Lecture slides for

*Automated Planning: Theory and Practice*

# Chapter 1
# Introduction

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1:39 PM February 1, 2012

# 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*.

- Which of these do you think this course is about?

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[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

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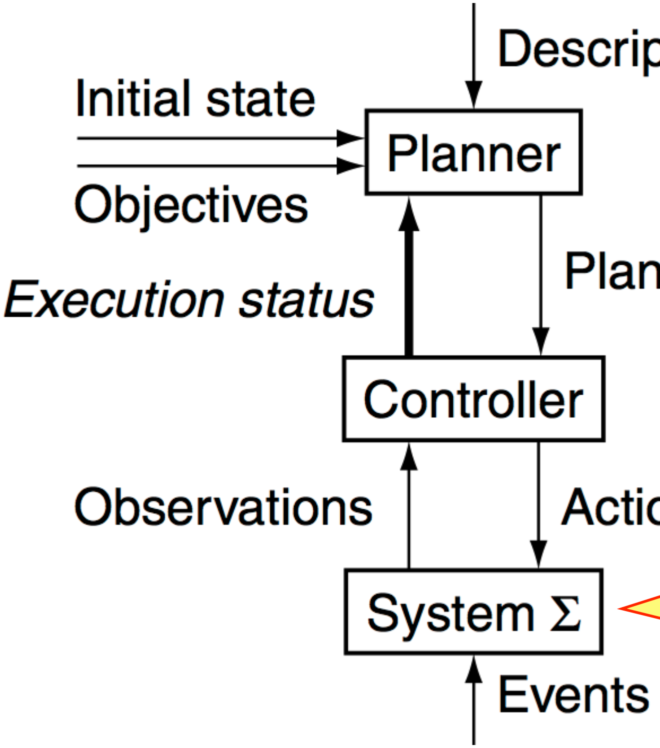
# Conceptual Model



State transition system
$\Sigma = (S, A, E, \gamma)$

$S$ = {states}

$A$ = {actions}

$E$ = {exogenous events}

$\gamma$ = state-transition function

- Σ is an abstraction
  - Deals only with the aspects that the planner needs to reason about

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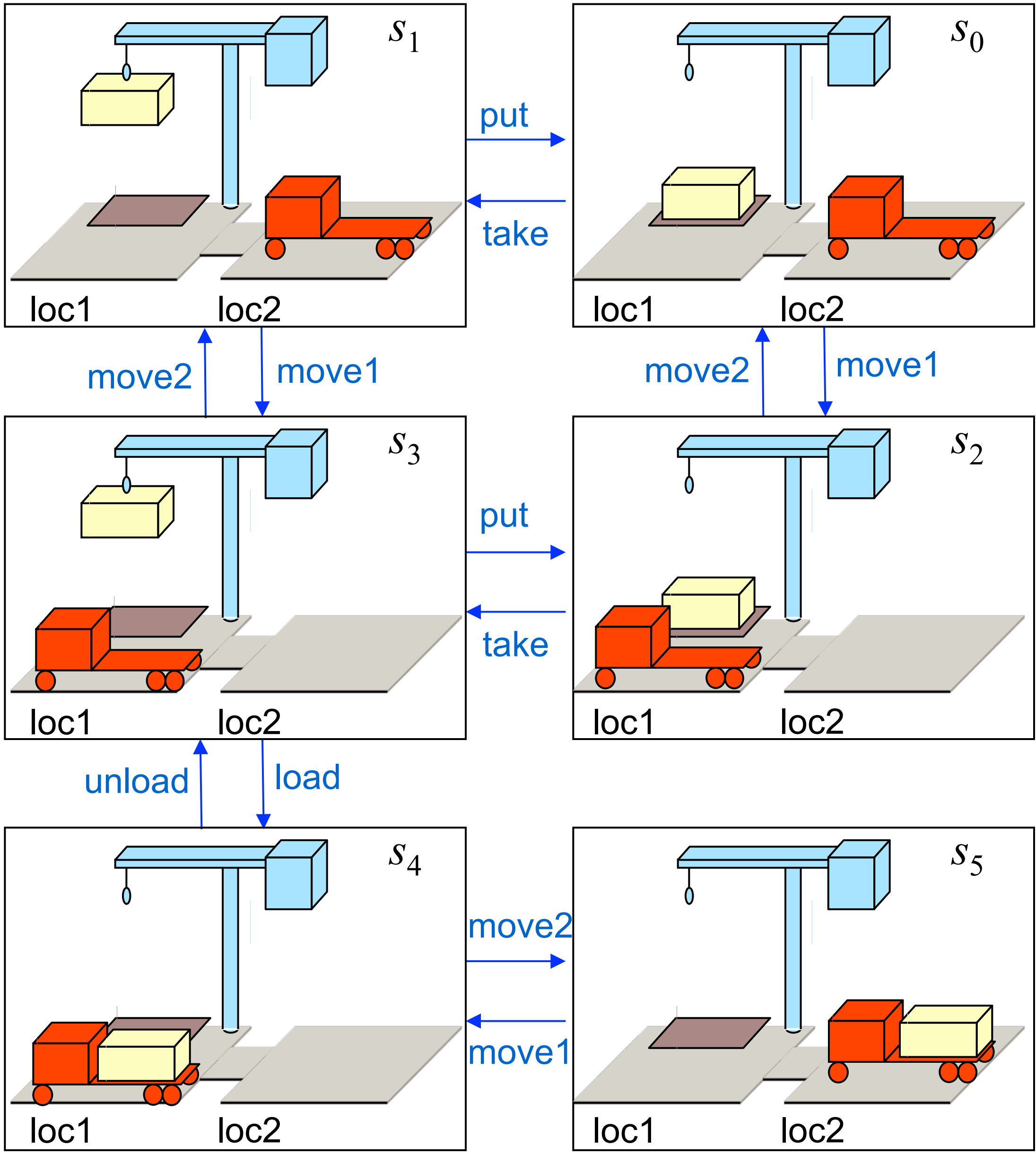
# Example

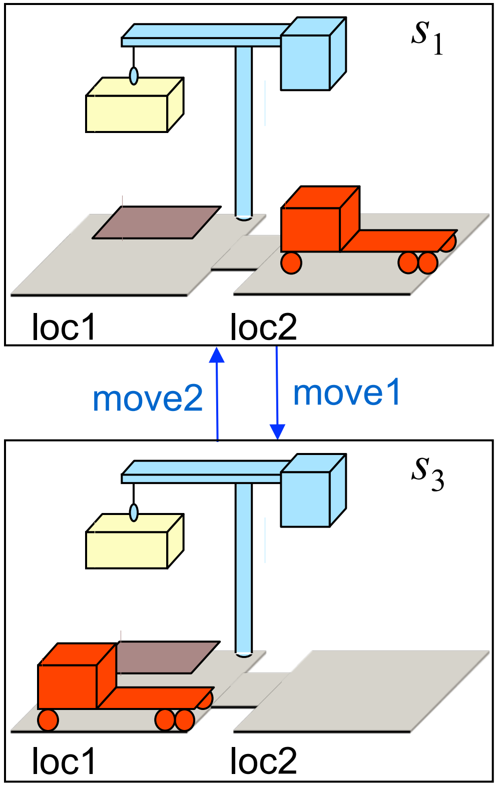
- $\Sigma = (S,A,E,\gamma)$
  - $S$ = {states}
  - $A$ = {actions}
  - $E$ = {exogenous events}
  - State-transition function $\gamma: S \times (A \cup E) \to 2^S$
- Example:
  - $S = \{s_0, \ldots, s_5\}$
  - $A$ = {move1, move2, put, take, load, unload}
  - $E = \{\}$
  - $\gamma$: see the arrows



