State Spaces & Partial-Order Planning

AI Class 22 (Ch. 10 through 10.4.4)

Material from Dr. Marie desJardin, Some material adopted from notes by Andreas Geyer-Schulz and Chuck Dyer

Planning Problem

- What is the planning problem?
- Find a **sequence of actions** that achieves a **goal** when executed from an **initial state**.
- That is, given
  - A set of operators (possible actions)
  - An initial state description
  - A goal (description or conjunction of predicates)
- Compute a sequence of operations: a **plan**.

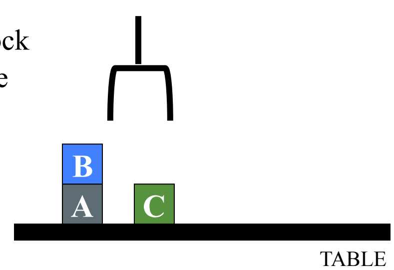
Typical Assumptions

- **Atomic time**: Each action is indivisible
- **No concurrent actions** allowed
- **Deterministic actions**
  - The result of actions are completely known – no uncertainty
- Agent is the **sole cause of change** in the world
- Agent is **omniscient:**
  - Has complete knowledge of the state of the world
- **Closed world assumption**:
  - Everything known-true about the world is in the *state description*
  - Anything not known-true is known-false

Blocks World

The **blocks world** consists of a table, set of blocks, and a robot gripper

Some domain constraints:
- Only one block on another block
- Any number of blocks on table
- Hand can only hold one block



Typical representation:

ontable(a) handempty
ontable(c) on(b,a)
clear(b) clear(c)

Major Approaches

- GPS / STRIPS
- **Situation calculus**
- **Partial order planning**
- Hierarchical decomposition (HTN planning)
- Planning with constraints (SATplan, Graphplan)
- ***Reactive planning***

General Problem Solver

- The **General Problem Solver (GPS)** system
  - An early planner (Newell, Shaw, and Simon)
- Generate actions that *reduce difference* between state and goal state
- Uses *Means-Ends Analysis*
  - Compare what is **given** or **known** with what is desired
  - Select a reasonable thing to do next
  - Use a **table of differences** to identify procedures to reduce differences
- GPS is a state space planner
  - Operates on state space problems specified by an initial state, some goal states, and a set of operations

Situation Calculus Planning

- Idea: Represent the **planning problem** using first-order logic
  - Situation calculus lets us reason about **changes** in the world
  - Use theorem proving to show ("prove") that a sequence of actions will lead to a desired result
  - When applied to a world state / situation

Situation Calculus Planning, cont.

- **Initial state**: a logical sentence about (situation) S_0
- **Goal state:** usually a conjunction of logical sentences
- **Operators**: descriptions of how the world changes as a result of the agent's actions:
  - Result(*a,s*) names the situation resulting from executing action *a* in situation *s*.
- Action sequences are also useful:
  - Result'(*l,s*): result of executing list of actions (*l*) starting in *s*

Situation Calculus Planning, cont.

- **Initial state**:
  At(Home, S_0) ∧ ¬Have(Milk, S_0) ∧ ¬Have(Bananas, S_0) ∧ ¬Have(Drill, S_0)
- **Goal state**:
  (∃s) At(Home,s) ∧ Have(Milk,s) ∧ Have(Bananas,s) ∧ Have(Drill,s)
- **Operators:**
  ∀(a,s) Have(Milk,Result(a,s)) ⇔
  ((a=Buy(Milk) ∧ At(Grocery,s)) ∨ (Have(Milk, s) ∧ a ≠ Drop(Milk)))
- Action sequence Result'(l,s):
  (∀s) Result'([ ],s) = s
  (∀a,p,s) Result'([a|p]s) = Result'(p,Result(a,s))

p=plan

Situation Calculus, cont.

- Solution: a **plan** that when applied to the **initial state** gives a situation satisfying the **goal query**:
  At(Home, Result'(p,S_0))
  ∧ Have(Milk, Result'(p,S_0))
  ∧ Have(Bananas, Result'(p,S_0))
  ∧ Have(Drill, Result'(p,S_0))
- Thus we would expect a plan (i.e., variable assignment through unification) such as:
  p = [Go(Grocery), Buy(Milk), Buy(Bananas), Go(HardwareStore), Buy(Drill), Go(Home)]

Situation Calculus: Blocks World

- Example situation calculus rule for blocks world:
  - clear(X, Result(A,S)) ↔
    [clear(X, S) ∧
      (¬(A=Stack(Y,X) ∨ A=Pickup(X))
       ∨ (A=Stack(Y,X) ∧ ¬(holding(Y,S))
       ∨ (A=Pickup(X) ∧ ¬(handempty(S) ∧ ontable(X,S) ∧ clear(X,S))))]
    ∨ [A=Stack(X,Y) ∧ holding(X,S) ∧ clear(Y,S)]
    ∨ [A=Unstack(Y,X) ∧ on(Y,X,S) ∧ clear(Y,S) ∧ handempty(S)]
    ∨ [A=Putdown(X) ∧ holding(X,S)]
- English translation: a block is **clear** if
  (a) in the previous state it was clear AND we didn't pick it up or stack something on it successfully, or
  (b) we stacked it on something else successfully, or
  (c) something was on it that we unstacked successfully, or
  (d) we were holding it and we put it down.

Wow.

