CSC2542
Introduction to Planning

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Fall 2010

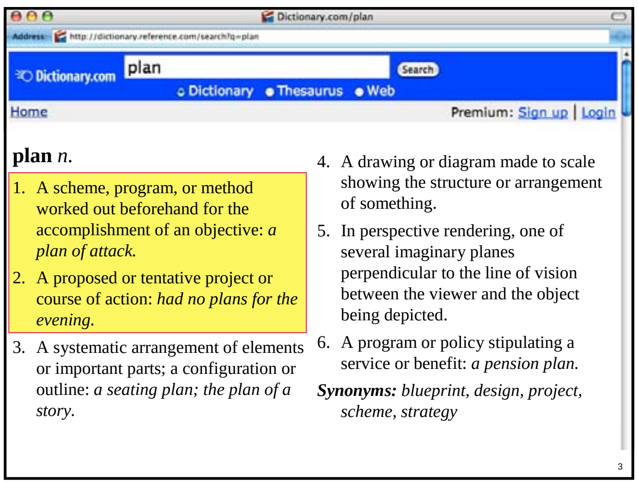
Acknowledgements

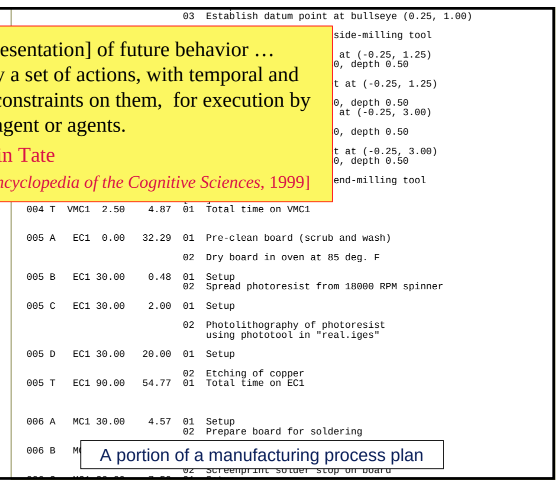
Some of the slides used in this course are modifications of Dana Nau's lecture slides for the textbook *Automated Planning,* licensed under the Creative Commons Attribution-NonCommercial-ShareAlike License: http://creativecommons.org/licenses/by-nc-sa/2.0/

Other slides are modifications of slides developed by Malte Helmert, Bernhard Nebel, and Jussi Rintanen.

I have also used some material prepared by P@trick Haslum.

I would like to gratefully acknowledge the contributions of these researchers, and thank them for generously permitting me to use aspects of their presentation material.





> [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]

A portion of a manufacturing process plan

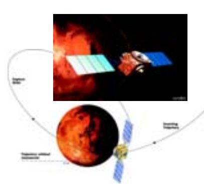
Modes of Planning

- Mixed Initiative Planning
- Automated Plan Generation

Example Planning Applications

Autonomous Agents for Space Exploration

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



Other Autonomous Systems

Not necessarily embodied!

Other Autonomous Systems:

Not necessarily embodied! →

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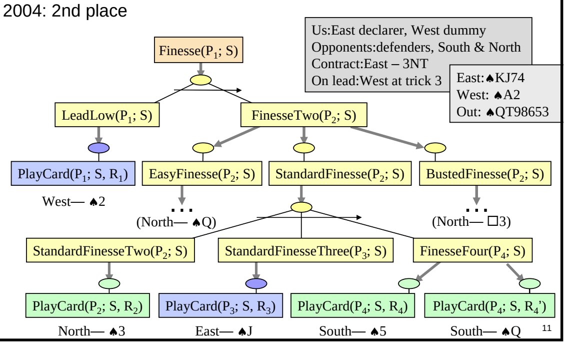
Manufacturing Automation

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

Games

E.g., *Bridge Baron* - Great Game Products

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



Other Applications

- Scheduling with Action Choices & Resource Requirements
  - Problems in supply chain management
  - HSTS (Hubble Space Telescope scheduler)
  - Workflow management
- Air Traffic Control
  - Route aircraft between runways and terminals. Crafts must be kept safely separated. Safe distance depends on craft and mode of transport. Minimize taxi and wait time.
- Character Animation
  - Generate step-by-step character behaviour from high-level spec
- Plan-based Interfaces
  - E.g. NLP to database interfaces
  - Plan recognition

Other Applications (cont.)