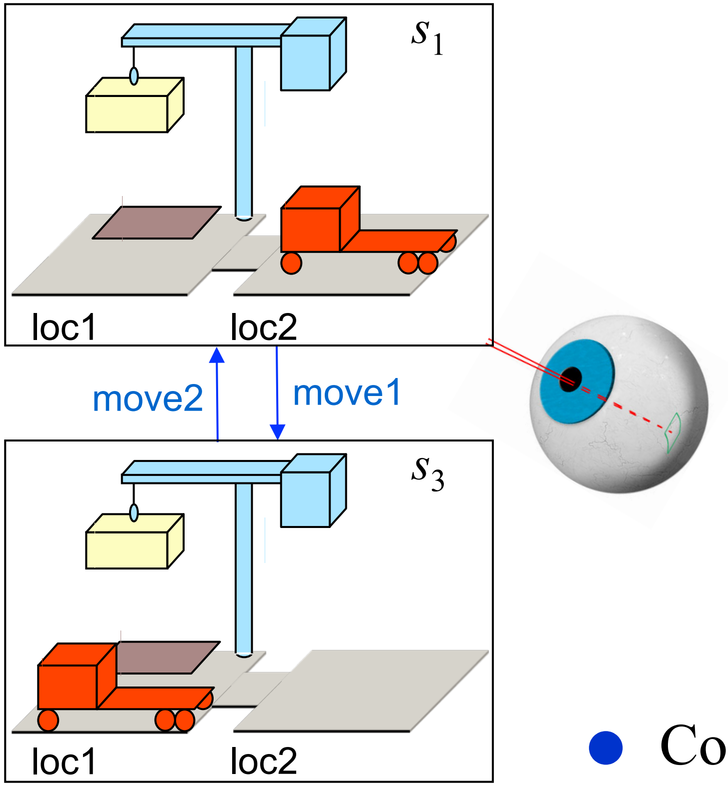
Dock Worker Robots (DWR) example

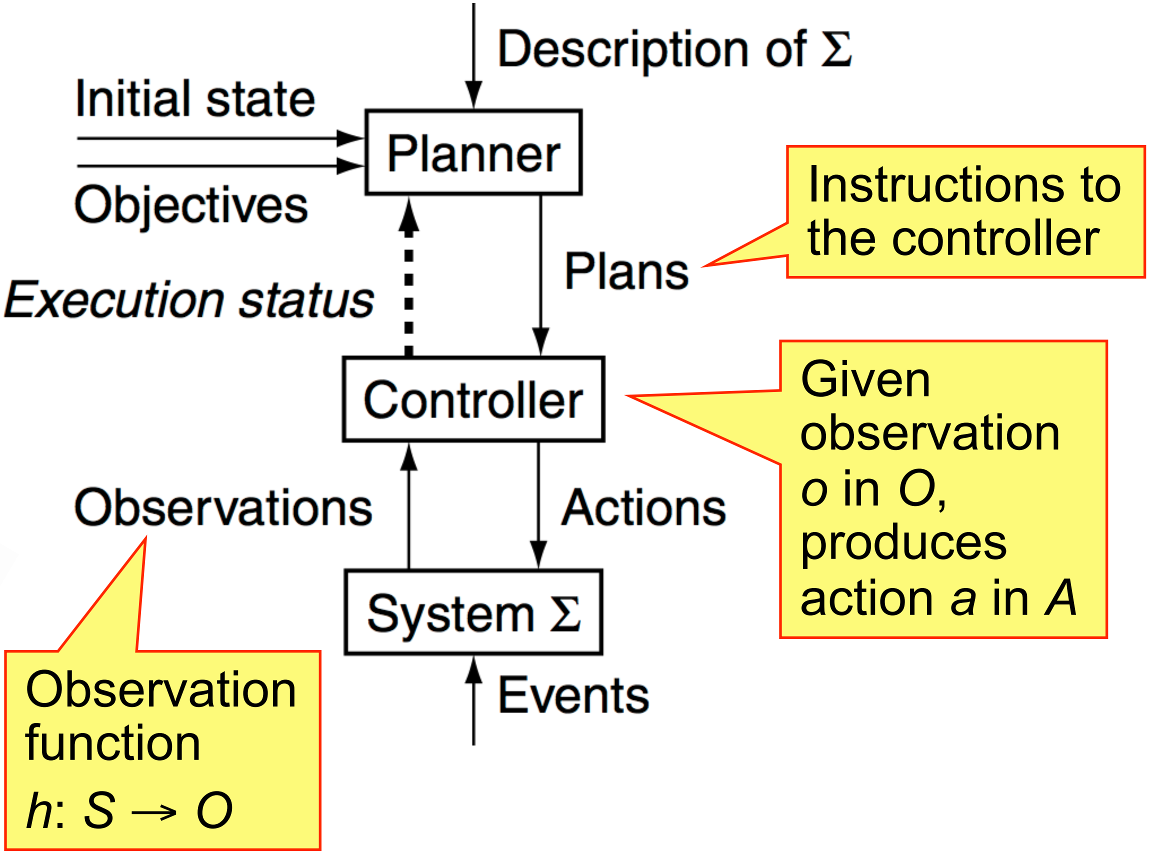
# Abstraction

- Real world is absurdly complex
  - Must be *abstracted*
- **Abstract state** = set of real states
  - $s_1$ specifies that the robot is at loc2, but not now it's positioned and oriented
- **Abstract action** = complex combination of real actions
  - Executing move1 may require a complex sequence of low-level actions
  - For guaranteed realizability, move1 must get the robot to loc1 no matter where how it's positioned in loc2



# Controller





Instructions to the controller

Given observation $o$ in $O$, produces action $a$ in $A$

Observation function $h: S \rightarrow O$

- Control may involve lower-level planning and/or plan execution
  - e.g., how to do move1

