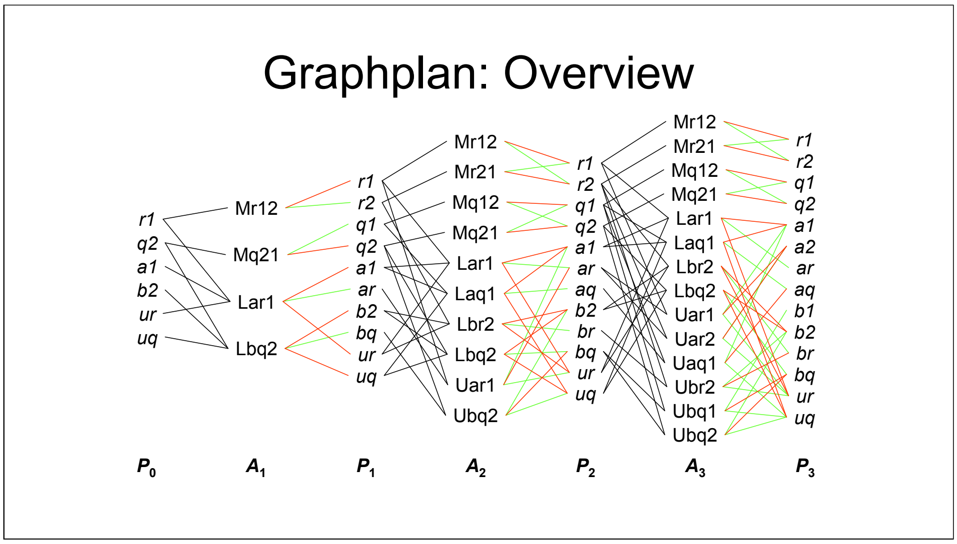
Artificial Intelligence Planning

Graphplan

Artificial Intelligence Planning

- **Graphplan**



Graphplan: Overview

•given a propositional planning domain and problem

•step 1: extend the graph with 2 layers (forward, left to right)

- edges shown are preconditions and effects
- other edges (not shown) express mutual exclusivity
- worst-case time complexity is polynomial

•step 2: search for a plan in the graph

- search backwards (right to left)
- worst-case time complexity is exponential

•repeat steps 1 and 2

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- A Propositional DWR Example
- The Basic Planning Graph (No Mutex)
- Layered Plans
- Mutex Propositions and Actions
- Forward Planning Graph Expansion
- Backwards Search in the Planning Graph
- The Graphplan Algorithm

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➢A Propositional DWR Example

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Classical Representations

- propositional representation
  - world state is set of propositions
  - action consists of precondition propositions, propositions to be added and removed
- STRIPS representation
  - like propositional representation, but first-order literals instead of propositions
- state-variable representation
  - state is tuple of state variables $\{x_1,\ldots,x_n\}$
  - action is partial function over states

Classical Representations

•**propositional representation**

•**world state is set of propositions**

•**action consists of precondition propositions, propositions to be added and removed**

•**STRIPS representation**

•named after STRIPS planner

•**like propositional representation, but first-order literals instead of propositions**

•most popular for restricted state-transitions systems

•**state-variable representation**

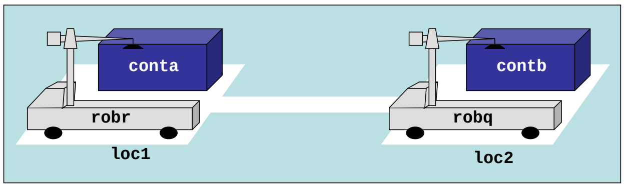
•**state is tuple of state variables $\{x_1,\ldots,x_n\}$**

•**action is partial function over states**

•useful where state is characterized by attributes over finite domains

•equally expressive: planning domain in one representation can also be represented in the others

Example: Simplified DWR Problem



- robots can load and unload autonomously
- locations may contain unlimited number of robots and containers
- problem: swap locations of containers

Example: Simplified DWR Problem

•[figure]

•initial state:

•2 locations: loc1 and loc2, connected by path

•2 robots: robr and robq, both unloaded initially at loc1 and loc2 respectively

•2 containers: conta and contb, initially at loc1 and loc2 respectively

•robots can load and unload autonomously

•locations may contain unlimited number of robots and containers

•problem: swap locations of containers

Simplified DWR Problem: STRIPS Operators

- move(*r*,*l*,*l'*)
  - precond: at(*r*,*l*), adjacent(*l*,*l'*)
  - effects: at(*r*,*l'*), ¬at(r,*l*)
- load(*c*,*r*,*l*)
  - precond: at(*r*,*l*), in(*c*,*l*), unloaded(*r*)
  - effects: loaded(*r*,*c*), ¬in(*c*,*l*), ¬unloaded(*r*)
- unload(*c*,*r*,*l*)
  - precond: at(*r*,*l*), loaded(*r*,*c*)
  - effects: unloaded(*r*), in(*c*,*l*), ¬loaded(*r*,*c*)

Simplified DWR Problem: STRIPS Actions

•**move(*r*,*l*,*l'*)**

•move robot *r* from location *l* to adjacent location *l'* (4 possible actions; with rigid adjacent relation evaluated)

•**precond: at(*r*,*l*), adjacent(*l*,*l'*)**

•**effects: at(*r*,*l'*), ¬at(r,*l*)**

•**load(*c*,*r*,*l*)**

•load container *c* onto robot *r* at location *l* (8 possible actions)

•**precond: at(*r*,*l*), in(*c*,*l*), unloaded(*r*)**

•**effects: loaded(*r*,*c*), ¬in(*c*,*l*), ¬unloaded(*r*)**

•**unload(*c*,*r*,*l*)**

•unload container *c* from robot *r* at location *l* (8 possible actions)

•**precond: at(*r*,*l*), loaded(*r*,*c*)**

•**effects: unloaded(*r*), in(*c*,*l*), ¬loaded(*r*,*c*)**

Simplified DWR Problem: State Proposition Symbols

- robots:
  - *r1* and *r2*: at(robr,loc1) and at(robr,loc2)
  - *q1* and *q2*: at(robq,loc1) and at(robq,loc2)
  - *ur* and *uq*: unloaded(robr) and unloaded(robq)
- containers:
  - *a1*, *a2*, *ar*, and *aq*: in(conta,loc1), in(conta,loc2), loaded(conta,robr), and loaded(conta,robq)
  - *b1*, *b2*, *br*, and *bq*: in(contb,loc1), in(contb,loc2), loaded(contb,robr), and loaded(contb,robq)
- initial state: {*r1*, *q2*, *a1*, *b2, ur, uq*}

Simplified DWR Problem: State Proposition Symbols

•idea: represent each atom that may occur in a state by a single (short) proposition symbol

•robots:

> **•*r1* and *r2*: at(robr,loc1) and at(robr,loc2)**
>
> **•*q1* and *q2*: at(robq,loc1) and at(robq,loc2)**
>
> **•*ur* and *uq*: unloaded(robr) and unloaded(robq)**

•containers:

> **•*a1*, *a2*, *ar*, and *aq*: in(conta,loc1), in(conta,loc2), loaded(conta,robr), and loaded(conta,robq)**
>
> **•*b1*, *b2*, *br*, and *bq*: in(contb,loc1), in(contb,loc2), loaded(contb,robr), and loaded(contb,robq)**

•14 state propositions

•initial state: {*r1*, *q2*, *a1*, *b2, ur, uq*}

Simplified DWR Problem: Action Symbols

- move actions:
  - Mr12: move(robr,loc1,loc2), Mr21: move(robr,loc2,loc1), Mq12: move(robq,loc1,loc2), Mq21: move(robq,loc2,loc1)
- load actions:
  - Lar1: load(conta,robr,loc1); Lar2, Laq1, Laq2, Lbr1, Lbr2, Lbq1, and Lbq2 correspondingly
- unload actions:
  - Uar1: unload(conta,robr,loc1); Uar2, Uaq1, Uaq2, Ubr1, Ubr2, Ubq1, and Ubq2 correspondingly

Simplified DWR Problem: Action Symbols

•move actions:

> **•Mr12: move(robr,loc1,loc2), Mr21: move(robr,loc2,loc1), Mq12: move(robq,loc1,loc2), Mq21: move(robq,loc2,loc1)**

•load actions:

> **•Lar1: load(conta,robr,loc1); Lar2, Laq1, Laq2, Lar1, Lbr2, Lbq1, and Lbq2 correspondingly**

•unload actions:

> **•Uar1: unload(conta,robr,loc1); Uar2, Uaq1, Uaq2, Uar1, Ubr2, Ubq1, and Ubq2 correspondingly**

•14 state symbols: lower case, italic

•20 action symbols: uppercase, not italic

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Solution Existence

- **Proposition**: A propositional planning problem $\mathcal{P}=(\Sigma,s_i,g)$ has a solution iff
  $$S_g \cap \Gamma^{>}(\{s_i\}) \neq \{\}.$$
- **Proposition**: A propositional planning problem $\mathcal{P}=(\Sigma,s_i,g)$ has a solution iff
  $$\exists s \in \Gamma^{<}(\{g\}) : s \subseteq s_i.$$

Solution Existence

•**Proposition: A propositional planning problem $\mathcal{P}=(\Sigma,s_i,g)$ has a solution iff $S_g \cap \Gamma^{>}(\{s_i\}) \neq \{\}$.**

 •… iff there is a goal state that is also a reachable state

•**Proposition: A propositional planning problem $\mathcal{P}=(\Sigma,s_i,g)$ has a solution iff $\exists s \in \Gamma^{<}(\{g\}) : s \subseteq s_i$.**

 •… iff there is a minimal set of propositions amongst all regression sets that is a subset of the initial state

Reachability Tree

- tree structure, where:
  - root is initial state s_i
  - children of node s are $\Gamma(\{s\})$
  - arcs are labelled with actions
- all nodes in reachability tree are $\Gamma^{>}(\{s_i\})$
  - all nodes to depth d are $\Gamma^{d}(\{s_i\})$
  - solves problems with up to d actions in solution
- problem: $O(k^d)$ nodes;
  k = applicable actions per state

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Planning Graph: Nodes

- layered directed graph G=(N,E):
  - $N = P_0 \cup A_1 \cup P_1 \cup A_2 \cup P_2 \cup \ldots$
    - state proposition layers: P_0, P_1, …
    - action layers: A_1, A_2, …
- first proposition layer P_0:
  - propositions in initial state s_i: P_0=s_i
- action layer A_j:
  - all actions a where: precond(a)$\subseteq P_{j\text{-}1}$
- proposition layer P_j:
  - all propositions p where: $p \in P_{j\text{-}1}$ or $\exists a \in A_j$: $p \in$effects$^+$(a)

Planning Graph: Nodes

- **layered directed graph G=(N,E):**
  - layered = each node belongs to exactly one layer
  - **$N = P_0 \cup A_1 \cup P_1 \cup A_2 \cup P_2 \cup \ldots$**
    - proposition and action layers alternate
    - **state proposition layers: P_0, P_1, …**
    - **action layers: A_1, A_2, …**
- **first proposition layer P_0:**
  - **propositions in initial state s_i: P_0=s_i**
- **action layer A_j:**
  - **all actions a where: precond(a)$\subseteq P_{j\text{-}1}$**
- **proposition layer P_j:**
  - **all propositions p where: $p \in P_{j\text{-}1}$ or $\exists a \in A_j$: $p \in$effects$^+$(a)**
  - propositions at layer P_j are all propositions in the union of all nodes in the reachability tree at depth j
    - note: negative effects are not deleted from next layer
- note: $P_{j\text{-}1} \subseteq P_j$; propositions in the graph monotonically increase from one proposition layer to the next

Planning Graph: Edges

- from proposition $p \in P_{j-1}$ to action $a \in A_j$:
  - if: $p \in$ precond(a)
- from action $a \in A_j$ to layer $p \in P_j$:
  - positive arc if: $p \in$ effects$^+$(a)
  - negative arc if: $p \in$ effects$^-$(a)
- no arcs between other layers

Planning Graph: Arcs

•directed and layered = arcs only from one layer to the next

•from proposition $p \in P_{j-1}$ to action $a \in A_j$:

•if: $p \in$ precond(a)

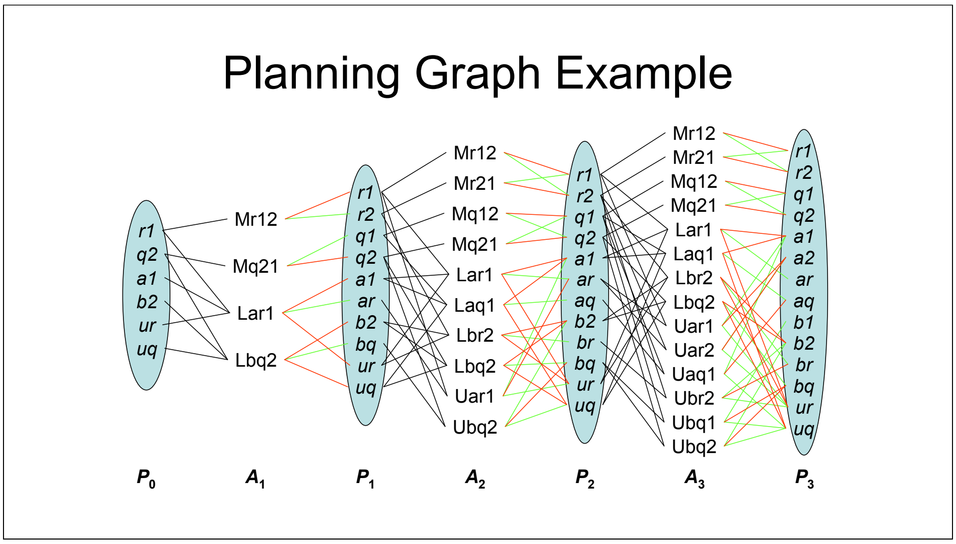
•from action $a \in A_j$ to layer $p \in P_j$:

•positive arc if: $p \in$ effects$^+$(a)

•negative arc if: $p \in$ effects$^-$(a)

•no arcs between other layers

•note: $A_{j-1} \subseteq A_j$; actions in the graph monotonically increase from one action layer to the next



Planning Graph Example

•**[figure]**

- •start with initial proposition layer
- •next action layer: applicable action; links from preconditions (black)
- •next proposition layer: previous proposition plus positive effects; links to positive effects (green); links to negative effects (red)
- •next action layer (A_2); precondition links; next proposition layer (P_2); effect links
- •next action layer (A_3); precondition links; next proposition layer (P_3); effect links

•action layers contain “inclusive disjunctions” of actions

Reachability in the Planning Graph

- reachability analysis:
  - if a goal g is reachable from initial state s_i
  - then there will be a proposition layer P_g in the planning graph such that $g \subseteq P_g$
- necessary condition, but not sufficient
- low complexity:
  - planning graph is of polynomial size and
  - can be computed in polynomial time

Reachability in the Planning Graph

•**reachability analysis:**

•**if a goal g is reachable from initial state s_i**

•**then there will be a proposition layer P_g in the planning graph such that $g \subseteq P_g$**

•or: if no proposition layer contains g then g is not reachable

•**necessary condition, but not sufficient**

•necessary vs. sufficient:

•reachability tree:

•nodes contain propositions that must necessarily hold

•propositions in one node are consistent

•planning graph:

•proposition layers contains propositions that may possibly hold

•propositions in one layer usually inconsistent (e.g. robots/containers in two places at once)

•similarly, incompatible actions in one layer may interfere with each other

•**low complexity:**

•**planning graph is of polynomial size and**

•**can be computed in polynomial time**

•need more conditions (for sufficient criterion)

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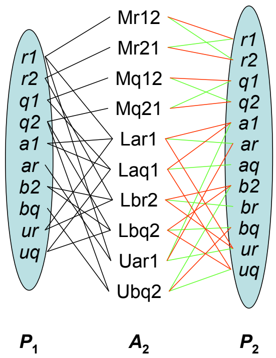
Independent Actions: Examples

- Mr12 and Lar1:
  - cannot occur together
  - Mr12 deletes precondition *r1* of Lar1
- Mr12 and Mr21:
  - cannot occur together
  - Mr12 deletes positive effect *r1* of Mr21
- Mr12 and Mq21:
  - may occur in same action layer



Independent Actions: Examples

•**Mr12 and Lar1:**

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  •**Mr12 deletes precondition *r1* of Lar1**

•**Mr12 and Mr21:**

  •**cannot occur together**

  •**Mr12 deletes positive effect *r1* of Mr21**

•**Mr12 and Mq21:**

  •**may occur in same action layer**

Independent Actions

- Two actions a_1 and a_2 are <u>independent</u> iff:
  - effects$^-(a_1) \cap (\text{precond}(a_2) \cup \text{effects}^+(a_2)) = \{\}$ and
  - effects$^-(a_2) \cap (\text{precond}(a_1) \cup \text{effects}^+(a_1)) = \{\}$.
- A set of actions π is independent iff every pair of actions $a_1,a_2 \in \pi$ is independent.

Independent Actions

•idea: independent actions can be executed in any order (in same layer)

•**Two actions a_1 and a_2 are <u>independent</u> iff:**

  •**effects$^-(a_1) \cap (\text{precond}(a_2) \cup \text{effects}^+(a_2)) = \{\}$ and**

  •**effects$^-(a_2) \cap (\text{precond}(a_1) \cup \text{effects}^+(a_1)) = \{\}$.**

  •two actions are dependent iff:

    •one deletes a precondition of the other or

    •one deletes a positive effect of the other

•**A set of actions π is independent iff every pair of actions $a_1,a_2 \in \pi$ is independent.**

•note: independence does not depend on planning problem; can be pre-computed

•note: independence relation is symmetrical (follows from definition)

Pseudo Code: independent

function independent(a_1,a_2)
  for all $p \in$ effects$^-$(a_1)
    if $p \in$ precond(a_2) **or** $p \in$ effects$^+$(a_2) **then**
      return false
  for all $p \in$ effects$^-$(a_2)
    if $p \in$ precond(a_1) **or** $p \in$ effects$^+$(a_1) **then**
      return false
  return true

Pseudo Code: independent

- **function independent(a_1,a_2)**
  - returns true iff the two given actions are independent
- **for all $p \in$ effects$^-$(a_1)**
- **if $p \in$ precond(a_2) or $p \in$ effects$^+$(a_2) then**
- **return false**
- **for all $p \in$ effects$^-$(a_2)**
- **if $p \in$ precond(a_1) or $p \in$ effects$^+$(a_1) then**
- **return false**
- **return true**
- complexity:
  - let b be max. number of preconditions, positive, and negative effects of any action
  - element test in hash-set takes constant time
  - complexity: $O(b)$

Applying Independent Actions

- A set π of independent actions is <u>applicable</u> to a state s iff $\cup_{a \in \pi}$precond(a) $\subseteq s$.
- The <u>result</u> of applying the set π in s is defined as: $\gamma(s,\pi) = (s - \text{effects}^-(\pi)) \cup \text{effects}^+(\pi)$, where:
  – precond(π) = $\cup_{a \in \pi}$precond(a),
  – effects$^+$(π) = $\cup_{a \in \pi}$effects$^+$(a), and
  – effects$^-$(π) = $\cup_{a \in \pi}$effects$^-$(a).

Applying Independent Actions

•**A set π of independent actions is <u>applicable</u> to a state s iff $\cup_{a \in \pi}$precond(a) $\subseteq s$.**

•note: applying a set of independent actions can be done in any order

•**The <u>result</u> of applying the set π in s is defined as:**
$\gamma(s,\pi) = (s - \text{effects}^-(\pi)) \cup \text{effects}^+(\pi)$, where:

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•**effects$^+$(π) = $\cup_{a \in \pi}$effects$^+$(a), and**

•**effects$^-$(π) = $\cup_{a \in \pi}$effects$^-$(a).**

Execution Order of Independent Actions

- **Proposition**: If a set π of independent actions is applicable in state s then, for any permutation $\langle a_1,\ldots,a_k\rangle$ of the elements of π:
  - the sequence $\langle a_1,\ldots,a_k\rangle$ is applicable to s, and
  - the state resulting from the application of π to s is the same as from the application of $\langle a_1,\ldots,a_k\rangle$, i.e.: $\gamma(s,\pi) = \gamma(s,\langle a_1,\ldots,a_k\rangle)$.

Execution Order of Independent Actions

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$\gamma(s,\pi) = \gamma(s,\langle a_1,\ldots,a_k\rangle)$.

Layered Plans

- Let $P = (A, s_i, g)$ be a statement of a propositional planning problem and $G = (N, E)$, $N = P_0 \cup A_1 \cup P_1 \cup A_2 \cup P_2 \cup \ldots$, the corresponding planning graph.
- A <u>layered plan</u> over G is a sequence of sets of actions: $\prod = \langle \pi_1, \ldots, \pi_k \rangle$ where:
  - $\pi_i \subseteq A_i \subseteq A$,
  - π_i is applicable in state P_{i-1}, and
  - the actions in π_i are independent.

