actions in the same order in which they'll be executed
- Whenever we plan the next task
  - we've already planned everything that comes before it
  - Thus, we know the current state of the world

Expressivity Relative to Classical Planning

- Any classical planning problem can be translated into an ordered-task planning problem in polynomial time
- Several ways to do this. One is roughly as follows:
  - For each goal or precondition e, create a task t_e
  - For each operator o and effect e, create a method $m_{o,e}$
    - Task: t_e
    - Subtasks: t_{c1}, t_{c2}, …, t_{cn}, o, where c1, c2, …, cn are the preconditions of o
    - Partial-ordering constraints: each t_{ci} precedes o
- There are HTN planning problems that cannot be translated into classical planning problems at all
- Example on the next page

Example: Classical planning can not represent this

- Two methods:
  - No arguments
  - No preconditions
- Two operators, a and b
  - Again, no arguments and no preconditions



- Initial state is empty, initial task is t
- Set of solutions is $\{a^n b^n \mid n > 0\}$

here we can have an infinite planning that is impossible in classical

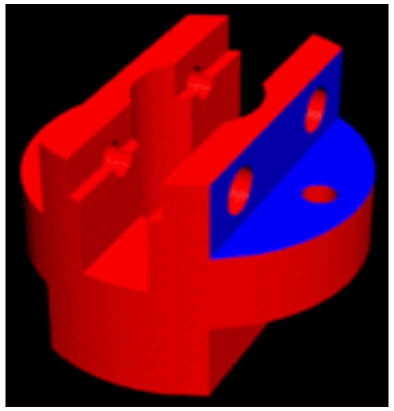
- No classical planning problem has this set of solutions
  - The state transition system is a finite state automaton
  - No finite state automaton can recognise $\{a^n b^n \mid n > 0\}$

Increasing Expressivity Further

- Knowing the current state makes it easy to do things that would be difficult otherwise
  - States can be arbitrary data structures

Us:	East declarer, West dummy
Opponents:	defenders, South & North
Contract:	East – 3NT
On lead:	West at trick 3

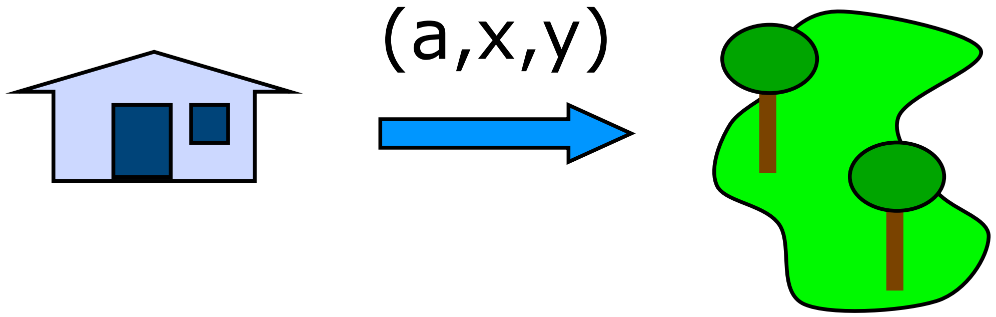
East:	♠KJ74
West:	♠A2
Out:	♠QT98653



- Preconditions and effects can include
  - logical inferences (e.g., Horn clauses)
  - complex numeric computations
  - interactions with other software packages
- Example: SHOP   http://www.cs.umd.edu/projects/shop

Example

- Simple travel planning domain:
  - Go from one location to another
  - State-variable formulation



method travel-by-foot
  precond: $distance(x, y) \leq 2$
  task: travel(a, x, y)
  subtasks: walk(a, x, y)

method travel-by-taxi
  task: travel(a, x, y)
  precond: $cash(a) \geq 1.5 + 0.5 \times distance(x, y)$
  subtasks: $\langle$call-taxi(a, x), ride(a, x, y), pay-driver$(a, x, y)\rangle$

operator walk
  precond: $location(a) = x$
  effects: $location(a) \leftarrow y$

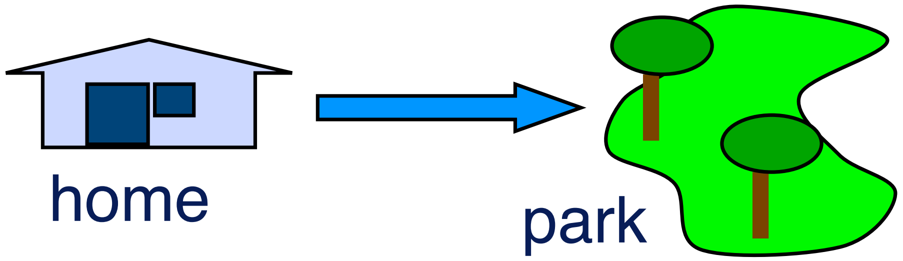
operator call-taxi(a, x)
  effects: $location(taxi) \leftarrow x$

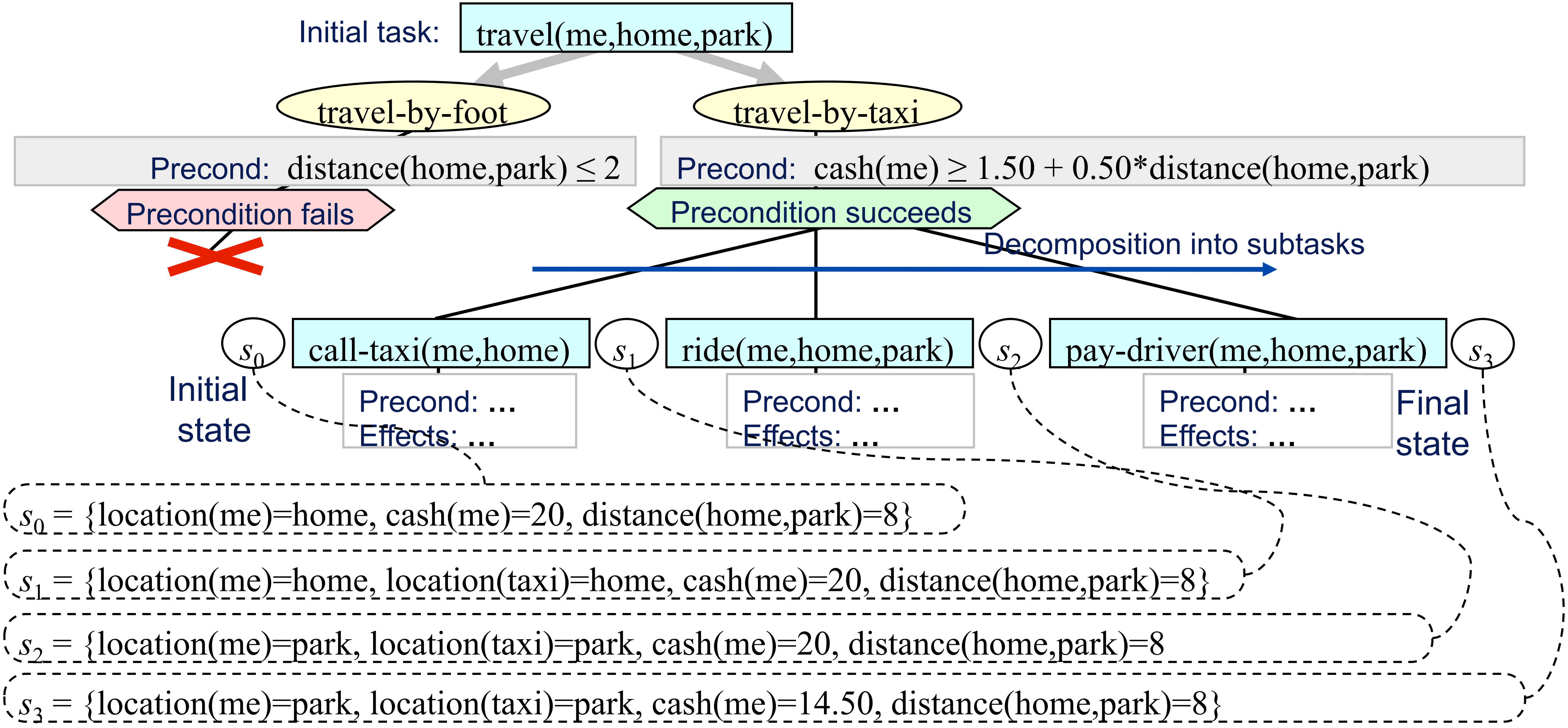
operator ride-taxi(a, x)
  precond: $location(taxi) = x$, $location(a) = x$
  effects: $location(taxi) \leftarrow y$, $location(a) \leftarrow y$

operator pay-driver(a, x, y)
  precond: $cash(a) \geq 1.5 + 0.5 \times distance(x, y)$
  effects: $cash(a) \leftarrow cash(a) - 1.5 + 0.5 \times distance(x, y)$

Planning Problem

I am at home, I have $20,
I want to go to a park 8 miles away





Initial task: travel(me,home,park)

travel-by-foot

Precond: distance(home,park) ≤ 2

Precondition fails

travel-by-taxi

Precond: cash(me) ≥ 1.50 + 0.50*distance(home,park)

Precondition succeeds

Decomposition into subtasks

s_0 call-taxi(me,home) s_1 ride(me,home,park) s_2 pay-driver(me,home,park) s_3

Initial state

Precond: …
Effects: …

Precond: …
Effects: …

Precond: …
Effects: …

Final state

s_0 = {location(me)=home, cash(me)=20, distance(home,park)=8}

s_1 = {location(me)=home, location(taxi)=home, cash(me)=20, distance(home,park)=8}

s_2 = {location(me)=park, location(taxi)=park, cash(me)=20, distance(home,park)=8

s_3 = {location(me)=park, location(taxi)=park, cash(me)=14.50, distance(home,park)=8}

SHOP (Simple Hierarchical Ordered Planner)

- Domain-independent algorithm for ordered task decomposition
  - Sound and complete