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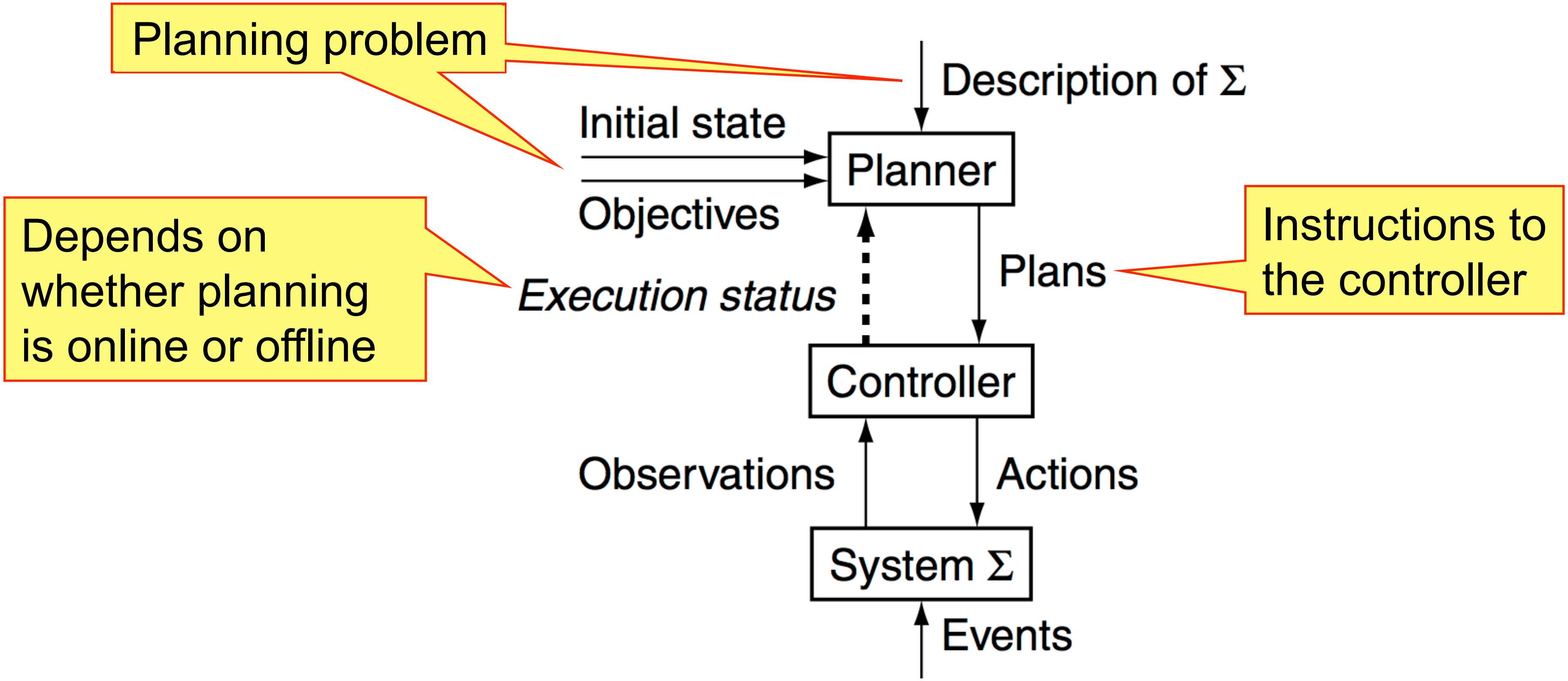
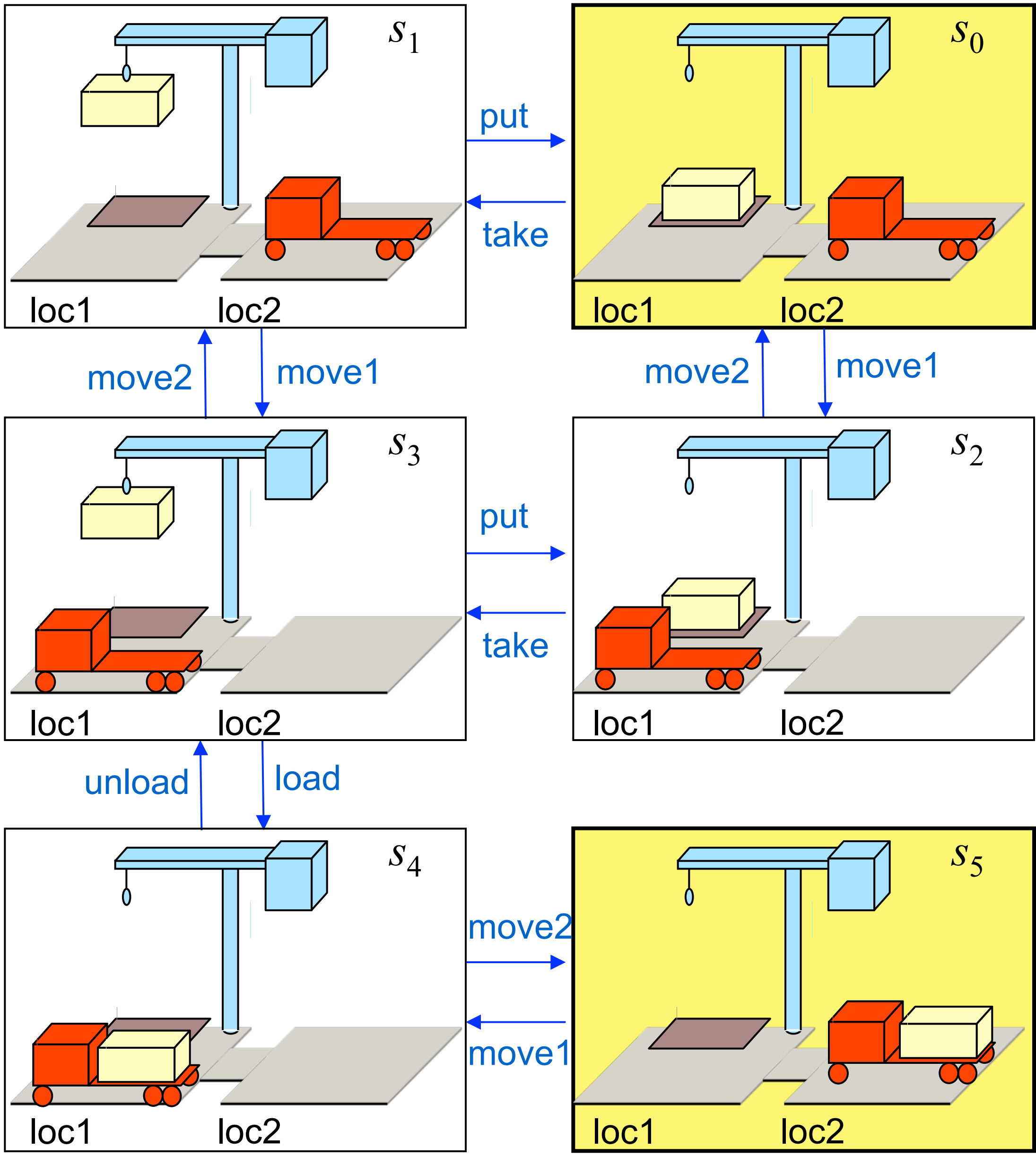
# Planner


Planning problem
Description of Σ
Initial state
Planner
Objectives
Depends on whether planning is online or offline
Execution status
Plans
Instructions to the controller
Controller
Observations
Actions
System Σ
Events

