# B(E)4M36PUI – Artificial Intelligence Planning
# Solving universe-sized puzzles with human-sized patience

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# Course Overview

- https://cw.fel.cvut.cz/wiki/courses/pui
- Lectures
  - 2 parts (Antonin Komenda and Stefan Edelkamp)
  - Invited lecture (Schlumberger – practically used automated planning)
- Seminars
  - 2 parts (Michaela Urbanovská and Jan Mrkos)
  - Synchronized topics with lectures
  - Two assignment projects with multiple parts
- Exam
  - Primarily written form (theory + exercises)
  - Points from the seminars
    - Maximum 50 points
    - 25 points required for the credit (zápočet)

# Lectures & Seminars Overview (Part 1)

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1. Introduction
2. Representations (for Classical Planning)
3. Search (for Classical Planning)
4. Automated Planning in Practice (invited lecture from Schlumberger)
5. Heuristics (for Classical Planning) I – Relaxations
6. Heuristics (for Classical Planning) II – Landmarks & Potentials
7. Heuristics (for Classical Planning) III – Abstractions

# Assignments

- Classical planning
  - PDDL modeling (5 points) deadline: week 3
  - Grounding implementation (10 points) deadline: week 4
  - Search algorithm + heuristic implementation (15 points) deadline: week 8
  - 30 points total
- Probabilistic planning
  - Implementation of probabilistic planning algorithm (up to 20 points)

Both assignments have to be submitted.

50 points in total → 25 required for the credit (zápočet)

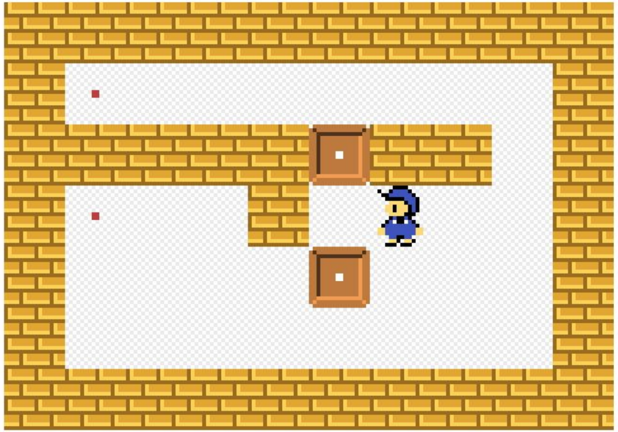
# Communication

- Email is the primary form of communication
- Ask at the lectures/tutorials!

Email addresses

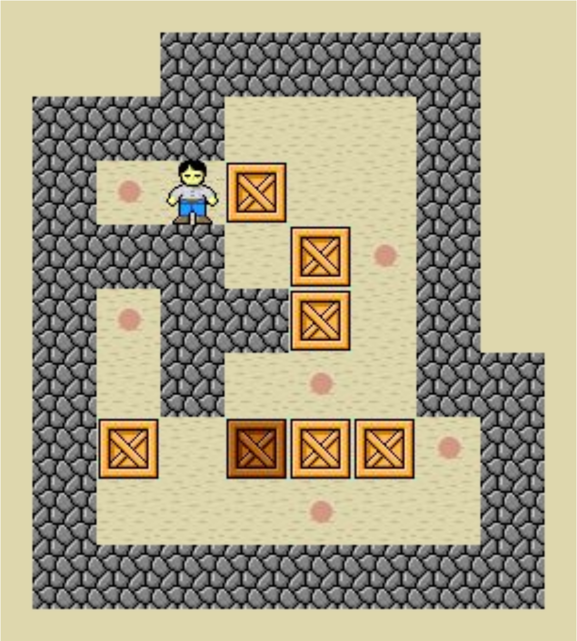
- Classical Planning (Part 1)
  - Antonín Komenda antonin.komenda@fel.cvut.cz
  - Michaela Urbanovská urbanm30@fel.cvut.cz
- Stochastic Planning (Part 2)
  - Stefan Edelkamp
  - Jan Mrkos

# Freshman's Sokoban Example



https://www.sokobanonline.com/play/community/experiment/127458_practice

# Pondering Sokoban Example



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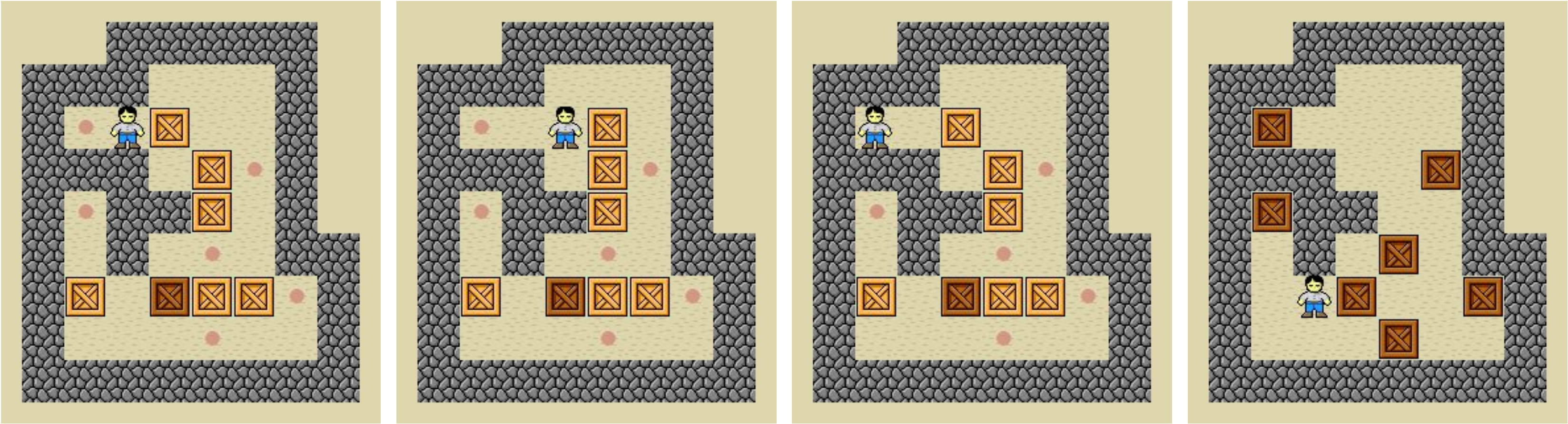
# Classical Planning Elements

