Planning

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Outline

- Search vs. planning
- STRIPS operators
- Partial-order planning
- The real world
- Conditional planning
- Monitoring and replanning
search vs. planning
Search vs. Planning

- Consider the task *get milk, bananas, and a cordless drill*

- Standard search algorithms seem to fail miserably:

  - After-the-fact heuristic/goal test inadequate
Search vs. Planning

- Planning systems do the following
  1. improve action and goal representation to allow selection
  2. divide-and-conquer by \textbf{subgoaling}
  3. relax requirement for sequential construction of solutions

- Differences

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strips operators
STRIPS Operators

- Tidily arranged actions descriptions, restricted language

\[
\begin{array}{c}
\text{At}(p) \quad \text{Sells}(p, x) \\
\text{Buy}(x) \\
\text{Have}(x)
\end{array}
\]

- **ACTION:** \(\text{Buy}(x)\)
  **PRECONDITION:** \(\text{At}(p), \text{Sells}(p, x)\)
  **EFFECT:** \(\text{Have}(x)\)

- Note: this abstracts away many important details!

- Restricted language \(\implies\) efficient algorithm
  
  Precondition: conjunction of positive literals
  
  Effect: conjunction of literals
partial-order planning
Partially Ordered Plans

- **Partially ordered** collection of steps with
  - *Start* step has the initial state description as its effect
  - *Finish* step has the goal description as its precondition
  - causal links from outcome of one step to precondition of another
  - temporal ordering between pairs of steps

- **Open condition** = precondition of a step not yet causally linked

- A plan is complete iff every precondition is achieved

- A precondition is achieved iff it is the effect of an earlier step and no possibly intervening step undoes it
Example

Start

At(Home)  Sells(HWS,Drill)  Sells(SM,Milk)  Sells(SM,Ban.)

Have(Milk)  At(Home)  Have(Ban.)  Have(Drill)

Finish
Example

\[
\begin{align*}
\text{Start} \\
\text{At(Home)} & \quad \text{Sells(HWS,Drill)} & \quad \text{Sells(SM,Milk)} & \quad \text{Sells(SM,Ban.)}
\end{align*}
\]
Example

At(Home)  Sells(HWS, Drill)  Sells(SM, Milk)  Sells(SM, Ban.)

At(x)

Go(SM)

At(SM)  Sells(SM, Milk)

Buy(Milk)

Have(Milk)  At(Home)  Have(Ban.)  Have(Drill)

Finish
Example

```
Start

At(Home)  Sells(HWS,Drill)  Sells(SM,Milk)  Sells(SM,Ban.)

At(HWS)  Sells(HWS,Drill)

Buy(Drill)

At(x)

Go(SM)

At(SM)  Sells(SM,Milk)

Buy(Milk)

Have(Milk)  At(Home)  Have(Ban.)  Have(Drill)

Finish
```
Planning Process

- Operators on partial plans
  - add a link from an existing action to an open condition
  - add a step to fulfill an open condition
  - order one step wrt another to remove possible conflicts

- Gradually move from incomplete/vague plans to complete, correct plans

- Backtrack if an open condition is unachievable or if a conflict is unresolvable
Partially Ordered Plans Algorithm

function POP(initial, goal, operators) returns plan

    plan ← MAKE-MINIMAL-PLAN(initial, goal)
    loop do
        if SOLUTION?(plan) then return plan
        S_{need}, c ← SELECT-SUBGOAL(plan)
        CHOOSE-OPERATOR(plan, operators, S_{need}, c)
        RESOLVE-THREATS(plan)
    end

function SELECT-SUBGOAL(plan) returns S_{need}, c

    pick a plan step S_{need} from STEPS(plan)
    with a precondition c that has not been achieved
    return S_{need}, c
**Partially Ordered Plans Algorithm**

