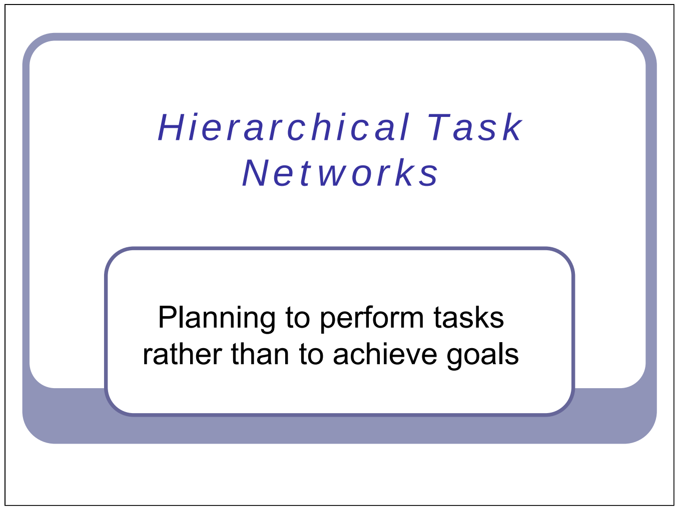
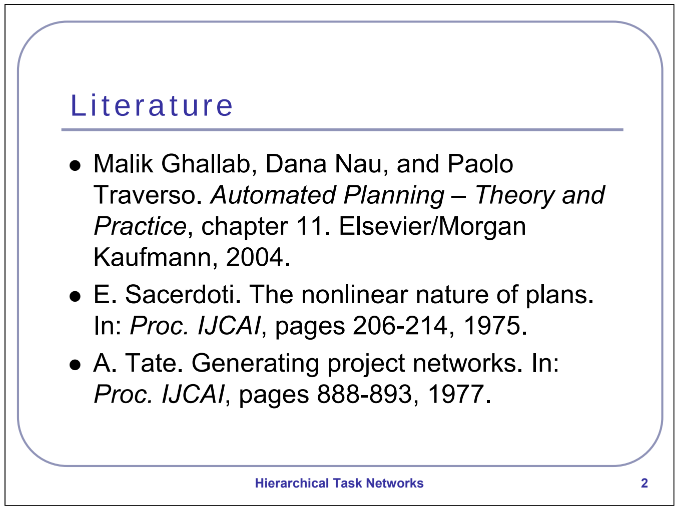


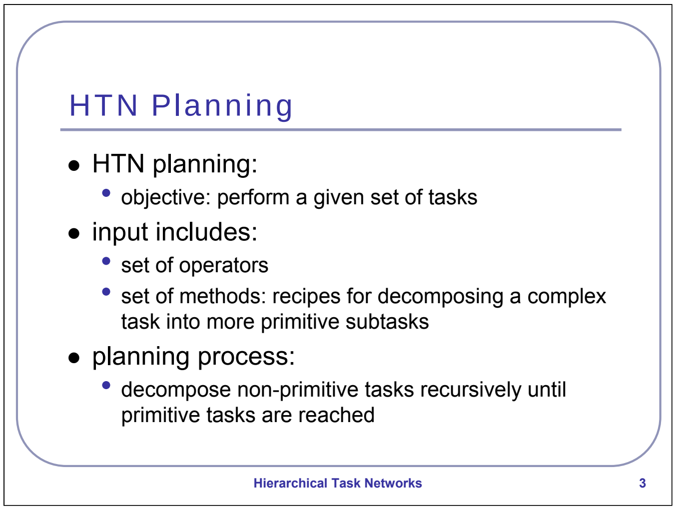
Hierarchical Task Networks

•Planning to perform tasks rather than to achieve goals



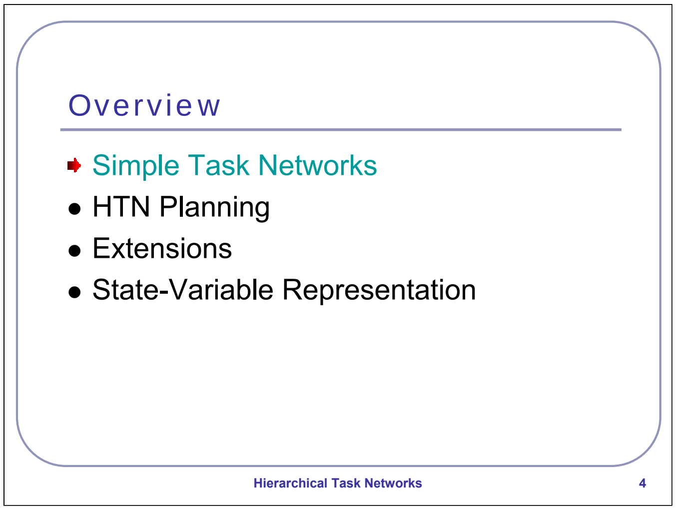
Literature

- **Malik Ghallab, Dana Nau, and Paolo Traverso. *Automated Planning – Theory and Practice*, chapter 11. Elsevier/Morgan Kaufmann, 2004.**
- **E. Sacerdoti. The nonlinear nature of plans. In: *Proc. IJCAI*, pages 206-214, 1975.**
- **A. Tate. Generating project networks. In: *Proc. IJCAI*, pages 888-893, 1977.**



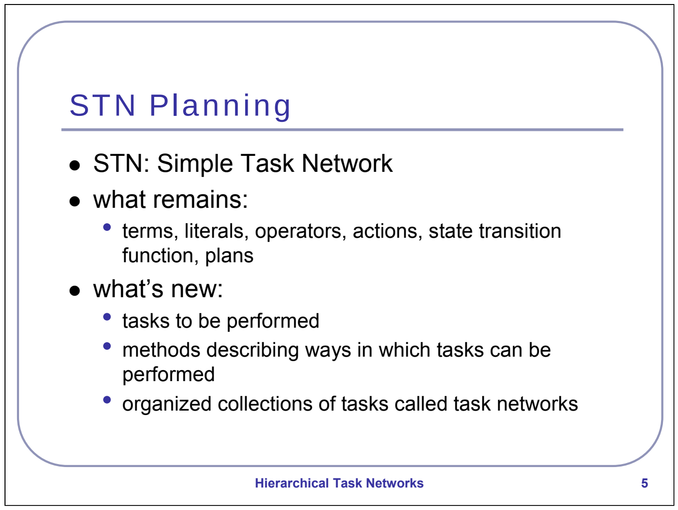
HTN Planning

- **HTN planning:**
  - world state represented by set of atoms and actions correspond to deterministic state transitions
  - **objective: perform a given set of tasks**
    - previously: achieve some goals
- **input includes:**
  - **set of operators**
  - **set of methods: recipes for decomposing a complex task into more primitive subtasks**
    - methods: at a higher level of abstraction
    - primitive task: can be performed directly by an operator instance
- **planning process:**
  - **decompose non-primitive tasks recursively until primitive tasks are reached**
- HTN most widely used technique for real-world planning applications
  - methods are a natural way to encode recipes (which should lead to solution plans only; reduces search significantly)
  - methods reflect the way experts think about planning problems



Overview

- **Simple Task Networks**
  - now: representation and planning algorithms for STNs
- **HTN Planning**
- **Extensions**
- **State-Variable Representation**



STN Planning

•STN: Simple Task Network

•STN: simplified version of the more general HTN case to be discussed later

•what remains:

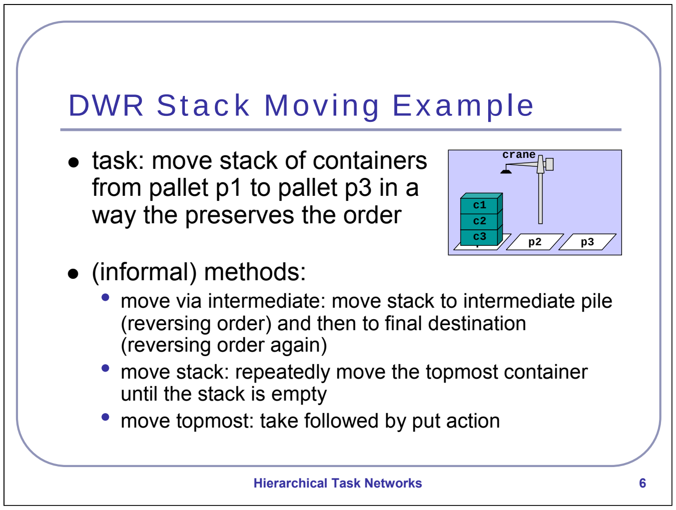
•terms, literals, operators, actions, state transition function, plans

•what's new:

•tasks to be performed

•methods describing ways in which tasks can be performed

•organized collections of tasks called task networks



DWR Stack Moving Example

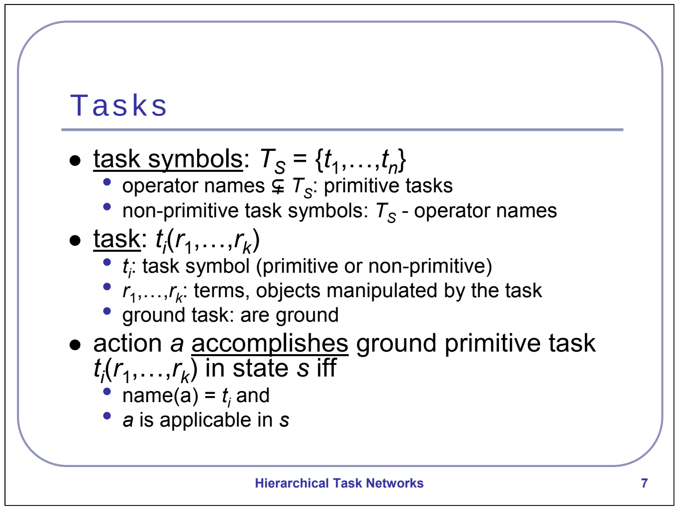
•task: move stack of containers from pallet p1 to pallet p3 in a way the preserves the order

- •preserve order: each container should be on same container it is on originally

•(informal) methods:

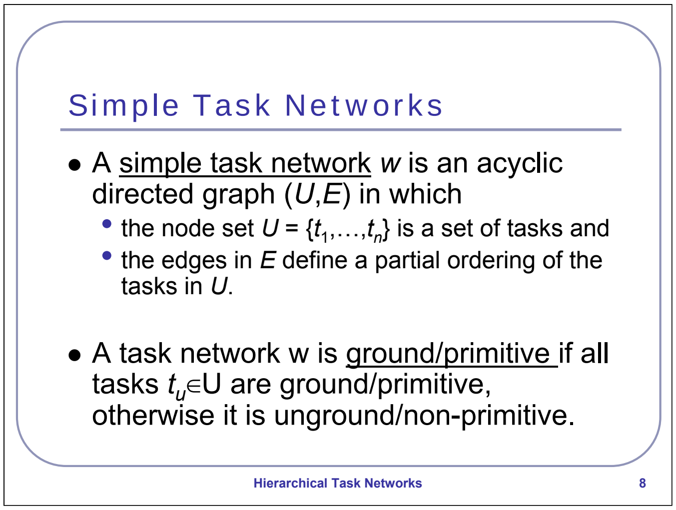
- •methods: possible subtasks and how they can be accomplished
- **•move via intermediate: move stack to intermediate pile (reversing order) and then to final destination (reversing order again)**
- **•move stack: repeatedly move the topmost container until the stack is empty**
- **•move topmost: take followed by put action**
  - •action: no further decomposition required

•note: abstract concept: stack



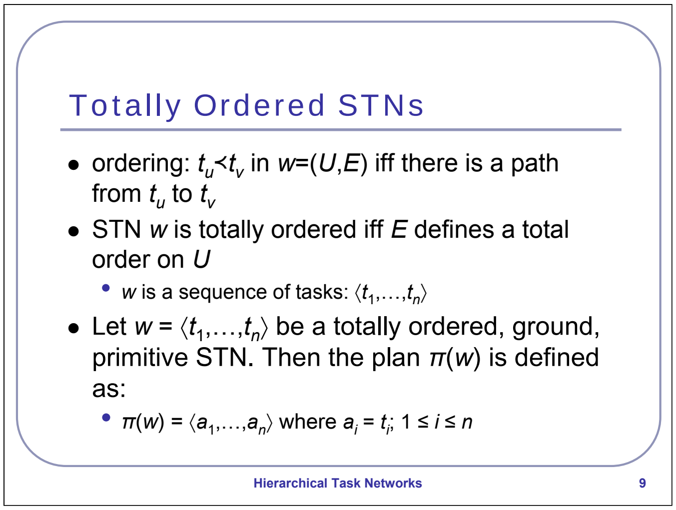
Tasks

- **<u>task symbols</u>: $T_S = \{t_1,\ldots,t_n\}$**
    - used for giving unique names to tasks
    - **operator names ⊊ T_S: primitive tasks**
    - **non-primitive task symbols: T_S - operator names**
- **<u>task</u>: $t_i(r_1,\ldots,r_k)$**
    - **t_i: task symbol (primitive or non-primitive)**
        - tasks: primitive iff task symbol is primitive
    - **$r_1,\ldots,r_k$: terms, objects manipulated by the task**
    - **ground task: are ground**
- **action *a* <u>accomplishes</u> ground primitive task $t_i(r_1,\ldots,r_k)$ in state *s* iff**
    - action a = (name(a), precond(a), effects(a))
    - **name(a) = t_i and**
    - ***a* is applicable in *s***
        - applicability: s satisfies precond(a)
- note: unique operator names, hence primitive tasks can only be performed in one way – no search!