Layered Plans

•Let $P = (A, s_i, g)$ be a statement of a propositional planning problem and $G = (N, E)$, $N = P_0 \cup A_1 \cup P_1 \cup A_2 \cup P_2 \cup \ldots$, the corresponding planning graph.

•A <u>layered plan</u> over G is a sequence of sets of actions: $\prod = \langle \pi_1, \ldots, \pi_k \rangle$ where:

- **$\pi_i \subseteq A_i \subseteq A$,**
- **π_i is applicable in state P_{i-1}, and**
- **the actions in π_i are independent.**

Layered Solution Plan

- A layered plan $\prod = \langle \pi_1,\ldots,\pi_k \rangle$ is a solution to a to a planning problem $P=(A,s_i,g)$ iff:
  - π_1 is applicable in s_i,
  - for $j\in\{2\ldots k\}$, π_j is applicable in state $\gamma(\ldots\gamma(\gamma(s_i,\pi_1), \pi_2), \ldots \pi_{j-1})$, and
  - $g \subseteq \gamma(\ldots\gamma(\gamma(s_i,\pi_1), \pi_2), \ldots, \pi_k)$.

Layered Solution Plan

•**A layered plan $\prod = \langle \pi_1,\ldots,\pi_k \rangle$ is a solution to a to a planning problem $P=(A,s_i,g)$ iff:**

•**π_1 is applicable in s_i,**

•**for $j\in\{2\ldots k\}$, π_j is applicable in state $\gamma(\ldots\gamma(\gamma(s_i,\pi_1), \pi_2), \ldots \pi_{j-1})$, and**

•**$g \subseteq \gamma(\ldots\gamma(\gamma(s_i,\pi_1), \pi_2), \ldots, \pi_k)$.**

•note: independence of actions still not sufficient criterion for solution

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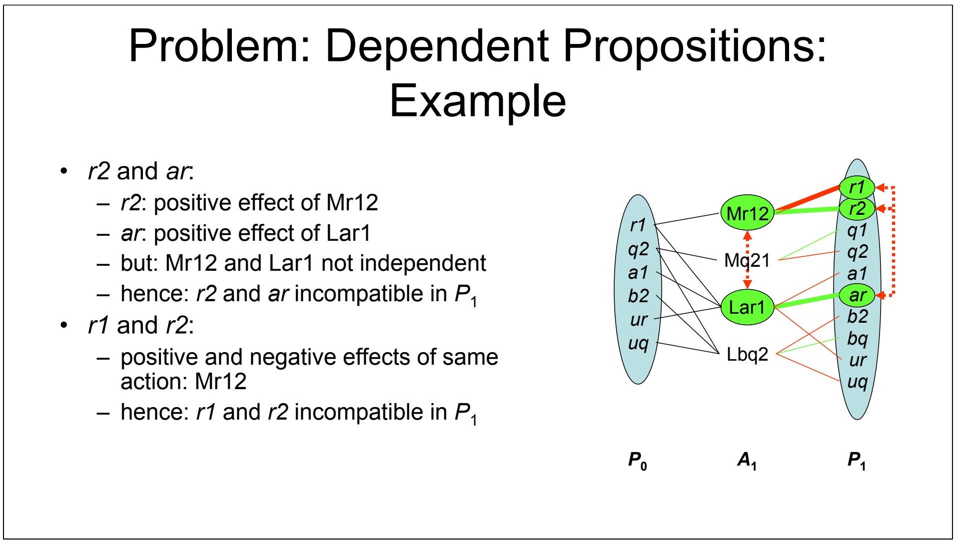


Problem: Dependent Propositions: Example

•***r2* and *ar***:

  •***r2*: positive effect of Mr12**

  •***ar*: positive effect of Lar1**

  •**but: Mr12 and Lar1 not independent**

    •dependent actions cannot occur together same set of actions in a layered plan, e.g. in π_1

  •**hence: *r2* and *ar* incompatible in P_1**

•***r1* and *r2***:

  •**positive and negative effects of same action: Mr12**

  •**hence: *r1* and *r2* incompatible in P_1**

•both cases: compatible if they are also

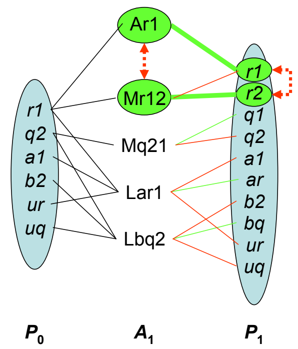
  •two positive effects of one action

  •the positive effects of two independent actions

•incompatible propositions: cannot be reached through preceding action layer (A_1)

No-Operation Actions

- No-Op for proposition *p*:
  - name: Ap
  - precondition: *p*
  - effect: p
- *r1* and *r2*:
  - *r1*: positive effect of Ar1
  - *r2*: positive effect of Mr12
  - but: Ar1 and Mr12 not independent
  - hence: *r1* and *r2* incompatible in P_1
- only one incompatibility test



No-Operation Actions

•No-Op for proposition *p*:

•for every action layer and every proposition that may persist

•name: Ap

•precondition: *p*

•effect: p

•*r1* and *r2*:

•*r1*: positive effect of Ar1

•*r2*: positive effect of Mr12

•but: Ar1 and Mr12 not independent

•hence: *r1* and *r2* incompatible in P_1

•only one incompatibility test

•previous slide: two types of incompatibility (positive effects of dependent actions + positive and negative effects of same action)

•with no-ops: only first type needed (simplification)

Mutex Propositions

- Two propositions *p* and *q* in proposition layer P_j are <u>mutex</u> (mutually exclusive) if:
  - every action in the preceding action layer A_j that has *p* as a positive effect (incl. no-op actions) is mutex with every action in A_j that has *q* as a positive effect, and
  - there is no single action in A_j that has both, *p* and *q*, as positive effects.
- notation: μP_j = { (p,q) | $p,q \in P_j$ are mutex}

Mutex Propositions

•**Two propositions *p* and *q* in proposition layer P_j are <u>mutex</u> (mutually exclusive) if:**

- •**every action in the preceding action layer A_j that has *p* as a positive effect (incl. no-op actions) is mutex with every action in A_j that has *q* as a positive effect, and**
- •need to define when two actions are mutex
  - •obvious case: if they are dependent
- •**there is no single action in A_j that has both, *p* and *q*, as positive effects.**

•**notation: μP_j = { (p,q) | $p,q \in P_j$ are mutex}**

•note: mutex relation for propositions is symmetrical (follows from definition)

•proposition layer P_1 contains 8 mutex pairs

Pseudo Code: mutex for Propositions

```
function mutex(p1,p2,μAj)
  for all a1∈p1.producers()
    for all a2∈p2.producers()
      if (a1,a2)∉μAj then
        return false
  return true
```