**procedure** \( \text{CHOOSE-OPERATOR}(\text{plan}, \text{operators}, S_\text{need}, c) \)

choose a step \( S_{\text{add}} \) from \( \text{operators} \) or \( \text{STEPS}(\text{plan}) \) that has \( c \) as an effect
if there is no such step then fail
add the causal link \( S_{\text{add}} \xrightarrow{c} S_\text{need} \) to \( \text{LINKS}(\text{plan}) \)
add the ordering constraint \( S_{\text{add}} < S_\text{need} \) to \( \text{ORDERINGS}(\text{plan}) \)
if \( S_{\text{add}} \) is a newly added step from \( \text{operators} \) then
  add \( S_{\text{add}} \) to \( \text{STEPS}(\text{plan}) \)
  add \( \text{Start} < S_{\text{add}} < \text{Finish} \) to \( \text{ORDERINGS}(\text{plan}) \)

**procedure** \( \text{RESOLVE-THREATS}(\text{plan}) \)

for each \( S_{\text{threat}} \) that threatens a link \( S_i \xrightarrow{c} S_j \) in \( \text{LINKS}(\text{plan}) \) do
  choose either
  \( \text{Demotion:} \) Add \( S_{\text{threat}} < S_i \) to \( \text{ORDERINGS}(\text{plan}) \)
  \( \text{Promotion:} \) Add \( S_j < S_{\text{threat}} \) to \( \text{ORDERINGS}(\text{plan}) \)
if not \( \text{CONSISTENT}(\text{plan}) \) then fail

end
A clobberer is a potentially intervening step that destroys the condition achieved by a causal link. E.g., $Go(Home)$ clobbers $At(Supermarket)$:

**Demotion**: put before $Go(Supermarket)$

**Promotion**: put after $Buy(Milk)$
Properties of Partially Ordered Plans

- Nondeterministic algorithm: backtracks at choice points on failure
  - choice of $S_{add}$ to achieve $S_{need}$
  - choice of demotion or promotion for clobberer
  - selection of $S_{need}$ is irrevocable

- Partially Ordered Plans is sound, complete, and systematic (no repetition)

- Extensions for disjunction, universals, negation, conditionals

- Can be made efficient with good heuristics derived from problem description

- Particularly good for problems with many loosely related subgoals
Example: Blocks World

"Sussman anomaly" problem

Start State

\[ \text{Clear}(x) \ \text{On}(x,z) \ \text{Clear}(y) \]
\[ \text{PutOn}(x,y) \]
\[ \sim \text{On}(x,z) \ \sim \text{Clear}(y) \]
\[ \text{Clear}(z) \ \text{On}(x,y) \]

Goal State

\[ \text{Clear}(x) \ \text{On}(x,z) \]
\[ \text{PutOnTable}(x) \]
\[ \sim \text{On}(x,z) \ \text{Clear}(z) \ \text{On}(x,\text{Table}) \]

+ several inequality constraints
Example

\[\text{On}(C,A) \quad \text{On}(A,\text{Table}) \quad \text{Cl}(B) \quad \text{On}(B,\text{Table}) \quad \text{Cl}(C)\]

\[\text{On}(A,B) \quad \text{On}(B,C)\]

\[\text{START} \quad \text{FINISH}\]
Example

```
START
On(C, A) On(A, Table) Cl(B) On(B, Table) Cl(C)

Cl(A) On(A, z) Cl(B)

PutOn(A, B)

On(A, B) On(B, C)

PutOn(B, C)

On(B, z) Cl(C)

PutOn(B, C)

Cl(B)

PutOn(A, B)

clobbers Cl(B)

=> order after PutOn(B, C)

FINISH

```

A

B

C

B

C

A

B

C
Example
the real world
The Real World

![Diagram of a car with a flat tire and symbols representing actions and states.]

- **START**
  - ~Flat(Spare)
  - Intact(Spare)
  - Off(Spare)
  - On(Tire1)
  - Flat(Tire1)

- **On(x) ~Flat(x)**

- **FINISH**

- **On(x)**
  - Remove(x)
  - Off(x) ClearHub

- **Off(x) ClearHub**
  - Puton(x)
  - Off(x) ClearHub

- **Intact(x) Flat(x)**
  - Inflate(x)
  - ~Flat(x)
Things Go Wrong

- **Incomplete information**
  - Unknown preconditions, e.g., $\text{Intact}(\text{Spare})$?
  - Disjunctive effects, e.g., $\text{Inflate}(x)$ causes $\text{Inflated}(x) \lor \text{SlowHiss}(x) \lor \text{Burst}(x) \lor \text{BrokenPump} \lor \ldots$

