CogSysI Lecture 2: Representations for Classical Planning

Intelligent Agents

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Slides are based on the lecture slides of Dana Nau

last change: April 29, 2008

Intuitions on Planning

- Intelligent Agents: Natural or artificial systems which act in an intelligent way
- Intelligent action is rational action, that is, the best possible action in a given situation
- Planning is the reasoning side of acting
- Abstract, explicit deliberation process that chooses and organizes actions by anticipating their expected outcomes
- Some actions require planning, many do not
  - we act more frequently than we explicitly plan
  - performing well-trained behaviors for which we have pre-stored plans
  - acting and adapting in flexible settings

Intuitions on Planning

- Planning is a complicated, time consuming, and costly process
- Planning is needed when
  - new situations, unfamiliar actions are involved
  - complex tasks, complex objectives are addressed
  - actions are constrained by high risks, high costs, joint activities, need for synchronization
- Typically we seek feasible, good plans, not optimal plans (cf. Simon's "bounded rationality")

Motivations for Automated Planning

- Practical
  - Designing information processing tools that give access to affordable and efficient planning resources
  - Some professionals face complex changing tasks that involve demanding safety and/or efficiency requirements
  - Example: disaster rescue operations
    large number of actors, deployment of communication and transportation infrastructure, time constrained, demands for immediate decisions relies on careful planning and assessment of several alternate plans
  - Example: organizers of social meetings

Motivations for Automated Planning cont.

- Theoretical
  - Planning is an important component of rational behavior
  - Purpose of AI: grasping computational aspects of intelligence
  - planning, as the reasoning side of acting, is a key element
  - Studying planning as abstract process (complexity, efficiency of algorithms, ...)
  - Planning as integrated component of deliberative behavior

Motivations for Automated Planning cont.

- Hot topic: study and design of autonomous intelligent machines
  - satellites, spacecrafts, roboters cannot always be teleoperated
  - interaction with nonexpert humans on task level rather than control signals
  - machines that can sense and act as well as reason on their actions

Automated Planning

- Plan: Sequence of actions to achieve a goal
- Planning: Computation of such a sequence
- Examples of succesful applications
  - Space Exploration
  - Manufacturing
  - Games

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Space Exploration

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

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Manufacturing

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

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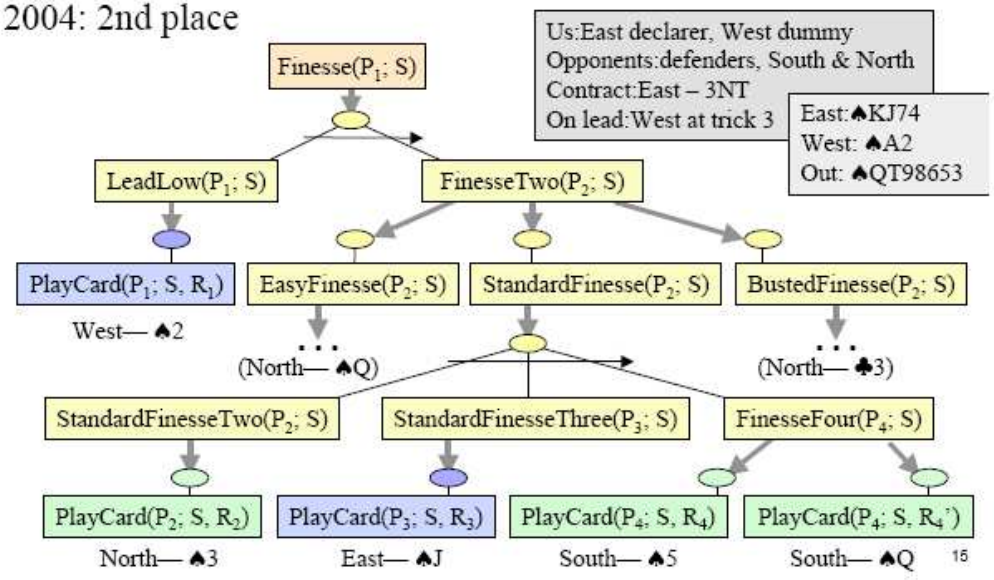
Games