- **States**
- Actions
- Initial state
- Goal states



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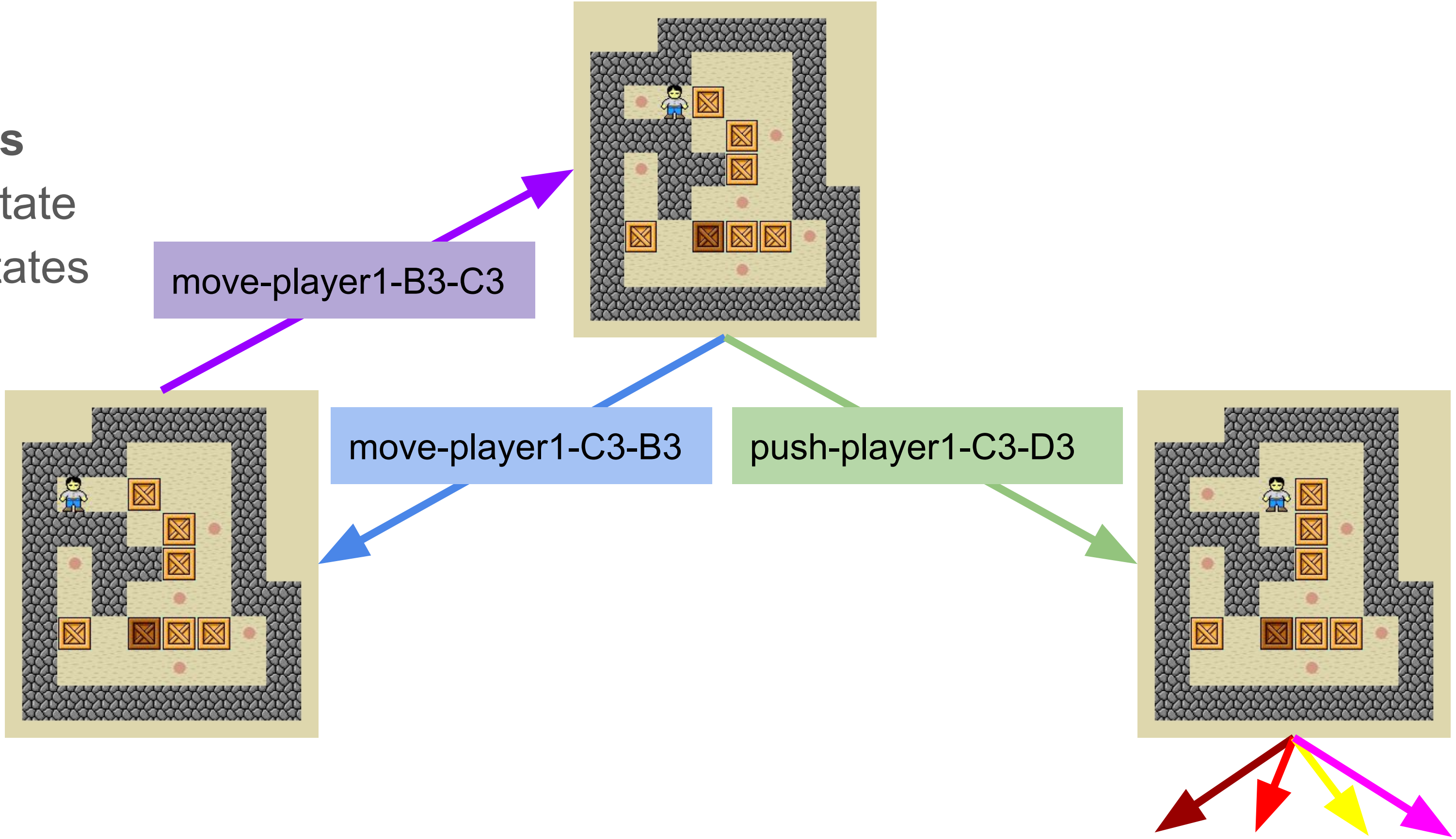
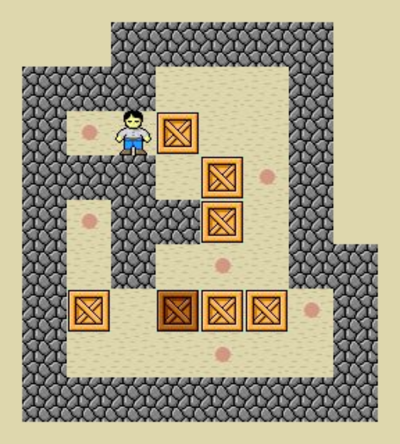


# Classical Planning Elements

- States
- Actions
- **Initial state**
- **Goal states**

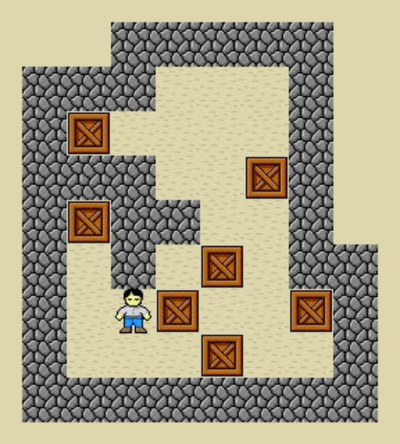
- **Problem:**

the initial state



$\rightsquigarrow$

a goal state



- **Solution: a plan**

  π=(move-player1-C3-B3, move-player1-B3-C3, push-player1-C3-D3, ...)

(under the regular Sokoban rules)

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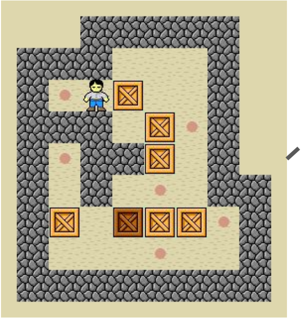
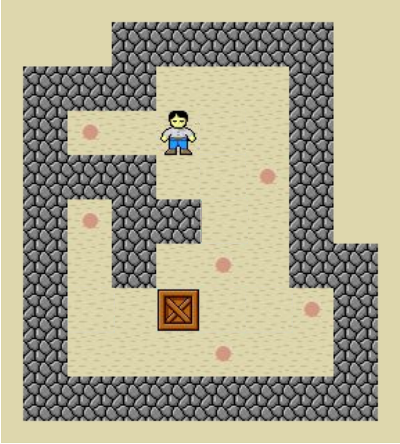
# Classical Planning Elements

- **States**
- Actions
- Initial state
- Goal states

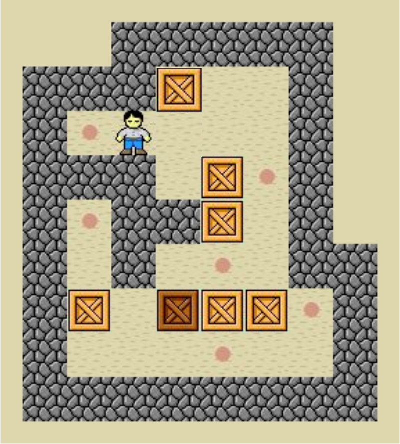
the initial state



an unreachable state



a dead-end state



(under the regular Sokoban rules)

# What is Automated Planning?

- Artificial Intelligence (sub-field)
  - (general) problem solving
- Decision Theory meets Computer Science
  - sequential decision making
  - various forms of combinatorial optimization problems
- Three approaches in AI to the problems of action selection or control
  - Learning: learn control from experience
  - Programming: specify control by hand
  - Planning: specify problem by hand, derive control automatically

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# Automated Planning is Hard

- just search in the space of states using actions?

