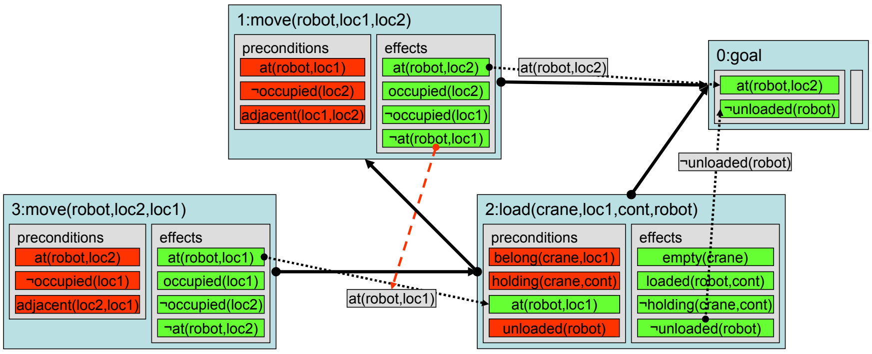
Artificial Intelligence Planning

Plan-Space Search

Artificial Intelligence Planning

•Informed Search

Example: Partial Plan



Overview

- Search States: Partial Plans
- Plan Refinement Operations
- The Plan-Space Search Problem
- Flawless Partial Plans
- The PSP Algorithm
- PSP Implementation Details
- Partial-Order Planning

Overview

➢**Search States: Partial Plans**

- now: introducing a completely different search space with partial plans as search states

•Plan Refinement Operations

•The Plan-Space Search Problem

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State-Space vs. Plan-Space Search

- state-space search:
  search through graph of nodes representing world states
- plan-space search:
  search through graph of partial plans
  - nodes: partially specified plans
  - arcs: plan refinement operations
  - solutions: partial-order plans

State-Space vs. Plan-Space Search

•state-space search: search through graph of nodes representing world states

- •search space directly corresponds to graph representation of state-transition system

•plan-space search: search through graph of partial plans

- **•nodes: partially specified plans**
- **•arcs: plan refinement operations**
  - •least commitment principle: do not add constraints to the plan that are not strictly needed
- **•solutions: partial-order plans**
  - •partial-order plan: set of actions + set of orderings; not necessarily total order
  - •state-space algorithms also maintain partial plan – but always in total order

Partial Plans

- plan: set of actions organized into some structure
- partial plan:
  - subset of the actions
  - subset of the organizational structure
    - temporal ordering of actions
    - rationale: what the action achieves in the plan
  - subset of variable bindings

Partial Plans

•plan: set of actions organized into some structure

•organization e.g. sequence

•partial plan:

•subset of the actions

•subset of the organizational structure

•temporal ordering of actions

•rationale: what the action achieves in the plan

•refers only to subset of actions

•subset of variable bindings

•plan refinement operators accordingly: add actions, add ordering constraints, add causal links, add variable bindings

Definition of Partial Plans

- A partial plan is a tuple $\pi = (A,\prec,B,L)$, where:
  - $A = \{a_1,\ldots,a_k\}$ is a set of partially instantiated planning operators;
  - $\prec$ is a set of ordering constraints on A of the form $(a_i \prec a_j)$;
  - B is a set of binding constraints on the variables of actions in A of the form $x=y$, $x\neq y$, or $x \in D_x$;
  - L is a set of causal links of the form $\langle a_i -[p]\rightarrow a_j \rangle$ such that:
    - a_i and a_j are actions in A;
    - the constraint $(a_i \prec a_j)$ is in $\prec$;
    - proposition p is an effect of a_i and a precondition of a_j; and
    - the binding constraints for variables in a_i and a_j appearing in p are in B.

Definition of Partial Plans

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    - **a_i and a_j are actions in A;**
    - **the constraint $(a_i \prec a_j)$ is in $\prec$;**
    - **proposition p is an effect of a_i and a precondition of a_j; and**
    - **the binding constraints for variables in a_i and a_j appearing in p are in B.**

- sub-gaols in a partial plan: preconditions without causal links
- different view: partial plan as set of (sequential) plans
  - those that meet the specified constraints and can be refined to a total order plan by adding constraints
- note: partial plans with two types of additional flexibility:
  - actions only partially ordered and
  - not all variables need to be instantiated

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- just done: introducing a completely different search space with partial plans as search states

➢Plan Refinement Operations

- now: state transitions in the new search space – refining partial plans

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Adding Actions

- partial plan contains actions
  - initial state
  - goal conditions
  - set of operators with different variables

- reason for adding new actions
  - to achieve unsatisfied preconditions
  - to achieve unsatisfied goal conditions

Adding Actions

•**partial plan contains actions**

•**initial state**

•**goal conditions**

•can be represented as two actions with only effects or preconditions

•**set of operators with different variables**

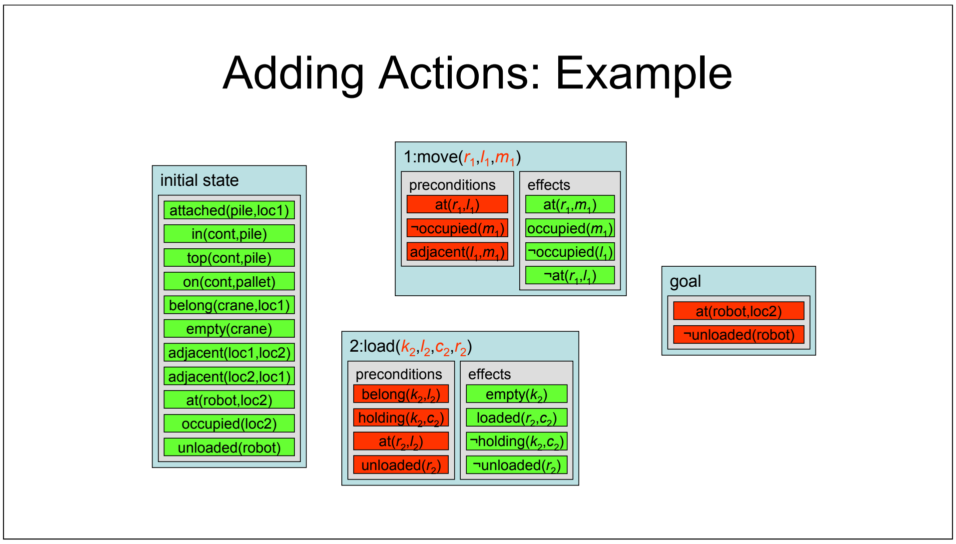
•least commitment principle: introduce actions only for a reason

