Current Trends in Automated Planning

Dana S. Nau

Homework

- Planning in games
  - Reading: Michael van Lent, Mark O. Riedl, Paul Carpenter, Ryan McAlinden, and Paul Brobst. Increasing Replayability with Deliberative and Reactive Planning. Proceedings of the 1st Conference on Artificial Intelligence and Interactive Digital Entertainment, Marina del Rey, California, 2005.

What is a 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]

```
                                    02  Stamp board
                                    03  Establish datum point at bullseye (0.25, 1.00)

                                        Install 0.15-diameter side-milling tool

                                        Rough side-mill pocket at (-0.25, 1.25)
                                        length 0.40, width 0.30, depth 0.50

                                        Finish side-mill pocket at (-0.25, 1.25)

                                        length 0.40, width 0.30, depth 0.50
                                        Rough side-mill pocket at (-0.25, 3.00)

                                        length 0.40, width 0.30, depth 0.50

                                        Finish side-mill pocket at (-0.25, 3.00)
                                        length 0.40, width 0.30, depth 0.50

                                        Install 0.08-diameter end-milling tool

                                    .]
                                        Total time on VMC1


                                        Pre-clean board (scrub and wash)

                                    02  Dry board in oven at 85 deg. F

005 B   EC1 30.00     0.48       01  Setup
                                    02  Spread photoresist from 18000 RPM spinner

005 C   EC1 30.00     2.00       01  Setup

                                    02  Photolithography of photoresist
                                        using phototool in "real.iges"

005 D   EC1 30.00    20.00       01  Setup

                                    02  Etching of copper
005 T   EC1 90.00    54.77       01  Total time on EC1



006 A   MC1 30.00     4.57       01  Setup
                                    02  Prepare board for soldering

006 B   MC

                                    02  Screenprint solder stop on board
006 C   MC1 30.00     7.50       01  Setup
```

A portion of a manufacturing process plan

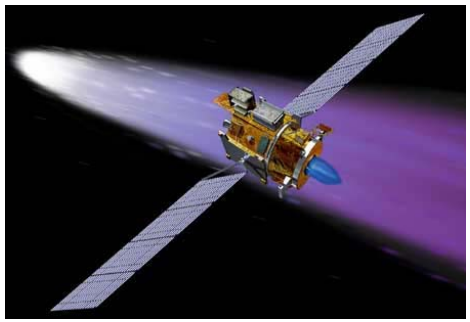
Generating Plans of Action

- Computer programs to aid human planners
  - Project management (consumer software)
  - Plan storage and retrieval
    - » e.g., ***variant process planning*** in manufacturing
  - Automatic schedule generation
    - » various OR and AI techniques
- For some problems, we would like generate plans (or pieces of plans) automatically
  - Much more difficult
  - Automated-planning research is starting to pay off

What are planners useful for?

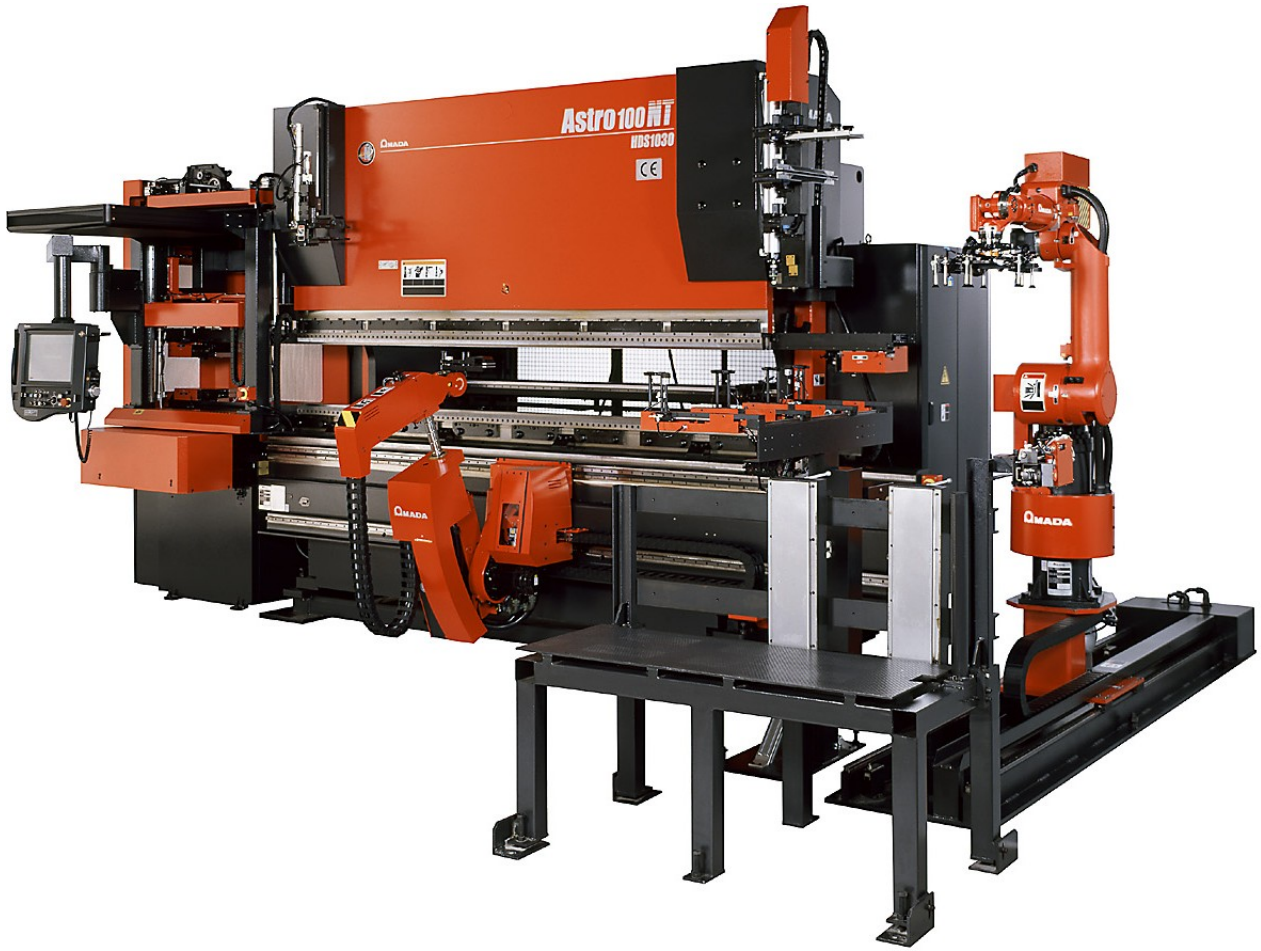
Space Exploration

- Autonomous planning, scheduling, control
  - NASA: JPL and Ames
- Remote Agent Experiment (RAX)
  - Deep Space 1
- Mars Exploration Rover (MER)



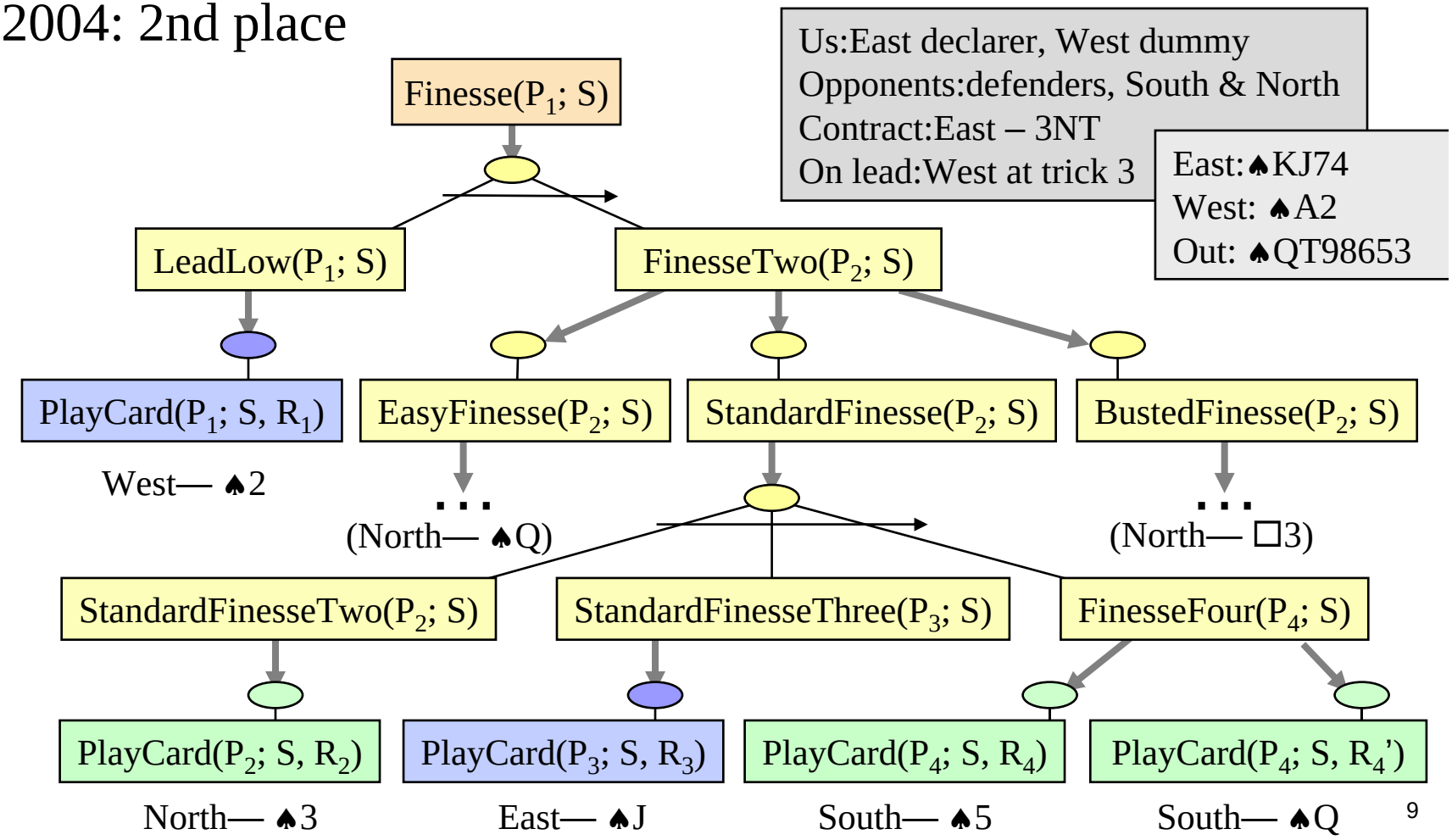
Manufacturing

- Sheet-metal bending machines - Amada Corporation
  - Software to plan the sequence of bends
    [Gupta and Bourne, *J. Manufacturing Sci. and Engr.*, 1999]