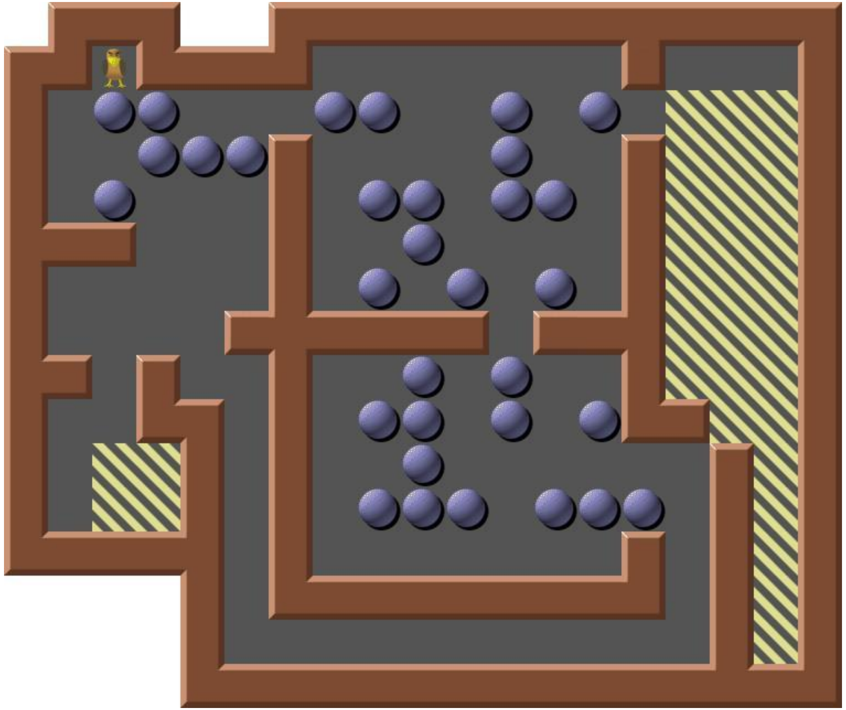
- **exponential** dependence on size of the problem
- **exponentially** long plans

- planning with “sane” length of plans is NP-complete
- classical planning is PSPACE-complete
- multi-agent variants are NEXP-complete

```
number of cells
 n | configs for (n/2) boxes

 2 | 2
 4 | 6
 6 | 20
 8 | 70
10 | 252
12 | 924
14 | 3432
16 | 12870
18 | 48620
20 | 184756
22 | 705432
24 | 2704156   | ~10^6
26 | 10400600  | ~10^7
28 | 40116600  | ~10^7
30 | 155117520 | ~10^8
...
```

# Serious Sokoban Example



[90 596 769 259 248 050 560 796 925 567 405 729]

~$10^{34}$ configurations of boxes

~$10^{70}$ +colored boxes

~$10^{81}$ +5 simultaneous players

estimated number of atoms in the observable universe: $10^{78}$–$10^{82}$, ups ;)

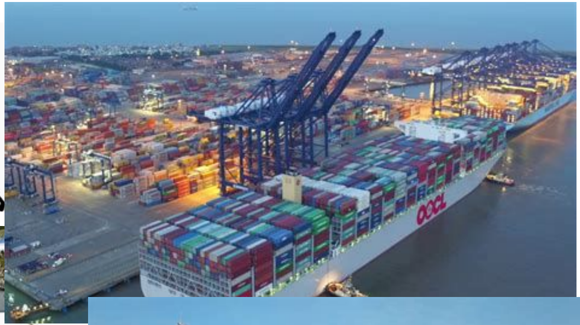
# Automated Planning is Hard

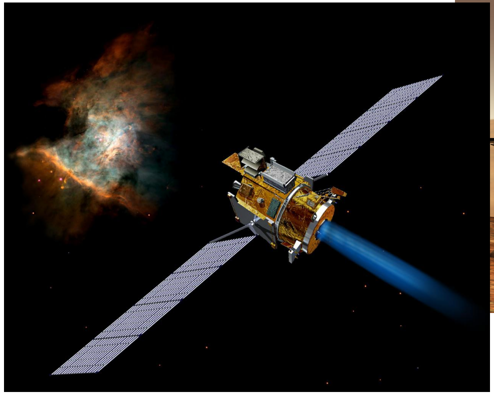
- computational hardness tells us nothing about the complexity of **individual problem instances**
- what about a problem, where each box is next to its goal cell and the player is not blocked to get to all of them?
- what about the Serious Sokoban example?
  solving such a problem is not hopeless!
  (it needs only ~$2 \cdot 10^7$ states to search through)

- → problem structure ($P \stackrel{?}{=} NP$)
- → clever representations
- → clever simplifications

# Domains

puzzles; computer, board, card games; production planning offshore drilling, and logistics; humanitarian and military missions; various-scale robotics; space missions



# Domain-independent and Domain-specific

Domain-independent:

- fundamental
- flexible
- reusable

Domain-specific:

- rigid
- efficient
- specialized

# Domain-independent and Domain-specific

Domain-independent:

- **fundamental**
- flexible
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Domain-specific:

- rigid
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- specialized


Until we get the fundamental principles ...

# Domain-independent and Domain-specific

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Domain-independent:

- fundamental
- **flexible**
- **reusable**

Domain-specific:

- rigid
- efficient
- specialized

… we cannot be flexible and we cannot reuse ...

# Domain-independent and Domain-specific

Domain-independent:

- fundamental
- flexible
- reusable

Domain-specific:

- **rigid**
- **efficient**
- specialized

… we cannot optimize or ...

# Domain-independent and Domain-specific

Domain-independent:

- fundamental
- flexible
- reusable

Domain-specific:

- rigid
- efficient
- **specialized**

… specialize.

# Domain-independent and Domain-specific

Domain-independent:

- general structural properties and general algorithms
- automatically derived heuristics
- graph theory or probability theory, optimization theory, logic, algebra

Domain-specific:

- specific problems or specific structural families
- hand-crafted heuristics
- data structures, algorithmization, code efficiency

# Wanna plan?

## Representation → Search + Heuristics

- Representation (Lecture 2)
  - structurally analyze and **compactly represent** the problem
  - **deduce information** helping with solution of the problem
- Search (Lecture 3)
  - do not enumerate all states and actions
  - **find path** through the **implicit graph**
- Heuristics (Lectures 5, 6, 7)
  - **navigate the search** using simplified variant of the problem
  - how? relaxation, abstraction, structural information (e.g., landmarks or potentials)
  - machine learned heuristics

# Wanna plan?

**Representation** → Search + Heuristics

# **Representation** → Search + Heuristics

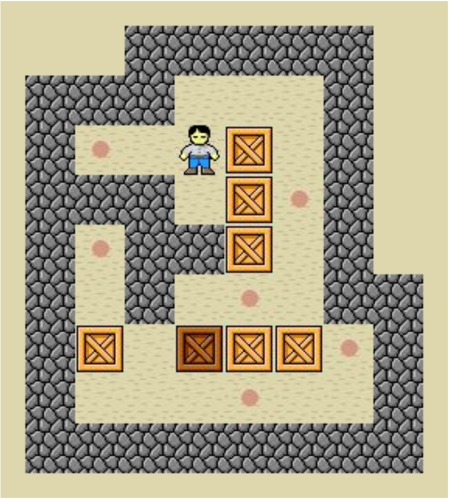
- factorized representation

```
{player1-at ∈ {A1, A2, …, B1, B2, ...},
 box1-at    ∈ {A1, A2, …, B1, B2, ...}, …}
```

- compact representation (+grounding)

```
move(who, from, to) → {move-player1-C3-B3, …}
```

- grounding of actions usable in reachable states only
- grounding of actions not leading to dead-ends only
- structural reductions
- prepare usable information for the search and heuristics

