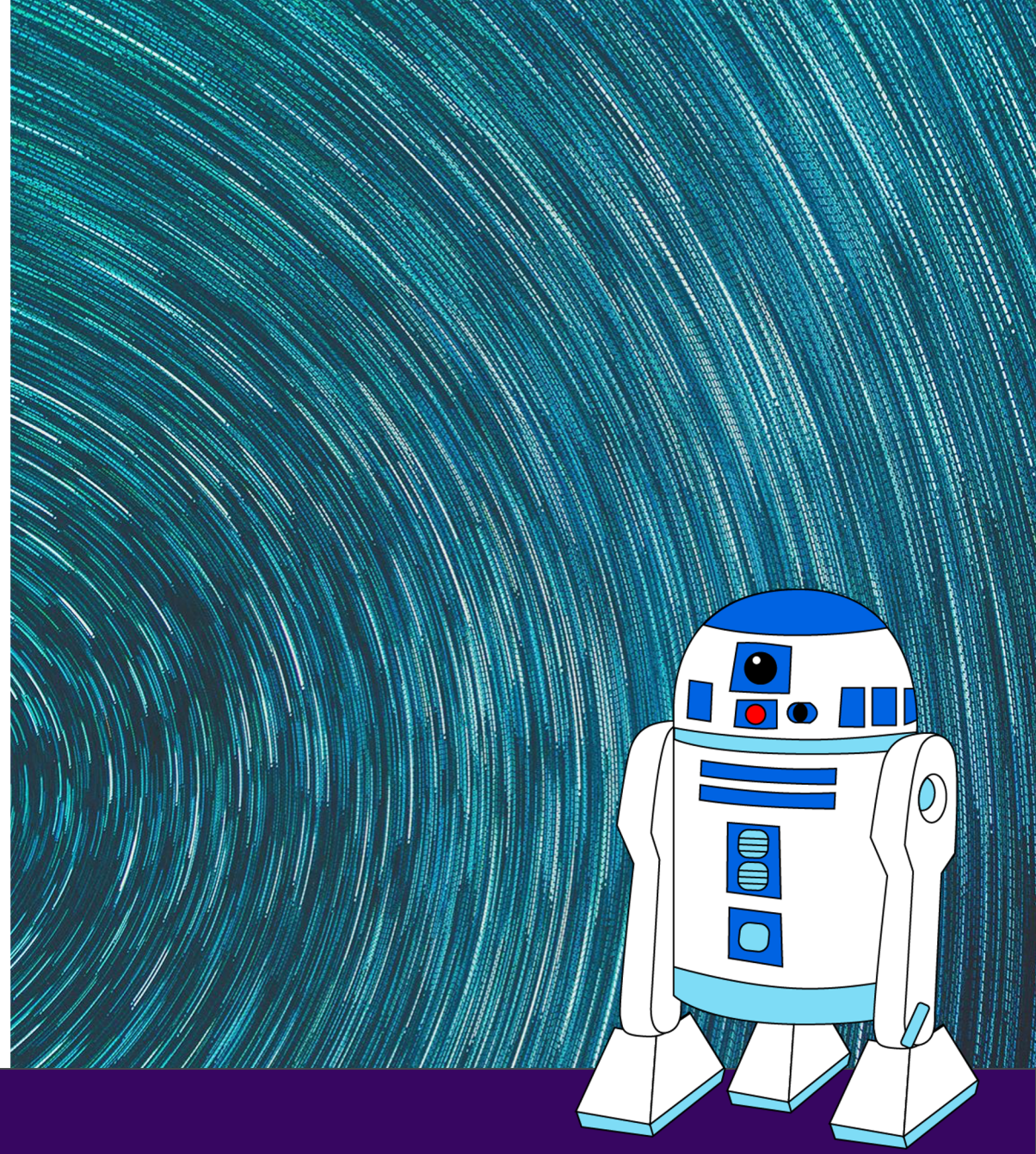
CIS 421/521:
ARTIFICIAL INTELLIGENCE

Rational Agents and Search Problems



Penn Engineering
University of Pennsylvania

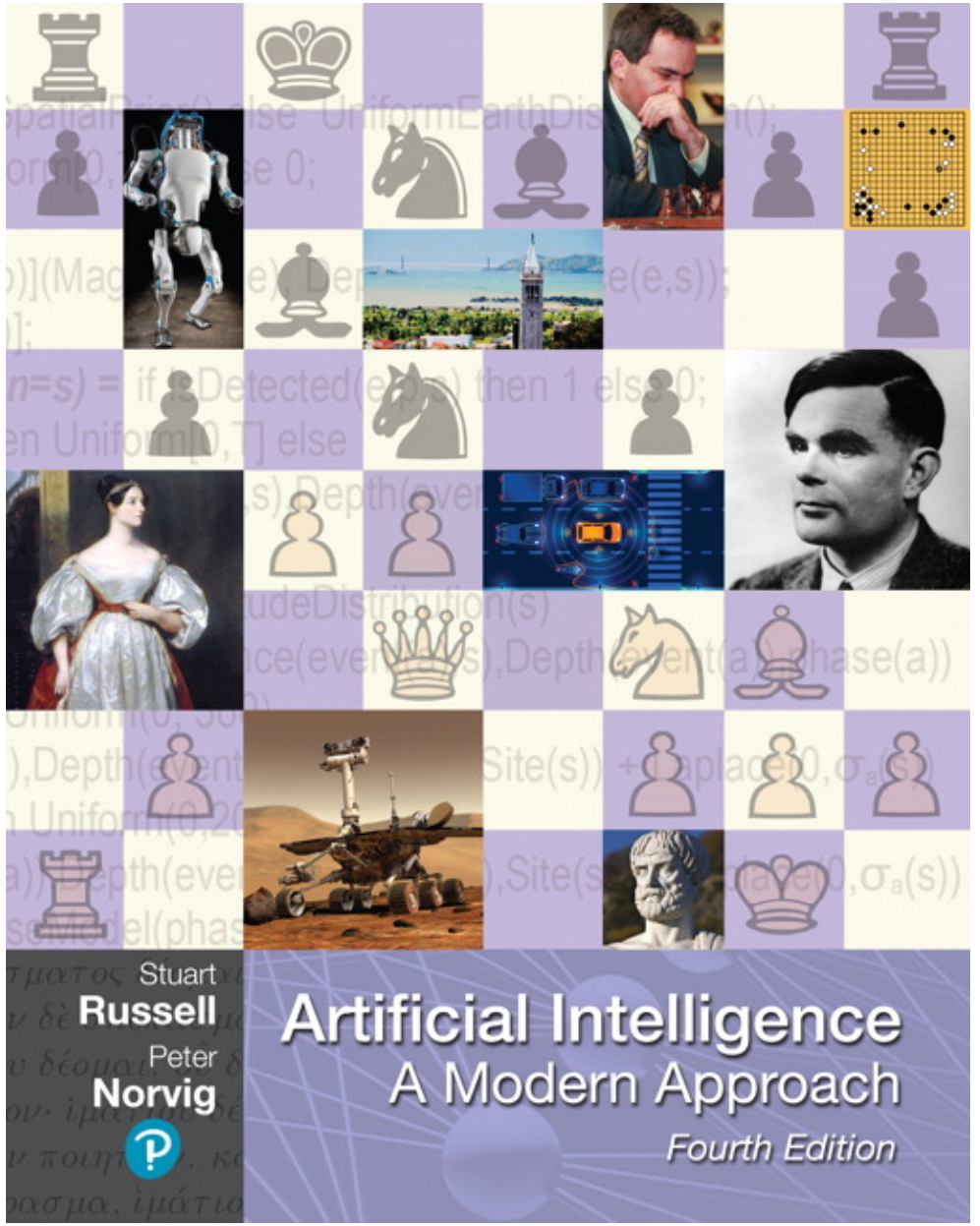
Outline for today's lecture

Intelligent Agents (AIMA 2.1-2.4)

Task Environments

Formulating Search Problems

Uninformed Search (AIMA 3.1-3.4)



