Automated Planning

Probabilistic AI and Reasoning - Lecture 7

Issa Hanou

Delft University of Technology

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These lecture slides are inspired by the lectures on Automated Planning by Christian Muise (Queen's University)

Who am I?

- Issa Hanou
- PhD candidate Algorithmics department
- Working on Planning and Scheduling for Railway logistics

Figure: Shunting yard in the Netherlands.

Outline

Story so far...

- Search Problems
- Logical Reasoning Problems
- Constraint Satisfaction Problems
- Bayesian Networks
- Utility

Story so far...

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- → Time component
- → Real-World Problems

Story so far...

- Search Problems
- Logical Reasoning Problems
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- Bayesian Networks
- Utility
- ➔ Time component
- ➔ Real-World Problems

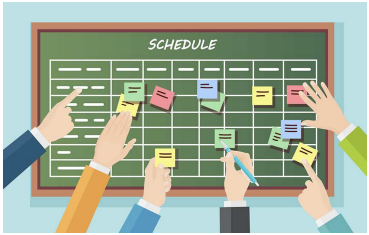
Figure: TODO example from previous lecture that illustrates planning

Automated Planning!

What is Planning?

What do you think planning is?

Examples of Planning



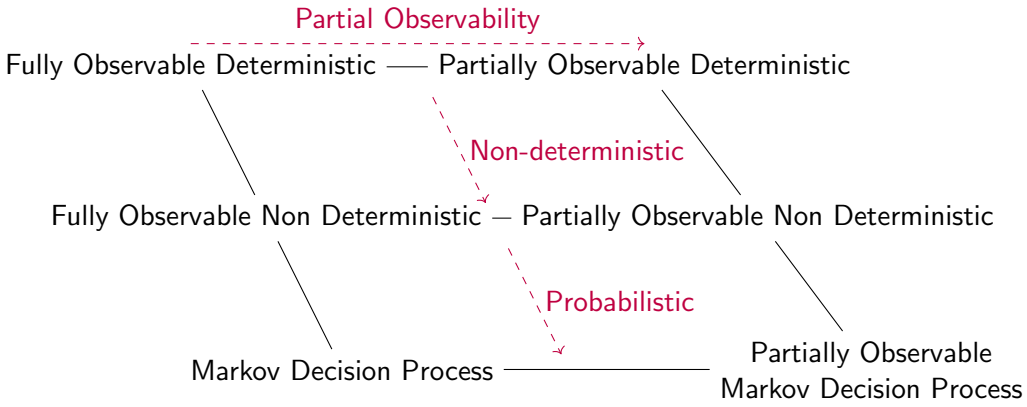
What is Planning?

Planning is the art and practice of thinking before acting.
–Patrik Haslum

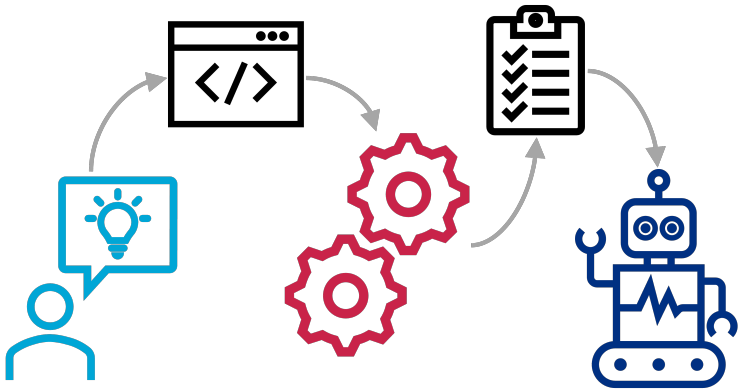
What is a Plan?

(pickup robot2 bowl)
(putdown robot2 bowl ontable)
(scoop robot1 corn)
(putdown robot1 corn inbowl)
(pickup robot2 mushrooms)
(putdown robot2 mushrooms inbowl)
...

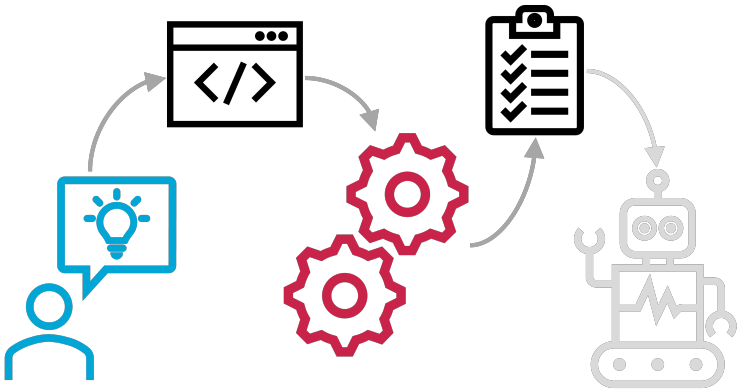
Types of Planning



Modeling vs Solving vs Executing



Modeling vs Solving vs Executing



Domain Independent Planning

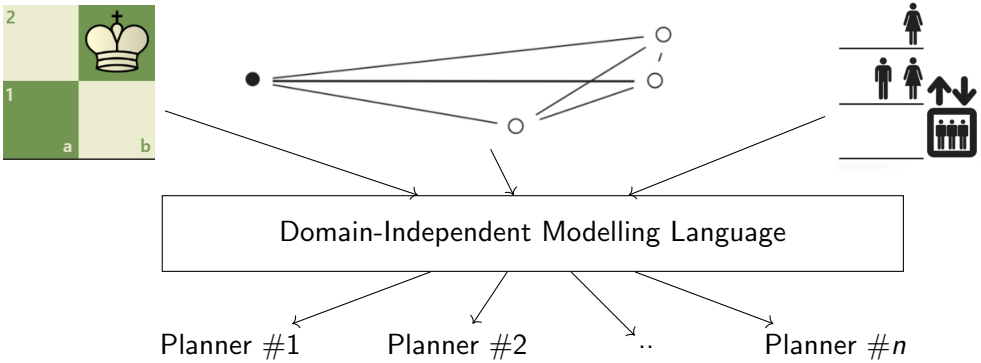
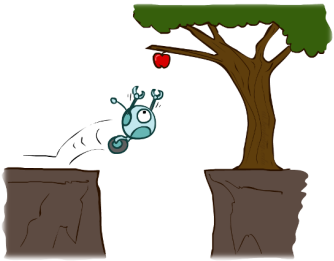


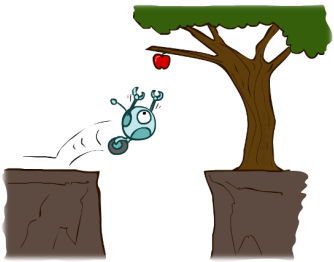
Figure: Domain-Independent Planning.

