Planning and Scheduling: Introduction to Planning

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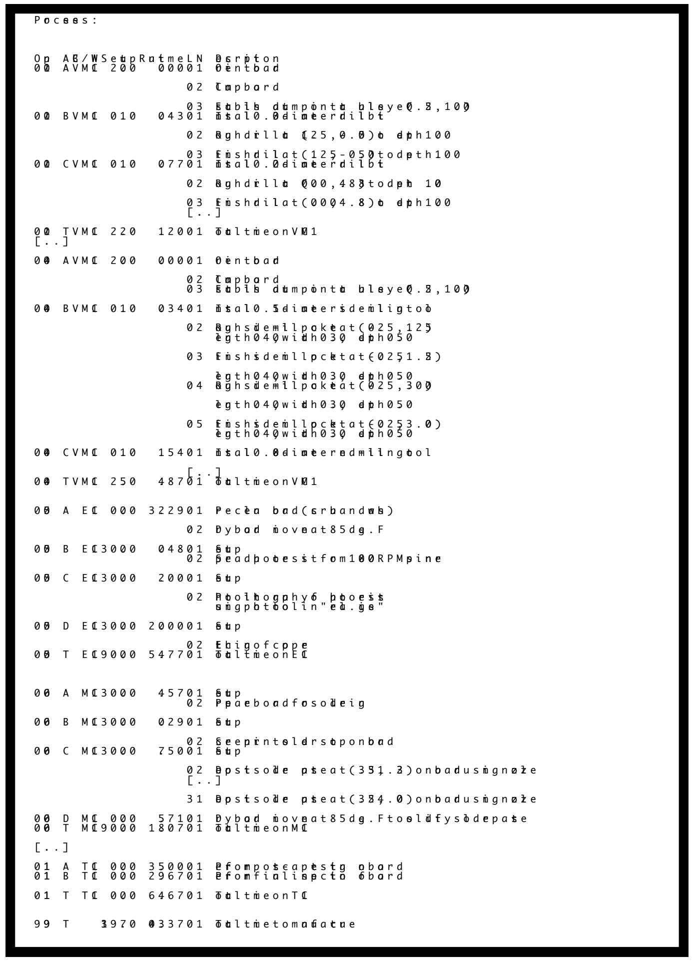
Acknowledgements

- These slides refer to Chapter 1 of the textbook:
  Malik Ghallab, Dana Nau, and Paolo Traverso:
  Automated Planning: Theory and Practice
  Morgan Kaufmann, 2004
- These slides are an adaptation of slides by Dana Nau
- The contributions of these authors are gratefully acknowledged

Plans and Planning

- Plan:
  - A collection of actions for performing some task or achieving some objective
- Planning:
  - There are many programs to aid human planners
    - Project management
    - Plan storage/retrieval
    - Automatic schedule generation
  - Automatic plan generation is much more difficult
    - Many research prototypes
    - Fewer practical systems
    - Research is starting to pay off
      - Several successes on difficult practical problems

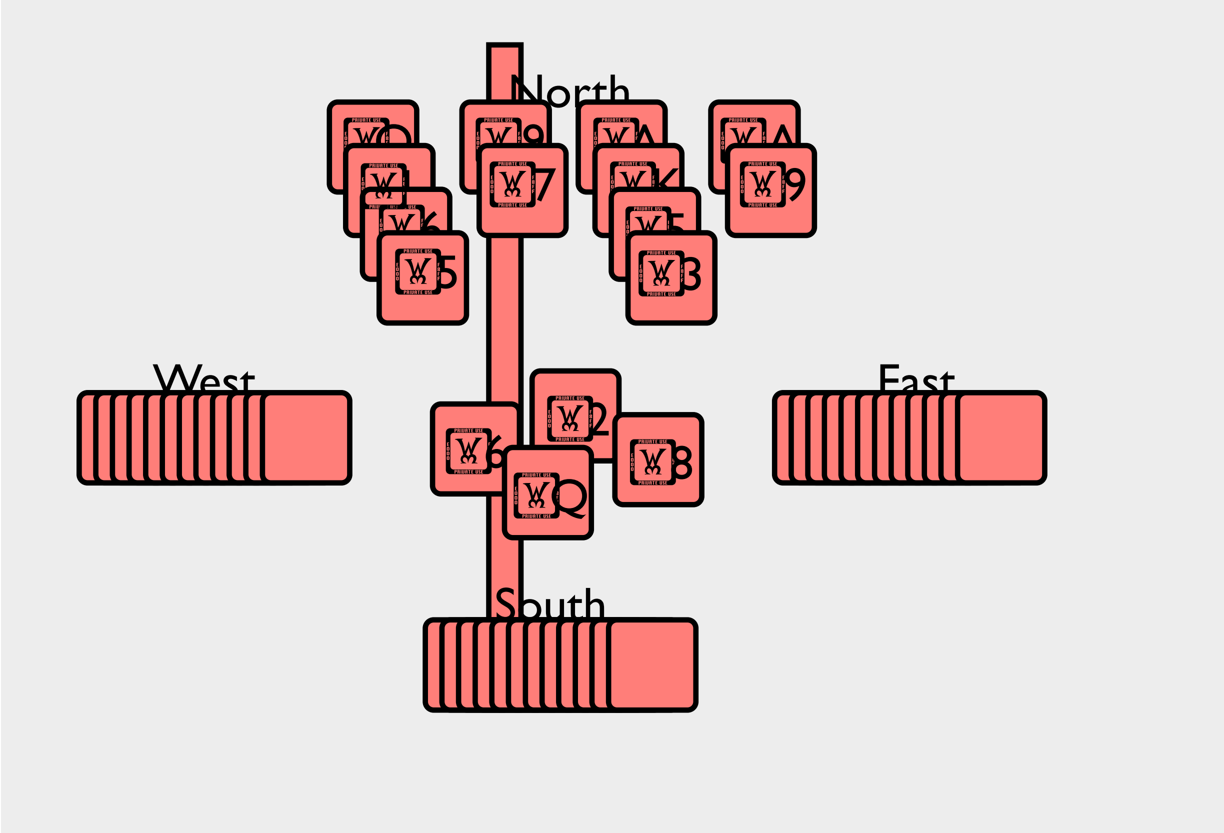


NASA Unmanned Spacecraft

- Remote Agent eXperiment (RAX)
  - Autonomous AI software for planning/control
  - Ran on the DS1 spacecraft in May 1998
  - For several minutes it was allowed to control the spacecraft
- Mars rover
  - Guided by autonomous AI planning/control software

Other Examples

- Computer bridge: Bridge Baron
  - Used AI planning to win the 1997 world computer bridge championship
  - Commercial software, thousands of copies sold
- Manufacturing process planning
  - Software included with Amada's sheet-metal bending machines
  - Used to plan bending operations

