

Lecture 10: Logical Agents and Planning

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Plan of today's lecture

- 1 Logic in AI in the past and now
- 2 Logical problem representations
- 3 Situation calculus
- 4 Intelligent planning

└ Plan of today's lecture

- Logic in AI in the past and now
- Logical problem representations
- Situation calculus
- Intelligent planning

Example of use of logic in a realistic system - slow, but does the job. Potentially useful for getting guarantees in AI. Will there be a logic renaissance? Structured knowledge useful - e.g. automatic construction of heuristics and their study = AI planning. Very core of classical AI and potential in the future = part of ZUI

Slides are heavily based on J. Klema's slides. For more details on logical agents see his [video](#) from the last year.

There has been a big hype of logical agents in 60s and 70s.

- + It can represent knowledge about the world
- + It can represent intelligent reasoning
 - It is not very convenient for working with uncertainty
 - It is usually extremely computationally expensive
(expressivity vs. completeness vs. effectivity)

Logic in AI 2020s

- Interpretable safe AI
- Relational ML/RL
- Theorem proving
- Model checking
- Knowledge graphs
- Automated planning

└ Logics in AI

There has been a big hype of logical agents in 60s and 70s.

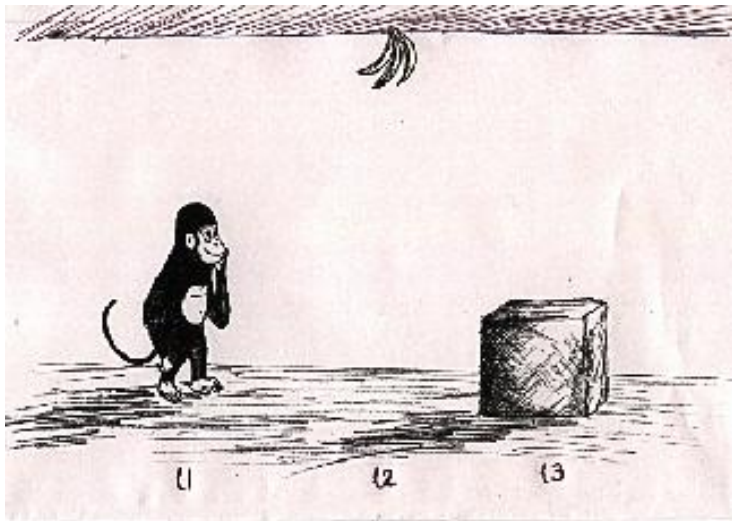
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Logic in AI 2020s

- Interpretable safe AI
- Relational ML/RL
- Theorem proving
- Model checking
- Knowledge graphs
- Automated planning

It is not mainstream at the moment, but clearly belongs to ZUI

Motivation example – monkey and banana



Vladimir Lifschitz: Planning course, The University of Texas at Austin.

2024-04-30

Introduction to Artificial Intelligence

└ Motivation example – monkey and banana



Explain how would it be represented so far. And in CSP?

Problem description

- a monkey is in a room, a banana hangs from the ceiling,
- the banana is beyond the monkey's reach,
- the monkey is able to walk, move and climb objects, grasp banana,
- the room is just the right height so that the monkey can move a box, climb it and grasp the banana,
- the goal is to generate this plan (sequence of actions) automatically.

Key characteristics

- a deterministic task
- a general description available
 - all the necessary knowledge is provided
 - we need to **represent it** in some **language**
 - and perform certain **reasoning / inference**
- a planning task

Remember B0B01LGR: Logic and Graphs

Jazyk

Jazyk predikátové logiky obsahuje tyto symboly:

1 logické symboly

- proměnné; Var je množina všech proměnných
- logické spojky: $\neg, \wedge, \vee, \Rightarrow, \Leftrightarrow$, popř. též $\text{tt}, \text{ff}, |, \downarrow, \oplus$
- kvantifikátory \forall (obecný) a \exists (existenční)
- symbol rovnosti: $=$

2 speciální symboly

- predikátové, kde každý má svou aritu $n \geq 0$;
Pred je množina predikátových symbolů
- funkční, kde každý má svou aritu $n > 0$;
Func je množina funkčních symbolů
- konstantní; Kons je množina konstantních symbolů