Games

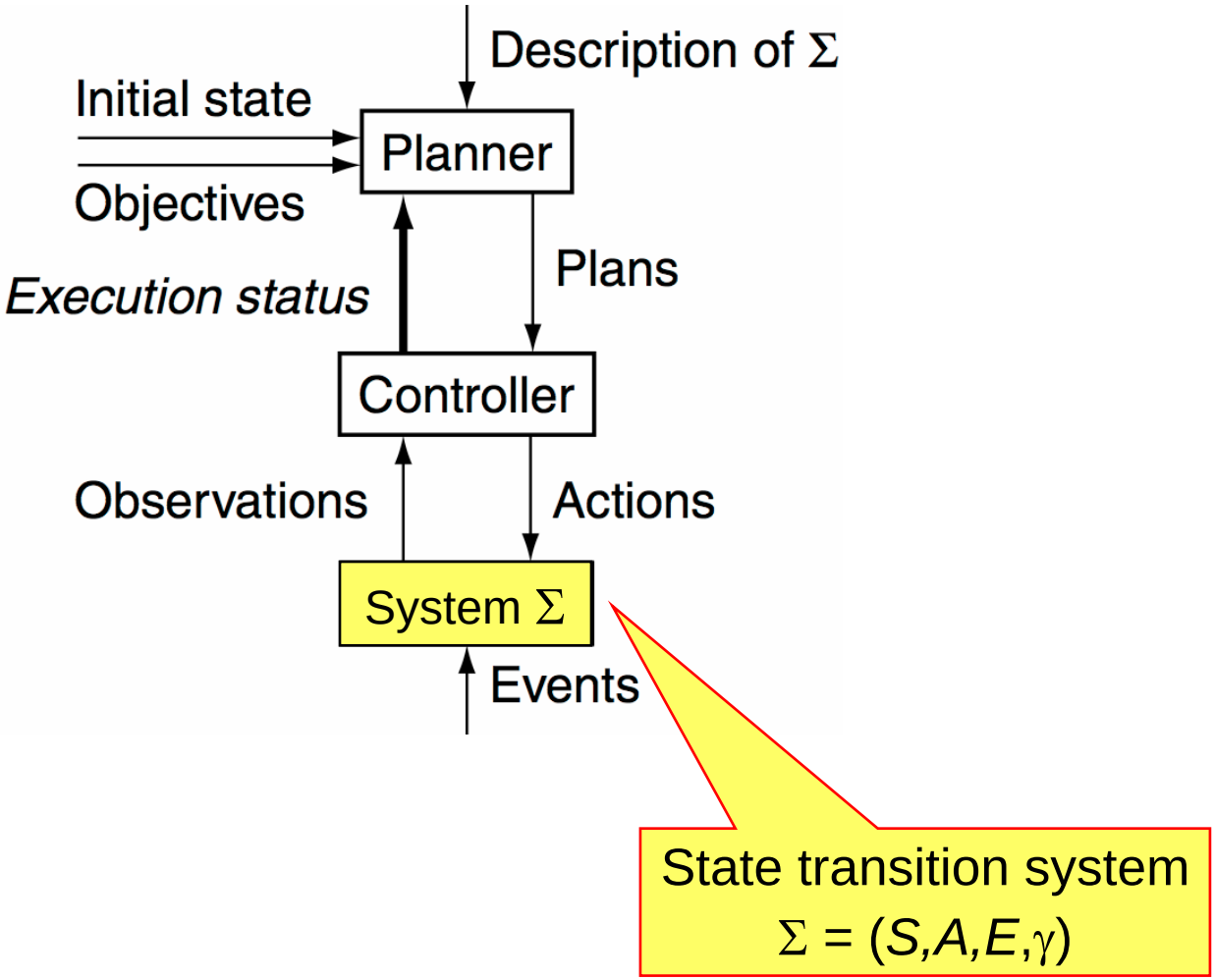
- *Bridge Baron* - Great Game Products
  - 1997 world champion of computer bridge [Smith, Nau, and Throop, *AI Magazine*, 1998]
  - 2004: 2nd place



Outline

- Conceptual model for planning
- Example domain
- Types of planners
  - Domain-dependent
  - Domain-independent
  - Configurable
- Classical planning assumptions

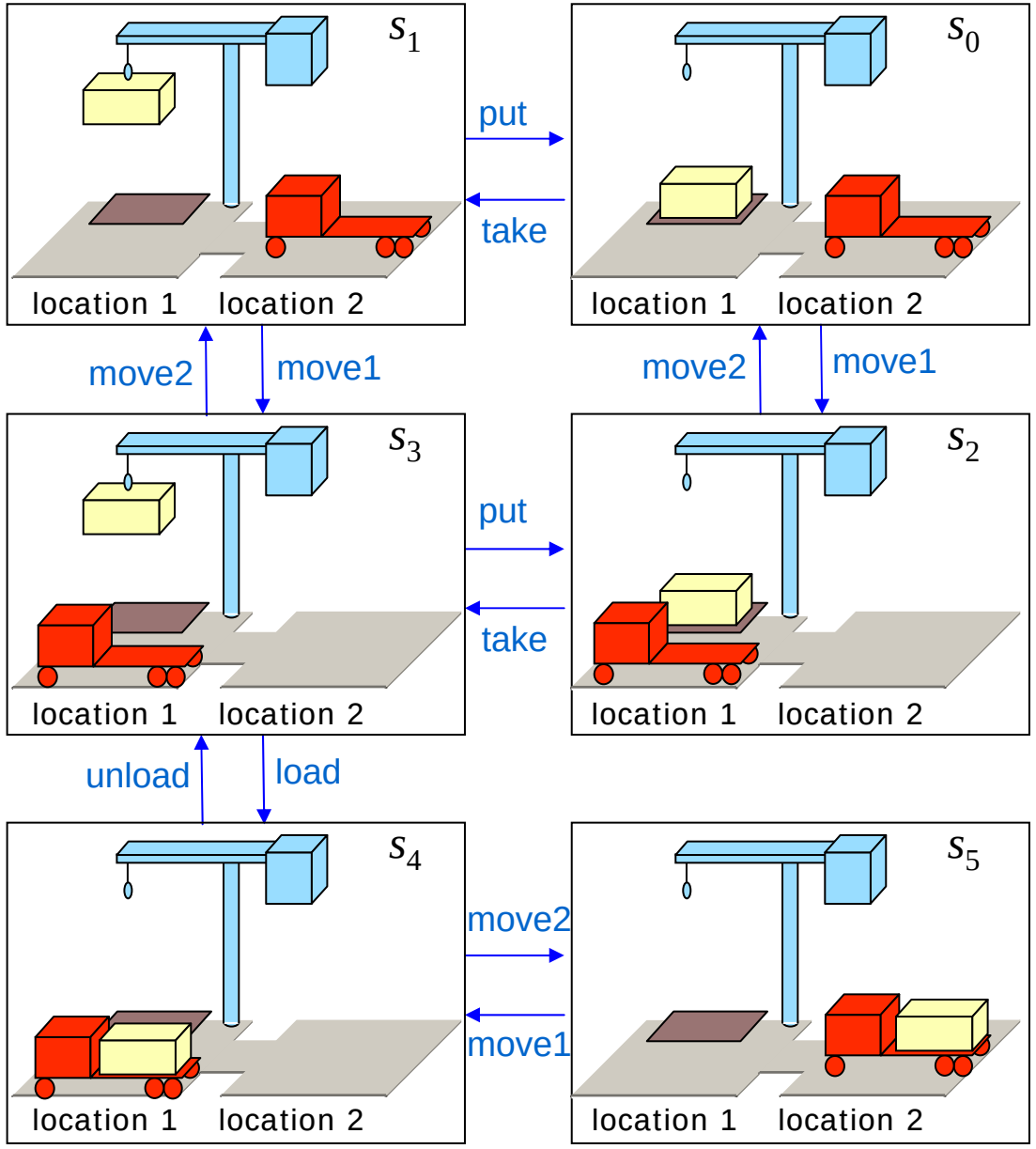
Conceptual Model
1. Environment



State Transition System

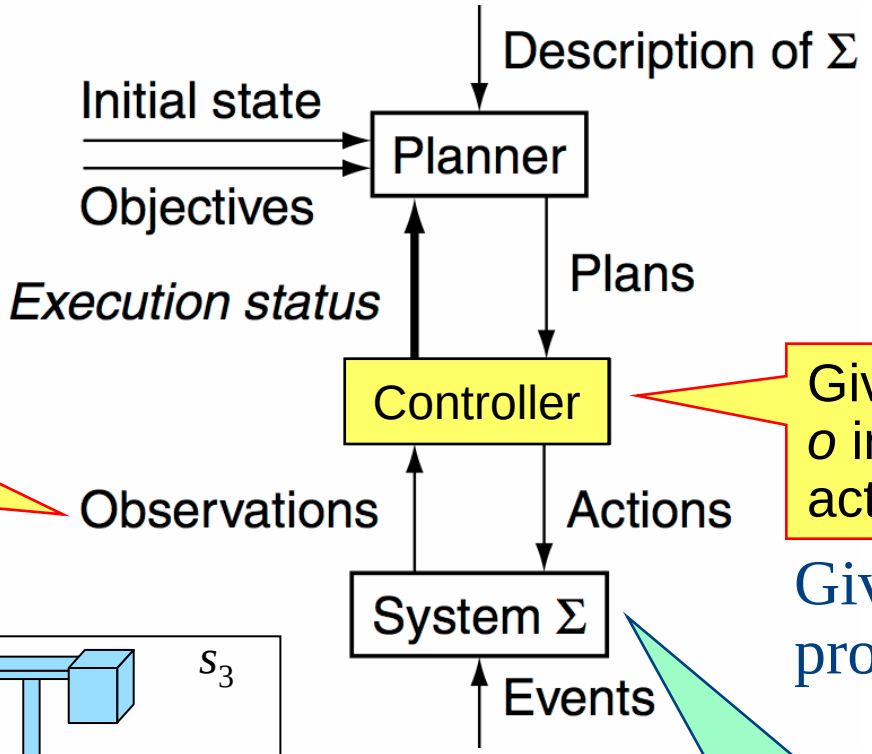
$\Sigma = (S,A,E,\gamma)$

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



The Dock Worker Robots (DWR) domain

Conceptual Model
2. Controller



Complete observability:

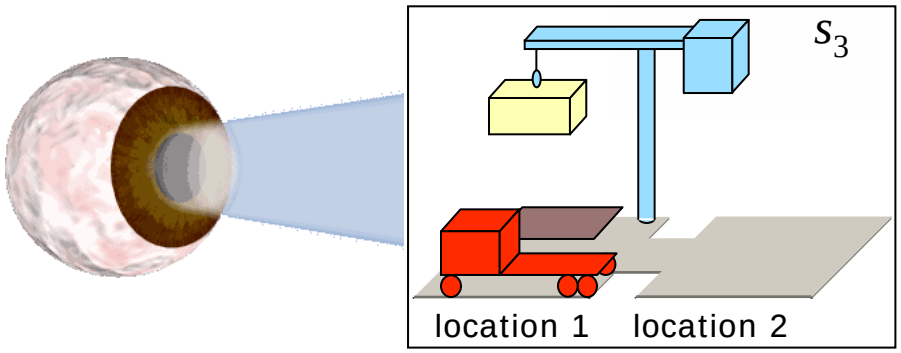
$h(s) = s$

Observation function

$h: S \rightarrow O$

Given observation o in O, produces action a in A

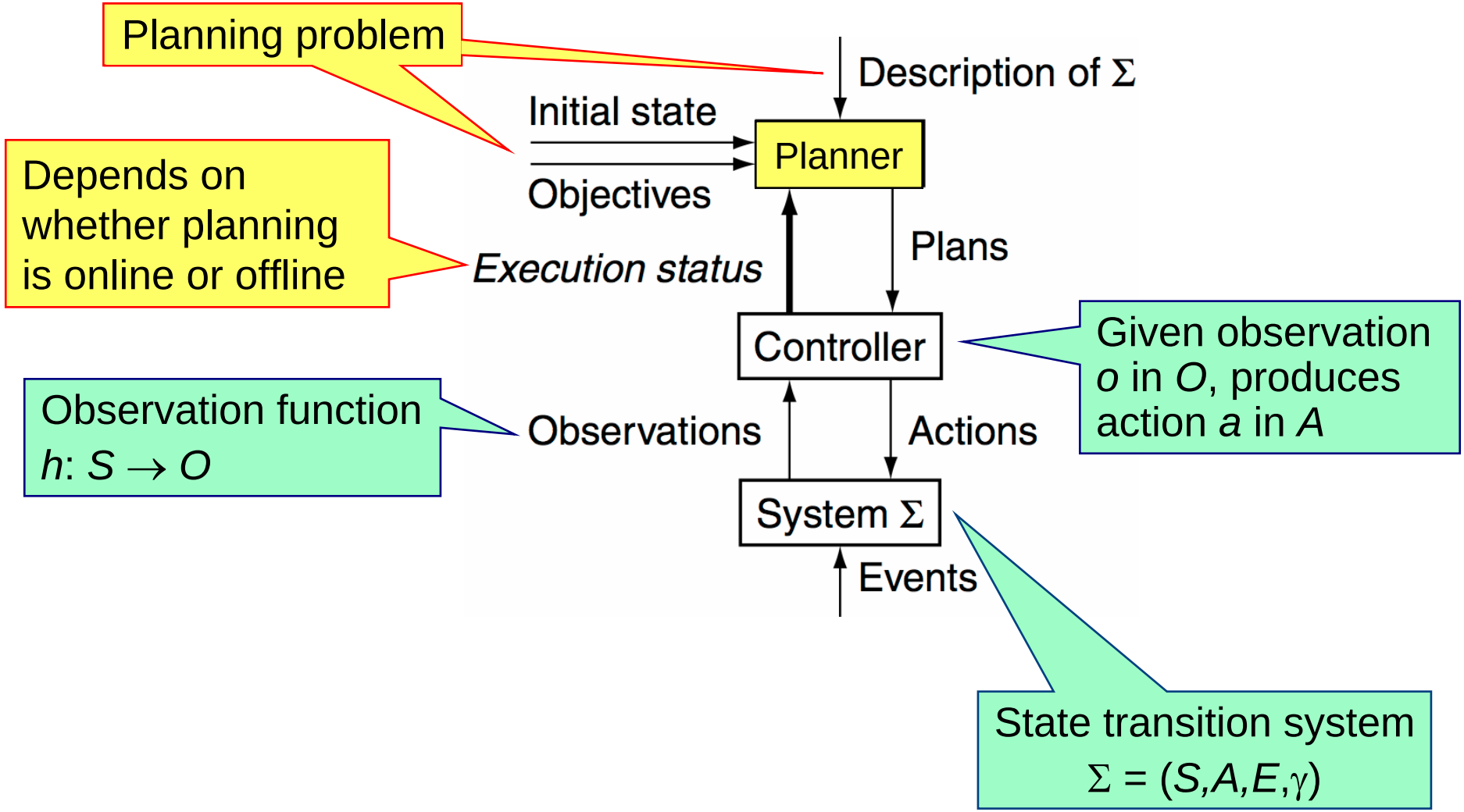
Given state s, produces action a



State transition system

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

Conceptual Model
3. Planner's Input



Planning Problem

Description of Σ

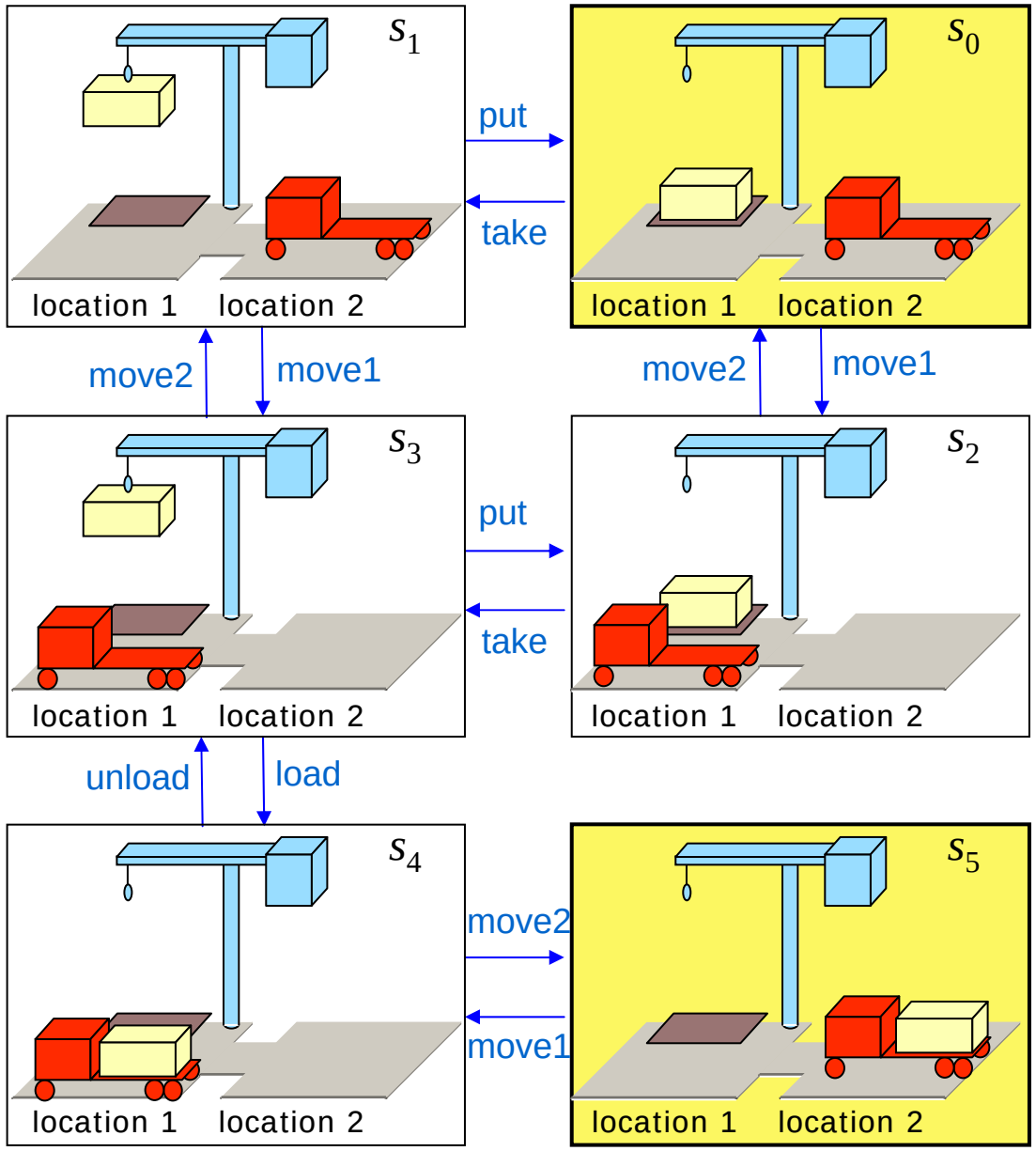
Initial state or set of states

Initial state = s_0

Objective

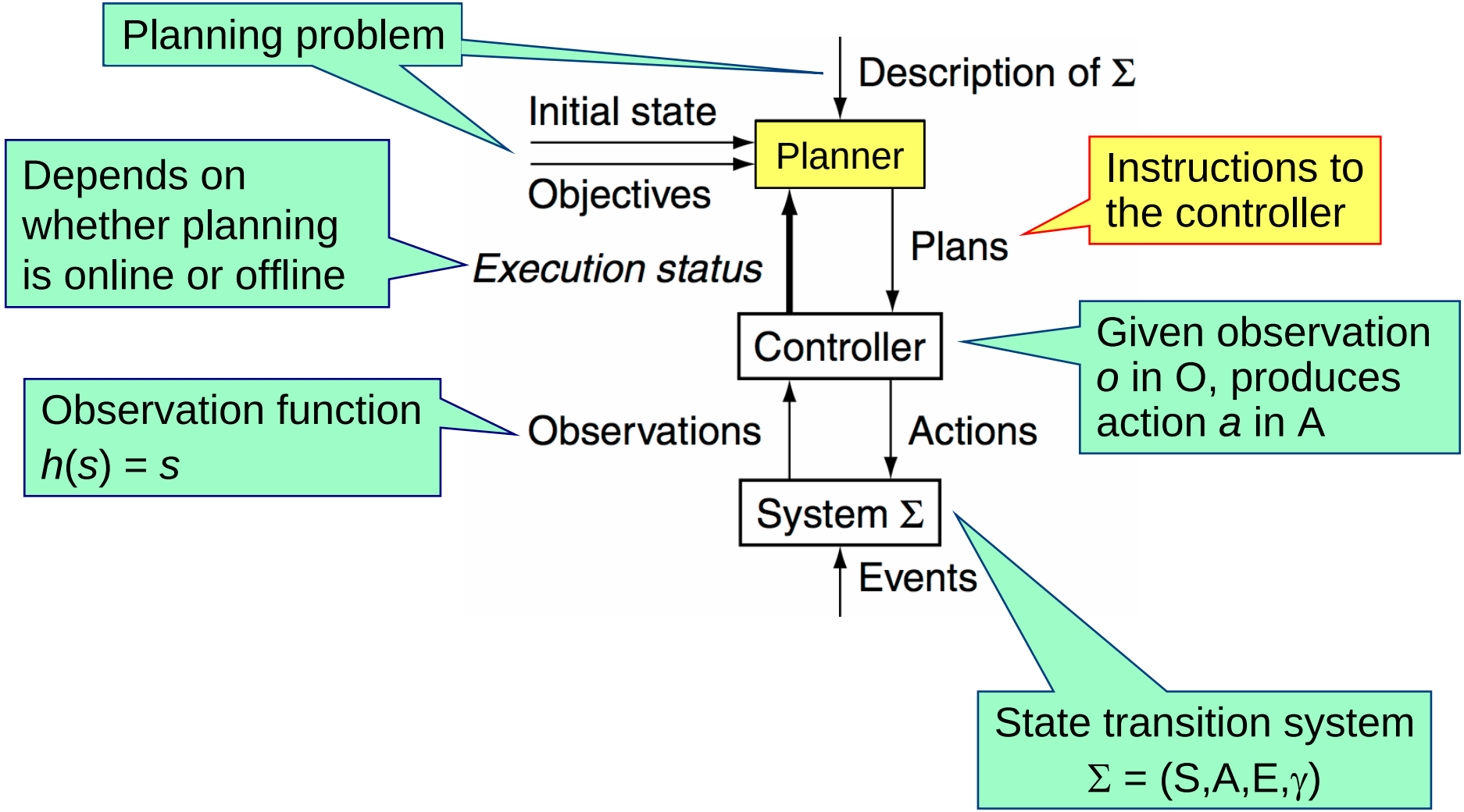
Goal state, set of goal states, set of tasks, "trajectory" of states, objective function, …