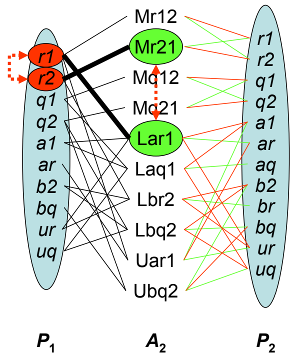
Pseudo Code: mutex for Propositions

- **function mutex(p_1,p_2, μA_j)**
  - input: two propositions (from same layer), mutex relation between the actions in the preceding layer
- **for all $a_1 \in p_1$.producers()**
  - producers: actions in the preceding layer that have p_1 as a positive effect; should be stored with proposition node
- **for all $a_2 \in p_2$.producers()**
  - producers: see above
- **if (a_1,a_2)$\notin \mu A_j$ then**
  - test whether the action are in the given set of mutually exclusive actions
- **return false**
  - if not: consistent producers found; propositions are not mutex
- **return true**
  - no consistent producers found; propositions are mutex

- note: single action producing both is covered: action cannot be mutex with itself
- complexity: let *m* be number of actions in domain (incl. no-ops); $O(m^2)$

Mutex Actions: Example

- *r1* and *r2* are mutex in P_1
- *r1* is precondition for Lar1 in A_2
- *r2* is precondition for Mr21 in A_2
- hence: Lar1 and Mr21 are mutex in A_2



Mutex Actions: Example

•***r1* and *r2* are mutex in P_1**

•***r1* is precondition for Lar1 in A_2**

•***r2* is precondition for Mr21 in A_2**

•**hence: Lar1 and Mr21 are mutex in A_2**

•dependency between actions in action layer A_j leads to mutex between propositions in P_j

•mutex between propositions in P_j leads to mutex between actions in action layer A_{j+1}

Mutex Actions

- Two actions a_1 and a_2 in action layer A_j are <u>mutex</u> if:
  - a_1 and a_2 are dependent, or
  - a precondition of a_1 is mutex with a precondition of a_2.
- notation: $\mu A_j = \{ (a_1,a_2) \mid a_1,a_2 \in A_j \text{ are mutex}\}$

Mutex Actions

•**Two actions a_1 and a_2 in action layer A_j are <u>mutex</u> if:**

•**a_1 and a_2 are dependent, or**

•dependent actions are necessarily mutex

•**a precondition of a_1 is mutex with a precondition of a_2.**

•dependency is domain-specific, i.e. not problem-specific

•mutex-relation is problem specific

•pair of actions/propositions may be mutex in one layer but not so in another

•**notation:**
$\mu A_j = \{ (a_1,a_2) \mid a_1,a_2 \in A_j \text{ are mutex}\}$

•action layer A_1 contains 2 mutex (dependent) pairs

•action layer A_2 contains 24 mutex pairs (not all dependent)

•note: mutex relation (for actions and propositions) is symmetrical (follows from definition)

Pseudo Code: mutex for Actions

function mutex(a_1,a_2,μP)
  if ¬independent(a_1,a_2) **then**
    return true
  for all $p_1 \in$precond(a_1)
    for all $p_2 \in$precond(a_2)
      if (p_1,p_2)$\in \mu P$ **then return** true
  return false

Pseudo Code: mutex for Actions

- **function mutex(a_1,a_2,μP)**
  - μP – mutex relations from the preceding proposition layer
- **if ¬independant(a_1,a_2) then**
- **return true**
- **for all $p_1 \in$precond(a_1)**
- **for all $p_2 \in$precond(a_2)**
- **if (p_1,p_2)$\in \mu P$ then return true**
- **return false**
- complexity: let b = max number preconditions/pos. effects/neg effects: $O(b^2)$

Decreasing Mutex Relations

- **Proposition**: If $p,q \in P_{j-1}$ and $(p,q) \notin \mu P_{j-1}$ then $(p,q) \notin \mu P_j$.
  - Proof:
    - if $p,q \in P_{j-1}$ then Ap,Aq$\in A_j$
    - if $(p,q) \notin \mu P_{j-1}$ then (Ap,Aq)$\notin \mu A_j$
    - since Ap,Aq$\in A_j$ and (Ap,Aq)$\notin \mu A_j$, $(p,q) \notin \mu P_j$ must hold
- **Proposition**: If $a_1,a_2 \in A_{j-1}$ and $(a_1,a_2) \notin \mu A_{j-1}$ then $(a_1,a_2) \notin \mu A_j$.
  - Proof:
    - if $a_1,a_2 \in A_{j-1}$ and $(a_1,a_2) \notin \mu A_{j-1}$ then
      - a_1 and a_2 are independent and
      - their preconditions in P_{j-1} are not mutex
    - both properties remain true for P_j
    - hence: $a_1,a_2 \in A_j$ and $(a_1,a_2) \notin \mu A_j$

Decreasing Mutex Relations

- **Proposition: If $p,q \in P_{j-1}$ and $(p,q) \notin \mu P_{j-1}$ then $(p,q) \notin \mu P_j$.**
  - Proof:
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    - if $(p,q) \notin \mu P_{j-1}$ then (Ap,Aq)$\notin \mu A_j$
    - since Ap,Aq$\in A_j$ and (Ap,Aq)$\notin \mu A_j$, $(p,q) \notin \mu P_j$ **must hold**
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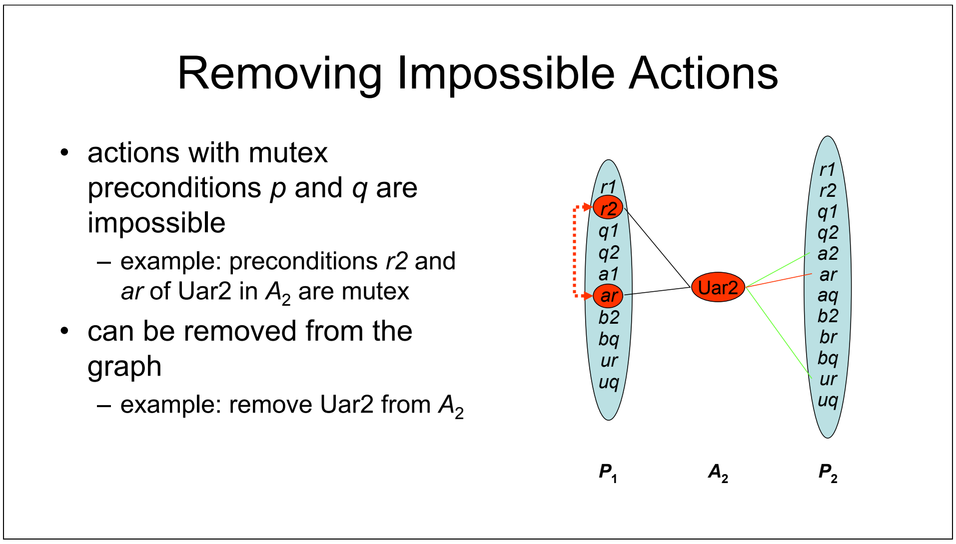
  - **Proof:**
    - **if $a_1,a_2 \in A_{j-1}$ and $(a_1,a_2) \notin \mu A_{j-1}$ then**
      - **a_1 and a_2 are independent and**
      - **their preconditions in P_{j-1} are not mutex**
    - **both properties remain true for P_j**
    - **hence: $a_1,a_2 \in A_j$ and $(a_1,a_2) \notin \mu A_j$**