Search



(a) Reflex agent

Search



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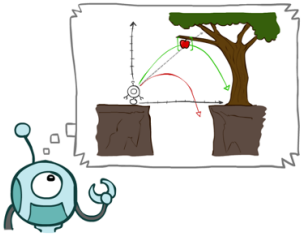
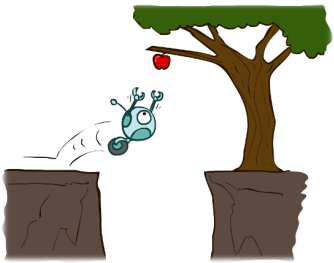


(b) Planning agent

Search



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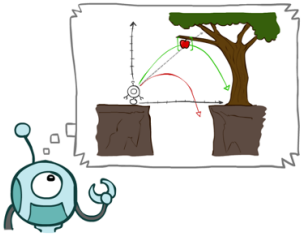

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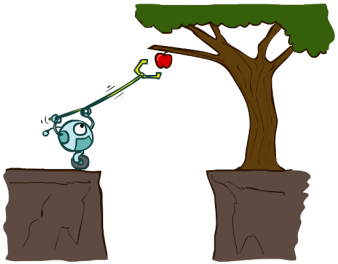


(c) Agent with a plan

Search Problem

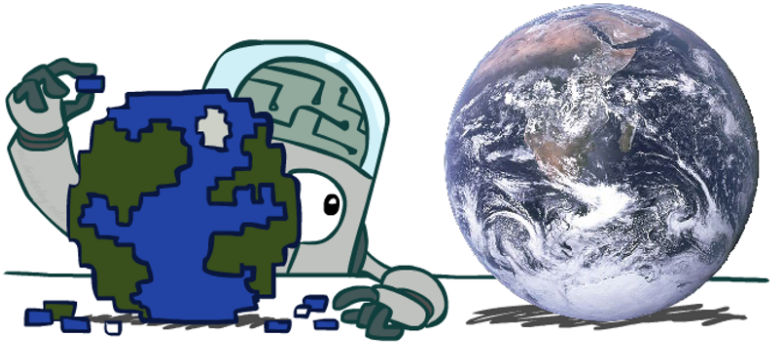
Definition

A *search problem* consists of:

- A state space
- A successor function
- A start state and goal test

A *solution* is a sequence of actions (a plan) that transforms the start state into a goal state

Modeling Search Problems



Example Search Problems

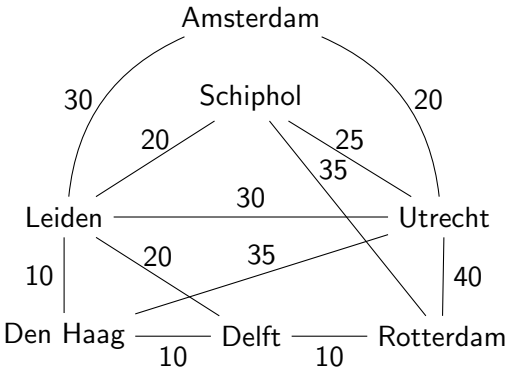
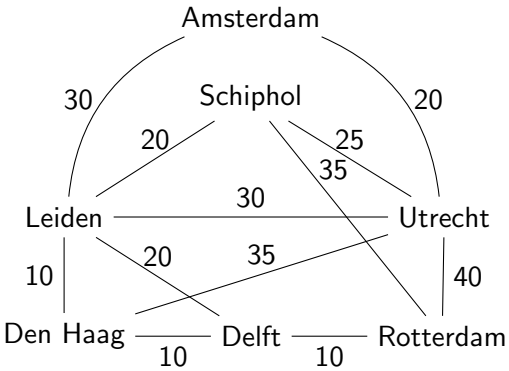


Figure: Partial railway network Netherlands.

Shows time between to travel between two cities

Example Search Problems



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Realistic model?

Example Search Problems

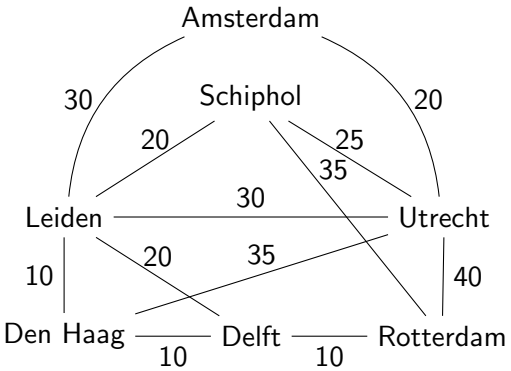


Figure: Partial railway network Netherlands.

Shows time between to travel between two cities
Realistic model? Goal-dependent: Delft to Utrecht

Other factors?

Example Search Problems

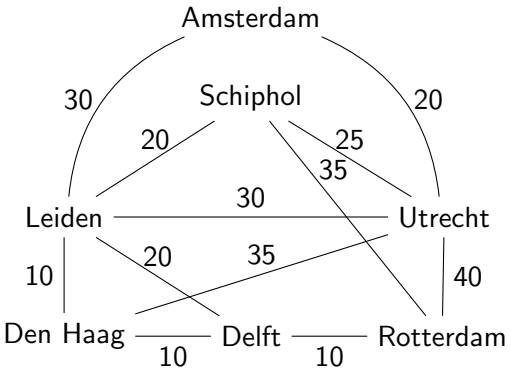


Figure: Partial railway network Netherlands.

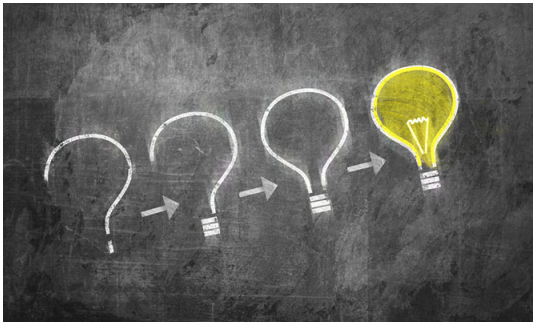
Shows time between to travel between two cities
Realistic model? Goal-dependent: Delft to Utrecht

Other factors?

- Transfer time
- Timetables
- (Expected) Train capacity
- ...

Solving a Planning Problem

Questions so far?



State Space Size

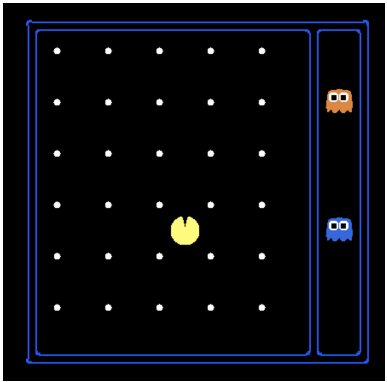
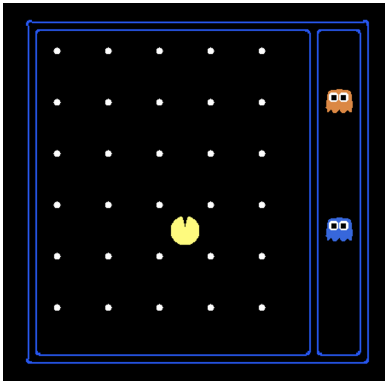


Figure: PacMan problem example with a 12×10 grid.