Situation Calculus Planning: Analysis

- Fine in theory, but:
  - Problem solving (search) is exponential in the worst case
  - Resolution theorem proving only finds *a* proof (plan), not necessarily a *good* plan
- So what can we do?
  - Restrict the language
    - Blocks world is already pretty small…
  - Use a special-purpose algorithm (a planner) rather than general theorem prover

Basic Representations for Planning

- Classic approach first used in the STRIPS planner circa 1970
- **States** represented as conjunction of ground literals
  - at(Home) ∧ ¬have(Milk) ∧ ¬have(bananas) ...
- Goals are conjunctions of literals, but may have variables*
  - at(?x) ∧ have(Milk) ∧ have(bananas) ...
- Don't need to fully specify state
  - Un-specified: either don't-care or assumed-false
  - Represent many cases in small storage
  - Often only represent **changes in state** rather than entire situation
- Unlike theorem prover, not finding whether the goal is **true**, but is there a sequence of actions to attain it

*generally assume ∃

Operator/Action Representation

- **Operators** contain three components:
  - **Action description**
  - **Precondition** - conjunction of positive literals
  - **Effect** - conjunction of positive or negative literals which describe how situation changes when operator is applied
- Example:

Op[Action: Go(there),
    Precond: At(here) ∧ Path(here,there),
    Effect: At(there) ∧ ¬At(here)]

At(here) ,Path(here,there)

Go(there)

At(there) , ¬At(here)

- All variables are **universally** quantified
- Situation variables are implicit
  - **Preconditions** must be true in the state immediately before operator is applied
  - **Effects** are true immediately after

Blocks World Operators

- Classic basic **operations** for the blocks world:
  - stack(X,Y): put block X on block Y
  - unstack(X,Y): remove block X from block Y
  - pickup(X): pickup block X
  - putdown(X): put block X on the table
- Each will be represented by
  - Preconditions
  - New facts to be added (add-effects)
  - Facts to be removed (delete-effects)
  - A set of (simple) variable constraints (optional!)

Blocks World Operators

- Classic basic **operations** for the blocks world:
  - stack(X,Y), unstack(X,Y), pickup(X), putdown(X)
- Need:
  - Preconditions, facts to be added (add-effects), facts to be removed (delete-effects), optional variable constraints

<u>Example: stack</u>
preconditions(stack(X,Y), [holding(X), clear(Y)])
deletes(stack(X,Y), [holding(X), clear(Y)]).
adds(stack(X,Y), [handempty, on(X,Y), clear(X)])
constraints(stack(X,Y), [X≠Y, Y≠table, X≠table])

Blocks World Operators II

operator(<u>stack</u>(X,Y),
Precond [holding(X), clear(Y)],
Add [handempty, on(X,Y), clear(X)],
Delete [holding(X), clear(Y)],
Constr [X≠Y, Y≠table, X≠table]).

operator(<u>pickup</u>(X),
[ontable(X), clear(X), handempty],
[holding(X)],
[ontable(X), clear(X), handempty],
[X≠table]).

operator(<u>unstack</u>(X,Y),
[on(X,Y), clear(X), handempty],
[holding(X), clear(Y)],
[handempty, clear(X), on(X,Y)],
[X≠Y, Y≠table, X≠table]).

operator(<u>putdown</u>(X),
[holding(X)],
[ontable(X), handempty, clear(X)],
[holding(X)],
[X≠table]).

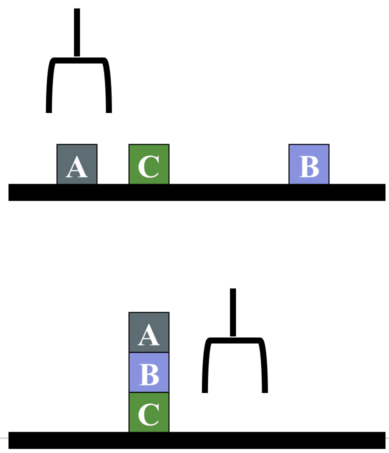
STRIPS Planning

- STRIPS maintains two additional data structures:
  - **State List** - all currently true predicates.
  - **Goal Stack** – push-down stack of goals to be solved, current goal at top.
- If current goal is not satisfied by present state:
  - Examine <u>add lists</u> of operators
  - Push operator and preconditions list on stack (and call them subgoals)
- When current goal *is* satisfied, POP it from stack.
- When an operator is on top stack
  - Record the application of that operator on the plan sequence
  - Use the operator's add and delete lists to update current state.

Typical Blocks World Planning Problem

Initial state:
- clear(a)
- clear(b)
- clear(c)
- ontable(a)
- ontable(b)
- ontable(c)
- handempty

Goal:
- on(b,c)
- on(a,b)
- ontable(c)

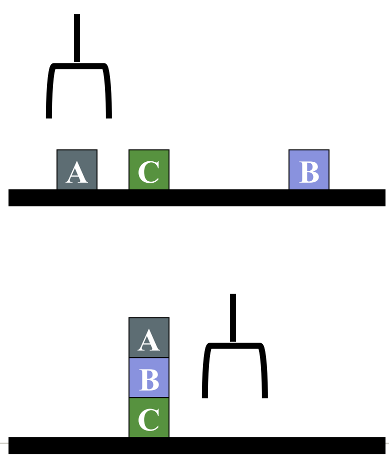


A plan:
- pickup(b)
- stack(b,c)
- pickup(a)
- stack(a,b)

Another Blocks World Planning Problem

Initial state:
- clear(a)
- clear(b)
- clear(c)
- ontable(a)
- ontable(b)
- ontable(c)
- handempty

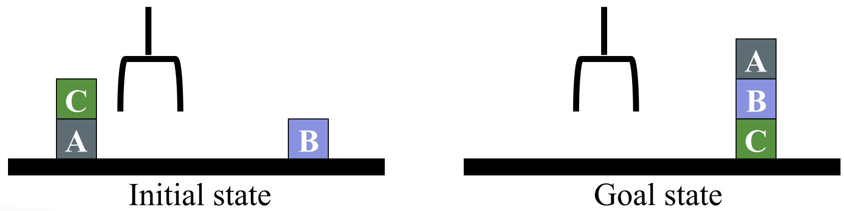
Goal:
- on(a,b)
- on(b,c)
- ontable(c)



A plan:
- pickup(a)
- stack(a,b)
- unstack(a,b)
- putdown(a)
- pickup(b)
- stack(b,c)
- pickup(a)
- stack(a,b)
- …

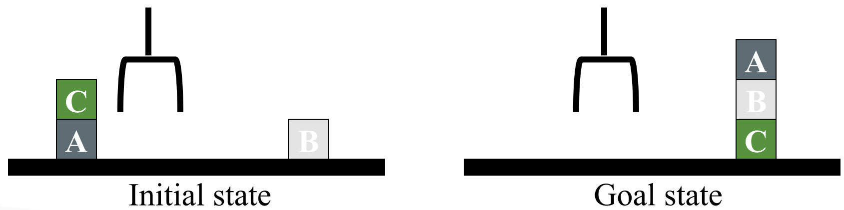
Goal Interactions

- Simple planning assumes that goals are **independent**
  - Each can be solved separately and then the solutions concatenated
- Let's look at when that fails