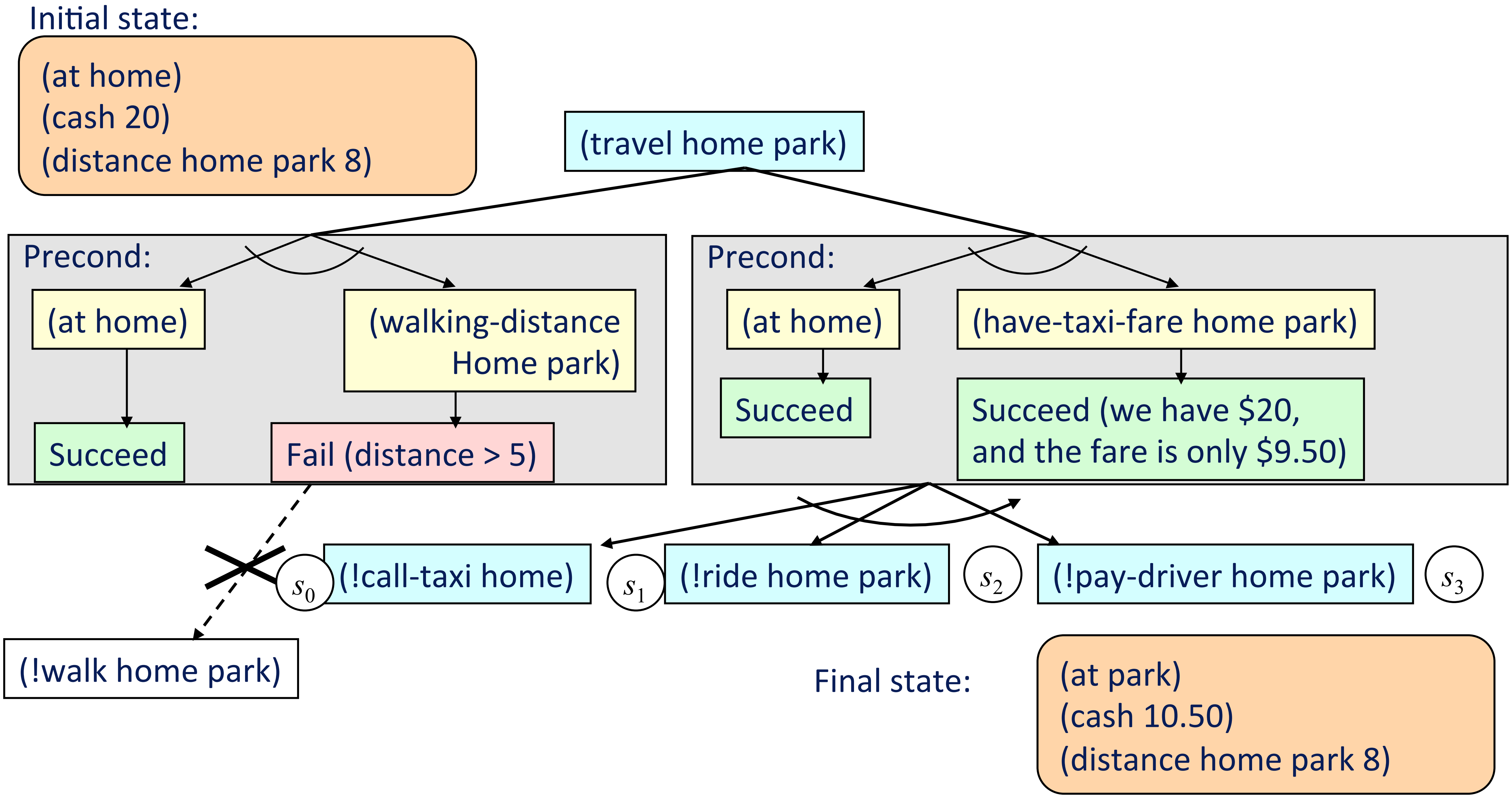
- Input:
  - State: a set of ground atoms
  - Task List: a linear list of tasks
  - Domain: methods, operators, axioms

- Output: one or more plans, it can return:
  - the first plan it finds
  - all possible plans
  - a least-cost plan
  - all least-cost plans

Example: SHOP

- **Initial task list:** ((travel home park))
- **Initial state:** ((at home) (cash 20) (distance home park 8))
- **Methods** (task, preconditions, subtasks):
  - (:method (travel ?x ?y)
    ((at x) (walking-distance ?x ?y)) ' ((!walk ?x ?y)) 1)
  - (:method (travel ?x ?y)
    ((at ?x) (have-taxi-fare ?x ?y))
    ' ((!call-taxi ?x) (!ride ?x ?y) (!pay-driver ?x ?y)) 1)
- **Axioms:**
  - (:- (walking-dist ?x ?y) ((distance ?x ?y ?d) (eval (<= ?d 5))))
  - (:- (have-taxi-fare ?x ?y)
    ((have-cash ?c) (distance ?x ?y ?d) (eval (>= ?c (+ 1.50 ?d))))
- **Primitive operators** (task, delete list, add list)
  - (:operator (!walk ?x ?y) ((at ?x)) ((at ?y)))
  - …

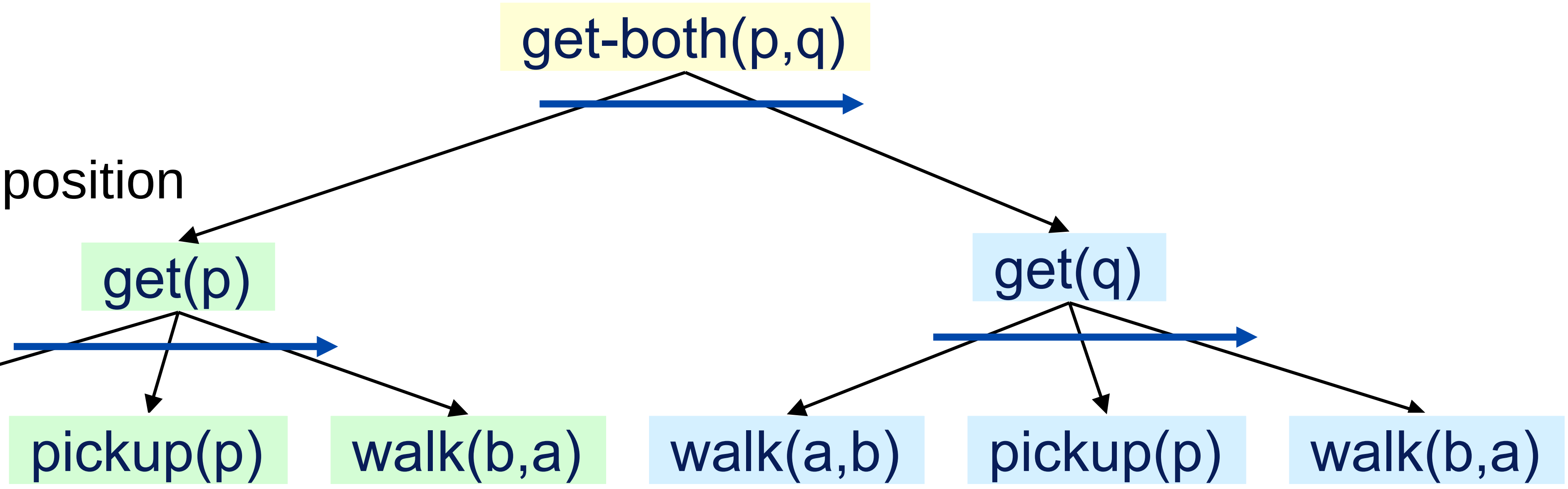
Example: SHOP (Continued)