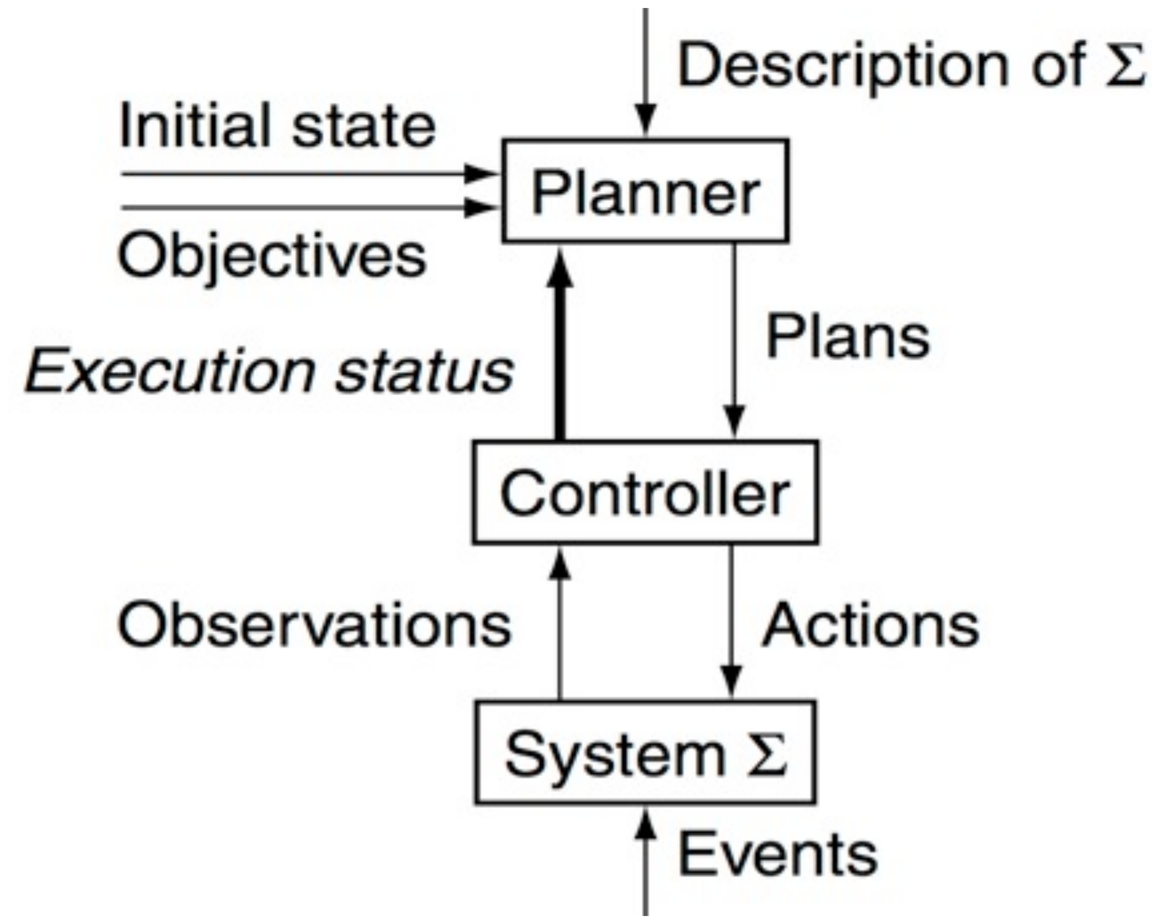


Outline

- Conceptual model
- Restrictive assumptions
- Classical planning
- Relaxing the assumptions
- A running example: Dock Worker Robots

Conceptual Model

- Ingredients:
- Model of the environment: possible states
- Model of how the environment can change: effects of actions
- Specification of initial conditions and objectives
- Plans of actions that are generated by a planner
- A model of execution of a plan in the environment
- A model of observation of the environment



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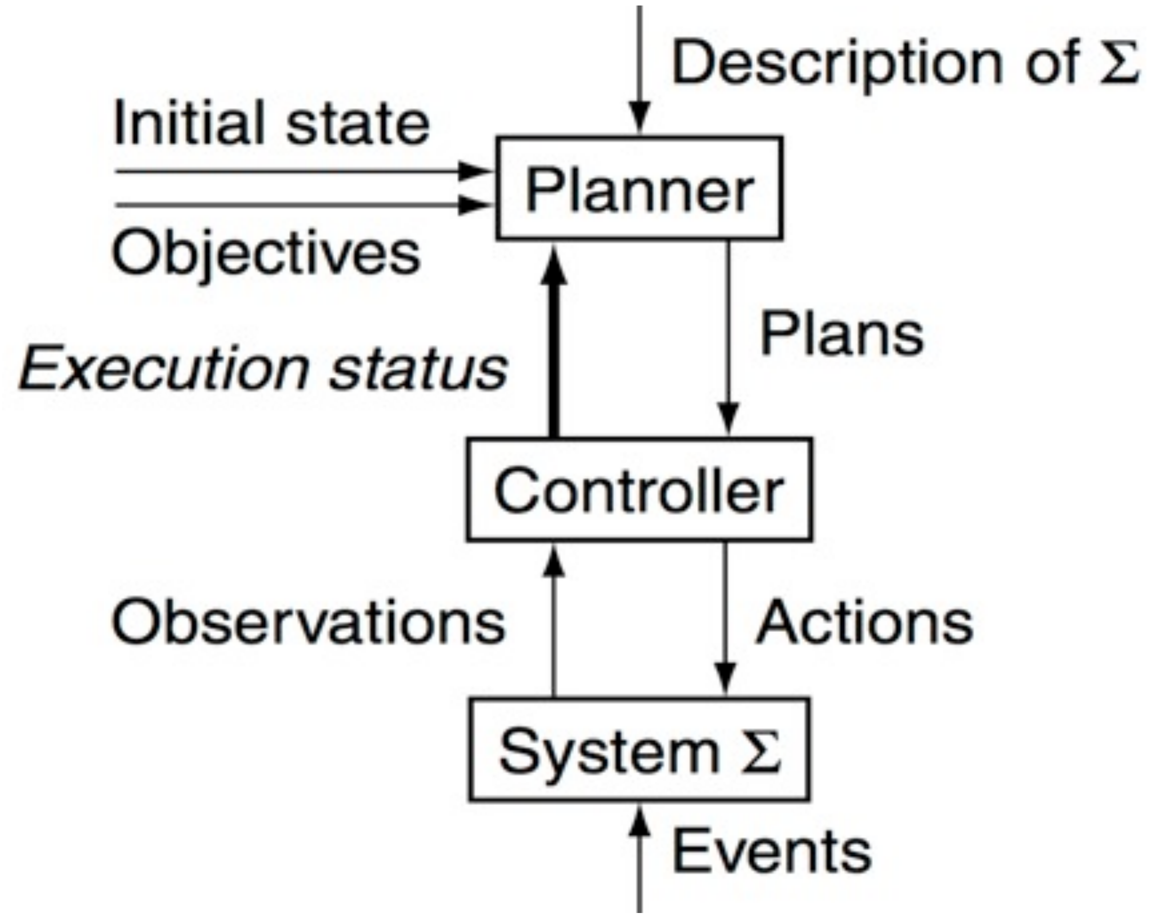
Conceptual Model

- State-transition system
  $$\Sigma = (S, A, E, \gamma)$$
  - S = {states}
  - A = {actions} (controllable)
  - E = {events} (uncontrollable)
  - state-transition function
    $$\gamma : S \times (A \cup E) \mapsto 2^S$$
- Observation function
  $$h : S \mapsto O$$
  - Produces observation o about current state s
- Controller: given observation $o \in O$, produces action $a \in A$
- Planner:
  - Input: description of Σ, initial state $s_0 \in S$, some objective
  - Output: produces a plan to drive the controller



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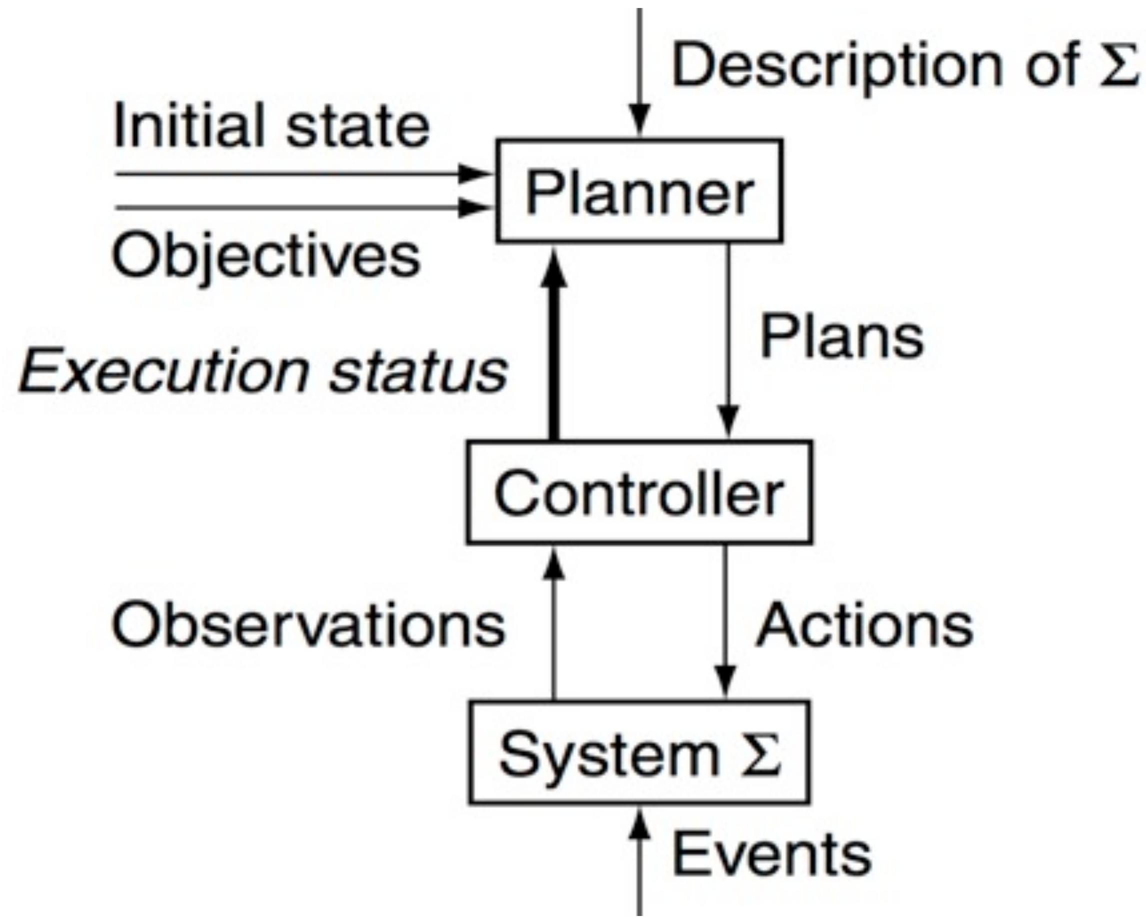
Conceptual Model