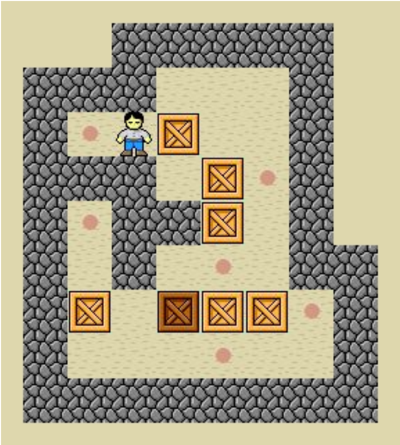


# Wanna plan?

Representation → **Search** + Heuristics

# Representation → **Search** + Heuristics

the initial state



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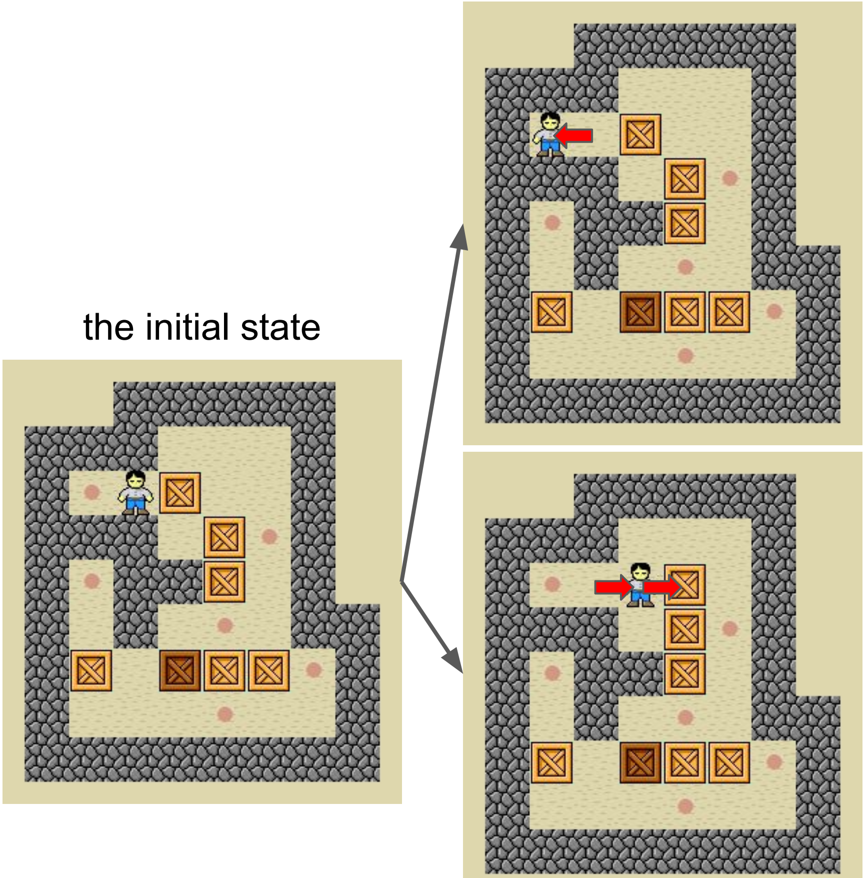

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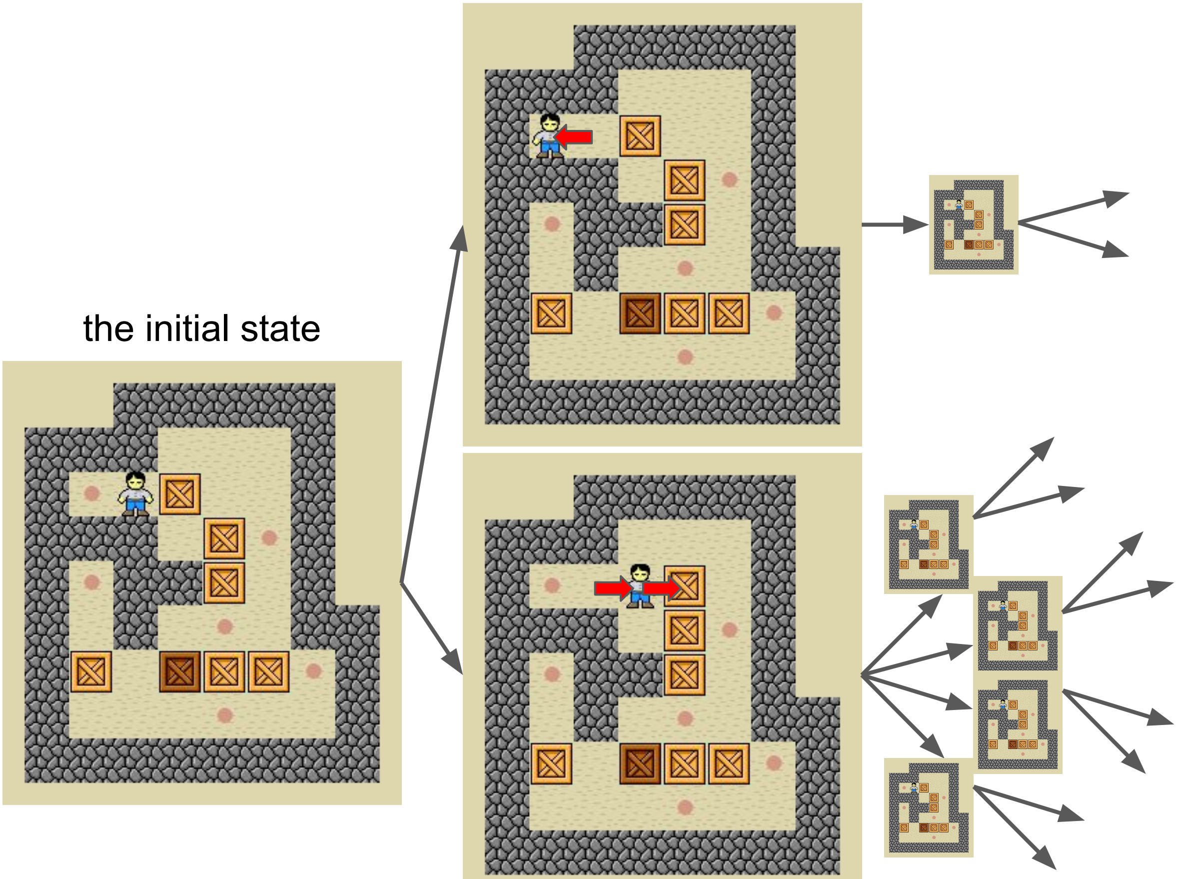