Four views of Artificial Intelligence

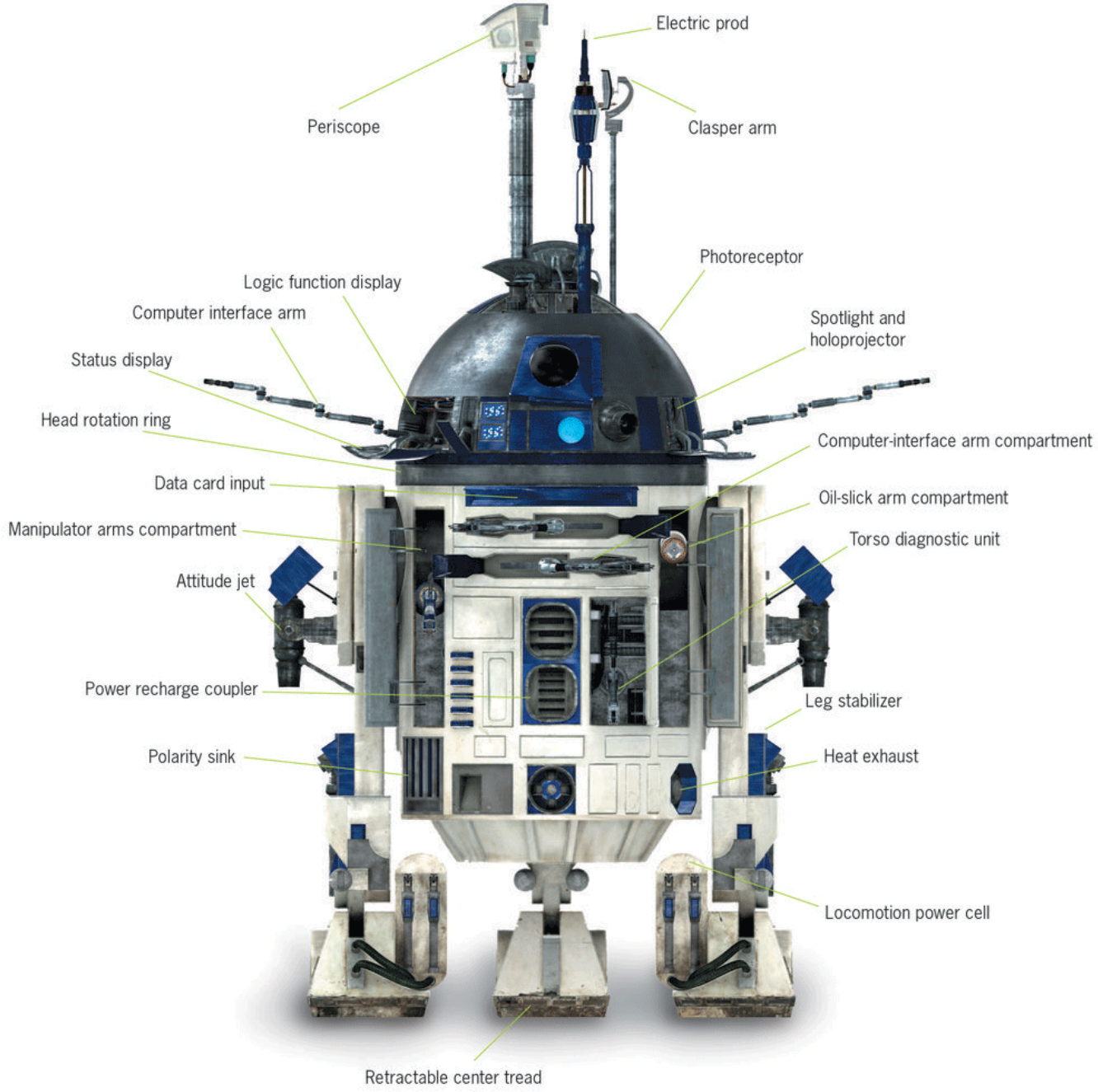
Thinking humanly	**Thinking rationally**
Acting humanly	**Acting rationally**

This course is about effective programming techniques for designing rational agents

Agents

An **agent** is anything that **perceives** its environment through **sensors** and can **act** on its environment through **actuators**

A **percept** is the agent's perceptual inputs at any given instance.

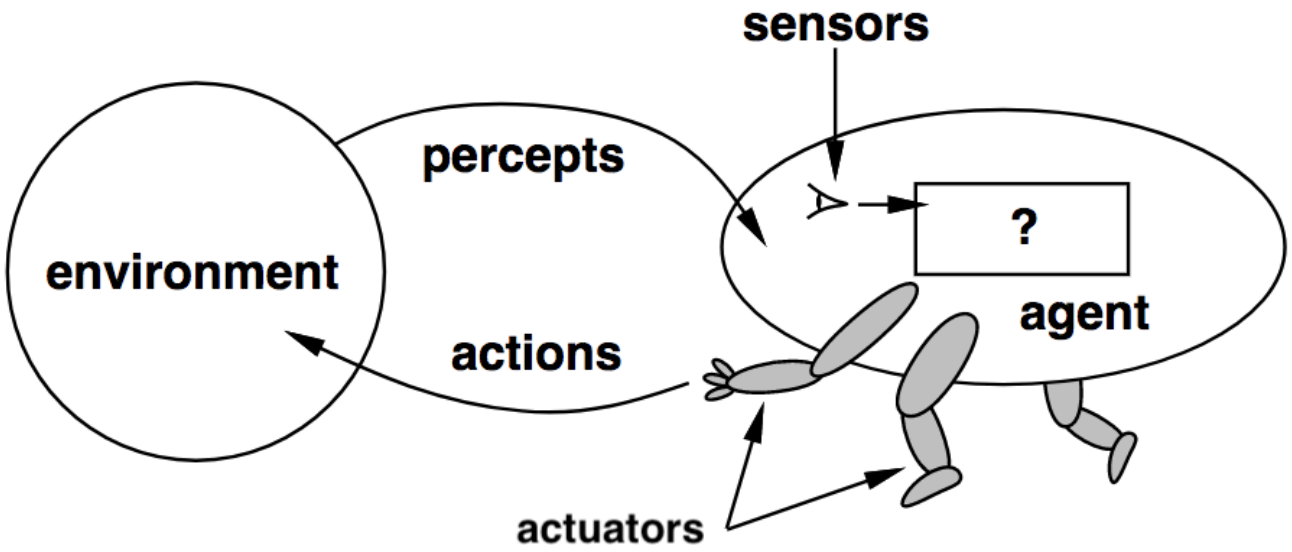


What about your robot?

What actuators does it have?

What sensors does it have?

Agents and environments



An agent is specified by an *agent function* $f:P \rightarrow a$ that maps a sequence of percept vectors P to an action a from a set A:

$P=[p_0, p_1, \ldots, p_t]$

$A=\{a_0, a_1, \ldots, a_k\}$

abstract mathematical description

Agent function & program

The *agent program* runs on the physical *architecture* to *produce* f

- *agent* = *architecture* + *program*

"Easy" solution: a giant table that maps every possible sequence P to an action a

- One small problem: exponential in length of P

Agents

An *agent* is anything that can be viewed as

- *perceiving* its *environment* through *sensors* and
- *acting* upon that environment through *actuators*

Human agent:

- Sensors: eyes, ears, …
- Actuators: hands, legs, mouth, …

Robotic agent:

- Sensors: cameras and infrared range finders
- Actuators: various motors

Agents include humans, robots, softbots, *thermostats*, …

Rational Agent

Let's try to define "rational agent".

A **rational agent** is an agent that perceives its environment and and behaves rationally

Rational behavior: doing the right thing

Obviously doing the right thing is better than doing the wrong thing, but *what does it mean to do the right thing?*

In Philosophy

Moral philosophy has developed different notions of “the right thing”.

AI is usually concerned with **Consequentialism.**

We evaluate an agent’s behavior by its consequences.

The Good Place

In Economics

A BEHAVIORAL MODEL OF RATIONAL CHOICE

Herbert A. Simon*

Summary: A model is proposed for the description of rational choice by organisms of limited computational ability.

Rational choice theory is a framework for understanding social and economic behavior.

The basic premise s that aggregate social behavior results from the behavior of individual actors, each of whom is making their individual decisions.

It assumes that individuals have preferences and choose the alternative that they prefer.

Herbert Simon

Performance measure

How do we know if an agent is acting rationally?

- Informally, we expect that it will do the right thing in all circumstances.

How do we know if it's doing the right thing?

We define a **performance measure:**

- An objective criterion for success of an agent's behavior
- given the evidence provided by the percept sequence.

Performance measure - example

A performance measure for a vacuum-cleaner agent might include e.g. some subset of:

- +1 point for each clean square in time T
- +1 point for clean square, -1 for each move
- -1000 for more than *k* dirty squares

Performance measure – rule of thumb

It is better to design performance measures according to **what you want to be achieved** in the environment, **rather than how you think the agent should behave.**

For example what might happen if we said

- +1 point for each time the robot cleans a square

instead of

- +1 point for each clean square in time T

Rational agents

Rational Agent:

- For each possible percept sequence *P*
- a rational agent selects an action *a*
- to *maximize* its *performance measure*

Is omniscience required?

Expected value

Rational Agent (initial definition):

- For each possible percept sequence P,
- a rational agent selects an action a
- to maximize its performance measure

Rational Agent (revised definition):

- For each possible percept sequence P,
- a rational agent selects an action a
- that maximizes the **expected value** of its performance measure

It doesn't have to know what the actual outcome will be.

Task environments

To design a rational agent we need to specify a *task environment*

- a problem specification for which the agent is a solution

PEAS: *to* specify a task environment

- ***P***erformance measure
- ***E***nvironment
- ***A***ctuators
- ***S***ensors

PEAS: Specifying an automated taxi driver

*P*erformance measure:

- ?

*E*nvironment:

- ?

*A*ctuators:

- ?

*S*ensors:

- ?

PEAS: Specifying an automated taxi driver

*P*erformance measure:

- safe, fast, legal, comfortable, maximize profits

*E*nvironment:

- roads, other traffic, pedestrians, customers

*A*ctuators:

- steering, accelerator, brake, signal, horn

*S*ensors:

- cameras, LiDAR, speedometer, GPS

PEAS: Amazon Prime Air

*P*erformance measure:

- ?

*E*nvironment:

- ?

*A*ctuators:

- ?