# 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

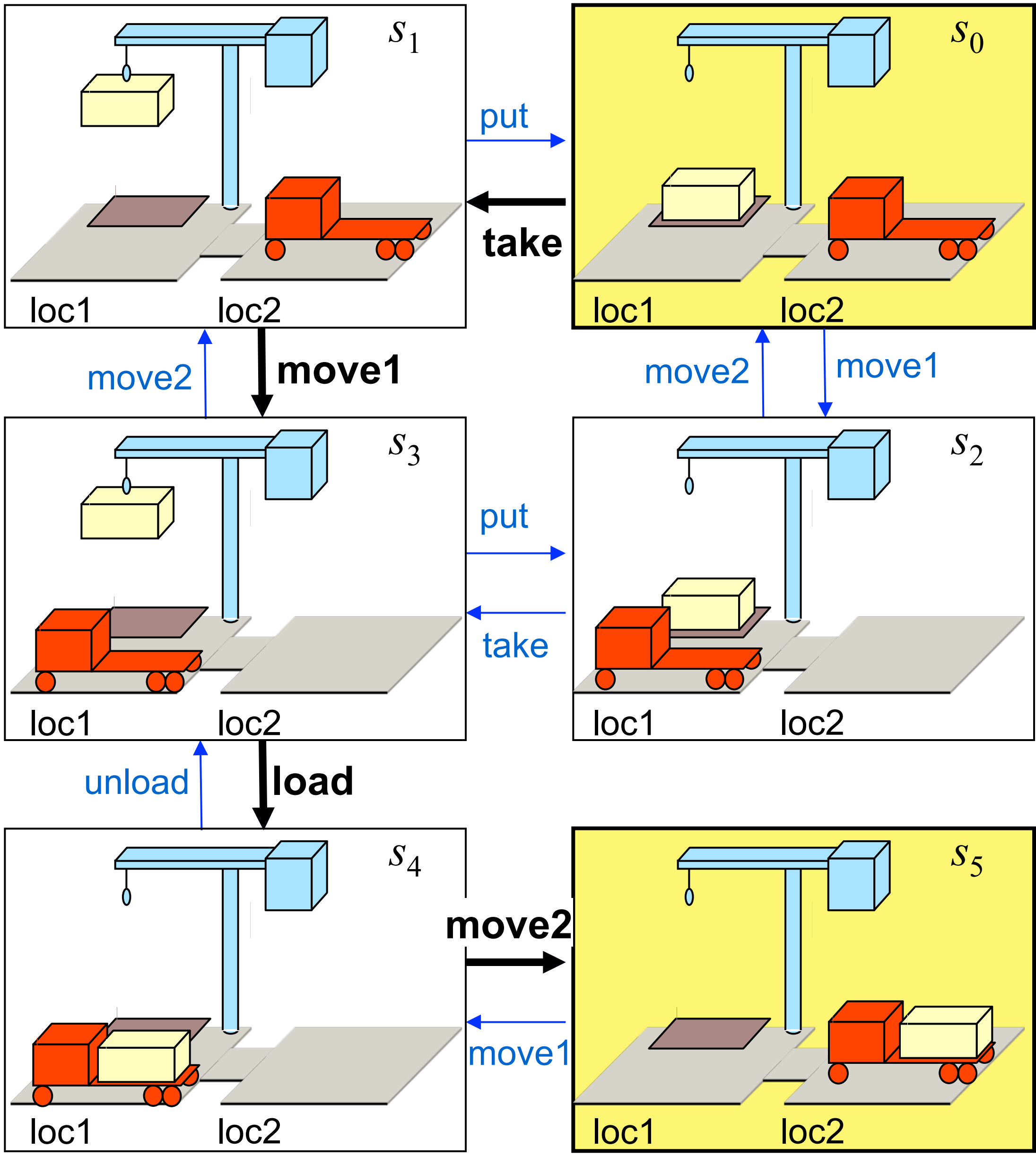
# Plans

- **Classical plan**: a sequence of actions

  $\langle$take, move1, load, move2$\rangle$

- **Policy**: partial function from $S$ into $A$

  { ($s_0$, take),
  ($s_1$, move1),
  ($s_3$, load),
  ($s_4$, move2) }



Dock Worker Robots (DWR) example

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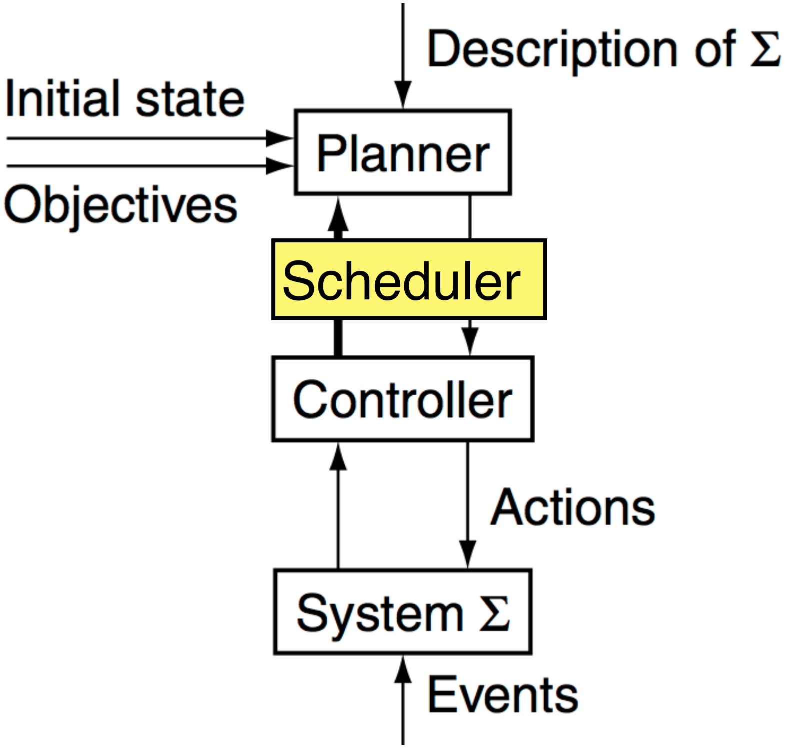
# Planning Versus Scheduling



- 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

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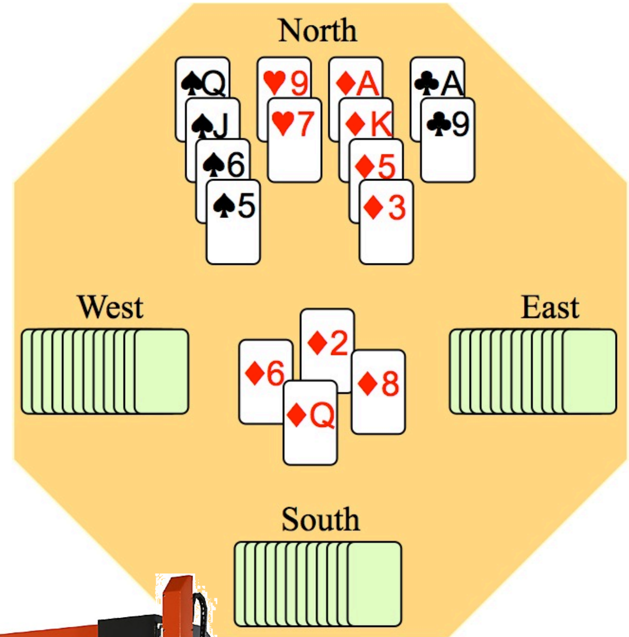
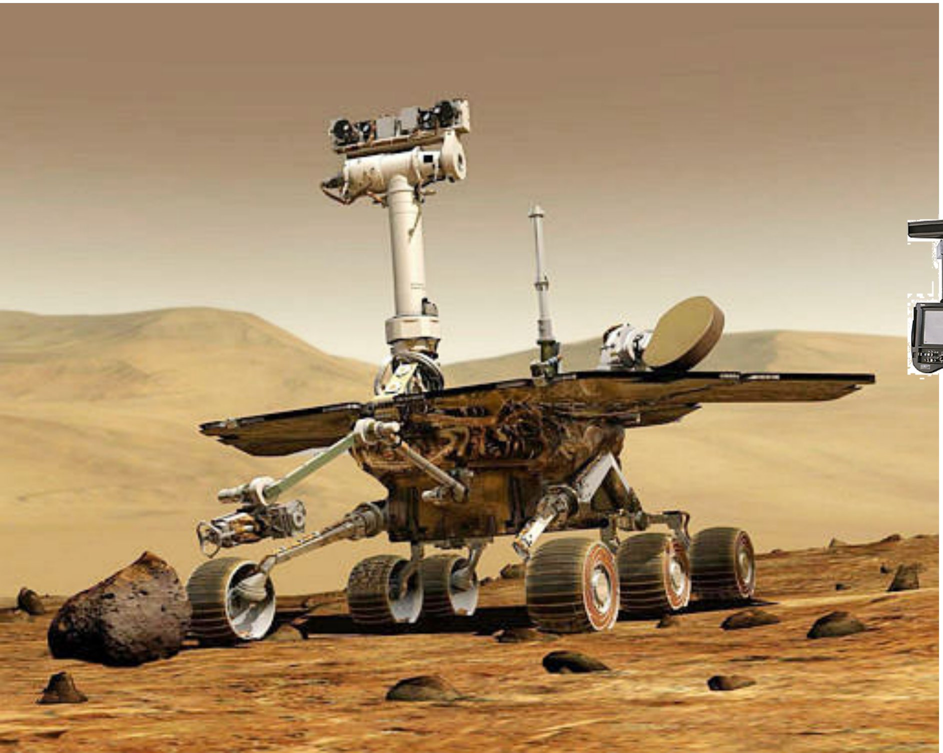
# Three Main Types of Planners

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)

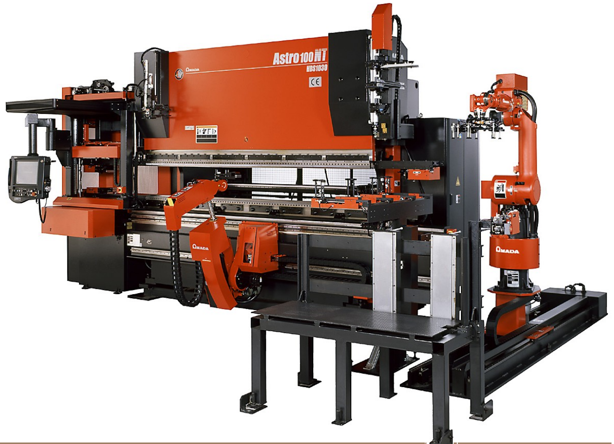
- Most successful real-world planning systems work this way
  - Mars exploration, sheet-metal bending, playing bridge, etc.
- Often use problem-specific techniques that are difficult to generalize to other planning domains