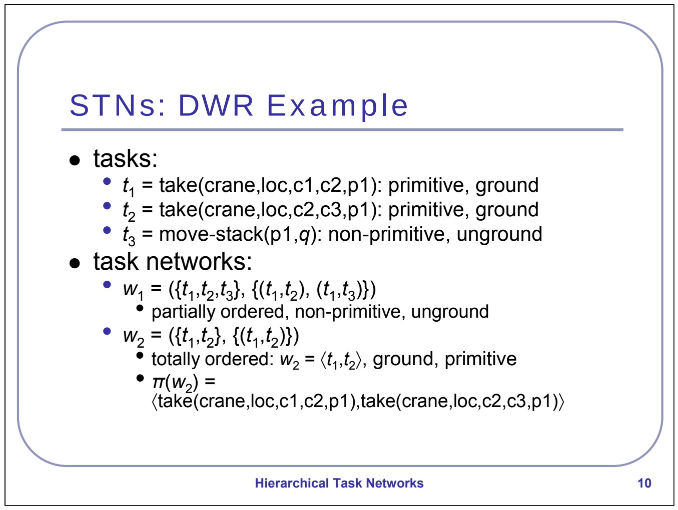
Simple Task Networks

- **A <u>simple task network</u> *w* is an acyclic directed graph (*U*,*E*) in which**
  - **the node set $U = \{t_1,\ldots,t_n\}$ is a set of tasks and**
  - **the edges in *E* define a partial ordering of the tasks in *U*.**
- **A task network w is <u>ground/primitive</u> if all tasks $t_u \in U$ are ground/primitive, otherwise it is unground/non-primitive.**
- simple task network: shortcut “task network”



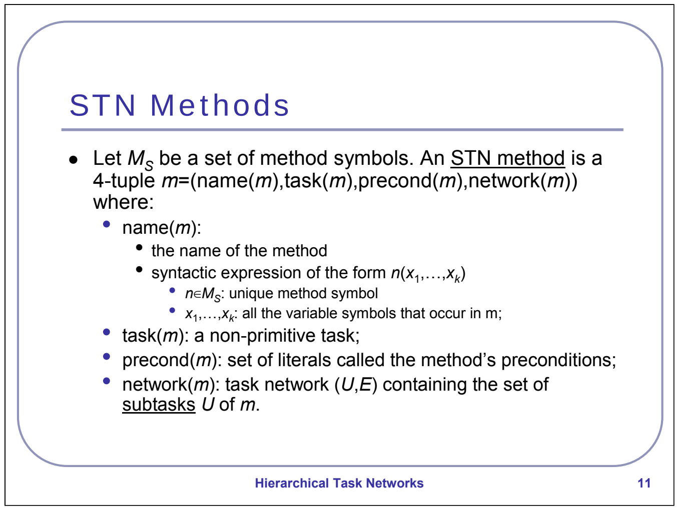
Totally Ordered STNs

- **ordering: $t_u \prec t_v$ in $w=(U,E)$ iff there is a path from t_u to t_v**
- **STN w is totally ordered iff E defines a total order on U**
  - **w is a sequence of tasks: $\langle t_1,\dots,t_n \rangle$**
    - sequence is special case of acyclic directed graph
    - t_1: first task in U; t_2 :second task in U; …; t_n: last task in U
- **Let $w = \langle t_1,\dots,t_n \rangle$** be a totally ordered, ground, primitive STN. Then the plan $\pi(w)$ is defined as:
  - **$\pi(w) = \langle a_1,\dots,a_n \rangle$** where **$a_i = t_i$; $1 \le i \le n$**



STNs: DWR Example

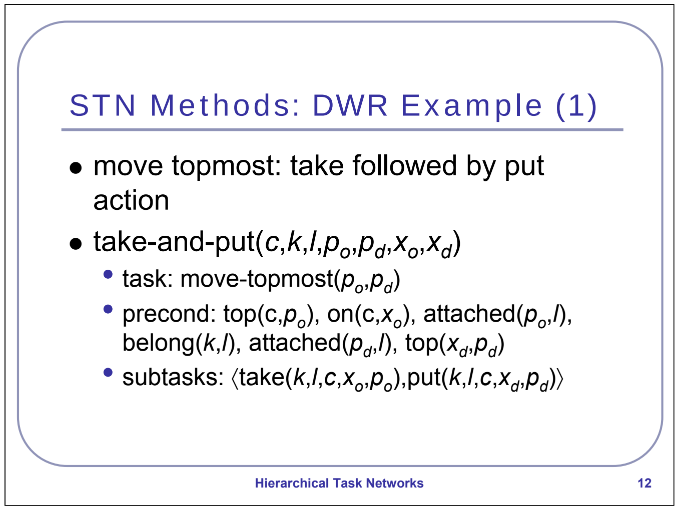
- **tasks:**
  - **t_1 = take(crane,loc,c1,c2,p1): primitive, ground**
    - carne "crane" at location "loc" takes container "c1" of container "c2" in pile "p1"
  - **t_2 = take(crane,loc,c2,c3,p1): primitive, ground**
  - **t_3 = move-stack(p1,q): non-primitive, unground**
    - move the stack of containers on pallet "p2" to pallet "q" (variable)
- **task networks:**
  - **w_1 = ({t_1,t_2,t_3}, {(t_1,t_2), (t_1,t_3)})**
    - **partially ordered, non-primitive, unground**
  - **w_2 = ({t_1,t_2}, {(t_1,t_2)})**
    - **totally ordered: $w_2 = \langle t_1,t_2 \rangle$,** ground, primitive
    - **$\pi(w_2)$ = ⟨take(crane,loc,c1,c2,p1),take(crane,loc,c2,c3,p1)⟩**



STN Methods

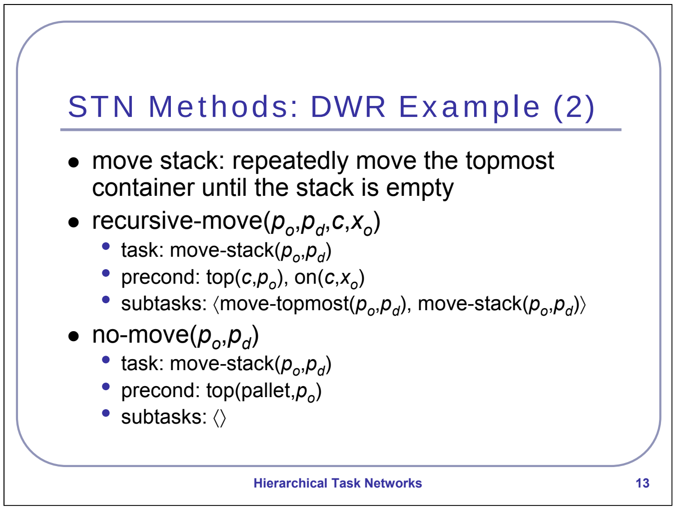
•Let M_S be a set of method symbols. An <u>STN method</u> is a 4-tuple *m*=(name(*m*),task(*m*),precond(*m*),network(*m*)) where:

- •method symbols: disjoint from other types of symbols
- •STN method: also just called method
- •**name(*m*):**
  - •**the name of the method**
    - •unique name: no two methods can have the same name; gives an easy way to unambiguously refer to a method instances
  - •**syntactic expression of the form $n(x_1,\ldots,x_k)$**
    - •**$n \in M_S$: unique method symbol**
    - •**$x_1,\ldots,x_k$: all the variable symbols that occur in m;**
      - •no "local" variables in method definition (may be relaxed in other formalisms)
- •**task(*m*): a non-primitive task;**
  - •what task can be performed with this method
    - •non-primitive: contains subtasks
- •**precond(*m*): set of literals called the method's preconditions;**
  - •like operator preconditions: what must be true in state *s* for *m* to be applicable
    - •no effects: not needed if problem is to refine/perform a task as opposed to achieving some effect



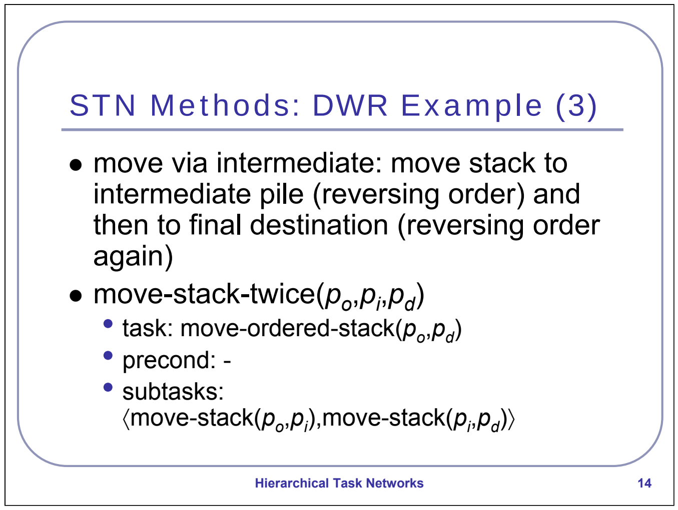
STN Methods: DWR Example (1)

- **move topmost: take followed by put action**
  - simplest method from previous example
- **take-and-put(c,k,l,p_o,p_d,x_o,x_d)**
  - using crane *k* at location *l*, take container *c* from object x_o (container or pallet) in pile p_o and put it onto object x_d in pile p_d (*o* for origin, *d* for destination)
  - **task: move-topmost(p_o,p_d)**
    - move topmost container from pile p_o to pile p_d
  - **precond:**
    - **top(c,p_o), on(c,x_o)**: pile must be empty with container *c* on top
    - **attached(p_o,l), belong(k,l), attached(p_d,l)**: piles and crane must be at same location
    - **top(x_d,p_d)**: destination object must be top of its pile
  - **subtasks:** ⟨take(k,l,c,x_o,p_o),put(take(k,l,c,x_d,p_d))⟩
    - simple macro operator combining two (primitive) operators (sequentially)



STN Methods: DWR Example (2)

- **move stack: repeatedly move the topmost container until the stack is empty**
- **recursive-move(p_o,p_d,c,x_o)**
  - move container *c* which must be on object x_o in pile p_o to the top of pile p_d
  - **task: move-stack(p_o,p_d)**
    - move the remainder of the satck from p_o to p_d: more abstract than method
  - **precond: top(c,p_o), on(c,x_o)**
    - p_o must be empty; *c* is the top container
    - method is not applicable to empty piles!
  - **subtasks: ⟨move-topmost(p_o,p_d), move-stack(p_o,p_d)⟩**
    - recursive decomposition: move top container and then recursive invocation of method through task
- **no-move(p_o,p_d)**
  - performs the task by doing nothing
  - **task: move-stack(p_o,p_d)**
    - as above
  - **precond: top(pallet,p_o)**
    - the pile must be empty (recursion ends here)
  - **subtasks: ⟨⟩**
    - do nothing does nothing

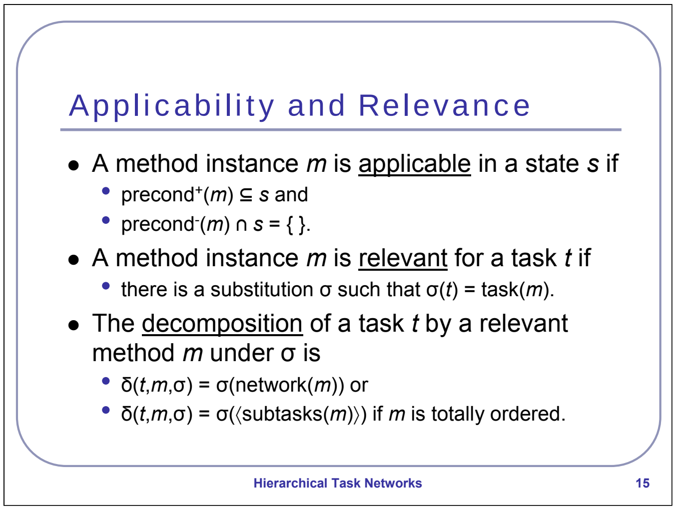


STN Methods: DWR Example (3)

•move via intermediate: move stack to intermediate pallet (reversing order) and then to final destination (reversing order again)

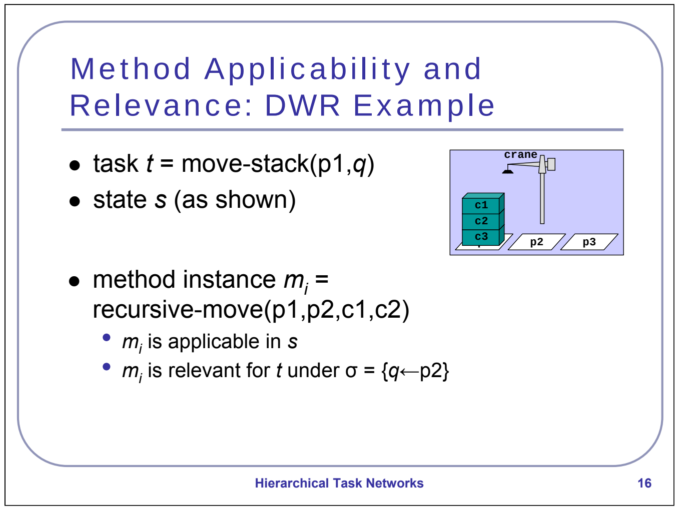
•move-stack-twice(p_o,p_i,p_d)

- •move the stack of containers in pile p_o first to intermediate pile p_i then to p_d, thus preserving the order
- **•task: move-ordered-stack(p_o,p_d)**
  - •move the stack from p_o to p_d in an order-preserving way
- **•precond: -**
  - •none; should mention that piles must be at same location and different
- **•subtasks: ⟨move-stack(p_o,p_i),move-stack(p_i,p_d)⟩**
  - •the two stack moves



Applicability and Relevance

- **A method instance *m* is applicable in a state *s* if**
    - **$\text{precond}^+(m) \subseteq s$ and**
    - **$\text{precond}^-(m) \cap s = \{\}$.**
- **A method instance *m* is relevant for a task *t* if**
    - **there is a substitution σ such that $\sigma(t) = \text{task}(m)$.**
- **The decomposition of a task *t* by a relevant method *m* under σ is**
    - **$\delta(t,m,\sigma) = \sigma(\text{network}(m))$ or**
    - **$\delta(t,m,\sigma) = \sigma(\langle\text{subtasks}(m)\rangle)$ if *m* is totally ordered.**