World state

- Agent positions: 120
- Food count: 30
- Ghost positions:12
- Agent facing: NSEW

State Space Size



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How many states?

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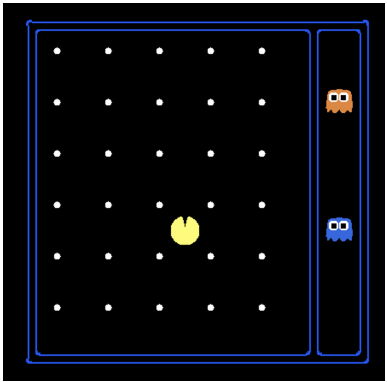

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How many states?

How many states for pathing?

State Space Size

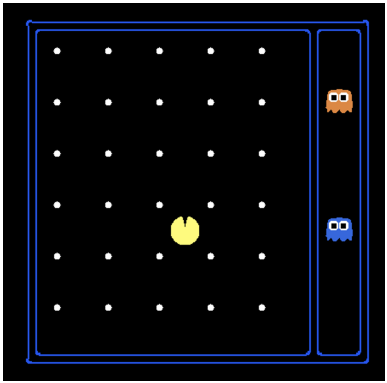


Figure: PacMan problem example with a 12×10 grid.

World state

- Agent positions: 120
- Food count: 30
- Ghost positions:12
- Agent facing: NSEW

How many states?

How many states for pathing?

How many states for eat-all-dots?

State Space Example

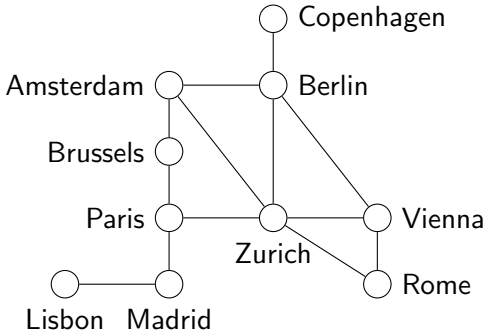


Figure: Logistics problem in Western Europe.

- Transport packages
- Take trains between connected cities
- Can fly longer distances

What does state space look like?

State Space Example Answers

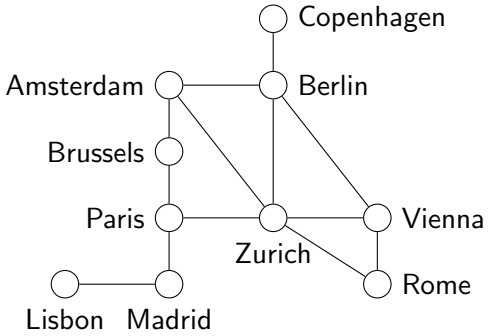


Figure: Logistics in Western Europe with train journeys.

State space components

- Connected cities
- Location per city
- Package objects (in locations)
- Set of trains and airplanes

State Space Graph

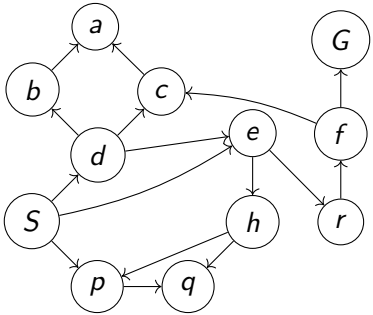


Figure: State space graph for search problem: find path from S to G.

Search Tree

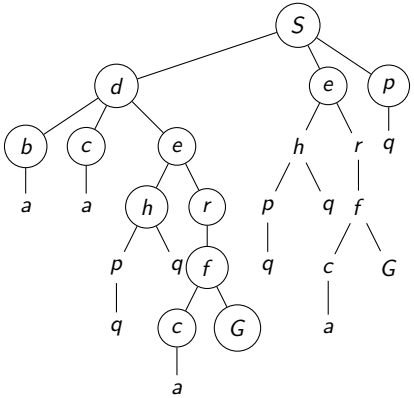
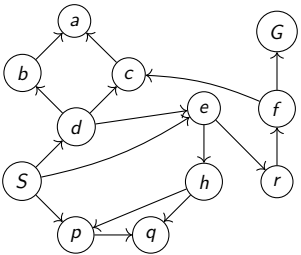
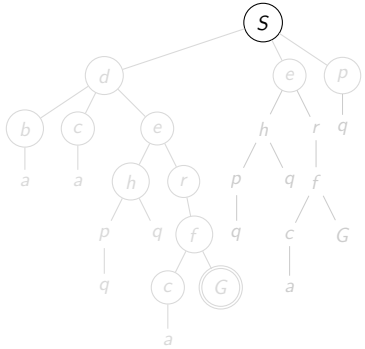


Figure: Search tree for previous search problem.

Example Tree Search



(a) Problem: path from S to G.



(b) Search tree.

S

$S \to d,\ S \to e,\ S \to p$

$S \to d \to b$

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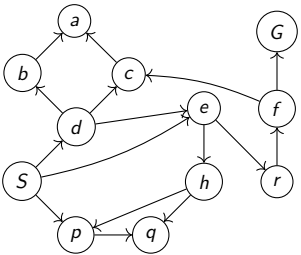

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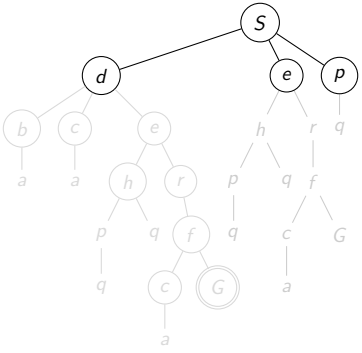

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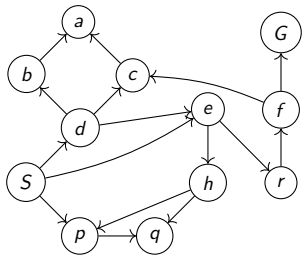

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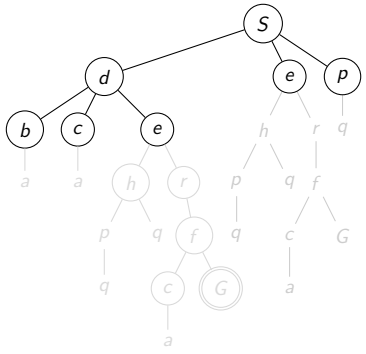

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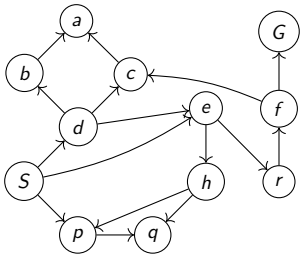

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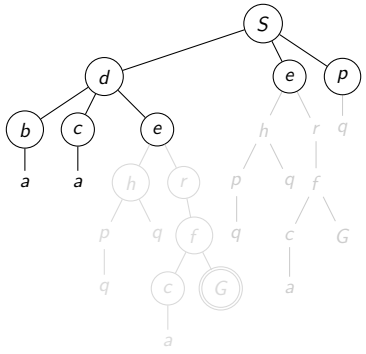

