Automated Planning

Introduction and Overview

Literature

- Malik Ghallab, Dana Nau, and Paolo Traverso. *Automated Planning–Theory and Practice*, chapter 1. Elsevier/Morgan Kaufmann, 2004.
- John E. Hopcroft and Jeffrey D. Ullman. *Introduction to Automata Theory, Languages, and Computation*, chapter 2. Addison Wesley, 1979.
- Qiang Yang. *Intelligent Planning–A Decomposition and Abstraction Based Approach*. Springer, 1997.
- James Allen, James Hendler, Austin Tate (eds). *Readings in Planning*. Morgan Kaufmann, 1990.

Overview

- What is AI Planning?
- A Conceptual Model for Planning
- Restricting Assumptions
- A Running Example: Dock-Worker Robots

Human Planning and Acting

- acting without (explicit) planning:
  - when purpose is immediate
  - when performing well-trained behaviours
  - when course of action can be freely adapted
- acting after planning:
  - when addressing a new situation
  - when tasks are complex
  - when the environment imposes high risk/cost
  - when collaborating with others

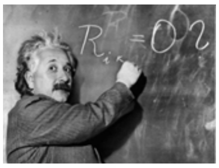
- people plan only when strictly necessary

Defining AI Planning

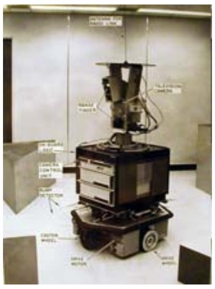
- planning:
  - explicit deliberation process that chooses and organizes actions by anticipating their outcomes
  - aims at achieving some pre-stated objectives
- AI planning:
  - computational study of this deliberation process

Why Study Planning in AI?

- scientific goal of AI: understand intelligence
  - planning is an important component of rational (intelligent) behaviour



- engineering goal of AI: build intelligent entities
  - build planning software for choosing and organizing actions for autonomous intelligent machines



Domain-Specific vs. Domain-Independent Planning

- domain-specific planning: use specific representations and techniques adapted to each problem
  - important domains: path and motion planning, perception planning, manipulation planning, communication planning
- domain-independent planning: use generic representations and techniques
  - exploit commonalities to all forms of planning
  - leads to general understanding of planning

- domain-independent planning complements domain-specific planning

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Why a Conceptual Model?

- conceptual model: theoretical device for describing the elements of a problem
- good for:
  - explaining basic concepts
  - clarifying assumptions
  - analyzing requirements
  - proving semantic properties
- not good for:
  - efficient algorithms and computational concerns

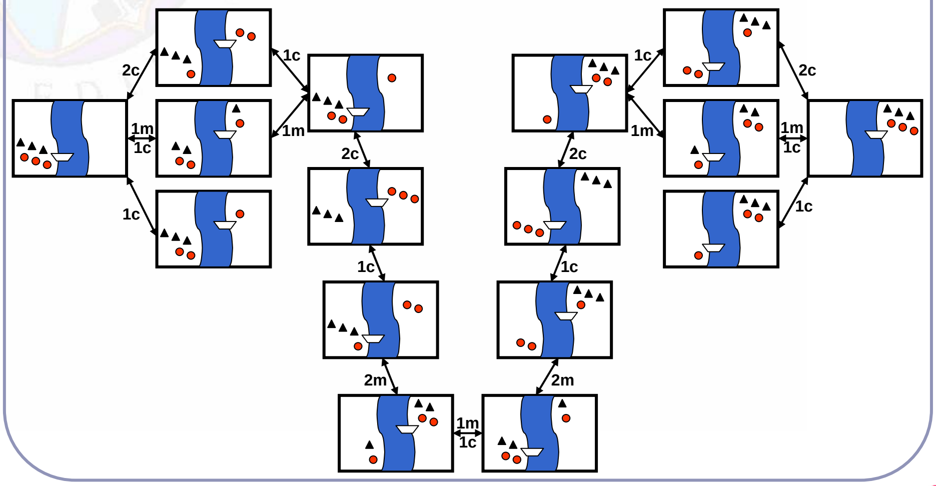
Conceptual Model for Planning: State-Transition Systems

- A state-transition system is a 4-tuple $\Sigma = (S,A,E,\gamma)$, where:
  - $S = \{s_1,s_2,\ldots\}$ is a finite or recursively enumerable set of states;
  - $A = \{a_1,a_2,\ldots\}$ is a finite or recursively enumerable set of actions;
  - $E = \{e_1,e_2,\ldots\}$ is a finite or recursively enumerable set of events; and
  - $\gamma: S\times(A\cup E)\rightarrow 2^S$ is a state transition function.
- if $a\in A$ and $\gamma(s,a) \neq \varnothing$ then a is applicable in s
- applying a in s will take the system to $s'\in\gamma(s,a)$

State-Transition Systems as Graphs

- A state-transition system $\Sigma = (S,A,E,\gamma)$ can be represented by a directed labelled graph $G = (N_G,E_G)$ where:
  - the nodes correspond to the states in S, i.e. N_G=S; and
  - there is an arc from $s \in N_G$ to $s' \in N_G$, i.e. $s \rightarrow s' \in E_G$, with label $u \in (A \cup E)$ if and only if $s' \in \gamma(s,a)$.