Possible objectives:

- A set of goal states S_g
  - Find sequence of state transitions ending at a goal
- Some condition over the set of states followed by the system
  - e.g., reach S_g and stay there
- Utility function attached to states
  - Optimize some function of the utilities
- Tasks to perform, specified recursively as sets of sub-tasks and actions

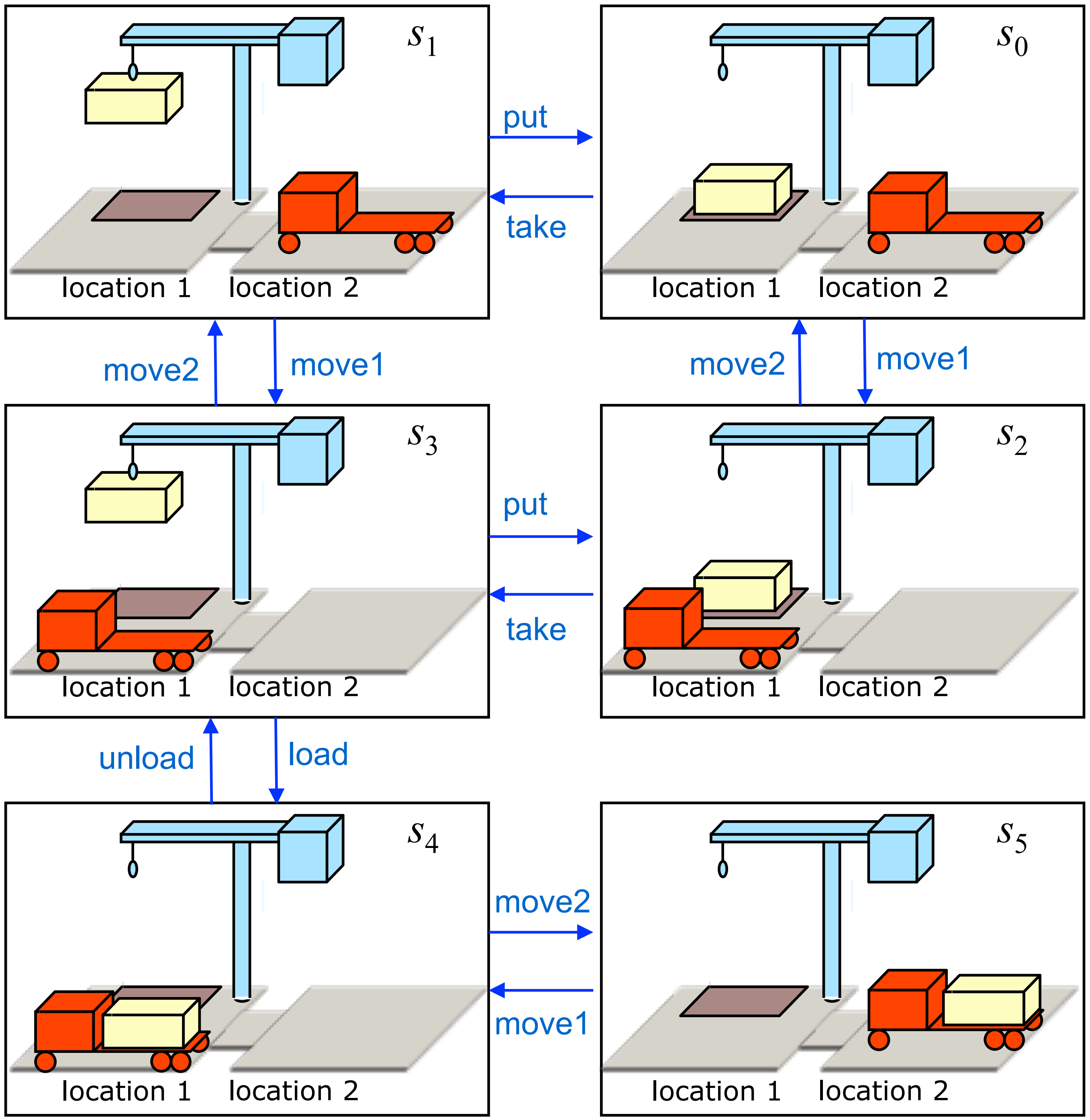


Conceptual Model: Example

- State transition system

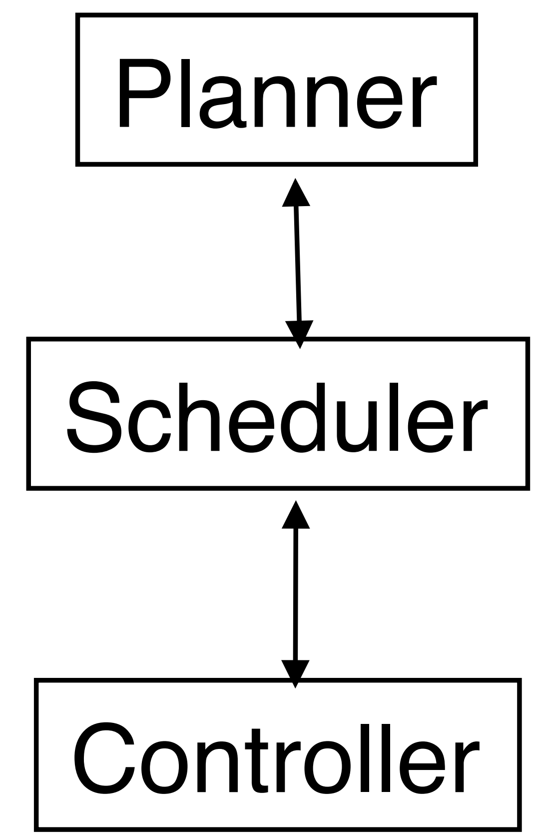
  $$\Sigma = (S, A, E, \gamma)$$

  where
  - $S = \{s_0, \ldots, s_5\}$
  - $A = \{\text{move\_1}, \text{move\_2}\}$
    $\cup\{\text{put}, \text{take}, \text{load}, \text{unload}\}$
  - $E = \varnothing$
  - γ : as shown
- h(s) = s for every s
- Input to planner:
  - System Σ
  - Initial state s0
  - Goal state s5