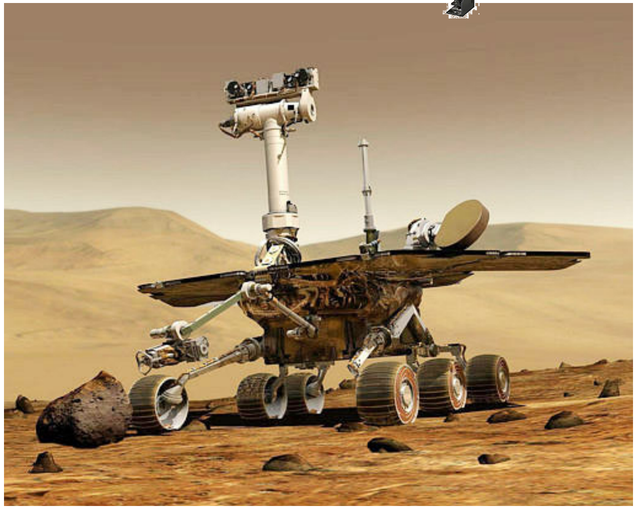




# Types of Planners
# 2. Domain-Independent

- In principle, works in any planning domain
- No domain-specific knowledge except the description of the system Σ
- In practice,
    - Not feasible to make domain-independent planners work well in all possible planning domains

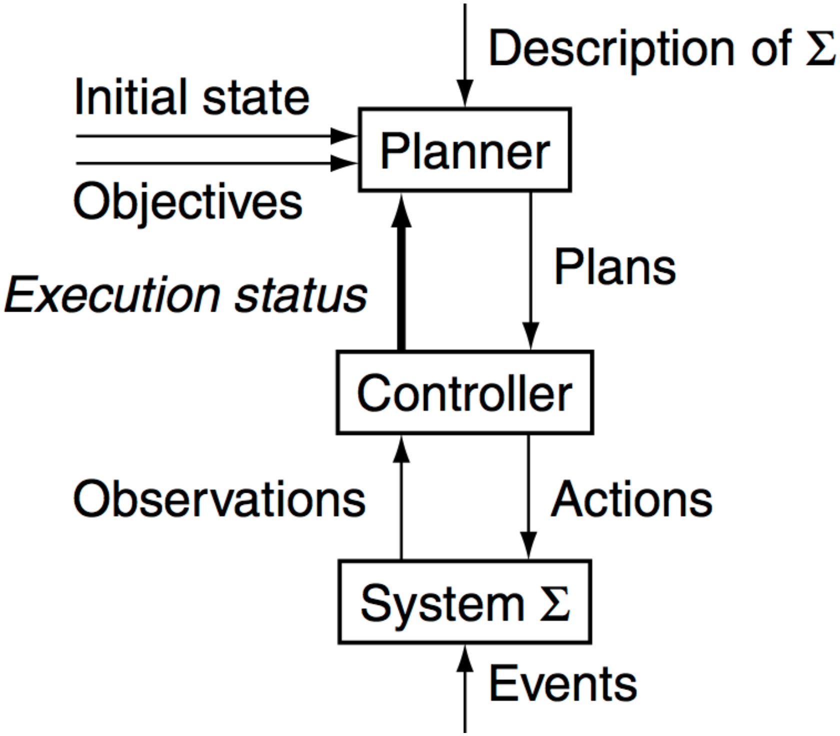




- Make simplifying assumptions to restrict the set of domains
    - *Classical planning*
    - Historical focus of most research on automated planning

# 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



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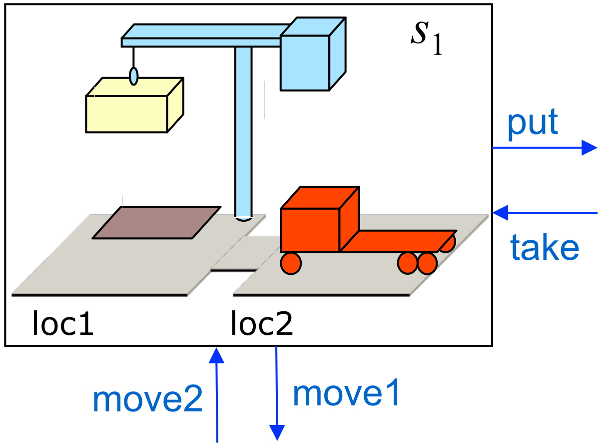
# Classical Planning (Chapters 2-9)

- 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 $(\Sigma, s_0, S_g)$
  - 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)

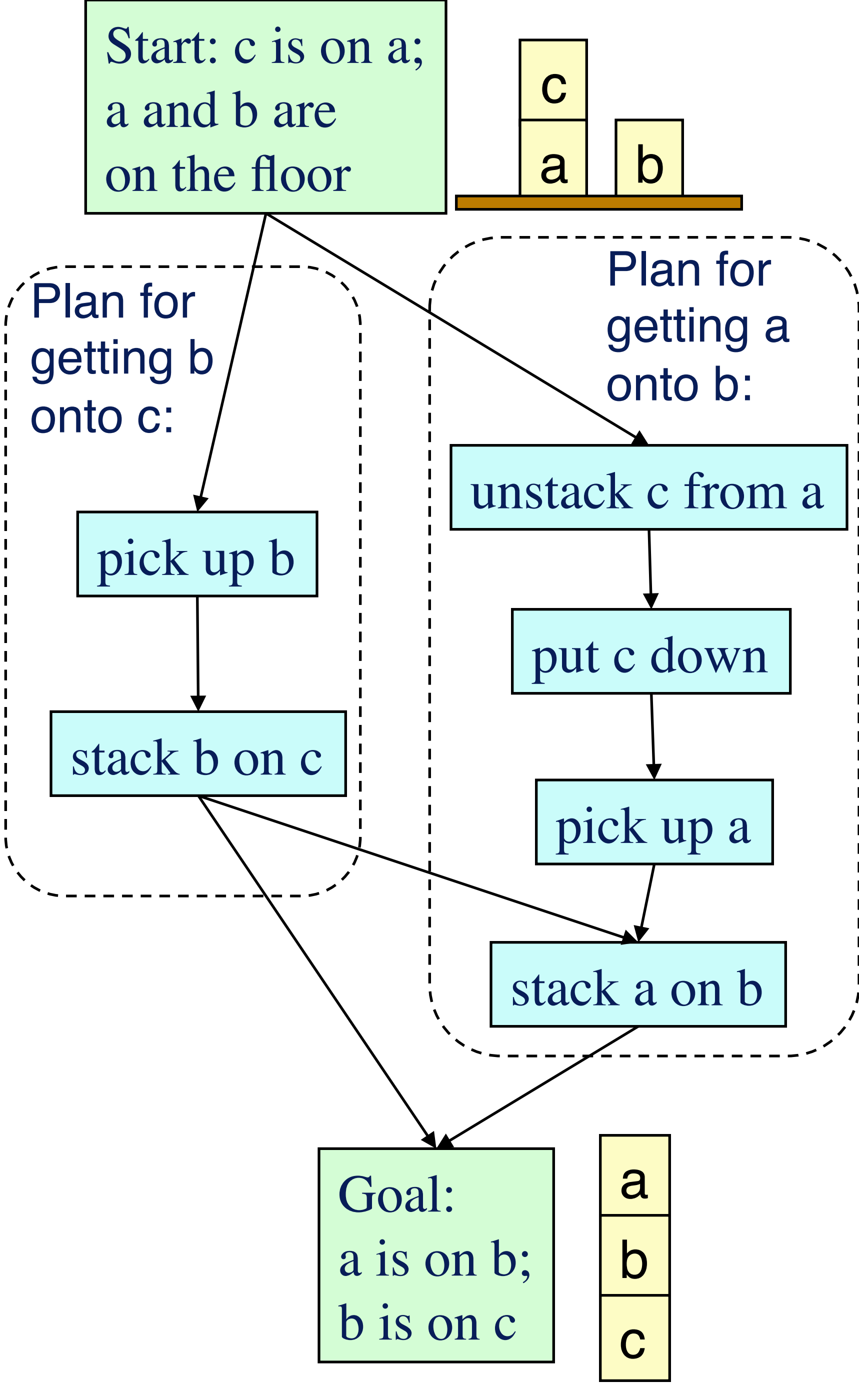


- Generalize the earlier example:
    - Five locations, three robot carts, 100 containers, three piles
        - Then there are $10^{277}$ states
- Number of particles in the universe is only about $10^{87}$
    - The example is more than $10^{190}$ times as large