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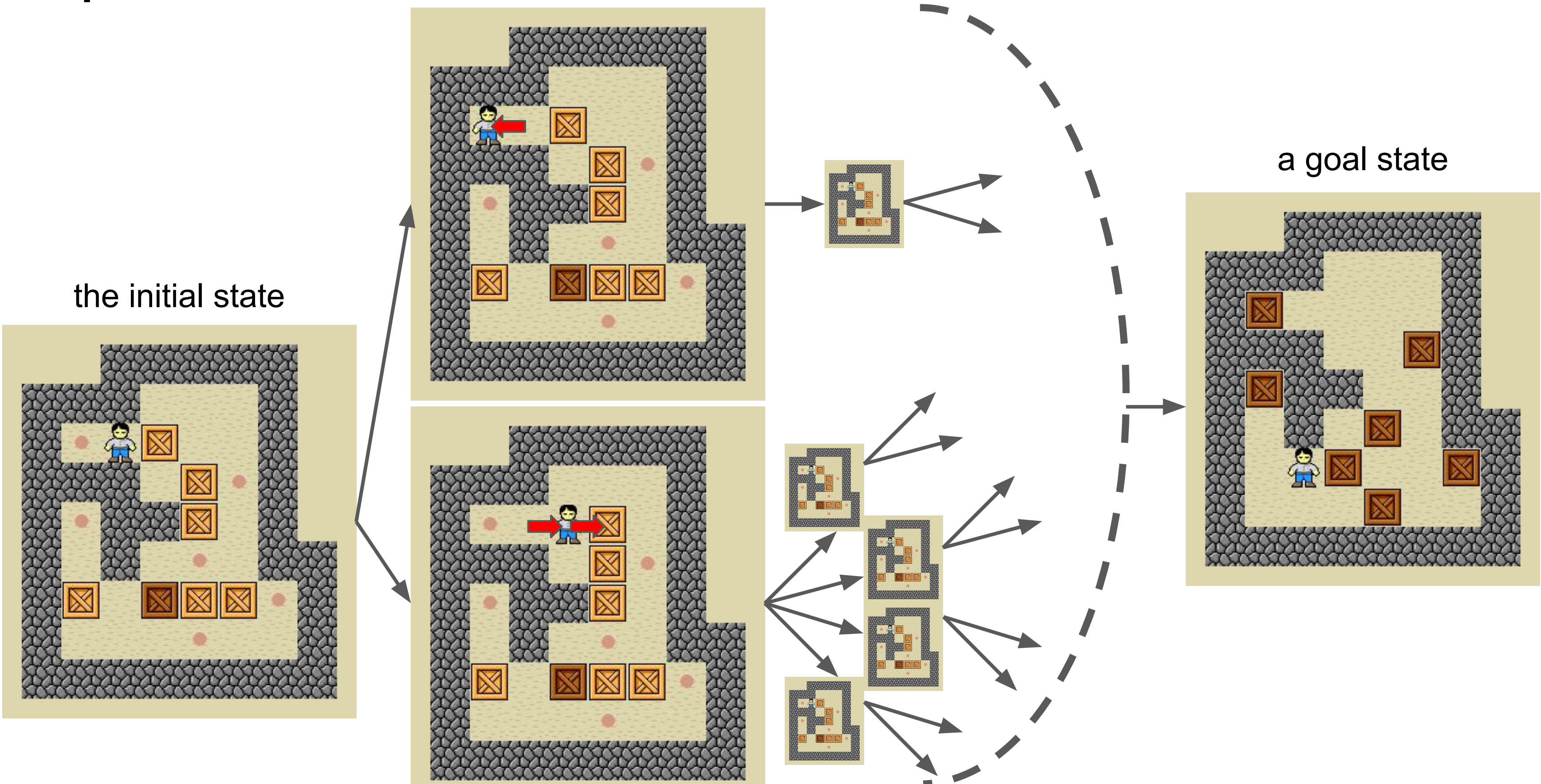

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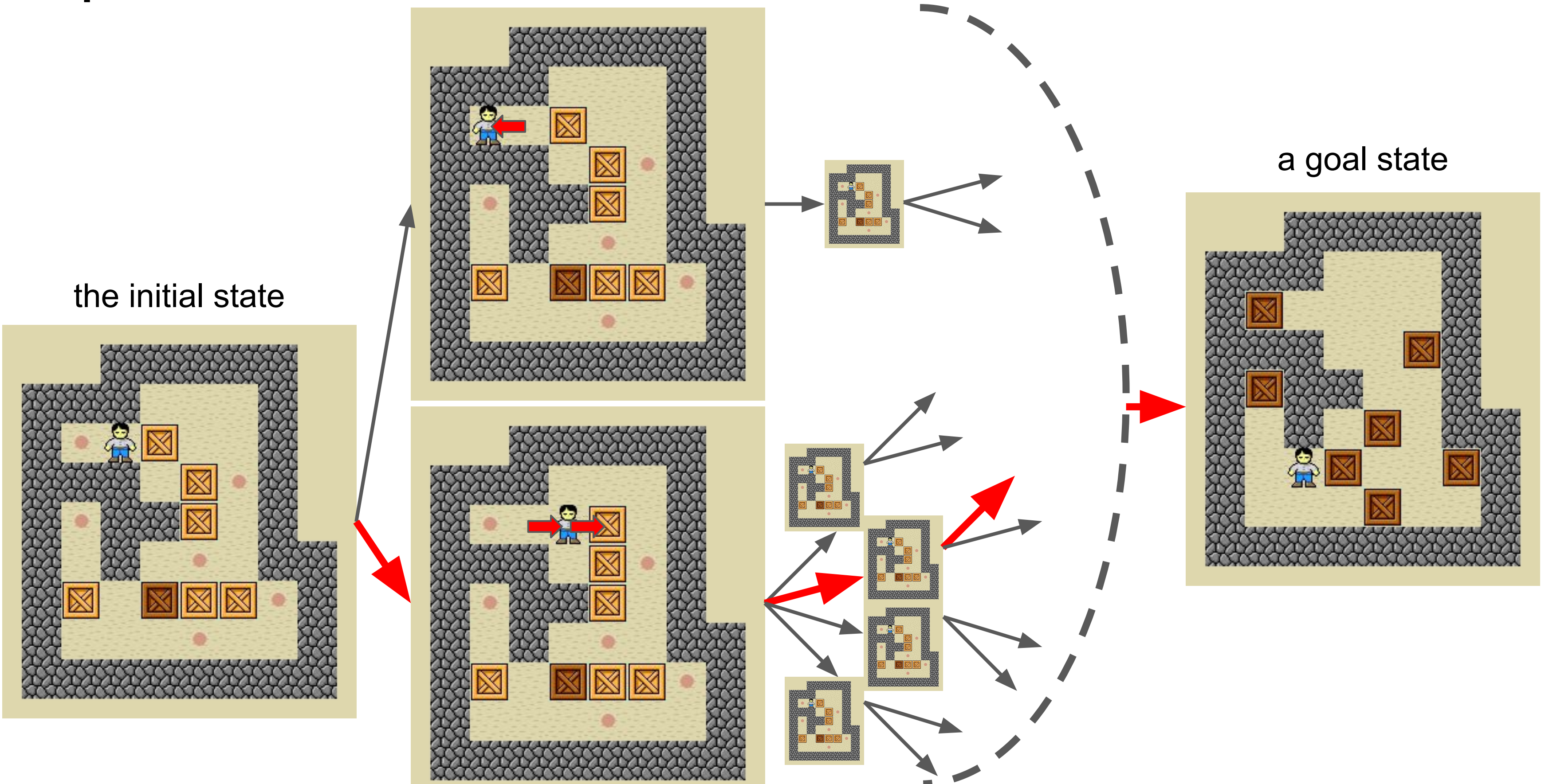

# Wanna plan?

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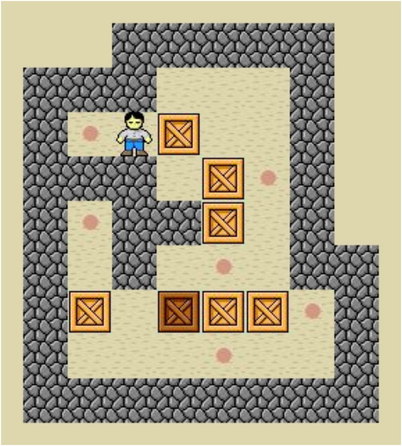
Representation → Search + **Heuristics**

