

# COMP219: Artificial Intelligence

## Lecture 11: Search in Complex Environments

## Overview

- Last time
  - Uniform cost search
  - Heuristics and heuristic search (greedy, A\*)
- Today:
  - Search with partial observations
  - Belief states
- Learning outcome covered today:  
Identify, contrast and apply to simple examples the major search techniques that have been developed for problem-solving in AI;

1

2

## Problem Types

- Deterministic, fully observable **single-state problem**
  - Agent knows exactly which state it will be in; solution is a sequence
- Non-observable **sensorless problem (conformant problem)**
  - Agent may have no idea where it is; solution is a sequence
- Non-deterministic and/or partially observable **contingency problem**
  - predicting the evolution of the environment becomes impossible
  - percepts provide **new** information about current state

“For this reason, many people keep their eyes open while walking around or driving” – Russel&Norvig

  - often **interleave** search, execution
- Unknown state space **exploration problem**

3



## Search Without Full Observation

- Agent’s percepts do not determine the exact state
- If agent in one of several possible states then an action may lead to one of several possible outcomes
- **Belief state:** agent’s **current belief** about the possible **physical states** it might be in (given history – sequence of actions + percepts)

4

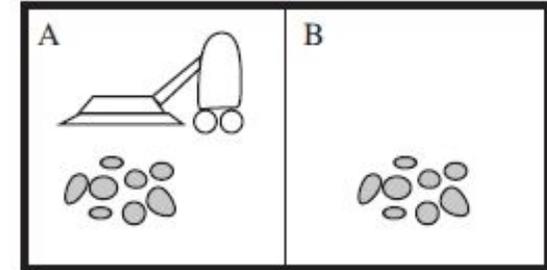
# Search with No Observations

- Sensorless problem
- No need to rely on sensors working properly, e.g. manufacturing
- Less costly
- Search in belief states not physical states



# Example: Robot Vacuum Cleaner World

- Actions:
  - Right
  - Left
  - Suck

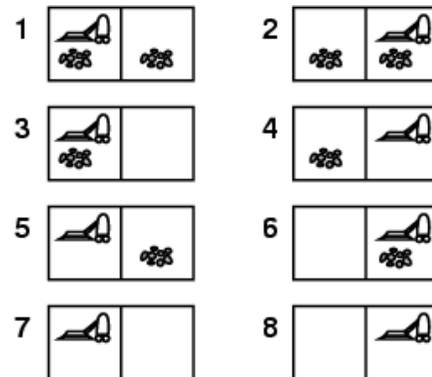


## Example: vacuum world - 1

Single-state:

- Start in #5

Solution?



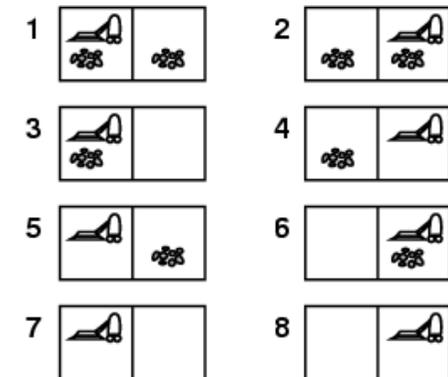
## Answer: vacuum world - 1

Single-state:

- Start in #5

Solution?

- *[Right, Suck]*

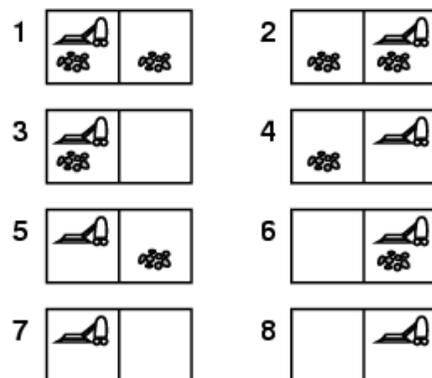


## Example: vacuum world - 2

### Sensorless:

- Start in {1,2,3,4,5,6,7,8}
- e.g. *Right* goes to {2,4,6,8}

Solution?