*S*ensors:

- ?

https://www.today.com/video/amazon-adebuts-new-package-delivery-drone-61414981780

PEAS: Specifying an Amazon delivery drone

*P*erformance measure:

maximize profits - minimize time - obey laws governing airspace restrictions - deliver package to right location - keep package in good condition - avoid accidents - reduce noise - preserve battery life

*E*nvironment:

- airspace - obstacles when airborne (other drones, birds, buildings, trees, utility poles) - obstacles when landing (pets, patio furniture, lawnmowers, people, cars) - weather - distances/route information between warehouse and destinations - position of houses, and spaces that are safe for drop-off- package weight

PEAS: Specifying an Amazon delivery drone

*A*ctuators:

- Propellers and flight control system- Payload actuators: E.g. Arm/basket/claw for picking up, dropping off packages- Lights or signals - Mechanism to announce/verify delivery- Device for delivering packages to customers

*S*ensors:

- GPS - radar/Lidar- altitude sensor- weather sensors (barometer, etc). - gyroscope- accelerometer- camera- rotor sensors- weight sensor to recognize package

The rational agent designer's goal

Goal of AI practitioner who designs rational agents:

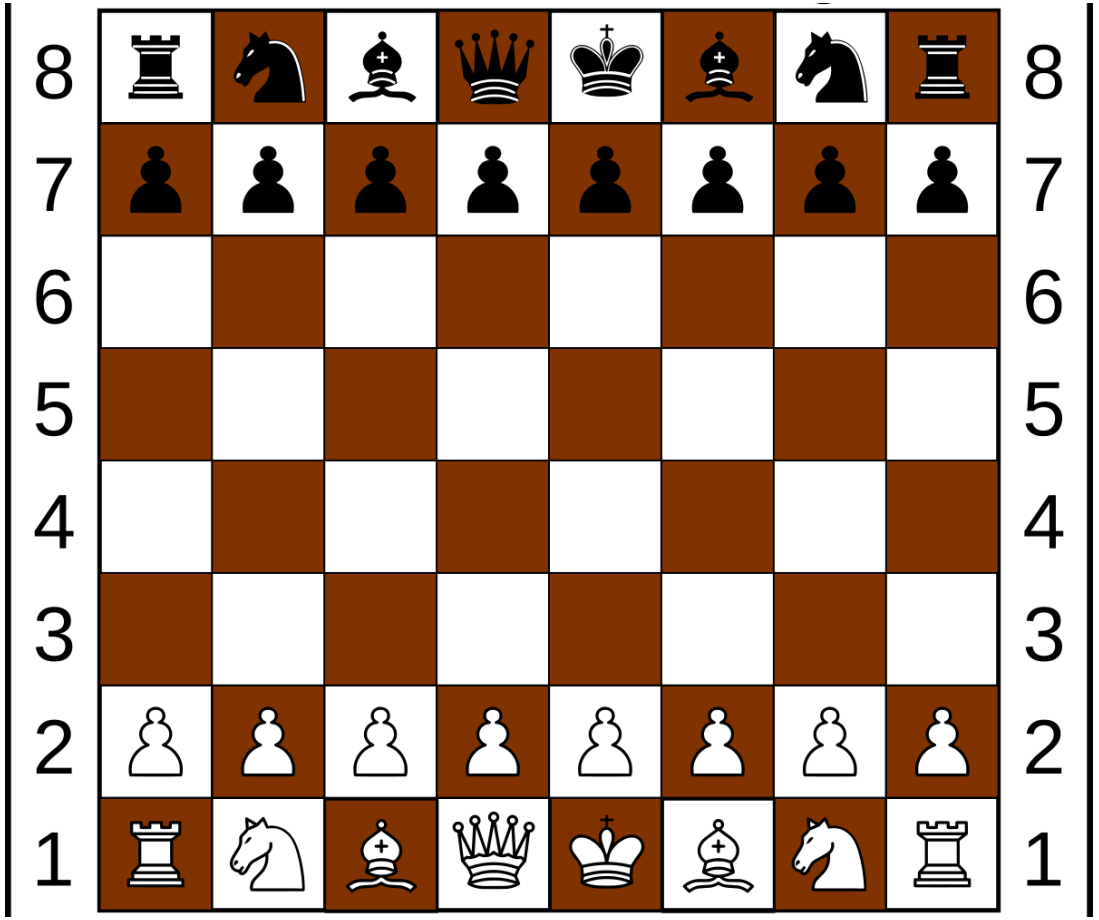
given a *PEAS* task environment,

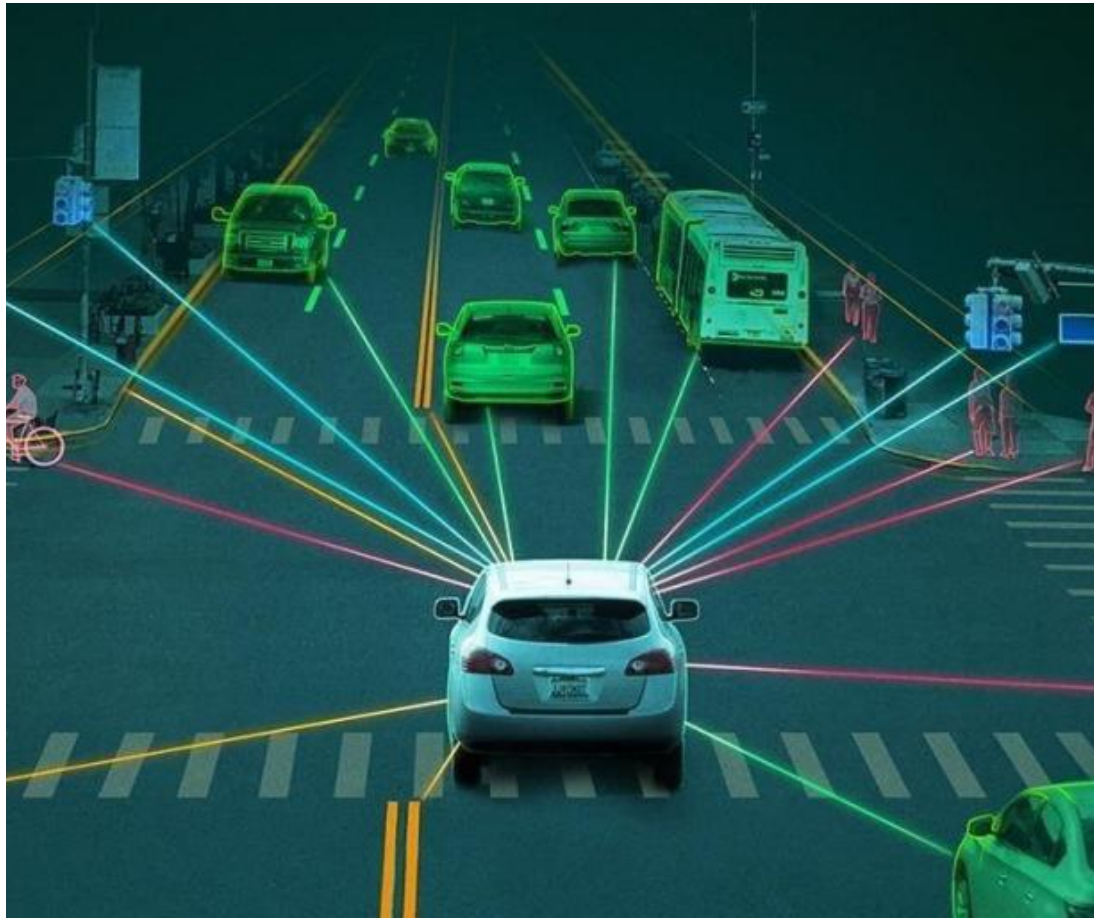
1. **Construct *agent function* f that maximizes the expected value of the performance measure,**
2. **Design an *agent program* that implements f on a particular architecture**