3 pomocné symboly, jako jsou závorky (,) a čárka ,

The following slides would, in principle, work with stronger logic!
Modal Logic, epistemic logic, temporal logic, ATL

Language \rightarrow First Order (Predicate) Logic (FOL)

Remember B0B01LGR: Logic and Graphs

First order logic

The language of first order predicate logic includes:

- logical symbols
 - variables: $\{a, b, c\} \subset Var$
 - logical operators: $\neg, \wedge, \vee, \rightarrow, \leftrightarrow$
 - quantifiers: \forall, \exists
 - equality operator: $=$
- special symbols
 - predicates (with a fixed arity $n \geq 0$)
 - functions (with a fixed arity $n > 0$)
 - constants
- auxiliary symbols, such as brackets () and comma ,

The following slides would, in principle, work with stronger logic!
Modal Logic, epistemic logic, temporal logic, ATL

Situation calculus is one way to represent changing world in FOL

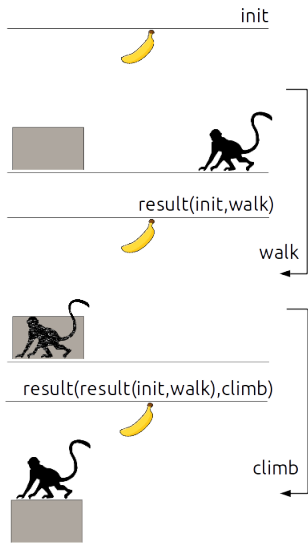
- facts hold in particular situations (\approx world state histories)
- predicates either rigid (eternal) or fluent (changing)
- fluent predicates include a situation argument
e.g., *agent(monkey, at_ban, now)*, term *now* denotes a situation
- rigid predicates hold regardless of a situation
e.g., *walks(monkey)*, *moveable(box)*
- situations are connected by the *result* function
if *s* is a situation than *result(s, a)* is also a situation

The monkey problem state can be represented using two predicates

- *agent(agent name, agent position, stands on, situation)*
- *object(object name, object position, who stands, situation)*

Keeping track of evolving situations

agent(agent name, agent position, stands on, situation)
object(object name, object position, who stands, situation)



`agent(monkey, right, ground, init).`
`object(box, left, none, init).`

`agent(monkey, left, ground, result(init,walk)).`
`object(box, left, none, result(init,walk)).`

`agent(monkey, left, box, result(result(init,walk),climb)).`
`object(box, left, monkey, result(result(init,walk),climb)).`

agent(agent name, agent position, stands on, situation)
object(object name, object position, who stands, situation)

Action “effect” axiom for *walk*(X, P_1, P_2):

$$\forall X, P_1, P_2, Z (agent(X, P_1, ground, Z) \wedge walks(X) \\ \rightarrow agent(X, P_2, ground, result(Z, walk(X, P_1, P_2))))$$

Action “effect” axiom for *climb*(X):

$$\forall X, P, Z (agent(X, P, ground, Z) \wedge object(box, P, none, Z) \\ \rightarrow agent(X, P, box, result(Z, climb(X))) \\ \wedge object(box, P, X, result(Z, climb(X))))$$

Action axioms describe how fluents change between situations
What happens to fluents, which are not used in the actions?
e.g., the objects while the agent walks

Frame problem: how to cope with the unchanged facts smartly

- many “frame” axioms may be necessary to express them in FOL

$$\forall X, V, W, Z, Y, P_1, P_2 \\ (object(X, V, W, Z) \rightarrow object(X, V, W, result(Z, walk(Y, P_1, P_2))))$$

- f fluent predicates and a actions require $O(f \cdot a)$ frame axioms
- many applications of axioms each step is computationally expensive
- some tricks diminish the problem, but it never goes away

FOL can be used to represent **states** and **actions**

Goal of planning: logical representation of the desired state

$$\mathcal{G} \equiv \exists Z \text{ agent}(\textit{monkey}, \textit{middle}, \textit{box}, Z)$$

Reasoning checks whether the goal formula follows from KB

$$KB \models \mathcal{G}$$

- knowledge base (KB) are the inference rules and the initial state
- reasoning finds a suitable Z or proves it does not exist
- desirable properties: **soundness, completeness, efficiency**
- reasoning procedures: **resolution**, deductive inference, etc.
 - see B0B01LGR
 - generally extremely computationally hard, possibly undecidable
 - the solution is correct, if reasoning successfully finishes
 - can be efficient and useful with **additional restrictions**

Subfield of AI dealing (mainly) with

- representation languages with reasonable tradeoffs of expressivity and efficiency
- algorithms for finding plans for problems expressed in these languages

(The following slides are heavily based on Carmel Domshlak's slides)

What is in common?