9

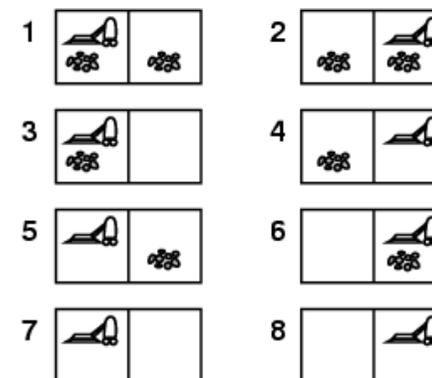
## Answer: vacuum world - 2

### Sensorless:

- Start in {1,2,3,4,5,6,7,8}
- e.g. *Right* goes to {2,4,6,8}

Solution?

- [*Right,Suck,Left,Suck*]



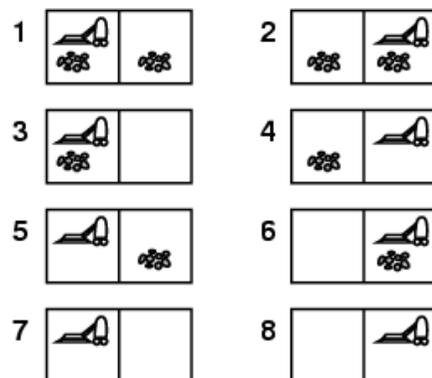
10

## Example: vacuum world - 3

### Contingency:

- *Non-deterministic*: suck may dirty a clean carpet
- *Partially observable*: location, dirt at current location
- Percept: [A, Clean] i.e. start in #5 or #7

Solution?



11

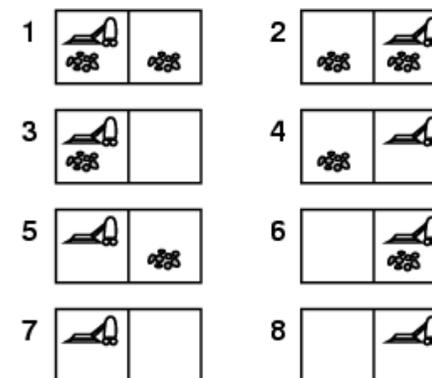
## Answer: vacuum world - 3

### Contingency:

- *Non-deterministic*: suck may dirty a clean carpet
- *Partially observable*: location, dirt at current location
- Percept: [A, Clean] i.e. start in #5 or #7

Solution?

- [*Right, if dirt then Suck*]



12

## No Observations: Constructing a Belief State Search Problem

- Physical problem  $P$  is defined by  $Actions_p$ ,  $Result_p$ ,  $Goal-Test_p$ ,  $Step-Cost_p$
- Sensorless problem is defined by:
  - **Belief States** – every possible set (B) of physical states
  - **Initial State** – set of all states in  $P$
  - **Actions**
  - **Transition model**
  - **Goal test** – all states in belief state must satisfy goal
  - **Path cost**

13

## Transition Model

- For deterministic actions, the set of states that might be reached is:
 
$$b' = Result(b, a) = \{s' : s' = Result_p(s, a) \text{ and } s \in b\}$$
  - $b'$  is never larger than  $b$
- For non-deterministic actions:  $b'$  may be larger
- Prediction step** is process of generating the new belief state after the action

$$b' = Predict_p(b, a)$$

15

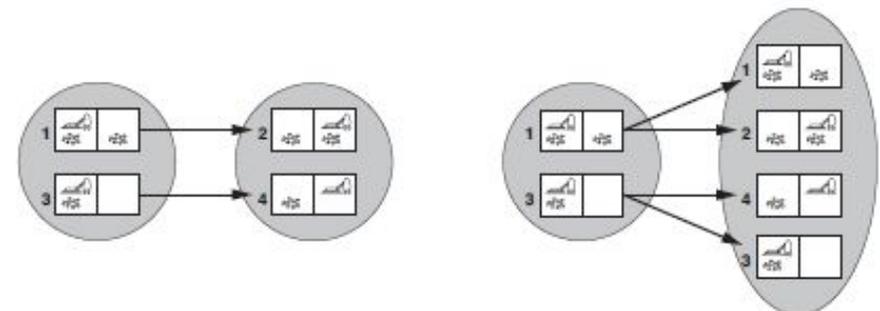
## Determining Possible Actions

- Depends on whether it's safe to execute actions in states where they are not applicable
  - have an effect on the environment?
- If safe, **union** of all actions:
 
$$Actions(b) = \bigcup_{s \in b} Actions_p(s)$$
- Otherwise, only allow the **intersection**, i.e. actions which are legal in **all** states