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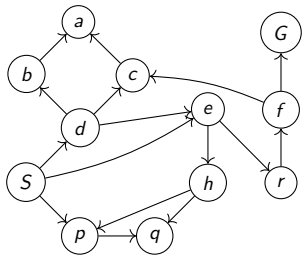

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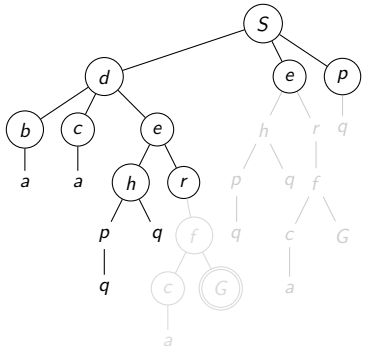

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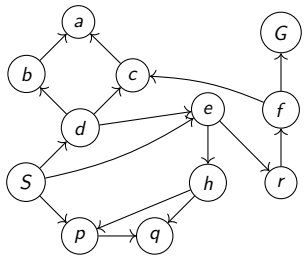

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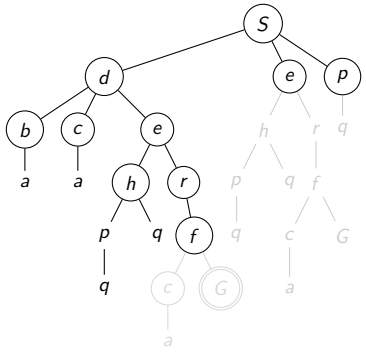

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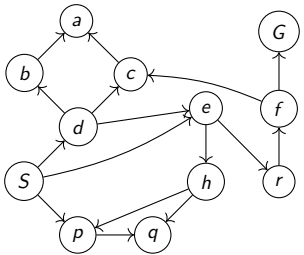

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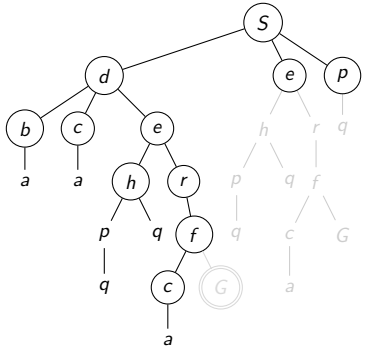

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$S \to d \to \{b, c\} \to a$

$S \to d \to e \to h \to \ldots$

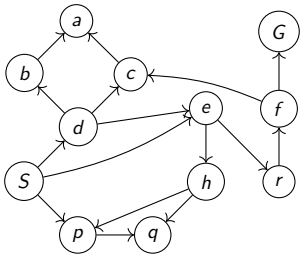
$S \to d \to e \to r$

$S \to d \to e \to r \to f$

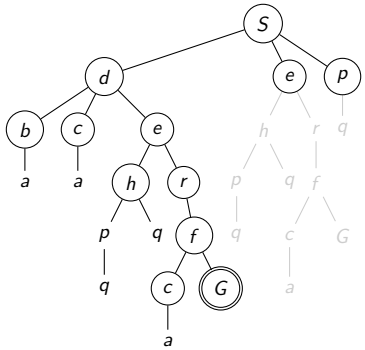
$S \to d \to e \to r \to f \to c$

$S \to d \to e \to r \to f \to G$

Example Tree Search



(a) Problem: path from S to G.



(b) Search tree.

S

$S \to d,\ S \to e,\ S \to p$

$S \to d \to b$

$S \to d \to c$

$S \to d \to e$

$S \to d \to \{b, c\} \to a$

$S \to d \to e \to h \to \ldots$

$S \to d \to e \to r$

$S \to d \to e \to r \to f$

$S \to d \to e \to r \to f \to c$

$S \to d \to e \to r \to f \to G$

Forward Search

$g_F(n)$ is cost of best-known path from *start* to n.

Forward Search

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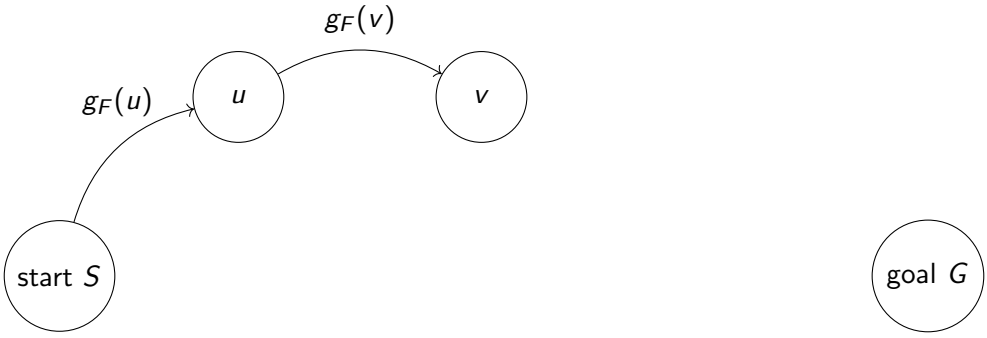
Forward Search



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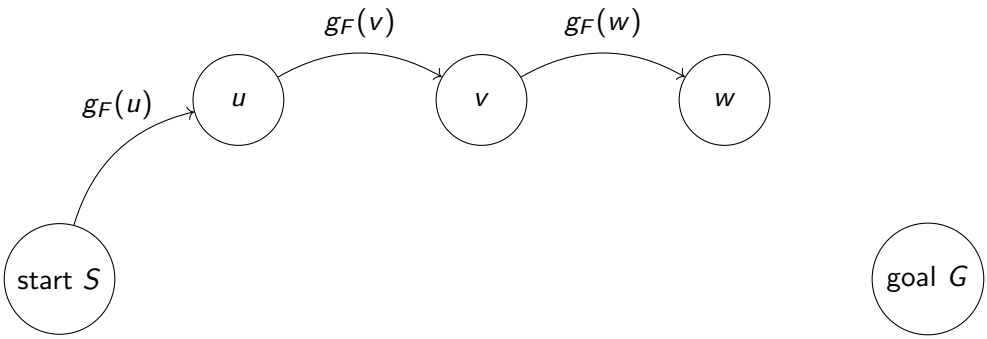

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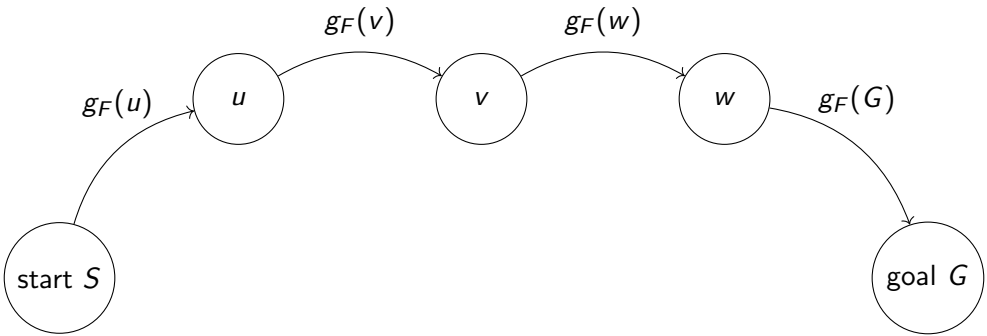
Forward Search



$g_F(n)$ is cost of best-known path from *start* to n.