Heuristics are strategies using readily accessible, though loosely applicable, information to control problem solving in human beings and machines. (J. Pearl)

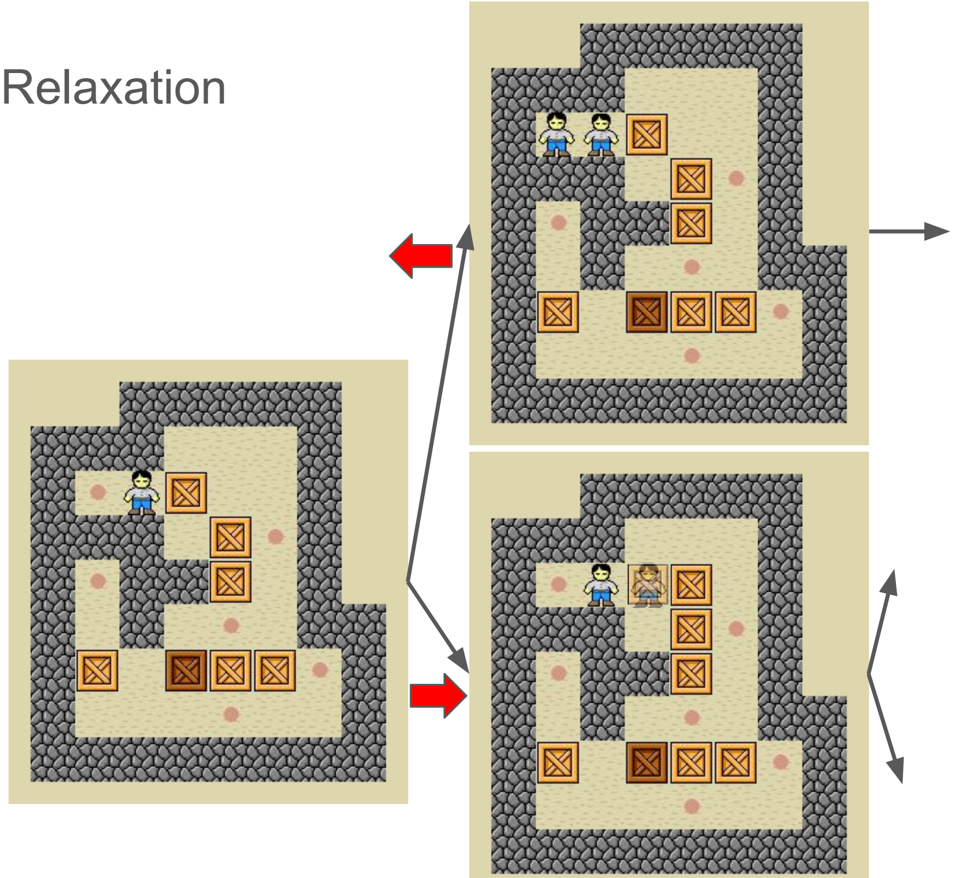
# Representation → Search + **Heuristics**

Relaxation



# Representation → Search + **Heuristics**

Relaxation



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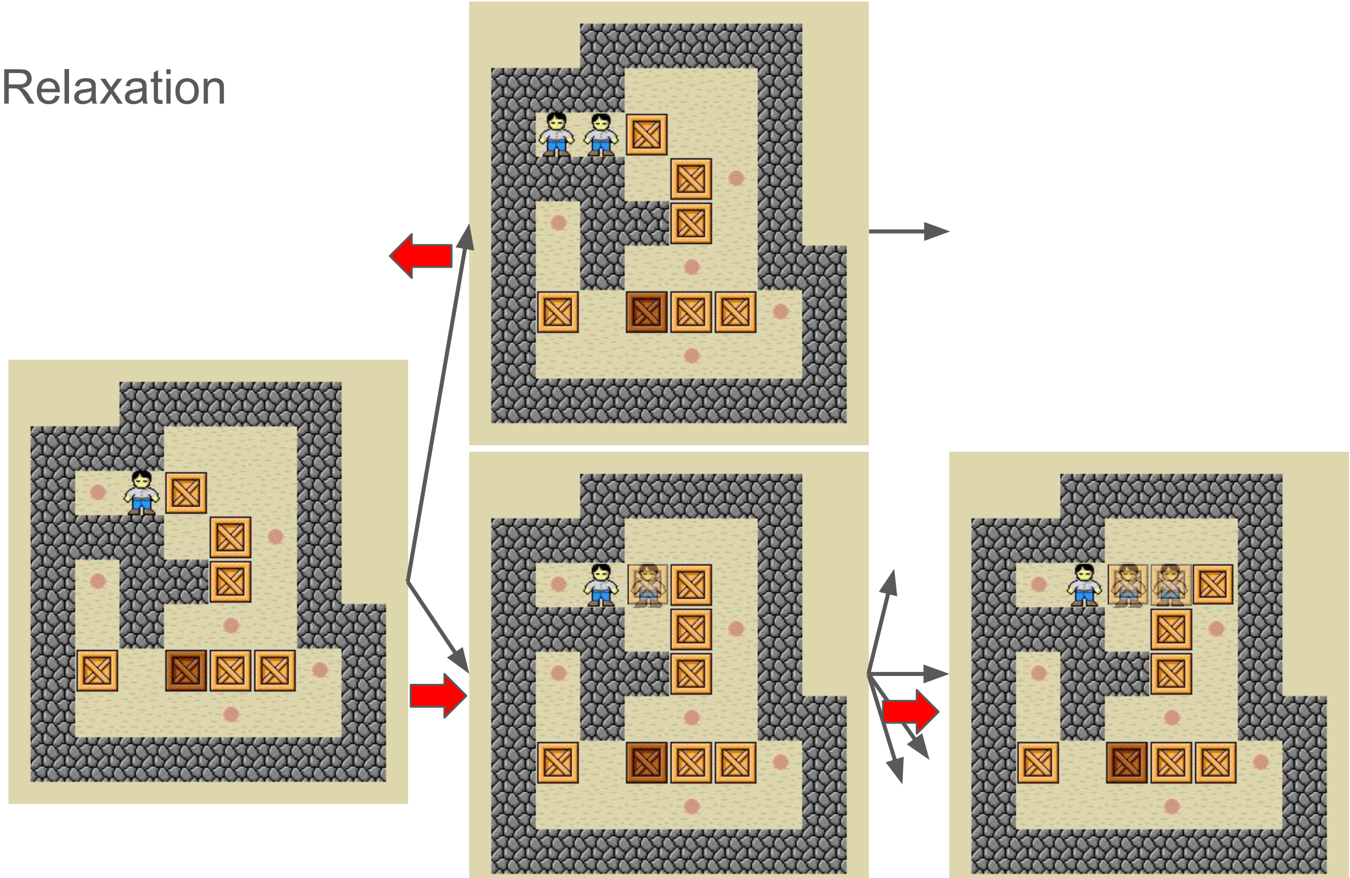