•**reason for adding new actions**

•**to achieve unsatisfied preconditions**

•**to achieve unsatisfied goal conditions**

•note: new actions can be added anywhere in the current partial plan



Adding Actions: Example

•empty plan:

  •initial state: all initially satisfied conditions (green)

  •goal: conditions that need to be satisfied (red)

•add operator: 1:move(r_1,l_1,m_1)

  •number (1) to provide unique reference to this operator instance

  •also used as variable index for unique variables

  •least commitment principle: choose values for variables only when necessary

•add operator:2:load(k_2,l_2,c_2,r_2)

Adding Causal Links

- partial plan contains causal links
  - links from the provider
    - an effect of an action or
    - an atom that holds in the initial state
  - to the consumer
    - a precondition of an action or
    - a goal condition
- reasons for adding causal links
  - prevent interference with other actions

Adding Causal Links

•**partial plan contains causal links**

•**links from the provider**

•**an effect of an action or**

•**an atom that holds in the initial state**

•**to the consumer**

•**a precondition of an action or**

•**a goal condition**

•causal link implies ordering constraint

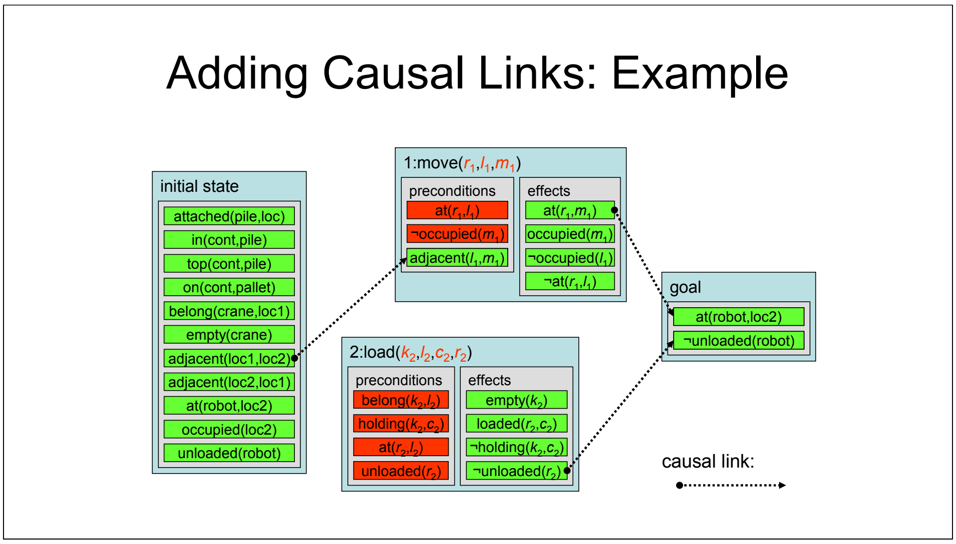
•but: provider need not come directly before consumer

•**reasons for adding causal links**

•**prevent interference with other actions**

•keeping track of rationale: any action inserted between provider and consumer must not clobber conditions in causal link

•preconditions without a causal link pointing to them are open sub-gaols



Adding Causal Links: Example

•add link from 1:move to goal

•changes colour of goal to green – now satisfied

•add link from 2:load to goal

•add link from initial state to 1:move

Adding Variable Bindings

- partial plan contains variable bindings
  - new operators introduce new (copies of) variables into the plan
  - solution plan must contain actions
  - variable binding constraints keep track of possible values for variables and co-designation
- reasons for adding variable bindings
  - to turn operators into actions
  - to unify and effect with the precondition it supports

Adding Variable Bindings

•partial plan contains variable bindings

•new operators introduce new (copies of) variables into the plan

•each copy of an operator has its own set of variables that are different from variables in other operators instances

•solution plan must contain actions

•variable binding constraints keep track of possible values for variables and co-designation

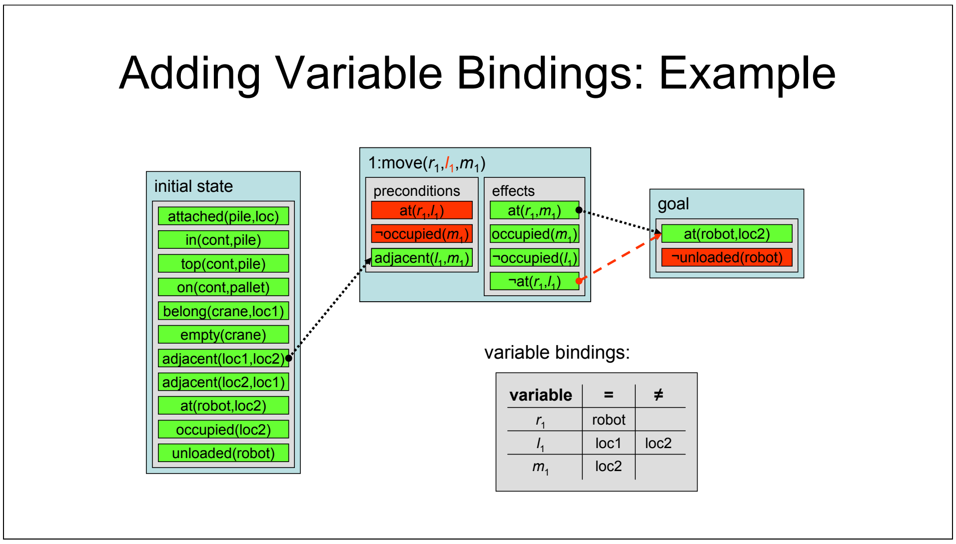
•convention (here): give number to operator instances to distinguish them; let variables have index of operator they belong to least commitment principle:

•least commitment principle: add only necessary variable binding constraints

•reasons for adding variable bindings

•to turn operators into actions

•to unify and effect with the precondition it supports



Adding Variable Bindings: Example

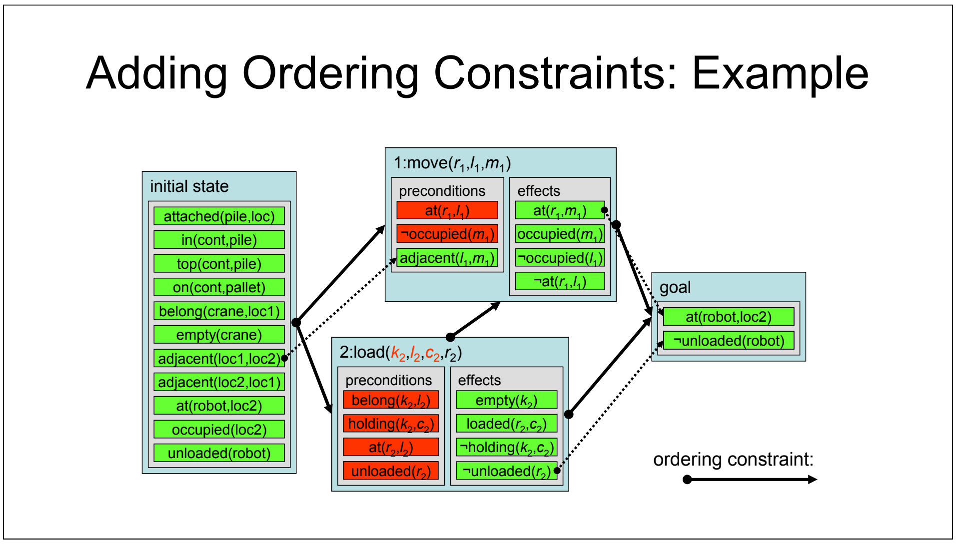
- bind variables due to causal link:
  - bind r_1 to robot
  - bind m_1 to loc2
  - note: variables in operator no longer red to indicate they are bound
- clobbering: move may also destroy goal condition
- introduce variable inequality: $l_1 \neq$ loc2
- clobbering now impossible
- introduce causal link from initial state
- bind l_1 to loc1
  - note consistency with inequality

Adding Ordering Constraints

- partial plan contains ordering constraints
  - binary relation specifying the temporal order between actions in the plan
- reasons for adding ordering constraints
  - all actions after initial state
  - all actions before goal
  - causal link implies ordering constraint
  - to avoid possible interference

Adding Ordering Constraints

- **partial plan contains ordering constraints**
  - **binary relation specifying the temporal order between actions in the plan**
  - temporal relation: qualitative, not quantitative (at this stage)
- **reasons for adding ordering constraints**
  - **all actions after initial state**
  - **all actions before goal**
  - **causal link implies ordering constraint**
  - **to avoid possible interference**
    - interference can be avoided by ordering the potentially interfering action before the provider or after the consumer of a causal link
    - least commitment principle: introduce ordering constraints only if necessary
- result: solution plan not necessarily totally ordered



Adding Ordering Constraints: Example

- ordering constraints
    - due to causal links
    - also: all actions before goal
- ordering: all actions after initial state
- orderings may occur between actions

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•Plan Refinement Operations

- just done: state transitions in the new search space – refining partial plans

➢The Plan-Space Search Problem

- now: definition of the plan-space search problem and solutions

•Flawless Partial Plans

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Plan-Space Search: Initial Search State

- represent initial state and goal as dummy actions
  - init: no preconditions, initial state as effects
  - goal: goal conditions as preconditions, no effects
- empty plan π_0 = ({init, goal},{(init$\prec$goal)},{},{}):
  - two dummy actions init and goal;
  - one ordering constraint: init before goal;
  - no variable bindings; and
  - no causal links.

Plan-Space Search: Initial Search State

•problem: plan space representation does not maintain states, but need to give initial state and goal description

•represent initial state and goal as dummy actions

•init: no preconditions, initial state as effects

•goal: goal conditions as preconditions, no effects

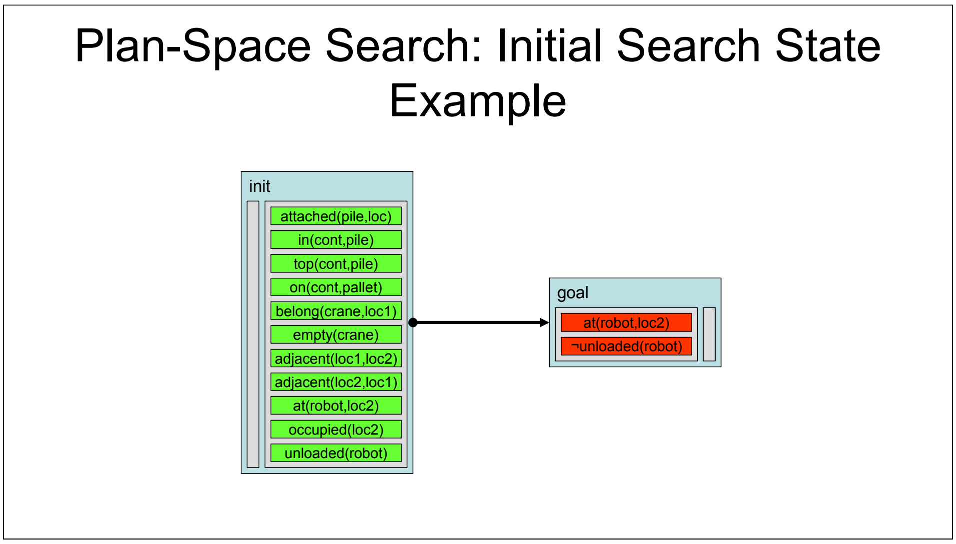
•empty plan π_0 = ({init, goal},{(init$\prec$goal)},{},{}):

•two dummy actions init and goal;

•one ordering constraint: init before goal;

•no variable bindings; and

•no causal links.