abstract mathematical description

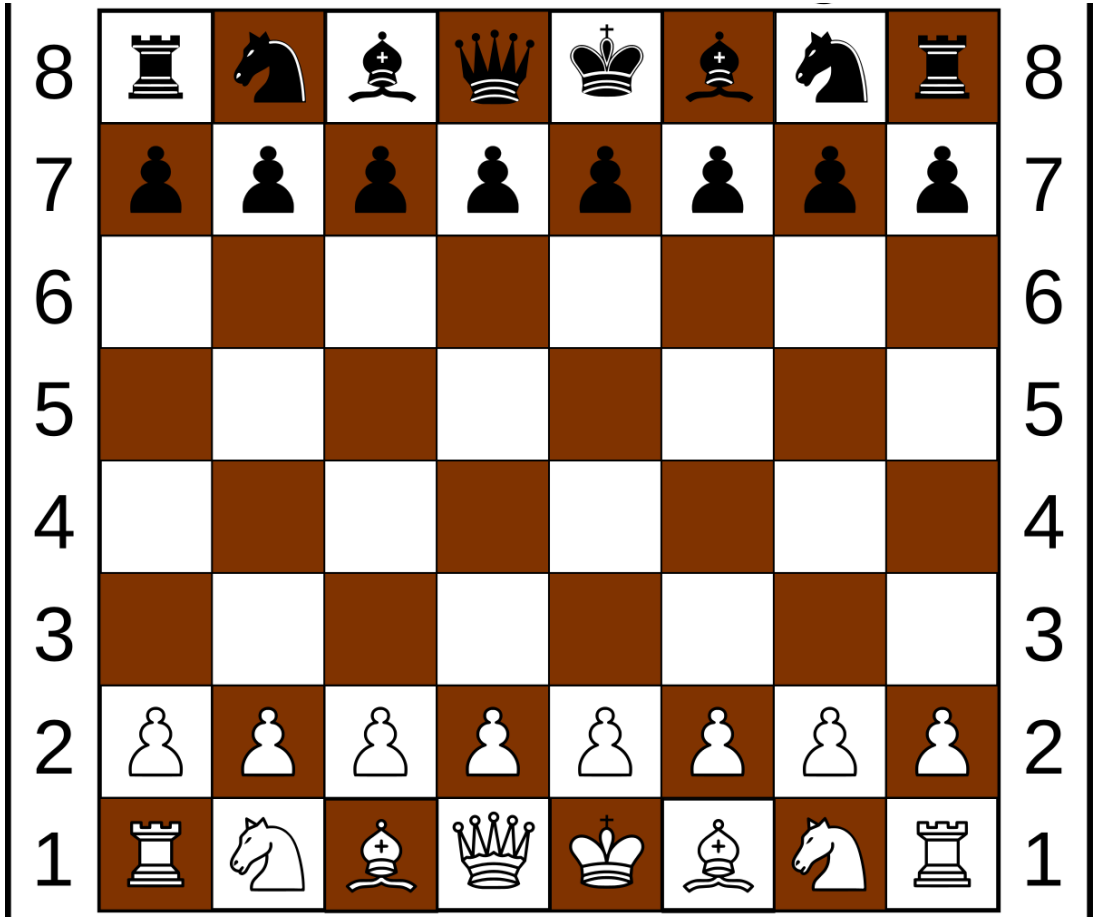
concrete implementation

Fully Observable v. Partially Observable

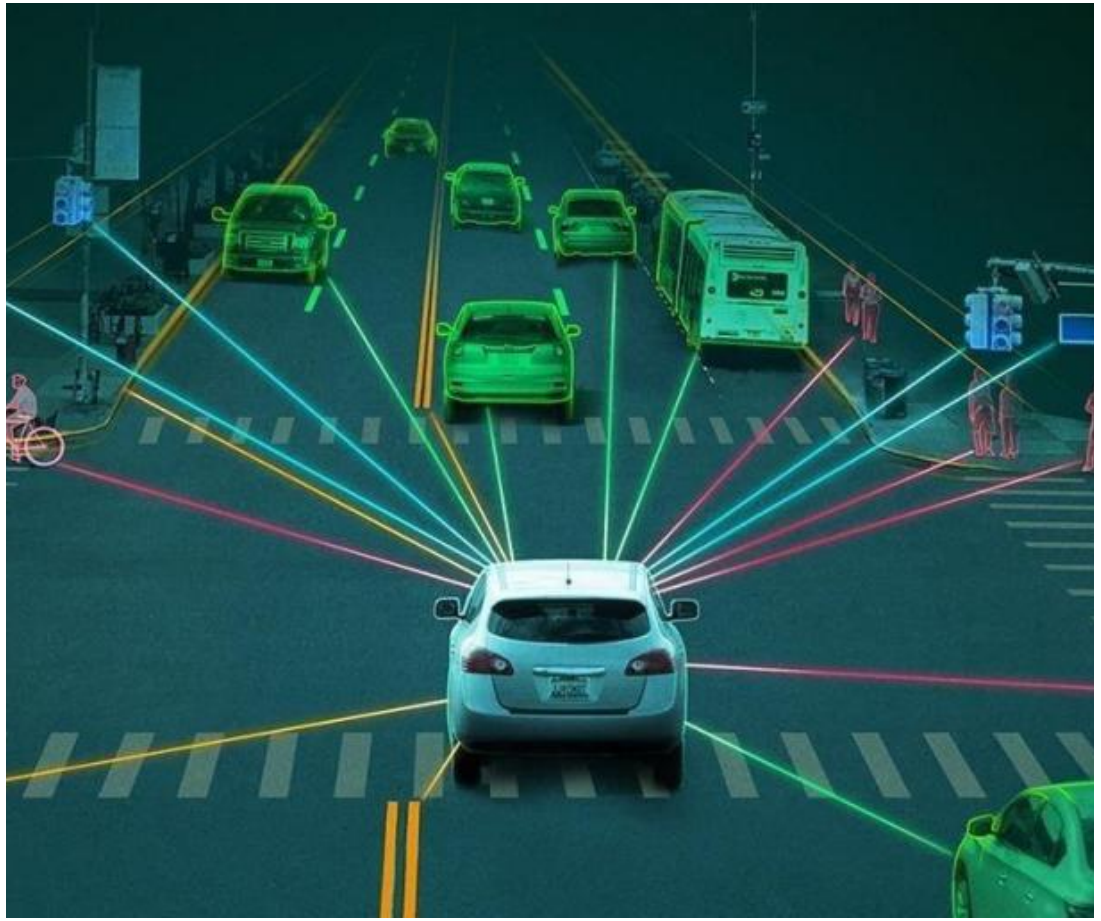




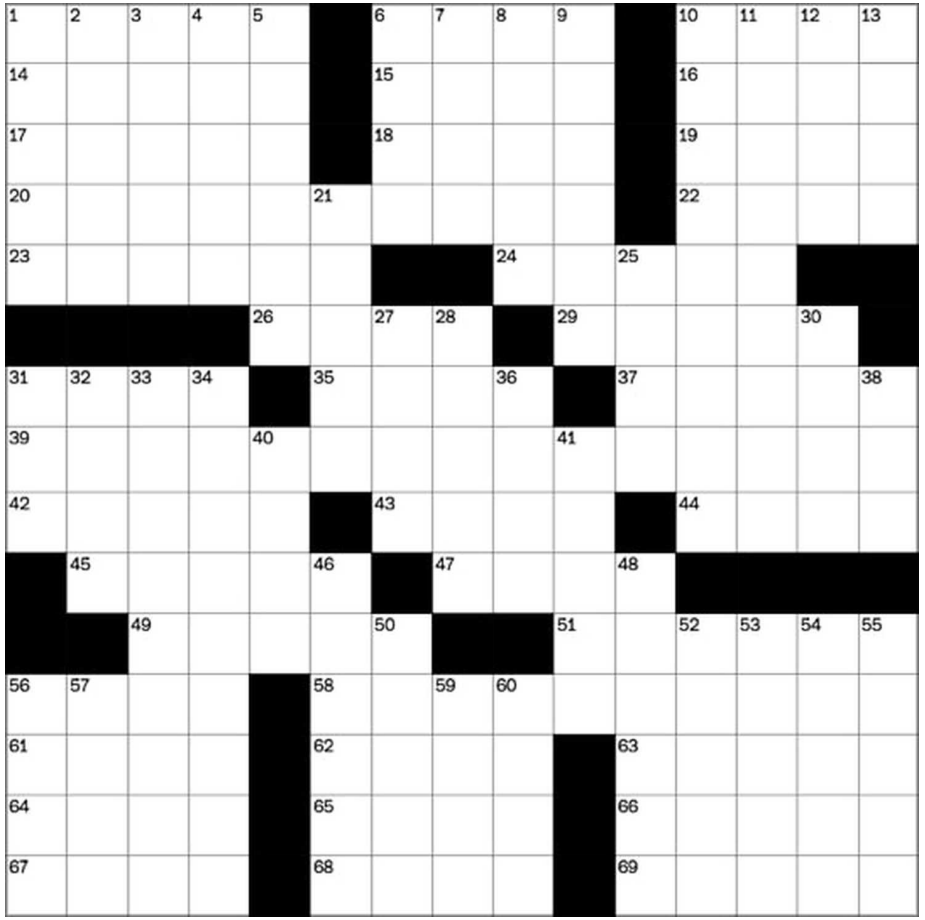
Deterministic v. Nondeterministic v. Stocastic