Goal Interactions

- The "Sussman Anomaly": classic **goal interaction problem**
  - Solving on(A,B) first (by doing unstack(C,A), stack(A,B)
  - Solve on(B,C) second (by doing unstack(A,B), stack(B,C))
- Solving on(B,C) first will be undone when solving on(A,B)
- Classic STRIPS can't handle this (minor modifications can do simple cases)



State-Space Planning

- We initially have a space of **situations** or world states
  - Where you are, what you have, ...
- Find plan by searching **situations** to reach goal
- **Progression planner**: searches forward
  - From initial state to goal state
- **Regression planner**: searches backward from goal
  - Works **iff** operators have enough information to go both ways
  - Ideally leads to reduced branching: planner is only considering things that are relevant to the goal

Planning Heuristics

- Need an **admissible** heuristic to apply to planning states
  - Estimate of the distance (number of actions) to the goal
- Planning typically uses **relaxation** to create heuristics
  - Ignore all or some selected preconditions
  - Ignore delete lists: Movement towards goal is never undone)
  - Use state abstraction (group together "similar" states and treat them as though they are identical) – e.g., ignore fluents*
  - Assume subgoal independence (use max cost; or, if subgoals actually are independent, sum the costs)
  - Use pattern databases to store exact solution costs of recurring subproblems

* an aspect of the world that changes - *R&N 266*

Plan-Space Planning

- Alternative: **search through space of *plans***, not situations
- Start from a **partial plan**; expand and refine until a complete plan that solves the problem is generated
- **Refinement operators** add constraints to the partial plan and modification operators for other changes
- We can still use STRIPS-style operators:
  Op(ACTION: RightShoe, PRECOND: RightSockOn, EFFECT: RightShoeOn)
  Op(ACTION: RightSock, EFFECT: RightSockOn)
  Op(ACTION: LeftShoe, PRECOND: LeftSockOn, EFFECT: LeftShoeOn)
  Op(ACTION: LeftSock, EFFECT: leftSockOn)

can result in a partial plan of [RightShoe, LeftShoe] ☹

Partial-Order Planning

Partial-Order Planning

- A **linear planner** builds a plan as a **totally ordered sequence** of plan steps
- A **non-linear planner (aka partial-order planner)** builds up a plan as a set of steps with some temporal constraints
  - E.g., S1<S2 (step S1 must come before S2)
- Partially ordered plan (POP) **refined** by either:
  - adding a new **plan step**, or
  - adding a new **constraint** to the steps already in the plan.
- A POP can be **linearized** (converted to a totally ordered plan) by topological sorting*

* from search - *R&N 223*

Least Commitment

- Non-linear planners embody the principle of **least commitment**
  - Only choose actions, orderings, and variable bindings that are absolutely necessary
  - Leave non-absolutely-necessary decisions till later
  - Avoids early commitment to decisions that don't really matter
- A **linear** planner always chooses to add a plan step in a particular place in the sequence
- A **non-linear** planner chooses to add a step and possibly some temporal constraints

Non-Linear Plan: Steps

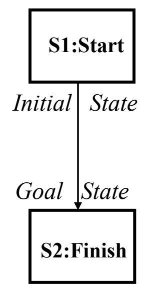
- A non-linear plan consists of
  (1) A set of **steps** $\{S_1, S_2, S_3, S_4 \ldots\}$
  Each step has an **operator description**, **preconditions** and **post-conditions**
  (2) A set of **causal links** $\{ \ldots (S_i,C,S_j) \ldots\}$
  (One) goal of step S_i is to achieve precondition C of step S_j
  (3) A set of **ordering constraints** $\{ \ldots S_i<S_j \ldots \}$
  if step S_i must come before step S_j

Non-Linear Plan: Completeness

- A non-linear plan consists of
  (1) A set of **steps** $\{S_1, S_2, S_3, S_4 \ldots\}$
  (2) A set of **causal links** $\{ \ldots (S_i,C,S_j) \ldots\}$
  (3) A set of **ordering constraints** $\{ \ldots S_i<S_j \ldots \}$
- A non-linear plan is **complete** iff
  - Every step mentioned in (2) and (3) is in (1)
  - If S_j has prerequisite C, then there exists a causal link in (2) of the form (S_i,C,S_j) for some S_i
  - If (S_i,C,S_j) is in (2) and step S_k is in (1), and S_k threatens (S_i,C,S_j) (makes C false), then (3) contains either $S_k<S_i$ or $S_j<S_k$

The Initial Plan

Every plan starts the same way



Trivial Example

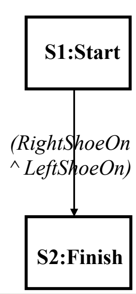
Operators:

Op(ACTION: RightShoe, PRECOND: RightSockOn, EFFECT: RightShoeOn)

Op(ACTION: RightSock, EFFECT: RightSockOn)

Op(ACTION: LeftShoe, PRECOND: LeftSockOn, EFFECT: LeftShoeOn)

Op(ACTION: LeftSock, EFFECT: leftSockOn)