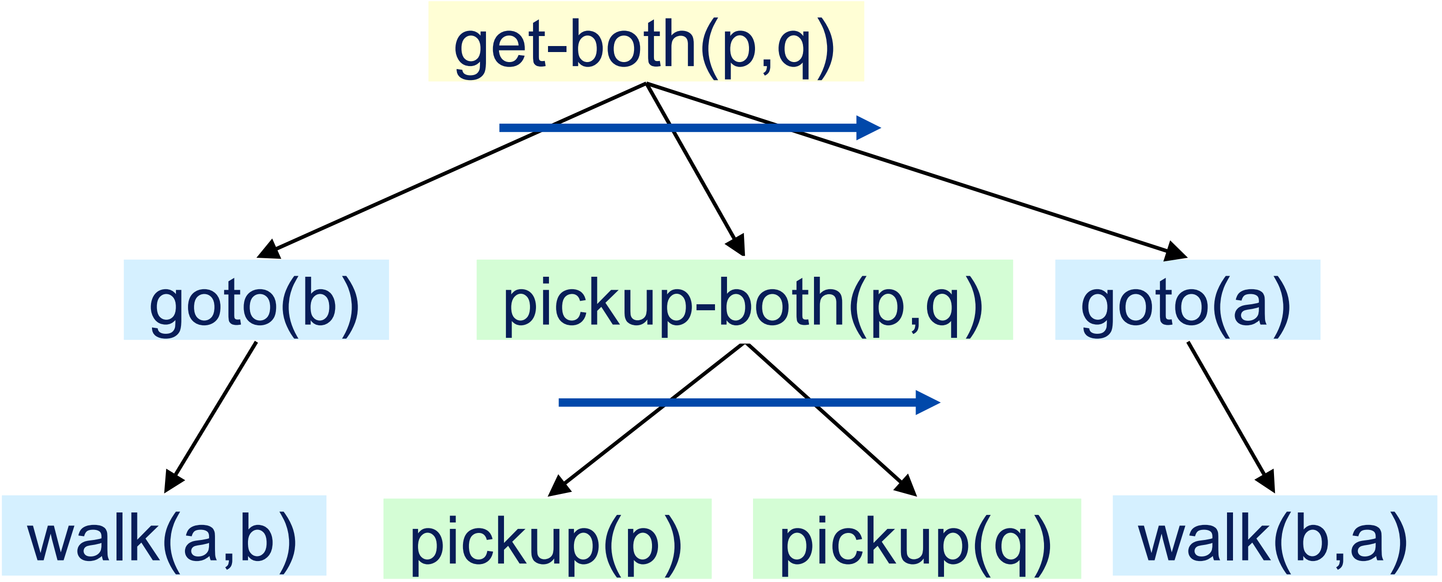
Limitation of Ordered-Task Planning

- TFD requires totally ordered methods

total forward decomposition

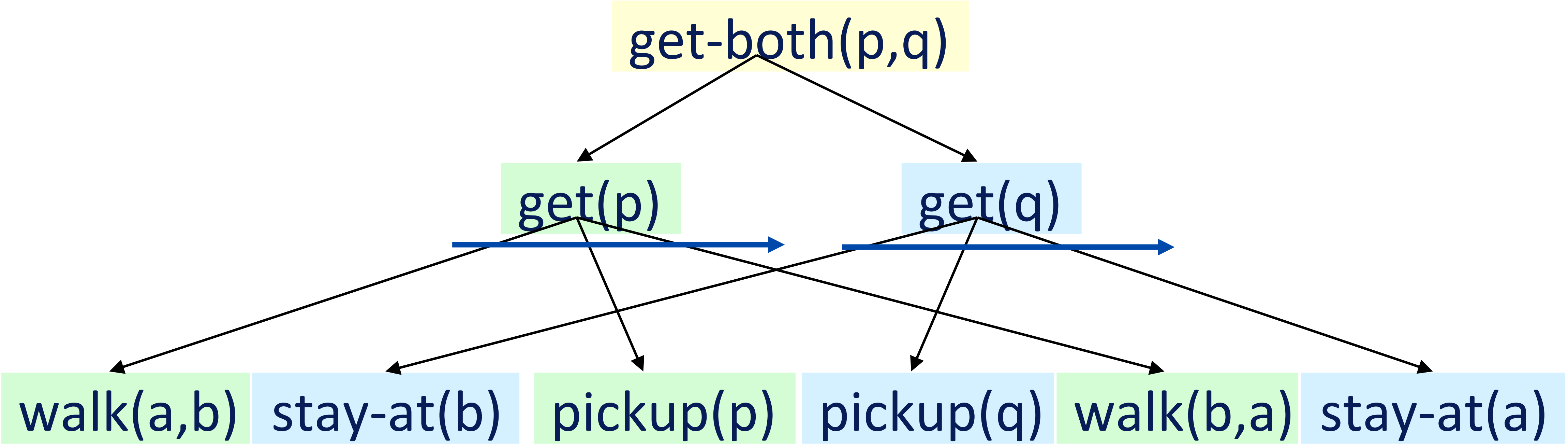

get-both(p,q)
get(p)
get(q)
walk(a,b)
pickup(p)
walk(b,a)
walk(a,b)
pickup(p)
walk(b,a)

- Can't interleave subtasks of different tasks
- Sometimes this makes things awkward:
  - Need to write methods that reason globally instead of locally


get-both(p,q)
goto(b)
pickup-both(p,q)
goto(a)
walk(a,b)
pickup(p)
pickup(q)
walk(b,a)

Generalize TFD to interleave subtasks

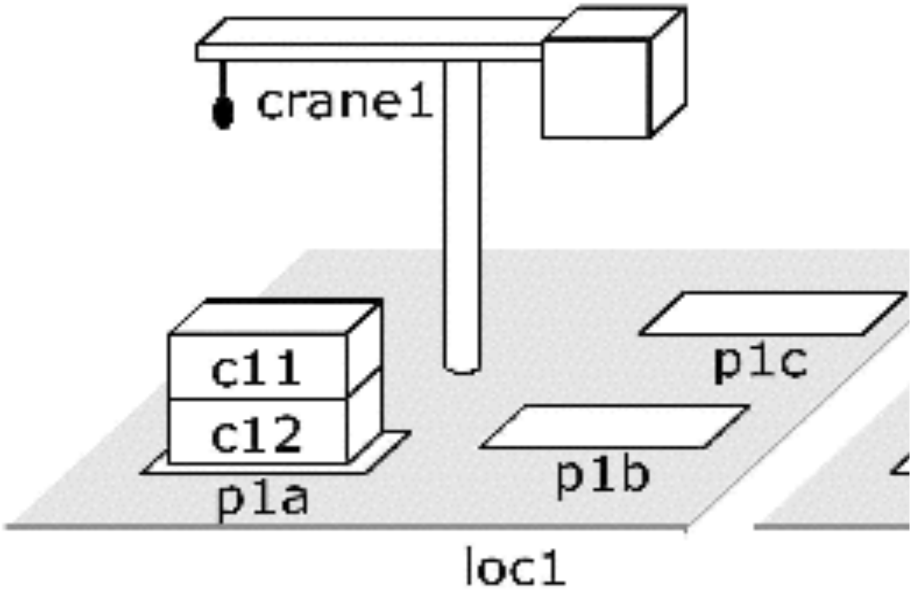
- Generalize methods to allow the subtasks to be partially ordered
- Consequence: plans may interleave subtasks of different tasks

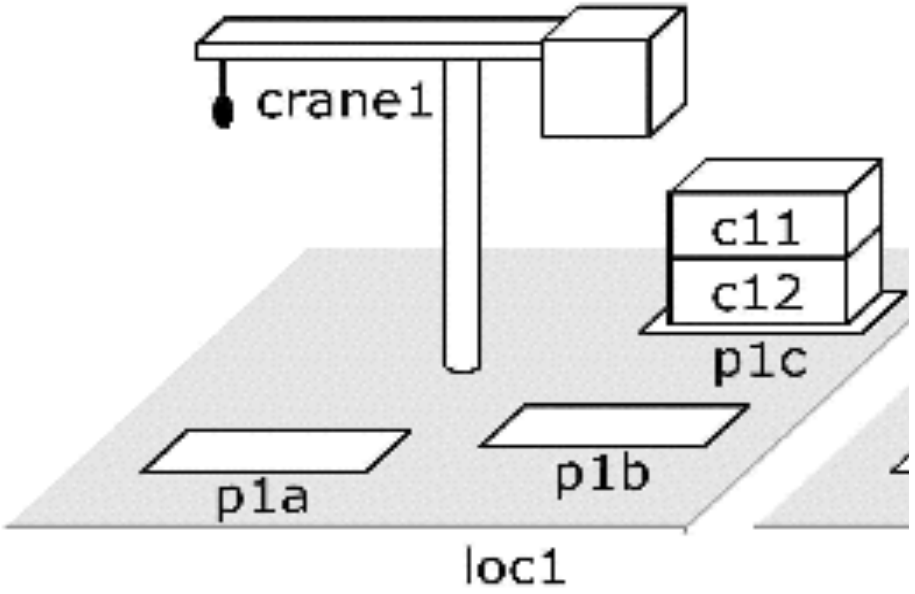


- This makes the planning algorithm more complicated

Example: DWR Partial-Order Formulation

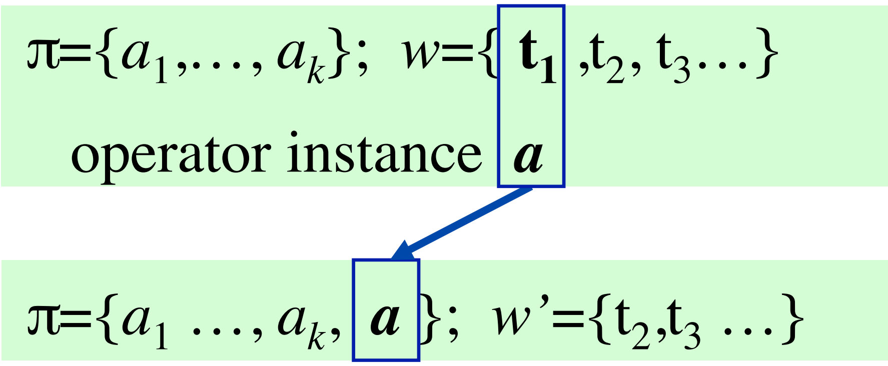
```
take-and-put($c, k, l_1, l_2, p_1, p_2, x_1, x_2$):
    task:      move-topmost-container($p_1, p_2$)
    precond:   top($c, p_1$), on($c, x_1$),        ; true if $p_1$ is not empty
               attached($p_1, l_1$), belong($k, l_1$),   ; bind $l_1$ and $k$
               attached($p_2, l_2$), top($x_2, p_2$)     ; bind $l_2$ and $x_2$
    subtasks:  ⟨take($k, l_1, c, x_1, p_1$), put($k, l_2, c, x_2, p_2$)⟩

recursive-move($p, q, c, x$):
    task:      move-stack($p, q$)
    precond:   top($c, p$), on($c, x$)     ; true if $p$ is not empty
    subtasks:  ⟨move-topmost-container($p, q$), move-stack($p, q$)⟩
               ;; the second subtask recursively moves the rest of the stack

do-nothing($p, q$)
    task:      move-stack($p, q$)
    precond:   top($pallet, p$)     ; true if $p$ is empty
    subtasks:  ⟨⟩   ; no subtasks, because we are done

move-each-twice()
    task:      move-all-stacks()
    precond:     ; no preconditions
    network:     ; move each stack twice:
               $u_1$ =move-stack(p1a,p1b), $u_2$ =move-stack(p1b,p1c),
               $u_3$ =move-stack(p2a,p2b), $u_4$ =move-stack(p2b,p2c),
               $u_5$ =move-stack(p3a,p3b), $u_6$ =move-stack(p3b,p3c),
               $\{(u_1, u_2), (u_3, u_4), (u_5, u_6)\}$
```