Backward Search

$g_B(n)$ is cost of best-known path from n to $goal$.

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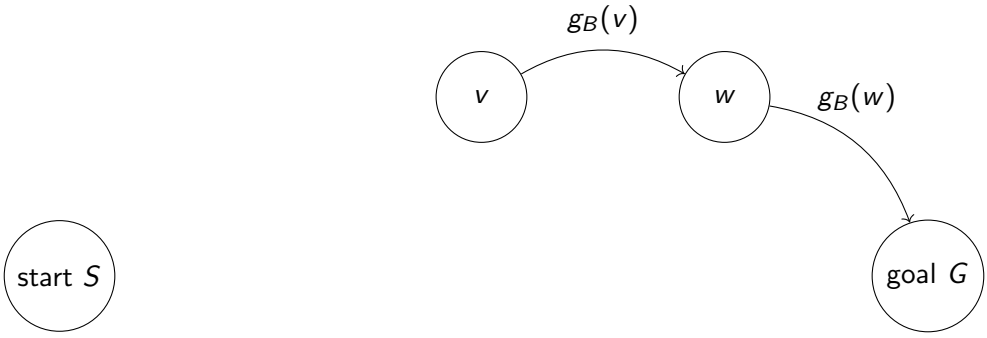
Backward Search



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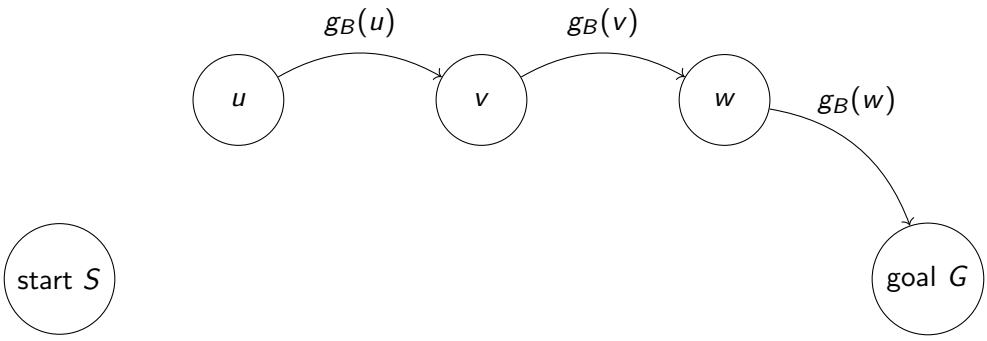
Backward Search



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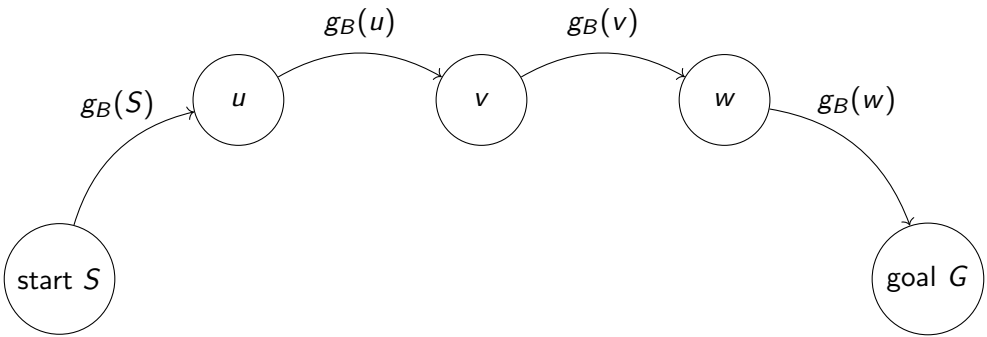

$g_B(n)$ is cost of best-known path from n to $goal$.

Bidirectional Search

$g_F(n)$ is cost of best-known path from *start* to n.
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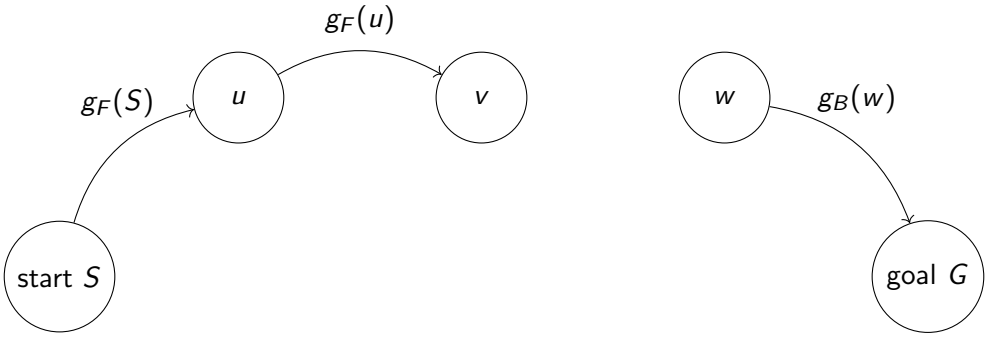
Bidirectional Search



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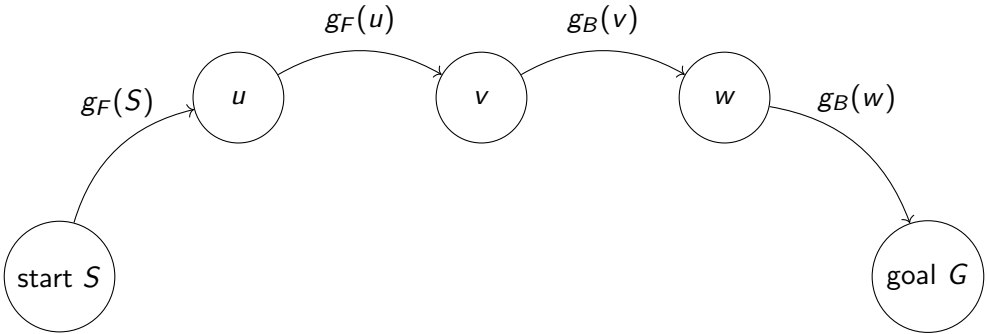
Bidirectional Search



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Search Directions

Bidirectional search can be either

- uniform-cost (Dijkstra): expand lowest $g(n)$
- goal-informed (A^*): expand lowest $f(n)$

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What queue to expand?

Search Directions

Bidirectional search can be either

- uniform-cost (Dijkstra): expand lowest $g(n)$
- goal-informed (A^*): expand lowest $f(n)$

What queue to expand? Solution: expand on $\max\{f_F(u),\ f_B(v),\ g_F(u) + g_B(v)\}$.