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



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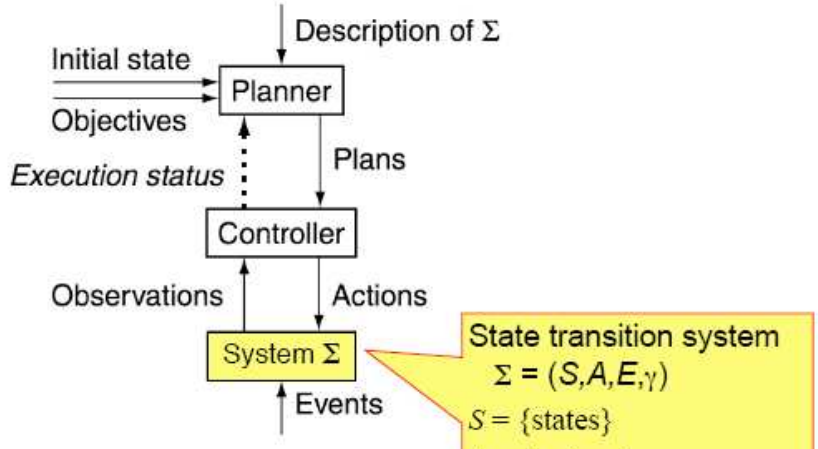
Conceptual Model
1. Environment



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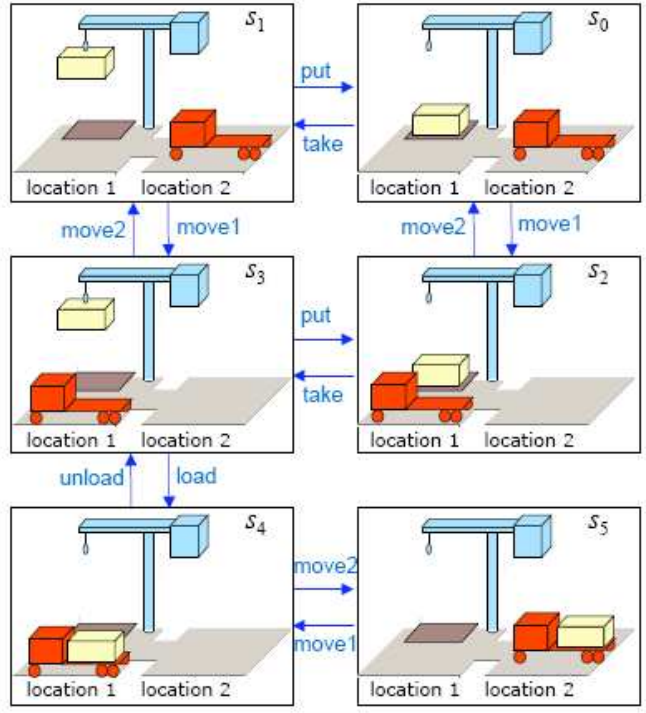
State Transition System

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

- 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

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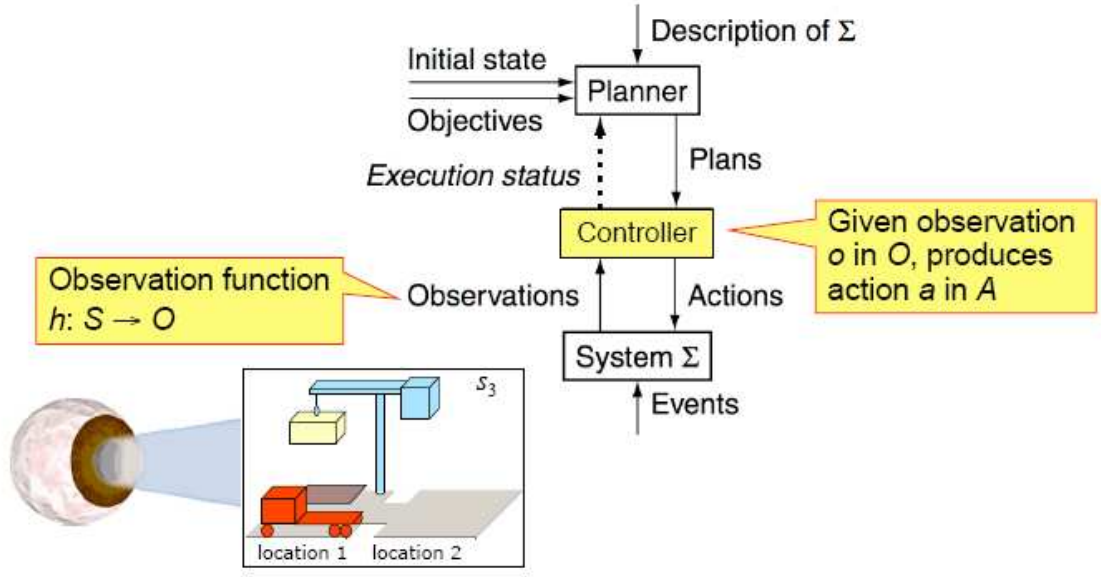
Conceptual Model
2. Controller