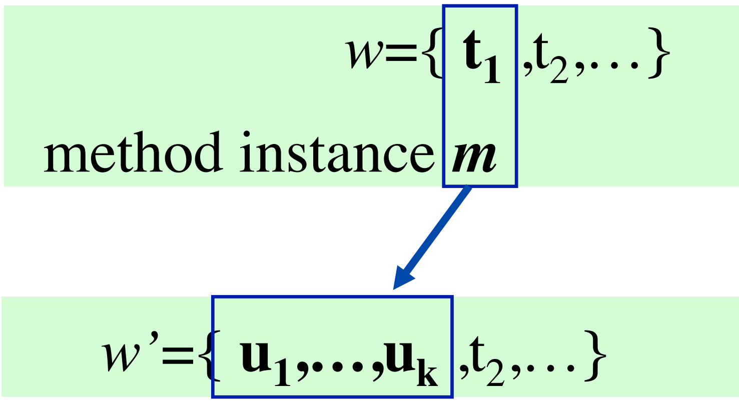


Solving Partial-Order STNs

```
PFD($s, w, O, M$)
    if $w = \emptyset$ then return the empty plan
    nondeterministically choose any $u \in w$ that has no predecessors in $w$
    if $t_u$ is a primitive task then
        $active \leftarrow \{(a, \sigma) \mid a$ is a ground instance of an operator in $O$,
                        $\sigma$ is a substitution such that name$(a) = \sigma(t_u)$,
                        and $a$ is applicable to $s\}$
        if $active = \emptyset$ then return failure
        nondeterministically choose any $(a, \sigma) \in active$
        $\pi \leftarrow$ PFD($\gamma(s, a), \sigma(w - \{u\}), O, M$)
        if $\pi =$ failure then return failure
        else return $a.\pi$
    else
        $active \leftarrow \{(m, \sigma) \mid m$ is a ground instance of a method in $M$,
                    $\sigma$ is a substitution such that name$(m) = \sigma(t_u)$,
                    and $m$ is applicable to $s\}$
        if $active = \emptyset$ then return failure
        nondeterministically choose any $(m, \sigma) \in active$
        nondeterministically choose any task network $w' \in \delta(w, u, m, \sigma)$
        return(PFD($s, w', O, M$))
```



$\pi=\{a_1,\ldots,a_k\}$; $w=\{\boxed{\mathbf{t_1}},t_2,t_3\ldots\}$
operator instance $\boxed{\boldsymbol{a}}$
$\pi=\{a_1\ \ldots,a_k,\boxed{\boldsymbol{a}}\}$; $w'=\{t_2,t_3\ \ldots\}$



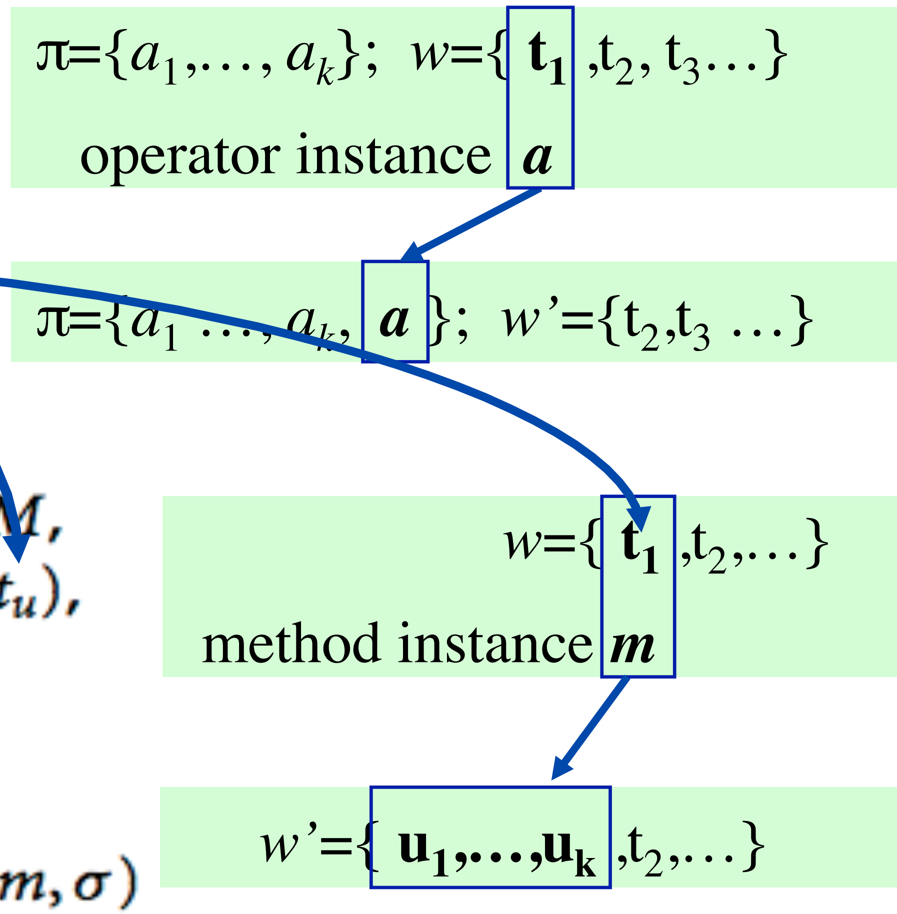
$w=\{\boxed{\mathbf{t_1}},t_2,\ldots\}$
method instance $\boxed{\boldsymbol{m}}$
$w'=\{\boxed{\mathbf{u_1,\ldots,u_k}},t_2,\ldots\}$

Solving Partial-Order STNs

```
PFD($s, w, O, M$)
    if $w = \emptyset$ then return the empty plan
                                                        rs in $w$
                                                        $O$,
                                                        $\sigma(t_u)$,
```

- Intuitively, *w* is a partially ordered set of tasks $\{t_1, t_2, \ldots\}$
  - But *w* may contain a task more than once
    - e.g., travel from UMD to LAAS twice
  - The mathematical definition of a set doesn't allow this
- Define *w* as a partially ordered set of *task nodes* $\{u_1, u_2, \ldots\}$
  - Each task node *u* corresponds to a task t_u
- In my explanations, I talk about *t* and ignore *u*

```
        else return $a.\pi$
    else
        active $\leftarrow \{(m,\sigma) \mid m$ is a ground instance of a method in $M$,
                    $\sigma$ is a substitution such that name($m$) $= \sigma(t_u)$,
                    and $m$ is applicable to $s\}$
        if active $= \emptyset$ then return failure
        nondeterministically choose any $(m,\sigma) \in$ active
        nondeterministically choose any task network $w' \in \delta(w, u, m, \sigma)$
        return(PFD($s, w', O, M$))
```


$\pi=\{a_1,\ldots,a_k\}$; $w=\{ \boxed{t_1} ,t_2, t_3\ldots\}$
operator instance $\boxed{a}$
$\pi=\{a_1 \ldots, a_k, \boxed{a} \}$; $w'=\{t_2,t_3 \ldots\}$
$w=\{ \boxed{t_1} ,t_2,\ldots\}$
method instance $\boxed{m}$
$w'=\{ \boxed{u_1,\ldots,u_k} ,t_2,\ldots\}$

Solving Partial-Order STNs

```
PFD($s, w, O, M$)
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    if $t_u$ is a primitive task then
        $active \leftarrow \{(a,\sigma) \mid a$ is a ground instance of an operator in $O$,
                    $\sigma$ is a substitution such that name$(a) = \sigma(t_u)$,
        if a
        non
        $\pi$ ←
        if $\pi$
        else
    else
        acti                                                    $M$,
                $\sigma$ is a substitution such that name$(m) = \sigma(t_u)$,
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        if $active = \emptyset$ then return failure
        nondeterministically choose any $(m,\sigma) \in active$
        nondeterministically choose any task network $w' \in \delta(w, u, m, \sigma)$
        return(PFD($s, w', O, M$))
```
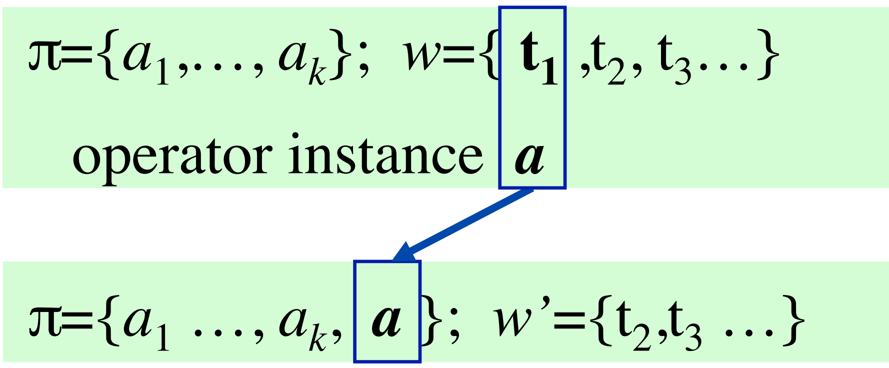
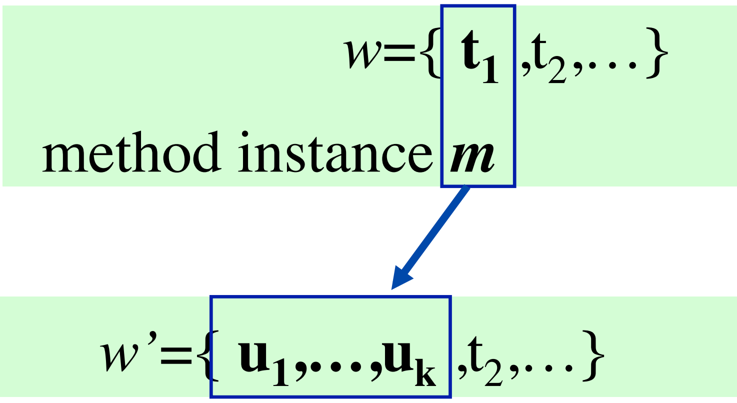