- 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
- Not the best approach for classical planning
- But important in some real-world applications
  - A temporal-planning extension was used in the Mars rovers



Start: c is on a; a and b are on the floor

Plan for getting b onto c:

pick up b

stack b on c

Plan for getting a onto b:

unstack c from a

put c down

pick up a

stack a on b

Goal: a is on b; b is on c

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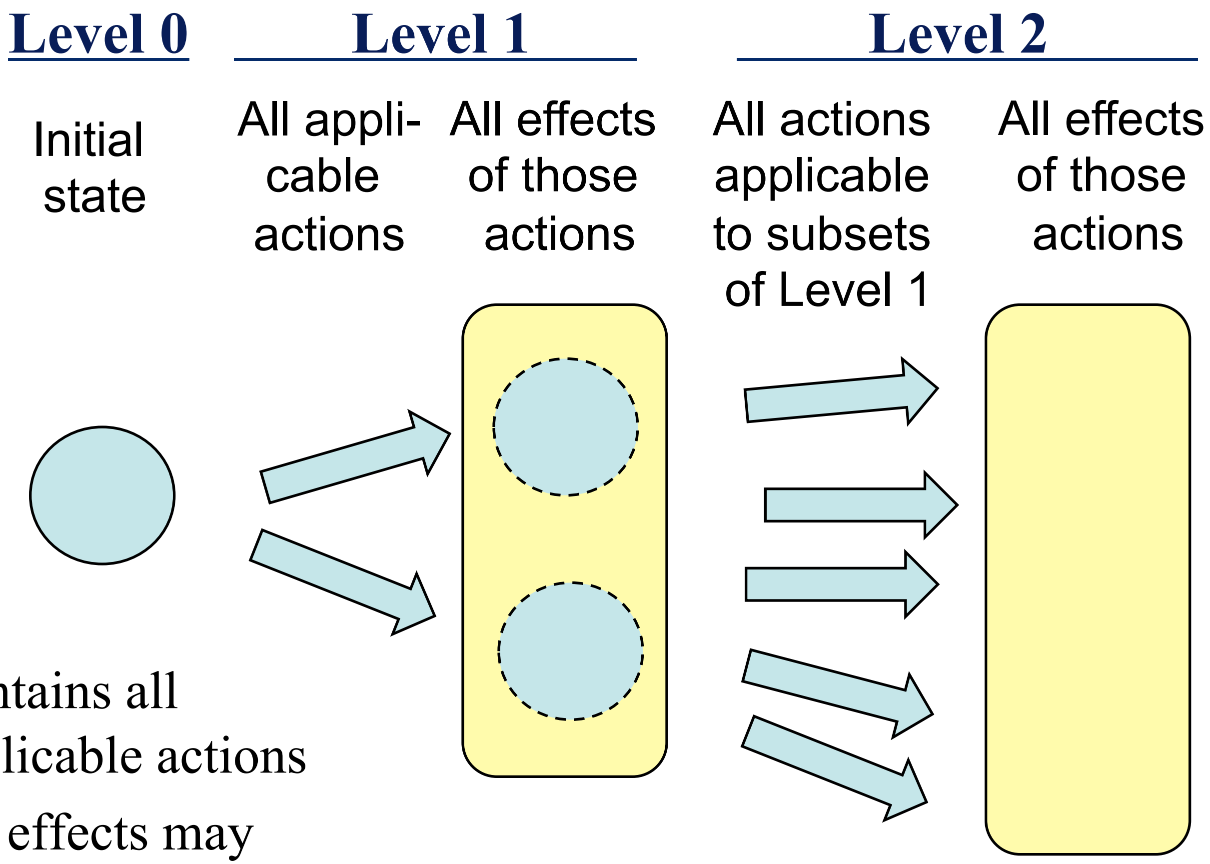
# Planning Graphs (Chapter 6)



- 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

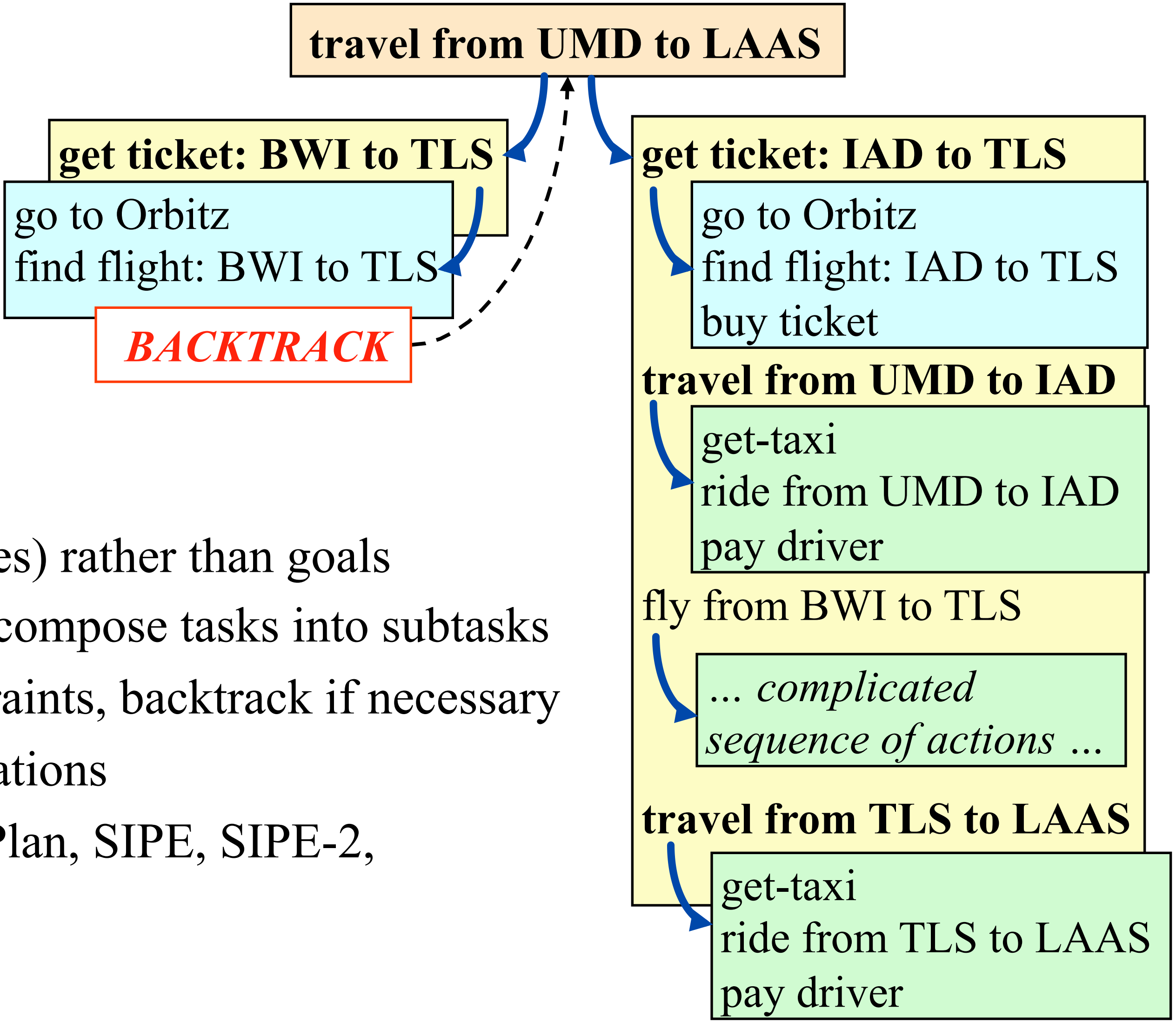
- Satisfiability solvers, especially those that use local search
  - Satplan and Blackbox [Kautz & Selman]

- Integer programming solvers such as Cplex
  - [Vossen *et al.*]