- All these problems deal with **action selection** or **control**
- Some notion of problem **state**
- (Often) specification of **initial state** and/or **goal state**
- Legal moves or **actions** that transform states into other state

For now focus on:

- **Plans** (aka **solutions**) are sequences of moves that transform the initial state into the goal state
- Intuitively, not all solutions are equally desirable

What is our task?

- 1 Find out whether there is a solution
- 2 Find any solution
- 3 Find an optimal (or near-optimal) solution
- 4 Fixed amount of time, find best solution possible
- 5 Find solution that satisfy property \aleph (what is \aleph ? you choose!)

Three Key Ingredients of Planning

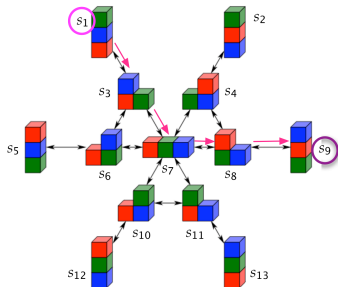
Planning is a form of **general problem solving**

Problem \implies Language \implies **Planner** \implies Solution

- 1 **models** for defining, classifying, and understanding problems
 - what is a *planning problem*
 - what is a *solution (plan)*, and
 - what is an *optimal solution*
- 2 **languages** for representing problems
- 3 **algorithms** for solving them

Why planning is difficult?

- Solutions to planning problems are **paths from an initial state to a goal state in the transition graph**
- Dijkstra's algorithm solves this problem in $O(|V| \log(|V|) + |E|)$
- Can we go home??



- Solutions to planning problems are **paths from an**

└ Why planning is difficult?

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- Can we go home??



- Solutions to planning problems are paths from an

Example with logistics with 50 trucks servicing 100 cities

What is “classical” planning?

- dynamics: **deterministic**, nondeterministic or probabilistic
 - observability: full, partial or **none**
 - horizon: **finite** or infinite
 - ...
- 1 **classical planning**
 - 2 conditional planning with full observability
 - 3 conditional planning with partial observability
 - 4 conformant planning
 - 5 Markov decision processes (MDP)
 - 6 partially observable MDPs (POMDP)

Succinct representation of transition systems

- More **compact** representation of actions than as relations is often
 - **possible** because of symmetries and other regularities,
 - **unavoidable** because the relations are too big.
- Represent different aspects of the world in terms of different **state variables**. \rightsquigarrow A state is a **valuation of state variables**.
- Represent actions in terms of changes to the state variables.

Key issue

Models represented **implicitly** in a **declarative language**

Play two roles

- **specification**: concise model description
- **computation**: reveal useful info about problem's *structure*

A problem in **STRIPS** is a tuple $\langle P, A, I, G \rangle$

- P stands for a finite set of **atoms** (boolean vars)
- $I \subseteq P$ stands for **initial situation**
- $G \subseteq P$ stands for **goal situation**
- A is a finite set of **actions** a specified via $\text{pre}(a)$, $\text{add}(a)$, and $\text{del}(a)$, all subsets of P

- States are **collections of atoms**
- An action a is applicable in a state s iff $\text{pre}(a) \subseteq s$
- Applying an applicable action a at s results in $s' = (s \setminus \text{del}(a)) \cup \text{add}(a)$

Why STRIPS is interesting?

- STRIPS operators are **particularly simple**, yet expressive enough to capture general planning problems.
- In particular, STRIPS planning is **no easier** than general planning problems.
- Many algorithms in the planning literature are **easier to present in terms of STRIPS**.