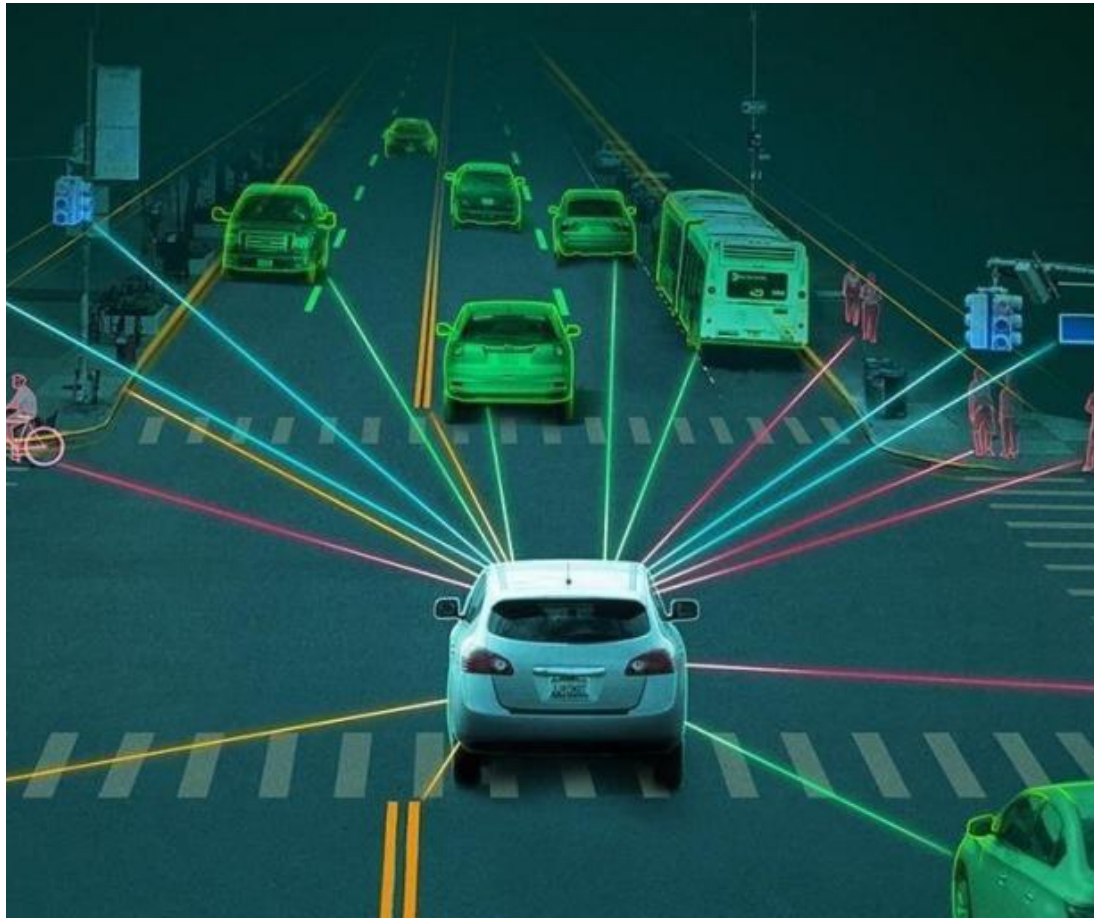


Episodic v. Sequential

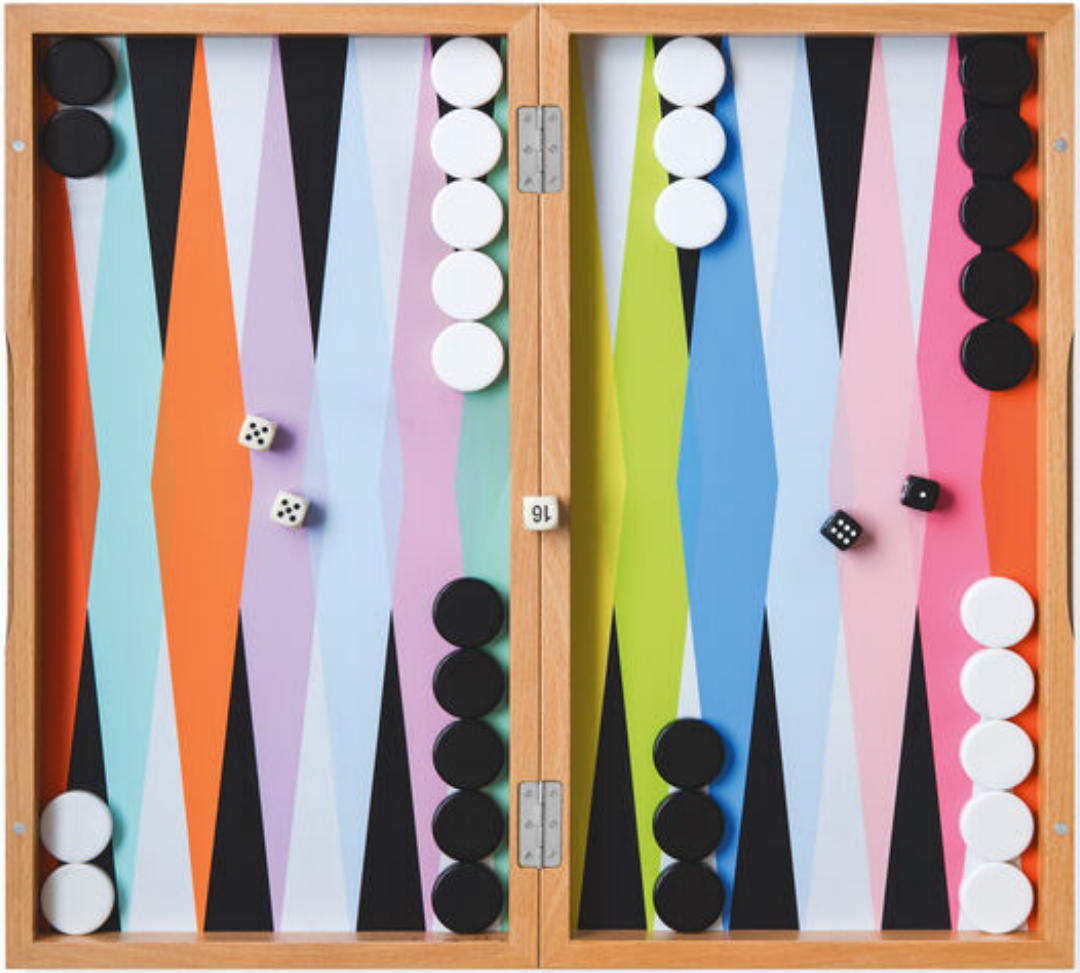


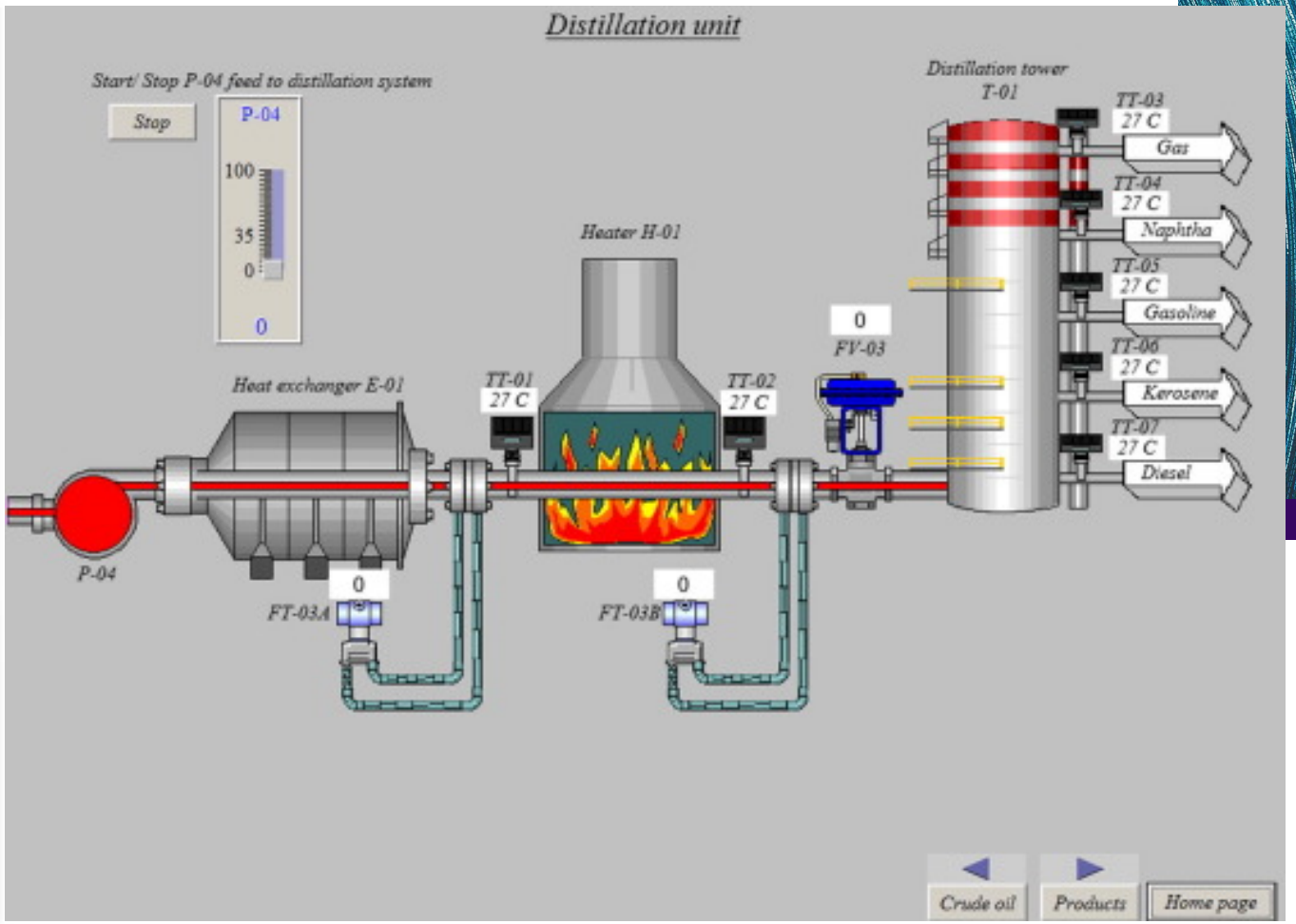
Static v. Dynamic



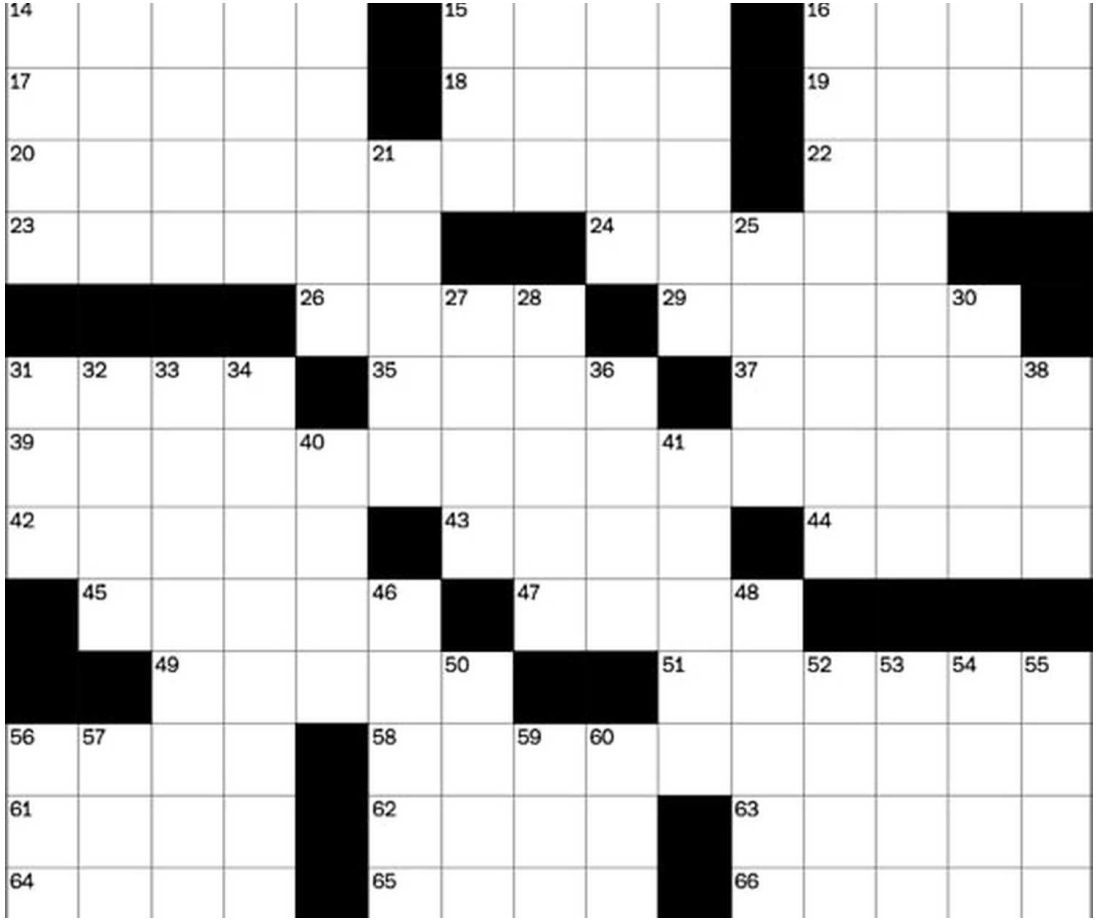


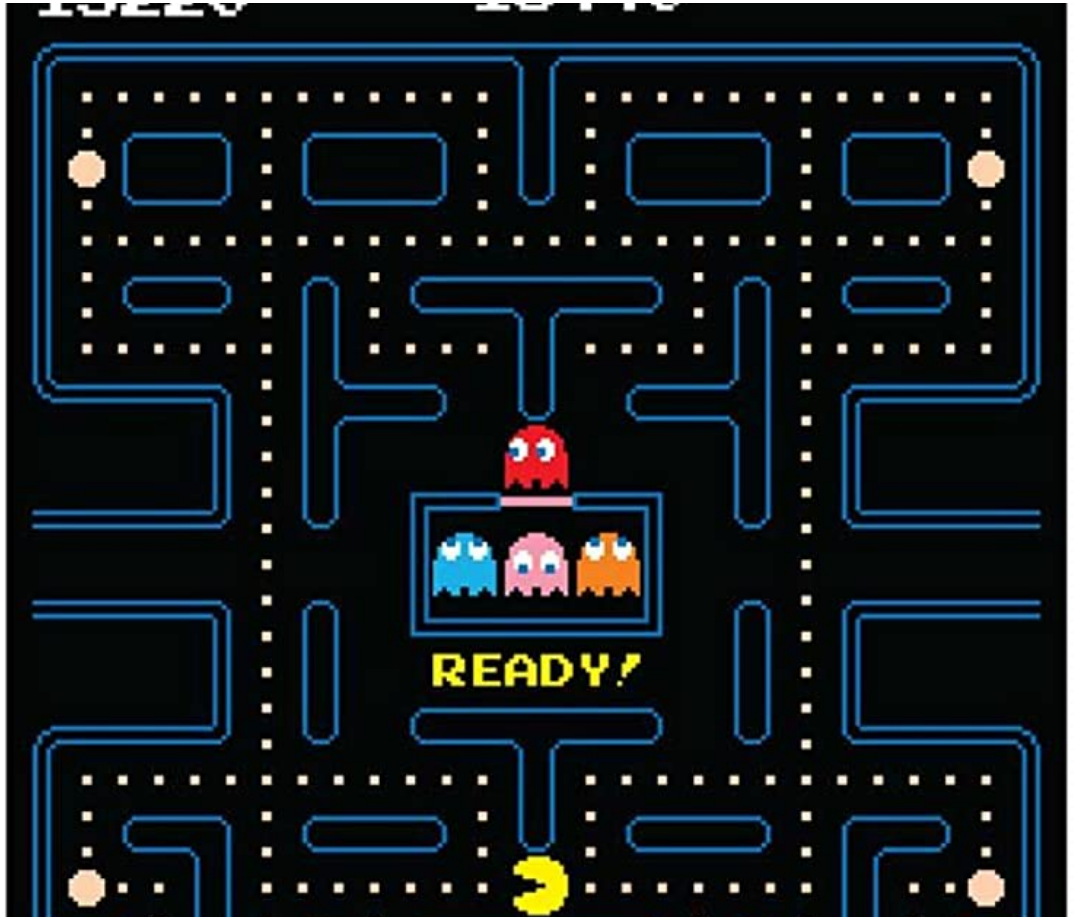
Discrete v. Continuous





Single Agent v. Multi Agent





When should something be considered an agent?

When should something be considered another agent?

If we're talking about a self driving taxi, when should we consider something part of the environment versus another agent?

For instance, a telephone pole is part of the environment, but a car might be another agent.

When something behavior can best be described as having its own performance measure, then we should consider it to be an agent.

Examples

Task Environment	Observable	Agents	Deterministic	Episodic	Static	Discrete
Crossword puzzle	Fully	Single	Deterministic	Sequential	Static	Discrete
Chess with a clock	Fully	Multi	Deterministic	Sequential	Semi	Discrete
Poker	Partially	Multi	Stochastic	Sequential	Static	Discrete
Backgammon	Fully	Multi	Stochastic	Sequential	Static	Discrete