# Types of Planners:
# 3. Configurable

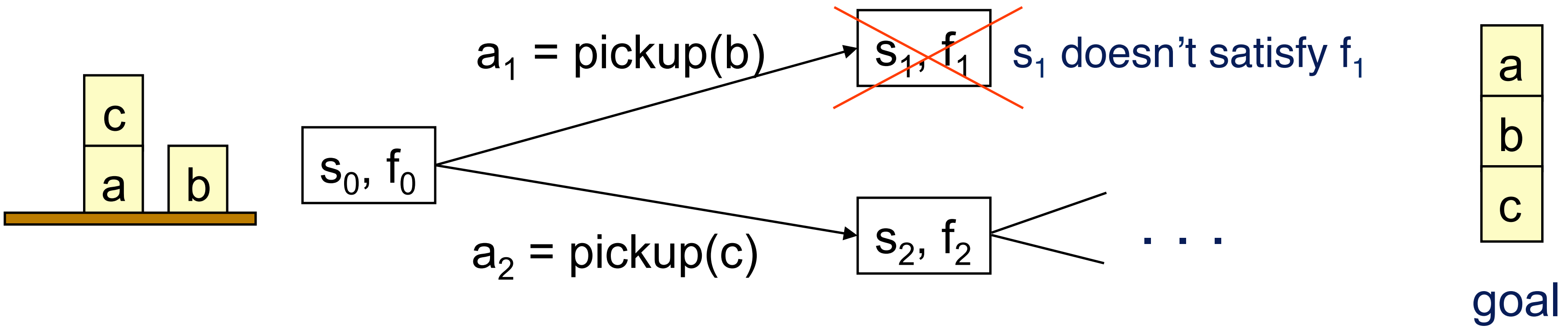
- In any fixed planning domain, a domain-independent planner usually won’t work as well as a domain-specific planner made specifically for that domain
    - A domain-specific planner may be able to go directly toward a solution in situations where a domain-specific planner would explore may alternative 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
        - 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

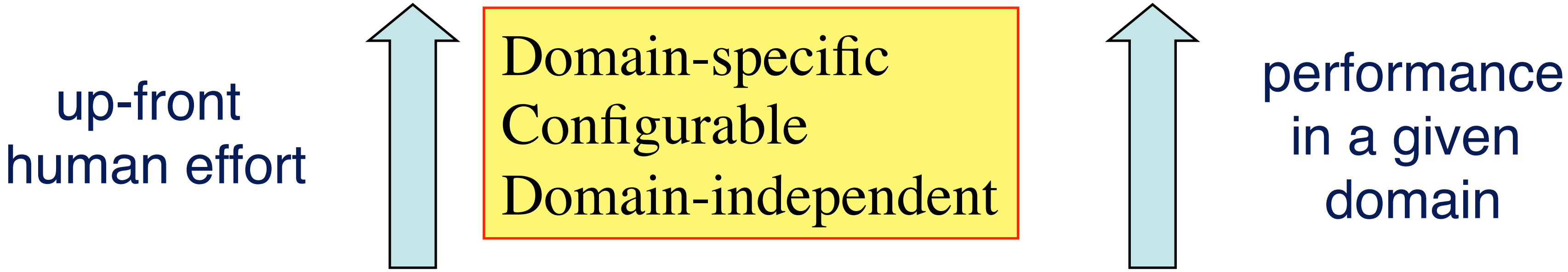
# Planning with Control Formulas (Chapter 10)



- At each state *s*, we have a *control formula* written in temporal logic
  - e.g., $ontable(x) \wedge \neg\exists[y{:}\mathrm{GOAL}(on(x,y))] \Rightarrow \bigcirc(\neg holding(x))$

    "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



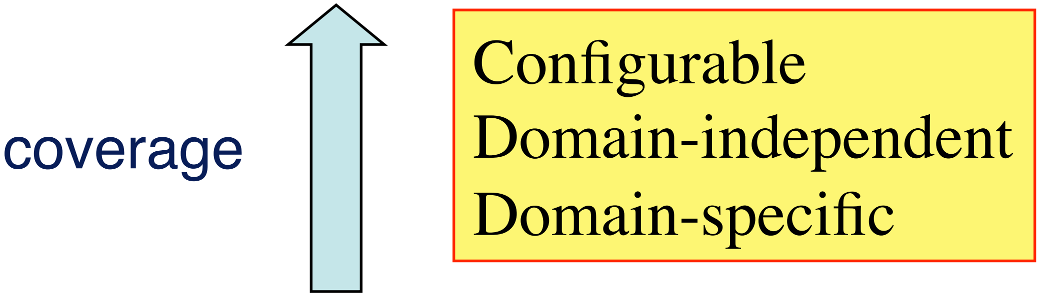
up-front human effort

Domain-specific
Configurable
Domain-independent

performance in a given domain

- 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

# 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

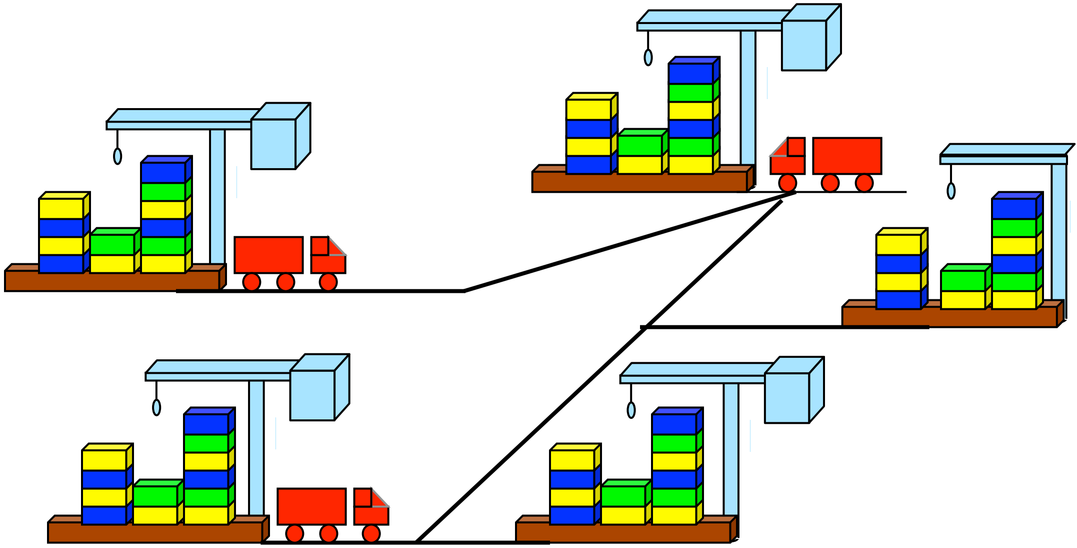
- Actions may have multiple possible outcomes
  - some actions are inherently random (e.g., flip a coin)
  - actions sometimes fail to have their desired effects
    - drop a slippery object
    - car not oriented correctly in a parking spot
- How to model the possible outcomes, and plan for them
  - **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

# A running example: Dock Worker Robots

- Generalization of the earlier example
  - A harbor with several locations
    - e.g., docks, docked ships, storage areas, parking areas
  - Containers
    - going to/from ships
  - Robot carts
    - can move containers
  - Cranes
    - can load and unload containers