Goal state = s_5



The Dock Worker Robots (DWR) domain

Conceptual Model
4. Planner's Output



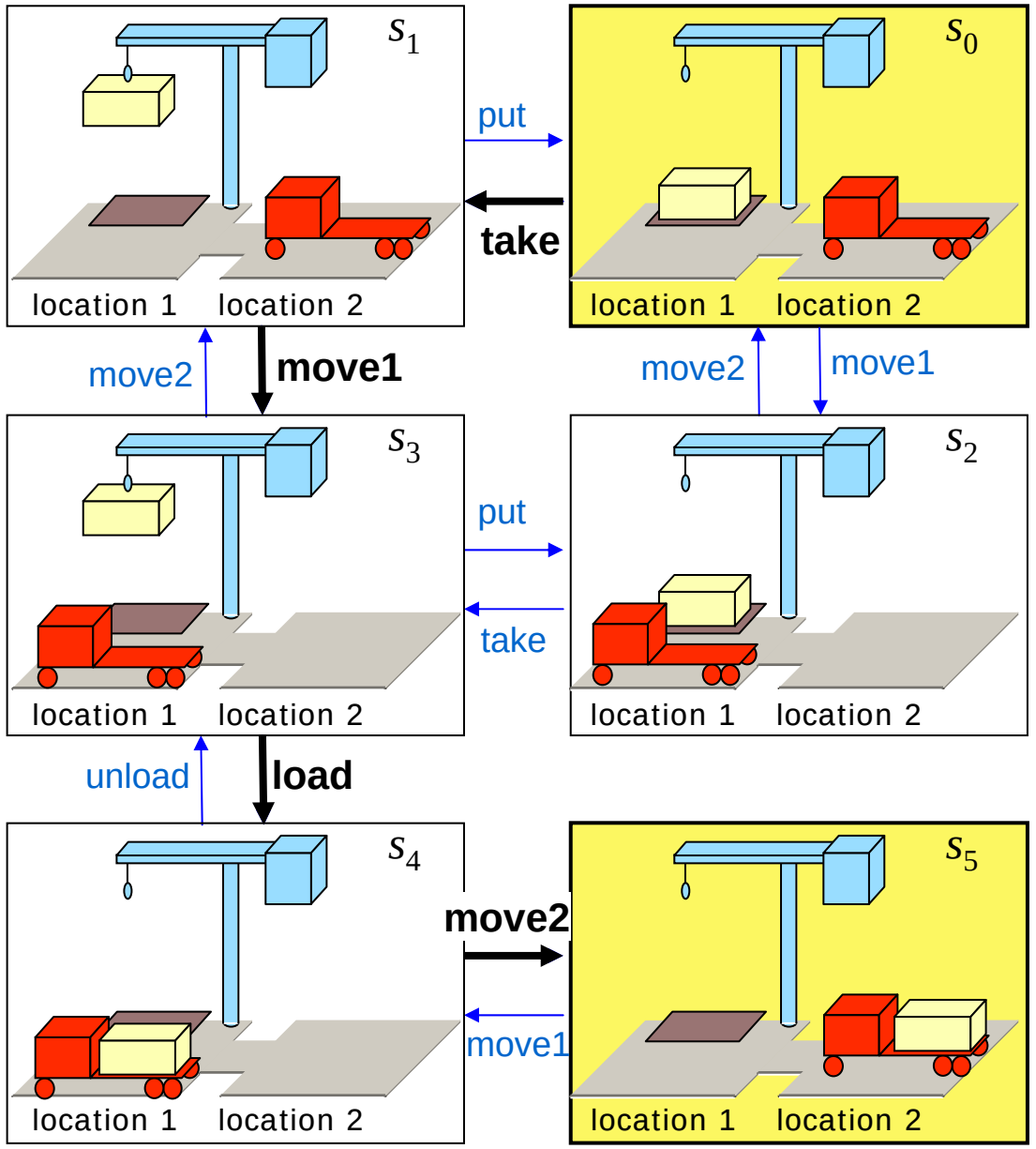
Plans

Classical plan: a sequence of actions

⟨take, move1, load, move2⟩

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

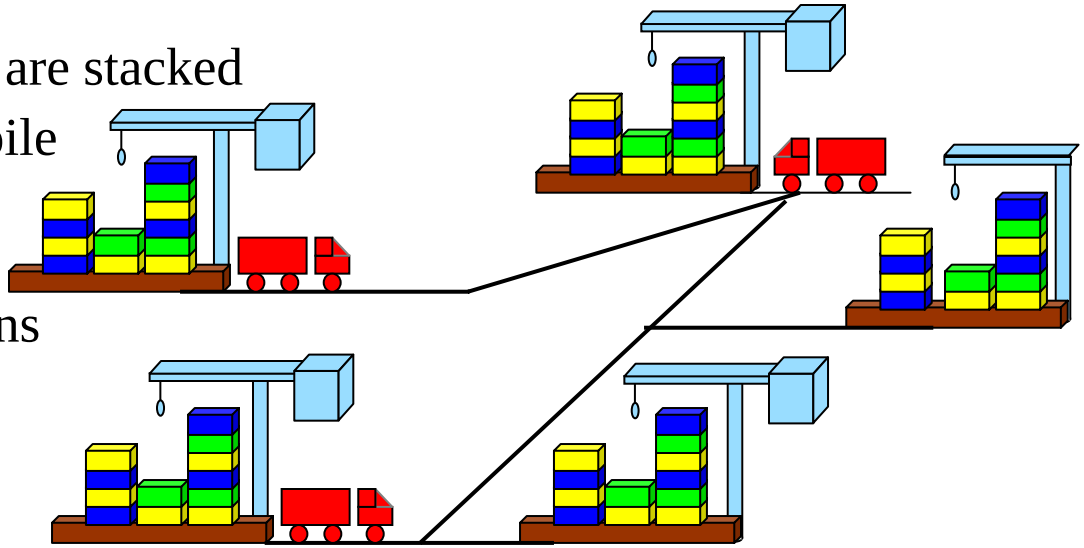
{(s_0, take),
(s_1, move1),
(s_3, load),
(s_4, move2)}



The Dock Worker Robots (DWR) domain

A running example: Dock Worker Robots

- **Locations**: l1, l2, …
- **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



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

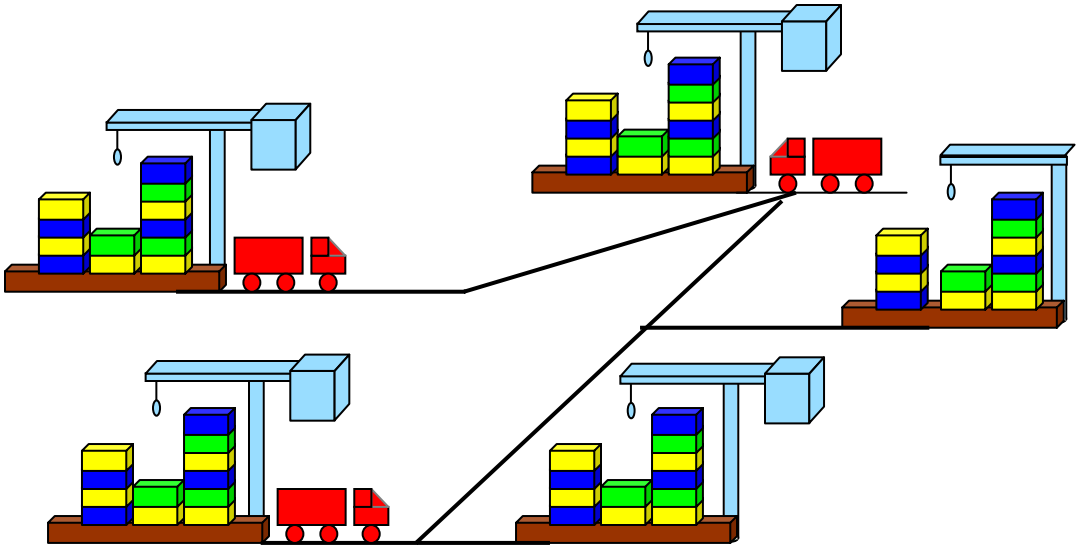
  occupied(l) at(r,l)

  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)

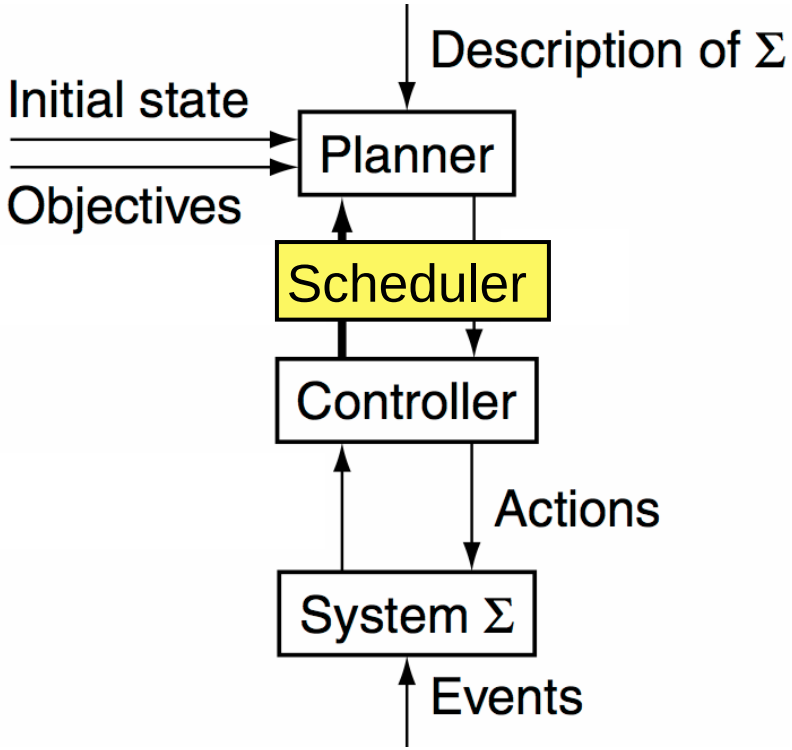
  load(r,c,k) unload(r) move(r,l,l')

Planning Versus Scheduling

- What is the difference between these two types of problems?