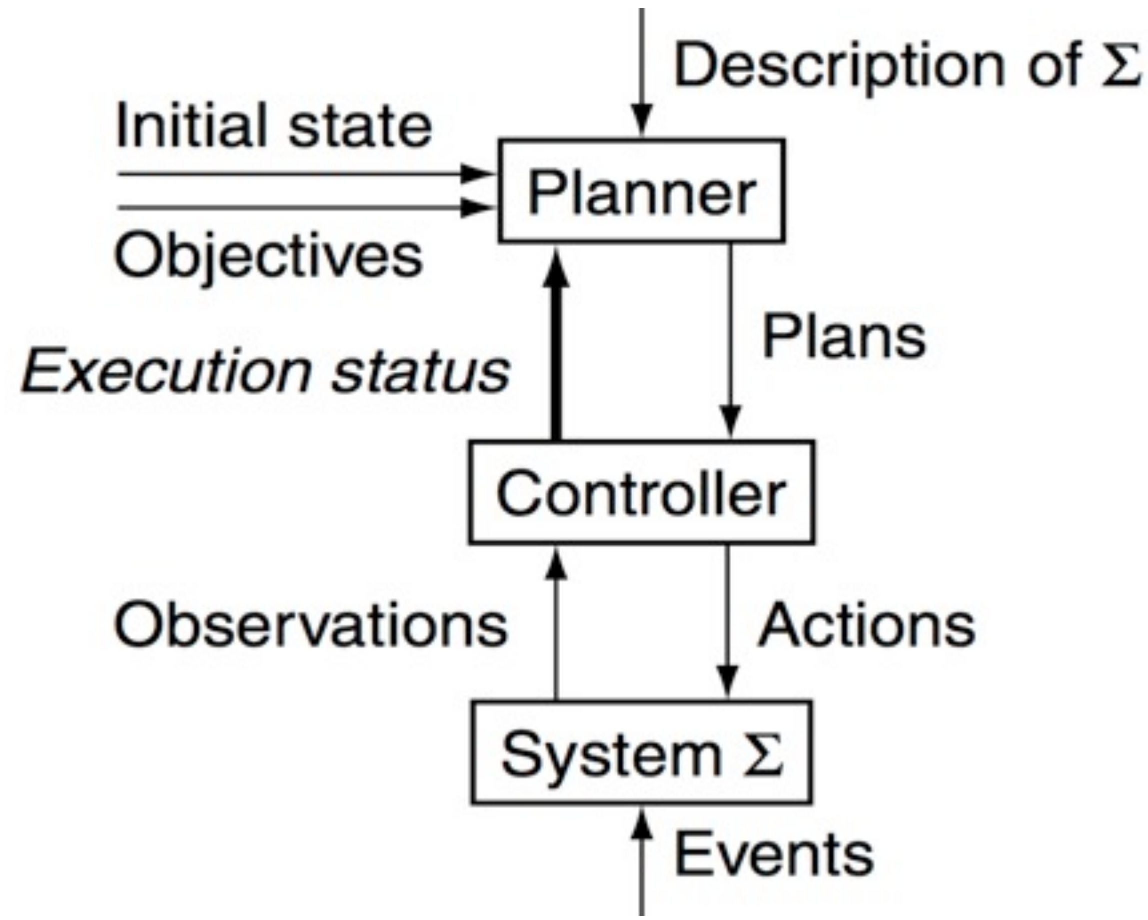


Planning Versus Scheduling

- Scheduling
  - Decide how to perform a given set of actions using a limited number of resources in a limited amount of time
  - Typically NP-complete
- Planning
  - Decide what actions to use to achieve some set of objectives
  - Can be much worse than NP-complete
    - In the most general case, it is undecidable
    - Most research assumes various collections of restrictions to guarantee decidability
  - We will now look at some of the restrictions



Restrictive Assumptions



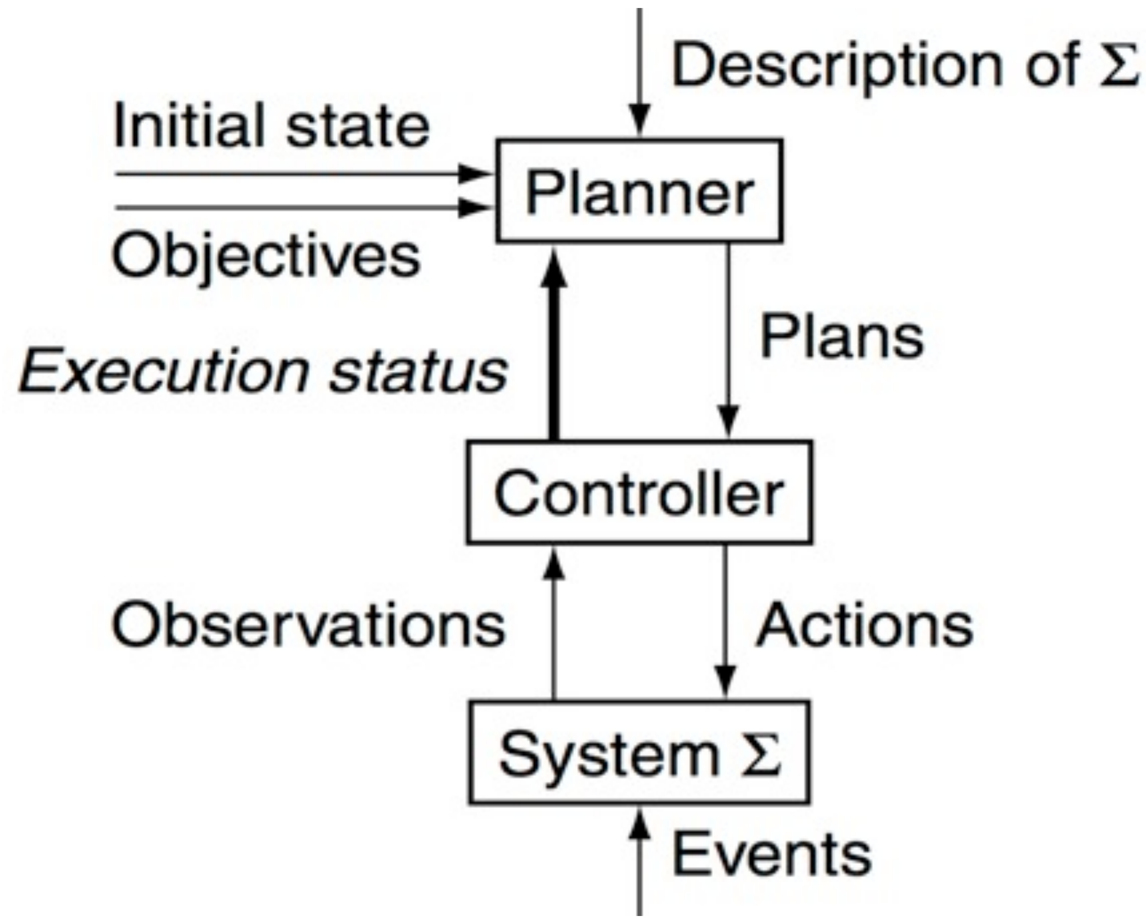
- A0 (finite Σ):
  - The state space S is finite
  - $S = \{s_0, s_1, s_2, \ldots, s_k\}$ for some k

- A1 (fully observable Σ):
  - The observation function $h : S \mapsto O$ is the identity function
  - I.e., the controller always knows what state Σ is in

$$\Sigma = (S, A; E, \gamma)$$
$$S = \{states\}$$
$$A = \{actions\}$$
$$E = \{events\}$$
$$\gamma : S \times (A \cup E) \mapsto 2^S$$

Restrictive Assumptions

- A2 (deterministic Σ):
  - $\forall u \in A \cup E : \|\gamma(s,u)\| = 1$
  - Each action or event has only one possible outcome
- A3 (static Σ):
  - E is empty: no changes except those performed by the controller
- A4 (attainment goals):
  - A goal state s_g or a set of goal states S_g



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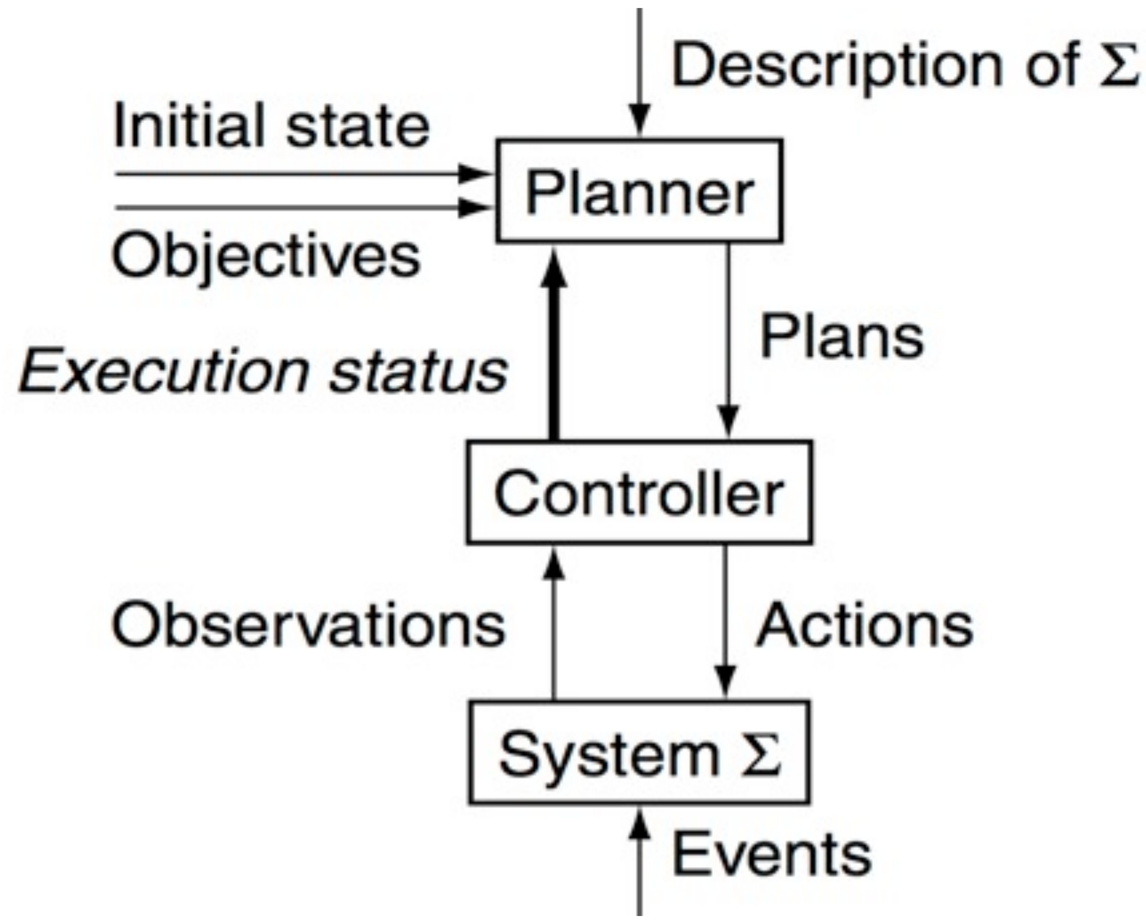
Restrictive Assumptions

