Chapter 1
Introduction
Some Dictionary Definitions of “Plan”

plan n.

1. A scheme, program, or method worked out beforehand for the accomplishment of an objective: a plan of attack.

2. A proposed or tentative project or course of action: had no plans for the evening.

3. A systematic arrangement of elements or important parts; a configuration or outline: a seating plan; the plan of a story.

4. A drawing or diagram made to scale showing the structure or arrangement of something.

5. A program or policy stipulating a service or benefit: a pension plan.

[a representation] of future behavior … usually a set of actions, with temporal and other constraints on them, for execution by some agent or agents.

– Austin Tate, MIT Encyclopedia of the Cognitive Sciences, 1999
Abstraction

- Real world is absurdly complex, need to approximate
  - Only represent what the planner needs to reason about
- **State transition system** $\Sigma = (S,A,E,\gamma)$
  - $S = \{\text{abstract states}\}$
    - e.g., states might include a robot’s location, but not its position and orientation
  - $A = \{\text{abstract actions}\}$
    - e.g., “move robot from loc2 to loc1” may need complex lower-level implementation
  - $E = \{\text{abstract exogenous events}\}$
    - Not under the agent’s control
  - $\gamma = \text{state transition function}$
    - Gives the next state, or possible next states, after an action or event
    - $\gamma: S \times (A \cup E) \rightarrow S$ or $\gamma: S \times (A \cup E) \rightarrow 2^S$
- In some cases, avoid ambiguity by writing $S_\Sigma, A_\Sigma, E_\Sigma, \gamma_\Sigma$
State Transition System

- $\Sigma = (S, A, E, \gamma)$
  - $S = \{\text{states}\}$
  - $A = \{\text{actions}\}$
  - $E = \{\text{exogenous events}\}$
  - $\gamma = \text{state-transition func.}$

Example:
- $S = \{s_0, \ldots, s_5\}$
- $A = \{\text{move1, move2, put, take, load, unload}\}$
- $E = \{\}$
  - so write $\Sigma = (S, A, \gamma)$
- $\gamma: S \times A \rightarrow S$
  - see the arrows

Dock Worker Robots (DWR) example
Control may involve lower-level planning and/or plan execution

- e.g., how to move from one location to another
Planning Problem

- Description of Σ
- Initial state or set of states
- Objective
  - Goal state, set of goal states, set of tasks, “trajectory” of states, objective function, …
- e.g.,
  - Initial state = $s_0$
  - Goal state = $s_5$

Dock Worker Robots (DWR) example
Plans

**Classical plan**: a sequence of actions
\[
\langle \text{take, move1, load, move2} \rangle
\]

**Policy**: partial function from $S$ into $A$
\[
\{(s_0, \text{take}),
(s_1, \text{move1}),
(s_3, \text{load}),
(s_4, \text{move2})\}
\]

- Both, if executed starting at $s_0$, produce $s_3$

Dock Worker Robots (DWR) example
Planning Versus Scheduling

- **Scheduling**
  - Decide when and how to perform a given set of actions
    - Time constraints
    - Resource constraints
    - Objective functions
  - Typically NP-complete

- **Planning**
  - Decide what actions to use to achieve some set of objectives
  - Can be much worse than NP-complete; worst case is undecidable

- Scheduling problems may require replanning
Three Main Types of Planners

1. Domain-specific
   - Made or tuned for a specific planning domain
   - Won’t work well (if at all) in other planning domains

2. Domain-independent
   - In principle, works in any planning domain
   - In practice, need restrictions on what kind of planning domain

3. Configurable
   - Domain-independent planning engine
   - Input includes info about how to solve problems in some domain
1. Domain-Specific Planners (Chapters 19-23)

- Most successful real-world planning systems work this way
  - Mars exploration, sheet-metal bending, playing bridge, etc.
- Often use problem-specific techniques that are difficult to generalize to other planning domains
Types of Planners
2. Domain-Independent