Taxi driving	Partially	Multi	Stochastic	Sequential	Dynamic	Continuous
Medical diagnosis	Partially	Single	Stochastic	Sequential	Dynamic	Continuous
Image analysis	Fully	Single	Deterministic	Episodic	Semi	Continuous
Part-picking robot	Partially	Single	Stochastic	Episodic	Dynamic	Continuous
Refinery controller	Partially	Single	Stochastic	Sequential	Dynamic	Continuous
Interactive English tutor	Partially	Multi	Stochastic	Sequential	Dynamic	Discrete

The Hardest Environment

The hardest case is

- ***Continuous***
- ***Partially Observable***
- ***Stochastic***
- ***Continuous***
- ***Multiagent***
- ***Unknown Outcomes***

Environment Restrictions for Now

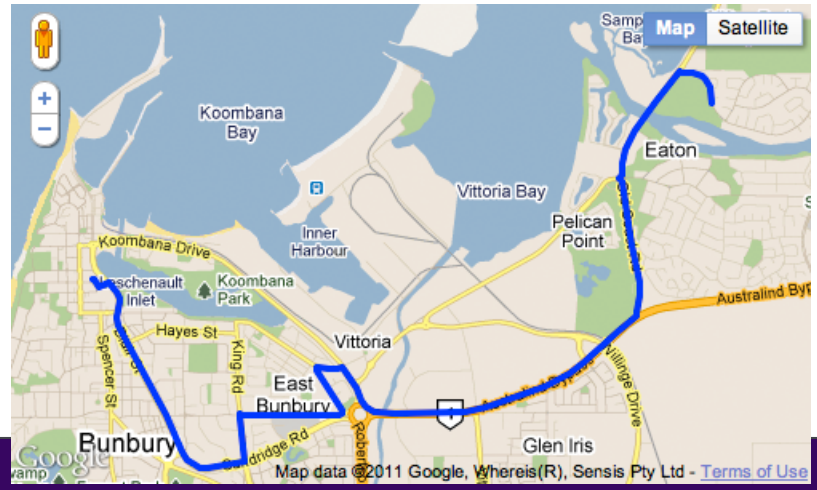
We will assume environment is

- ***Static***
- ***Fully Observable***
- ***Deterministic***
- ***Discrete***

Reflex agents v. Problem solving agents

A simple reflex agent is one that selects an action based on the current percept, and ignores the rest of the percept history.

A problem-solving agent must plan ahead. It will consider a sequence of actions that form a path to a goal state. The computational process that it undertakes is called search.