- A5 (sequential plans):
  - Solution is a linearly ordered sequence of actions $\langle a_1, a_2, \ldots, a_n \rangle$
- A6 (implicit time):
  - No durations, instantaneous state transitions
- A7 (off-line planning):
  - Planner does not know the execution status



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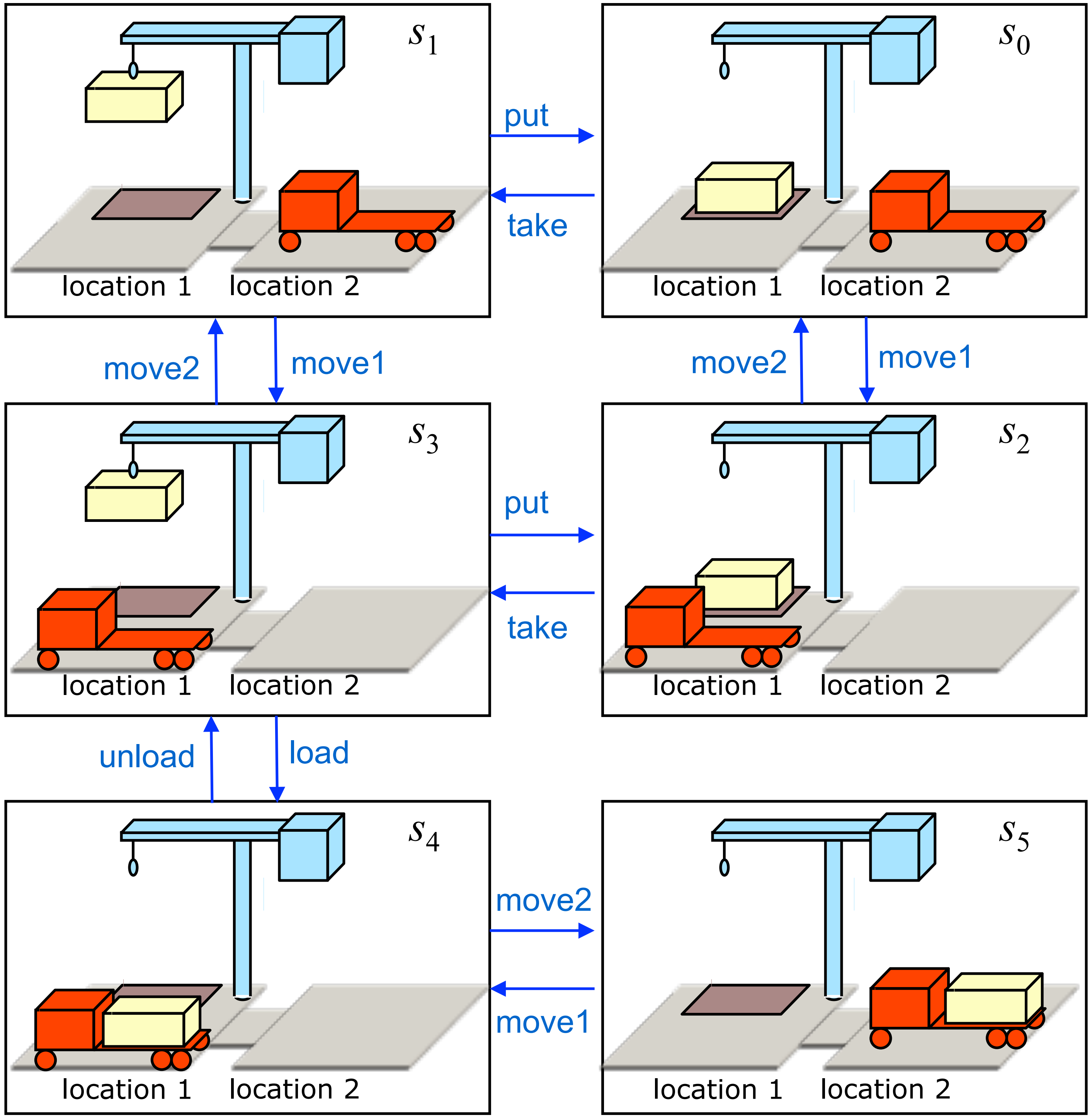
Classical Planning

- Classical planning requires all eight restrictive assumptions
  - Complete knowledge about a deterministic, static, finite-state system with attainment goals and implicit time

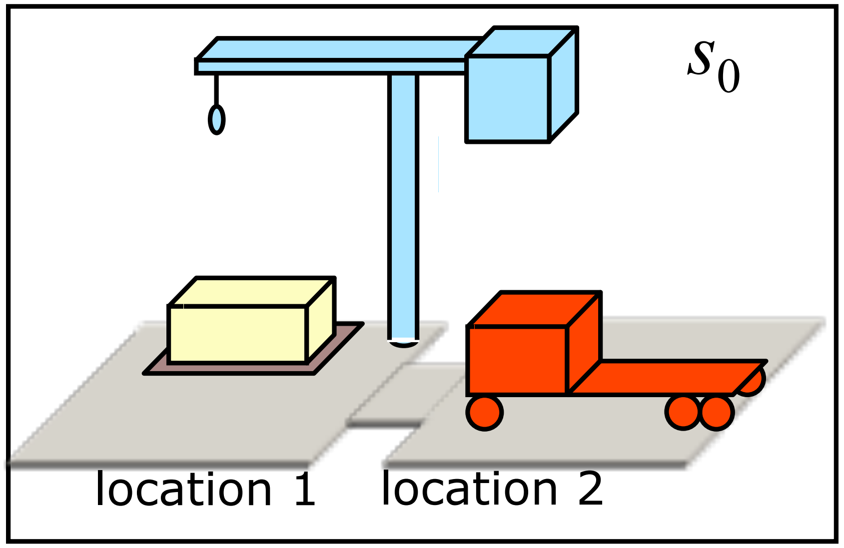
- Reduces to the following problem:
  - Given (Σ, s_0, S_g)
  - find a sequence of actions $\langle a_1, a_2, \ldots, a_n \rangle$
  - that produces a sequence of state transitions
    - $$\begin{aligned} s_1 &= \gamma(s_0, a_1) \\ s_2 &= \gamma(s_1, a_2) \\ &\vdots \\ s_n &= \gamma(s_{n-1}, a_n) \end{aligned}$$
  - such that $s_n \in S_g$

Classical Planning: Example

- Same example as before:
  - System is finite, deterministic, static
  - Complete knowledge
  - Attainment goals
  - Implicit time
  - Offline planning
- Classical planning is just path-searching in a graph
  - States are nodes
  - Actions are edges
- Is this trivial?