Steps: {S1:[Op(Action:Start)],

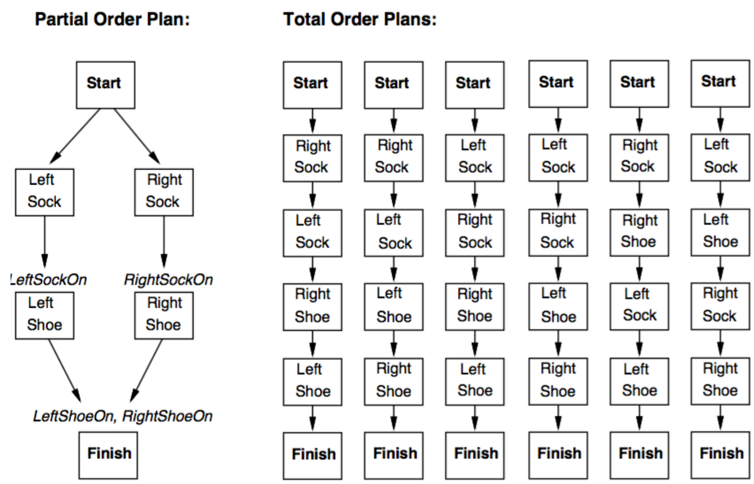
S2:[Op(Action:Finish,

Pre: RightShoeOn^LeftShoeOn)]}

Links: {}

Orderings: {S1<S2}

Solution

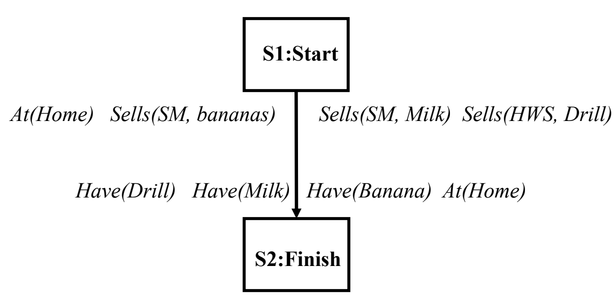


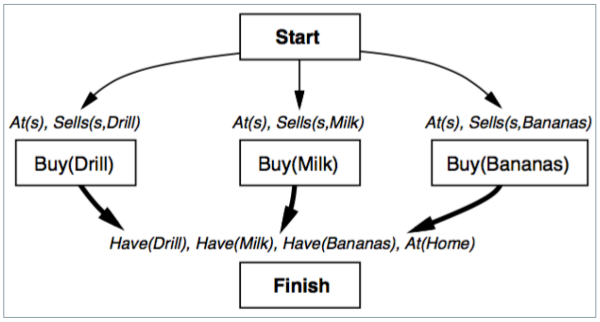
POP Constraints and Search Heuristics

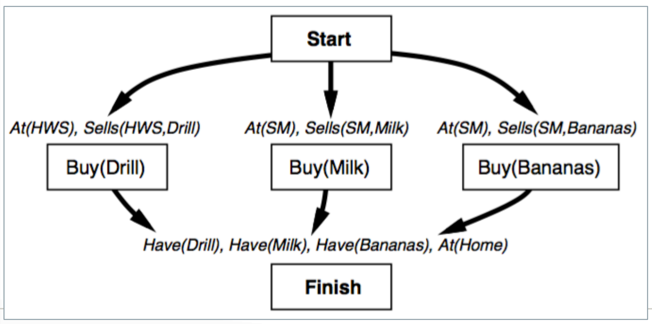
- Only add steps that reach a not-yet-achieved precondition
- Use a least-commitment approach:
  - Don't order steps unless they need to be ordered
- Honor causal links $S_1 \xrightarrow{c} S_2$ that **protect** a condition *c*:
  - Never add an intervening step S_3 that violates *c*
  - If a parallel action **threatens** *c* (i.e., has the effect of negating or **clobbering** *c*), resolve that threat by adding ordering links:
    - Order S_3 before S_1 (**demotion**)
    - Order S_3 after S_2 (**promotion**)

Partial-Order Planning Example

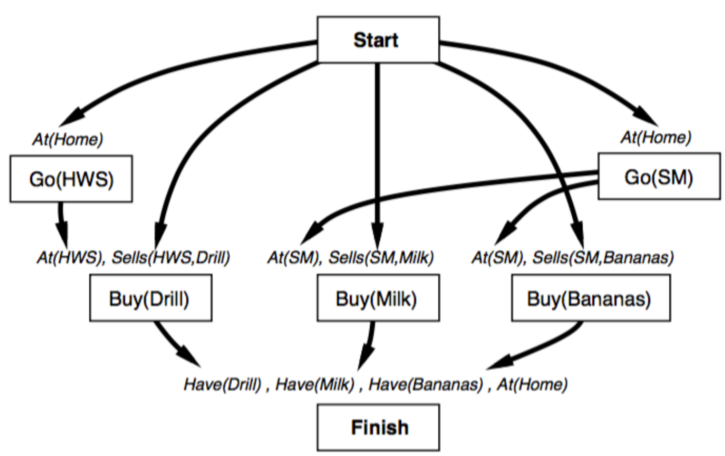
- Goal: Have milk, bananas, and a drill



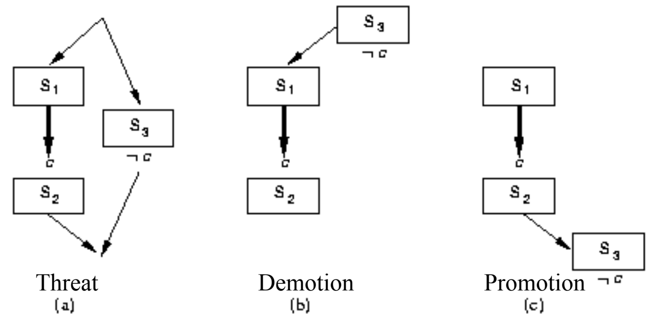


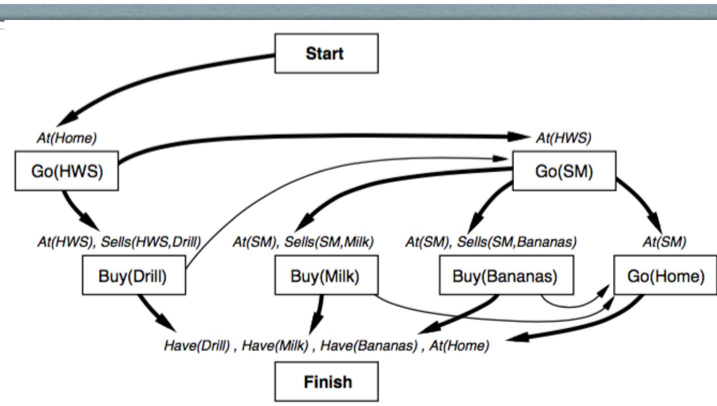


- Add three actions to achieve basic goals
- Use initial state to achieve the "Sells" preconditions
- Bold links are causal, regular are just ordering constraints