Plan-Space Search: Initial Search State Example

•note empty box for preconditions in init and empty box for effects in goal

Plan-Space Search: Successor Function

- states are partial plans
- generate successor through plan refinement operators (one or more):
  - adding an action to *A*
  - adding an ordering constraint to $\prec$
  - adding a binding constraint to *B*
  - adding a causal link to *L*

Plan-Space Search: Successor Function

•**states are partial plans**

•**generate successor through plan refinement operators (one or more):**

•more required to keep partial plans consistent, e.g. adding a causal link implies adding an ordering constraint

•**adding an action to *A***

•**adding an ordering constraint to** $\prec$

•**adding a binding constraint to *B***

•**adding a causal link to *L***

•successors must be consistent: constraints in a partial plan must be satisfiable

•plan-space planning decouple two sub-problems:

•which actions need to be performed

•how to organize these actions

•partial plan as set of plans: refinement operation reduces the set to smaller subset

•next: to define planning as plan-space search problem: need to define goal state

Total vs. Partial Order

- Let $\mathcal{P}=(\Sigma,s_i,g)$ be a planning problem. A plan π is a <u>solution</u> for $\mathcal{P}$ if $\gamma(s_i,\pi)$ satisfies g.
- problem: $\gamma(s_i,\pi)$ only defined for sequence of ground actions
  - partial order corresponds to total order in which all partial order constraints are respected
  - partial instantiation corresponds to grounding in which variables are assigned values consistent with binding constraints

Total vs. Partial Order

•**Let $\mathcal{P}=(\Sigma,s_i,g)$ be a planning problem. A plan π is a <u>solution</u> for $\mathcal{P}$ if $\gamma(s_i,\pi)$ satisfies g.**

- •solution defined for state transition system

•**problem: $\gamma(s_i,\pi)$ only defined for sequence of ground actions**

- •**partial order corresponds to total order in which all partial order constraints are respected**
  - •partial ordering is consistent iff it is free of loops
  - •note: there may be an exponential number of total ordering consistent with a given partial ordering
- •**partial instantiation corresponds to grounding in which variables are assigned values consistent with binding constraints**
  - •note: exponential combinatorics of assigning values to variables

Partial Order Solutions

- Let $\mathcal{P}=(\Sigma,s_i,g)$ be a planning problem. A plan $\pi = (A,\prec,B,L)$ is a (partial order) <u>solution</u> for $\mathcal{P}$ if:
  - its ordering constraints $\prec$ and binding constraints B are consistent; and
  - for every sequence $\langle a_1,\ldots,a_k\rangle$ of all the actions in A-{init, goal} that is
    - totally ordered and grounded and respects $\prec$ and B
    - $\gamma(s_i, \langle a_1,\ldots,a_k\rangle)$ must satisfy g.

Partial Order Solutions

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•totally ordered and grounded and respects $\prec$ and B

•$\gamma(s_i, \langle a_1,\ldots,a_k\rangle)$ must satisfy g.

•note: causal links do not play a role in the definition of a solution

•with exponential number of sequences to check, definition is not very useful (as computational procedure for goal test)

•idea: use causal links to verify that every precondition of every action is supported by some other action

•problem: condition not strong enough

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•Search States: Partial Plans

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- just done: definition of the plan-space search problem and solutions (without goal test)

➢Flawless Partial Plans

- now: the goal test that completes the search problem

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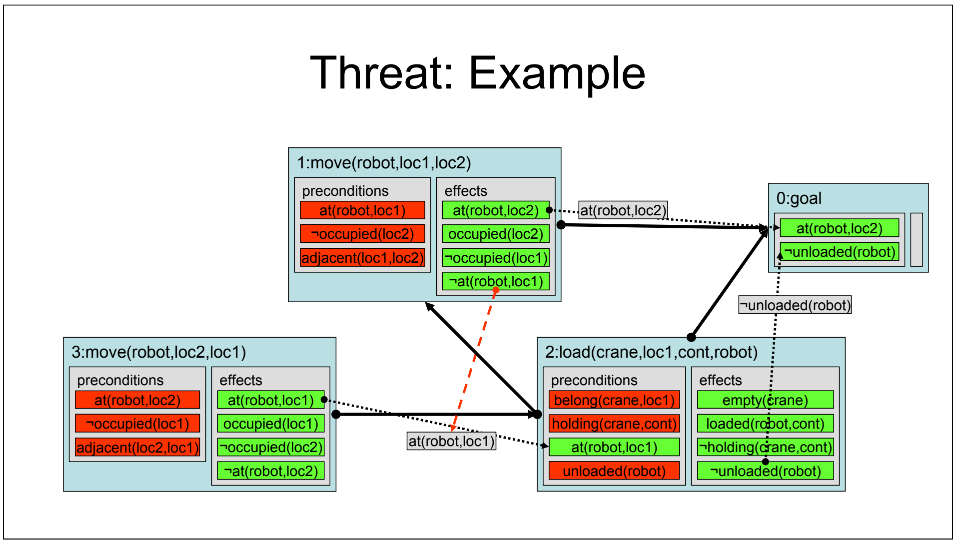