$\delta(w, u, m, \sigma)$ has a complicated definition in the book. Here's what it means:

- We non-deterministically selected t_1 as the task to do first
- Must do t_1's first subtask before the first subtask of every $t_i \neq t_1$
- Insert ordering constraints to ensure that this happens


$\pi=\{a_1,\ldots,a_k\}$; $w=\{\boxed{t_1},t_2,t_3\ldots\}$
operator instance $\boxed{a}$
$\pi=\{a_1 \ldots, a_k, \boxed{a}\}$; $w'=\{t_2,t_3 \ldots\}$


$w=\{\boxed{t_1},t_2,\ldots\}$
method instance $\boxed{m}$
$w'=\{\boxed{u_1,\ldots,u_k},t_2,\ldots\}$

STN Summary

- PFD is sound and complete
- STN – simplified version of HTN
  - TFD – Total-order Forward Decomposition (used in SHOP)
    - Input: tasks are totally ordered
    - Output: totally ordered plan
  - PFD – Partial-order Forward Decomposition (SHOP2)
    - Input: tasks are partially ordered
    - Output: totally ordered plan

- SHOP2:
  - Won one of the top four awards in the AIPS-2002 Planning Competition
  - Freeware, open source
  - Implementation available at http://www.cs.umd.edu/projects/shop

STN v HTN

- HTN – generalization of STN
  - More freedom about how to construct the task networks.
  - Can use other decomposition procedures not just forward-decomposition.
  - Like Partial-Order Planning combined with STN
    - Input: Partial-order tasks
    - Output: The resulting plan is partially ordered
  - Plans can be totally ordered or partially ordered
  - Can have constraints associated with tasks and methods
  - Things that must be true before a state, in between two given states, or after a state (replaces STN preconditions)
  - Some algorithms use causal links and threats like those in PSP

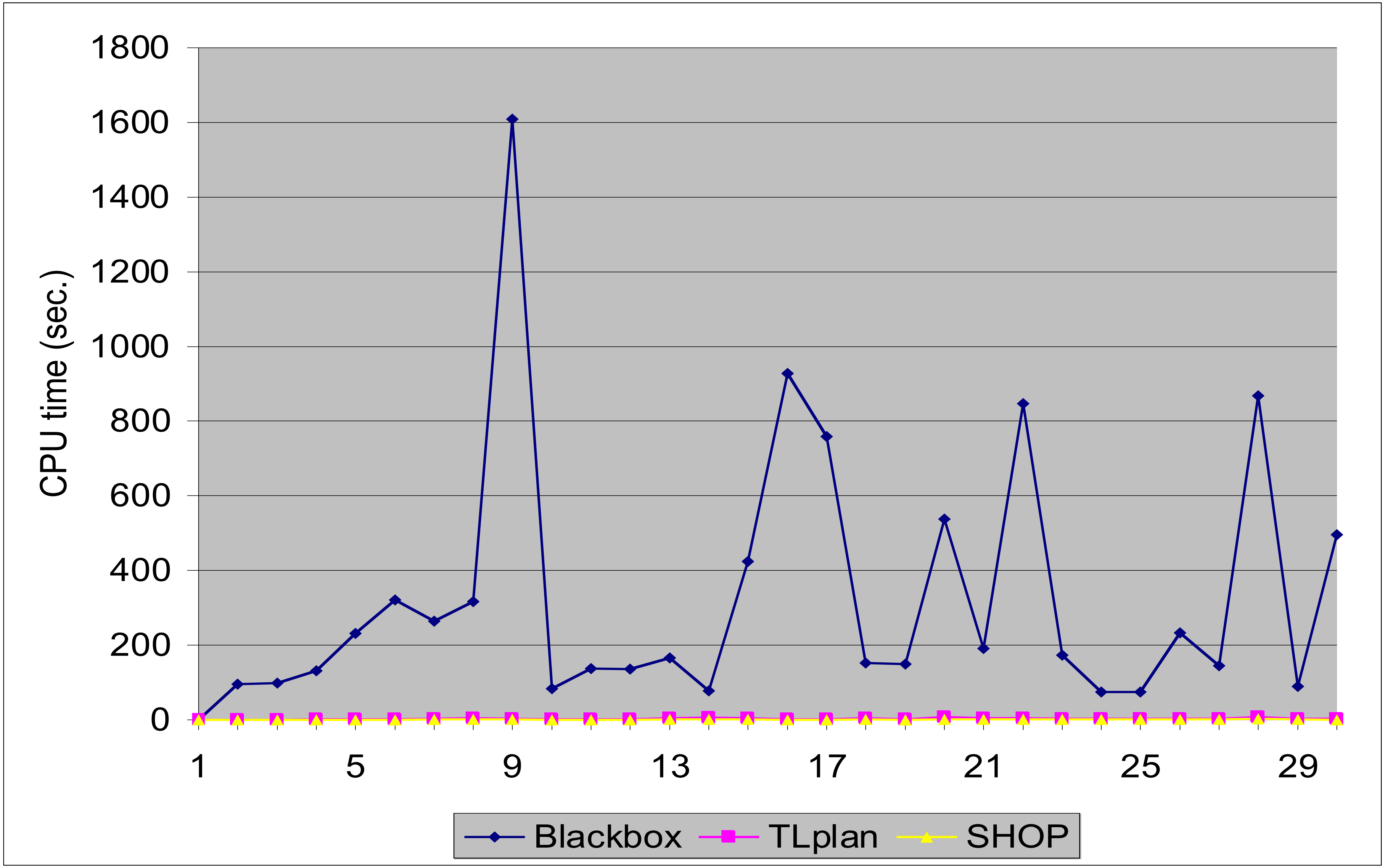
TLPlan's Expressivity Compared with SHOP and SHOP2

- Equivalent expressive power
- Both know the current state at each step of the planning process, and use this to prune operators
- Both can call external subroutines
  - SHOP uses "eval" to call LISP functions
  - In TLPlan, a function symbol can correspond to a computed function
- Main difference
  - in SHOP and SHOP2, the methods talk about what can be done
    - SHOP and SHOP2 don't do anything unless a method says to do it
  - TLPlan's control rules talk about what cannot be done
    - TLPlan will try everything that the control rules don't prohibit
- Which approach is more convenient depends on the problem domain

Experimental Comparison

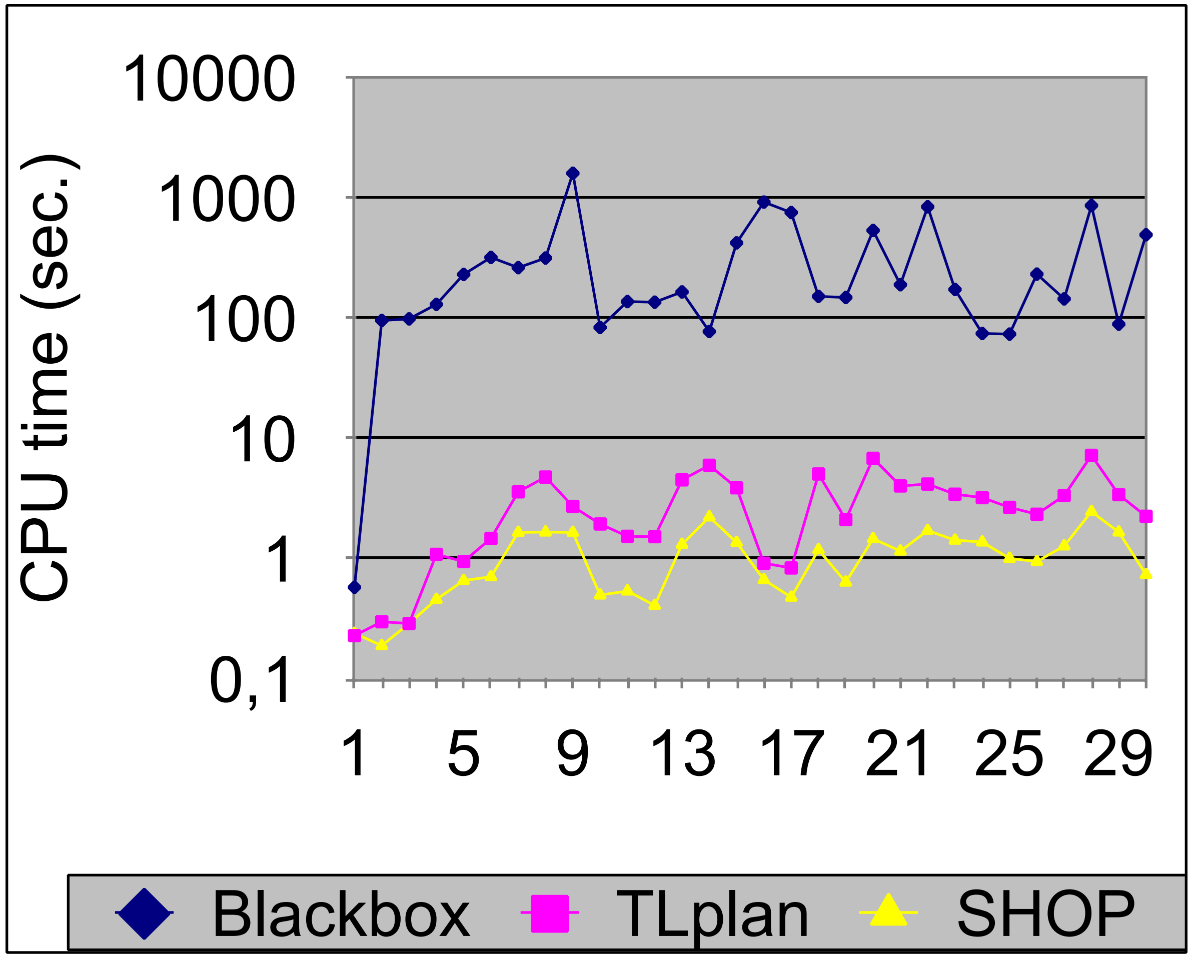
- Several years ago, we did a comparison of SHOP, TLPlan, and Blackbox
    - Blackbox is a domain-independent planner that uses a combination of Graphplan and satisfiability
    - One of the two fastest planners in the 1998 planning competition
- Test domain: the logistics domain
    - A classical planning problem
        - Much simpler than real logistics planning
    - Scenario: use trucks and airplanes to deliver packages
    - Like a simplified version of the DWR domain in which containers don't get stacked on each other
- Test conditions
    - SHOP and TLPlan on a 167-MHz Sun Ultra with 64 MB of RAM
    - We couldn't run Blackbox on our machine
    - Published results: Blackbox on a faster machine with 8 GB of RAM