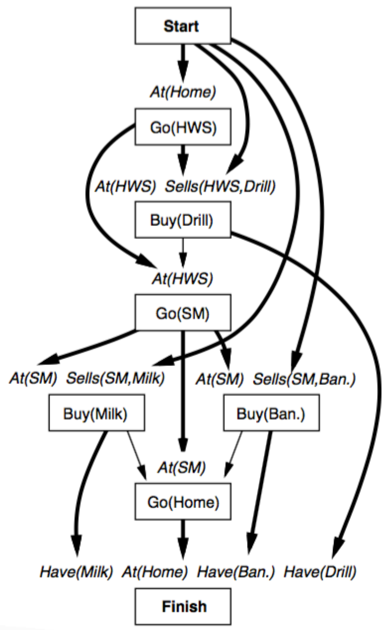


Resolving Threats



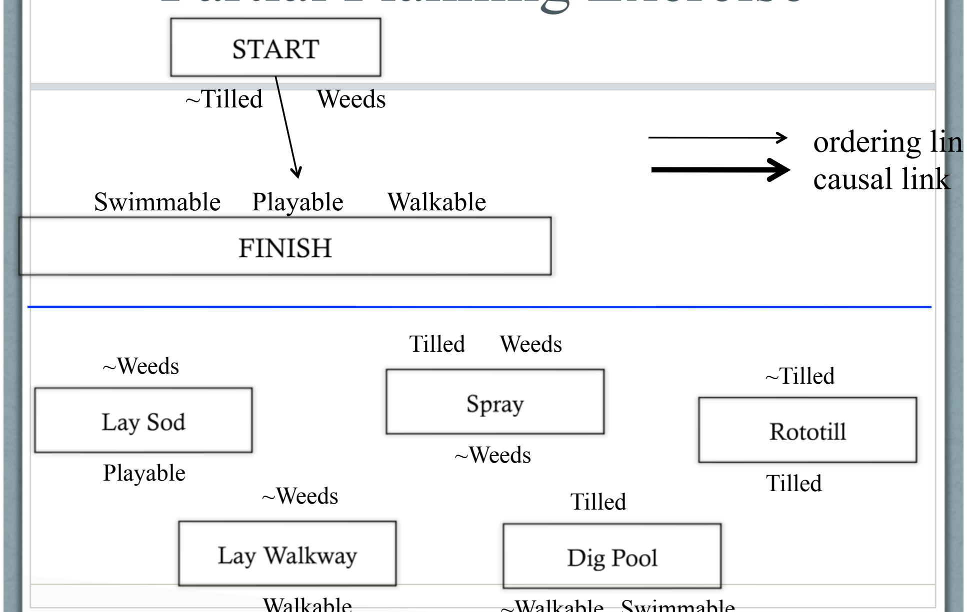


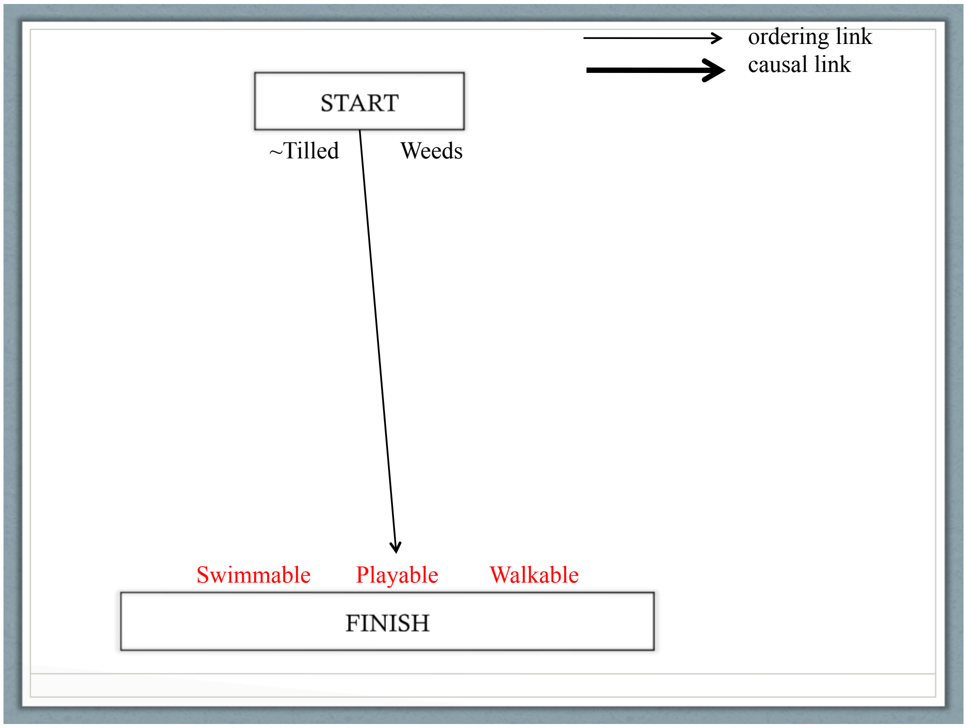
- Cannot resolve threat to At(Home) preconditions of both Go(HWS) and Go(SM).
- Must backtrack to supporting At(x) precondition of Go(SM) from intial state At(Home) and support it instead from the At(HWS) effect of Go(HWS).
- Since Go(SM) still threatens At(HWS) of Buy(Drill), must promote Go(SM) to come after Buy(Drill). Demotion is not possible due to causal link supporting At(HWS) precondition of Go(SM)