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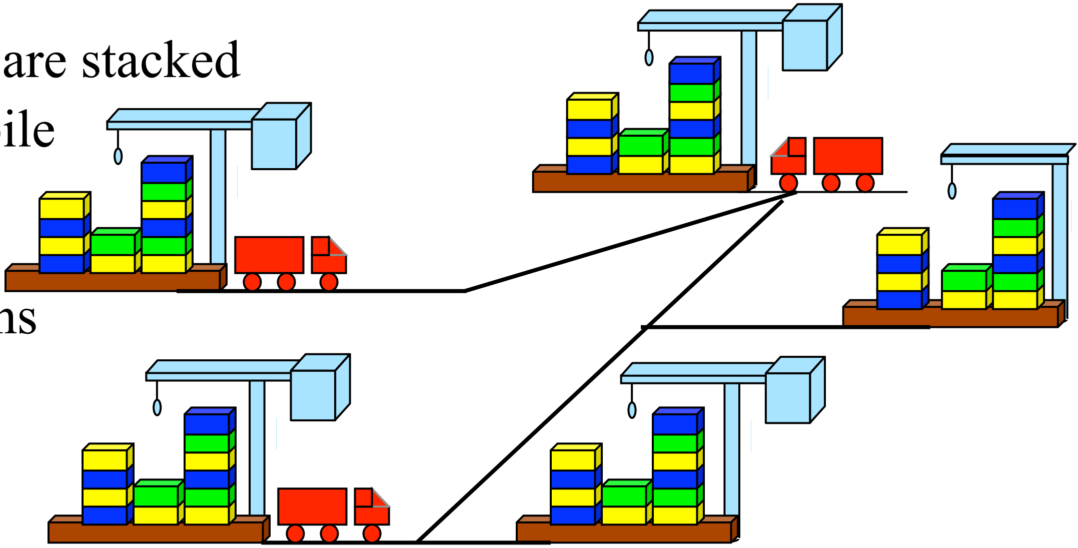
# A running example: Dock Worker Robots

- **Locations**: l1, l2, …, or loc1, loc2, …
- **Containers**: c1, c2, …
  - can be stacked in piles, loaded onto robots, or held by cranes
- **Piles**: p1, p2, …
  - fixed areas where containers are stacked
  - pallet at the bottom of each pile
- **Robot carts**: r1, r2, …
  - can move to adjacent locations
  - carry at most one container
- **Cranes**: k1, k2, …
  - each belongs to a single location
  - move containers between piles and robots
  - if there is a pile at a location, there must also be a crane there



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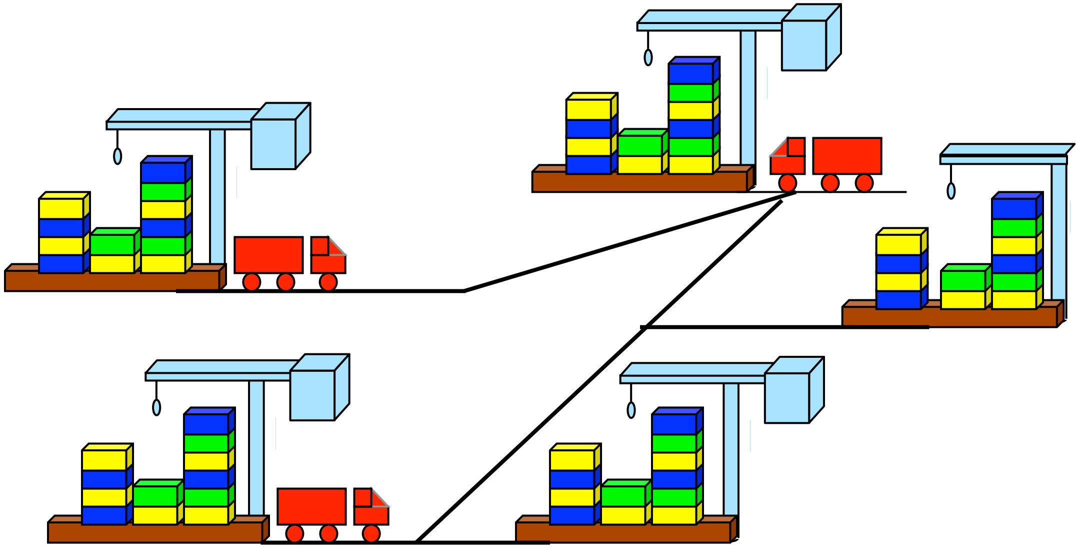
# A running example: Dock Worker Robots

- Fixed relations: same in all states

  adjacent($l,l'$)  attached($p,l$)  belong($k,l$)

- Dynamic relations: differ from one state to another

  occupied($l$)  at($r,l$)
  loaded($r,c$)  unloaded($r$)
  holding($k,c$)  empty($k$)
  in($c,p$)  on($c,c'$)
  top($c,p$)  top(pallet,$p$)



- Actions:

  take($c,k,p$)  put($c,k,p$)
  load($r,c,k$)  unload($r$)  move($r,l,l'$)

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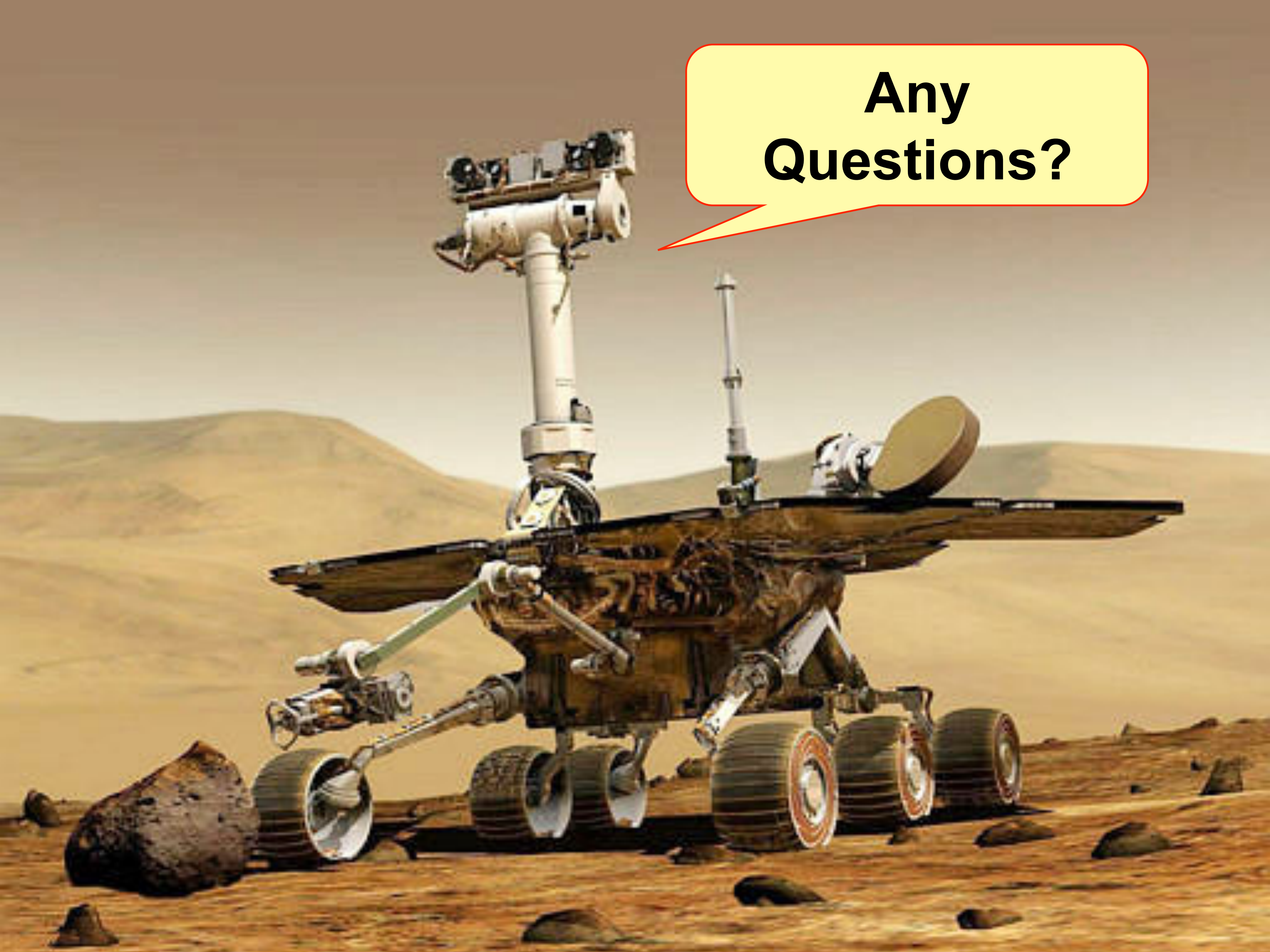

Any Questions?