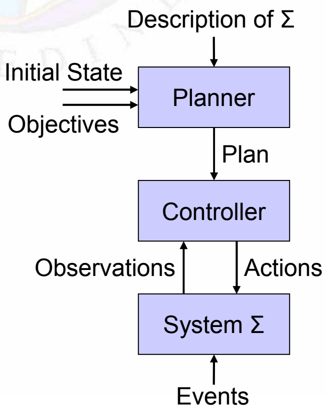
State-Transition Graph Example: Missionaries and Cannibals



Objectives and Plans

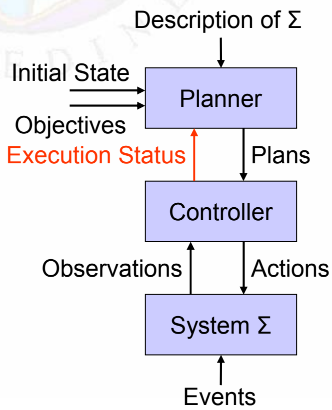
- state-transition system:
  - describes all ways in which a system may evolve
- plan:
  - a structure that gives appropriate actions to apply in order to achieve some objective when starting from a given state
- types of objective:
  - goal state s_g or set of goal states S_g
  - satisfy some conditions over the sequence of states
  - optimize utility function attached to states
  - task to be performed

Planning and Plan Execution



- planner:
  - given: description of Σ, initial state, objective
  - generate: plan that achieves objective
- controller:
  - given: plan, current state (observation function: $\eta:S\rightarrow O$)
  - generate: action
- state-transition system:
  - evolves as actions are executed and events occur

Dynamic Planning



- problem: real world differs from model described by Σ
- more realistic model: interleaved planning and execution
  - plan supervision
  - plan revision
  - re-planning
- dynamic planning: closed loop between planner and controller
  - execution status

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A0: Finite Σ

- Assumption A0
  - system Σ has a finite set of states
- Relaxing A0
  - why?
    - to describe actions that construct or bring new objects into the world
    - to handle numerical state variables
  - issues:
    - decidability and termination of planners

A1: Fully Observable Σ

- Assumption A1
  - system Σ is fully observable, i.e. η is the identity function
- Relaxing A1
  - why?
    - to handle states in which not every aspect is or can be known
  - issues:
    - if $\eta(s)=o$, $\eta^{-1}(o)$ usually more than one state (ambiguity)
    - determining the successor state

A2: Deterministic Σ

- Assumption A2
  - system Σ is <u>deterministic</u>, i.e. for all $s \in S$, $u \in A \cup E$: $|\gamma(s,u)| \leq 1$
  - short form: $\gamma(s,u)=s'$ for $\gamma(s,u)=\{s'\}$
- Relaxing A2
  - why?
    - to plan with actions that may have multiple alternative outcomes
  - issues:
    - controller has to observe actual outcomes of actions
    - solution plan may include conditional and iterative constructs

A3: Static Σ

- Assumption A3
  - system Σ is <u>static</u>, i.e. $E = \emptyset$
  - short form: $\Sigma = (S,A,\gamma)$ for $\Sigma = (S,A,\emptyset,\gamma)$
- Relaxing A3
  - why?
    - to model a world in which events can occur
  - issues:
    - world becomes nondeterministic from the point of view of the planner (same issues)

A4: Restricted Goals

- Assumption A4
  - the planner handles only restricted goals that are given as an explicit goal state s_g or set of goal states S_g
- Relaxing A4
  - why?
    - to handle constraints on states and plans, utility functions, or tasks
  - issues:
    - representation and reasoning over constraints, utility, and tasks

A5: Sequential Plans

- Assumption A5
  - a solution plan is a linearly ordered finite sequence of actions
- Relaxing A5
  - why?
    - to handle dynamic systems (see A3: static Σ)
    - to create different types of plans
  - issues:
    - must not shift problem to the controller
    - reasoning about (more complex) data structures

A6: Implicit Time

- Assumption A6
  - actions and events have no duration in state transition systems
- Relaxing A6
  - why?
    - to handle action duration, concurrency, and deadlines
  - issues:
    - representation of and reasoning about time
    - controller must wait for effects of actions to occur