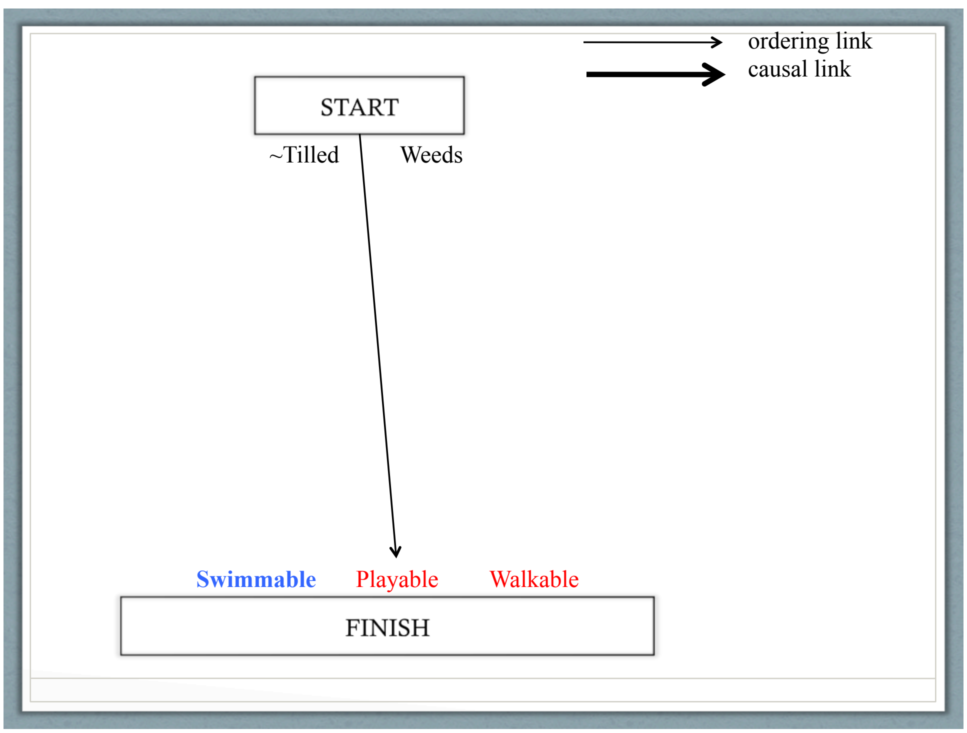


- Add Go(Home) action to achieve At(Home)
- Use At(SM) to achieve its precondition, and
- Order it after Buy(Milk) and Buy(Banana) to resolve threats to At(SM)