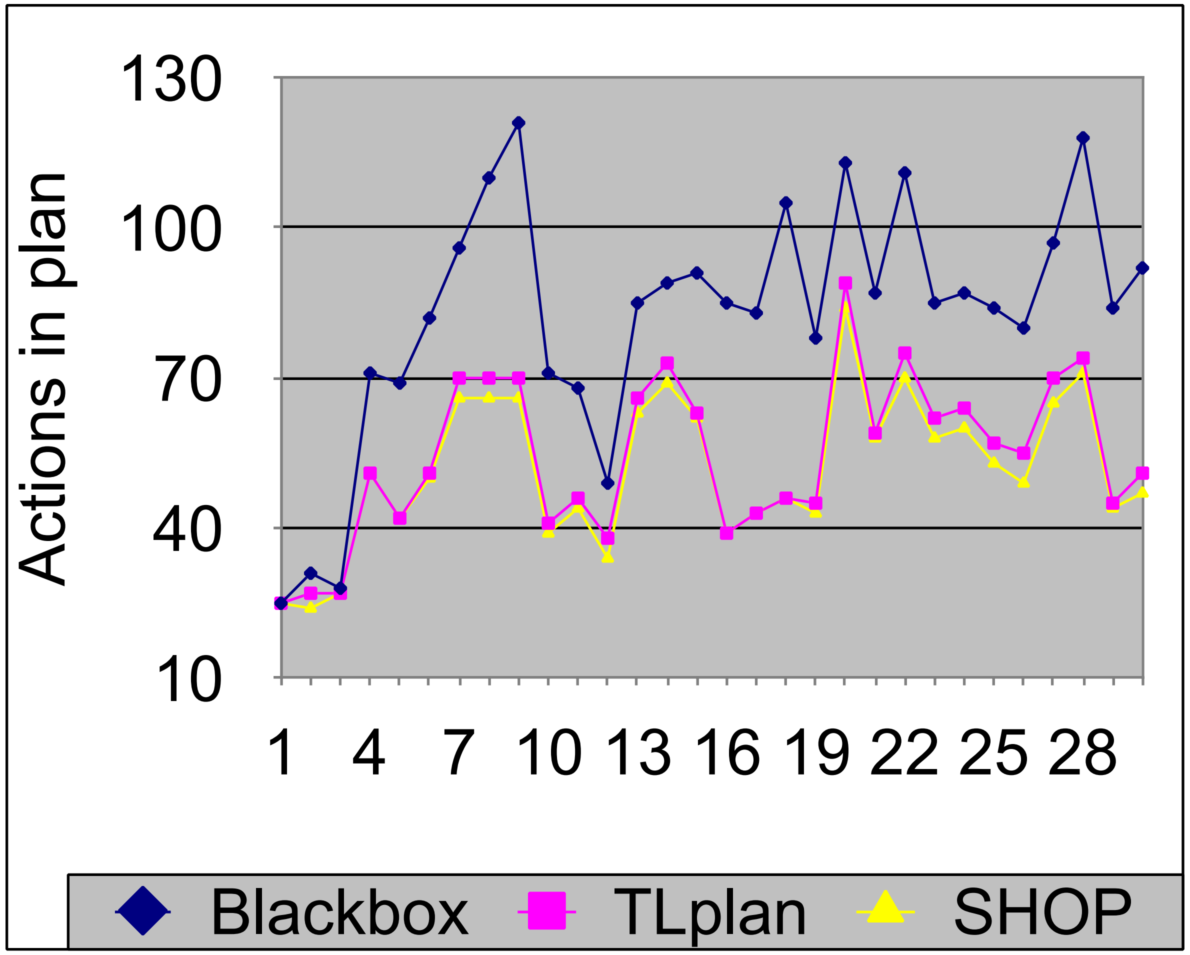
Logistics Domain Results



Logistics Domain Results (continued)

- Same graph as before, but on a logarithmic scale





Average CPU time	Blackbox	TLPlan	SHOP
	327.1	2.9	1.1

Average no. of actions	Blackbox	TLPlan	SHOP
	82.5	54.5	51.9

Summary: Results

- TLPlan and SHOP took similar amounts of time
  - In this experiment, SHOP was slightly faster, but in others TLPlan may be faster
- Blackbox took about 1000 times as much time and needed about 100 times as much memory
- Reasons why:
  - SHOP's input included domain-specific methods & axioms
  - TLPlan's input included domain-specific control rules
    - This enabled them to find near-optimal solutions in low-order polynomial time and space
  - Blackbox is a fully automated planner
    - No domain-specific knowledge
    - trial-and-error search, exponential time and space

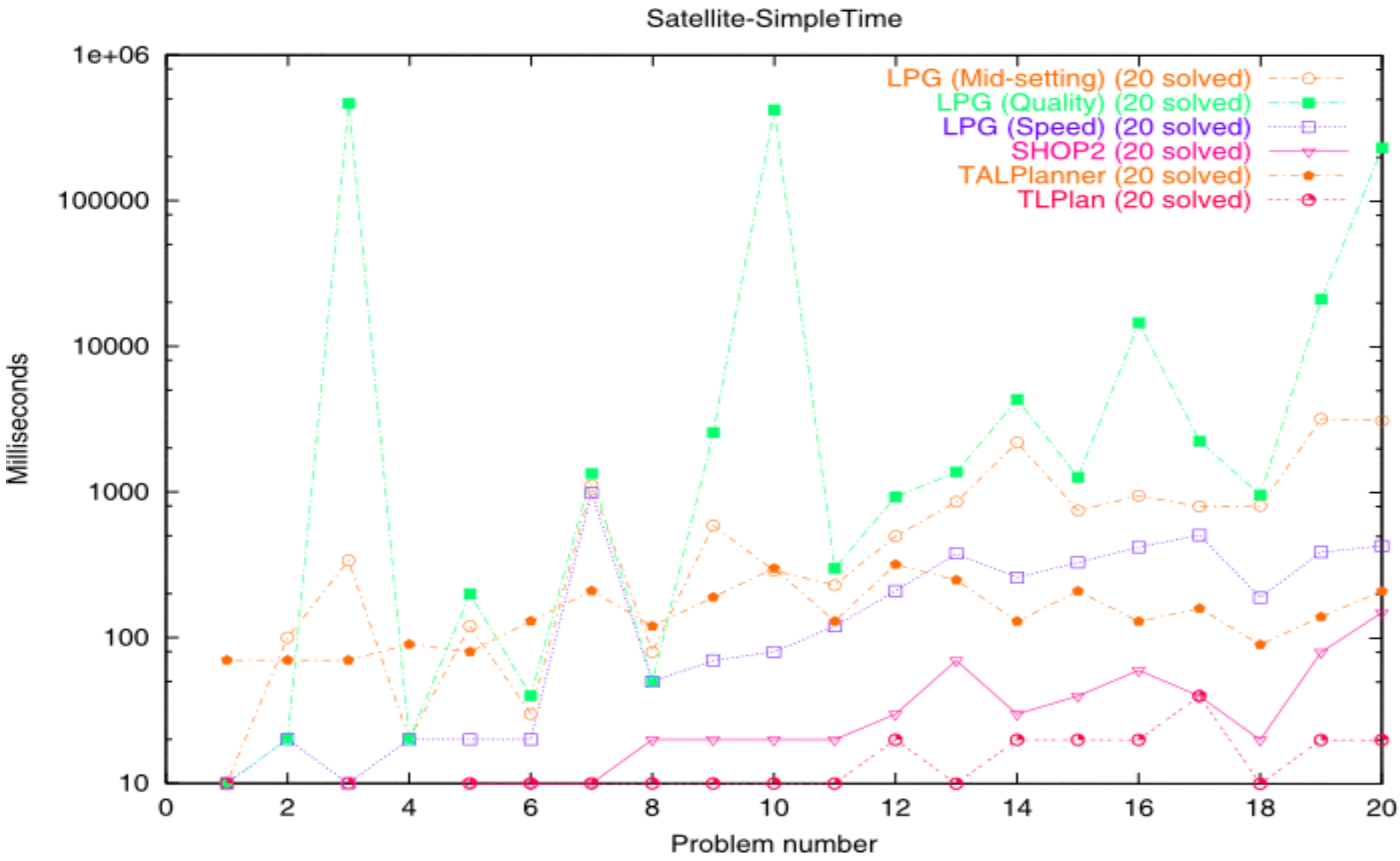
Domain-Configurable Planners Compared to Classical Planners

- Disadvantage:
  - Writing a knowledge base can be more complicated than just writing classical operators
- Advantage:
  - We can encode "recipes" as collections of methods and operators
    - Express things that can't be expressed in classical planning
    - Specify standard ways of solving problems
      - Otherwise, the planning system would have to derive these again and again from "first principles," every time it solves a problem
      - Can speed up planning by many orders of magnitude (e.g., polynomial time versus exponential time)