- mutex relations are monotonically decreasing (between layers with the same propositions)



Removing Impossible Actions

•actions with mutex preconditions *p* and *q* are impossible

        •example: preconditions *r2* and *ar* of Uar2 in A_2 are mutex

•action with mutex preconditions can never be part of any layered plan (will violate applicability condition in definition)

•can be removed from the graph

        •example: remove Uar2 from A_2

•mutex pair of actions must remain in graph because one of the actions may be used in final plan

•note: still consistent with monotonically increasing actions

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Reachability in Planning Graphs

- **Proposition**: Let $P = (A,s_i,g)$ be a propositional planning problem and $G = (N,E)$, $N = P_0 \cup A_1 \cup P_1 \cup A_2 \cup P_2 \cup \ldots$, the corresponding planning graph. If
  - g is reachable from s_i

  then
  - there is a proposition layer P_g such that
    - $g \subseteq P_g$ and
    - $\neg\exists\, g_1,g_2 \in g$: $(g_1,g_2) \in \mu P_g$.

Reachability in Planning Graphs

•**Proposition: Let $P = (A,s_i,g)$ be a propositional planning problem and $G = (N,E)$, $N = P_0 \cup A_1 \cup P_1 \cup A_2 \cup P_2 \cup \ldots$, the corresponding planning graph. If**

•**g is reachable from s_i**

• **then**

•**there is a proposition layer P_g such that**

•**$g \subseteq P_g$ and**

•**$\neg\exists\, g_1,g_2 \in g$: $(g_1,g_2) \in \mu P_g$.**

•still only necessary condition, but relatively efficient to compute

The Graphplan Algorithm: Basic Idea

- expand the planning graph, one action layer and one proposition layer at a time
- from the first graph for which P_g is the last proposition layer such that
  - $g \subseteq P_g$ and
  - $\neg\exists\ g_1,g_2 \in g$: $(g_1,g_2) \in \mu P_g$
- search backwards from the last (proposition) layer for a solution

The Graphplan Algorithm: Basic Idea

•expand the planning graph, one action layer and one proposition layer at a time

•similar to iterative deepening: discover new part of the search space with each iteration

•from the first graph for which P_g is the last proposition layer such that

•$g \subseteq P_g$ and

•$\neg\exists\ g_1,g_2 \in g$: $(g_1,g_2) \in \mu P_g$

•no need to search for solutions in graph with fewer layers; see last proposition

•search backwards from the last (proposition) layer for a solution

•two major steps:

•expansion of planning graph to next proposition layer

•searching a given planning graph for a solution

Planning Graph Data Structure

- k-th planning graph G_k:
  - nodes N:
    - array of proposition layers $P_0 \ldots P_k$
      - proposition layer j: set of proposition symbols
    - array of action layers $A_1 \ldots A_k$
      - proposition layer j: set of action symbols
  - edges E:
    - precondition links: $pre_j \subseteq P_{j-1} \times A_j$, $j \in \{1 \ldots k\}$
    - positive effect links: $e_j^+ \subseteq A_j \times P_j$, $j \in \{1 \ldots k\}$
    - negative effect links: $e_j^- \subseteq A_j \times P_j$, $j \in \{1 \ldots k\}$
    - proposition mutex links: $\mu P_j \subseteq P_j \times P_j$, $j \in \{1 \ldots k\}$
    - action mutex links: $\mu A_j \subseteq A_j \times A_j$, $j \in \{1 \ldots k\}$

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•proposition layer j: set of action symbols

•edges E:

•precondition links: $pre_j \subseteq P_{j-1} \times A_j$, $j \in \{1 \ldots k\}$

•positive effect links: $e_j^+ \subseteq A_j \times P_j$, $j \in \{1 \ldots k\}$

•negative effect links: $e_j^- \subseteq A_j \times P_j$, $j \in \{1 \ldots k\}$

•proposition mutex links: $\mu A_j \subseteq A_j \times A_j$, $j \in \{1 \ldots k\}$

•action mutex links: $\mu P_j \subseteq P_j \times P_j$, $j \in \{1 \ldots k\}$

•note: instance of this data structure does not depend on problem

•initial planning graph: $P_0 = s_i$; rest is empty sets

Pseudo Code: expand

function expand(G_{k-1})
$A_k \leftarrow \{a \in A \mid \text{precond}(a) \subseteq P_{k-1}$ and
$\{(p_1,p_2) \mid p_1,p_2 \in \text{precond}(a)\} \cap \mu P_{k-1} = \{\}\ \}$
$\mu A_k \leftarrow \{(a_1,a_2) \mid a_1,a_2 \in A_k,\ a_1 \neq a_2$, and $\text{mutex}(a_1,a_2,\mu P_{k-1})\ \}$
$P_k \leftarrow \{p \mid \exists a \in A_k : p \in \text{effects}^+(a)\ \}$
$\mu P_k \leftarrow \{(p_1,p_2) \mid p_1,p_2 \in P_k,\ p_1 \neq p_2$, and $\text{mutex}(p_1,p_2,\mu A_k)\ \}$
for all $a \in A_k$
$pre_k \leftarrow pre_k \cup (\{p \mid p \in P_{k-1}$ and $p \in \text{precond}(a)\} \times a)$
$e_k^+ \leftarrow e_k^+ \cup (a \times \{p \mid p \in P_k$ and $p \in \text{effects}^+(a)\})$
$e_k^- \leftarrow e_k^- \cup (a \times \{p \mid p \in P_k$ and $p \in \text{effects}^-(a)\})$

Pseudo Code: expand

- **function expand(G_{k-1})**
- **$A_k \leftarrow \{a \in A \mid \text{precond}(a) \subseteq P_{k-1}$ and $\{(p_1,p_2) \mid p_1,p_2 \in \text{precond}(a)\} \cap \mu P_{k-1} = \{\}\ \}$**
  - actions with satisfied, non-mutex preconditions (incl. no-ops)
- **$\mu A_k \leftarrow \{(a_1,a_2) \mid a_1,a_2 \in A_k,\ a_1 \neq a_2$, and $\text{mutex}(a_1,a_2,\mu P_{k-1})\ \}$**
- **$P_k \leftarrow \{p \mid \exists a \in A_k : p \in \text{effects}^+(a)\ \}$**
  - union of all positive effects
- **$\mu P_k \leftarrow \{(p_1,p_2) \mid p_1,p_2 \in P_k,\ p_1 \neq p_2$, and $\text{mutex}(p_1,p_2,\mu A_k)\ \}$**
- **for all $a \in A_k$**
- **$pre_k \leftarrow pre_k \cup (\{p \mid p \in P_{k-1}$ and $p \in \text{precond}(a)\} \times a)$**
- **$e_k^+ \leftarrow e_k^+ \cup (a \times \{p \mid p \in P_k$ and $p \in \text{effects}^+(a)\})$**
- **$e_k^- \leftarrow e_k^- \cup (a \times \{p \mid p \in P_k$ and $p \in \text{effects}^-(a)\})$**