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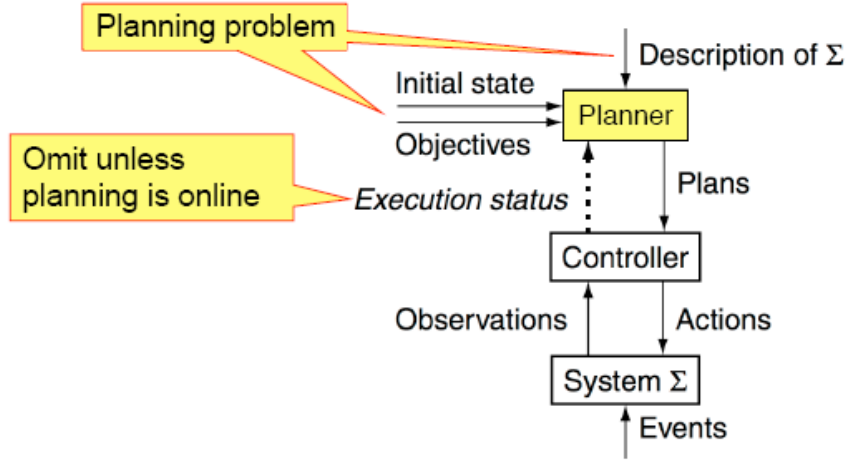
Conceptual Model
3. Planner's Input



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Planning Problem

Description of Σ

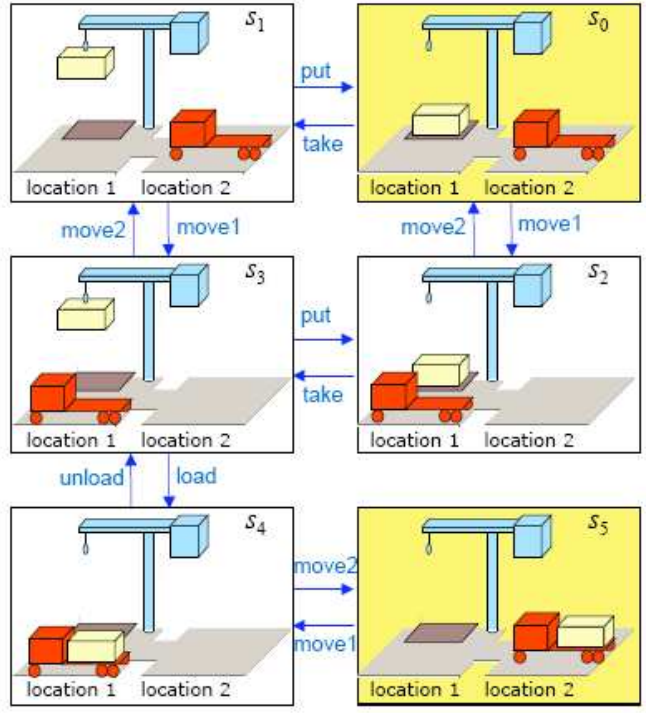
Initial state or set of states

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

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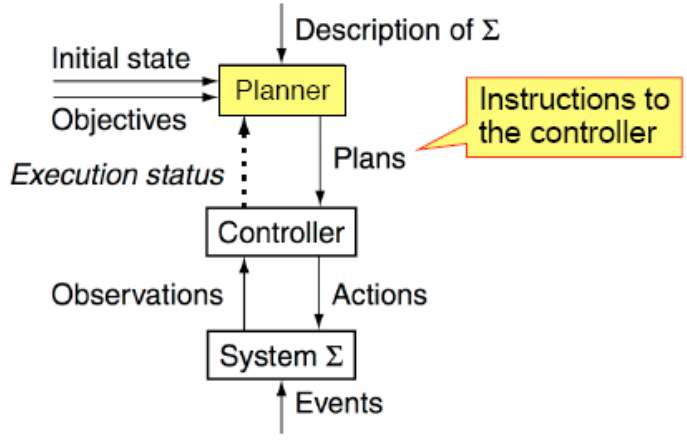
Conceptual Model
4. Planner's Output