Method Applicability and Relevance: DWR Example

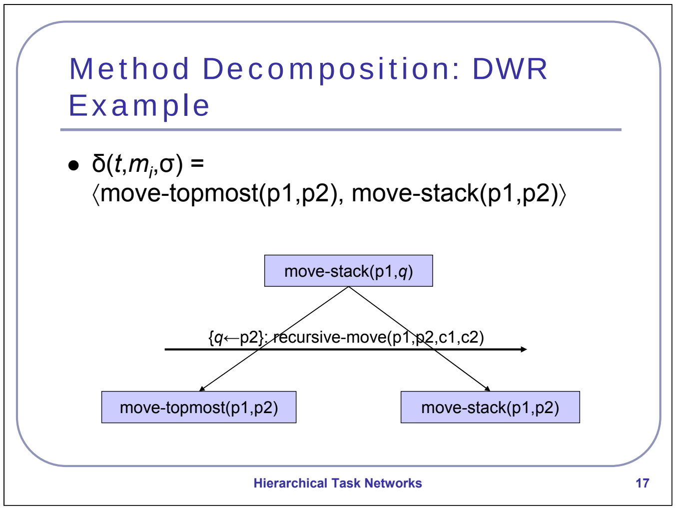
•task *t* = move-stack(p1,*q*)

•state *s* (as shown)

•method instance m_i = recursive-move(p1,p2,c1,c2)

  •m_i is applicable in *s*

  •m_i is relevant for *t* under σ = {*q*←p2}



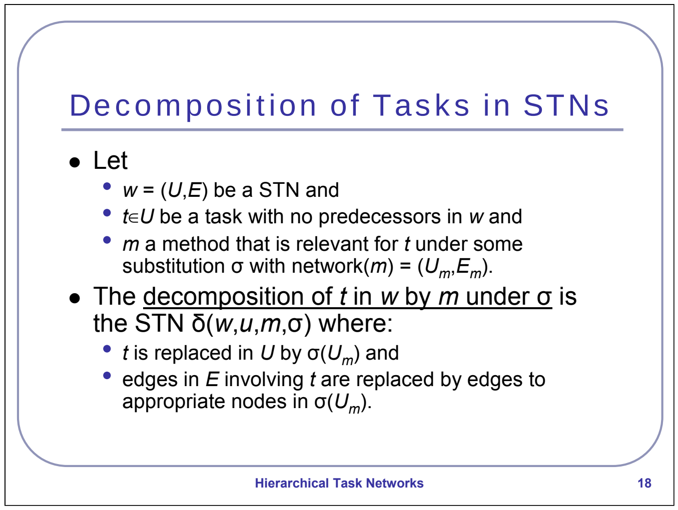
Method Decomposition: DWR Example

•$\delta(t,m_i,\sigma)$ = ⟨move-topmost(p1,p2), move-stack(p1,p2)⟩

•[figure]

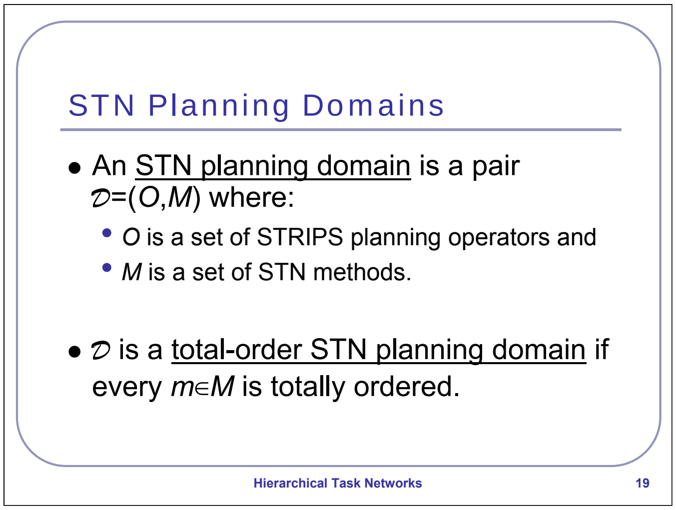
•graphical representation (called a decomposition tree):

- •view as AND/OR-graph: AND link – both subtasks need to be performed to perform super-task
- •link is labelled with substitution and method instance used
- •arrow under label indicates order in which subtasks need to be performed
- •often leave out substitution (derivable) and sometimes method parameters (to save space)



Decomposition of Tasks in STNs

- idea: applying a method to a task in a network results in another network
- **Let**
    - **$w = (U,E)$ be a STN and**
    - **$t \in U$ be a task with no predecessors in w and**
    - **m a method that is relevant for t under some substitution σ with network(m) = (U_m,E_m).**
- **The <u>decomposition of t in w by m under σ</u> is the STN $\delta(w,u,m,\sigma)$ where:**
    - **t is replaced in U by $\sigma(U_m)$ and**
        - replacement with copy (method maybe used more than once)
    - **edges in E involving t are replaced by edges to appropriate nodes in $\sigma(U_m)$.**
        - every node in $\sigma(U_m)$ should come before nodes that came after t in E
        - $\sigma(E_m)$ needs to be added to E to preserve internal method ordering
        - ordering constraints must ensure that precond(m) remains true even after subsequent decompositions

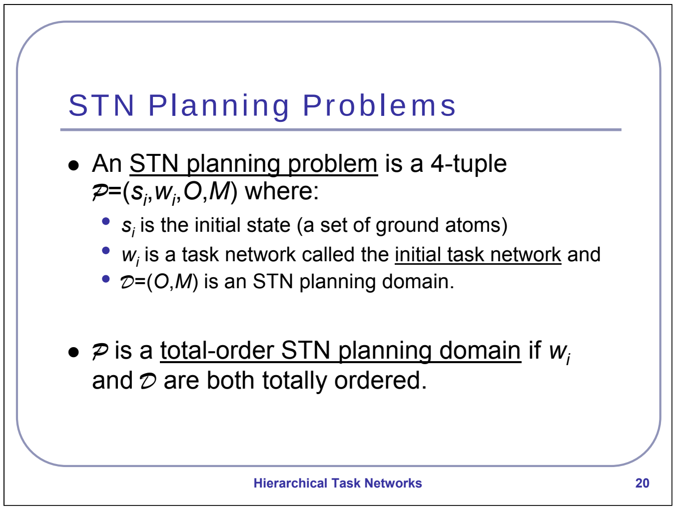


STN Planning Domains

•An <u>STN planning domain</u> is a pair $\mathcal{D}=(O,M)$ where:

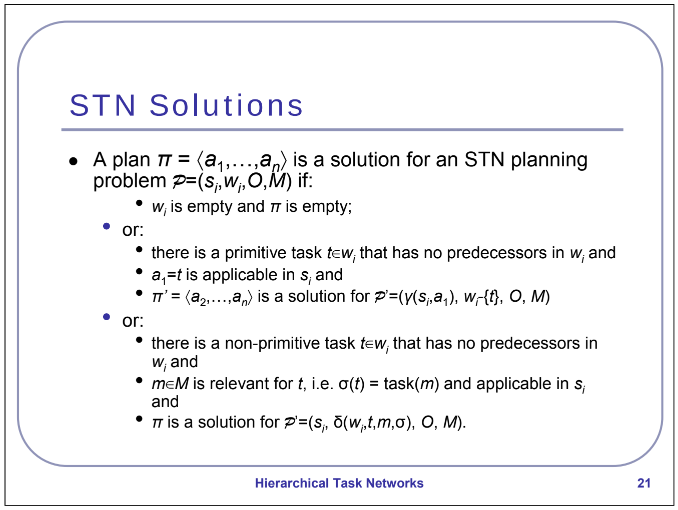
- **O is a set of STRIPS planning operators and**
- **M is a set of STN methods.**

•$\mathcal{D}$ is a <u>total-order STN planning domain</u> if every $m \in M$ is totally ordered.



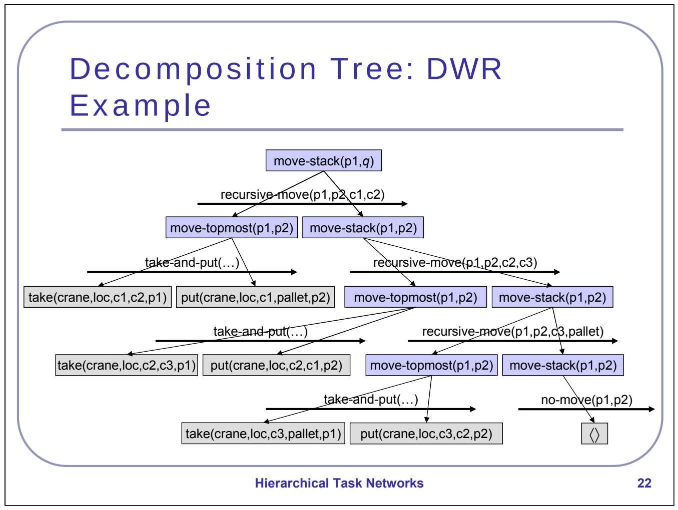
STN Planning Problems

- **An <u>STN planning problem</u> is a 4-tuple $\mathcal{P}=(s_i,w_i,O,M)$ where:**
  - **s_i is the initial state (a set of ground atoms)**
  - **w_i is a task network called the <u>initial task network</u> and**
  - **$\mathcal{D}=(O,M)$ is an STN planning domain.**
- **$\mathcal{P}$ is a <u>total-order STN planning domain</u> if w_i and $\mathcal{D}$ are both totally ordered.**



STN Solutions

- **A plan $\pi = \langle a_1,\ldots,a_n \rangle$ is a solution for an STN planning problem $\mathcal{P}=(s_i,w_i,O,M)$ if:**
  - if π is a solution for $\mathcal{P}$, then we say that <u>π accomplishes P</u>
  - intuition: there is a way to decompose w_i into π such that:
    - π is executable in s_i and
    - each decomposition is applicable in an appropriate state of the world
    - **w_i is empty and π is empty;**
  - **or:**
    - **there is a primitive task $t \in w_i$ that has no predecessors in w_i and**
    - **$a_1=t$ is applicable in s_i and**
    - **$\pi' = \langle a_2,\ldots,a_n \rangle$ is a solution for $\mathcal{P}'=(\gamma(s_i,a_1), w_i-\{t\}, O, M)$**
  - **or:**
    - **there is a non-primitive task $t \in w_i$ that has no predecessors in w_i and**
    - **$m \in M$ is relevant for t, i.e. $\sigma(t)$ = task(m) and applicable in s_i and**
    - **π is a solution for $\mathcal{P}'=(s_i, \delta(w_i,t,m,\sigma), O, M)$.**
  - 2nd and 3rd case: recursive definition
    - if w_i is not totally ordered more than one node may have no predecessors and both cases may apply



Decomposition Tree: DWR Example

•choose method: recursive-move(p1,p2,c1,c2) – binds variable *q*

•decompose into two sub-tasks

•choose method for first subtask: take-and-put: c1 from c2 onto pallet

•decompose into subtasks – primitive subtasks (grey) cannot be decomposed/correspond to actions

•choose method for second sub-task: recursive-move (recursive part)

•decompose (recursive)

•choose method and decompose (into primitive tasks): take-and-put: c2 from c3 onto c1

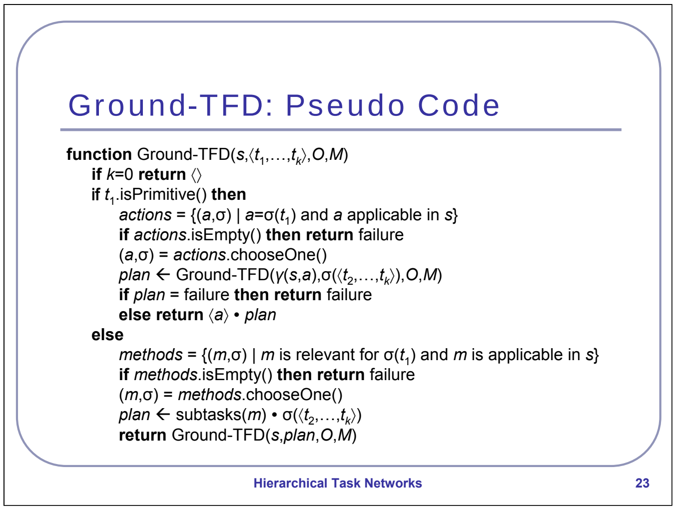
•choose method and decompose (recursive)

•choose method and decompose: take-and-put: c3 from pallet onto c2

•choose method (no-move) and decompose (empty plan)

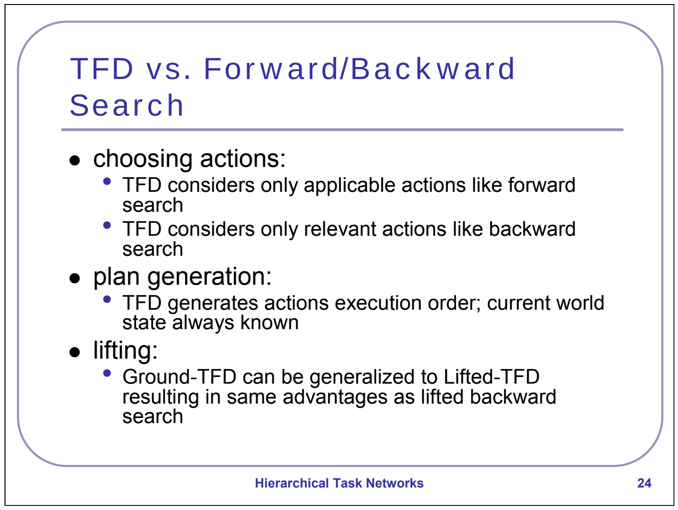
•note:

- •(grey) leaf nodes of decomposition tree (primitive tasks) are actions of solution plan
- •(blue) inner nodes represent non-primitive task; decomposition results in sub-tree rooted at task according to decomposition function δ
- •no search required in this example



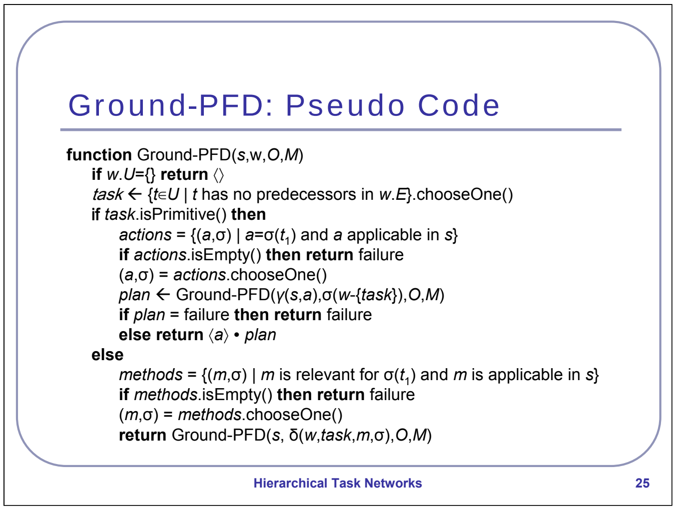
Ground-TFD: Pseudo Code

- TFD = Total-order Forward Decomposition; direct implementation of definition of STN solution
- **function Ground-TFD(*s*,⟨t_1,…,t_k⟩,*O*,*M*)**
- **if *k*=0 return ⟨⟩**
- if **t_1.isPrimitive() then**
- ***actions* = {(*a*,σ) | *a*=σ(t_1) and *a* applicable in *s*}**
- **if *actions*.isEmpty() then return failure**
- **(*a*,σ) = *actions*.chooseOne()**
- ***plan* ← Ground-TFD(γ(*s*,*a*),σ(⟨t_2,…,t_k⟩),*O*,*M*)**
- **if *plan* = failure then return failure**
- **else return ⟨*a*⟩ • *plan***
- **else** t_1 is non-primitive
- ***methods* = {(*m*,σ) | *m* is relevant for σ(t_1) and *m* is applicable in *s*}**
- **if *methods*.isEmpty() then return failure**
- **(*m*,σ) = *methods*.chooseOne()**
- ***plan* ← subtasks(*m*) • σ(⟨t_2,…,t_k⟩)**
- **return Ground-TFD(*s*,*plan*,*O*,*M*)**



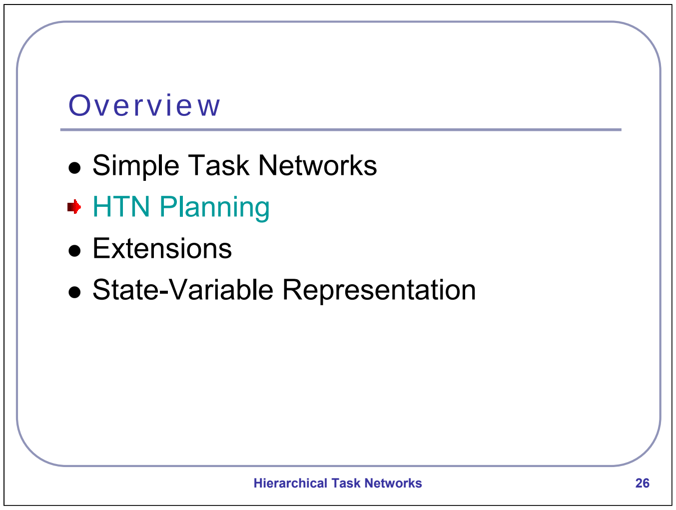
TFD vs. Forward/Backward Search

- **choosing actions:**
  - **TFD considers only applicable actions like forward search**
  - **TFD considers only relevant actions like backward search**
  - TFD combines advantages of both search directions – better efficiency
- **plan generation:**
  - **TFD generates actions execution order; current world state always known**
    - e.g. good for domain-specific heuristics
- **lifting:**
  - **Ground-TFD can be generalized to Lifted-TFD resulting in same advantages as lifted backward search**
  - avoids generating unnecessarily many actions (smaller branching factor)
  - works for initial task list that is not ground



Ground-PFD: Pseudo Code

- PFD = Partial-order Forward Decomposition; direct implementation of definition of STN solution
- **function Ground-PFD(*s*,w,*O*,*M*)**
- **if *w*.*U*={} return 〈〉**
- ***task* ← {*t*∈*U* | *t* has no predecessors in *w*.*E*}.chooseOne()**
- **if *task*.isPrimitive() then**
- ***actions* = {(*a*,σ) | *a*=σ(t_1) and *a* applicable in *s*}**
- **if *actions*.isEmpty() then return failure**
- **(*a*,σ) = *actions*.chooseOne()**
- ***plan* ← Ground-PFD(γ(*s*,*a*),σ(*w*-{*task*}),*O*,*M*)**
- **if *plan* = failure then return failure**
- **else return 〈*a*〉 • *plan***
- **else**
- ***methods* = {(*m*,σ) | *m* is relevant for σ(t_1) and *m* is applicable in *s*}**
- **if *methods*.isEmpty() then return failure**
- **(*m*,σ) = *methods*.chooseOne()**
- **return Ground-PFD(*s*, δ(*w*,*task*,*m*,σ),*O*,*M*)**



Overview

Simple Task Networks

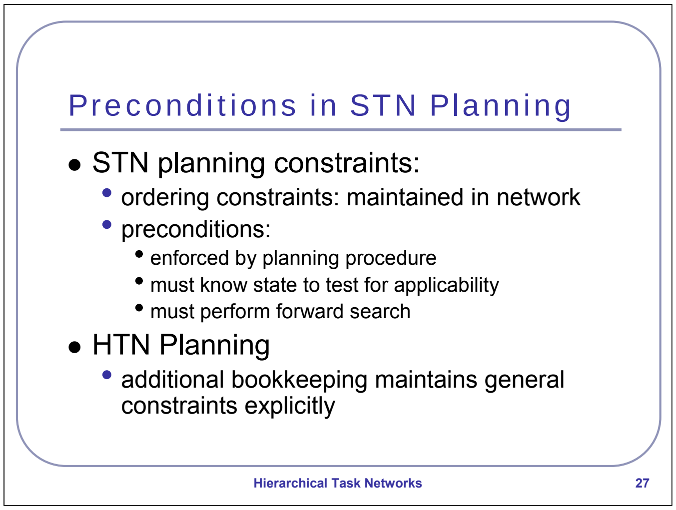
- just done: representation and planning algorithms for STNs

•**HTN Planning**

- •now: generalizing the formalism and algorithm

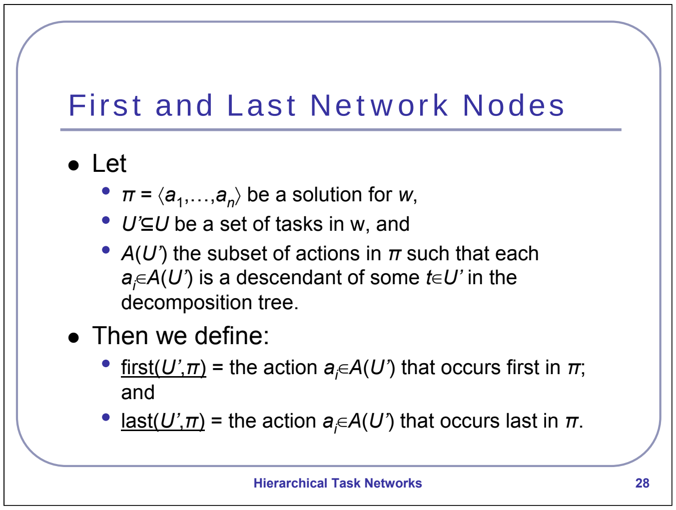
•**Extensions**

•**State-Variable Representation**



Preconditions in STN Planning

- **STN planning constraints:**
  - **ordering constraints: maintained in network**
  - **preconditions:**
    - **enforced by planning procedure**
    - **must know state to test for applicability**
    - **must perform forward search**
- **HTN Planning**
  - **additional bookkeeping maintains general constraints explicitly**



First and Last Network Nodes

•for defining the constraints in an HTN network

•**Let**

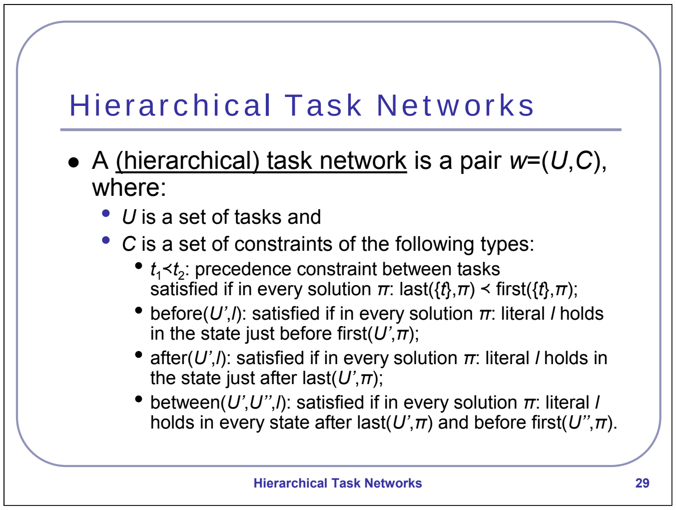
- **•$\pi = \langle a_1,\ldots,a_n \rangle$ be a solution for w,**
  - •HTN solution will be defined later
- **•$U' \subseteq U$ be a set of tasks in w, and**
- **•$A(U')$ the subset of actions in π such that each $a_i \in A(U')$ is a descendant of some $t \in U'$ in the decomposition tree.**

•**Then we define:**

- **•<u>first(U',π)</u> = the action $a_i \in A(U')$ that occurs first in π; and**
- **•<u>last(U',π)</u> = the action $a_i \in A(U')$ that occurs last in π.**

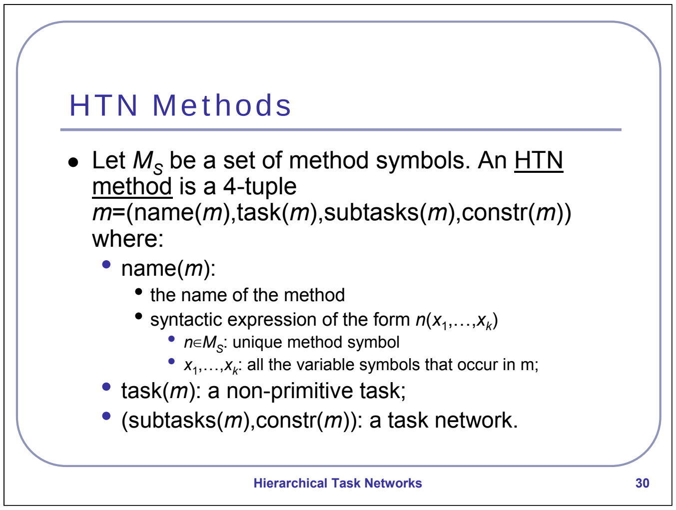
•network is partially ordered; solution is totally ordered

- •for a given set of subtasks, one action decomposing *U'* must occur first/last in the solution plan



Hierarchical Task Networks

- **A <u>(hierarchical) task network</u> is a pair w=(U,C), where:**
  - **U is a set of tasks and**
  - **C is a set of constraints of the following types:**
    - **$t_1 \prec t_2$: precedence constraint between tasks satisfied if in every solution π: last({t},π) ≺ first({t},π);**
      - corresponds to edge in STN
    - **before(U',l): satisfied if in every solution π: literal l holds in the state just before first(U',π);**
    - **after(U',l): satisfied if in every solution π: literal l holds in the state just after last(U',π);**
    - **between(U',U'',l): satisfied if in every solution π: literal l holds in every state after last(U',π) and before first(U'',π).**

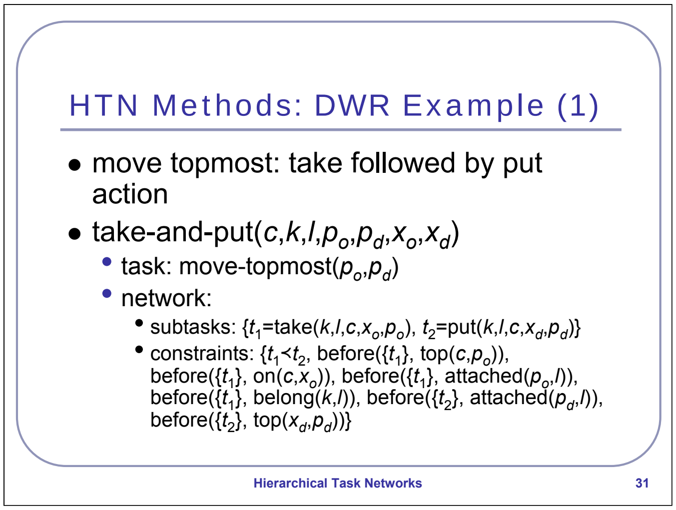


HTN Methods

•extension of the definition of an STN method

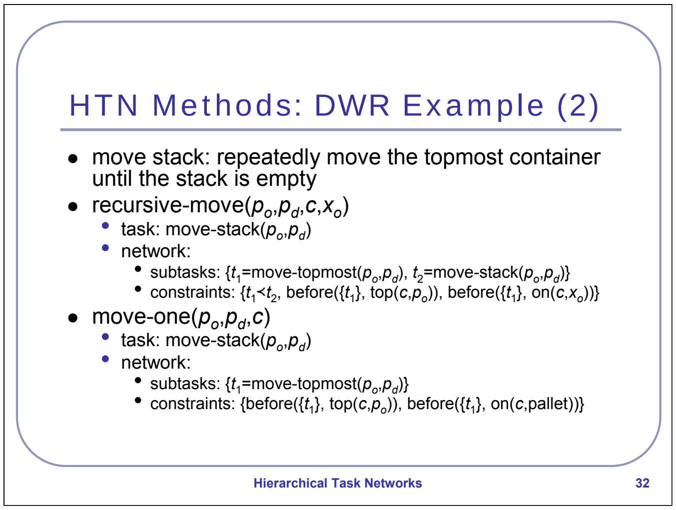
•Let M_S be a set of method symbols. An <u>HTN method</u> is a 4-tuple m=(name(m),task(m),subtasks(m),constr(m)) where:

- **•name(m):**
  - **•the name of the method**
  - **•syntactic expression of the form $n(x_1,\ldots,x_k)$**
    - **•$n \in M_S$: unique method symbol**
    - **•$x_1,\ldots,x_k$: all the variable symbols that occur in m;**
- **•task(m): a non-primitive task;**
- **•(subtasks(m),constr(m)): a task network.**



HTN Methods: DWR Example (1)

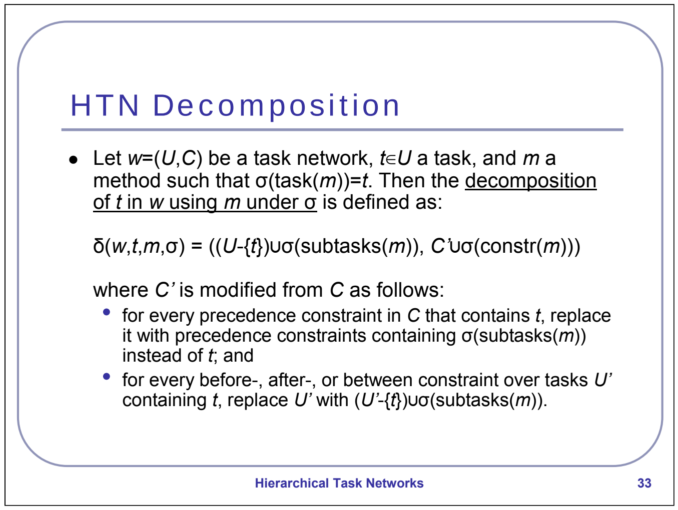
- **move topmost: take followed by put action**
- **take-and-put(c,k,l,p_o,p_d,x_o,x_d)**
  - **task: move-topmost(p_o,p_d)**
  - **network:**
    - **subtasks: {t_1=take(k,l,c,x_o,p_o), t_2=put(k,l,c,x_d,p_d)}**
    - **constraints: {$t_1 \prec t_2$, before({t_1}, top(c,p_o)), before({t_1}, on(c,x_o)), before({t_1}, attached(p_o,l)), before({t_1}, belong(k,l)), before({t_2}, attached(p_d,l)), before({t_2}, top(x_d,p_d))}**
    - note: before-constraints refer to both tasks; more precise than STN representation of preconditions



HTN Methods: DWR Example (2)

- **move stack: repeatedly move the topmost container until the stack is empty**
- **recursive-move(p_o,p_d,c,x_o)**
  - **task: move-stack(p_o,p_d)**
  - **network:**
    - **subtasks: {t_1=move-topmost(p_o,p_d), t_2=move-stack(p_o,p_d)}**
    - **constraints: {$t_1 \prec t_2$, before({t_1}, top(c,p_o)), before({t_1}, on(c,x_o))}**
- **move-one(p_o,p_d,c)**
  - **task: move-stack(p_o,p_d)**
  - **network:**
    - **subtasks: {t_1=move-topmost(p_o,p_d)}**
    - **constraints: {before({t_1}, top(c,p_o)), before({t_1}, on(c,pallet))}**
    - note: problem with no-move: cannot add before-constraint when there are no tasks

- move-stack-twice(p_o,p_i,p_d) trivial; not shown again



HTN Decomposition

•Let w=(U,C) be a task network, $t \in U$ a task, and m a method such that σ(task(m))=t. Then the <u>decomposition of t in w using m under σ</u> is defined as:
δ(w,t,m,σ) = ((U-{t})∪σ(subtasks(m)), C'∪σ(constr(m)))

- •new, additional constraints may introduce threats that need to be resolved

  where C' is modified from C as follows:

  •for every precedence constraint in C that contains t, replace it with precedence constraints containing σ(subtasks(m)) instead of t; and

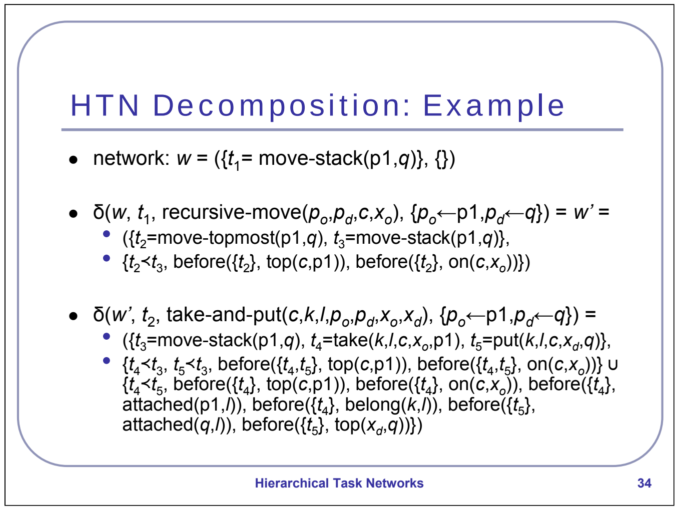
  •example: let subtasks(m)={t_1,t_2} and $t \prec t' \in C$

    - •then replace $t \prec t'$ with $t_1 \prec t'$ and $t_2 \prec t'$
    - •cannot introduce inconsistencies (circles) since subtasks are new nodes

  •for every before-, after-, or between constraint over tasks U' containing t, replace U' with (U'-{t})∪σ(subtasks(m)).

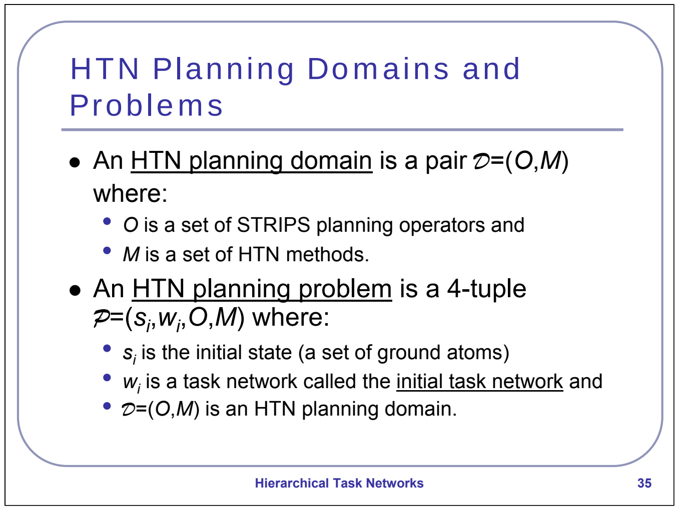
  •example (other constraints): let subtasks(m)={t_1,t_2} and before({t,t'},l)$\in C$

    - •then replace before({t,t'},l) with before({t_1,t_2,t'},l)
    - •cannot introduce inconsistencies either



HTN Decomposition: Example

- **network: w = ({t_1= move-stack(p1,q)}, {})**
  - initial, single task with no constraints
- **δ(w, t_1, recursive-move(p_o,p_d,c,x_o), {p_o←p1,p_d←q}) = w' =**
  - **({t_2=move-topmost(p1,q), t_3=move-stack(p1,q)},**
    - 2 instantiated subtasks from method
  - **{$t_2 \prec t_3$, before({t_2}, top(c,p1)), before({t_2}, on(c,x_o))})**
    - instantiated constraints from method
- **δ(w', t_2, take-and-put(c,k,l,p_o,p_d,x_o,x_d), {p_o←p1,p_d←q}) =**
  - **({t_3=move-stack(p1,q), t_4=take(k,l,c,x_o,p1), t_5=put(k,l,c,x_d,q)},**
    - t_3: from input network w'; t_4 and t_5 from method
  - **{$t_4 \prec t_3$, $t_5 \prec t_3$,**
    - ordering did involve t_2 – replace with two constraints for new subtasks t_4 and t_5
  - **before({t_4,t_5}, top(c,p1)), before({t_4,t_5}, on(c,x_o))}** ∪
    - replaced {t_2} with {t_4,t_5}
  - **{$t_4 \prec t_5$, before({t_4}, top(c,p1)), before({t_4}, on(c,x_o)), before({t_4}, attached(p1,l)), before({t_4}, belong(k,l)), before({t_5}, attached(q,l)), before({t_5}, top(x_d,q))})**
    - instantiated constraints from new method



HTN Planning Domains and Problems

- An <u>HTN planning domain</u> is a pair $\mathcal{D}=(O,M)$ where:
  - O is a set of STRIPS planning operators and
  - M is a set of HTN methods.
- An <u>HTN planning problem</u> is a 4-tuple $\mathcal{P}=(s_i,w_i,O,M)$ where:
  - s_i is the initial state (a set of ground atoms)
  - w_i is a task network called the <u>initial task network</u> and
  - $\mathcal{D}=(O,M)$ is an HTN planning domain.

Solutions for Primitive HTNs

- Let (U,C) be a primitive HTN. A plan $\pi = \langle a_1,\ldots,a_n \rangle$ is a solution for $\mathcal{P}=(s_i,(U,C),O,M)$ if there is a ground instance $(\sigma(U),\sigma(C))$ of (U,C) and a total ordering $\langle t_1,\ldots,t_n \rangle$ of tasks in $\sigma(U)$ such that:
  - for i=1…n: name(a_i) = t_i;
  - π is executable in s_i, i.e. $\gamma(s_i,\pi)$ is defined;
  - the ordering of $\langle t_1,\ldots,t_n \rangle$ respects the ordering constraints in $\sigma(C)$;
  - for every constraint before(U',l) in $\sigma(C)$ where t_k=first(U',π): l must hold in $\gamma(s_i, \langle a_1,\ldots,a_{k-1} \rangle)$;
  - for every constraint after(U',l) in $\sigma(C)$ where t_k=last(U',π): l must hold in $\gamma(s_i, \langle a_1,\ldots,a_k \rangle)$;
  - for every constraint between(U',U'',l) in $\sigma(C)$ where t_k=first(U',π) and t_m=last(U'',π): l must hold in every state $\gamma(s_i, \langle a_1,\ldots,a_j \rangle)$, $j \in \{k \ldots m-1\}$.

Solutions for Primitive HTNs

•Let (U,C) be a primitive HTN. A plan $\pi = \langle a_1,\ldots,a_n \rangle$ is a solution for $\mathcal{P}=(s_i,(U,C),O,M)$ if there is a ground instance $(\sigma(U),\sigma(C))$ of (U,C) and a total ordering $\langle t_1,\ldots,t_n \rangle$ of tasks in $\sigma(U)$ such that:

•for i=1…n: name(a_i) = t_i;

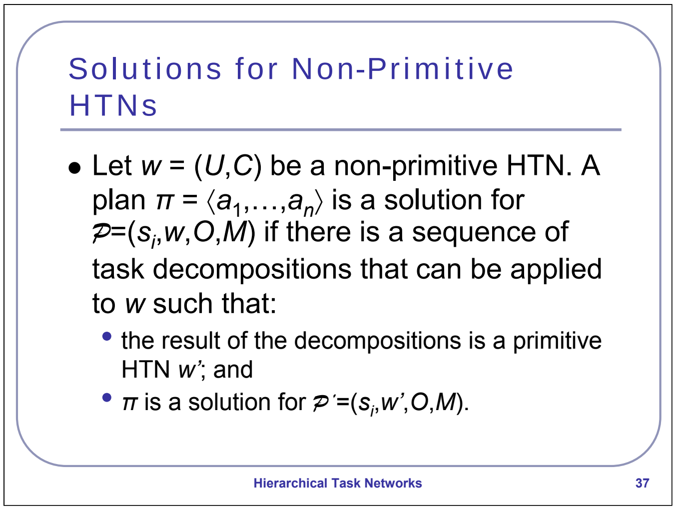
•π is executable in s_i, i.e. $\gamma(s_i,\pi)$ is defined;

•the ordering of $\langle t_1,\ldots,t_n \rangle$ respects the ordering constraints in $\sigma(C)$;

•for every constraint before(U',l) in $\sigma(C)$ where t_k=first(U',π): l must hold in $\gamma(s_i, \langle a_1,\ldots,a_{k-1} \rangle)$;

•for every constraint after(U',l) in $\sigma(C)$ where t_k=last(U',π): l must hold in $\gamma(s_i, \langle a_1,\ldots,a_k \rangle)$;

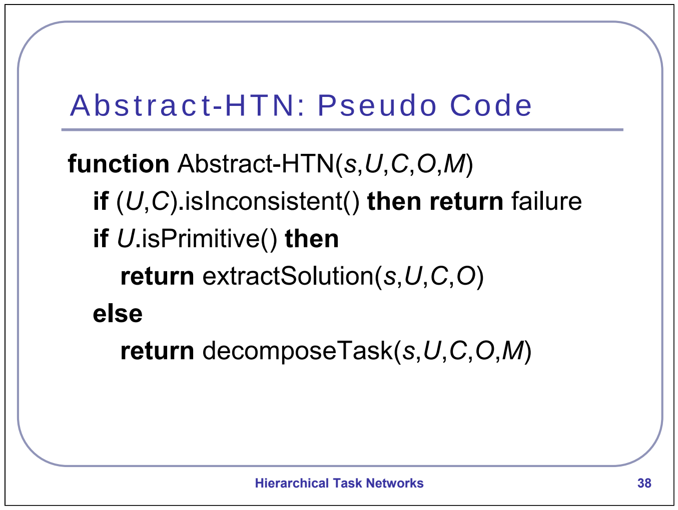
•for every constraint between(U',U'',l) in $\sigma(C)$ where t_k=first(U',π) and t_m=last(U'',π): l must hold in every state $\gamma(s_i, \langle a_1,\ldots,a_j \rangle)$, $j \in \{k \ldots m-1\}$.