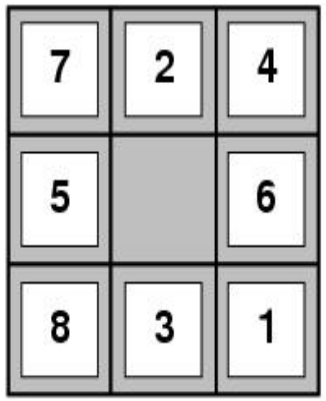
Problem Solving Agents & Problem Formulation

AIMA 3.1-3.2

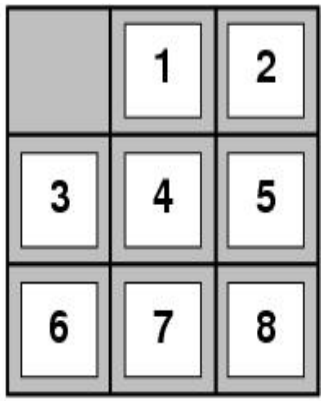
Example search problem: 8-puzzle

Formulate *goal*

- Pieces to end up in order as shown…



Start State



Goal State

Formulate *search problem*

- ***States:*** configurations of the puzzle (9! configurations)
- ***Actions***: Move one of the movable pieces (≤4 possible)
- ***Performance measure***: minimize total moves

Find *solution*

- Sequence of pieces moved: 3,1,6,3,1,…

Example search problem: holiday in Romania

Holiday in Romania

On holiday in Romania; currently in Arad

- Flight leaves tomorrow from Bucharest

Formulate *goal*

- Be in Bucharest

Formulate *search problem*

- States: various cities
- Actions: drive between cities
- Performance measure: minimize travel time / distance

Find *solution*

- Sequence of cities; e.g. Arad, Sibiu, Fagaras, Bucharest, …

More formally, a problem is defined by:

1. *States*: a set S
2. An *initial state* $s_i \in S$
3. *Actions: a set* A
   $\forall s$ $Actions(s)$ = *the set of actions that can be executed in* s, *that are applicable* in s.
4. *Transition Model*: $\forall s \forall a \in Actions(s)$ $Result(s, a) \rightarrow s_r$
   s_r *is called a successor of* s
   $\{s_i\} \cup Successors(s_i)^*$ = *state space*
5. *Path cost (Performance Measure)*: Must be additive
   e.g. sum of distances, number of actions executed, …
   $c(x,a,y)$ is the step cost, assumed ≥ 0
   - (where action a goes from state x to state y)
6. *Goal test:* $Goal(s)$
   Can be implicit, e.g. $checkmate(s)$
   s is a *goal state* if $Goal(s)$ is *true*

Solutions & Optimal Solutions

- A *solution* is a sequence of *actions* from the *initial state* to a *goal state.*

- *Optimal Solution:* A solution is *optimal* if no solution has a lower *path cost*.

Art: Formulating a Search Problem

Decide:

Which properties matter & how to represent

- *Initial State, Goal State, Possible Intermediate States*

Which actions are possible & how to represent

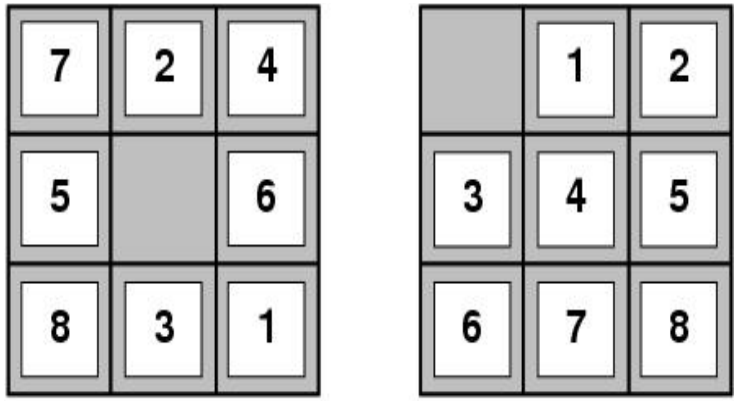
- *Operator Set: Actions and Transition Model*

Which action is next

- *Path Cost Function*

Formulation greatly affects combinatorics of search space and therefore speed of search

Example: 8-puzzle



States??

Initial state??

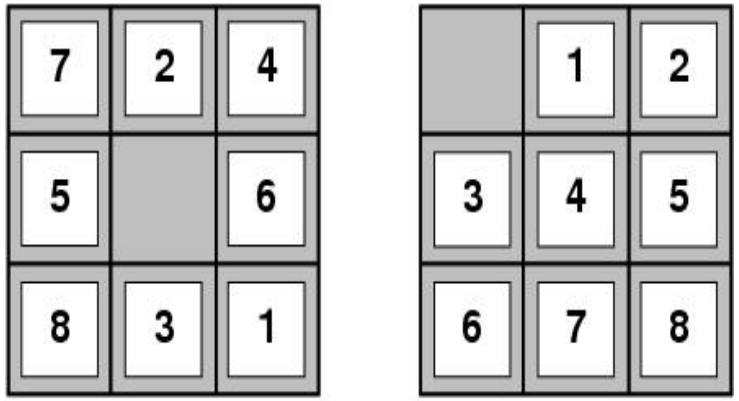
Actions??

Transition Model??

Goal test??

Path cost??

Example: 8-puzzle



Start State Goal State

States??

Initial state?? [7,2,4,5

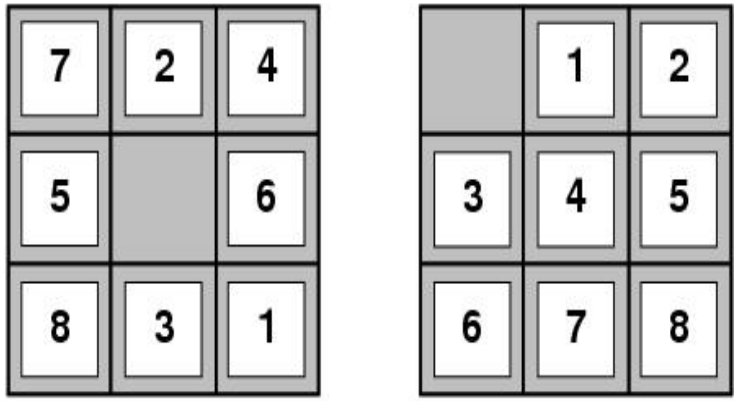
Actions??

Transition Model??

Goal test??

Path cost?? Numbe

Example: 8-puzzle



Start State Goal State

States?? List of 9 locations- e.g., [7,2,4,5,-,6,8,3,1]

Initial state?? [7,2,4,5,-,6,8,3,1]

Actions?? *{Left, Right, Up, Down}*

Transition Model?? …

Goal test?? Check if goal configuration is reached

Path cost?? Number of actions to reach goal

Hard subtask: Selecting a state space

Real world is absurdly complex

State space must be *abstracted* for problem solving

(abstract) *State* = set (equivalence class) of real world states

(abstract) *Action* = equivalence class of combinations of real world actions

- e.g. *Arad* $\rightarrow$ *Zerind* represents a complex set of possible routes, detours, rest stops, etc
- The abstraction is valid if the path between two states is reflected in the real world

Each abstract action should be "easier" than the real problem

Outline for today's lecture

Intelligent Agents

Task Environments

Formulating Search Problems

Search Fundamentals (AIMA 3.3)

Useful Concepts

State space: the set of all states reachable from the initial state by *any* sequence of actions

- *When several operators can apply to each state, this gets large very quickly*
- *Might be a proper subset of the set of configurations*

Path: a sequence of actions leading from one state s_j to another state s_k

Frontier: those states that are available for *expanding* (for applying legal actions to)

Solution: a path from the initial state s_i to a state s_f that satisfies the goal test

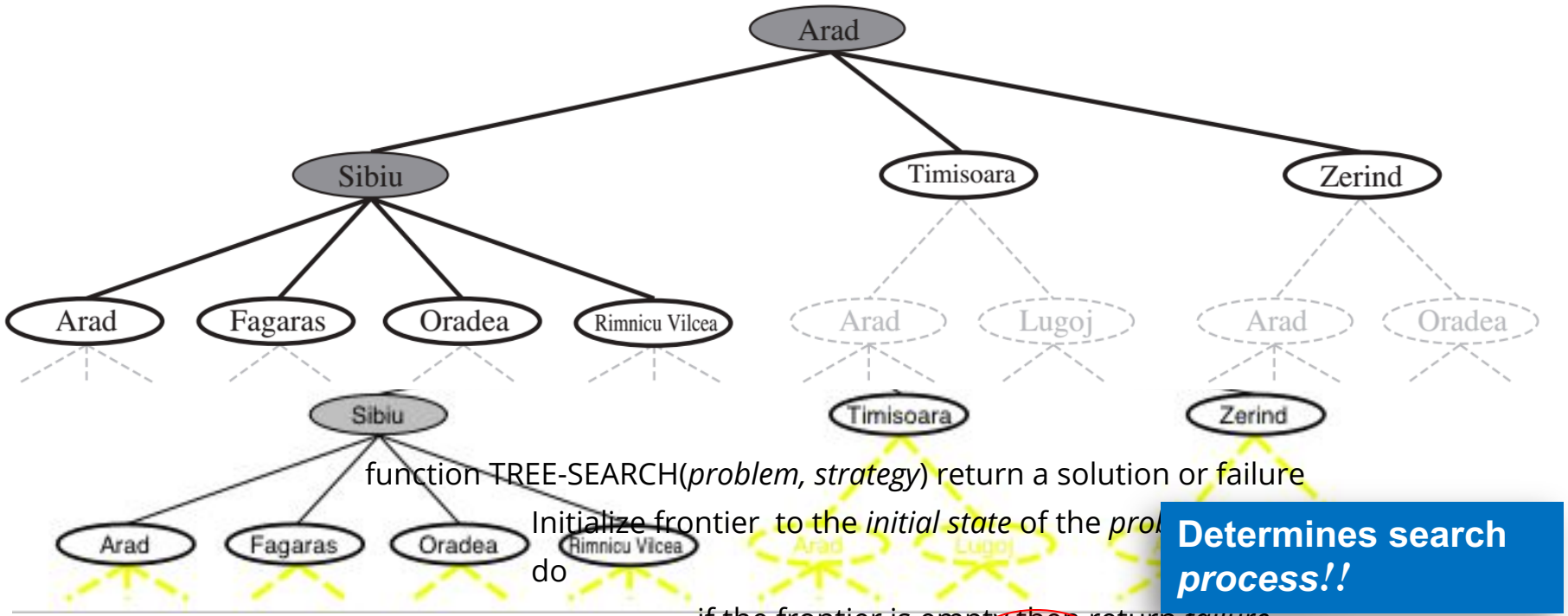
Basic search algorithms: *Tree Search*

Generalized algorithm to solve search problems

Enumerate in some order all possible paths from the initial state

- Here: search through *explicit tree generation*
  - ROOT= initial state.
  - Nodes in search tree generated through *transition model*
  - Tree search treats different paths to the same node as distinct