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

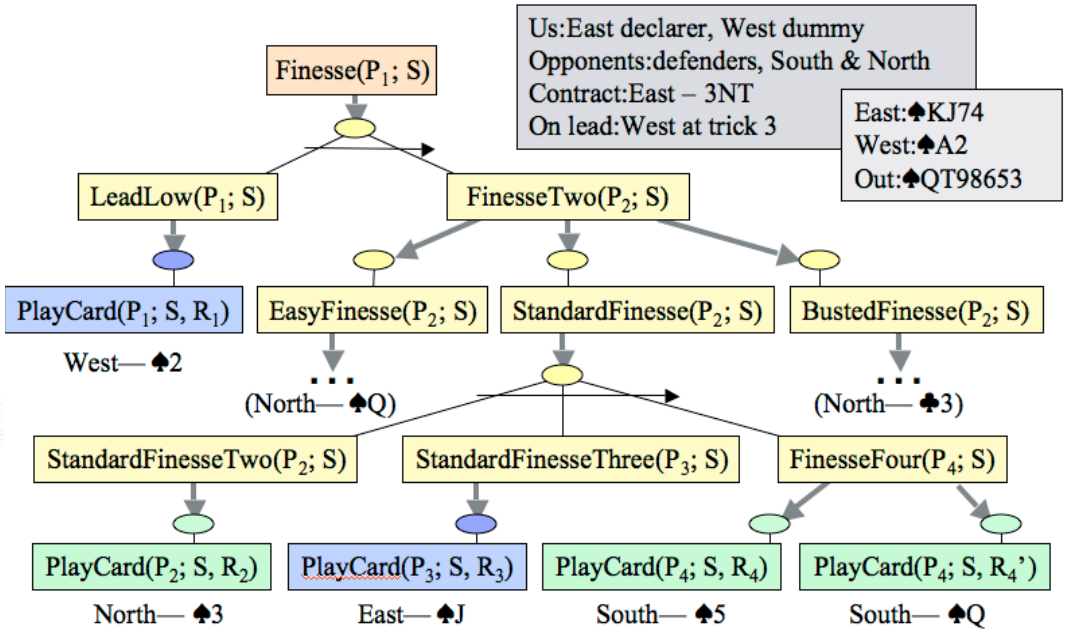
Three Main Types of Planners

1. Domain-specific
2. Domain-independent
3. Configurable

Types of Planners:
1. Domain-Specific

- Made or tuned for a specific domain
- Won't work well (if at all) in any other domain

- Most successful real-world planning systems work this way

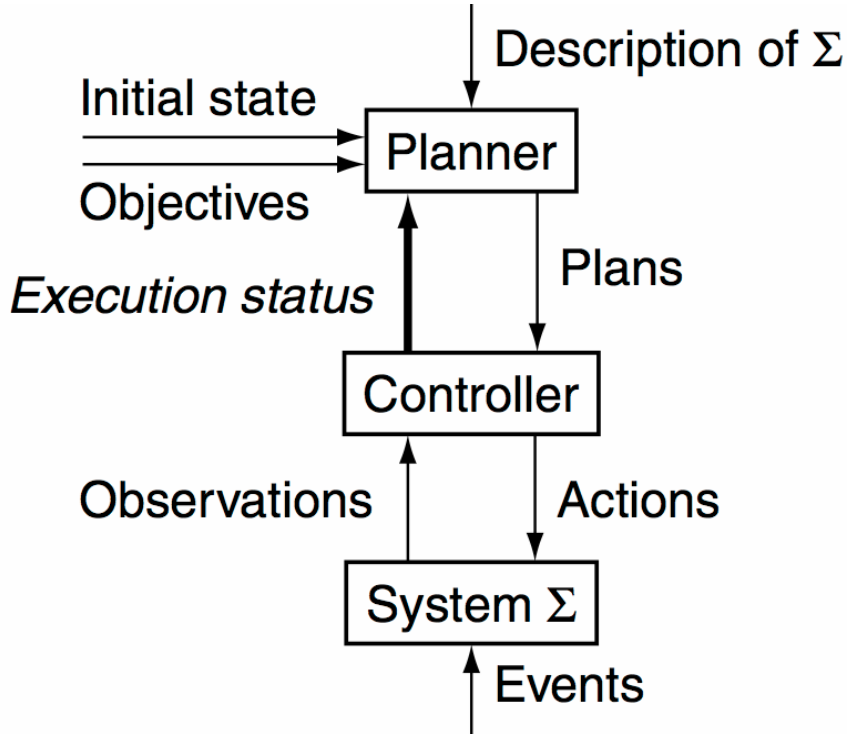


Types of Planners
2. Domain-Independent

- In principle, a domain-independent planner works in any planning domain
- Uses no domain-specific knowledge except the definitions of the basic actions
- Representation written in a STRIPS or PDDL-type formalism
- In practice,
  - Not feasible to develop domain-independent planners that work in *every* possible domain
- Make simplifying assumptions to restrict the set of domains
  - *Classical planning*
  - Historical focus of most automated-planning research

Restrictive Assumptions

- A0: Finite system
  - finitely many states, actions, and events
- A1: Fully observable
  - the controller always knows what state Σ is in
- A2: Deterministic
  - each action or event has only one possible outcome
- A3: Static
  - No exogenous events: no changes except those performed by the controller



Restrictive Assumptions

A4: Attainment goals

- a set of goal states S_g

A5: Sequential plans

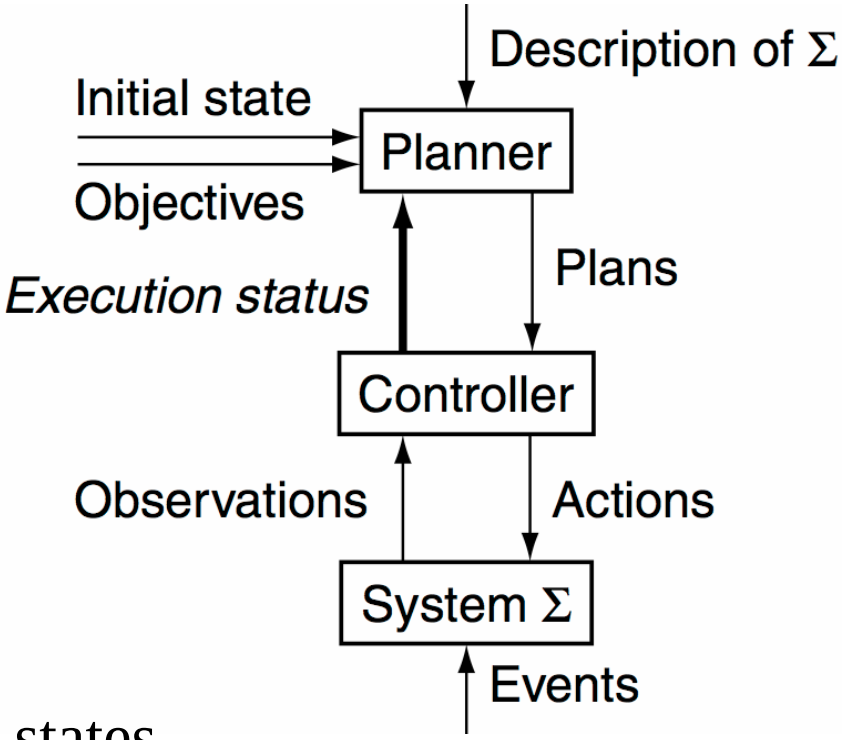
- a plan is a linearly ordered sequence of actions $(a_1, a_2, \ldots a_n)$

A6 :Implicit time

- no time durations
- linear sequence of instantaneous states

A7: Off-line planning

- planner doesn't know the execution status

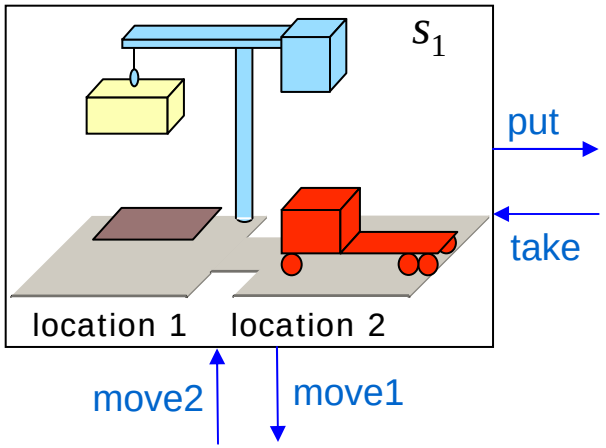


Classical Planning

- 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 (Σ, 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?***

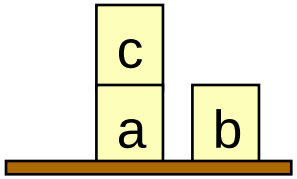
Classical Planning

- 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!

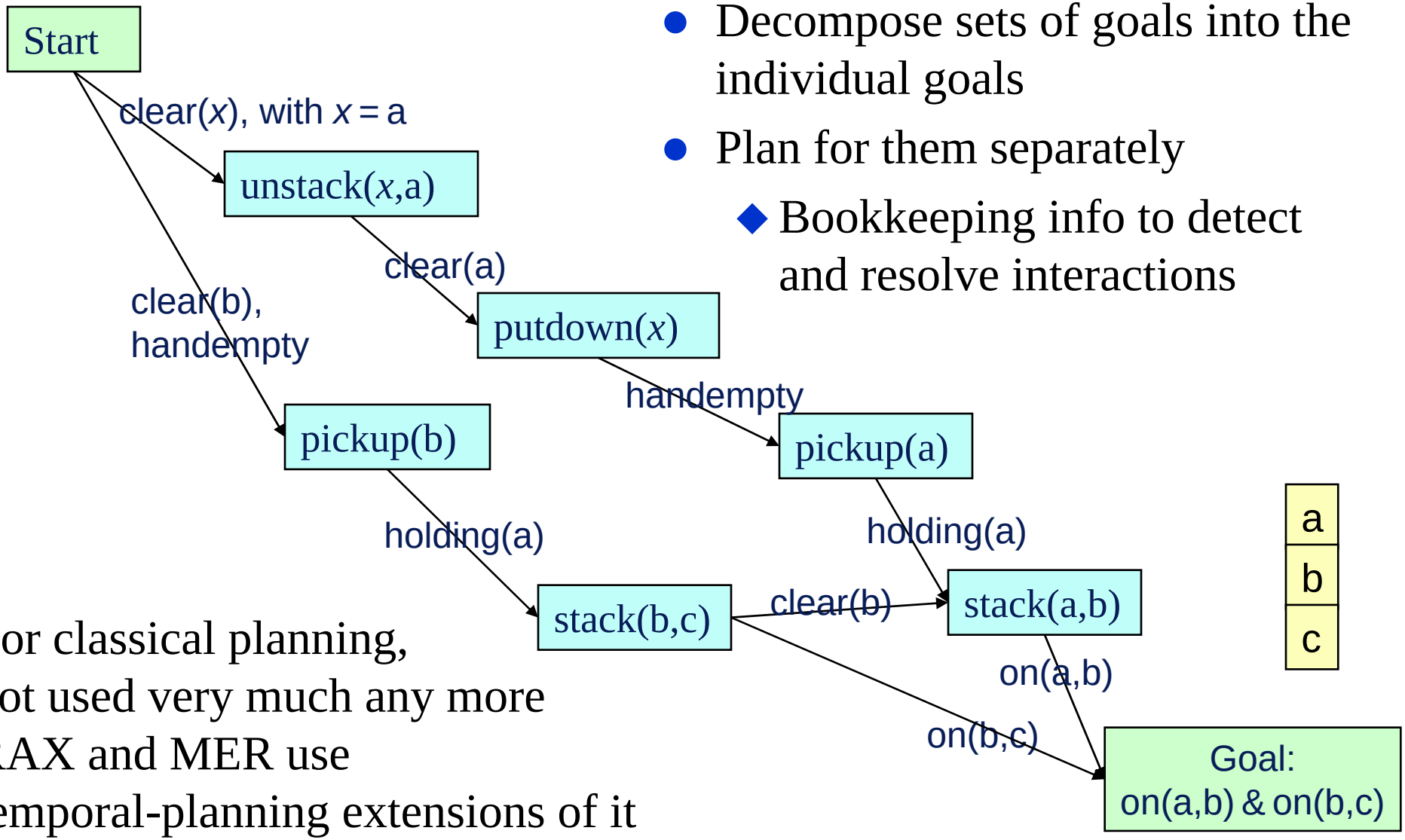


- Automated-planning research has been heavily dominated by classical planning
  - Dozens (hundreds?) of different algorithms