Solutions for Non-Primitive HTNs

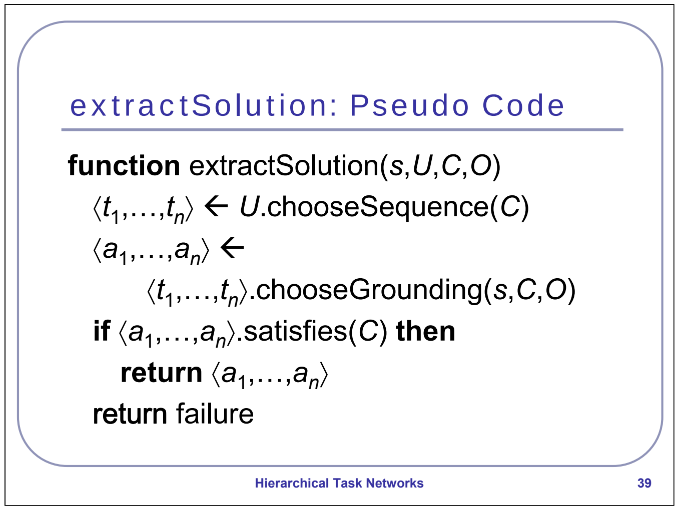
•Let w = (U,C) be a non-primitive HTN. A plan $\pi = \langle a_1,\ldots,a_n \rangle$ is a solution for $\mathcal{P}=(s_i,w,O,M)$ if there is a sequence of task decompositions that can be applied to w such that:

- **the result of the decompositions is a primitive HTN w'; and**
- **π is a solution for $\mathcal{P}'=(s_i,w',O,M)$.**



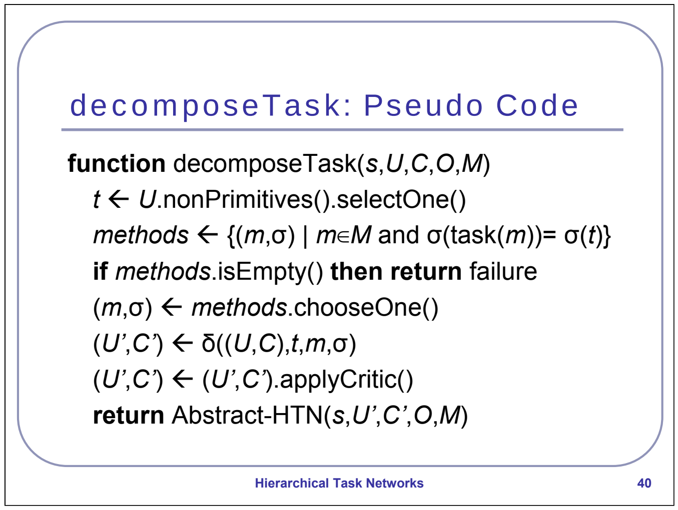
Abstract-HTN: Pseudo Code

- general schema for a function that implements HTN planning
- **function Abstract-HTN(*s*,*U*,*C*,*O*,*M*)**
- **if (*U*,*C*).isInconsistent() then return failure**
    - e.g. test for inconsistency of *C*, or apply other, domain-specific tests
- **if *U*.isPrimitive() then**
    - no further decompositions of tasks possible
- **return extractSolution(*s*,*U*,*C*,*O*)**
    - compute a total-order, grounded plan; may fail
- **else**
    - network still contains decomposable tasks
- **return decomposeTask(*s*,*U*,*C*,*O*,*M*)**
    - will recursively call Abstract-HTN function



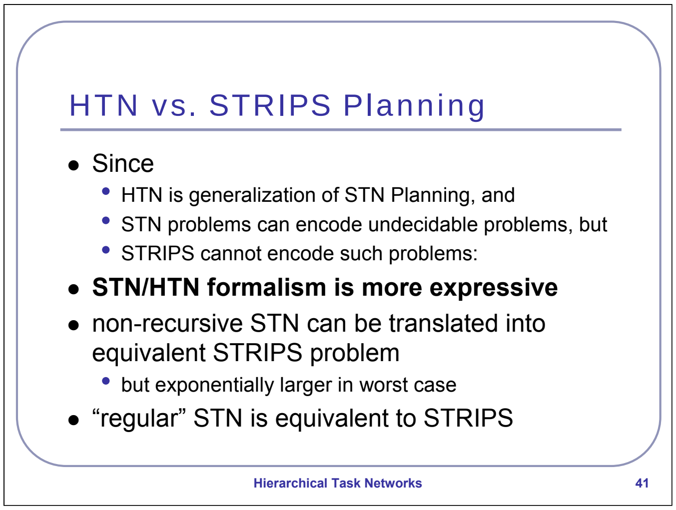
extractSolution: Pseudo Code

- **function extractSolution(s,U,C,O)**
- **$\langle t_1,\ldots,t_n\rangle \leftarrow U$.chooseSequence($C$)**
    - non-deterministically choose a serialization of the tasks in U that respects the ordering constraints in C
- **$\langle a_1,\ldots,a_n\rangle \leftarrow \langle t_1,\ldots,t_n\rangle$.chooseGrounding($s$,$C$,$O$)**
    - non-deterministically choose a grounding of the variables in $t_1,\ldots,t_n$
        - use s and C to ensure constraints hold, and O for type information if present
- **if $\langle a_1,\ldots,a_n\rangle$.satisfies($C$) then**
    - this test can be performed during the grounding
- **return $\langle a_1,\ldots,a_n\rangle$**
    - plan is a solution, return it
- **return failure**



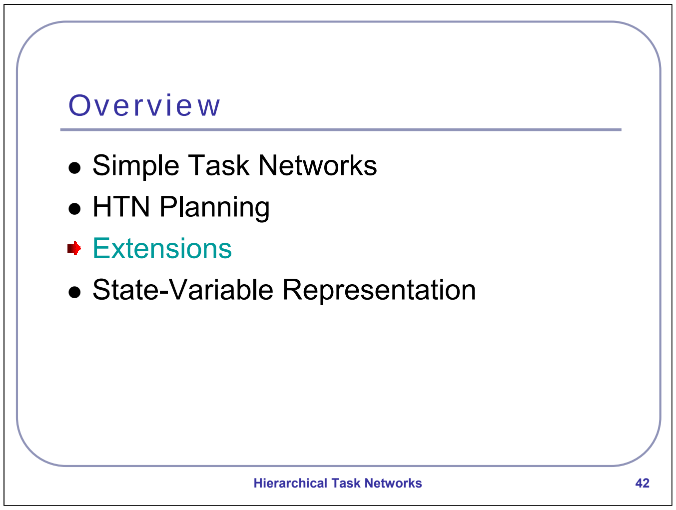
decomposeTask: Pseudo Code

- **function decomposeTask(*s*,*U*,*C*,*O*,*M*)**
- ***t* ← *U*.nonPrimitives().selectOne()**
    - deterministically select a non-primitive task-node from the network
        - no backtracking required, all tasks must be decomposed eventually; selection important for efficiency
- ***methods* ← {(*m*,σ) | *m*∈*M* and σ(task(*m*))= σ(*t*)}**
    - substitution should be mgu for least commitment planner (generates smaller search space)
- **if *methods*.isEmpty() then return failure**
- **(*m*,σ) ← *methods*.chooseOne()**
    - non-deterministically choose a method that can be applied to decompose the task
- **(*U'*,*C'*) ← δ((*U*,*C*),*t*,*m*,σ)**
    - compute the decomposition
- **(*U'*,*C'*) ← (*U'*,*C'*).applyCritic()**
    - optional; may make arbitrary modifications, e.g. application-specific computations
    - soundness and completeness depends on this function
- **return Abstract-HTN(*s*,*U'*,*C'*,*O*,*M*)**



HTN vs. STRIPS Planning

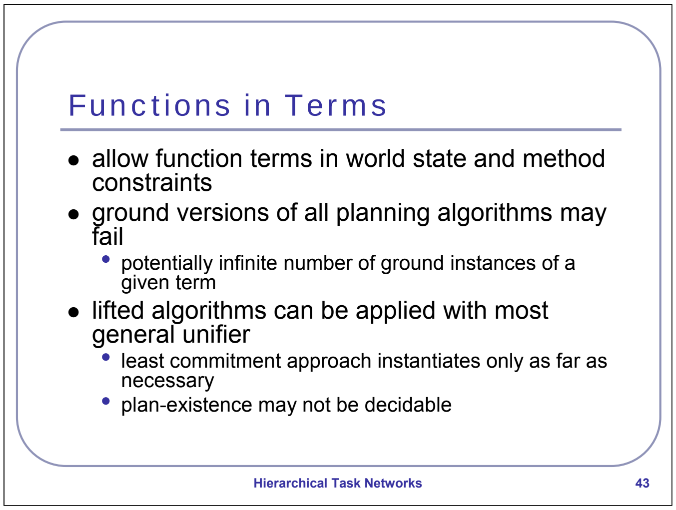
- **Since**
  - **HTN is generalization of STN Planning, and**
  - **STN problems can encode undecidable problems, but**
  - **STRIPS cannot encode such problems:**
- **STN/HTN formalism is more expressive**
- **non-recursive STN can be translated into equivalent STRIPS problem**
  - **but exponentially larger in worst case**
- **"regular" STN is equivalent to STRIPS**
  - non-recursive
  - at most one non-primitive subtask per method
  - non-primitive sub-task must be last in sequence



Overview

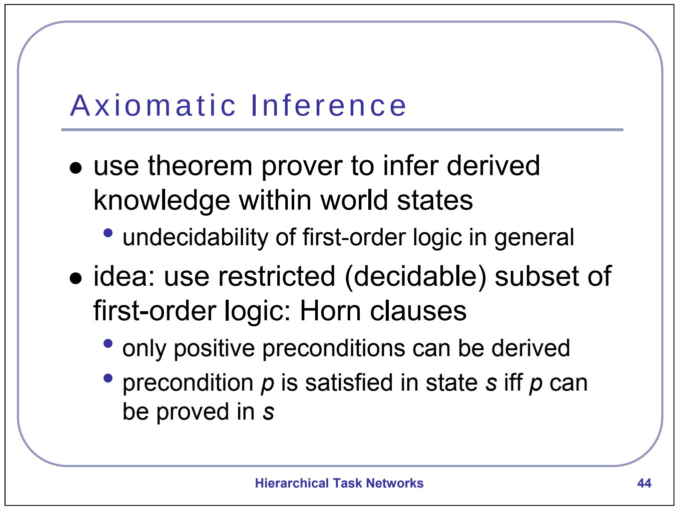
Simple Task Networks

- **HTN Planning**
  - just done: generalizing the formalism and algorithm
- **Extensions**
  - now: approaches to extending the formalism and algorithm
- **State-Variable Representation**



Functions in Terms

- **allow function terms in world state and method constraints**
- **ground versions of all planning algorithms may fail**
  - **potentially infinite number of ground instances of a given term**
- **lifted algorithms can be applied with most general unifier**
  - **least commitment approach instantiates only as far as necessary**
  - **plan-existence may not be decidable**



Axiomatic Inference

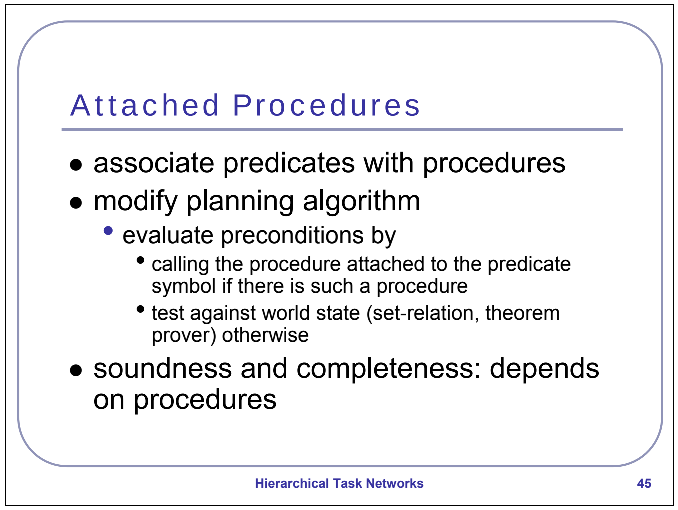
•use theorem prover to infer derived knowledge within world states

- **•undecidability of first-order logic in general**

•idea: use restricted (decidable) subset of first-order logic: Horn clauses

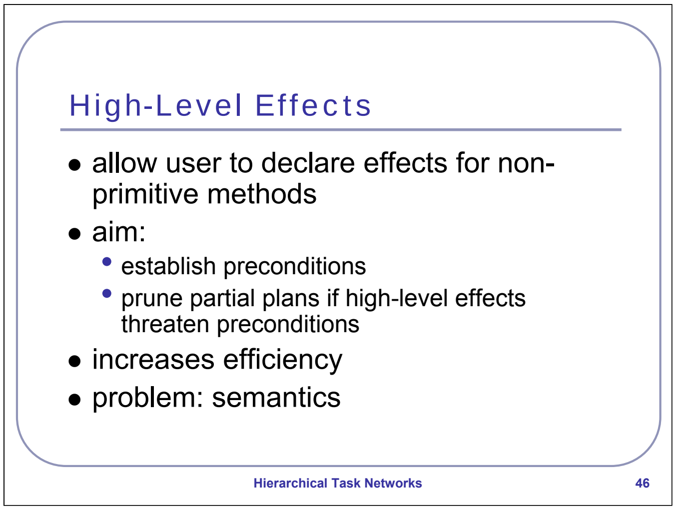
- **•only positive preconditions can be derived**
- **•precondition *p* is satisfied in state *s* iff *p* can be proved in *s***

•semantics of negative preconditions: closed world assumption?