14

## Prediction Step: Vacuum World

- Action: [Right]

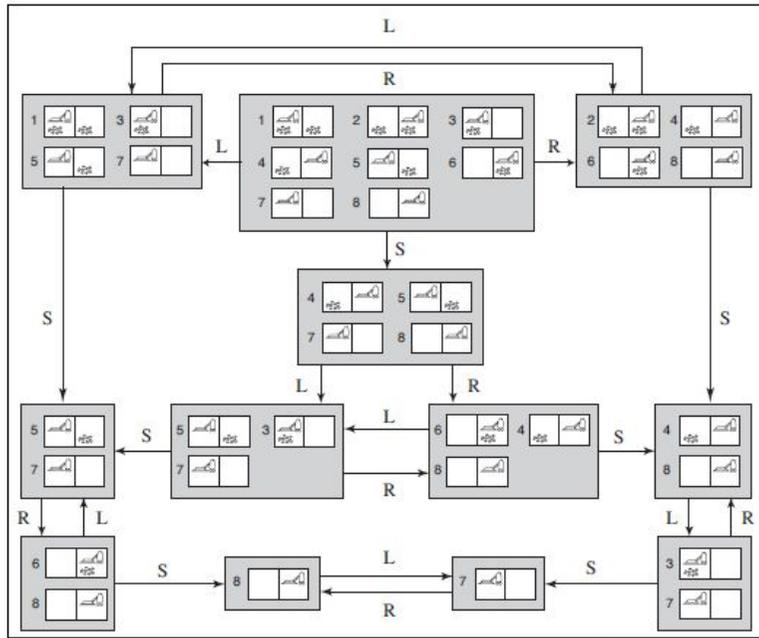


Deterministic

Non-deterministic  
'slippery'

16

# Belief State Problem: Vacuum World



17

# Pruning the Belief State Graph

- Repeated belief states: don't add to agenda
  - E.g.,  $[Suck, Left, Suck]$  reaches the same  $b$  as  $[Right, Left, Suck] = \{5, 7\}$
- Moreover, if an action sequence is a solution for a belief state  $b$ , it is also a solution for any subset of  $b$ 
  - Suppose  $\{5, 7\}$  has already been generated
  - Consider  $[Left]$ :  $b = \{1, 3, 5, 7\}$
  - Can **discard** that path as its subset  $\{5, 7\}$  will lead to solution whenever  $\{1, 3, 5, 7\}$  does

18

# Sensorless Problem Solving

- **Problem:** Size of each belief state
- e.g.
  - 10 x 10 vacuum world
  - $100 \times 2^{100} = 10^{32}$  physical states

19

# Incremental Belief State Search

- Unlike standard search algorithms, look **inside**  $b$
- Build up solution **one physical state at a time**
- One solution for all states
- Find action sequence that works for all states:
  - Find solution for state 1
  - Check if it works for state 2, then state 3, etc.
  - If not, find different solution for state 1, etc.
- Advantage: detects failure quickly
  - If  $b$  unsolvable, usually the small subset of first few states examined is also unsolvable

20

# Searching with Partial Observations

- Specify how the environment generates percepts
  - e.g. vacuum agent has position and local dirt sensor but no dirt sensor for other squares
  - Percept(state 1) = [A,Dirty]
- Usually several states could have produced the same percept
  - e.g. [A,Dirty] = {1, 3}

# Searching with Partial Observations - Transitions

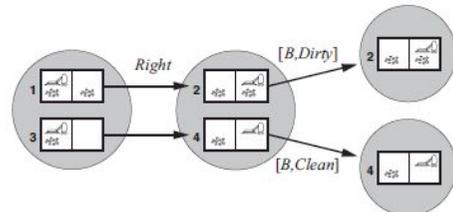
- 3 stages:
  - Prediction** stage - same as sensorless problems
 
$$\hat{b} = \text{Predict}(b, a)$$
  - Observation prediction** stage determines set of percepts  $o$  that could be observed in predicted belief state
 
$$\text{Possible-Percepts}(\hat{b}) = \{o : o = \text{Percept}(s) \text{ and } s \in \hat{b}\}$$
  - Update** stage - for each possible percept, determine which belief states could result from the percept
 
$$b_o = \text{Update}(\hat{b}, o) = \{s : o = \text{Percept}(s) \text{ and } s \in \hat{b}\}$$
- Percepts reduce uncertainty