Classical Planning



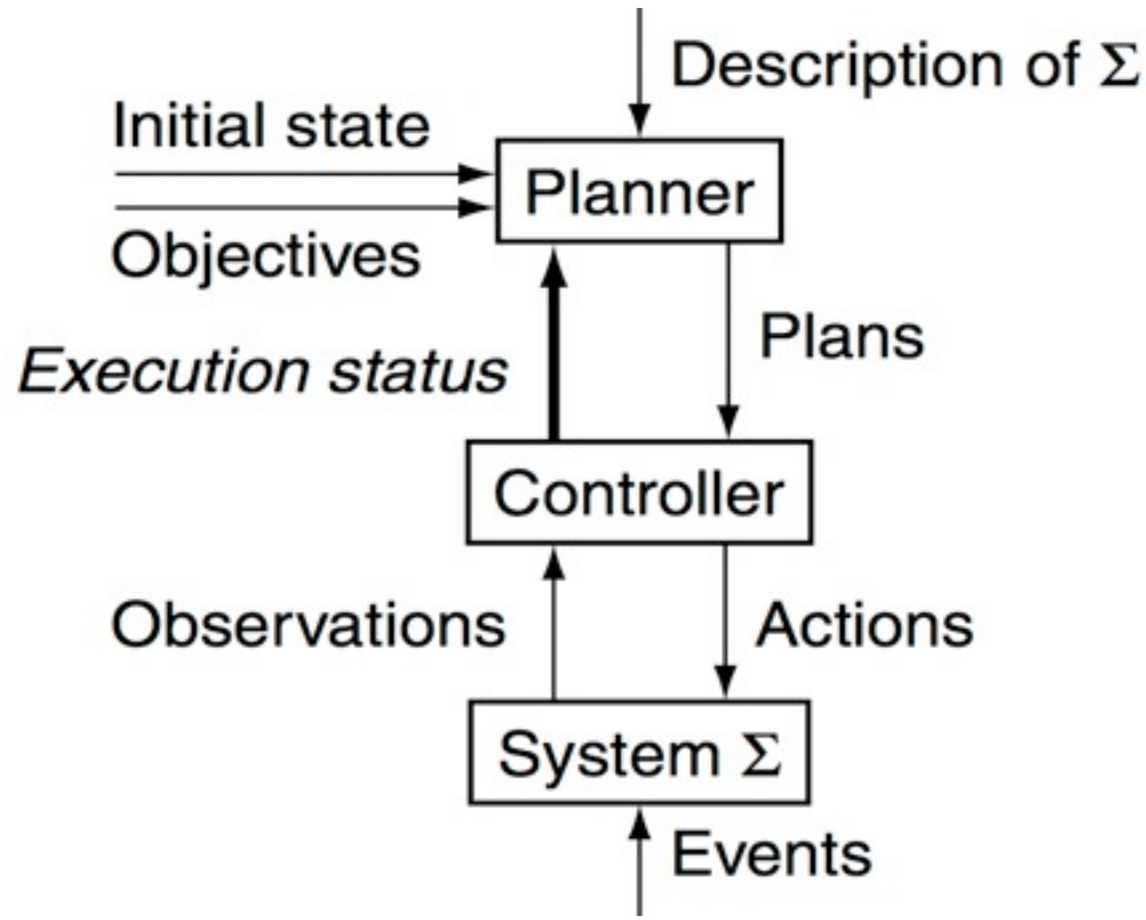
- Very difficult computationally
  - Generalize the earlier example:
    - Five locations, three piles, three robots, 100 containers
  - Then there are 10^{277} states
    - More than 10^{190} times as many states as the number of particles in the universe!

- The vast majority of AI research has been on classical planning
  - Parts I and II of the book

- Too restricted to fit most problems of practical interest
  - But the ideas can sometimes be useful in those problems

Relax the Assumptions

- Relax A0 (finite Σ):
  - Discrete, e.g. 1st-order logic:
  - Continuous, e.g. numeric variables
  - Sections:
    - 2.4 (extensions to classical)
    - 10.5 (control-rule planners)
    - 11.7 (HTN planning)
  - Case study: Chapter 21 (manufacturability analysis)
- Relax A1 (fully observable Σ):
  - If we don't relax any other restrictions, then the only uncertainty is about s_0



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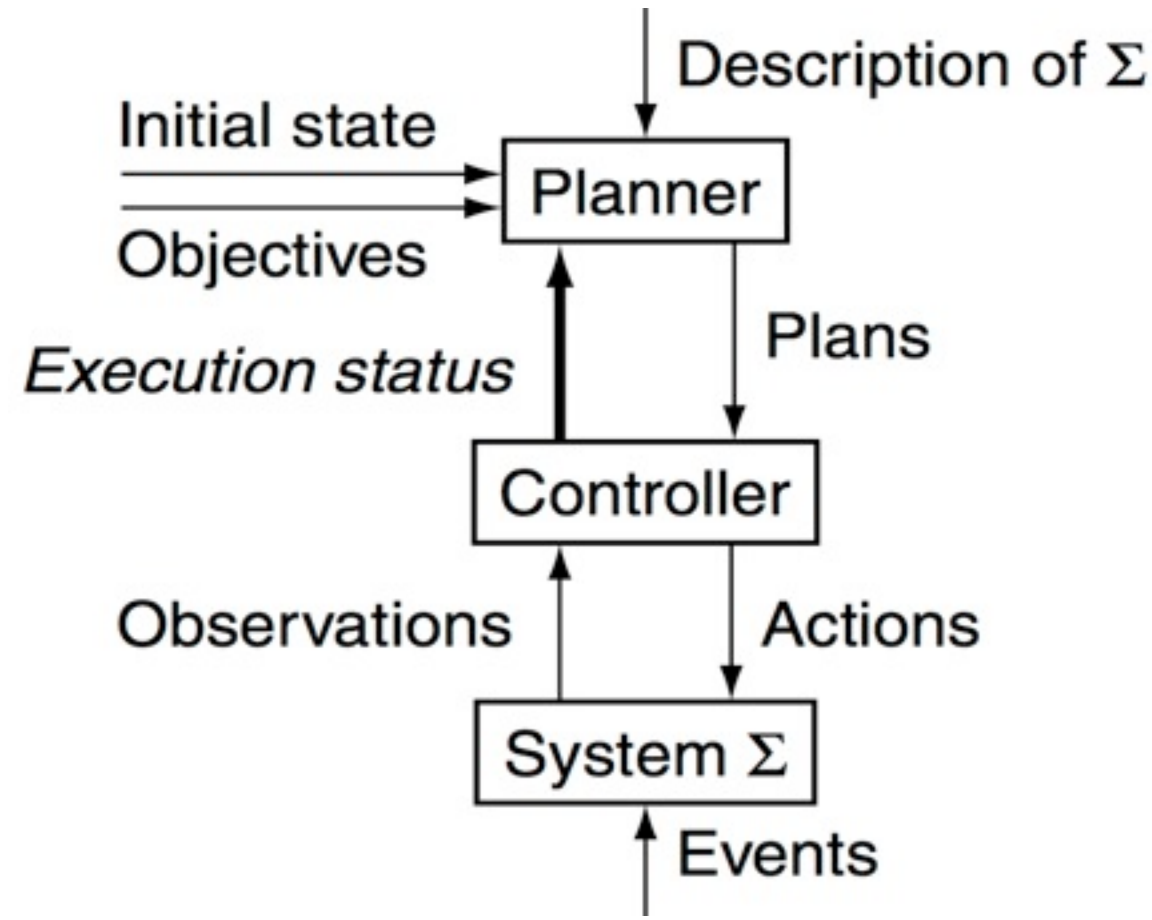
Relax the Assumptions

- Relax A2 (deterministic Σ):
  - Actions have more than one possible outcome
  - Seek policy or contingency plan
  - With probabilities:
    - Discrete Markov Decision Processes (MDPs)
    - Chapter 11
  - Without probabilities:
    - Nondeterministic transition systems
    - Chapters 12, 18



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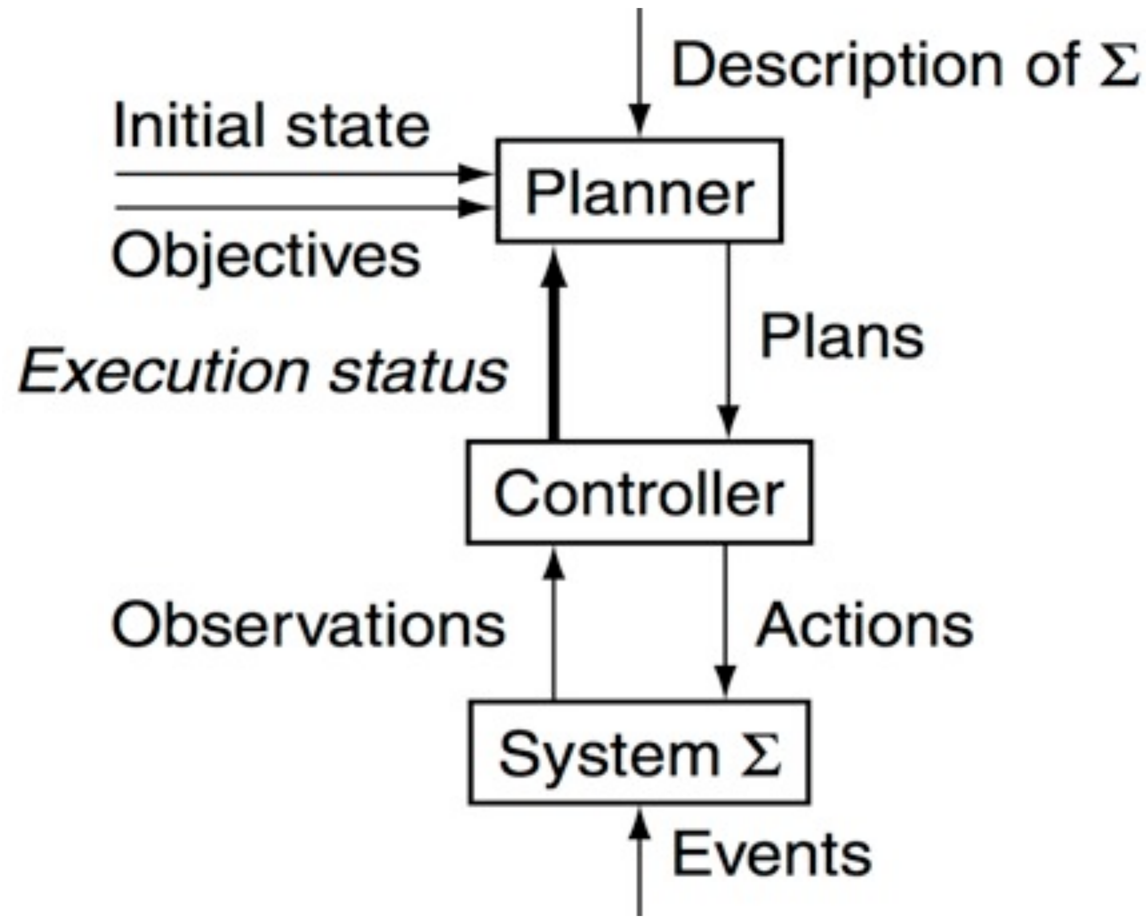
Relax the Assumptions