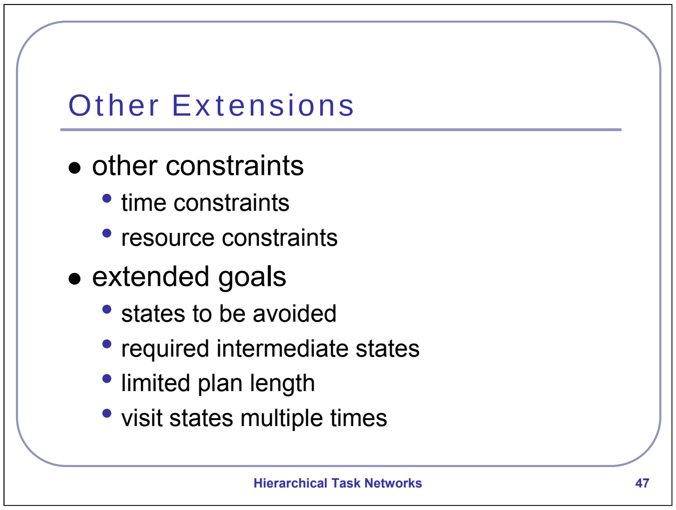
Attached Procedures

- **associate predicates with procedures**
- **modify planning algorithm**
  - **evaluate preconditions by**
    - **calling the procedure attached to the predicate symbol if there is such a procedure**
    - **test against world state (set-relation, theorem prover) otherwise**
- applications:
  - perform numeric computations
  - query external data sources
- **soundness and completeness: depends on procedures**
- attached procedures to function symbols: critics



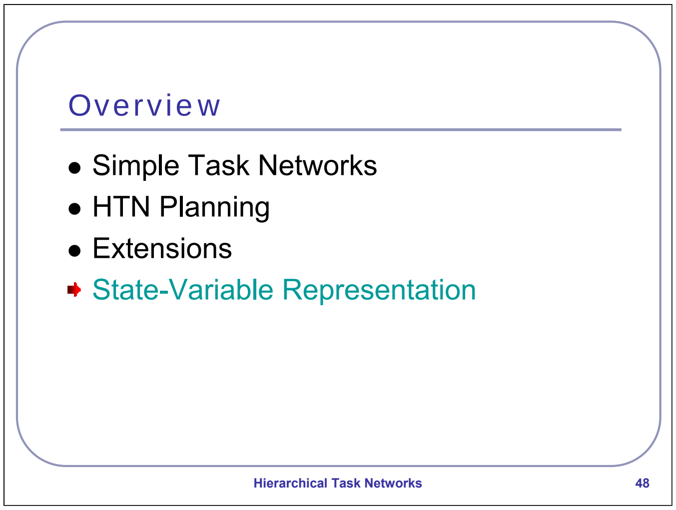
High-Level Effects

- **allow user to declare effects for non-primitive methods**
- **aim:**
  - **establish preconditions**
  - **prune partial plans if high-level effects threaten preconditions**
- **increases efficiency**
- **problem: semantics**
  - can be defined in different ways



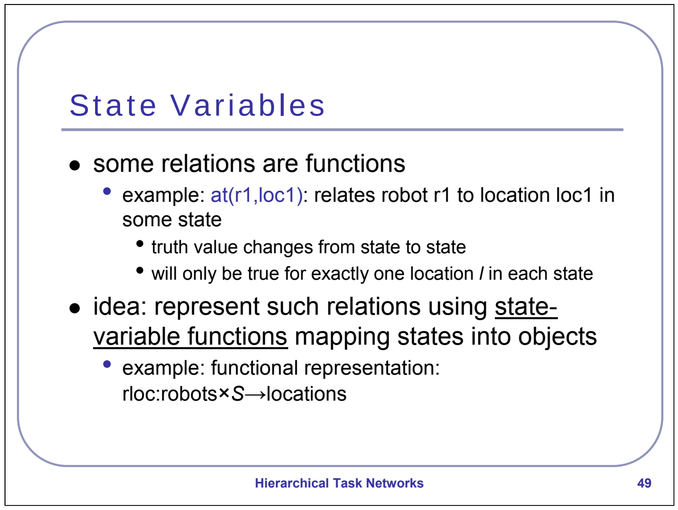
Other Extensions

- **other constraints**
  - **time constraints**
  - **resource constraints**
- **extended goals**
  - **states to be avoided**
  - **required intermediate states**
  - **limited plan length**
  - **visit states multiple times**



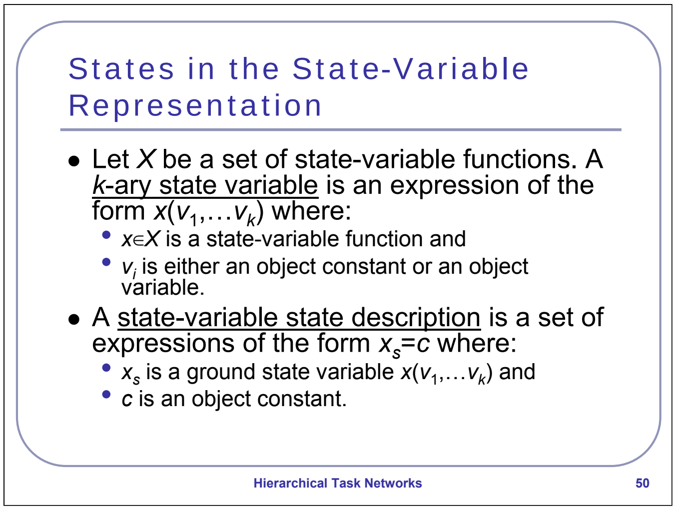
Overview

- **Simple Task Networks**
- **HTN Planning**
- **Extensions**
  - just done: approaches to extending the formalism and algorithm
- **State-Variable Representation**
  - now: different style of representation (used in O-Plan/I-Plan)



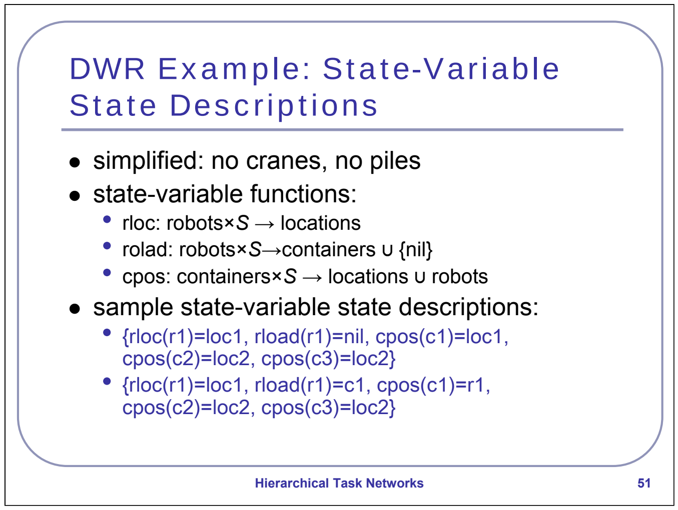
State Variables

- **some relations are functions**
  - **example: at(r1,loc1): relates robot r1 to location loc1 in some state**
    - **truth value changes from state to state**
    - **will only be true for exactly one location *l* in each state**
      - STRIPS state containing at(r1,loc1) and at(r1,loc2) usually inconsistent
- **idea: represent such relations using <u>state-variable functions</u> mapping states into objects**
  - advantage: reduces possibilities for inconsistent states, smaller state space
  - **example: functional representation: rloc:robots×*S*→locations**
    - in general: maps objects and state into object
    - rloc is state-variable symbol that denotes state-variable function



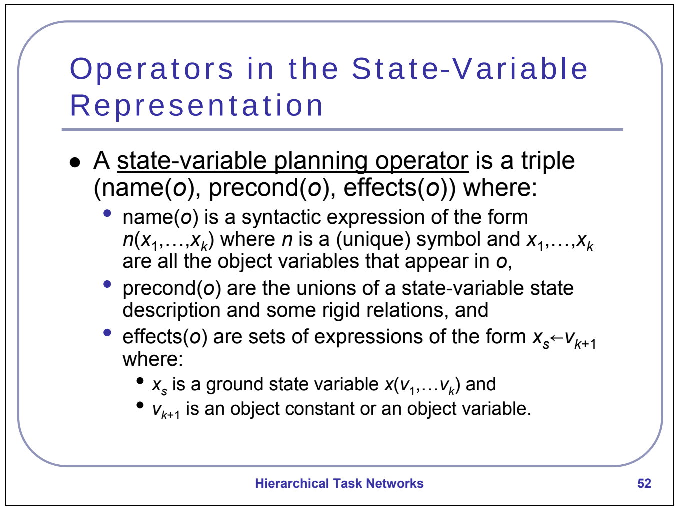
States in the State-Variable Representation

- **Let X be a set of state-variable functions. A <u>k-ary state variable</u> is an expression of the form $x(v_1,\dots v_k)$ where:**
    - **$x \in X$ is a state-variable function and**
    - **v_i is either an object constant or an object variable.**
        - object variables as opposed to state variables
        - ground if all v_i are object constants
        - additionally: v_i may be typed
    - state variable is a characteristic attribute of a state
- **A <u>state-variable state description</u> is a set of expressions of the form x_s=c where:**
    - **x_s is a ground state variable $x(v_1,\dots v_k)$ and**
    - **c is an object constant.**
    - as for ground atoms in STRIPS states, state is implicit
    - state description will usually give all values of ground state variables
    - values of state variables are not independent



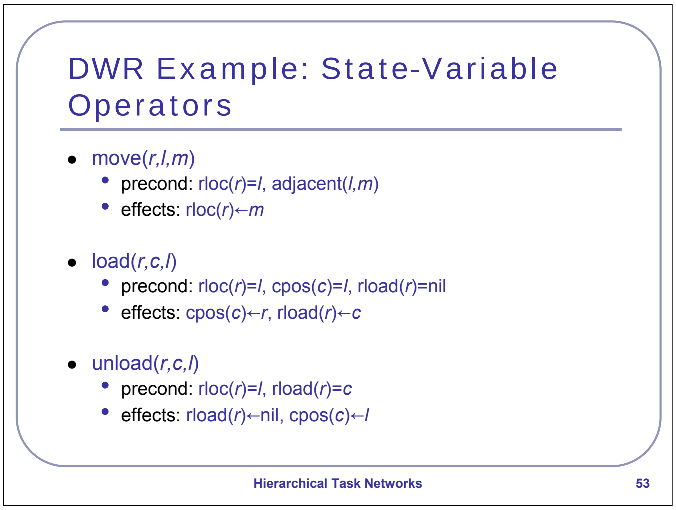
DWR Example: State-Variable State Descriptions

- **simplified: no cranes, no piles**
  - robots can load and unload containers autonomously
- **state-variable functions:**
  - **rloc: robots×*S* → locations**
    - location of a robot in a state
  - **rolad: robots×*S*→containers ∪ {nil}**
    - what a robot has loaded in a state; nil for nothing loaded
  - **cpos: containers×*S* → locations ∪ robots**
    - where a container is in a state; at a location or on some robot
- sample state-variable state descriptions:
  - {rloc(r1)=loc1, rload(r1)=nil, cpos(c1)=loc1, cpos(c2)=loc2, cpos(c3)=loc2}
  - {rloc(r1)=loc1, rload(r1)=c1, cpos(c1)=r1, cpos(c2)=loc2, cpos(c3)=loc2}



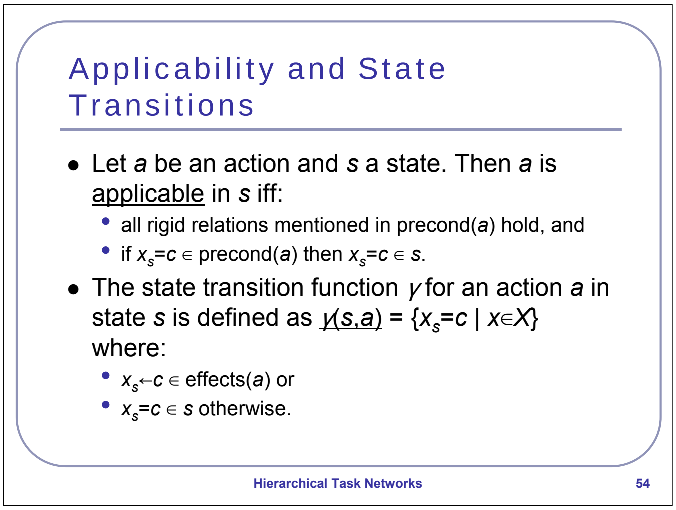
Operators in the State-Variable Representation

- **A <u>state-variable planning operator</u> is a triple (name(*o*), precond(*o*), effects(*o*)) where:**
    - **name(*o*) is a syntactic expression of the form $n(x_1,\ldots,x_k)$ where n is a (unique) symbol and $x_1,\ldots,x_k$ are all the object variables that appear in *o*,**
        - looks like name of a STRIPS planning operator
    - **precond(*o*) are the unions of a state-variable state description and some rigid relations, and**
        - set of state variable equals value expressions and some rigid relations (as in STRIPS operators)
        - values of state variables refer to state before the operator is applied
    - **effects(*o*) are sets of expressions of the form $x_s \leftarrow v_{k+1}$ where:**
        - **x_s is a ground state variable $x(v_1,\ldots v_k)$ and**
        - **v_{k+1} is an object constant or an object variable.**
        - similar to state but assignment operator instead of equals sign
        - updates in effects refer to state after operator is applied
- as for STRIPS operators, actions are ground instances of operators