(The following example is based on Antonin Komanda's slides)

Sokoban - Example planning domain

State representation:

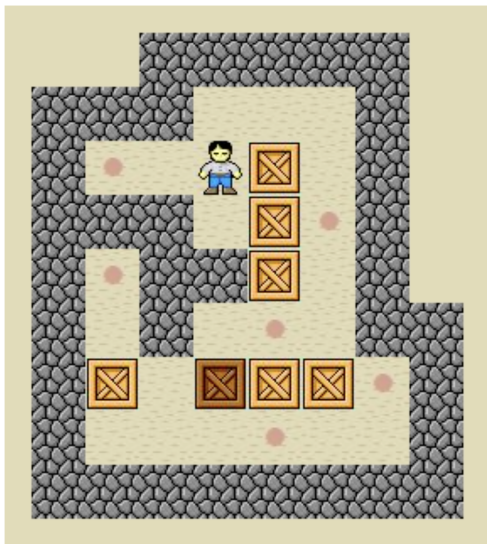
```
positions: a1, ... a6,...  
           f1, ..., f2  
box_at(P), free(P)  
player_at(P)  
adjacent(P1,P2)  
adjacent2(P1,P2)
```

Operators (Actions):

```
move(X,Y):  
  pre: player_at(X)  
       adjacent(X,Y)  
       free(Y)  
  add: player_at(Y)  
  del: player_at(X)
```

```
push(X, Y, Z):  
  pre: player_at(X)  
       box_at(Y)  
       free(Z)  
       adjacent(X,Y)  
       adjacent(Y,Z)  
       adjacent2(X,Z)
```

...



Grounding of Actions

Operators (Actions):

```
move(X,Y):
  pre: player_at(X)
      adjacent(X,Y)
      free(Y)
  add: player_at(Y)
  del: player_at(X)

push(X, Y, Z):
  pre: player_at(X)
      box_at(Y)
      free(Z)
      adjacent(X,Y)
      adjacent(Y,Z)
      adjacent2(X,Z)
  add: player_at(Y)
      box_at(Z)
      free(Y)
  del: player_at(X)
      box_at(Y)
      free(Z)
```

Grounding:

```
move_a1_a2
  pre: player_at_a1, adjacent_a1_a2, free_a2
  add: player_at_a2
  del: player_at_a1

move_a2_a3
  pre: player_at_a2, adjacent_a2_a3, free_a3
  add: player_at_a3
  del: player_at_a2

...

push_a1_a2_a3
  pre: player_at_a1, box_at_a2, free_a3
      adjacent_a1_a2, adjacent_a2_a3,
      adjacent_a1_a3
  add: player_at_a2, box_at_a3, free_a2
  del: player_at_a1, box_at_a2, free_a3

...
```

STRIPS Representation of Sokoban

A problem in **STRIPS** is a tuple $\langle P, A, I, G \rangle$

- P stands for a finite set of **atoms** (boolean vars)
- $I \subseteq P$ stands for **initial situation**
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- A is a finite set of **actions** a specified via $\text{pre}(a)$, $\text{add}(a)$, and $\text{del}(a)$, all subsets of P

$P = \{ \text{player_at_a2}, \dots, \text{player_at_d3},$
 $\text{box_at_a2}, \dots, \text{box_at_d3},$
 $\text{free_a2}, \dots, \text{free_d3},$
 $\text{adjacent_a2_b2}, \dots, \text{adjacent_d2_d3},$
 $\text{adjacent2_a2_c2}, \dots, \text{adjacent2_d1_d3} \}$

$I = \{ \text{player_at_b2}, \text{box_at_c1}, \text{box_at_c2},$
 $\text{free_a2}, \text{free_b1}, \dots, \text{free_d3},$
 $\text{adjacent_a2_b2}, \dots, \text{adjacent_d2_d3}, \text{adjacent2_a2_c2}, \dots, \text{adjacent2_d1_d3} \}$

$G = \{ \text{box_at_a2}, \text{box_at_d1} \}$



We can just use A*:

- State: a set of true atoms
- Applicable actions: based on preconditions
- Action application: add the “add” atoms and delete the “del” atoms
(No need for separate simulator implementation)

Problem structure allows **automated** construction of **heuristics!**

- Allows exploring general heuristics domain independently
- Simple heuristic: $h(s) = |G \setminus s|$
- Solve a suitable **simpler** version of the problem
- Abstraction: solve a smaller problem
e.g., completely remove a predicate from the problem
- **Relaxation**: solve a less constraint problem
- Landmarks

Relaxation heuristics

Whole sub-field of planning in STRIPs and beyond

- Relaxation is a general technique for heuristic design:
 - **Straight-line heuristic** (route planning): Ignore the fact that one must stay on roads.
 - **Manhattan heuristic** (15-puzzle): Ignore the fact that one cannot move through occupied tiles.
- We want to apply the idea of relaxations to planning.
- Informally, we want to ignore **bad side effects** of applying actions.