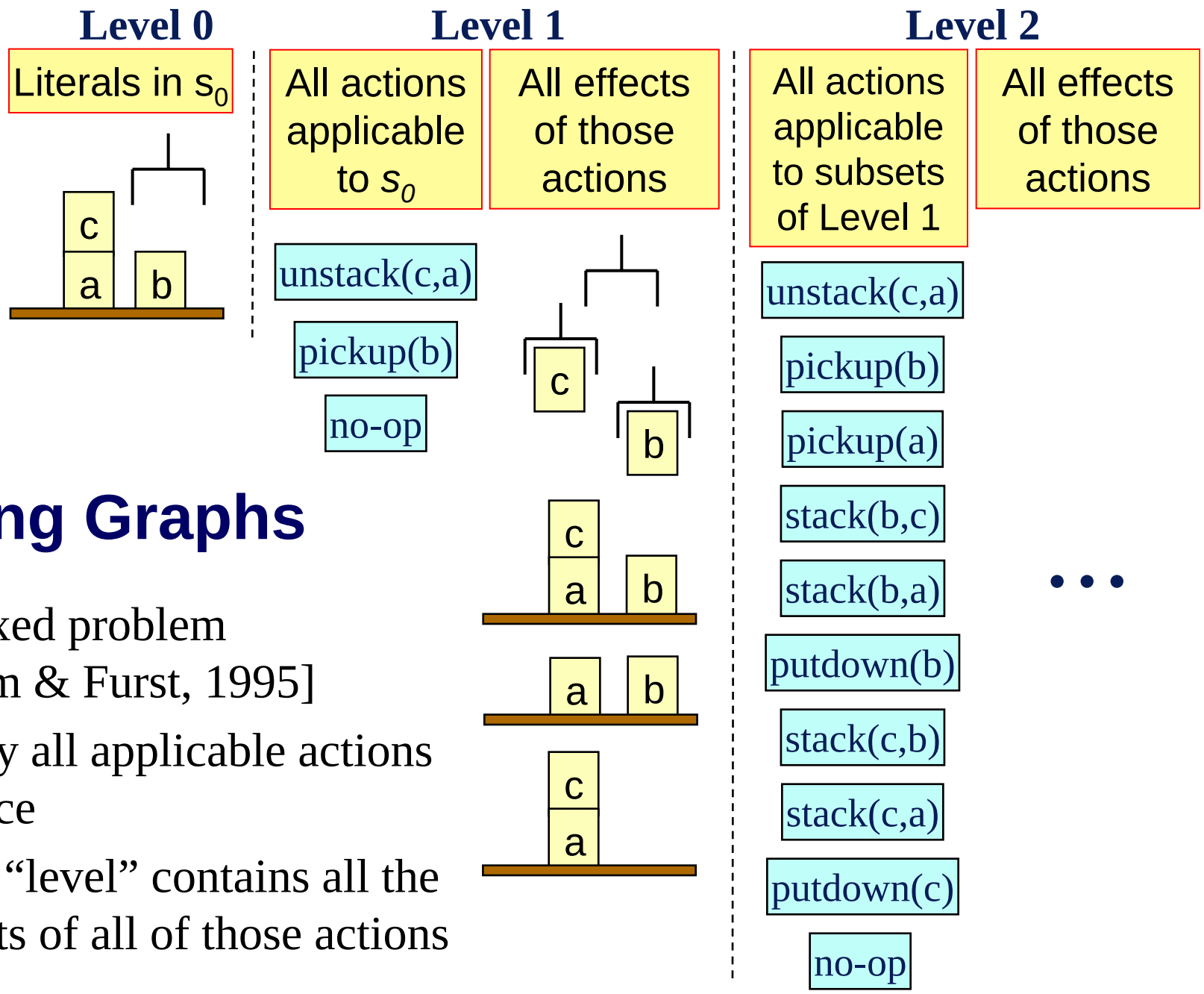
Plan-Space Planning (UCPOP)



- Decompose sets of goals into the individual goals
- Plan for them separately
  - Bookkeeping info to detect and resolve interactions

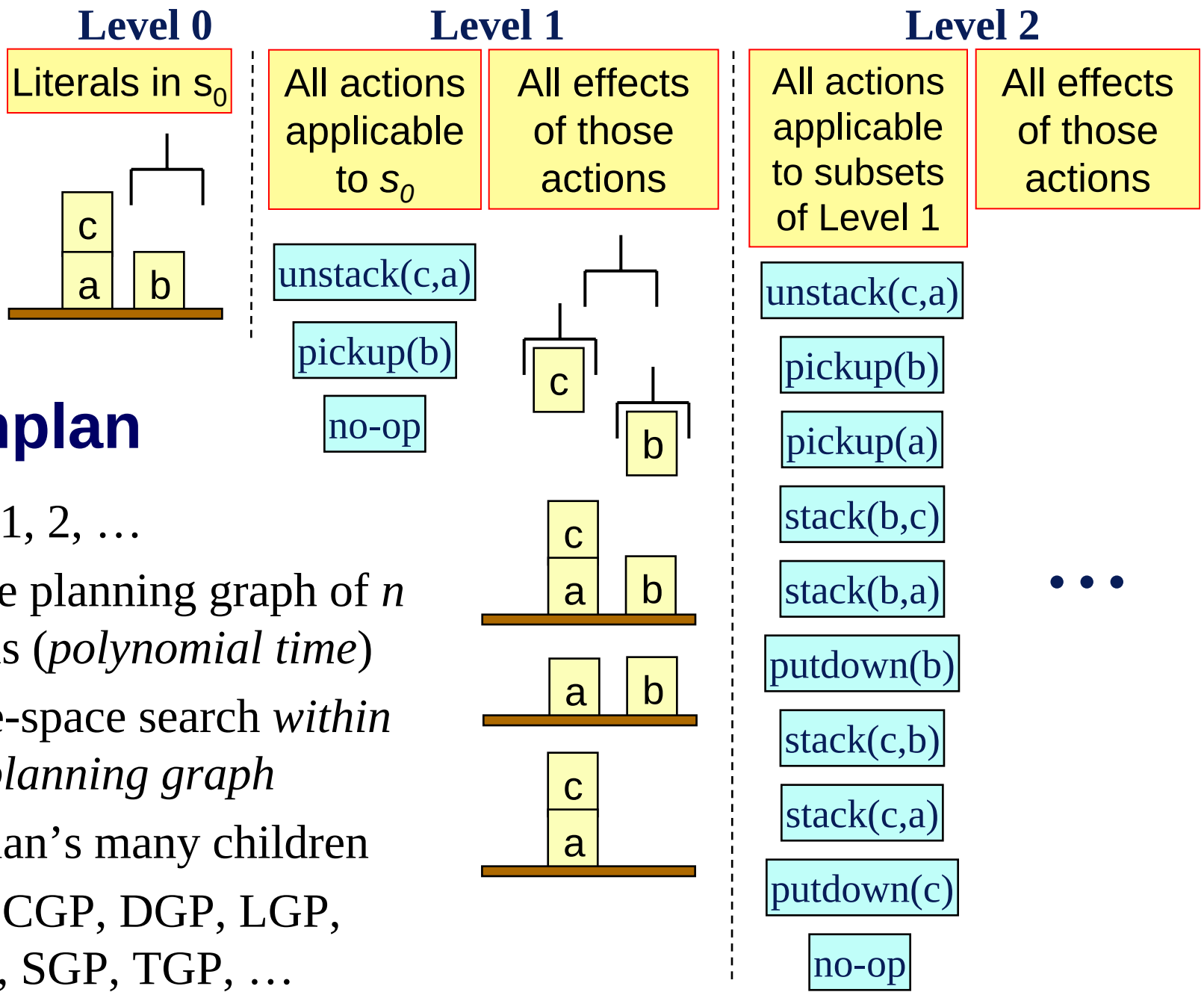


For classical planning,
not used very much any more
RAX and MER use
temporal-planning extensions of it



Planning Graphs

- Relaxed problem [Blum & Furst, 1995]
- Apply all applicable actions at once
- Next "level" contains all the effects of all of those actions



Graphplan

- For n = 1, 2, …
  - Make planning graph of n levels (*polynomial time*)
  - State-space search *within the planning graph*
- Graphplan's many children
  - IPP, CGP, DGP, LGP, PGP, SGP, TGP, …

Heuristic Search

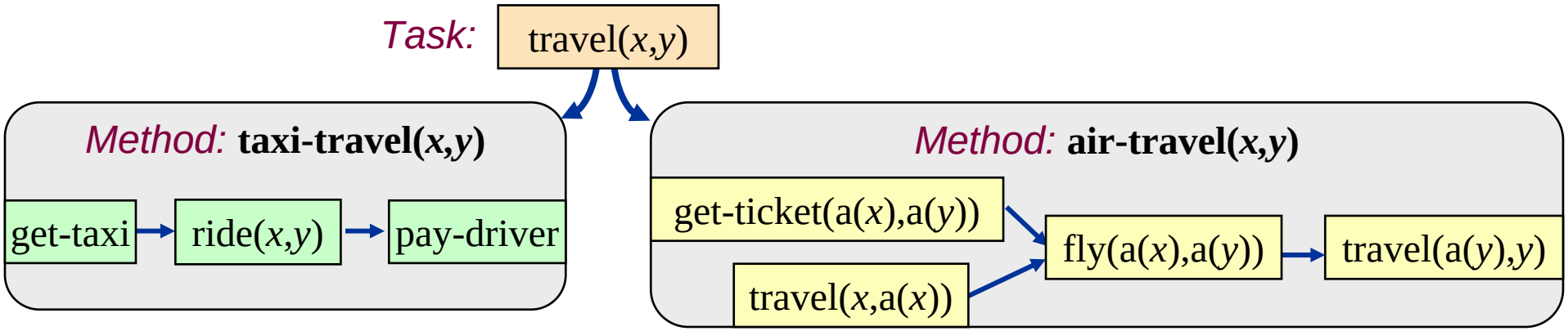
- Can we do an A*-style heuristic search?
- For many years, nobody could come up with a good *h* function
  - But planning graphs make it feasible
    - » Can extract *h* from the planning graph
- Problem: A* quickly runs out of memory
  - So do a greedy search
- Greedy search can get trapped in local minima
  - Greedy search plus local search at local minima
- HSP [Bonet & Geffner]
- FastForward [Hoffmann]