Threat: Example

•start with partial plan from previous example (grounded; initial state not shown due to limited space on slide)

•introduce new 3:move action to achieve at(robot,loc1) precondition of 2:load action

•note: still many unachieved preconditions – not a solution yet

•add causal link to maintain rationale

•add ordering to be consistent with causal link

•new: label causal link with condition it protects

•threat: effect of 1:move is negation of condition protected by causal link

•if 1:move is executed between 3:move and 2:load the plan is no longer valid

•possible solution: additional ordering constraint

Threats

- An action a_k in a partial plan $\pi = (A,\prec,B,L)$ is a threat to a causal link $\langle a_i - [p] \rightarrow a_j \rangle$ iff:
  - a_k has an effect $\neg q$ that is possibly inconsistent with p, i.e. q and p are unifiable;
  - the ordering constraints $(a_i \prec a_k)$ and $(a_k \prec a_j)$ are consistent with $\prec$; and
  - the binding constraints for the unification of q and p are consistent with B.

Threats

•An action a_k in a partial plan $\pi = (A,\prec,B,L)$ is a threat to a causal link $\langle a_i - [p] \rightarrow a_j \rangle$ iff:

- **•a_k has an effect $\neg q$ that is possibly inconsistent with p, i.e. q and p are unifiable;**
- **•the ordering constraints $(a_i \prec a_k)$ and $(a_k \prec a_j)$ are consistent with $\prec$; and**
- **•the binding constraints for the unification of q and p are consistent with B.**

Flaws

- A flaw in a plan $\pi = (A,\prec,B,L)$ is either:
  - an unsatisfied sub-goal, i.e. a precondition of an action in *A* without a causal link that supports it; or
  - a threat, i.e. an action that may interfere with a causal link.

Flaws

•A flaw in a plan $\pi = (A,\prec,B,L)$ is either:

•an unsatisfied sub-goal, i.e. a precondition of an action in *A* without a causal link that supports it; or

•a threat, i.e. an action that may interfere with a causal link.

Flawless Plans and Solutions

- **Proposition**: A partial plan π = (A,≺,B,L) is a solution to the planning problem $\mathcal{P}$=(Σ,s_i,g) if:
  - π has no flaw;
  - the ordering constraints ≺ are not circular; and
  - the variable bindings B are consistent.
- Proof: by induction on number of actions in A
  - base case: empty plan
  - induction step: totally ordered plan minus first step is solution implies plan including first step is a solution: $\gamma(s_i, \langle a_1,\ldots,a_k\rangle) = \gamma(\gamma(s_i, a_1), \langle a_2,\ldots,a_k\rangle)$

Flawless Plans and Solutions

•Proposition: A partial plan π = (A,≺,B,L) is a solution to the planning problem $\mathcal{P}$=(Σ,s_i,g) if:

•π has no flaw;

•the ordering constraints ≺ are not circular; and

•the variable bindings B are consistent.

•computation:

•let partial plans in the search space only violate the first condition (have flaws)

•partial plans that violate either of the last two conditions cannot be refined into a solution and need not be generated

•Proof: by induction on number of actions in A

•base case: empty plan

•no flaws – every goal condition is supported by causal link from initial state

•induction step: totally ordered plan minus first step is solution implies plan including first step is a solution:
$\gamma(s_i, \langle a_1,\ldots,a_k\rangle) = \gamma(\gamma(s_i, a_1), \langle a_2,\ldots,a_k\rangle)$

•truncated plan is solution to different problem

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- just done: the goal test that completes the search problem

➢The PSP Algorithm

- now: a generic plan-space search planning algorithm

•PSP Implementation Details

•Partial-Order Planning

Plan-Space Planning as a Search Problem

- given: statement of a planning problem $P=(O,s_i,g)$
- define the search problem as follows:
  - initial state: π_0 = ({init, goal},{(init$\prec$goal)},{},{})
  - goal test for plan state p: p has no flaws
  - path cost function for plan π: $|\pi|$
  - successor function for plan state p: refinements of p that maintain $\prec$ and B

Plan-Space Planning as a Search Problem

•**given: statement of a planning problem $P=(O,s_i,g)$**

•**define the search problem as follows:**

•**initial state: π_0 = ({init, goal},{(init$\prec$goal)},{},{})**

•**goal test for plan state p: p has no flaws**

•**path cost function for plan π: $|\pi|$**

•**successor function for plan state p: refinements of p that maintain $\prec$ and B**

•note: plan space may be infinite even when state space is finite

PSP Procedure: Basic Operations

- PSP: Plan-Space Planner
- main principle: refine partial π plan while maintaining $\prec$ and B consistent until π has no more flaws
- basic operations:
  - find the flaws of π, i.e. its sub-goals and its threats
  - select one of the flaws
  - find ways to resolve the chosen flaw
  - choose one of the resolvers for the flaw
  - refine π according to the chosen resolver

PSP Procedure: Basic Operations

•PSP: Plan-Space Planner

•main principle: refine partial π plan while maintaining $\prec$ and B consistent until π has no more flaws

•basic operations:

- **•find the flaws of π, i.e. its sub-goals and its threats**
  - •simple for empty plan – all goal conditions are unachieved sub-goals and no threats
- **•select one of the flaws**
- **•find ways to resolve the chosen flaw**
- **•choose one of the resolvers for the flaw**
- **•refine π according to the chosen resolver**
  - •modify the plan in such a way that $\prec$ and B are in a consistent state for the generated successor
    - •aim: no need to verify consistency of $\prec$ and B for goal test

PSP: Pseudo Code

function PSP(*plan*)
  allFlaws ← *plan*.openGoals() + *plan*.threats()
  if *allFlaws*.empty() **then return** *plan*
  flaw ← *allFlaws*.selectOne()
  allResolvers ← *flaw*.getResolvers(*plan*)
  if *allResolvers*.empty() **then return** failure
  resolver ← *allResolvers*.chooseOne()
  newPlan ← *plan*.refine(*resolver*)
  return PSP(*newPlan*)