- Relax A1 and A2:
  - Finite POMDPs
    - Plan over belief states
    - Exponential time & space
    - Section 16.3
- Relax A0 and A2:
  - Continuous or hybrid MDPs
    - Control theory
      (see engineering courses)
- Relax A0, A1, and A2
  - Continuous or hybrid POMDPs
    - Case study: Chapter 20 (robotics)



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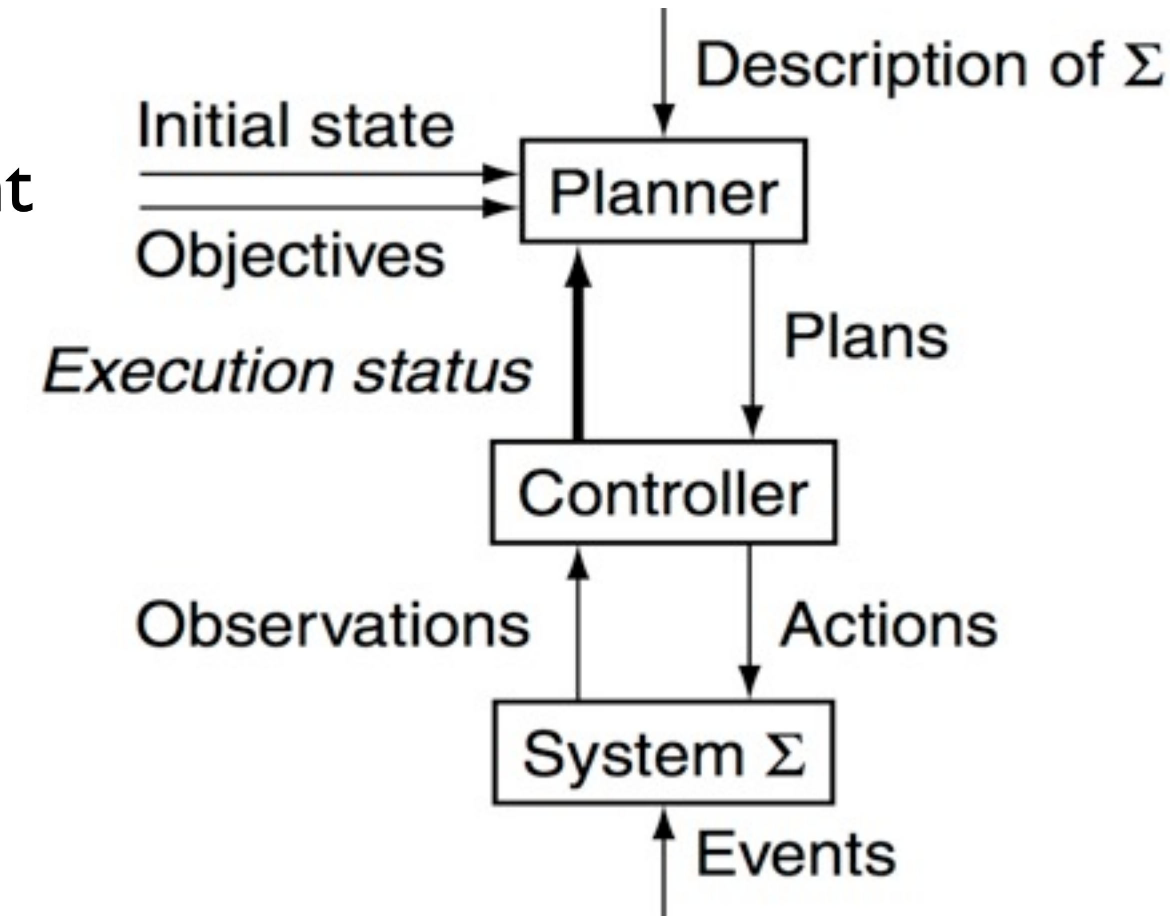
Relax the Assumptions

- Relax A3 (static Σ):
  - Other agents or dynamic environment
    - Finite perfect-info zero-sum games (introductory AI courses)
  - Randomly behaving environment
    - Decision analysis (business, operations research)
    - Can sometimes map this into MDPs or POMDPs
  - Case studies: Chapters 19 (space), 22 (emergency evacuation)
- Relax A1 and A3
  - Imperfect-information games
  - Case study: Chapter 23 (bridge)



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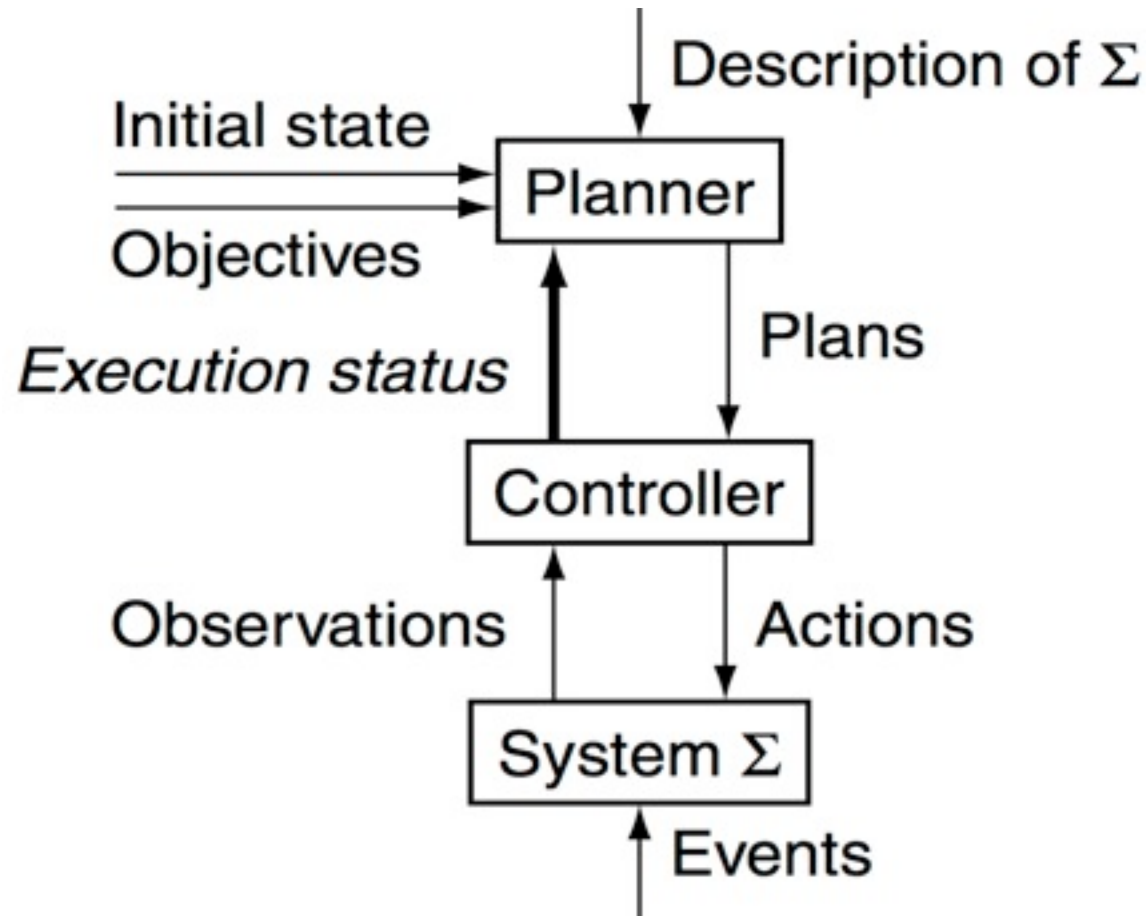
Relax the Assumptions

- Relax A5 (sequential plans) and A6 (implicit time):
  - Temporal planning
  - Chapters 13, 14
- Relax A0, A5, A6
  - Planning and resource scheduling
  - Chapter 15
- 247 other combinations
  - We won't discuss them all!