Partial Planning Exercise




ordering link
causal link
START
~Tilled
Weeds
Swimmable
Playable
Walkable
FINISH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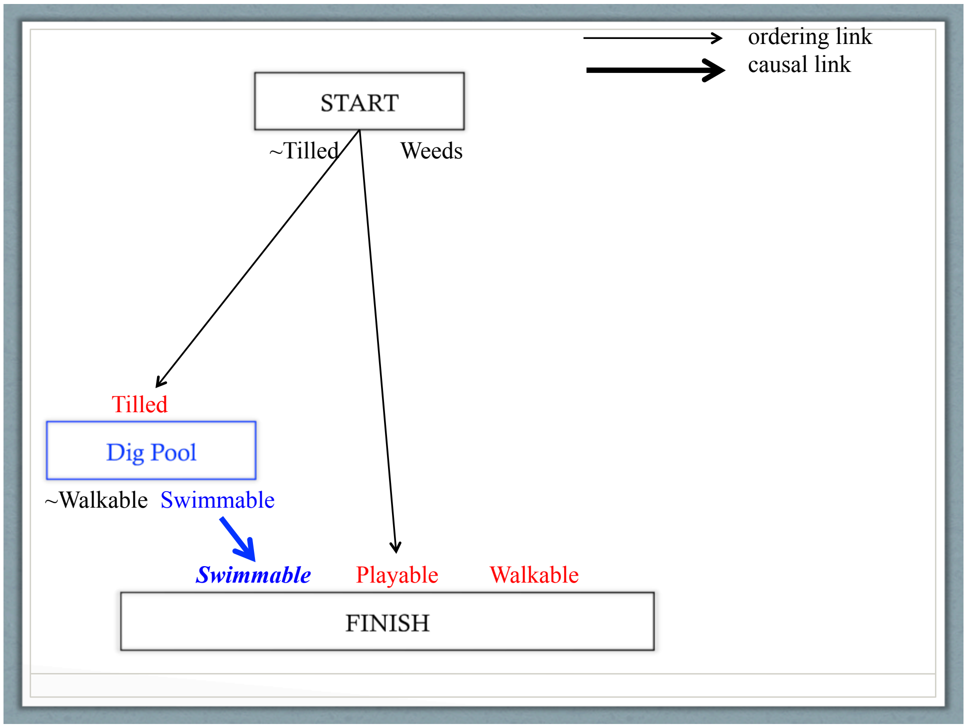
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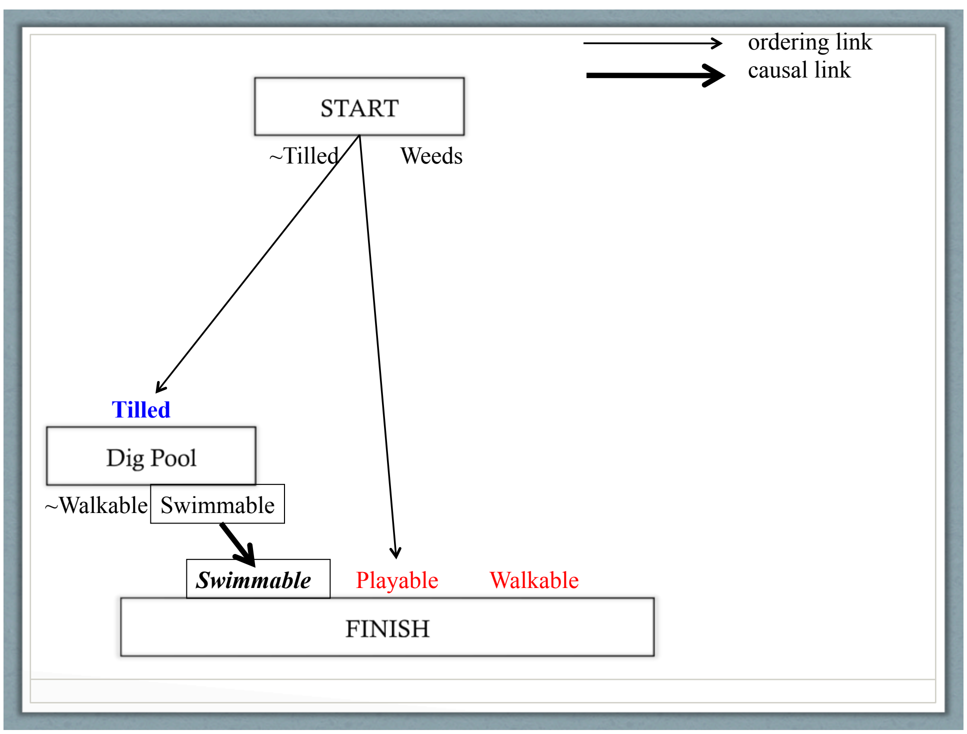
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Walkable
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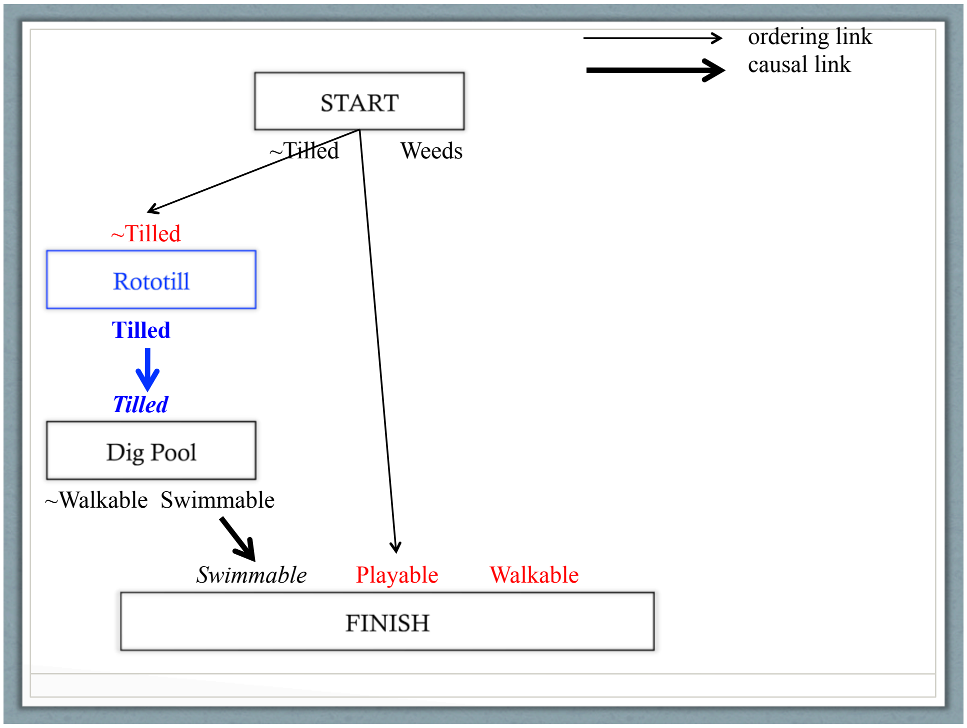
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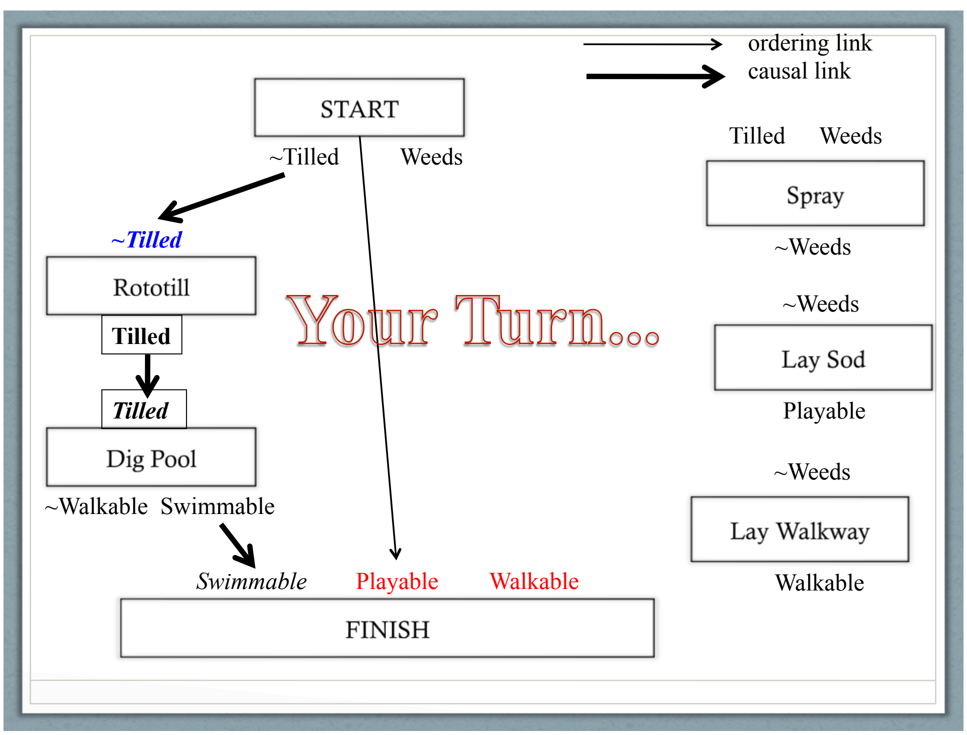
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causal link
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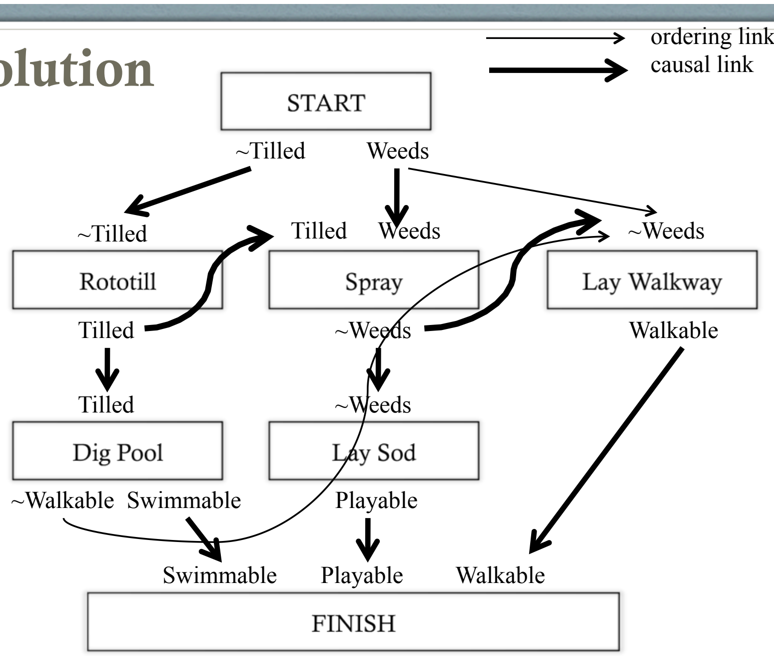
Weeds
~Tilled
Rototill
Tilled
Tilled
Dig Pool
~Walkable Swimmable
Swimmable
Playable
Walkable
FINISH
Your Turn...
Tilled Weeds
Spray
~Weeds
~Weeds
Lay Sod
Playable
~Weeds
Lay Walkway
Walkable