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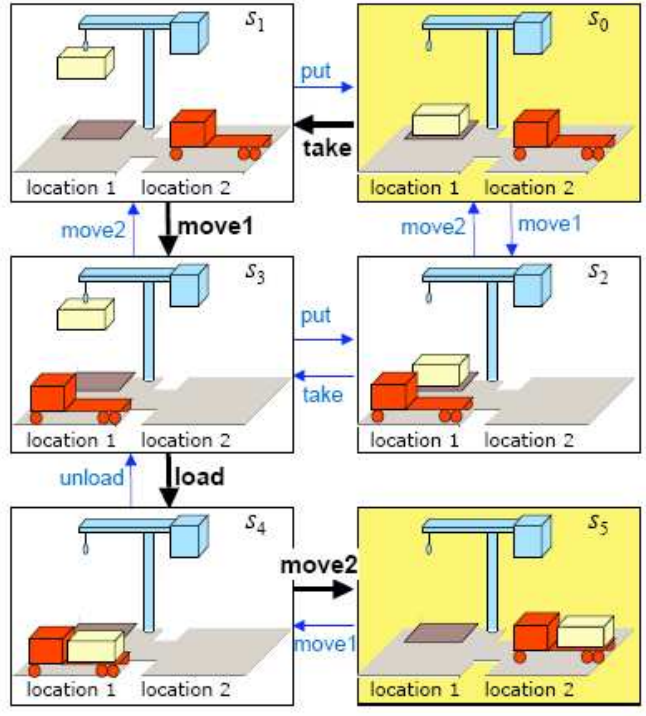
Plans

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

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Planning, Problem Solving, Scheduling

- Problem solving: using domain-specific heuristics to search for a (optimal) sequence of actions
- Scheduling: decide when and how to perform a given set of actions obeying time constraints, resource constraints, objective functions
- Planning: decide what actions to use in what sequence to achieve some set of objectives
  biggest algorithmical challenge: often worse than NP-complete, worst case is undecidable (see lecture about complexity of classical planning)

Domain-Independent Planning

- In principle, a domain-independent planner works in any planning domain
- Uses no domain-specific knowledge except the definition of the basic actions
- In practice, it is not feasible to develop a planner that works in every possible domain
- Make simplifying assumptions to restrict the set of domains: mostly classical planning
- Domain-specific planners can be very successful in specific domains but one needs to write an entire program (lots of work)

Classical Planning

- Restrictive assumptions (see next slide): finite set of states and actions; fully observable states; deterministic outcome of actions, ...
- Reduces to the problem of path searching in a graph with nodes as states and edges as actions (which is still hard enough):
  - Generalize the earlier example to 5 locations, 3 robot carts, 100 containers, 3 piles: 10^{277} states
  - Number of particles in the universe is about 10^{87}
- Most research is on classical planning with many different algorithms
- Planning Competition (AIPS 1998, AIPS 2000, IPC 2002, ...) shows the progress every two years

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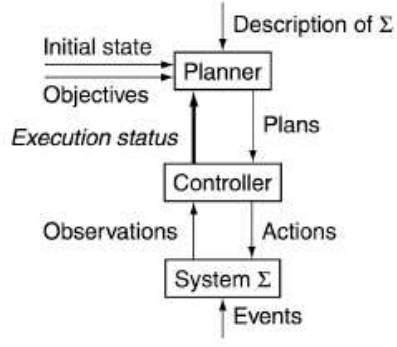
Restrictive Assumptions

- **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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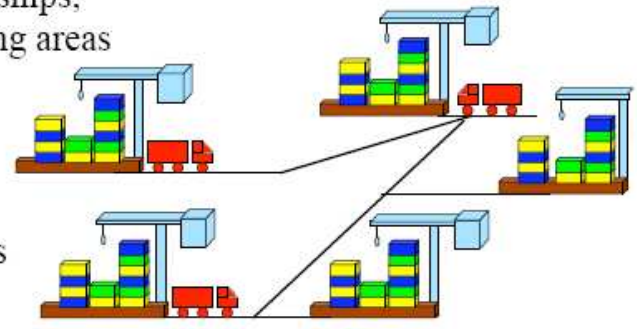
A running example: Dock Worker Robots

- 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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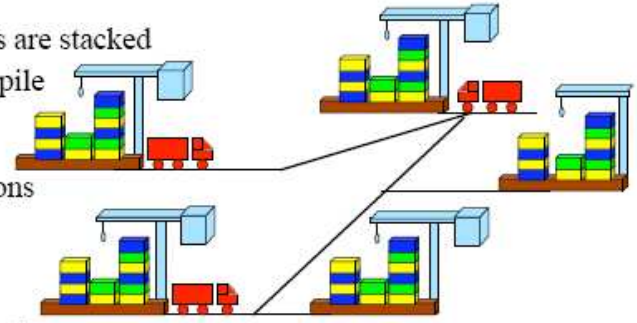
A running example: Dock Worker Robots