- **Incorrect information**
  - Current state incorrect, e.g., spare NOT intact
  - Missing/incorrect postconditions in operators

- **Qualification problem**
  - can never finish listing all the required preconditions and
  - possible conditional outcomes of actions
Solutions

- Conformant or sensorless planning
  Devise a plan that works regardless of state or outcome
  *Such plans may not exist*

- Conditional planning
  Plan to obtain information *(observation actions)*
  Subplan for each contingency, e.g.,
  \[ \text{Check}(\text{Tire1}), \text{if } \text{Intact}(\text{Tire1}) \text{ then } \text{Inflate}(\text{Tire1}) \text{ else } \text{CallAAA} \]
  *Expensive because it plans for many unlikely cases*

- Monitoring/Replanning
  Assume normal states, outcomes
  Check progress *during execution*, replan if necessary
  *Unanticipated outcomes may lead to failure (e.g., no AAA card)*

⇒ Really need a combination; plan for likely/serious eventualities, deal with others when they arise, as they must eventually.
Conformant Planning

- Search in space of belief states (sets of possible actual states)
conditional planning
Conditional Planning

- If the world is nondeterministic or partially observable then percepts usually provide information, i.e., split up the belief state
Conditional Planning

- Conditional plans check (any consequence of KB +) percept
- \[\ldots, \text{if } C \text{ then } Plan_A \text{ else } Plan_B, \ldots\]
- Execution: check $C$ against current KB, execute “then” or “else”
- Need *some* plan for every possible percept
  - game playing: *some* response for every opponent move
  - backward chaining: *some* rule such that every premise satisfied
- AND–OR tree search (very similar to backward chaining algorithm)
Example

- Double Murphy: sucking or arriving may dirty a clean square
monitoring and replanning
Execution Monitoring

- Plan with Partially Ordered Plans algorithms
- Process plan, one step at a time
- Validate planned conditions against perceived reality
- "Failure" = preconditions of remaining plan not met
- Preconditions of remaining plan
  - = all preconditions of remaining steps not achieved by remaining steps
  - = all causal links crossing current time point
Responding to Failure

- Run Partially Ordered Plans algorithms again
- Resume Partially Ordered Plans to achieve open conditions from current state
- IPEM (Integrated Planning, Execution, and Monitoring)
  - keep updating \textit{Start} to match current state
  - links from actions replaced by links from \textit{Start} when done
Example

Start

- At(Home)
- Go(HWS)
  - At(HWS)
  - Sells(HWS, Drill)
  - Buy( Drill)
    - At(HWS)
    - Go(SM)
      - At(SM)
      - Sells(SM, Milk)
      - Buy(Milk)
        - At(SM)
        - Go(Home)
          - Have(Milk)
          - At(Home)
          - Have(Ban.)
          - Have( Drill)
          - Finish

- Sells(HWS, Drill)
- Sells(SM, Ban.)
- Sells(SM, Milk)
Example
Example
Example
Example

```plaintext
Start

At(Home)

Go(HWS)

At(HWS)  Sells(HWS,Drill)

Buy(Drill)

At(HWS)

Go(SM)

At(SM)  Sells(SM,Milk)

Buy(Milk)

At(SM)  Sells(SM,Ban)

Buy(Ban.)

At(SM)

Have(Drill)

Have(Ban.)

Have(Milk)

Go(Home)

At(SM)

Finish

Have(Milk)  At(Home)  Have(Ban.)  Have(Drill)
```
Example
Emergent Behavior

PRECONDITIONS

START

\[ \text{Color(Chair,Blue)} \land \neg \text{Have(Red)} \]

Get(Red)

Have(Red)

Paint(Red)

\[ \text{Color(Chair,Red)} \]

FINISH

FAILURE RESPONSE

Have(Red)

Fetch more red
Emergent Behavior
Emergent Behavior

- “Loop until success” behavior emerges from interaction between monitor/replan agent design and uncooperative environment
Summary

- Planning
  - break down problem into subgoals
  - search for plans for subgoals
  - merge sub-plans

- Defined actions in terms of preconditions and effects

- Partially Ordered Plans algorithm

- Clobbering: need to deal with steps that destroy clausal link in plan

- Real world: incomplete and incorrect information

⇒ conformant or conditional planning, monitoring and replanning