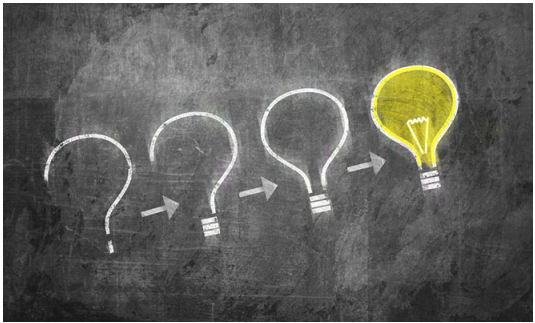
Eckerle, et al. (2017). Sufficient Conditions for Node Expansion in Bidirectional Heuristic Search.

Planning as Constraint Satisfaction Problem

- State is a black box: arbitrary data structure
- Goal test is a function: set of constraints
- Use general-purpose algorithms
- Theorem proving

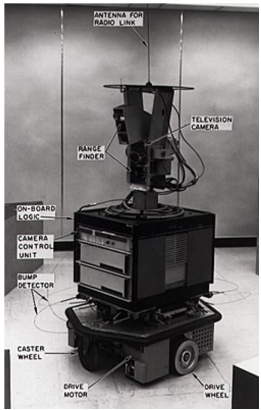
Solving Planning Problems

Questions so far?



STRIPS

- Stanford Research Institute Problem Solver
- Language + Solver + Search procedure
- Shakey the robot (1971)
- Factored representation of the world



STRIPS: The Language

Problem: $\langle P, A, I, G \rangle$

- P: set of predicates → What can true of false
- A: set of actions → What can agent do
- I: initial state → Atoms that hold at start of problem setting
- G: goal state → Atoms that the agent wants to hold eventually

Predicate: function over domain objects to truth-values `(at Agent Location)`.
Atom: predicate instantiation with specific objects `(at shakey table1)`.

Example

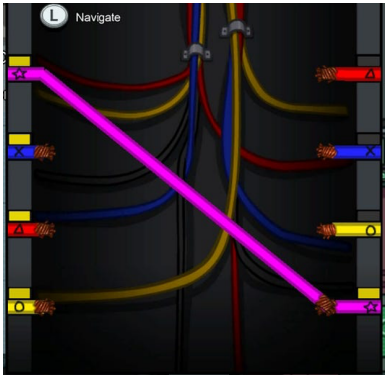
Problem: Connect the right wires and then turn on the power.


What are the predicates?


What are the actions?


What is the initial state?

- Goal: `(power-on)`



Example

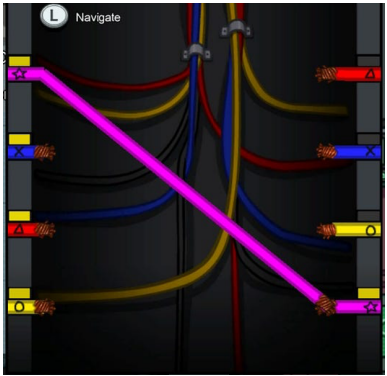
Problem: Connect the right wires and then turn on the power.

- Predicates: `(connected Link)`, `(link Link1 Link2)`, `(color Link1 Color)`, ...

What are the actions?

What is the initial state?

- Goal: `(power-on)`



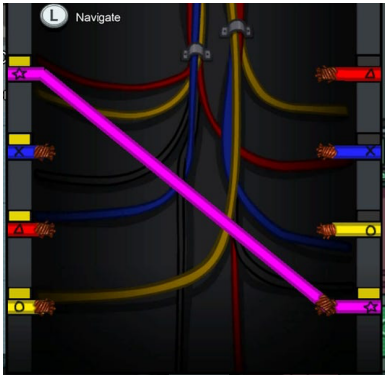
Example

Problem: Connect the right wires and then turn on the power.

- Predicates: `(connected Link)`, `(link Link1 Link2)`, `(color Link1 Color)`, ...
- Actions: `(connect Link1 Link2)`, `(turn-on-power)`, ...

What is the initial state?

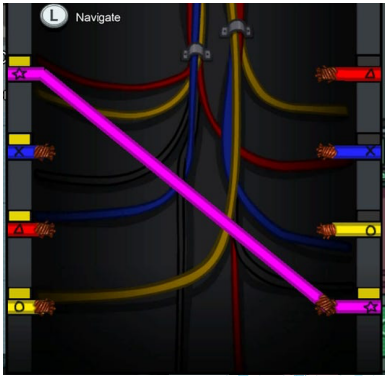
- Goal: `(power-on)`



Example

Problem: Connect the right wires and then turn on the power.

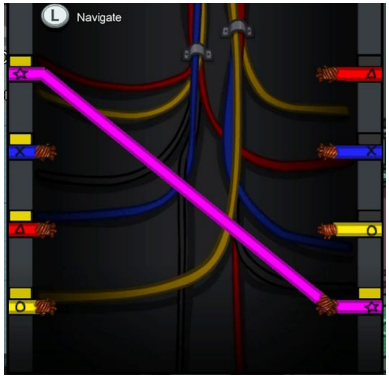
- Predicates: `(connected Link)`, `(link Link1 Link2)`, `(color Link1 Color)`, ...
- Actions: `(connect Link1 Link2)`, `(turn-on-power)`, ...
- Initially: `(color l3 red)`, `(connected l1 r4)`, `(power-off)`, ...
- Goal: `(power-on)`



Example

Problem: Connect the right wires and then turn on the power.

- Predicates: `(connected Link)`, `(link Link1 Link2)`, `(color Link1 Color)`, ...
- Actions: `(connect Link1 Link2)`, `(turn-on-power)`, ...
- Initially: `(color l3 red)`, `(connected l1 r4)`, `(power-off)`, ...



Action Definition

State

State is a conjunction of atoms that currently hold.

- *Complete* state: all other predicate instantiations are assumed to be false.
- *Partial* state: doesn't matter if the other predicate instantiations are true/false.

Action

Action $a \in A$ defines the conditions and effects of moving between states.

- $\text{PRE}(a)$: Set of predicates that must hold to execute a
- $\text{DEL}(a)$: Set of atoms removed from state after executing a
- $\text{ADD}(a)$: Set of atoms added to state after executing a
- $c(a)$: Cost of executing a

Action Applicability

Can we perform this action in the current state?

$\text{PRE}(a) \subseteq s$

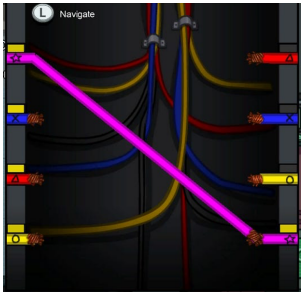


Figure: Current state.

Action: `(turn-on-power)`

- $\text{PRE}(a)$: {`(connected r1)`, `(connected r2)`, `(connected r3)`, `(connected r4)`}
- $\text{DEL}(a)$: {`(power-off)`}
- $\text{ADD}(a)$: {`(power-on)`}

Action Progression

What happens if we perform this action in the current state?

$$\text{PROGRESS}(s, a) = \big(s - \text{DEL}(a)\big) \cup \text{ADD}(a)$$

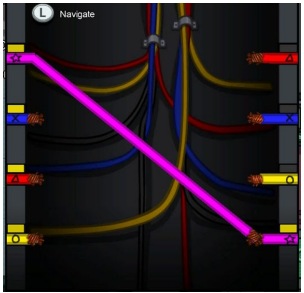


Figure: Current state.