Example (8-puzzle)

If we move a tile from x to y , then the **good effect** is (in particular) that x is now free.

The **bad effect** is that y is not free anymore, preventing us for moving tiles through it.

In STRIPS, good and bad effects are easy to distinguish:

- Effects that make atoms true are good (add effects).
- Effects that make atoms false are bad (delete effects).

Idea for the heuristic: ignore all delete effects.

Definition (relaxation of actions)

The **relaxation** a^+ of a STRIPS action $a = \langle \text{pre}(a), \text{add}(a), \text{del}(a) \rangle$ is the action $a^+ = \langle \text{pre}(a), \text{add}(a), \emptyset \rangle$.

Definition (relaxation of planning tasks)

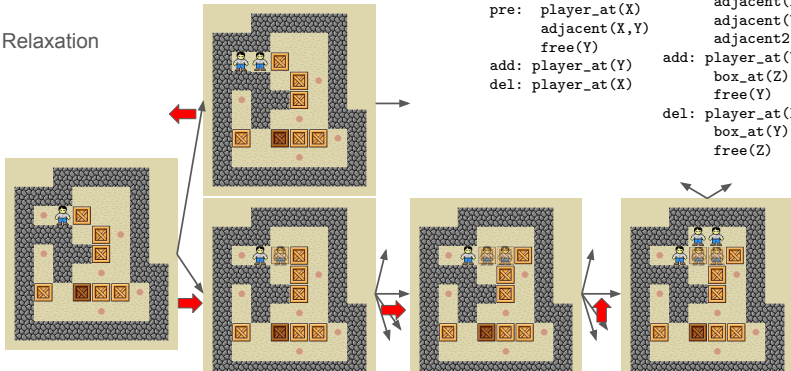
The **relaxation** Π^+ of a STRIPS planning task $\Pi = \langle P, A, I, G \rangle$ is the planning task $\Pi^+ := \langle P, \{a^+ \mid a \in A\}, I, G \rangle$.

Definition (relaxation of action sequences)

The **relaxation** of an action sequence $\pi = a_1 \dots a_n$ is the action sequence $\pi^+ := a_1^+ \dots a_n^+$.

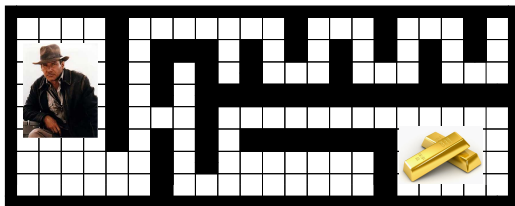
Relaxation of actions in Sokoban

Relaxation



```
move(X,Y):  
  pre: player_at(X)  
       adjacent(X,Y)  
       free(Y)  
  add: player_at(Y)  
  del: player_at(X)  
  
push(X, Y, Z):  
  pre: player_at(X)  
       box_at(Y)  
       free(Z)  
       adjacent(X,Y)  
       adjacent(Y,Z)  
       adjacent2(X,Z)  
  add: player_at(Y)  
       box_at(Z)  
       free(Y)  
  del: player_at(X)  
       box_at(Y)  
       free(Z)
```

Questionnaire



Question!

In this domain, h^+ is equal to?

- (A): Manhattan Distance.
- (B): Horizontal distance.
- (C): Vertical distance.
- (D): h^* .