Planning Graph Complexity

- **Proposition**: The size of a planning graph up to level *k* and the time required to expand it to that level are polynomial in the size of the planning problem.
- Proof:
  - problem size: *n* propositions and *m* actions
  - $|P_j| \leq n$ and $|A_j| \leq n+m$ (incl. no-op actions)
  - algorithms for generating each layer and all link types are polynomial in size of layer

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- **problem size: *n* propositions and *m* actions**
- **$|P_j| \leq n$ and $|A_j| \leq n+m$ (incl. no-op actions)**
- **algorithms for generating each layer and all link types are polynomial in size of layer**

Fixed-Point Levels

- A <u>fixed-point level</u> in a planning graph G is a level κ such that for all i, $i>\kappa$, level i of G is identical to level κ, i.e. $P_i=P_\kappa$, $\mu P_i=\mu P_\kappa$, $A_i=A_\kappa$, and $\mu A_i=\mu A_\kappa$.

- **Proposition**: Every planning graph G has a fixed-point level κ, which is the smallest k such that $|P_k|=|P_{k+1}|$ and $|\mu P_k|=|\mu P_{k+1}|$.
- Proof:
  - P_i grows monotonically and μP_i shrinks monotonically
  - A_i and P_i only depend on P_{i-1} and μP_{i-1}

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    •$|P_k|=|P_{k+1}|$ implies $P_k=P_{k+1}$

•**Proof:**

    •**P_i grows monotonically and μP_i shrinks monotonically**

        •μP_i shrinks monotonically: for equal P_i

    •**A_i and P_i only depend on P_{i-1} and μP_{i-1}**

•time complexity: $O(n+m)$ from fixed point level; only copying required

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Searching the Planning Graph

- general idea:
  - search backwards from the last proposition layer P_k in the current graph
  - let g be the set of goal propositions that need to be achieved at a given proposition layer P_j (initially the last layer)
  - find a set of actions $\pi_j \subseteq A_j$ such that these actions are not mutex and together achieve g
  - take the union of the preconditions of π_j as the new goal set to be achieved in proposition layer $P_{j\text{-}1}$

Searching the Planning Graph

•general idea:

•search backwards from the last proposition layer P_k in the current graph

•let g be the set of goal propositions that need to be achieved at a given proposition layer P_j (initially the last layer)

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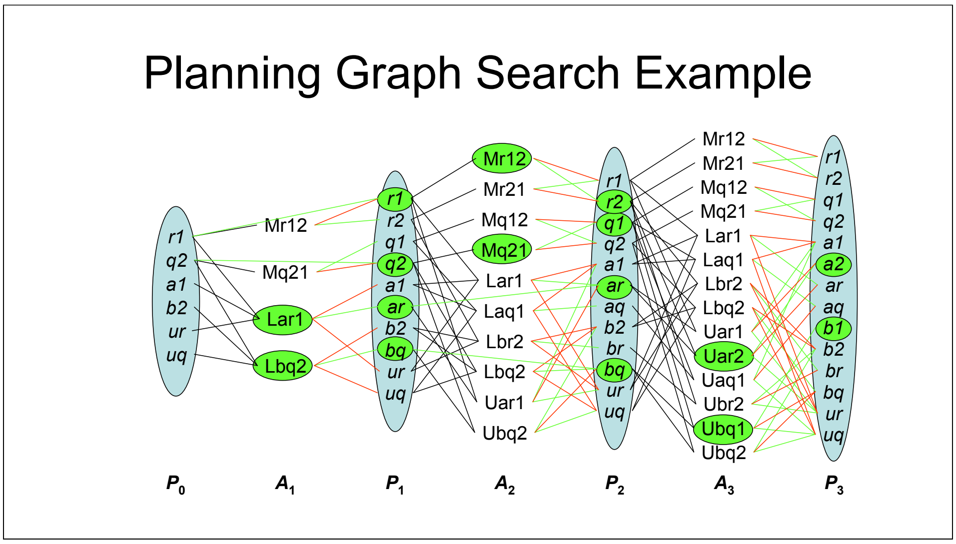


Planning Graph Search Example

•initial goal: *a2* and *b1*

•only one incoming positive effect link per goal (but no-ops not shown)

•achievable with Uar2 and Ubq1 (which are not mutex; mutex relations not shown)

•precondition links indicate sub-goal at next layer

•new sub-goal at P_2: *r2*, *q1*, *ar*, *bq*

•only one incoming positive effect link per goal condition (but no-ops not shown)

- •achieve *ar* and *bq* with no-ops
- •achieve *r2* with Mr12 and *q1* with Mq21

•precondition links (for Mr12 and Mq21) indicate some sub-goal at next layer

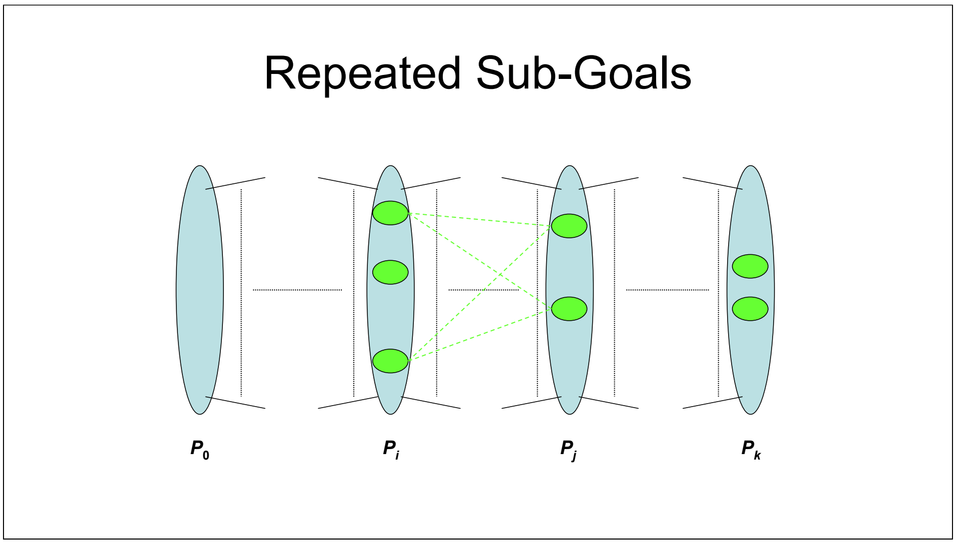
•complete sub-goal (incl. preconditions of no-ops) at P_1: *r1*, *q2*, *ar*, *bq*

•only one incoming positive effect link per goal condition (but no-ops not shown)

- •achieve *r1* and *q2* with no-ops
- •achieve *ar* with Lar1 and *bq* with Lbq2