- **PSP: Pseudo Code**
- **function PSP(*plan*)**
  - refines the given partial plan into a solution plan; start with initial plan π_0
- ***allFlaws* ← *plan*.openGoals() + *plan*.threats()**
- **if *allFlaws*.empty() then return *plan***
  - see proposition in previous section: no flaws implies solution
- ***flaw* ← *allFlaws*.selectOne()**
- ***allResolvers* ← *flaw*.getResolvers(*plan*)**
  - represents all possible ways of removing the selected flaw from the partial plan
- **if *allResolvers*.empty() then return failure**
  - no resolvers means plan cannot be made flawless
- ***resolver* ← *allResolvers*.chooseOne()**
- ***newPlan* ← *plan*.refine(*resolver*)**
  - must maintain consistency of $\prec$ and *B*; new plan may contain new flaws
- **return PSP(*newPlan*)**

PSP: Choice Points

- *resolver* ← *allResolvers*.chooseOne()
  - non-deterministic choice
- *flaw* ← *allFlaws*.selectOne()
  - deterministic selection
  - all flaws need to be resolved before a plan becomes a solution
  - order not important for completeness
  - order is important for efficiency

PSP: Choice Points

•*resolver* ← *allResolvers*.chooseOne()

•non-deterministic choice

•*flaw* ← *allFlaws*.selectOne()

•deterministic selection

•all flaws need to be resolved before a plan becomes a solution

•order not important for completeness

•order is important for efficiency

•for finding first plan, not so for finding all plans

•deterministic implementation: using IDA*, for example

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- just done: a generic plan-space search planning algorithm (overview)

➢PSP Implementation Details

- now: functions for identifying flaws and resolving them (used in PSP)

•Partial-Order Planning

Implementing *plan*.openGoals()

- finding unachieved sub-goals (incrementally):
  - in π_0: goal conditions
  - when adding an action: all preconditions are unachieved sub-goals
  - when adding a causal link: protected proposition is no longer unachieved

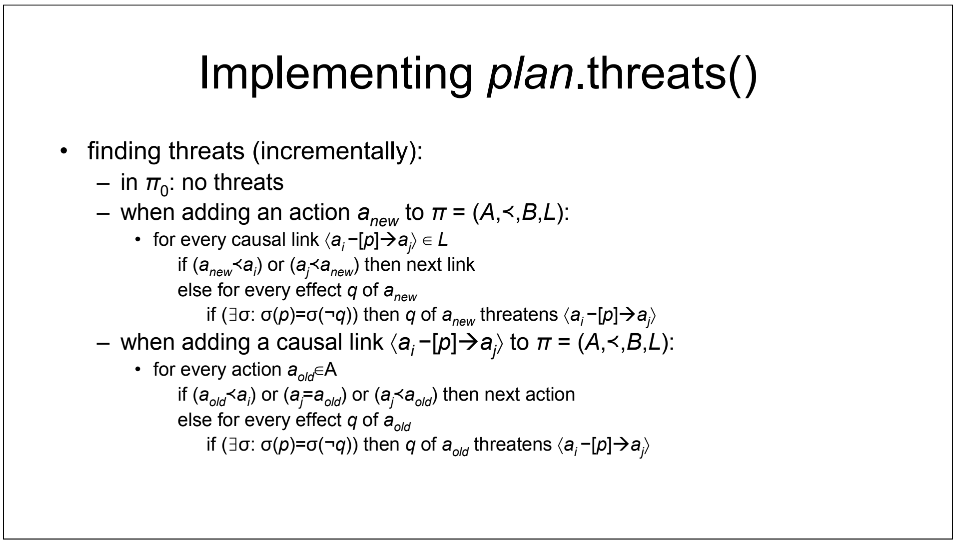
Implementing *plan*.openGoals()

•finding unachieved sub-goals (incrementally):

•in π_0: goal conditions

•when adding an action: all preconditions are unachieved sub-goals

•when adding a causal link: protected proposition is no longer unachieved



Implementing *plan*.threats()

- **finding threats (incrementally):**
  - **in π_0: no threats**
  - **when adding an action a_{new} to $\pi = (A,\prec,B,L)$:**
    - **for every causal link $\langle a_i -[p]\rightarrow a_j\rangle \in L$**
    - **if ($a_{new} \prec a_i$) or ($a_j \prec a_{new}$) then next link**
      - if the new action must occur before the provider or after the consumer of the link
    - **else for every effect q of a_{new}**
    - **if ($\exists\sigma$: $\sigma(p)=\sigma(\neg q)$) then q of a_{new} threatens $\langle a_i -[p]\rightarrow a_j\rangle$**
      - $\exists\sigma$: test whether there is a substitution consistent with B!
  - **when adding a causal link $\langle a_i -[p]\rightarrow a_j\rangle$ to $\pi = (A,\prec,B,L)$:**
    - **for every action $a_{old} \in$A**
    - **if ($a_{old} \prec a_i$) or ($a_j = a_{old}$) or ($a_j \prec a_{old}$) then next action**
    - **else for every effect q of a_{old}**
    - **if ($\exists\sigma$: $\sigma(p)=\sigma(\neg q)$) then q of a_{old} threatens $\langle a_i -[p]\rightarrow a_j\rangle$**

Implementing *flaw*.getResolvers(*plan*)

- for unachieved precondition p of a_g:
  - – add causal links to an existing action:
    - for every action $a_{old} \in A$
      if ($a_g = a_{old}$) or ($a_g \prec a_{old}$) then next action
      else for every effect q of a_{old}
        if ($\exists\sigma$: $\sigma(p)=\sigma(q)$) then adding
          $\langle a_{old} - [\sigma(p)] \rightarrow a_g \rangle$ is a resolver
  - – add a new action and a causal link:
    - for every effect q of every operator o
      if ($\exists\sigma$: $\sigma(p)=\sigma(q)$) then adding
        a_{new}=o.newInstance() and
        $\langle a_{new} - [\sigma(p)] \rightarrow a_g \rangle$ is a resolver