Action: `(connect l2 r2)`

- PRE(a): {`(not (connected l2))`, `(not (connected r2))`, `(= (color l2) (color r2))`}
- DEL(a): {`(not (connected l2))`, `(not (connected r2))`}
- ADD(a): {`(connected l2) (connected r2)`}

Goal achievement

When are we done?

$G \subseteq s$

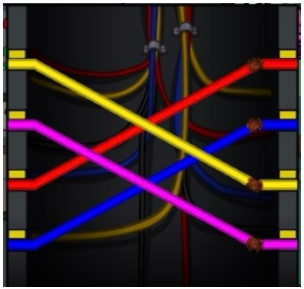


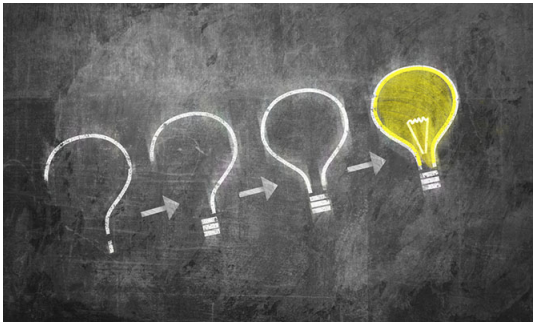
Figure: Current state.

Action: `(turn-on-power)`

- PRE(a): {`(connected r1)`, `(connected r2)`, `(connected r3)`, `(connected r4)`}
- DEL(a): {`(power-off)`}
- ADD(a): {`(power-on)`}

Modeling Search Problems

Questions so far?



The Planning Domain Definition Language (PDDL)

- PDDL: A common language for arbitrary problem specs
- Contains the STRIPS formalism
- Many variations for various formalisms: extensions with more expressiveness
- Supported by a variety of planners
- Driven by the (roughly) bi-annual International Planning Contest
- Lisp-like syntax `(many (((brackets!)))))`
  - Learn to read
  - Can use tools to write (Python library)

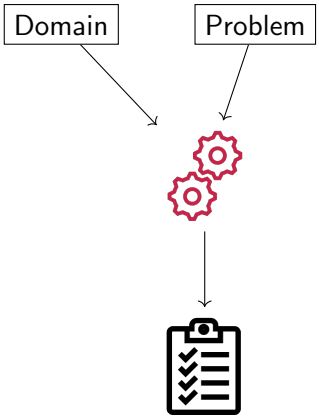
PDDL Input Files

Domain

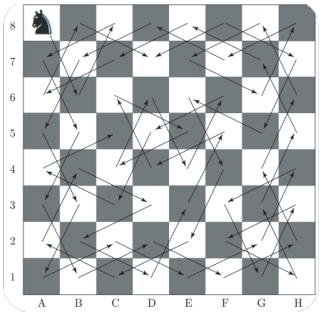
- Requirements
- Types
- Predicates
- Actions

Problem

- Objects
- Initial state
- Goal atoms

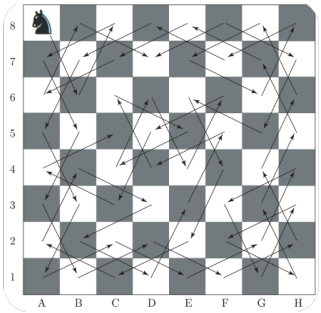


Domain specification




```
(define (domain knights-tour)
    (:requirements )
    (:predicates
        (at ?square)
        (visited ?square)
        (valid_move ?square_from ?square_to)
    )
    (:action move
        :parameters (?current ?to)
        :precondition (and (at ?current)
            (valid_move ?current ?to)
            (not (visited ?to)))
        :effect (and (not (at ?current))
            (at ?to) (visited ?to))
    ))
```

Domain specification

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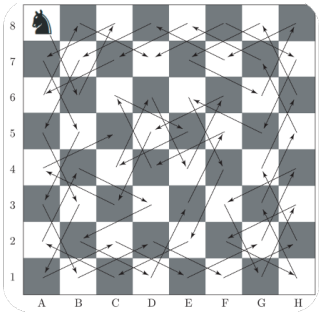


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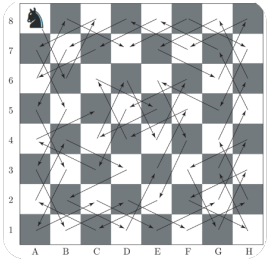
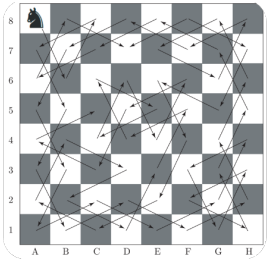
Problem specification




```
(define (problem knight-tour)
    (:domain knights-tour)
    (:objects
        a1 a2 a3 a4 a5 a6 a7 a8
        b1 b2 b3 b4 b5 b6 b7 b8
        ...
        h1 h2 h3 h4 h5 h6 h7 h8
    )
    (:init
        (at a8)
        (visited a8)
        (valid_move a8 b6)
        (valid_move b6 a8)
        (valid_move a8 c7)
        (valid_move c7 a8)
        ...
    )
    (:goal (and
        (visited a1)
        (visited a2)
        ...
        (visited h8)
    )))
```

Problem specification

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        b1 b2 b3 b4 b5 b6 b7 b8
        ...
        h1 h2 h3 h4 h5 h6 h7 h8
    )
```

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    (at a8)
    (visited a8)
    (valid_move a8 b6)
    (valid_move b6 a8)
    (valid_move a8 c7)
    (valid_move c7 a8)
    ...
)
(:goal (and
    (visited a1)
    (visited a2)
    ...
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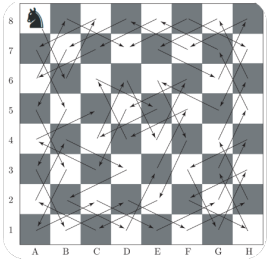
)))
```

Problem specification

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        ...
        h1 h2 h3 h4 h5 h6 h7 h8
    )
```

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    (valid_move b6 a8)
    (valid_move a8 c7)
    (valid_move c7 a8)
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    (visited h8)
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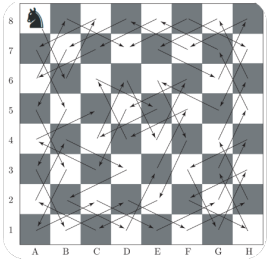
```

Problem specification

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        ...
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    )
```

```
(:init
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    (visited a8)
    (valid_move a8 b6)
    (valid_move b6 a8)
    (valid_move a8 c7)
    (valid_move c7 a8)
    ...
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    (visited a2)
    ...
    (visited h8)
)))
```

Exercise: Missing precondition

- Ferry boat domain
- Three actions: `board`, `sail`, `debark`
- Predicates: `car`, `location`, `at-ferry`, `at`, `empty-ferry`, `on`
- What precondition is missing for board?