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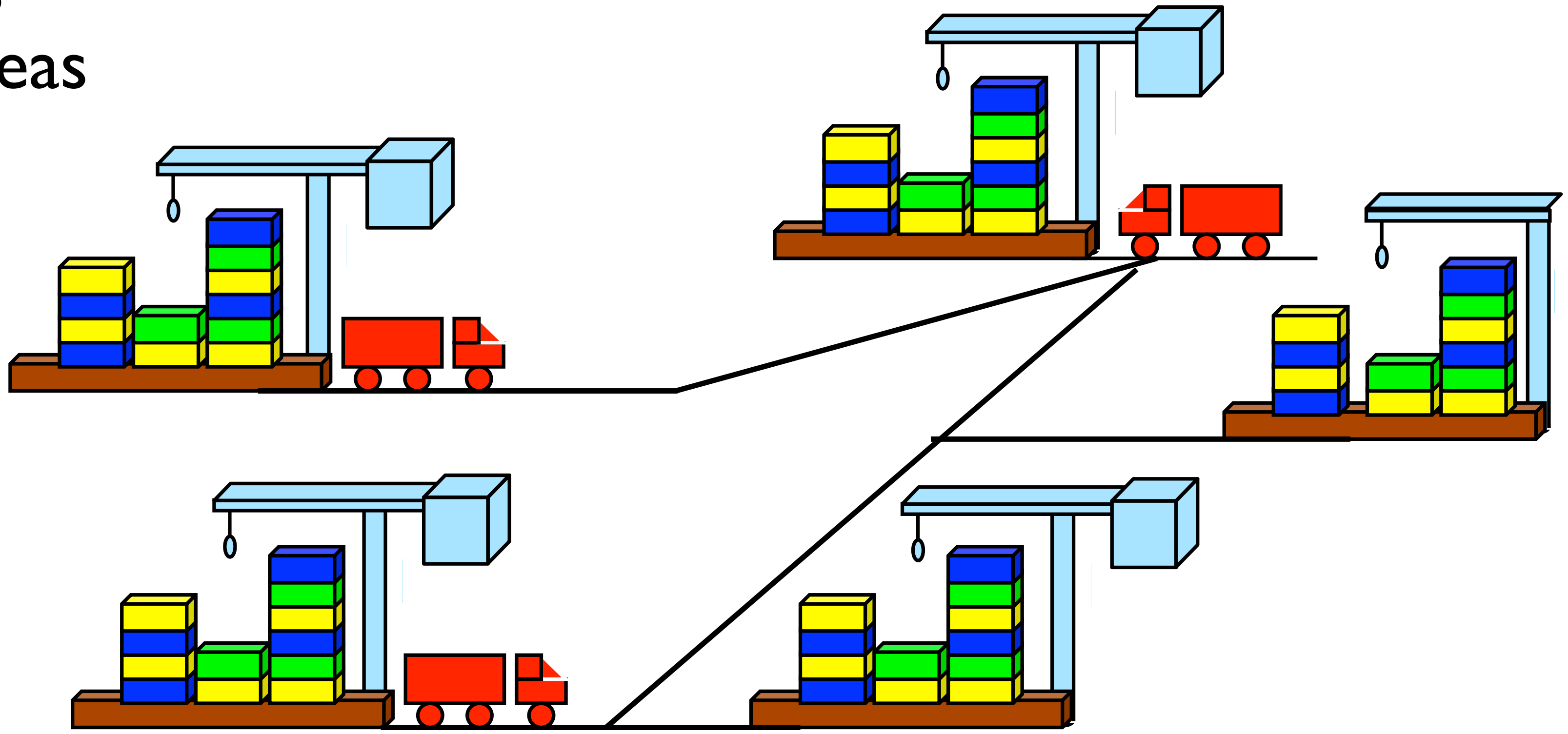
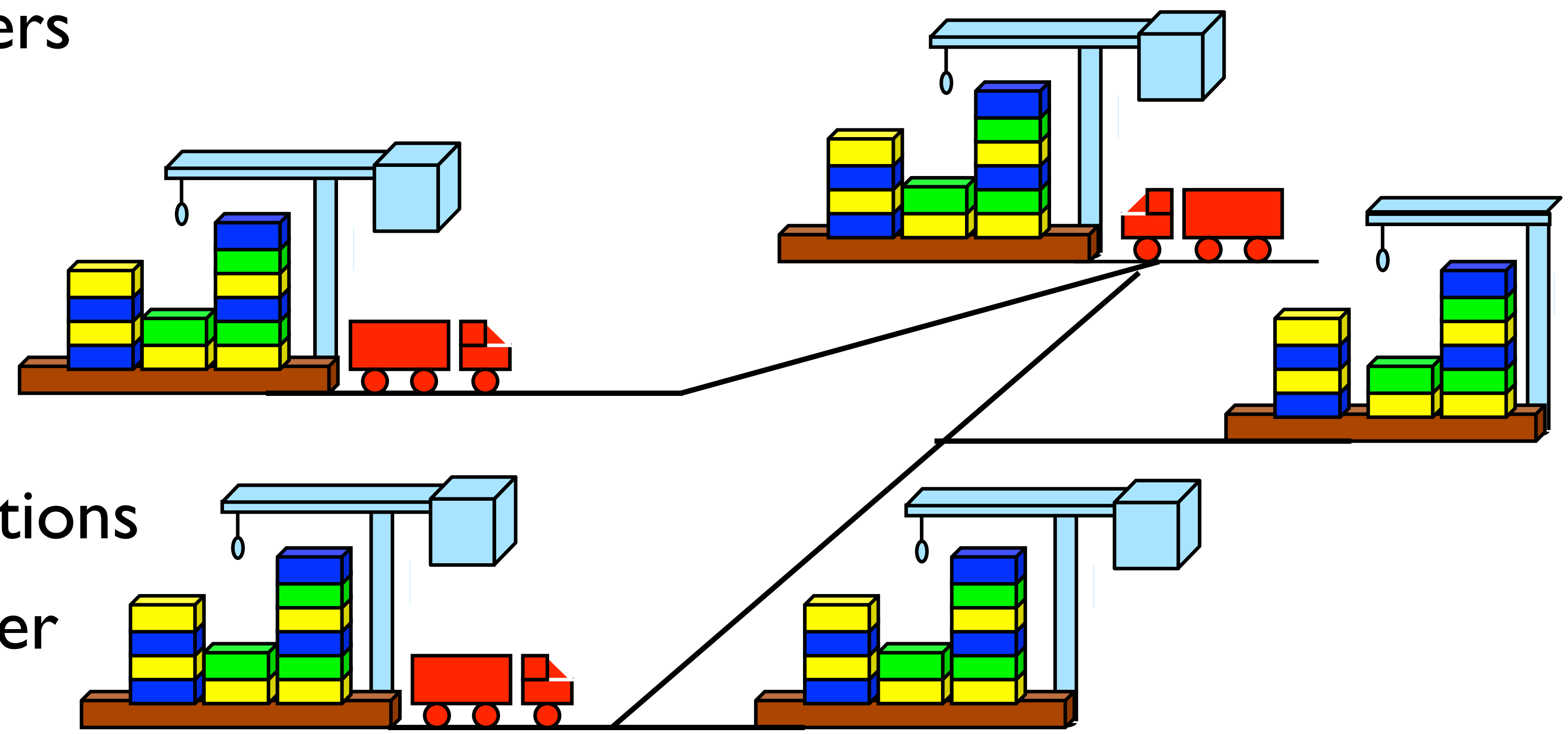
A running example: Dock Worker Robots

- 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



A running example: Dock Worker Robots

- Locations: $l_1, l_2, \ldots$
- Containers: $c_1, c_2, \ldots$
  - Can be stacked in piles, loaded onto robots, or held by cranes
- Piles: $p_1, p_2, \ldots$
  - Fixed areas where containers are stacked
  - Pallet at the bottom of each pile
- Robot carts: $r_1, r_2, \ldots$
  - Can move to adjacent locations
  - Carry at most one container
- Cranes: $k_1, k_2, \ldots$
  - 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



A running example: Dock Worker Robots

- Fixed relations: same in all states

  $adjacent(l, l')$ $\quad attached(p, l)$ $\quad belongs\_to(k, l)$

- Dynamic relations: differ from one state to another

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

- Actions:

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