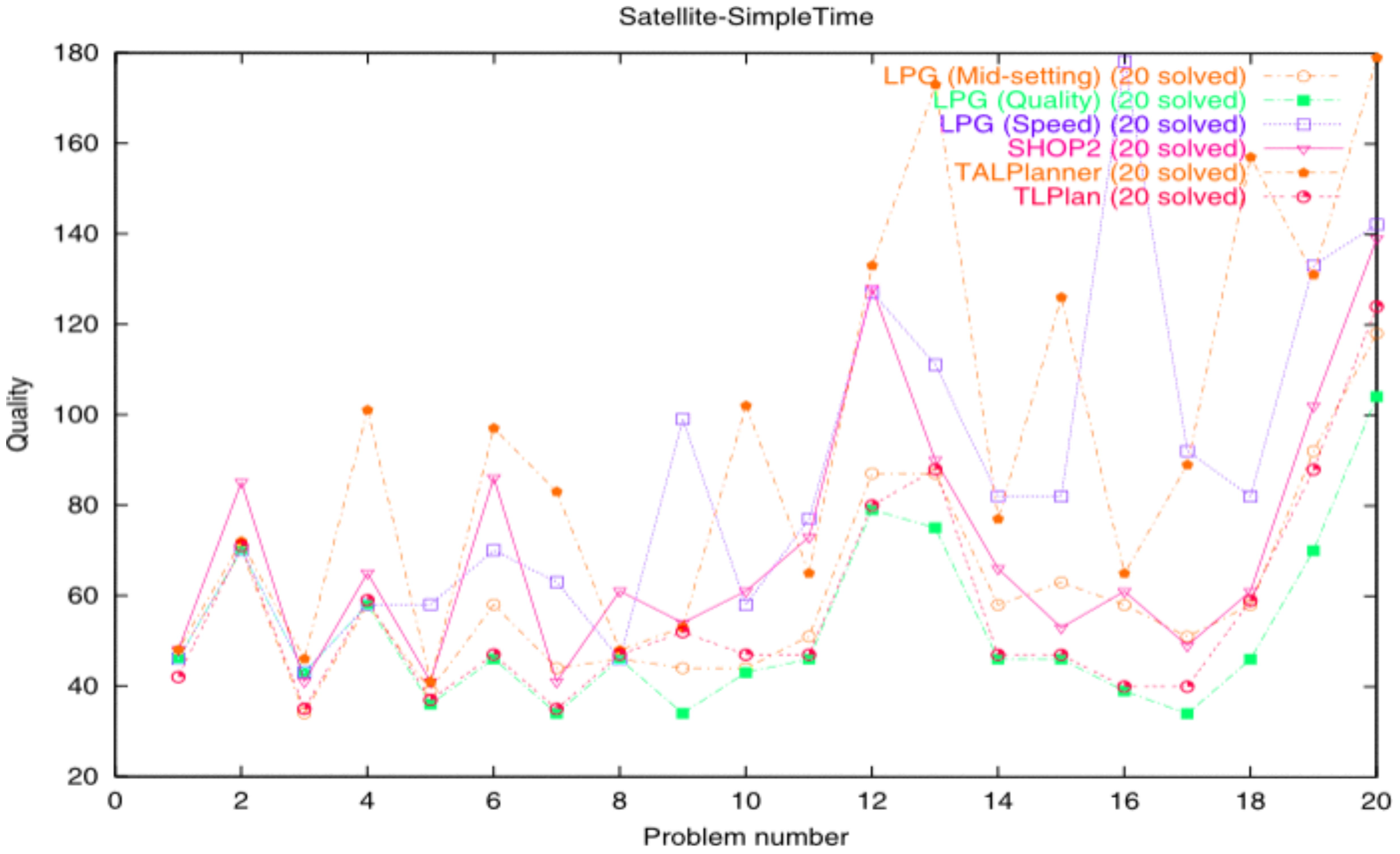
Example from the AIPS-2002 Competition

- The satellite domain
  - Planning and scheduling observation tasks among multiple satellites
  - Each satellite equipped in slightly different ways
- Several different versions. Results are shown for the following:
  - Simple time:
    - concurrent use of different satellites
    - data can be acquired more quickly if they are used efficiently
  - Numeric:
    - fuel costs for satellites to slew between targets; finite amount of fuel available.
    - data takes up space in a finite capacity data store
    - Plans are expected to acquire all the necessary data at minimum fuel cost.
  - Hard Numeric:
    - no logical goals at all – thus even the null plan is a solution
    - Plans that acquire more data are better – thus the null plan has no value
    - None of the classical planners could handle this

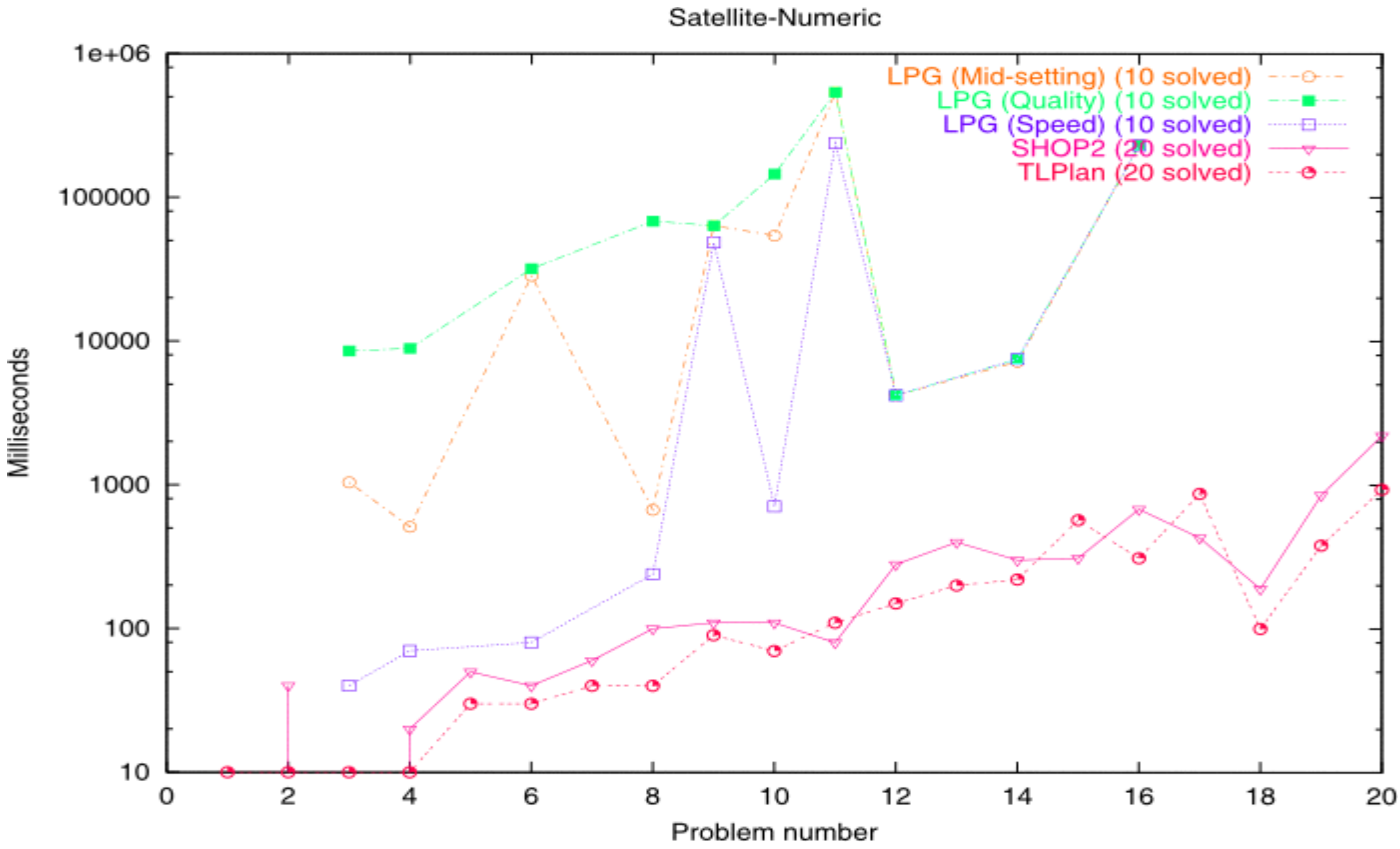
Satellite Problem Domain: Simple Time: Runtime