```
(:action board
    :parameters (?car ?loc)
    :precondition (and
        (car ?car)
        (location ?loc)
        (at ?car ?loc)
        (empty-ferry))
    :effect (and (on ?car)
        (not (at ?car ?loc))
        (not (empty-ferry)))
)
```

Solution: Missing precondition

- Ferry boat domain
- Three actions: `board`, `sail`, `debark`
- Predicates: `car`, `location`, `at-ferry`, `at`, `empty-ferry`, `on`
- What precondition is missing for board?

```
(:action board
    :parameters (?car ?loc)
    :precondition (and
        (car ?car)
        (location ?loc)
        (at ?car ?loc)
        (at-ferry ?loc)
        (at-ferry ?loc)
        (empty-ferry))
    :effect (and (on ?car)
        (not (at ?car ?loc))
        (not (empty-ferry)))
```

Exercise: Spot the mistake

```
(define (domain hanoi)
    (:requirements :strips)
    (:predicates (clear ?x) (on ?x ?y)
        (smaller ?x ?y))

    (:action move
        :parameters (?disc ?orig ?to)
        :precondition (and
            (smaller ?to ?disc)
            (on ?disc ?orig) (clear ?disc)
            (clear ?to))
        :effect  (and (clear ?orig)
            (on ?disc ?to)
            (not (on ?disc ?orig))))
)
```

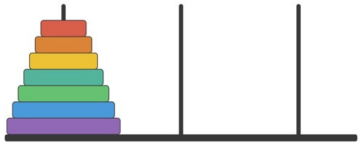


Figure: Towers of Hanoi.

Solution: Missing effect

```
(define (domain hanoi)
    (:requirements :strips)
    (:predicates (clear ?x) (on ?x ?y)
        (smaller ?x ?y))
    (:action move
        :parameters (?disc ?orig ?to)
        :precondition (and
            (smaller ?to ?disc)
            (on ?disc ?orig) (clear ?disc)
            (clear ?to))
        :effect  (and (clear ?orig)
            (on ?disc ?to)
            (not (on ?disc ?orig))
            (not (clear ?to))
        )))
```

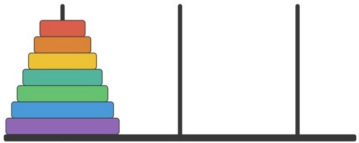
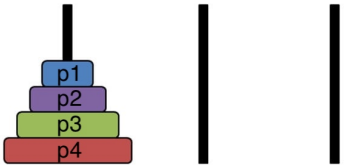


Figure: Towers of Hanoi.

Exercise: Valid plan?

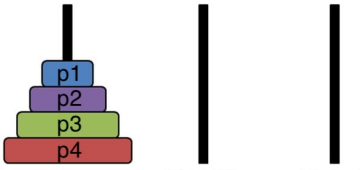
```
(define (domain hanoi)
    (:requirements :strips)
    (:predicates (clear ?x) (on ?x ?y)
        (smaller ?x ?y))
    (:action move
        :parameters (?disc ?orig ?to)
        :precondition (and
            (smaller ?to ?disc)
            (on ?disc ?orig) (clear ?disc)
            (clear ?to))
        :effect  (and (clear ?orig)
            (on ?disc ?to)
            (not (on ?disc ?orig))
            (not (clear ?to))
        )))
```




```
(move p1 p2 b)
(move p2 g3 c)      (move p1 p2 p4)
(move p1 b p2)      (move p2 p3 a)
(move p3 p4 b)      (move p3 b p4)
(move p1 p2 p4)     (move p1 p2 b)
(move p2 b p3)      (move p2 a p3)
(move p1 p4 p2)     (move p1 a p2)
(move p4 a c)
```

Solution: invalid plan

```
(define (domain hanoi)
    (:requirements :strips)
    (:predicates (clear ?x) (on ?x ?y)
        (smaller ?x ?y))
    (:action move
        :parameters (?disc ?orig ?to)
        :precondition (and
            (smaller ?to ?disc)
            (on ?disc ?orig) (clear ?disc)
            (clear ?to))
        :effect  (and (clear ?orig)
            (on ?disc ?to)
            (not (on ?disc ?orig))
            (not (clear ?to))
        )))
```




```
(move p1 p2 b)
(move p2 g3 c)
(move p1 b p2)
(move p3 p4 c)
(move p1 p2 p4)
(move p2 c p3)
(move p1 p4 p2)
(move p4 a c)
```

```
(move p1 p2 p4)
(move p2 p3 a)
(move p1 p4 p2)
(move p3 b p4)
(move p1 p2 b)
(move p2 a p3)
(move p1 a p2)
```

PDDL Extension: numeric fluents

- Predicates vs fluents
- Express numeric properties
- Precondition: `=`, `>`, `<`
- Effect: `increase`, `decrease`

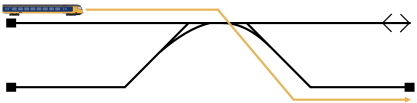


Figure: Shunting Yard Layout.

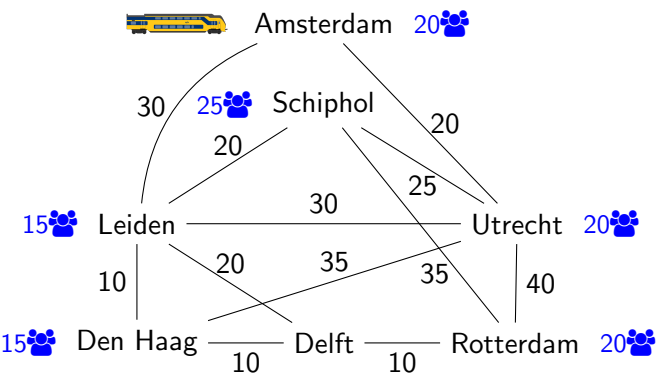
```
(:functions
    (length ?t - track)
    (battery)
)
(:init
    (length track1 50)
    (battery 100)
)
(:effect
    (decrease (maxTrips) (length ?t))
)
```

Exercise: Modeling in PDDL

Blue is initial, get everyone to Delft
Train starts at Amsterdam, fits 60

- What are the predicates?
- What are the actions?
- What is the initial state?
- What is the goal state?

Discuss with neighbour



Relation to Other Lectures

- Search, Inference, Learning, and Optimization
- Effectiveness for solving planning problems

Conclusion

- Planning problems in the real world
- Planning as a search problem
- How to model a planning problem

Questions?

Next Steps & Further Information

Homework

- Homework exercises week 4

Exam material

- Lecture notes
- Lecture slides
- Homework

Extra information

- Book: *Russel & Norvig: Artificial Intelligence, Ch.11*
- `http://planning.wiki/` General info on PDDL and planners
- `http://editor.planning.domains/` Online editor for PDDL

More Applications

- Plan Recognition
- Logistics
- Game testing