

# Foundations of Artificial Intelligence

## B1. State-Space Search: State Spaces

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March 4, 2024 — B1. State-Space Search: State Spaces

B1.1 State-Space Search Problems

B1.2 Formalization

B1.3 State-Space Search

B1.4 Summary

# State-Space Search: Overview

## Chapter overview: state-space search

- ▶ B1–B3. Foundations
  - ▶ B1. State Spaces
  - ▶ B2. Representation of State Spaces
  - ▶ B3. Examples of State Spaces
- ▶ B4–B8. Basic Algorithms
- ▶ B9–B15. Heuristic Algorithms

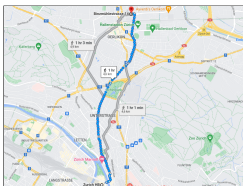
# B1.1 State-Space Search Problems

# State-Space Search Applications

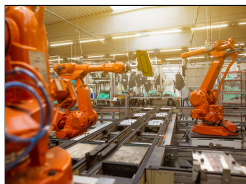
## Mario AI competition



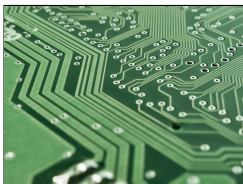
## route planning



## multi-agent path finding



## scheduling



## software/hardware verification



## NPC behaviour

# Classical Assumptions

“classical” assumptions considered in this part of the course:

- ▶ no other agents in the environment (**single-agent**)
- ▶ always knows state of the world (**fully observable**)
- ▶ state only changed by the agent (**static**)
- ▶ finite number of states/actions (in particular **discrete**)
- ▶ actions have **deterministic** effect on the state

↪ can all be generalized (but not in this part of the course)

# Classification

classification:

State-Space Search

environment:

- ▶ static vs. dynamic
- ▶ deterministic vs. non-deterministic vs. stochastic
- ▶ fully vs. partially vs. not observable
- ▶ discrete vs. continuous
- ▶ single-agent vs. multi-agent

problem solving method:

- ▶ problem-specific vs. general vs. learning

# Informal Description

State-space search problems are among the “simplest” and most important classes of AI problems.

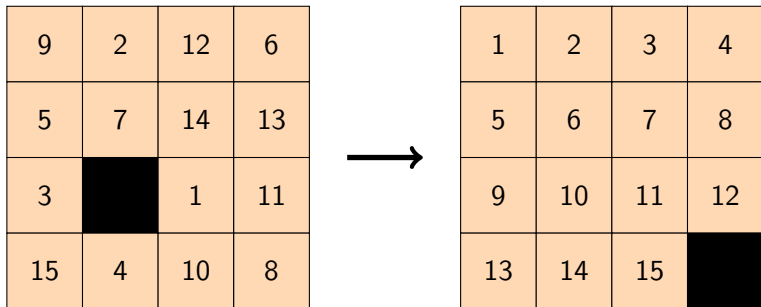
objective of the agent:

- ▶ apply a sequence of actions
- ▶ that reaches a goal state
- ▶ from a given initial state

performance measure: minimize total action cost



# Motivating Example: 15-Puzzle



## B1.2 Formalization

# State Spaces

## Definition (state space)

A state space or transition system is a 6-tuple  $\mathcal{S} = \langle S, A, cost, T, s_1, S_G \rangle$  with

- ▶ finite set of states  $S$
- ▶ finite set of actions  $A$
- ▶ action costs  $cost : A \rightarrow \mathbb{R}_0^+$
- ▶ transition relation  $T \subseteq S \times A \times S$  that is deterministic in  $\langle s, a \rangle$  (see next slide)
- ▶ initial state  $s_1 \in S$
- ▶ set of goal states  $S_G \subseteq S$

**German:** Zustandsraum, Transitionssystem, Zustände, Aktionen, Aktionskosten, Transitions-/Übergangsrelation, deterministisch, Anfangszustand, Zielzustände

# State Spaces: Terminology & Notation

## Definition (transition, deterministic)

Let  $\mathcal{S} = \langle S, A, cost, T, s_1, S_G \rangle$  be a state space.

The triples  $\langle s, a, s' \rangle \in T$  are called (state) transitions.

We say  $\mathcal{S}$  has the transition  $\langle s, a, s' \rangle$  if  $\langle s, a, s' \rangle \in T$ .

We write this as  $s \xrightarrow{a} s'$ , or  $s \rightarrow s'$  when  $a$  does not matter.

Transitions are deterministic in  $\langle s, a \rangle$ : it is forbidden to have both  $s \xrightarrow{a} s_1$  and  $s \xrightarrow{a} s_2$  with  $s_1 \neq s_2$ .

# State Space: Running Example

Consider the **bounded inc-and-square** search problem.

informal description:

- ▶ find a sequence of
  - ▶ **increment-mod10** (*inc*) and
  - ▶ **square-mod10** (*sqr*) actions
- ▶ on the natural numbers from 0 to 9
- ▶ that reaches the number 6 or 7
- ▶ starting from the number 1
- ▶ assuming each action costs 1.