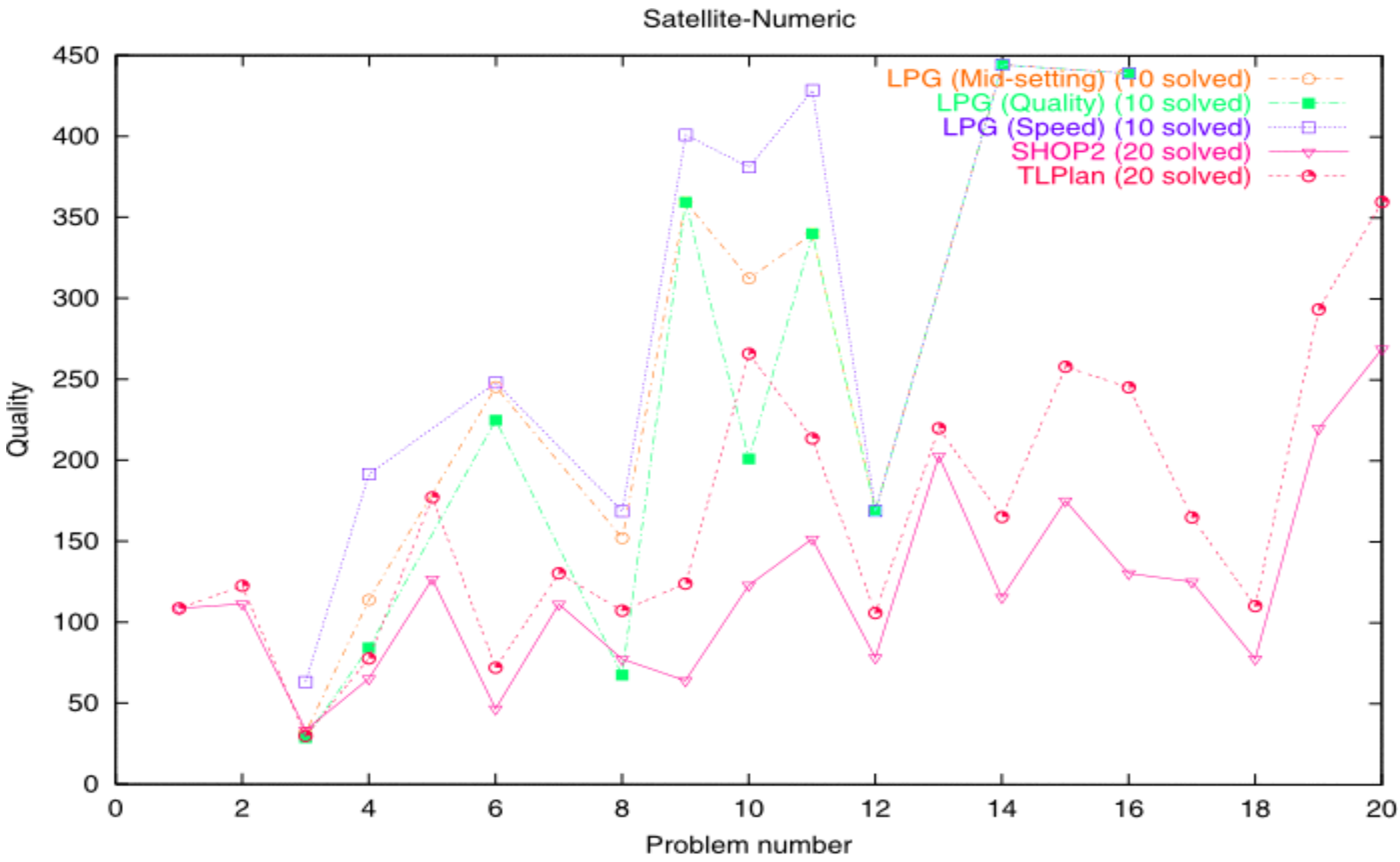
Satellite Problem Domain: Simple Time: Plan Quality



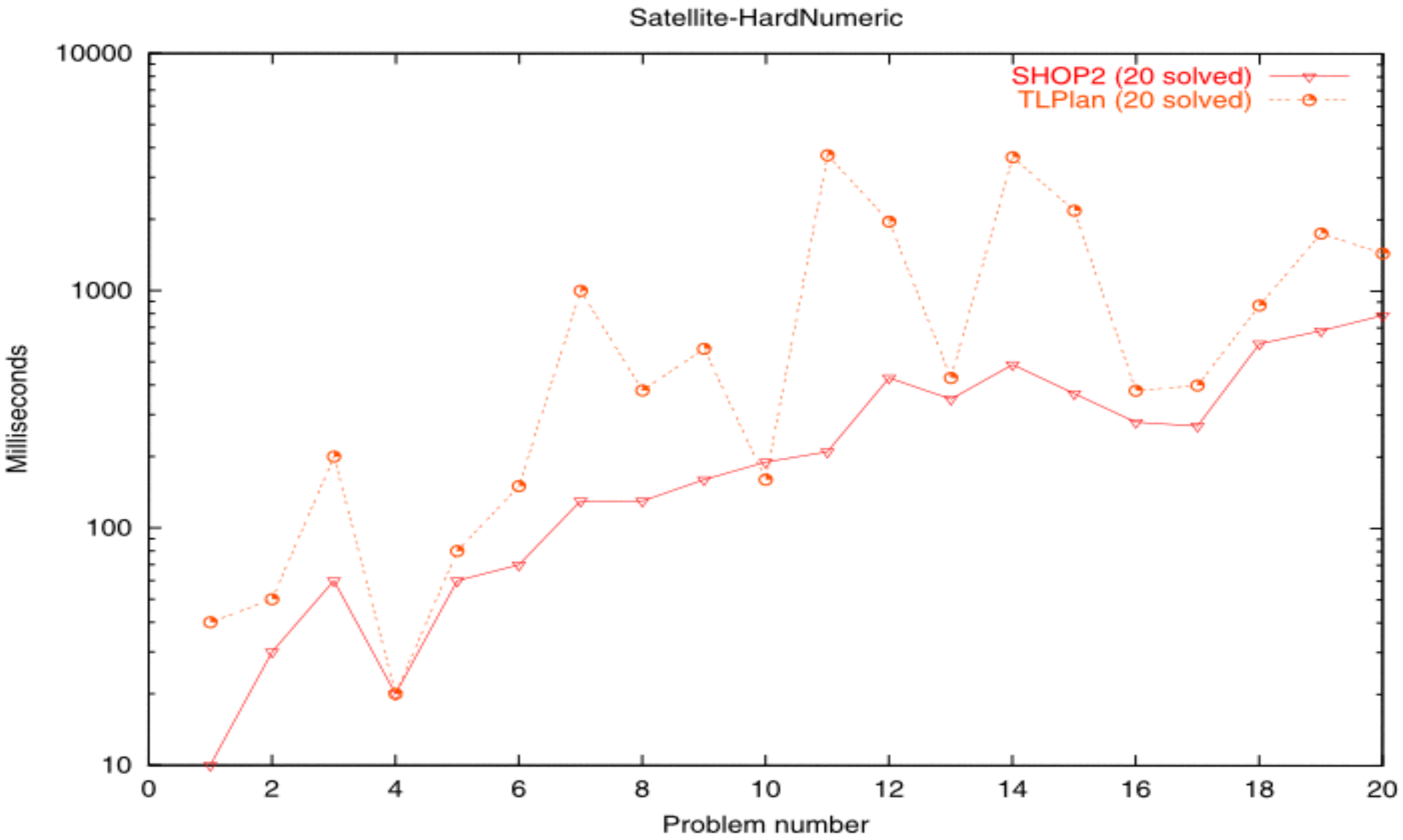
Satellite Problem Domain: Numeric: Runtime



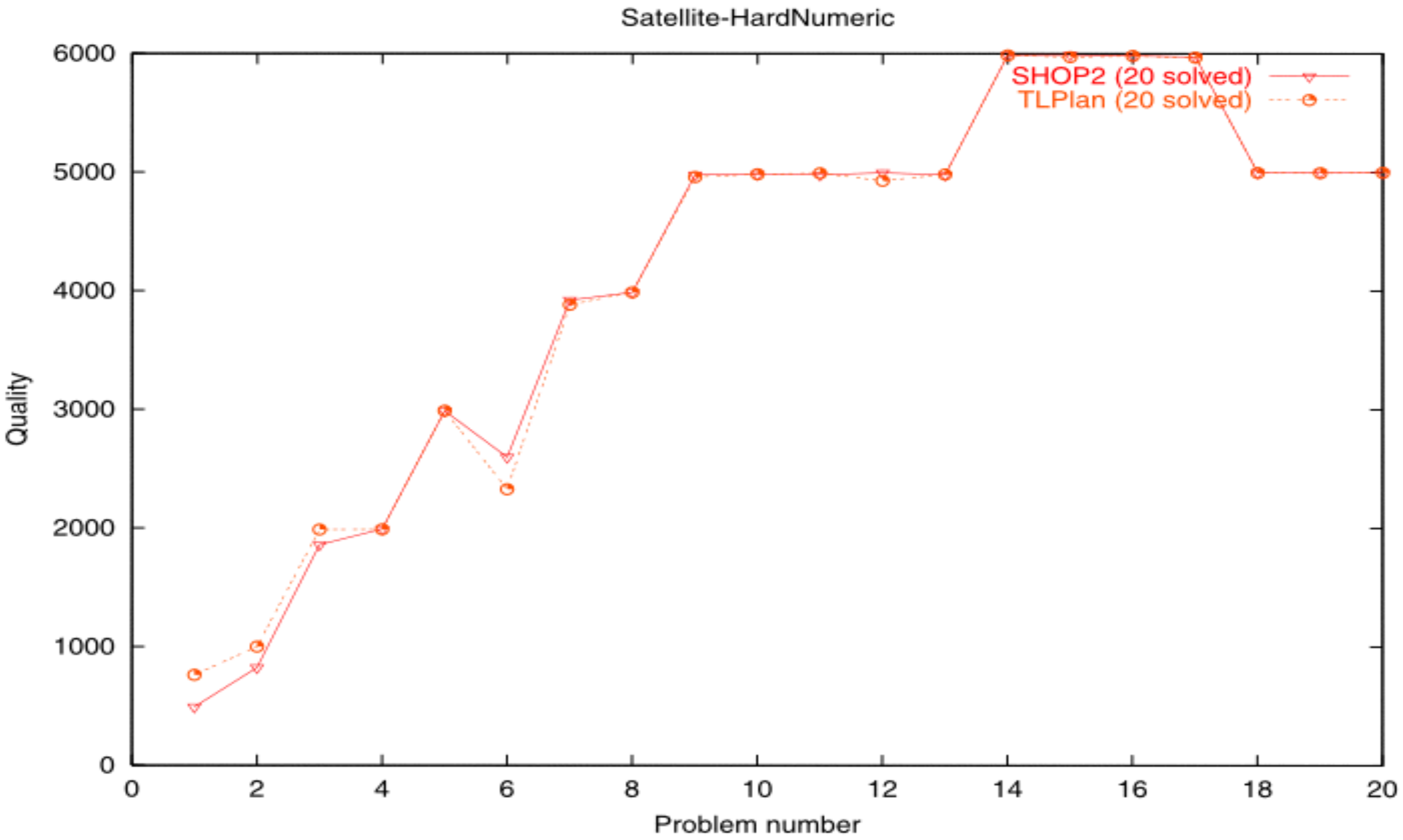
Satellite Problem Domain: Numeric: Plan Quality



Satellite Problem Domain: Hard Numeric: Runtime



Satellite Problem Domain: Hard Numeric: Plan Quality


Satellite-HardNumeric
Quality
Problem number
SHOP2 (20 solved)
TLPlan (20 solved)