Building Relaxed Planning Graph

Computing the optimal relaxed plan is still NP hard

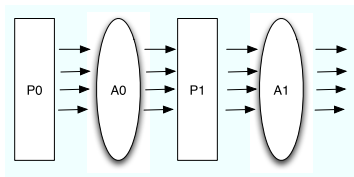
But we can do something simpler

- Build a layered **reachability graph** $P_0, A_0, P_1, A_1, \dots$

$$P_0 = \{p \in I\}$$

$$A_i = \{a \in A \mid \text{pre}(a) \subseteq P_i\}$$

$$P_{i+1} = P_i \cup \{p \in \text{add}(a) \mid a \in A_i\}$$



- Terminate when $G \subseteq P_i$

$$I = \{a = 1, b = 0, c = 0, d = 0, e = 0, f = 0, g = 0, h = 0\}$$

$$a_1 = \langle \{a\}, \{b, c\}, \emptyset \rangle$$

$$a_2 = \langle \{a, c\}, \{d\}, \emptyset \rangle$$

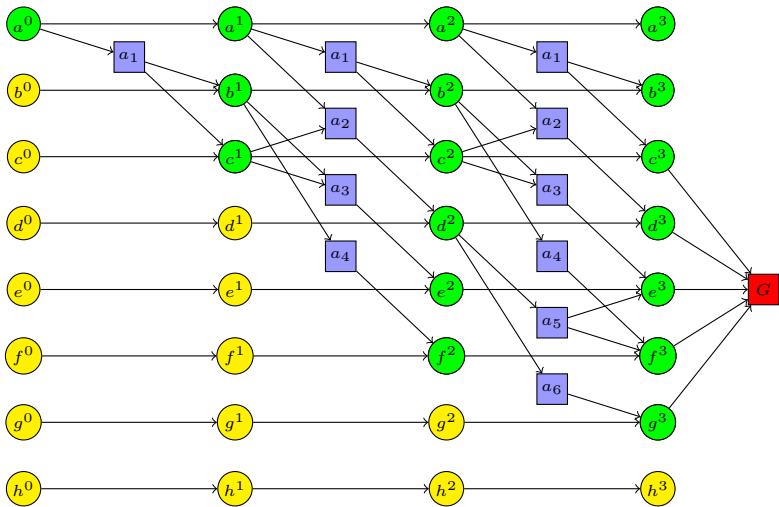
$$a_3 = \langle \{b, c\}, \{e\}, \emptyset \rangle$$

$$a_4 = \langle \{b\}, \{f\}, \emptyset \rangle$$

$$a_5 = \langle \{d\}, \{g\}, \emptyset \rangle$$

$$G = \{c = 1, d = 1, e = 1, f = 1, g = 1\}$$

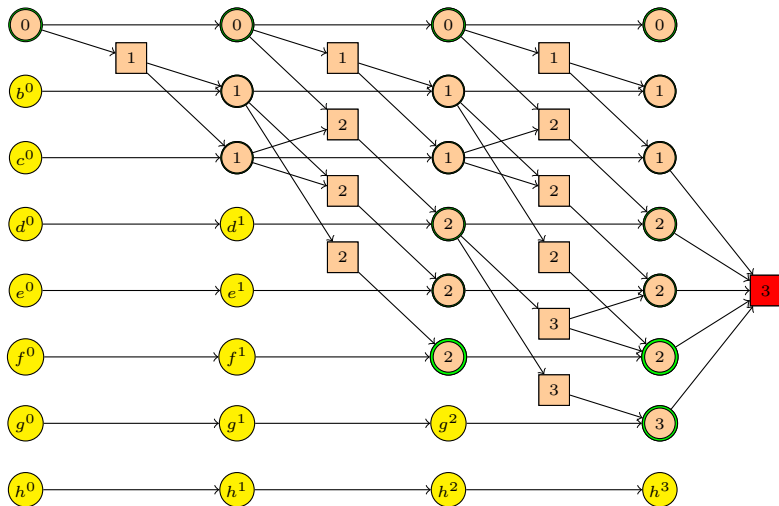
Relaxed Planning Graph



Forward cost heuristic h_{max}

- Computes a lower bound on the cost of achieving the **most expensive** goal atom
- Propagate cost layer by layer from start to goal
- At actions, take maximum cost of achieving preconditions +1
- At propositions, take the cheapest action to achieve it

Computing heuristic h_{max}



Logic is a powerful language for describing **diverse AI problems**

Situation calculus is a logical formalism for reasoning about situations **developing in time**

Of-the-shelf logical reasoning methods, such as resolution, are usable for **problem-independent** planning

However, **expressivity** goes against **efficiency**

The field of **AI planning** creates logical representations and algorithms specially designed for planning

STRIPS is a simple, but powerful language for representing planning problems

Logical representation of problems allows **automated construction** of A* **heuristics**