Implementing *flaw*.getResolvers(*plan*)

•for unachieved precondition p of a_g:

•add causal links to an existing action:

•for every action $a_{old} \in A$

•if ($a_g = a_{old}$) or ($a_g \prec a_{old}$) then next action

•else for every effect q of a_{old}

•if ($\exists\sigma$: $\sigma(p)=\sigma(q)$) then adding
$\langle a_{old} - [\sigma(p)] \rightarrow a_g \rangle$ is a resolver

•add a new action and a causal link:

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a_{new}=o.newInstance() and
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Implementing *flaw*.getResolvers(*plan*)

- for effect q of action a_t threatening $\langle a_i - [p] \rightarrow a_j \rangle$:
  - order action before threatened link:
    - if (a_t=a_i) or (a_j≺a_t) then not a resolver
      else adding (a_t≺a_i) is a resolver
  - order threatened link before action:
    - if (a_t=a_i) or (a_t≺a_i) then not a resolver
      else adding (a_j≺a_t) is a resolver
  - extend variable bindings such that unification fails:
    - for every variable v in p or q
      if $v \neq \sigma(v)$ is consistent with B then
      adding $v \neq \sigma(v)$ is a resolver

Implementing *flaw*.getResolvers(*plan*)

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•extend variable bindings such that unification fails:

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adding $v \neq \sigma(v)$ is a resolver

Implementing *plan*.refine(*resolver*)

- refines partial plan with elements in resolver by adding:
  - an ordering constraint;
  - one or more binding constraints;
  - a causal link; and/or
  - a new action.
- no testing required
- must update flaws:
  - unachieved preconditions (see: *plan*.openGoals())
  - threats (see: *plan*.threats())

Implementing *plan*.refine(*resolver*)

•refines partial plan with elements in resolver by adding:

- **•an ordering constraint;**
- **•one or more binding constraints;**
- **•a causal link; and/or**
- **•a new action.**

•no testing required

- •all testing already done in *flaw*.getResolvers(*plan*)

•must update flaws:

- **•unachieved preconditions (see: *plan*.openGoals())**
- **•threats (see: *plan*.threats())**

Maintaining Ordering Constraints

- required operations:
  - query whether ($a_i \prec a_j$)
  - adding ($a_i \prec a_j$)
- possible internal representations:
  - maintain set of predecessors/successors for each action as given
  - maintain only direct predecessors/successors for each action
  - maintain transitive closure of $\prec$ relation

Maintaining Ordering Constraints

- **required operations:**
  - **query whether ($a_i \prec a_j$)**
  - **adding ($a_i \prec a_j$)**
    - without consistency testing
- **possible internal representations:**
  - **maintain set of predecessors/successors for each action as given**
  - **maintain only direct predecessors/successors for each action**
  - **maintain transitive closure of $\prec$ relation**
  - operations have different time and space complexity
- note: query performed more often than addition

Maintaining Variable Binding Constraints

- types of constraints:
  - unary constraints: $x \in D_x$
  - equality constraints: $x = y$
  - inequalities: $x \neq y$

- note: general CSP problem is NP-complete

Maintaining Variable Binding Constraints

- **types of constraints:**
  - **unary constraints: $x \in D_x$**
  - **equality constraints: $x = y$**
    - unary and equality constraints can be solved in linear time
  - **inequalities: $x \neq y$**
    - inequalities give rise to general CSP problem
- **note: general CSP problem is NP-complete**

PSP: Sound and Complete

- **Proposition**: The PSP procedure is sound and complete: whenever π_0 can be refined into a solution plan, PSP(π_0) returns such a plan.
- Proof:
  - soundness: $\prec$ and *B* are consistent at every stage of the refinement
  - completeness: induction on the number of actions in the solution plan

PSP: Sound and Complete

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•Proof:

•soundness: $\prec$ and *B* are consistent at every stage of the refinement

•completeness: induction on the number of actions in the solution plan

•note: non-deterministic version is complete, deterministic implementation must avoid infinite branches

Overview

- Search States: Partial Plans
- Plan Refinement Operations
- The Plan-Space Search Problem
- Flawless Partial Plans
- The PSP Algorithm
- PSP Implementation Details
- Partial-Order Planning

Overview

•Search States: Partial Plans

•Plan Refinement Operations

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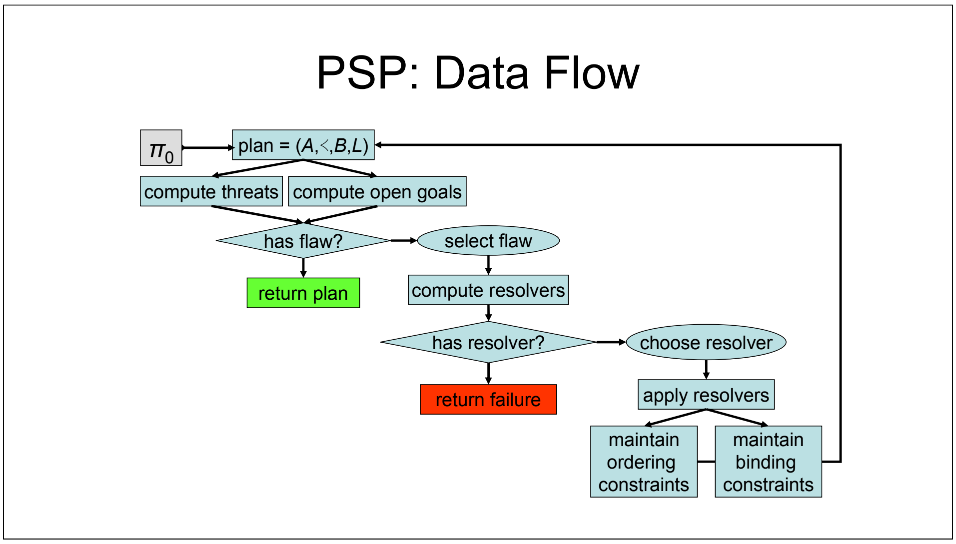
•The PSP Algorithm