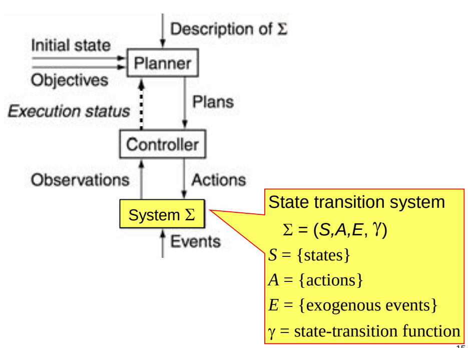
- Web Service Composition
  - Compose web services, and monitor their execution
  - Many of the web standards have a lot of connections to action representation languages
    - BPEL; BPEL-4WS allow workflow specifications
    - DAML-S allows process specifications
- Business Process Composition /Workflow Management
  - Including Grid Services/Scientific Workflow Management
- Genome Rearrangement
  - The relationship between different organisms can be measured by the number of “evolution events” (rearrangements) that separate their genomes
  - Find shortest (or most likely) sequence of rearrangements between a pair of genomes

Outline

- ➔ Conceptual model for planning
- Classes of planning problems
- Classes of planners and example instances
- Beyond planning
- Planning research – the big picture
- Some of what I hope you’ll get from the course

Conceptual Model

1. Environment

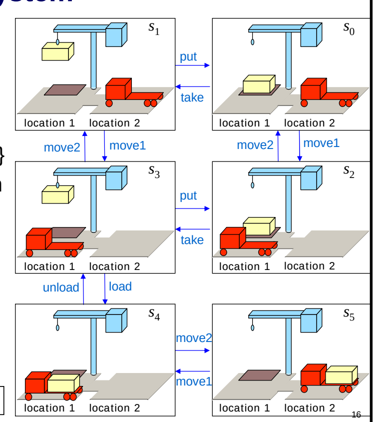


State Transition System

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

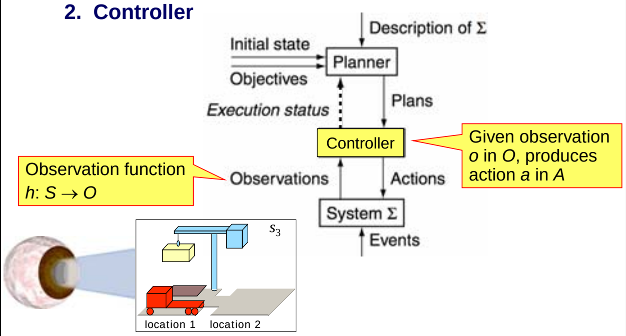
- S = {states}
- A = {actions}
- E = {exogenous events}
- State-transition function
  $\gamma : S \times (A \cup E) \rightarrow 2^S$
  - $S = \{s_0, \ldots, s_5\}$
  - A = {move1, move2, put, take, load, unload}
  - $E = \{\}$
  - γ: see the arrows

Dock Worker Robots (DWR):



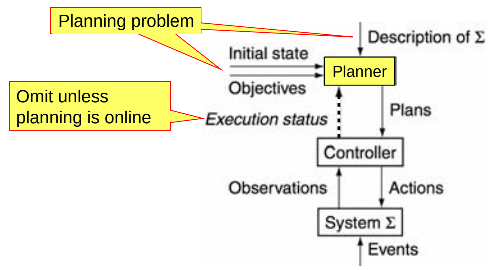
Conceptual Model

2. Controller



Conceptual Model

3. Planner's Input



Planning Problem

$\boldsymbol{P} = (\Sigma, s_0, G)$

Σ: System Description

s_0: Initial state(s)

E.g., Initial state = s_0

G: Objective

Goal state,

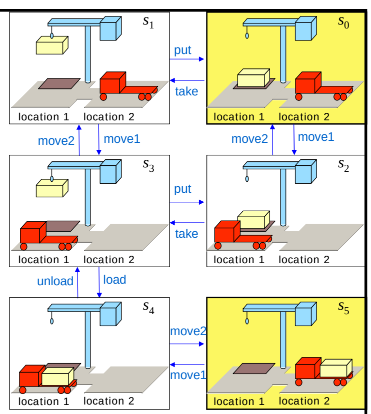
Set of goal states,

Set of tasks,

"trajectory" of states,

Objective function, …

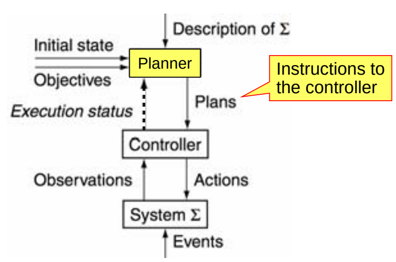
E.g., Goal state = s_5



The Dock Worker Robots (DWR) domain

Conceptual Model

4. Planner's Output



Plans

Classical plan:

a sequence of actions

E.g.,

⟨take, move1, load, move2⟩

Policy:

partial function from *S* into *A*

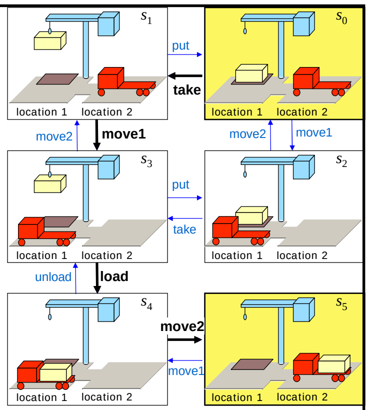
E.g.,

{(s_0, take),

(s_1, move1),

(s_3, load),

(s_4, move2)}



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Different Classes Planning Problems

Varying components of the planning problem specification yields different classes of problems. E.g.,

dynamics: deterministic, nondeterministic, probabilistic

observability: full, partial, none

horizon: finite, infinite

objective requirement: satisfying, optimizing

…

Different Classes Planning Problems

dynamics: **deterministic**, nondeterministic, probabilistic

observability: full, partial, **none**

horizon: **finite**, infinite

objective requirement: **satisfying**, optimizing

…

- **classical planning**
- conditional planning with full observability
- conditional planning with partial observability
- conformant planning
- markov decision processes (MDP)
- partial observable MDP (POMDP)
- preference-based/over-subscription planning

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Other Dimensions

dynamics: deterministic, nondeterministic, probabilistic
: explicit time, implicit time
: instantaneous, durative
: continuous, discrete, hybrid
perception: perfect, noisy
horizon: finite, infinite
objective requirement: satisfying, optimizing
objective form: final-state goal, temporally-extended goal, control knowledge, hierarchical task network (HTN), script/program (Golog)
plan form: sequential plan, partial order plan, controller, generalized plan, program…
…

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Why is Planning Difficult?

- solutions to classical planning problems are paths from an initial state to a goal state in the transition graph
  - Efficiently solvable by Dijkstra's algorithm in $O(|V| \log |V| + |E|)$ time
  - Why don't we solve all planning problems this way?
- state space may be huge: 10^9, 10^{12}, 10^{15}, …states
- constructing the transition graph is infeasible!
- planning algorithms try to avoid constructing whole graph
- planning algorithms often are – but not guaranteed to be more effiencient that obvious solution methods constructing the transition graph and using e.g., Dijkstra's algorithm

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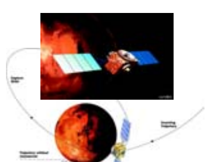
Three Main Classes of Planners

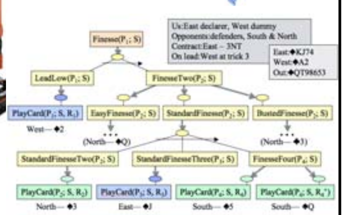
1. Domain-specific
2. Domain-independent
3. Domain-customizable

** Ghallab, Nau, and Traverso's use "configurable" (which I don't like)*
Also called "Domain-specific" or "Knowledge-Based"

1. Domain-Specific Planners

- Made or tuned for specific domain
- Won't work well (if at all) in any other domain
- Many successful real-world planning systems work this way





2. Domain-Independent Planners

- In principle, a domain-independent planner works in any planning domain
- Uses no domain-specific knowledge except the definitions of the basic actions

2. Domain-Independent Planners

- 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

Very active area of research. Many excellent planning systems.

Restrictive Assumptions

- **A0: Finite system:**
  - finitely many states, actions, events
- **A1: Fully observable:**
  - the controller always knows the system's current state
- **A2: Deterministic:**
  - each action has only one outcome
- **A3: Static** (no exogenous events):
  - changes only occur as the result of 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:**
  - Actions are instantaneous (have no duration)
- **A7: Off-line planning:**
  - planner doesn't know the execution status

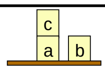
Classical Planning

- 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, 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 $G$is in s_n.
- This is just path-searching in a graph
  - Nodes = states
  - Edges = actions
- ***Is this trivial?***

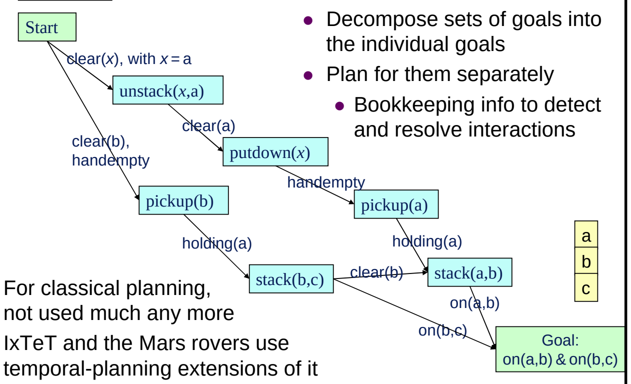
Classical Planning (cont.)