•precondition links (for Lar1 and Lbq2) indicate some sub-goal at next layer

•complete sub-goal (incl. preconditions of no-ops) at P_0: complete initial state



Repeated Sub-Goals

•ultimate goal leads to possible sub-goals at P_j

•possible sub-goals at P_j lead to possible sub-goals at P_i

  •search to initial proposition layer to see whether sub-goals can be achieved

  •suppose: sub-goals at P_i cannot be achieved

•backtrack to later layer, say P_j

•possible sub-goals at P_j may lead to same possible sub-goals at P_i, but in a different way

  •no need to repeat search: same sub-goals at same layer still cannot be achieved

  •generalization: same some sub-goals at same or earlier layer still cannot be achieved

    •otherwise no-op would achieve sub-goal at later layer

The *nogood* Table

- *nogood* table (denoted ∇) for planning graph up to layer k:
  - array of k sets of sets of goal propositions
    - inner set: one combination of propositions that cannot be achieved
    - outer set: all combinations that cannot be achieved (at that layer)
- before searching for set g in P_j:
  - check whether $g \in \nabla(j)$
- when search for set g in P_j has failed:
  - add g to $\nabla(j)$

The *nogood* Table

- ***nogood* table (denoted ∇) for planning graph up to layer k:**
  - **array of k sets of sets of goal propositions**
    - **inner set: one combination of propositions that cannot be achieved**
    - **outer set: all combinations that cannot be achieved (at that layer)**
  - mutex only gives pairs of propositions that cannot be achieved together, *nogood* table gives impossible tuples
- **before searching for set g in P_j:**
  - **check whether $g \in \nabla(j)$**
  - actually: in j or later layer
- **when search for set g in P_j has failed:**
  - **add g to $\nabla(j)$**
  - or move?

Pseudo Code: extract

function extract(G,g,i)
  if i=0 **then return** $\langle\rangle$
  if $g \in \nabla(i)$ **then return** failure
  $\prod \leftarrow$ gpSearch(G,g,{},i)
  if $\prod \neq$failure **then return** $\prod$
  $\nabla(i) \leftarrow \nabla(i) + g$
  return failure

Pseudo Code: extract

- **function extract(G,g,i)**
  - inputs: planning graph G, set of propositions (sub-goals) g, and layer at which sub-goals need to be achieved i
  - output: a layered plan $\langle \pi_1,\ldots,\pi_i \rangle$ that achieves g at i in G or failure if there is no such plan
- **if i=0 then return** $\langle\rangle$
  - trivial success with empty plan
- **if $g \in \nabla(i)$ then return failure**
  - sub-goals have resulted in failure before
- **$\pi_i \leftarrow$ gpSearch(G,g,{},i)**
  - perform the search
- **if $\pi_i \neq$failure then return π_i**
  - the search was successful
- **$\nabla(i) \leftarrow \nabla(i) + g$**
  - unsuccessful search: remember unachievable sub-goals
- **return failure**

Pseudo Code: gpSearch

function gpSearch(G,g,π,i)
  if g={} **then**
    $\prod \leftarrow$ extract(G,$\cup_{a\in\pi}$precond(a),i-1)
    if $\prod$ =failure **then return** failure
    return $\prod \bullet\langle\pi\rangle$
  $p \leftarrow g$.selectOne()
  $providers \leftarrow \{a\in A_i \mid p\in$effects$^+(a)$ and $\neg\exists a'\in\pi$: $(a,a')\in\mu A_i\}$
  if $providers$={} **then return** failure
  $a \leftarrow providers$.chooseOne()
  return gpSearch(G,g-effects$^+(a)$,$\pi+a$,i)

Pseudo Code: gpSearch

- **function gpSearch(G,g,π,i)**
  - inputs: planning graph G, remaining sub-goals g, and set of actions already committed to π, both at level i
  - outputs: layered plan
- **if g={} then**
  - all actions chosen
- $\prod \leftarrow$ extract(G,$\cup_{a\in\pi}$**precond(a),i-1)**
- **if $\prod$=failure then return failure**
- **return $\prod\bullet\langle\pi\rangle$**
- **$p \leftarrow g$.selectOne()**
  - no need to backtrack here; order only important for efficiency
- **resolvers $\leftarrow \{a\in A_i \mid p\in$effects$^+(a)$ and $\neg\exists a'\in\pi$: $(a,a')\in\mu A_i\}$**
- **if *resolvers*={} then return failure**
- **$a \leftarrow$ *resolvers*.chooseOne()**
  - non-deterministic choice point; backtrack to here
- **return GPSearch(G,g-effects$^+(a)$,$\pi+a$,i)**

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➢The Graphplan Algorithm

Pseudo Code: Graphplan

function graphplan(A,s_i,g)
  $i \leftarrow 0$; $\nabla \leftarrow []$; $P_0 \leftarrow s_i$; $G \leftarrow (P_0,\{\})$
  while ($g \not\subseteq P_i$ **or** $g^2 \cap \mu P_i \neq \{\}$) **and** $\neg$fixedPoint(G) **do**
    $i \leftarrow i+1$; expand(G)
  if $g \not\subseteq P_i$ **or** $g^2 \cap \mu P_i \neq \{\}$ **then return** failure
  $\eta \leftarrow$ fixedPoint(G) ? $|\nabla(\kappa)|$: 0
  $\prod \leftarrow$ extract(G,g,i)
  while $\prod$=failure **do**
    $i \leftarrow i+1$; expand(G)
    $\prod \leftarrow$ extract(G,g,i)
    if $\prod$=failure **and** fixedPoint(G) **then**
      if $\eta = |\nabla(\kappa)|$ **then return** failure
      $\eta \leftarrow |\nabla(\kappa)|$
  return $\prod$

Pseudo Code: graphplan

- **function graphplan(A,s_i,g)**
  - given planning problem, return layered solution plan
- **$i \leftarrow 0$; $\nabla \leftarrow []$; $P_0 \leftarrow s_i$; $G \leftarrow (P_0,\{\})$**
- **while ($g \not\subseteq P_i$ or $g^2 \cap \mu P_i \neq \{\}$) and $\neg$fixedPoint(G) do**
- **$i \leftarrow i+1$; expand(G)**
  - planning graph expanded until solution possible or fixed point reached
- **if $g \not\subseteq P_i$ or $g^2 \cap \mu P_i \neq \{\}$ then return failure**
  - test necessary criterion
- **$\eta \leftarrow$ fixedPoint(G) ? $|\nabla(\kappa)|$: 0**
  - used to test when expansion will not work
- **$\prod \leftarrow$ extract(G,g,i)**
- **while $\prod$=failure do**
- **$i \leftarrow i+1$; expand(G)**
- **$\prod \leftarrow$ extract(G,g,i)**
- **if $\prod$=failure and fixedPoint(G) then**
- **if $\eta = |\nabla(\kappa)|$ then return failure**
- **$\eta \leftarrow |\nabla(\kappa)|$**
- **return $\prod$**

Graphplan Properties

- **Proposition**: The Graphplan algorithm is sound, complete, and always terminates.
  - It returns failure iff the given planning problem has no solution;
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