- In principle, works in any planning domain
- No domain-specific knowledge except the description of the system $\Sigma$
- In practice,
  - Not feasible to make domain-independent planners work well in all possible planning domains
- Make simplifying assumptions to restrict the set of domains
  - Classical planning
  - Historical focus of most research on automated planning
Restrictive Assumptions

A0: Finite system:
   - finitely many states, actions, events

A1: Fully observable:
   - the controller always Σ’s current state

A2: Deterministic:
   - each action has only one outcome

A3: Static (no exogenous events):
   - no changes but the controller’s actions

A4: Attainment goals:
   - a set of goal states $S_g$

A5: Sequential plans:
   - a plan is a linearly ordered sequence of actions $(a_1, a_2, \ldots a_n)$

A6: Implicit time:
   - no time durations; linear sequence of instantaneous states

A7: Off-line planning:
   - planner doesn’t know the execution status
Classical Planning (Chapters 2–9)

- Classical planning requires all eight restrictive assumptions
  - Offline generation of action sequences for a deterministic, static, finite system, with complete knowledge, attainment goals, and implicit time
- Reduces to the following problem:
  - Given a planning problem \( P = (\Sigma, s_0, S_g) \)
  - Find a sequence of actions \( (a_1, a_2, \ldots a_n) \) that produces a sequence of state transitions \( (s_1, s_2, \ldots, s_n) \) such that \( s_n \) is in \( S_g \).
- This is just path-searching in a graph
  - Nodes = states
  - Edges = actions
- Is this trivial?
Classical Planning (Chapters 2–9)

- Generalize the earlier example:
  5 locations,
  3 robot vehicles,
  100 containers,
  3 pallets to stack containers on
  - Then there are $10^{277}$ states

- Number of particles in the universe is only about $10^{87}$
  - The example is more than $10^{190}$ times as large

- Automated-planning research has been heavily dominated by classical planning
  - Dozens (hundreds?) of different algorithms
Plan-Space Planning (Chapter 5)

- Decompose sets of goals into the individual goals
- Plan for them separately
  - Bookkeeping info to detect and resolve interactions
- Produce a partially ordered plan that retains as much flexibility as possible
- The Mars rovers used a temporal-planning extension of this
Planning Graphs (Chapter 6)

- Rough idea:
  - First, solve a relaxed problem
    - Each “level” contains all effects of all applicable actions
    - Even though the effects may contradict each other
  - Next, do a state-space search within the planning graph

- Graphplan, IPP, CGP, DGP, LGP, PGP, SGP, TGP, ...
Heuristic Search (Chapter 9)

- Heuristic function like those in A*
  - Created using techniques similar to planning graphs
- Problem: A* quickly runs out of memory
  - So do a greedy search instead

- Greedy search can get trapped in local minima
  - Greedy search plus local search at local minima

- HSP [Bonet & Geffner]
- FastForward [Hoffmann]
Translation to Other Kinds of Problems (Chapters 7, 8)

- Translate the planning problem or the planning graph into another kind of problem for which there are efficient solvers
  - Find a solution to that problem
  - Translate the solution back into a plan

- Satisfiability solvers, especially those that use local search
  - Satplan and Blackbox [Kautz & Selman]

- Integer programming solvers such as Cplex
  - [Vossen et al.]
Types of Planners: 3. Configurable

- In any fixed planning domain, a domain-independent planner usually won’t work as well as a domain-specific planner made specifically for that domain
  - A domain-specific planner may be able to go directly toward a solution in situations where a domain-independent planner would explore many alternative paths
- But we don’t want to write a whole new planner for every domain
- **Configurable planners**
  - Domain-independent planning engine
  - Input includes info about how to solve problems in the domain
- Generally this means one can write a planning engine with fewer restrictions than domain-independent planners
  - Hierarchical Task Network (HTN) planning
  - Planning with control formulas
HTN Planning (Chapter 11)

- Problem reduction
  - Tasks (activities) rather than goals
  - Methods to decompose tasks into subtasks
  - Enforce constraints, backtrack if necessary
- Real-world applications
  - Noah, Nonlin, O-Plan, SIPE, SIPE-2, SHOP, SHOP2