It's hard because problems are huge!

- Generalize the earlier example:
  - 5 locations, 3 robot carts, 100 containers, 3 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 larger!
- Automated planning research has been heavily dominated by domain-independent classical planning
  - Dozens of different algorithms
  - We'll cover the state-of-the-art in this area



Approach: Plan-Space Planning



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

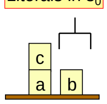
For classical planning, not used much any more

IxTeT and the Mars rovers use temporal-planning extensions of it

Approach: Planning Graphs

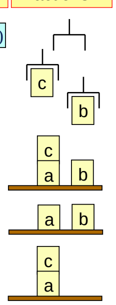
- Relaxed problem [Blum & Furst, 1995]
- Apply all applicable actions at once
- Next "level" contains all the effects of all of those actions

Level 0 — Literals in s_0



Level 1 — All actions applicable to s_0 | All effects of those actions

unstack(c,a)
pickup(b)
no-op



Level 2 — All actions applicable to subsets of Level 1 | All effects of those actions

unstack(c,a)
pickup(b)
pickup(a)
stack(b,c)
stack(b,a)
putdown(b)
stack(c,b)
stack(c,a)
putdown(c)
no-op

• • •

E.g., Graphplan

- For n = 1, 2, …
  - Make planning graph of n levels (*polynomial time*)
  - State-space search *within the planning graph*
- Such a plan graph is used in many SAT and heuristic search planners

Approach: Heuristic Search

- Can we do an A*-style heuristic search?
- Historically, it was difficult to find a good h function
  - 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 (FF) [Hoffmann], Fast Downward [Helmert], LAMA [Richter], etc.

Approach: Translation to General Problem Solver

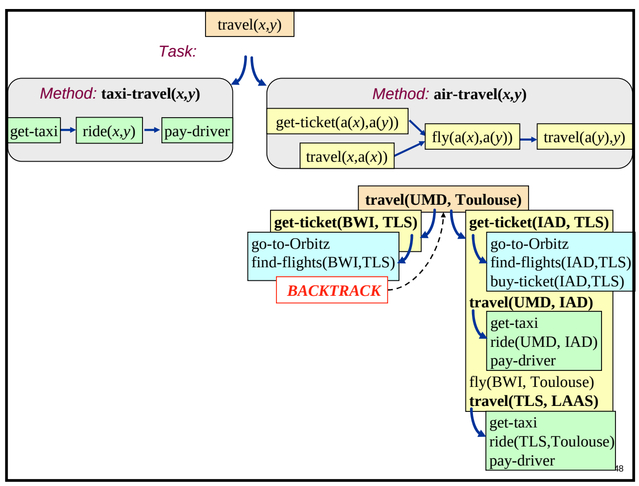
- Translate the planning problem or the planning graph into another kind of problem for which there are efficient solvers
  - Find a solution to that problem
  - Extract the plan from the solution
- SAT solvers
  - SATplan and Blackbox [Kautz & Selman]
- Answer Set Programming (ASP) solvers
  - [Son *et al.*], [Lifschitz *et al.*], etc.
- Integer programming solvers such as Cplex
  - [Vossen *et al.*]

3. Domain-customizable

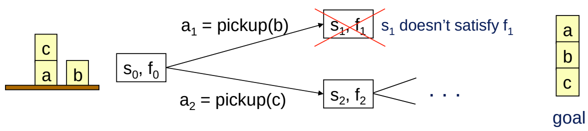
- Domain-independent planners are quite slow compared with domain-specific planners
  - Blocks world in linear time [Slaney and Thiébaux, *A.I.*, 2001]
  - Can get analogous results in many other domains
- But don't want to write a new planner for every domain!
- **Domain-customizable planners**
  - Domain-independent planning engine
  - Input (the "objective") includes info about how to solve problems in the domain.
    - Hierarchical Task Network (HTN) planning
    - Planning with control formulas
    - Planning with a plan script or agent program

Approach: 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



Approach: Planning with Control Formulas



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

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

"never pick up *x* from table unless *x* needs to be on another block"

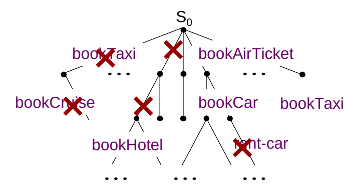
- For each successor of *s*, derive a control formula using *logical progression*
- Prune any successor state in which the progressed formula is false
  - TLPlan [Bacchus & Kabanza]
  - TALplanner [Kvarnstrom & Doherty]