Translation to Other Domains

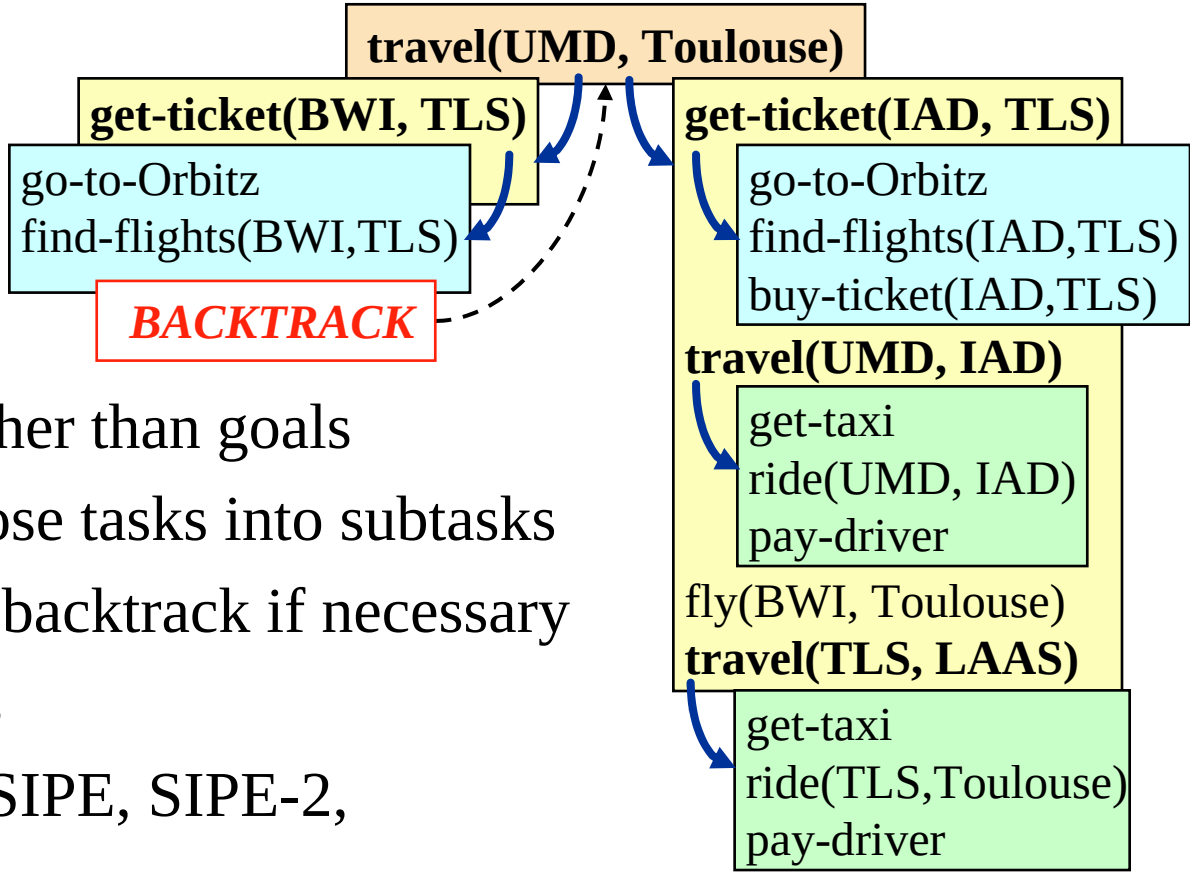
- Translate the planning problem or the planning graph into another kind of problem for which there are efficient solvers
  - Find a solution to that problem
  - Translate the solution back into a plan
- Satisfiability solvers, especially those that use local search
  - Satplan and Blackbox [Kautz & Selman]
- Integer programming solvers such as Cplex
  - [Vossen *et al.*]

Types of Planners

- Domain-independent planners are quite slow compared with domain-specific planners
  - Blocks world in linear time [Slaney and Thiébaux, *A.I.*, 2001]
  - Can get analogous results in many other domains
- 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
    - Hierarchical Task Network (HTN) planning
    - Planning with control formulas

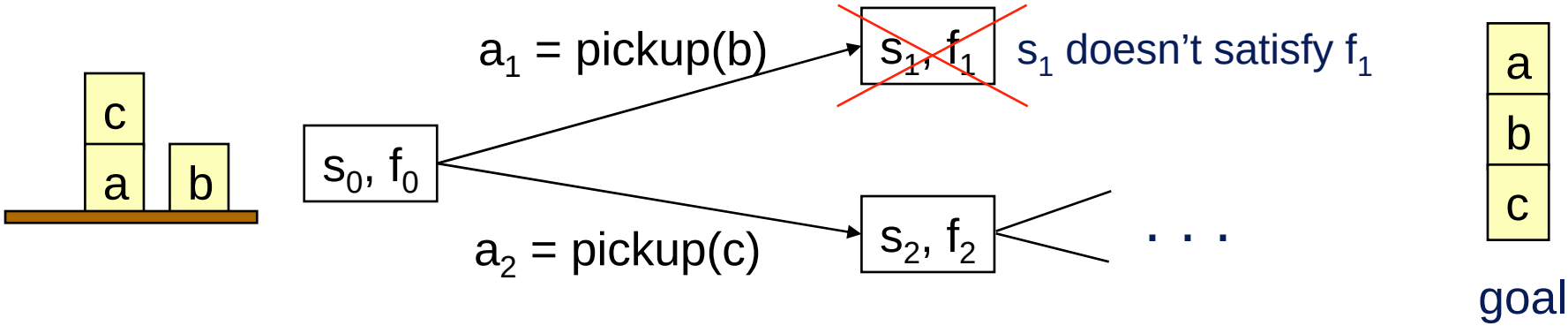


HTN Planning



- 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



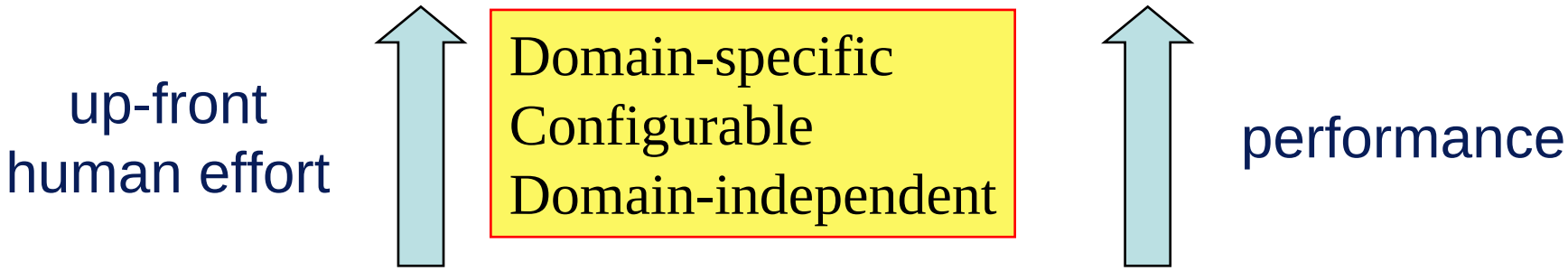
- At each state s_i we have a *control formula* f_i in temporal logic

$$ontable(x) \wedge \neg\exists[y{:}\mathrm{GOAL}(on(x,y))] \Rightarrow \bigcirc(\neg holding(x))$$

  "never pick up *x* from table unless *x* needs to be on another block"
- For each successor of *s*, derive a control formula using *logical progression*
- Prune any successor state in which the progressed formula is false
  - TLPlan [Bacchus & Kabanza]
  - TALplanner [Kvarnstrom & Doherty]

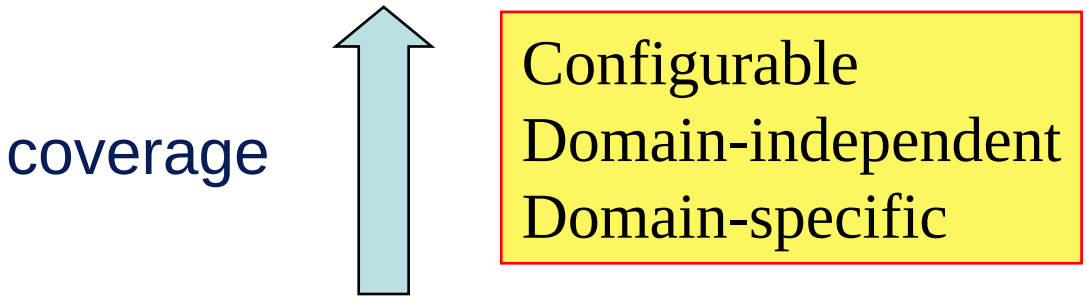
Which type of planner is better?

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 due to expressive power

Example

- The planning competitions
  - All of them included domain-independent planners
- In addition, AIPS 2000 and *IPC* 2002 included configurable planners
- The configurable planners
  - Solved the most problems
  - Solved them the fastest
  - Usually found better solutions
  - Worked in many non-classical planning domains that were beyond the scope of the domain-independent planners

But Wait …

- The 2004 International Planning Competition contained ***no*** configurable planners.
  - Why not?

But Wait …

- The 2004 International Planning Competition contained ***no*** configurable planners.
  - Why not?
- Hard to enter them in the competition
  - Must write all the domain knowledge yourself
  - Too much trouble except to make a point
  - The authors of TLPlan, TALplanner, and SHOP2 felt they had already made their point
- Why not provide the domain knowledge?
  - Drew McDermott proposed this at *ICAPS-05*
  - There was a surprising amount of resistance
  - Cultural bias against the idea