21

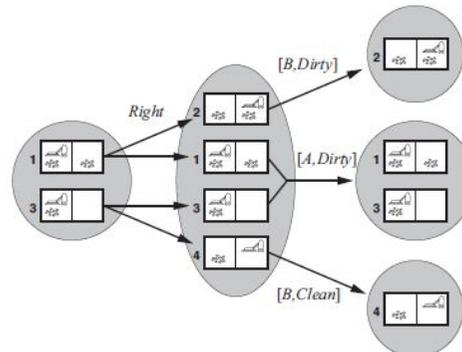
22

## Transitions: Vacuum World

Deterministic



Non-deterministic 'slippery'



23

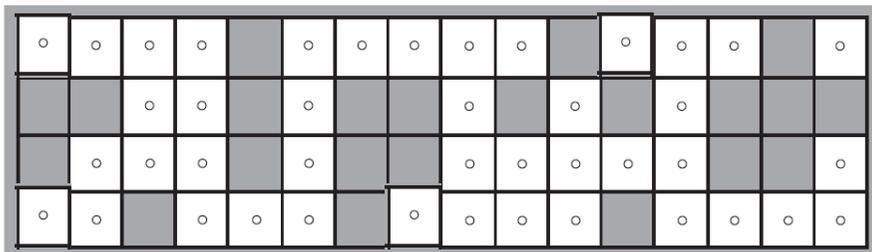
## Exercise

- A robot has the task of localisation, i.e. working out where it is given a map of the world and a sequence of percepts and actions
- 4 sonar sensors tell the robot whether there is an obstacle in each compass direction (NESW)
- MOVE action moves randomly to an adjacent square

24

## Exercise: Localisation

- Where is the robot?

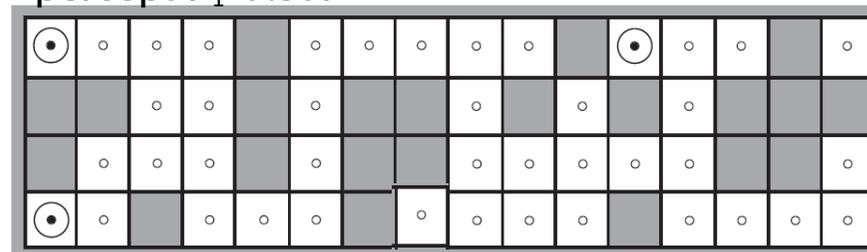


- After one percept  $P_1=NSW$ ?

25

## Exercise: Localisation

- Possible locations of the robot after one percept  $P_1=NSW$

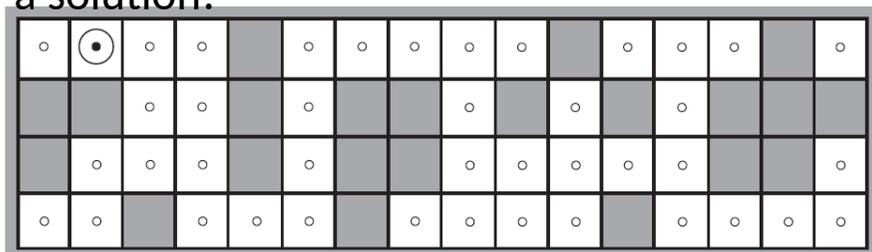


- After MOVE and next percept  $P_2=NS$ ?

26

## Exercise: Localisation

- After MOVE and next percept  $P_2=NS$  we have a solution!



27

## Summary

- Search with no observation
  - Belief states
  - Pruning the belief state graph
  - Incremental belief state search
- Search with partial observation
  - Transitions: prediction; observation prediction; update
- Next time
  - Applying search to games

28