- **Locations**: l1, l2, …
- **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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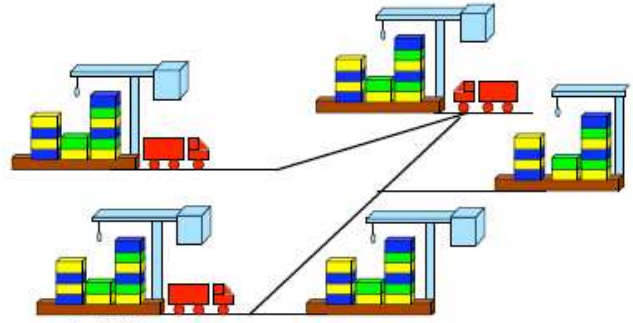
A running example: Dock Worker Robots

- 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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Representations for Classical Planning

- See slides from Dana Nau, chapter02.pdf
- Supplementary information (next slides)
  - Syntax of First Order Logic
  - Closed World Assumption
  - Extended Classical Representation
  - PDDL

Syntax of FOL/Terms

Inductive definition:

- Terms:
  - A variable $v \in V$ is a term.
  - If f is a function symbol with arity n and $t_1 \ldots t_n$ are terms, then $f(t_1, \ldots, t_n)$ is a term. (including constant symbols as 0-ary function symbols)
  - That are all terms.

Syntax of FOL/Formulas

Inductive definition:

- Formulas:
  - if P is a predicate symbol with arity n and $t_1 \ldots t_n$ are terms, then $P(t_1, \ldots, t_n)$ is a formula. (atomic formula)
  - For all formulas F and G, $\neg F$, $F \wedge G$, $F \vee G$, $F \rightarrow G$ and $F \leftrightarrow G$ are formula. (connectives *"not"*, *"and"*, *"or"*, *"implies"*, *"equivalent"*)
  - If v is a variable and F is a formula, then $\exists v\ F$ and $\forall v\ F$ are formulas. (existential and universal quantifier, *"exists"*, *"for all"*)
  - That are all formulas.

Remarks on Syntax of FOL

- Formula are constructed over terms.
  Never confuse this categories!
- Additionally, parentheses can be used to group sub-expressions.
- Expressions which obey the given inductive definition are called well-formed formulas (wwfs).
  The closure “that are all terms/formulas” is necessary to exclude all other kinds of (not well-formed) expressions.
- We refer to atomic formulas also as “atoms”. Positive and negated atoms (P, $\neg P$) are called positive/negative literals.

Remarks on Syntax of FOL cont.

- A variable which is in the scope of a quantor is called bound, otherwise it is is called free.
  $P(x) \vee \forall y \exists z \; Q(y, z)$
  x is free and y and z are bound.
  A formula without free variables is called sentence.
- Propositional logic is a special case of FOL: use only unary predicate symbols (then there are no terms, no variable and no quantors) or just forbid variables and quantors (use only grounded formulas).

Closed-World Assumption (CWA)

- An atom that is not explicitly given in a state does not hold in the state
- That is: Assumption of the value *false* for every atom which is not explictly stated
- Classical, set-theoretical and state-variable representation all rely on the CWA
- CWA is a restriction of the logic calculus: no true negation but *negation by failure*
  (If a proposition cannot be proven to be true, it is assumed to be false.)

CWA cont

- This restriction makes state-based planning more efficient than deductive planning in full FOL where the *frame problem* exists
- Frame problem: not only the propositions which change by an action must be specified but also all propositions which are not affected by an action (e.g. If I put block x from block y on the table, *on(y,z) still holds)*

Extended Representation

- Typed variables and relations
- Conditional Operators
- Quantified Expressions
- Equality Constraints
- Disjunctive Preconditions
- Function Symbols
- Axiomatic Inference
- Attached Procedures

PDDL

- Problem Domain Definition Language as common language for most modern planners (see PDDL Specification)
- Example: Equality constraints and conditioned effects

```
(define (domain blocksworld-adl)
(:requirements :strips :equality :conditional-effects)
(:predicates (on ?x ?y)
             (clear ?x)) ; clear(Table) is static
(:action puton
:parameters (?x ?y ?z)
:precondition (and (on ?x ?z) (clear ?x) (clear ?y)
                                (not  (= ?y ?z)) (not (= ?x ?z))
                                  (not (= ?x ?y)) (not (= ?x Table)))
:effect
               (and (on ?x ?y) (not (on ?x ?z))
                    (when (not (eq ?z Table)) (clear ?z))
                    (when (not (eq ?y Table)) (not (clear ?y)))))
)
```