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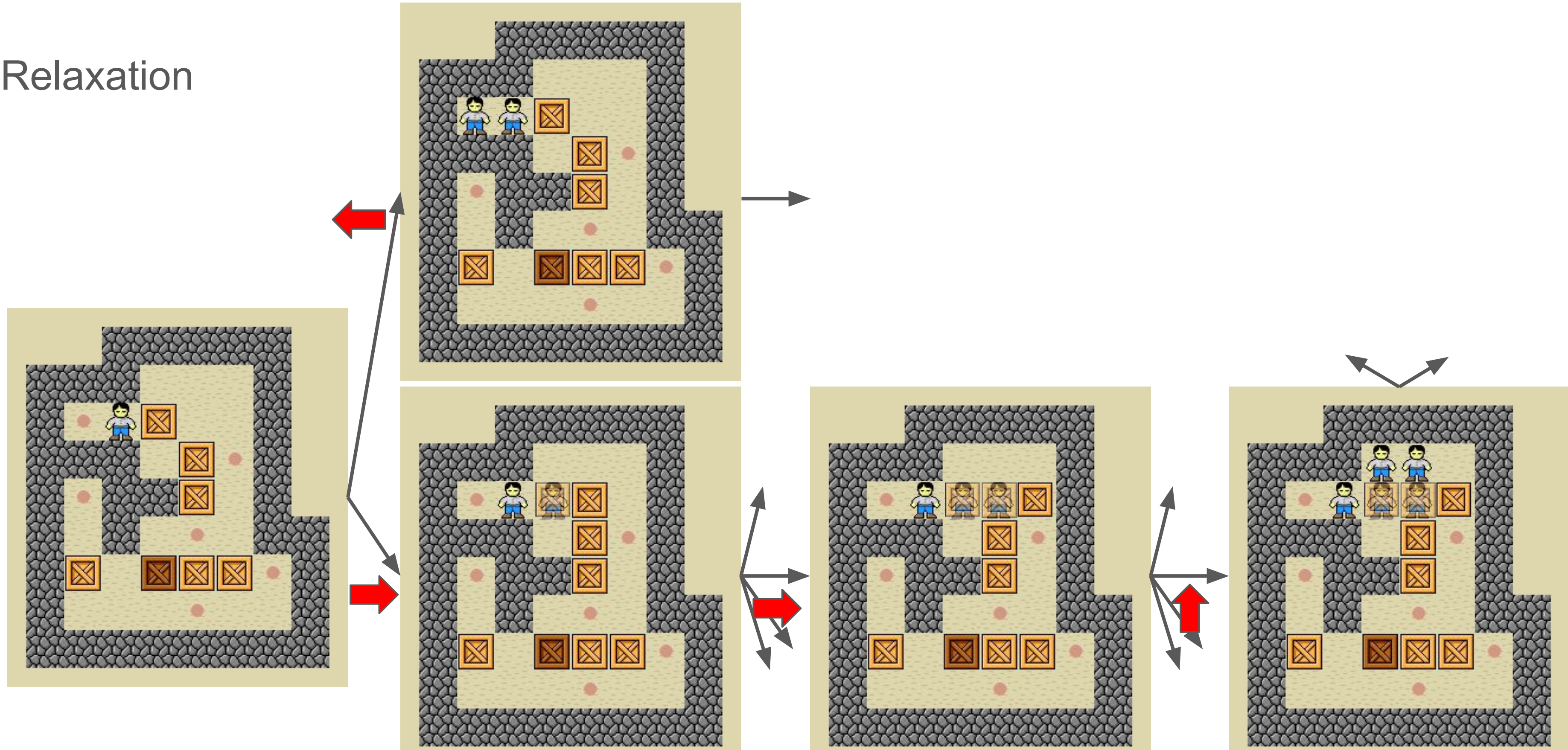
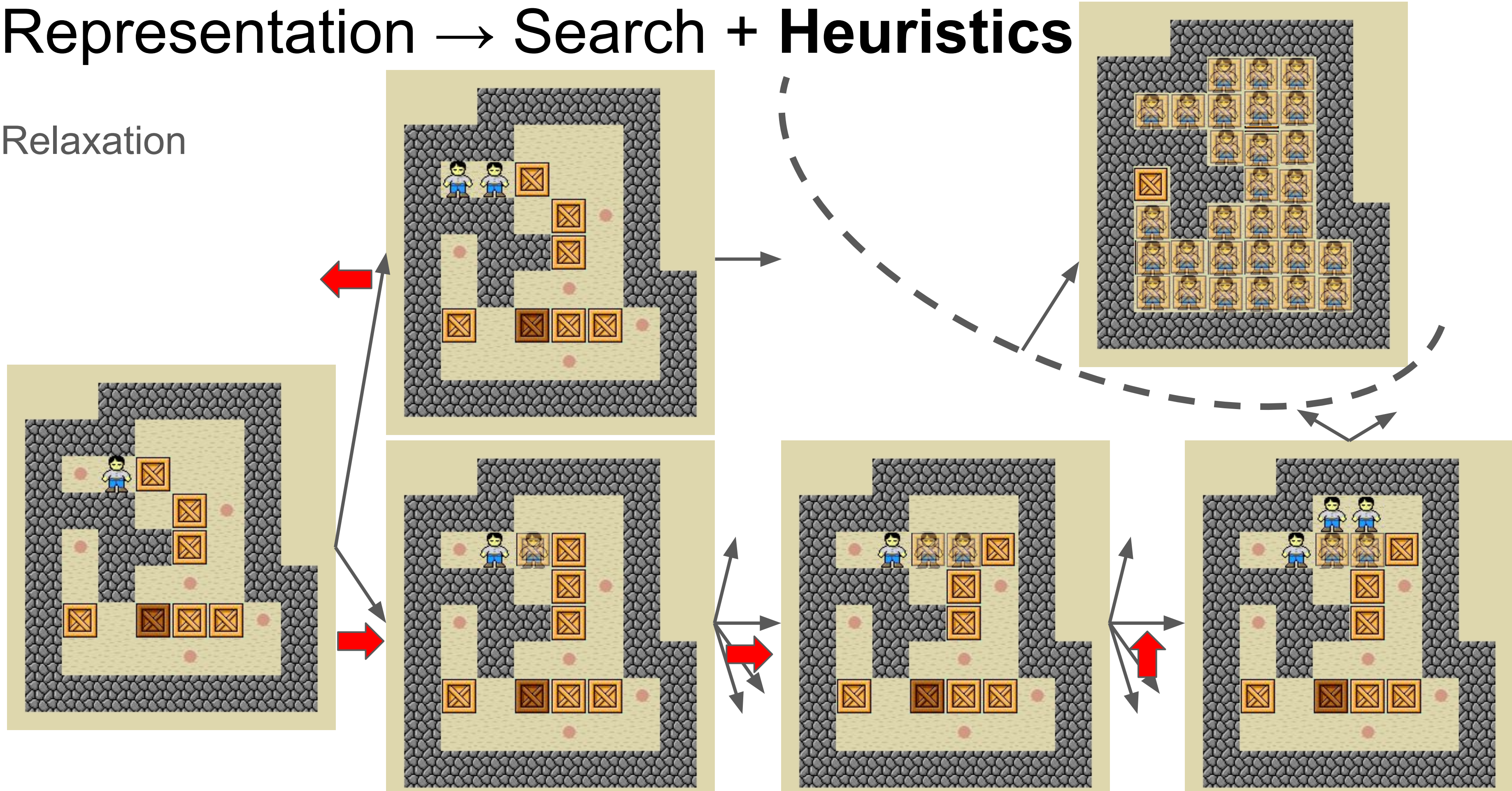