A7: Offline Planning

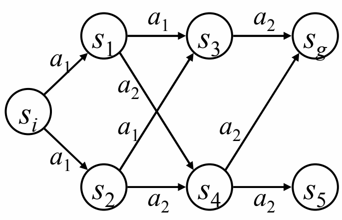
- Assumption A7
  - planner is not concerned with changes of Σ while it is planning
- Relaxing A7
  - why?
    - to drive a system towards some objectives
  - issues:
    - check whether the current plan remains valid
    - if needed, revise current plan or re-plan

The Restricted Model

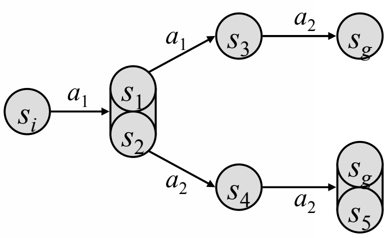
- restricted model: make assumptions A0-A7
- Given a planning problem $\mathcal{P}=(\Sigma,s_i,S_g)$ where
  - $\Sigma = (S,A,\gamma)$ is a state transition system,
  - $s_i \in S$ is the initial state, and
  - $S_g \subset S$ is a set of goal states,
- find a sequence of actions $\langle a_1,a_2,\ldots,a_k\rangle$
  - corresponding to a sequence of state transitions $\langle s_i,s_1,\ldots,s_k\rangle$ such that
  - $s_1 = \gamma(s_i,a_1)$, $s_2 = \gamma(s_1,a_2),\ldots$, $s_k = \gamma(s_{k-1},a_k)$, and $s_k \in S_g$.

Restrictedness?

- non-deterministic state-transition system:



- equivalent deterministic state-transition system:



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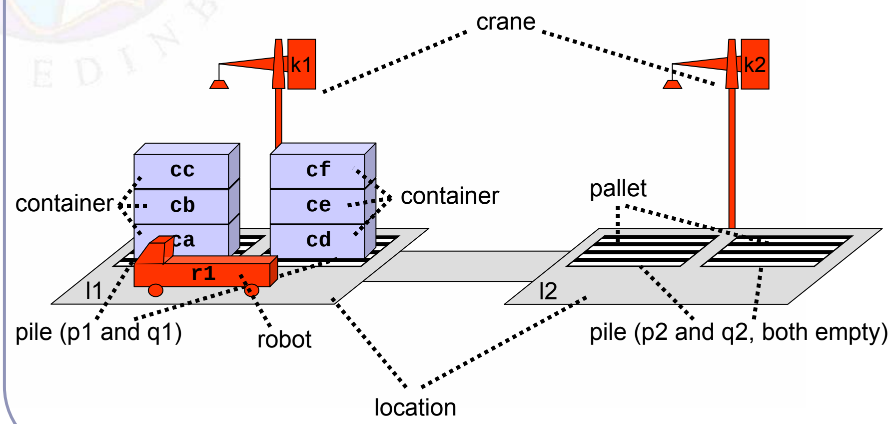
The Dock-Worker Robots (DWR) Domain

- aim: have one example to illustrate planning procedures and techniques
- informal description:
  - harbour with several locations (docks), docked ships, storage areas for containers, and parking areas for trucks and trains
  - cranes to load and unload ships etc., and robot carts to move containers around

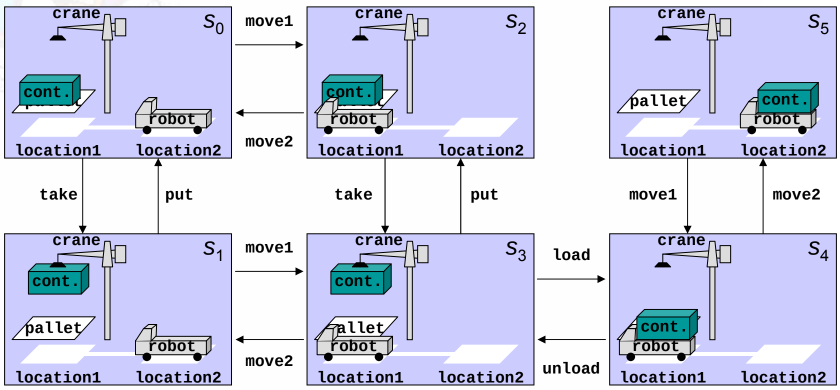
DWR Example State



Actions in the DWR Domain

- **move** robot *r* from location *l* to some adjacent and unoccupied location *l'*
- **take** container *c* with empty crane *k* from the top of pile *p*, all located at the same location *l*
- **put** down container *c* held by crane *k* on top of pile *p*, all located at location *l*
- **load** container *c* held by crane *k* onto unloaded robot *r*, all located at location *l*
- **unload** container *c* with empty crane *k* from loaded robot *r*, all located at location *l*

State-Transition Systems: Graph Example



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