Approach: Planning w/ Program or Plan Script

E.g., **Golog** [Levesque et al.]
Nondeterministic programs that act as procedural control knowledge, placing constraints on the valid action sequence/plans

E.g., *bookAirTicket(x);* if *far* then *bookCar(x)* else *bookTaxi(y)*

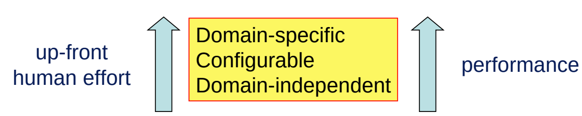
procedural constructs:
- sequence
- if-then-else
- nondeterministic choice
- while-do, etc.



Three Main Classes of Planners

1. Domain-specific
2. Domain-independent
   E.g.,
   Planning graph-based, SAT-based, heuristic search
3. Domain-customizable
   E.g.,
   HTN, domain control formula, agent programs/scripts

Comparisons (in general)



- 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
  - Can be less efficient (but not always)!

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Broad Application of Planning Techniques

Planning algorithms are applicable to a broad range of applications that can roughly be viewed as reachability problems. E.g.,

- Software verification
- Diagnosis of dynamical systems
- Story understanding
- Situation assessment/Plan recognition
- Gene rearrangement

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Planning Research – The big picture

Two research communities that make fundamental contributions to research in planning:

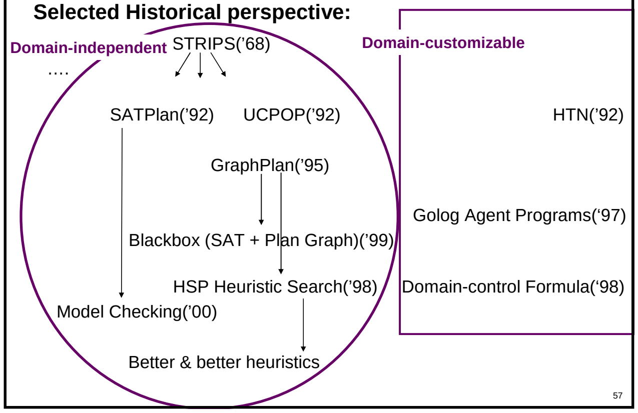
1) Knowledge Representation and Reasoning Community
   - mathematical foundations of planning
   - knowledge representation, formal properties, etc.

2) Automated Planning and Scheduling Community
   - Driven largely by the objective of developing fast and effective planning algorithms

We will look at research from both communities.

Planning Algorithms – Recent Advances

Selected Historical perspective:



Planning Research – The big picture

The Landscape:

CONFERENCES

ICAPS* (Int. Conf on AI Planning and Scheduling)
*merging of AIPS and ECP
AAMAS (Int. Conf. on Autonomous Agents and Multiagent Systems)
KR
IJCAI, AAAI, ECAI

JOURNALS

JAIR, AIJ

BIENNIAL COMPETITION and BENCHMARKING DOMAINS

IPC-*n* (International Planning Competition)
PDDL (Planning Domain Definition Language)
standard input language for most benchmark problem sets

Planning Research – The big picture

Recent Advances

Very "active" field -- lots of papers in top conferences

- Tremendous strides in deterministic plan synthesis
  - Biennial Intl. Planning Competitions
- Current interest is in exploiting the insights from deterministic planning techniques to other planning scenarios

Some topics of recent focus:

- Better heuristics
- Richer domain customization (including preferences)
- From discrete to timed hybrid and/or continuous systems
- Planning and learning

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What will you get from this course?

- big picture of different kinds of planning problems
- logical foundations of planning
- algorithms for solving different problem classes, with an emphasis on the classical ("simplest") setting:
  - algorithms based on heuristic search
  - algorithms based on SAT
  - algorithms that exploit rich objectives (domain control knowledge, temporally extended goals, preferences)
- many of these techniques are applicable to problems outside AI as well
- hands-on experience with a classical planner (optional)

For Next Week (Sept 23)

Skim/review Chapters 1, 2, and 4, 5 in the reference textbook.

(The URL is posted on our course web page.)

Important Announcement

- ✓ Please add your name to the list that is circulating
- ✓ We may change classrooms (though perhaps not imminently). Watch the web announcements.
- ✓ From time to time we will need to have a tutorial (especially for the assignment). There will be a doodle poll regarding scheduling of the tutorial. I'll schedule the tutorial hour at a time when all registered students can attend.