•PSP Implementation Details

- just done: functions for identifying flaws and resolving them (used in PSP)

➢Partial-Order Planning

- now: the algorithm implemented by the UCPOP planner



PSP: Data Flow

•deterministic step: selecting a a flaw

  •no backtracking required

  •selection important for efficiency

  •heuristic guidance required

•non-deterministic step: choosing a resolver for a flaw

  •implemented as backtracking

    •order in which resolvers are tried important for efficiency

    •heuristic guidance required

•note: admissible heuristics (A*) must have step cost greater than zero

PSP Implementation: PoP

- extended input:
  - partial plan (as before)
  - agenda: set of pairs (*a*,*p*) where *a* is an action an *p* is one of its preconditions
- search control by flaw type
  - unachieved sub-goal (on agenda): as before
  - threats: resolved as part of the successor generation process

PSP Implementation: PoP

•based on UCPOP

•extended input:

- **•partial plan (as before)**
- **•agenda: set of pairs (*a*,*p*) where *a* is an action an *p* is one of its preconditions**
- •initial agenda: one pair for each precondition of the goal step

•search control by flaw type

- **•unachieved sub-goal (on agenda): as before**
- **•threats: resolved as part of the successor generation process**

PoP: Pseudo Code (1)

function PoP(*plan*, *agenda*)
  if *agenda*.empty() **then return** *plan*
  $(a_g,p_g) \leftarrow$ *agenda*.selectOne()
  agenda $\leftarrow$ *agenda* - (a_g,p_g)
  relevant $\leftarrow$ *plan*.getProviders(p_g)
  if *relevant*.empty() **then return** failure
  $(a_p,p_p,\sigma) \leftarrow$ *relevant*.chooseOne()
  plan.L $\leftarrow$ *plan.L* $\cup \langle a_p -[\sigma(p_g)]\rightarrow a_g\rangle$
  plan.B $\leftarrow$ *plan.B* $\cup\ \sigma$

PoP: Pseudo Code (1)

- **function PoP(*plan*, *agenda*)**
- **if *agenda*.empty() then return *plan***
- **$(a_g,p_g) \leftarrow$ *agenda*.selectOne()**
  - deterministic choice point
- ***agenda* $\leftarrow$ *agenda* - (a_g,p_g)**
- ***relevant* $\leftarrow$ *plan*.getProviders(p_g)**
  - finds all actions
    - either from within the *plan* or
    - from new instances of an operator
  - that have an effect that unifies with *condition*
- **if *relevant*.empty() then return failure**
- **$(a_p,p_p,\sigma) \leftarrow$ *relevant*.chooseOne()**
  - non-deterministic choice point
- ***plan.L* $\leftarrow$ *plan.L* $\cup \langle a_p -[p]\rightarrow a_g\rangle$**
- ***plan.B* $\leftarrow$ *plan.B* $\cup\ \sigma$**
  - must succeed for elements of relevant

PoP: Pseudo Code (2)

if $a_p \notin$ *plan.A* **then**
  plan.add(a_p)
  agenda ← *agenda* + a_p.*preconditions*
newPlan ← *plan*
for each *threat* on $\langle a_p -[p]\rightarrow a_g \rangle$ **or** due to a_p **do**
  allResolvers ← *threat*.getResolvers(*newPlan*)
  if *allResolvers*.empty() **then return** failure
  resolver ← *allResolvers*.chooseOne()
  newPlan ← *newPlan*.refine(*resolver*)
return PoP(*newPlan,agenda)*

PoP: Pseudo Code (2)

- **if $a_p \notin$ *plan.A* then**
  - if the action is new and needs to be added to the plan
- ***plan*.add(a_p)**
  - involves updating set of actions and ordering constraints
- ***agenda* ← *agenda* + a_p.*preconditions***
  - all preconditions of the new action are new sub-goals
- ***newPlan* ← *plan***
- **for each *threat* on $\langle a_p -[p]\rightarrow a_g \rangle$ or due to a_p do**
  - note: two sources of threats are treated identically
- ***allResolvers* ← *threat*.getResolvers(*newPlan*)**
- **if *allResolvers*.empty() then return failure**
- ***resolver* ← *allResolvers*.chooseOne()**
  - second non-deterministic choice point
- ***newPlan* ← *newPlan*.refine(*resolver*)**
  - note: loop does not add to agenda
- **return PSP(*newPlan,agenda)***

State-Space vs. Plan-Space Planning

- state-space planning
  - finite search space
  - explicit representation of intermediate states
  - action ordering reflects control strategy
  - causal structure only implicit
  - search nodes relatively simple and successors easy to compute
- plan-space planning
  - infinite search space
  - no intermediate states
  - choice of actions and organization independent
  - explicit representation of rationale
  - search nodes are complex and successors expensive to compute

State-Space vs. Plan-Space Planning

•state-space planning vs. plan-space planning

•finite search space vs. infinite search space

•important: portion of search space explored/generated; both search trees potentially infinite

•explicit representation of intermediate states vs. no intermediate states

•explicit representation allows for efficient domain specific heuristics and control knowledge

•action ordering reflects control strategy vs. choice of actions and organization independent

•causal structure only implicit vs. explicit representation of rationale

•important for plan execution

•search nodes relatively simple and successors easy to compute vs. search nodes are complex and successors expensive to compute

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- just done: the algorithm implemented by the UCPOP planner