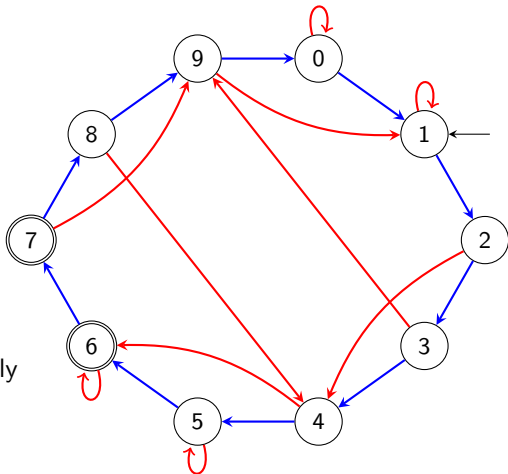
formal model:

- ▶  $S = \{0, 1, \dots, 9\}$
- ▶  $A = \{inc, sqr\}$
- ▶  $cost(inc) = cost(sqr) = 1$
- ▶  $T$  s.t. for  $i = 0, \dots, 9$ :
  - ▶  $\langle i, inc, (i + 1) \bmod 10 \rangle \in T$
  - ▶  $\langle i, sqr, i^2 \bmod 10 \rangle \in T$
- ▶  $s_1 = 1$
- ▶  $S_G = \{6, 7\}$

# Graph Interpretation

state spaces are often depicted as **directed, labeled graphs**

- ▶ **states:** graph vertices
- ▶ **transitions:** labeled arcs  
(here: colors instead of labels)
- ▶ **initial state:** incoming arrow
- ▶ **goal states:** double circles
- ▶ **actions:** the arc labels
- ▶ **action costs:** described separately  
(or implicitly = 1)



# State Spaces: More Terminology (1)

We use common terminology from graph theory.

**Definition (predecessor, successor, applicable action)**

Let  $\mathcal{S} = \langle S, A, cost, T, s_I, S_G \rangle$  be a state space.

Let  $s, s' \in S$  be states with  $s \rightarrow s'$ .

- ▶  $s$  is a **predecessor** of  $s'$
- ▶  $s'$  is a **successor** of  $s$

If  $s \xrightarrow{a} s'$ , then action  $a$  is **applicable** in  $s$ .

**German:** Vorgänger, Nachfolger, anwendbar

## State Spaces: More Terminology (2)

### Definition (path)

Let  $\mathcal{S} = \langle S, A, cost, T, s_1, S_G \rangle$  be a state space.

Let  $s_0, \dots, s_n \in S$  be states and  $a_1, \dots, a_n \in A$  be actions such that  $s_0 \xrightarrow{a_1} s_1, \dots, s_{(n-1)} \xrightarrow{a_n} s_n$ .

- ▶  $\pi = \langle a_1, \dots, a_n \rangle$  is a **path** from  $s_0$  to  $s_n$
- ▶ **length** of  $\pi$ :  $|\pi| = n$
- ▶ **cost** of  $\pi$ :  $cost(\pi) = \sum_{i=1}^n cost(a_i)$

**German:** Pfad, Länge, Kosten

- ▶ paths may have length 0
- ▶ sometimes “path” is used for state sequence  $\langle s_0, \dots, s_n \rangle$  or sequence  $\langle s_0, a_1, s_1, \dots, s_{(n-1)}, a_n, s_n \rangle$



## State Spaces: More Terminology (3)

More terminology:

### Definition (reachable, solution, optimal)

Let  $\mathcal{S} = \langle S, A, cost, T, s_I, S_G \rangle$  be a state space.

- ▶ state  $s$  is **reachable** if a path from  $s_I$  to  $s$  exists
- ▶ paths from  $s \in S$  to some state  $s_* \in S_G$  are **solutions for/from  $s$**
- ▶ solutions for  $s_I$  are called **solutions for  $\mathcal{S}$**
- ▶ **optimal solutions** (for  $s$ ) have minimal costs among all solutions (for  $s$ )

**German:** erreichbar, Lösung für/von  $s$ , optimale Lösung

## B1.3 State-Space Search

# Solving Search Problems

Consider again the running example.

informal description:

- ▶ find a sequence of
  - ▶ `increment-mod10` (*inc*) and
  - ▶ `square-mod10` (*sqr*) actions
- ▶ on the natural numbers from 0 to 9
- ▶ that reaches the number 6 or 7
- ▶ starting from the number 1
- ▶ assuming each action costs 1.

How do you solve this?

...and then square...?

What if I increment...?

...or alternatively...?



# State-Space Search

## State-Space Search

State-space search is the algorithmic problem of finding solutions in state spaces or proving that no solution exists.

In optimal state-space search, only optimal solutions may be returned.

German: Zustandsraumsuche, optimale Zustandsraumsuche

# Learning Objectives for State-Space Search

## Learning Objectives for the Topic of State-Space Search

- ▶ understanding state-space search:  
What is the problem and how can we formalize it?
- ▶ evaluate search algorithms:  
completeness, optimality, time/space complexity
- ▶ get to know search algorithms:  
uninformed vs. informed; tree and graph search
- ▶ evaluate heuristics for search algorithms:  
goal-awareness, safety, admissibility, consistency
- ▶ efficient implementation of search algorithms
- ▶ experimental evaluation of search algorithms
- ▶ design and comparison of heuristics for search algorithms

## B1.4 Summary

# Summary

- ▶ **state-space search problems:**  
find action sequence leading from initial state to a goal state
- ▶ **performance measure:** sum of action costs
- ▶ formalization via **state spaces:**
  - ▶ **states, actions, action costs, transitions, initial state, goal states**
- ▶ terminology for transitions, paths, solutions
- ▶ definition of (optimal) state-space search