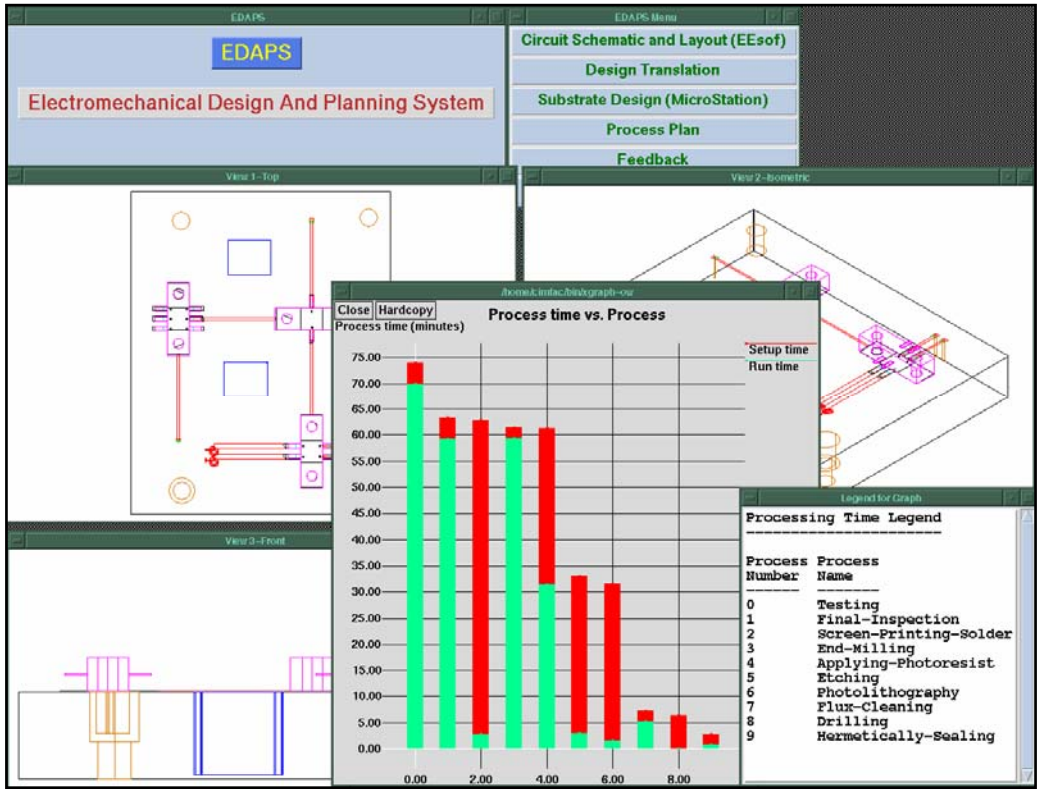
Cultural Bias

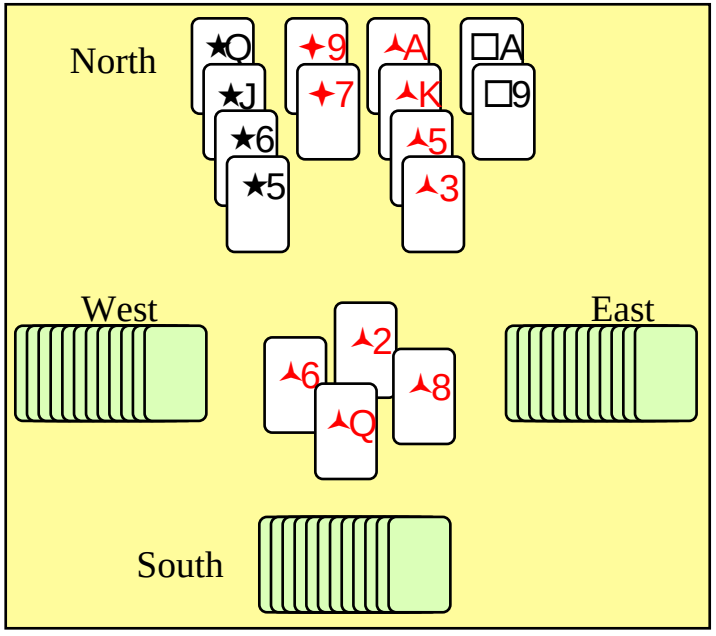
- Most automated-planning researchers feel that using domain knowledge is “cheating”
- Researchers in other fields have trouble comprehending this
  - Operations research, control theory, engineering, …
  - Why would anyone *not* want to use the knowledge they have about a problem they’re trying to solve?
- In the past, the bias has been very useful
  - Without it, automated planning wouldn’t have grown into a separate field from its potential application areas
- But it’s not useful any more
  - The field has matured
  - The bias is too restrictive

What are classical planners bad at?

Example

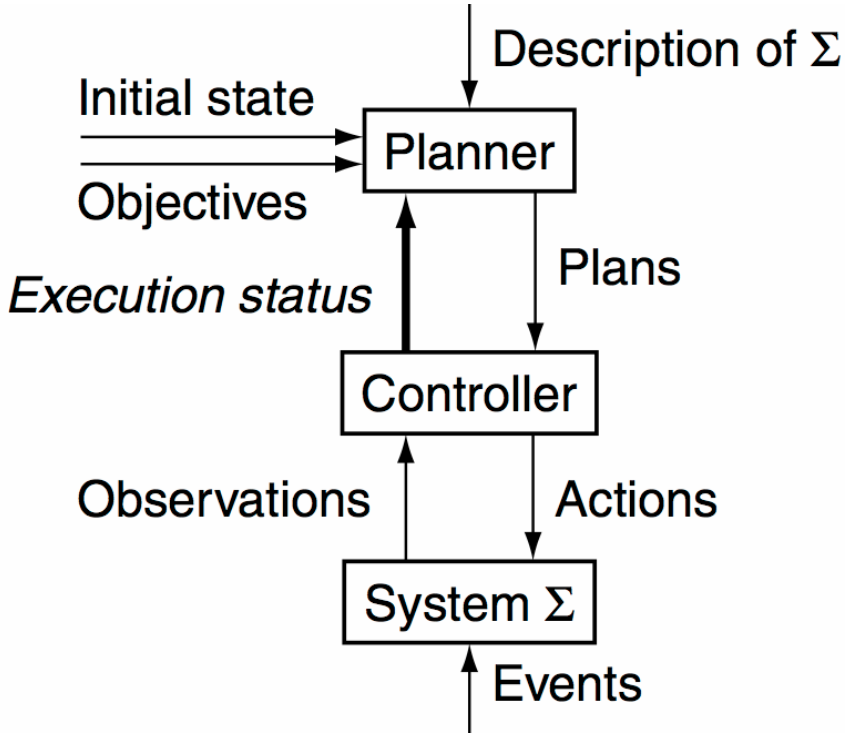
- Typical characteristics of application domains
  - Dynamic world
  - Multiple agents
  - Imperfect/uncertain info
  - External info sources
    - » users, sensors, databases
  - Durations, time constraints, asynchronous actions
  - Numeric computations
    - » geometry, probability, etc.
- Classical planning excludes all of these





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)
  - Without probabilities:
    - » Nondeterministic transition systems



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

S = {states}

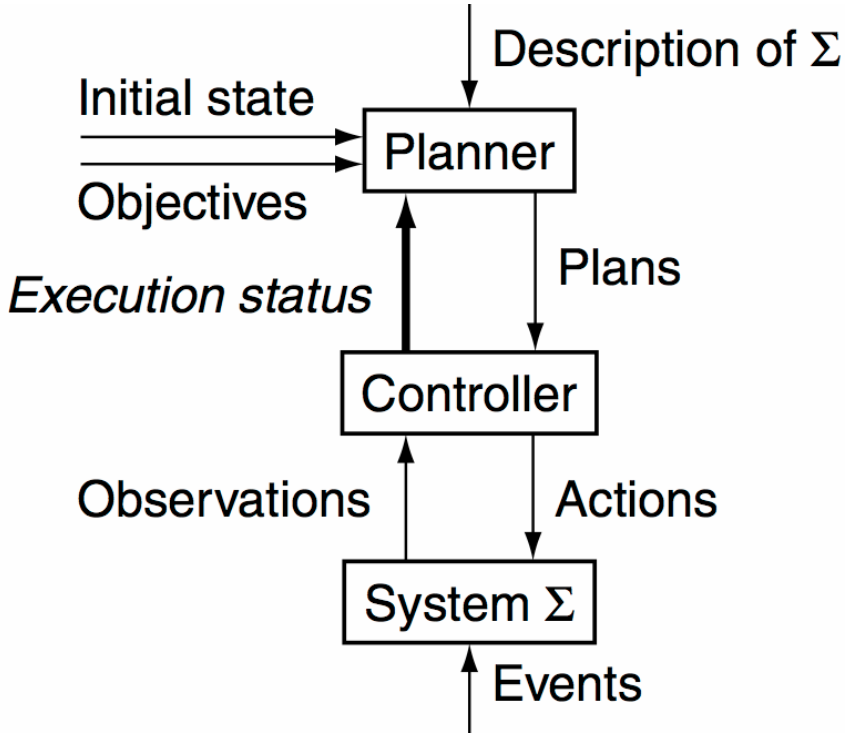
A = {actions}

E = {events}

$\gamma: S \times (A \cup E) \rightarrow 2^S$

Relax the Assumptions

- Relax A1 and A2:
  - Finite POMDPs
    - » Plan over *belief states*
    - » Exponential time & space
- Relax A0 and A2:
  - Continuous or hybrid MDPs
    - » Control theory
- Relax A0, A1, and A2
  - Continuous or hybrid POMDPs
    - » Robotics



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

S = {states}

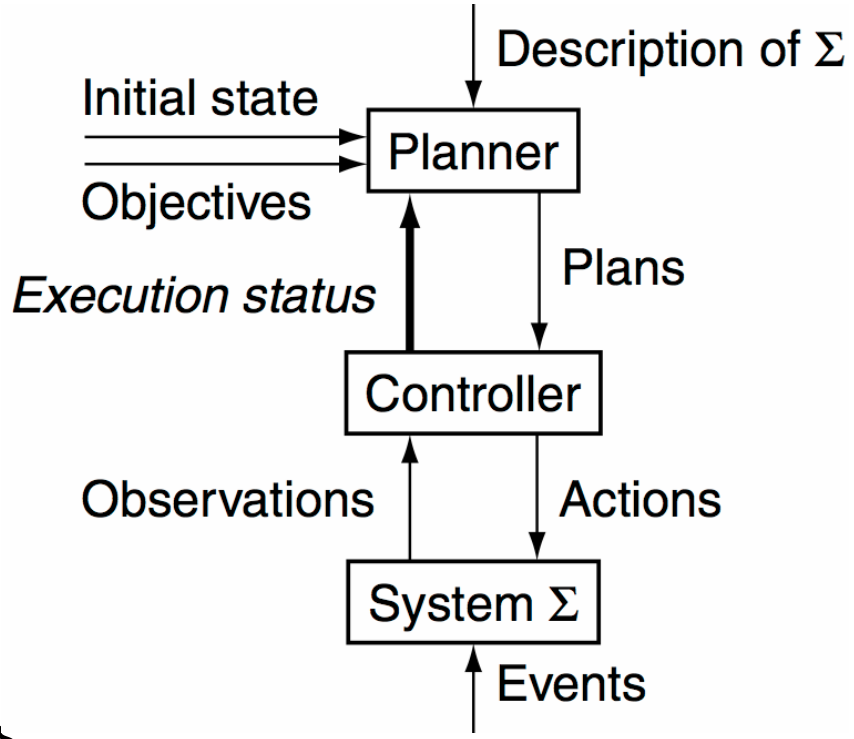
A = {actions}

E = {events}

$\gamma: S \times (A \cup E) \rightarrow 2^S$

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)



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

S = {states}

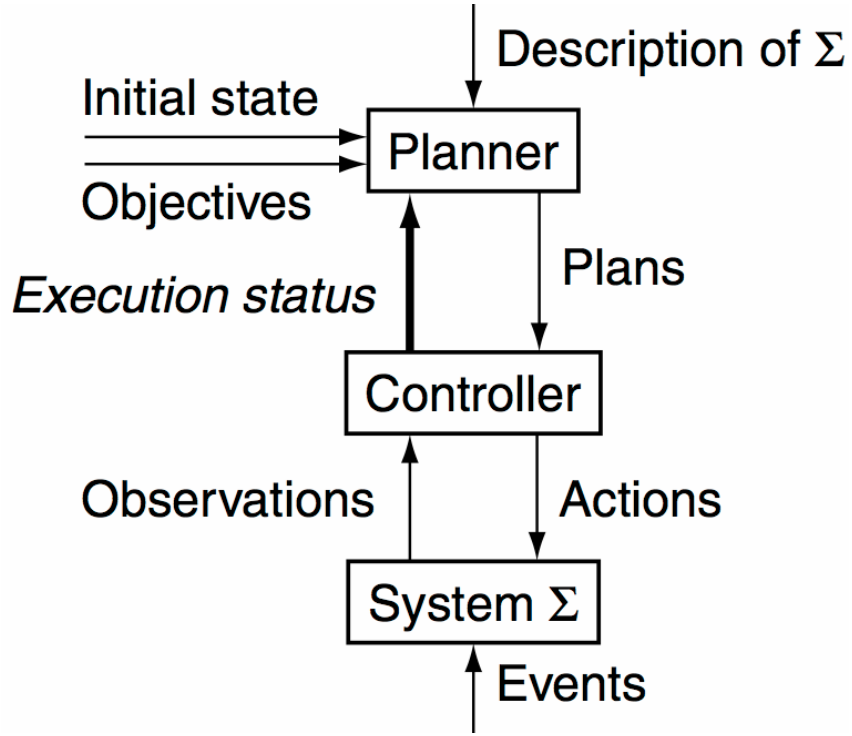
A = {actions}

E = {events}

$\gamma: S \times (A \cup E) \rightarrow 2^S$

Relax the Assumptions

- Relax A5 (sequential plans) and A6 (implicit time):
  - Temporal planning
- Relax A0, A5, A5
  - Planning and resource scheduling



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