Diagram:
- Travel from UMD to LAAS
  - Get ticket: BWI to TLS
  - Go to web service
  - Find flights: BWI to TLS
  - Get taxi
  - Ride from UMD to IAD
  - Pay driver
  - Fly from BWI to TLS
  - ... complicated sequence of actions ...
  - Travel from TLS to LAAS
  - Get taxi
  - Ride from TLS to LAAS
  - Pay driver

Note: The diagram illustrates the planning process with HTN (Hierarchical Task Network) planning.
Planning with Control Formulas (Chapter 10)

- At each state $s$, we have a *control formula* written in temporal logic
  - e.g.,
    
    $$ontable(x) \land \neg \exists y:GOAL(on(x,y)) \Rightarrow \Diamond(\neg holding(x))$$
    
    “never pick up $x$ unless $x$ needs to go on top of something else”

- For each successor of $s$, derive a control formula using *logical progression*
- Prune any successor state in which the progressed formula is false
  - TLPlan, TALplanner, …
Comparisons

- **Domain-specific planner**
  - Write an entire computer program - lots of work
  - Lots of domain-specific performance improvements
- **Domain-independent planner**
  - Just give it the basic actions - not much effort
  - Not very efficient
Comparisons

- A domain-specific planner only works in one domain.

- **In principle**, configurable and domain-independent planners should both be able to work in any domain.

- **In practice**, configurable planners work in a larger variety of domains:
  - Partly due to efficiency.
  - Partly because of the restrictions required by domain-independent planners.

But only if you can write the domain knowledge.
Reasoning about Time during Planning

- **Temporal planning (Chapter 14)**
  - Explicit representation of time
  - Actions have duration, may overlap with each other

- **Planning and scheduling (Chapter 15)**
  - What a scheduling problem is
  - Various kinds of scheduling problems, how they relate to each other
  - Integration of planning and scheduling
Planning in Nondeterministic Environments

- Actions may have multiple possible outcomes
  - some actions are inherently random (e.g., flip a coin)
  - actions sometimes fail to have their desired effects
    - drop a slippery object
    - car not oriented correctly in a parking spot
- How to model the possible outcomes, and plan for them
  - Markov Decision Processes (Chapter 16)
    - outcomes have probabilities
  - Planning as Model Checking (Chapter 17)
    - multiple possible outcomes, but don’t know the probabilities
Example Applications

- **Robotics (Chapter 20)**
  - Physical requirements
  - Path and motion planning
    - Configuration space
    - Probabilistic roadmaps
  - Design of a robust controller

- **Planning in the game of bridge (Chapter 23)**
  - Game-tree search in bridge
  - HTN planning to reduce the size of the game tree
Dock Worker Robots

- Used as a source of examples throughout the book
  - A harbor with several locations
    - e.g., docks, docked ships, storage areas, parking areas
  - Containers
    - going to/from ships
  - Robot vehicles
    - can move containers
  - Cranes
    - can load and unload containers
Objects

- **Locations**: l1, l2, ..., or loc1, loc2, ...

- **Containers**: c1, c2, ...
  - can be stacked in piles, loaded onto robots, or held by cranes

- **Piles**: p1, p2, ...
  - places to stack containers
  - pallet at the bottom of each pile

- **Robot vehicles**: r1, r2, ...
  - carry at most one container
  - can move to adjacent locations
  - limit on how many can be at a location

- **Cranes**: k1, k2, ...
  - each belongs to a single location or a single robot
  - move containers between piles and robots
Properties of the Objects

- **Rigid** properties: same in all states
  - which locations are adjacent
  - which cranes and piles are at which locations

- **Variable** properties:
  differ from one state to another
  - location of each robot
  - for each container
    - which location
    - which pile/crane/robot
    - at top of pile?

- **Actions:**
  - A crane make **take** a container from a stack, **put** it onto a stack, **load** it onto a robot, or **unload** it from a robot
  - A robot may **move** from a location to another adjacent location
Any Questions?