Solution



Real-World Planning Domains

- Real-world domains are complex
- Don't satisfy assumptions of STRIPS or partial-order planning methods
- Some of the characteristics we may need to deal with:
  - Modeling and reasoning about resources
  - Representing and reasoning about time
  - Planning at different levels of abstractions

  } Scheduling

  - Conditional outcomes of actions
  - Uncertain outcomes of actions

  } Planning under uncertainty

  - Exogenous events
  - Incremental plan development
  - Dynamic real-time replanning

  } HTN planning

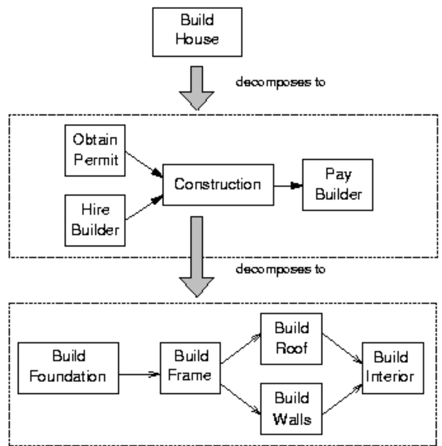
Hierarchical Decomposition

- Hierarchical decomposition, or hierarchical task network (**HTN**) planning, uses **abstract operators** to **incrementally** decompose a planning problem from a **high-level goal** statement to a **primitive plan network**
- **Primitive operators** represent actions that are **executable**, and can appear in the final plan
- **Non-primitive operators** represent **goals** (equivalently, **abstract actions**) that require further decomposition (or *operationalization*) to be executed
- There is no "right" set of primitive actions: One agent's goals are another agent's actions!

HTN Operator: Example

```
OPERATOR decompose
PURPOSE: Construction
CONSTRAINTS:
    Length (Frame) <= Length (Foundation),
    Strength (Foundation) > Wt(Frame) + Wt(Roof)
        + Wt(Walls) + Wt(Interior) + Wt(Contents)
PLOT: Build (Foundation)
      Build (Frame)
      PARALLEL
            Build (Roof)
            Build (Walls)
      END PARALLEL
      Build (Interior)
```

HTN Planning: Example



HTN Operator Representation

- Russell & Norvig explicitly represent causal links
- Can also be computed dynamically by using a model of preconditions and effects
- Dynamically computing causal links means that actions from one operator can safely be interleaved with other operators, and subactions can safely be removed or replaced during plan repair
- R&N representation only includes variable bindings
- Can actually introduce a wide array of variable constraints

Truth Criterion

- Determining whether a **formula is true** at a particular point in a partially ordered plan is, in the general case, NP-hard
- Intuition: there are exponentially many ways to **linearize** a partially ordered plan
- In the worst case, if there are N actions unordered with respect to each other, there are N! linearizations
- Ensuring soundness of truth criterion requires checking the formula under all possible linearizations
- Use heuristic methods instead to make planning feasible
- Check later to be sure no constraints have been violated

Truth Criterion in HTN Planners

- Heuristic:
  1. Prove that there exists *one* possible ordering of the actions that makes the formula true
  2. But don't insert ordering links to enforce that order
- Such a proof is efficient
  - Suppose you have an action A1 with a precondition P
  - Find an action A2 that achieves P (A2 can be initial world state)
  - Make sure there is no action *necessarily* between A2 and A1 that negates P
- Applying this heuristic for all preconditions in the plan can result in infeasible plans

Increasing Expressivity

- Conditional effects
  - Instead of different operators for different conditions, use a single operator with conditional effects
  - Move (block1, from, to) and MoveToTable (block1, from) collapse into one Move (block1, from, to):
    - Op(ACTION: Move(block1, from, to), PRECOND: On (block1, from) ^ Clear (block1) ^ Clear (to) EFFECT: On (block1, to) ^ Clear (from) ^ ~On(block1, from) ^ ~Clear(to) when to<>Table
    - There's a problem with this operator: can you spot what it is?
- Negated and disjunctive goals
- Universally quantified preconditions and effects

Reasoning About Resources

- Introduce numeric variables that can be used as *measures*
- These variables represent resource quantities, and change over the course of the plan
- Certain actions may produce (increase the quantity of) resources
- Other actions may consume (decrease the quantity of) resources
- More generally, may want different types of resources
  - Continuous vs. discrete
  - Sharable vs. nonsharable
  - Reusable vs. consumable vs. self-replenishing

Other Real-World Planning Issues

- Conditional planning
- Partial observability
- Information gathering actions
- Execution monitoring and replanning
- Continuous planning
- Multi-agent (cooperative or adversarial) planning

Planning Summary

- Planning representations
  - Situation calculus
  - STRIPS representation: Preconditions and effects
- Planning approaches
  - State-space search (STRIPS, forward chaining, ….)
  - Plan-space search (partial-order planning, HTN, …)
  - *Constraint-based search (GraphPlan, SATplan, …)*
- Search strategies
  - Forward planning
  - Goal regression
  - Backward planning
  - Least-commitment
  - Nonlinear planning