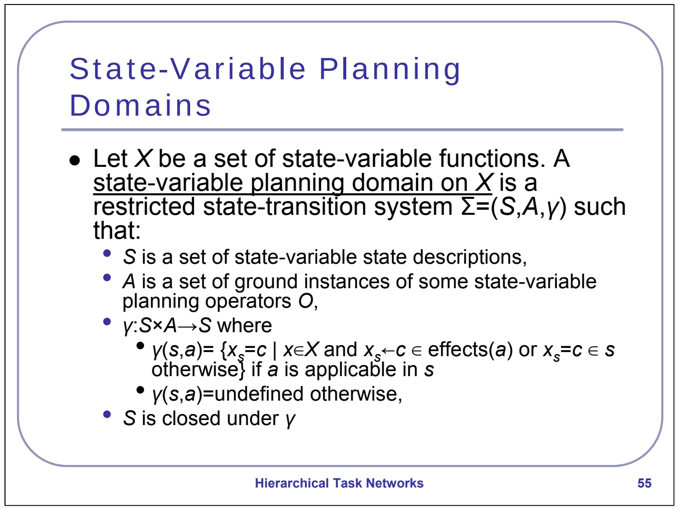
DWR Example: Operators

- simplified domain: no piles, no cranes – only three operators:
- **move(*r*,*l*,*m*)**
    - move robot *r* from location *l* to adjacent location *m*
    - **precond: rloc(*r*)=*l*, adjacent(*l*,*m*)**
        - adjacent: rigid relation
    - **effects: rloc(*r*)←*m***
- **load(*r*,*c*,*l*)**
    - robot *r* loads container *c* at location *l*
    - **precond: rloc(*r*)=*l*, cpos(*c*)=*l*, rload(*r*)=nil**
    - **effects: cpos(*c*)←*r*, rload(*r*)←*c***
- unload(***r*,*c*,*l***)
    - robot *r* unloads container *c* at location *l*
    - precond: **rloc(*r*)=*l*, rload(*r*)=*c***
    - effects: **rload(*r*)←nil, cpos(*c*)←*l***



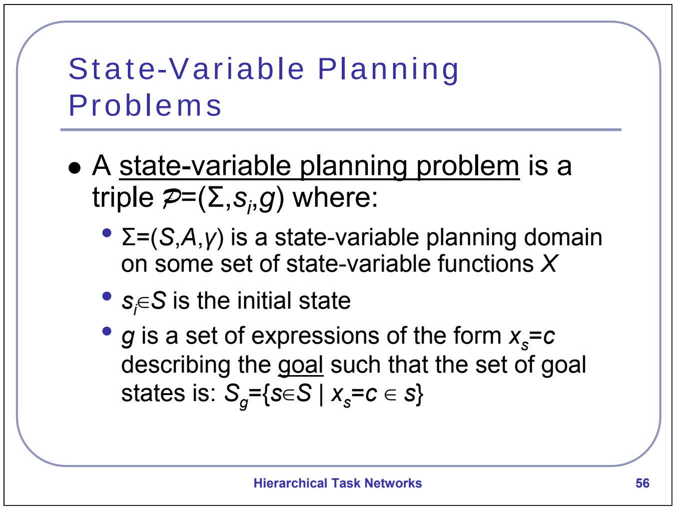
Applicability and State Transitions

- **Let *a* be an action and *s* a state. Then *a* is <u>applicable</u> in *s* iff:**
  - **all rigid relations mentioned in precond(*a*) hold, and**
    - as in STRIPS representation
  - **if $x_s = c \in$ precond(a) then $x_s = c \in s$.**
    - if values of state variables in preconditions agree with same values in state
- **The state transition function γ for an action *a* in state *s* is defined as $\underline{\gamma(s,a)} = \{x_s = c \mid x \in X\}$ where:**
  - **$x_s \leftarrow c \in$ effects(a) or**
    - update the values of state variables in the effects
  - **$x_s = c \in s$ otherwise.**
    - keep other values from previous state



State-Variable Planning Domains

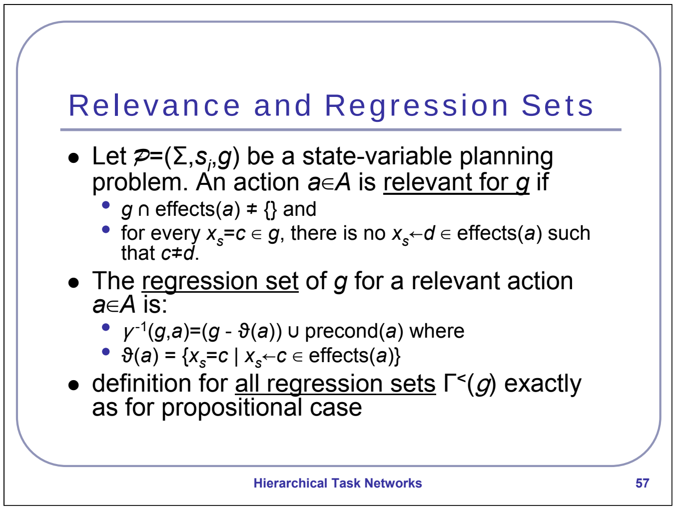
- **Let *X* be a set of state-variable functions. A state-variable planning domain on *X* is a restricted state-transition system Σ=(*S*,*A*,*γ*) such that:**
  - ***S* is a set of state-variable state descriptions,**
  - ***A* is a set of ground instances of some state-variable planning operators *O*,**
  - ***γ*:*S*×*A*→*S* where**
    - **$\gamma(s,a) = \{x_s = c \mid x \in X$ and $x_s \leftarrow c \in$ effects(a) or $x_s = c \in s$ otherwise} if *a* is applicable in *s***
    - **$\gamma(s,a)$=undefined otherwise,**
  - ***S* is closed under *γ***



State-Variable Planning Problems

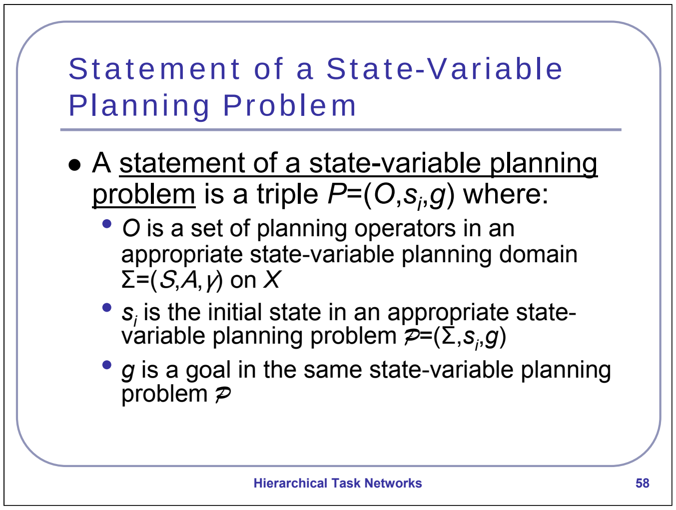
- **A <u>state-variable planning problem</u> is a triple $\mathcal{P}=(\Sigma,s_i,g)$ where:**
  - **$\Sigma=(S,A,\gamma)$ is a state-variable planning domain on some set of state-variable functions X**
  - **$s_i \in S$ is the initial state**
  - **g is a set of expressions of the form $x_s=c$ describing the <u>goal</u> such that the set of goal states is: $S_g=\{s \in S \mid x_s=c \in s\}$**
    - a goal is a specification of the values of some ground state variables
    - goals are like preconditions without rigid relations

- definitions for plan, reachable states, and solutions as for propositional case



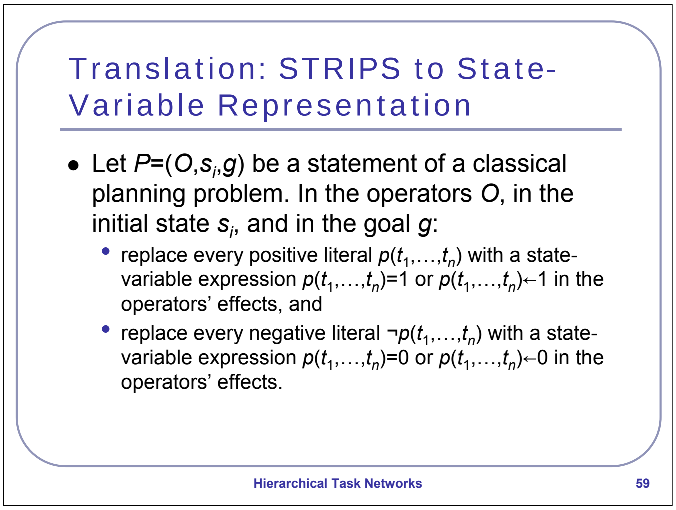
Relevance and Regression Sets

- **Let $\mathcal{P}=(\Sigma,s_i,g)$ be a state-variable planning problem. An action $a \in A$ is <u>relevant for *g*</u> if**
    - **$g \cap$ effects(a) ≠ {} and**
        - *a* has an effect that contributes to *g*
    - **for every $x_s=c \in g$, there is no $x_s \leftarrow d \in$ effects(a) such that $c \neq d$.**
        - effects of *a* do not change any of the state variables in *g*
- **The <u>regression set</u> of *g* for a relevant action $a \in A$ is:**
    - **$\gamma^{-1}(g,a)=(g - \vartheta(a)) \cup$ precond(a) where**
    - **$\vartheta(a) = \{x_s=c \mid x_s \leftarrow c \in$ effects(a)$\}$**
        - necessary to change syntax: replace left arrow with equals sign
        - otherwise definition is as before
- **definition for <u>all regression sets</u> $\Gamma^{<}(g)$ exactly as for propositional case**



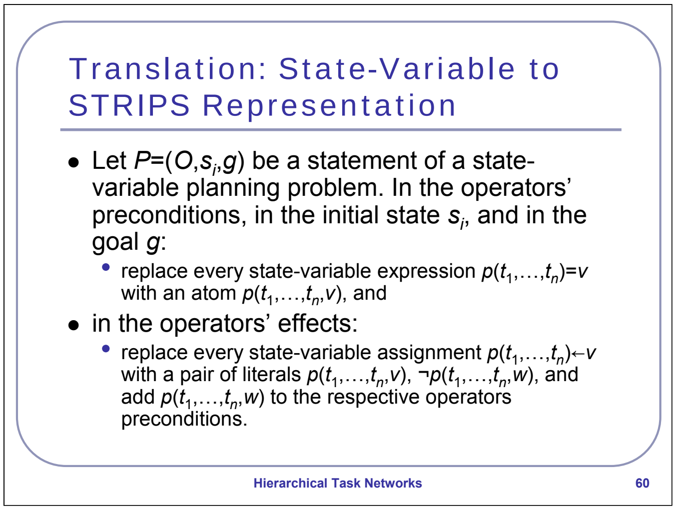
Statement of a State-Variable Planning Problem

- **A <u>statement of a state-variable planning problem</u> is a triple $P=(O,s_i,g)$ where:**
  - **O is a set of planning operators in an appropriate state-variable planning domain $\Sigma=(S,A,\gamma)$** on **X**
  - **s_i is the initial state in an appropriate state-variable planning problem $\mathcal{P}=(\Sigma,s_i,g)$**
  - **g** is a goal **in the same state-variable planning problem $\mathcal{P}$**



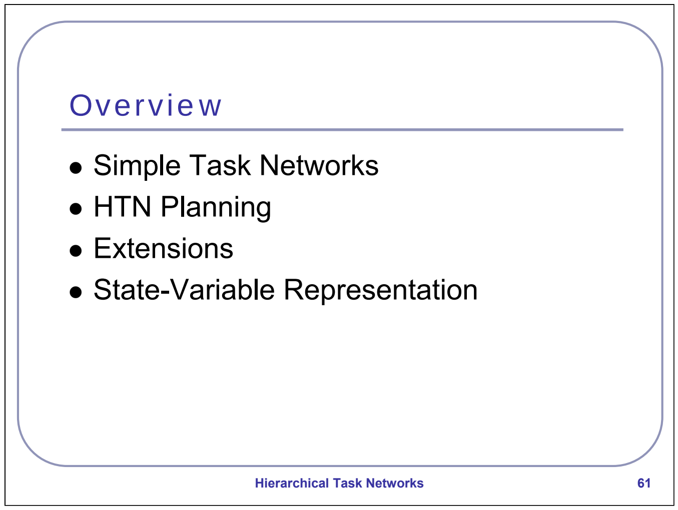
Translation: STRIPS to State-Variable Representation

- **Let $P=(O,s_i,g)$ be a statement of a classical planning problem. In the operators O, in the initial state s_i, and in the goal g:**
    - **replace every positive literal $p(t_1,\ldots,t_n)$ with a state-variable expression $p(t_1,\ldots,t_n)=1$ or $p(t_1,\ldots,t_n)\leftarrow 1$ in the operators' effects, and**
    - **replace every negative literal $\neg p(t_1,\ldots,t_n)$ with a state-variable expression $p(t_1,\ldots,t_n)=0$ or $p(t_1,\ldots,t_n)\leftarrow 0$ in the operators' effects.**
- result is a statement of a state-variable planning problem



Translation: State-Variable to STRIPS Representation

- **Let $P=(O,s_i,g)$ be a statement of a state-variable planning problem. In the operators' preconditions, in the initial state s_i, and in the goal g:**
  - **replace every state-variable expression $p(t_1,\ldots,t_n)=v$ with an atom $p(t_1,\ldots,t_n,v)$, and**
- **in the operators' effects:**
  - **replace every state-variable assignment $p(t_1,\ldots,t_n)\leftarrow v$ with a pair of literals $p(t_1,\ldots,t_n,v)$, $\neg p(t_1,\ldots,t_n,w)$, and add $p(t_1,\ldots,t_n,w)$ to the respective operators preconditions.**
- result is a statement of a STRIPS planning problem



Overview

➨**Simple Task Networks**

•**HTN Planning**

•**Extensions**

•**State-Variable Representation**

- •just done: different style of representation (used in O-Plan/I-Plan)