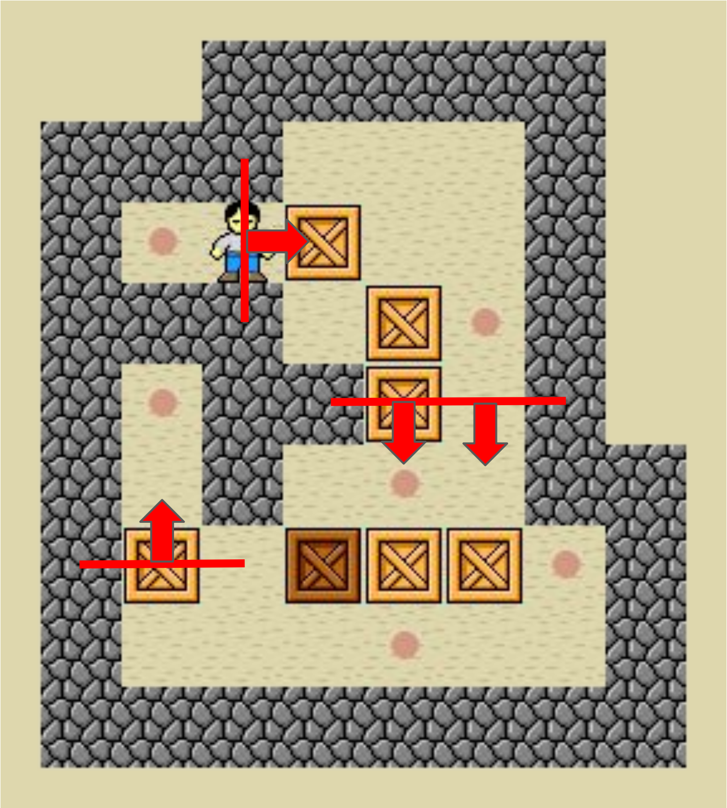
# Representation → Search + **Heuristics**

Relaxation



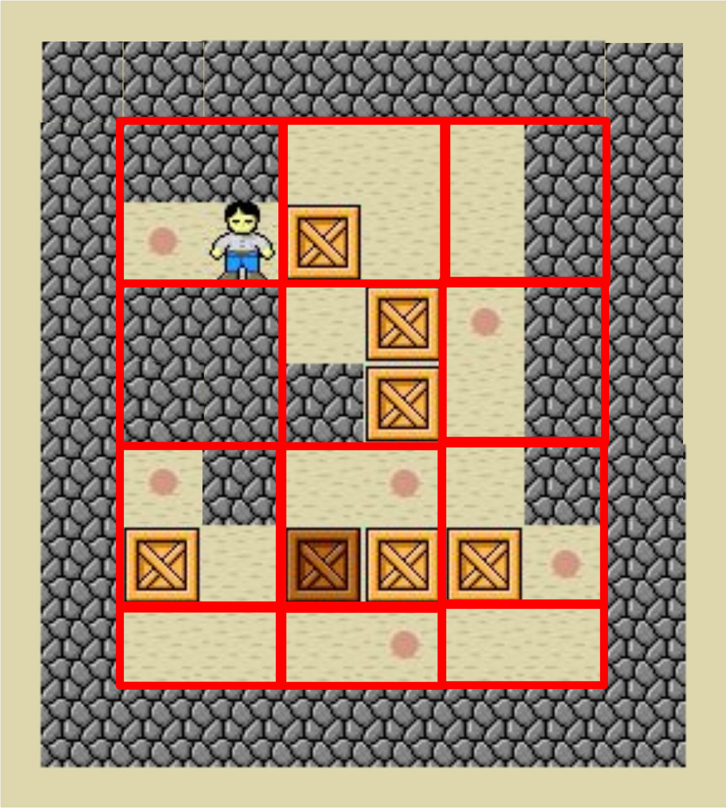
# Representation → Search + **Heuristics**

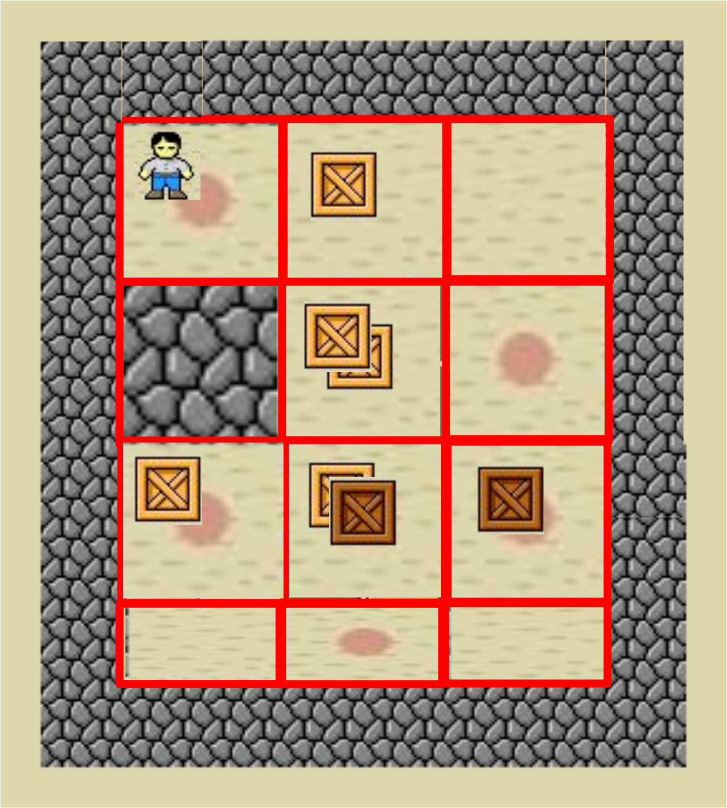
Landmarks



# Representation → Search + **Heuristics**

Abstraction





# Not Enough?

Are you trying to understand fundamentals of solving toy problems and puzzles?

# Not Enough?

Are you trying to understand fundamentals of solving toy problems and puzzles?

That’s not enough for me!

# Not Enough? Good.

- **domain-independent** ↔ domain-specific
- **off-line** ↔ on-line
- **deterministic** ↔ stochastic ↔ non-deterministic
- **fully-observable** ↔ partially-observable ↔ unobservable
- **instantaneous actions** ↔ durative actions
- **discrete** ↔ continuous fluents
- **linear** ↔ partially ordered/temporal
- **hard goals** ↔ soft goals
- **satisficing** (approximative) ↔ optimal
- **single-agent** ↔ multi-agent
- **plan** ↔ policy

# Not Enough? Good.

- domain-independent ↔ **domain-specific**
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# Not Enough? Good. But Be Aware, Because ...

- domain-inde
- off-line ↔ **o**
- deterministic
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# Automated Planning Elements (Recall)

- States
- Actions
- Initial state
- Goal states

# Automated Planning Elements (→ Real World)

- Agents
- States
- Observations
- Actions
- Transitions
- Costs
- Stochasticity
- Temporal, deontic, modal logics
- (Unknown) Initial state
- Common (Cumulative) Reward
- ...

# Automated Planning Elements (→ Real World)

- Agents
- States
- Observations
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- ...

Challenge Accepted!