Generalized tree search



function TREE-SEARCH(*problem, strategy*) return a solution or failure

Initialize frontier to the *initial state* of the *prob*

do

if the frontier is empty then return *failure*

choose leaf node for expansion according to strategy & remove from frontier

if node contains goal state then return *solution*

else expand the node and add resulting nodes to the frontier

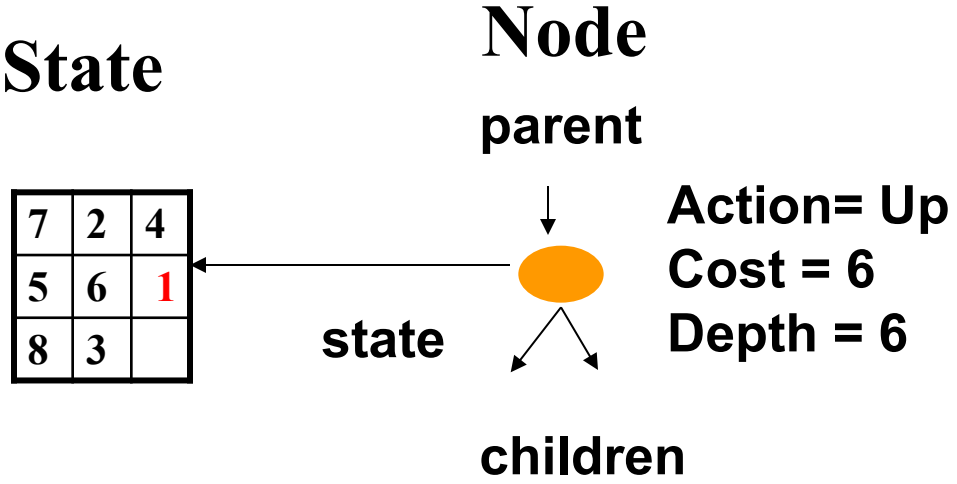
Determines search *process!!*

8-Puzzle: States and Nodes

A *state* is a (representation of a) *physical configuration*
A *node* is a data structure constituting *part of a search tree*

- Also includes *parent, children, depth, path cost g(x)*
- Here *node= <state, parent-node, children, action, path-cost, depth>*

States do not have parents, children, depth or path cost!



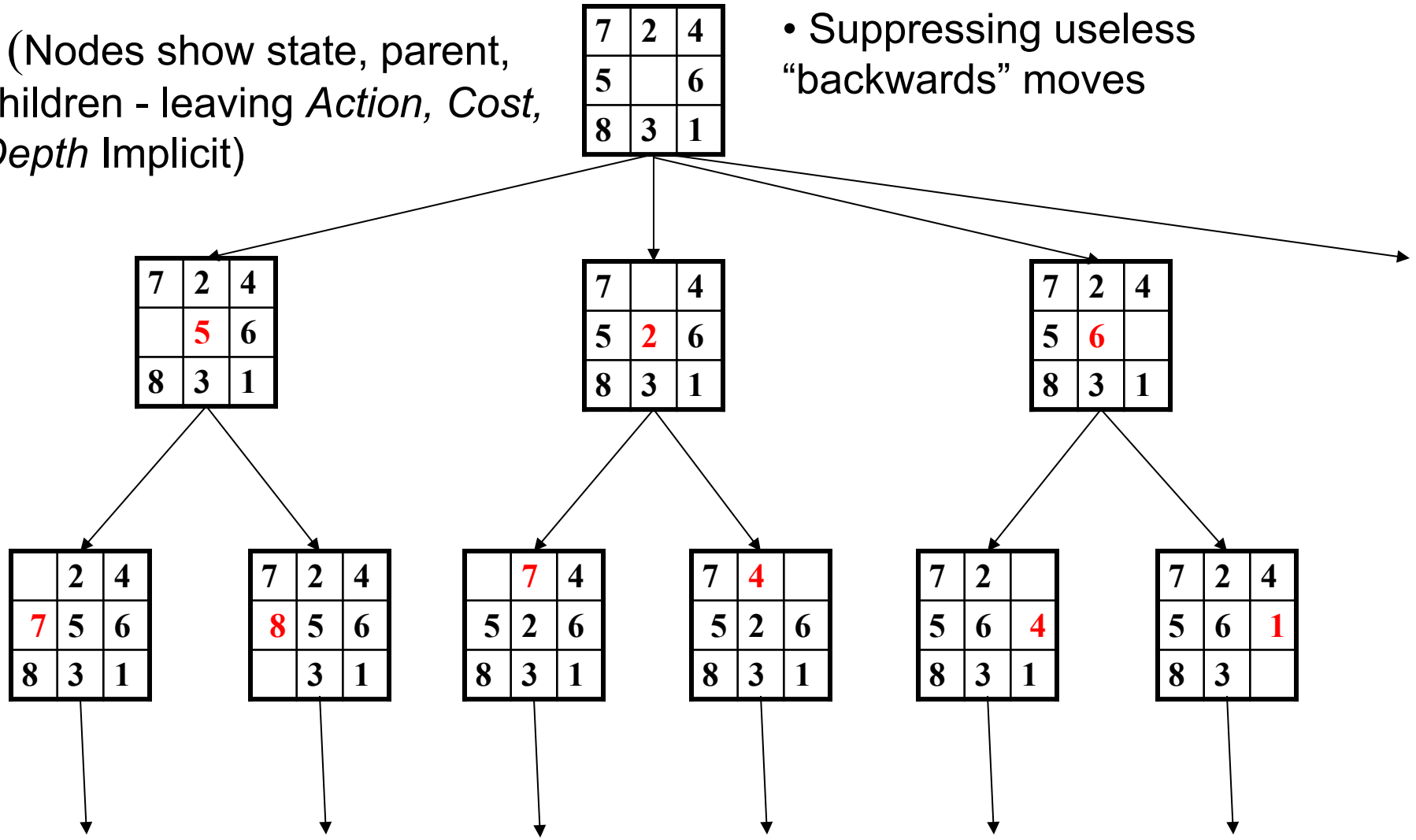
The EXPAND function

- uses the Actions and Transition Model to create the corresponding states
  - creates new nodes,
  - fills in the various fields

8-Puzzle *Search Tree*

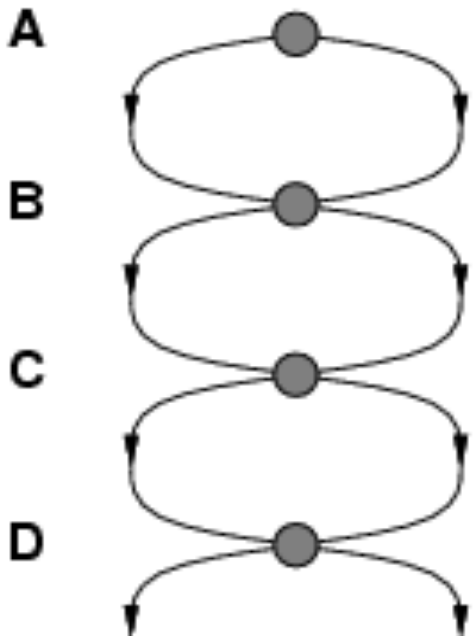
- (Nodes show state, parent, children - leaving *Action, Cost, Depth* Implicit)

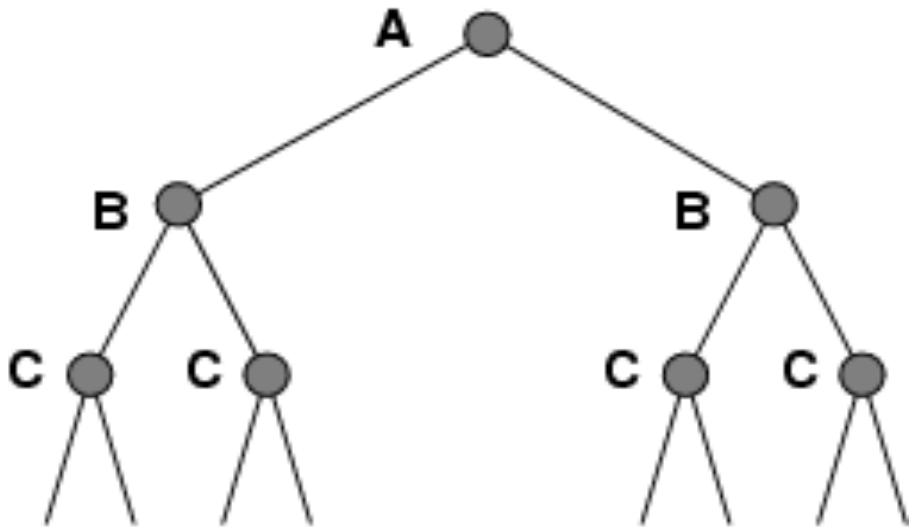
- Suppressing useless "backwards" moves



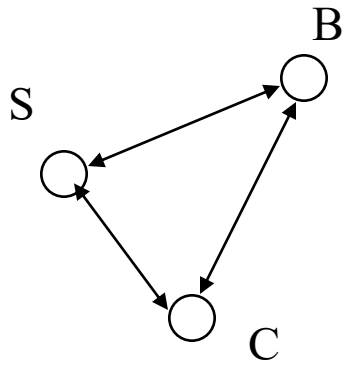
Problem: Repeated states

Failure to detect *repeated states* can turn a linear problem into an *exponential* one!

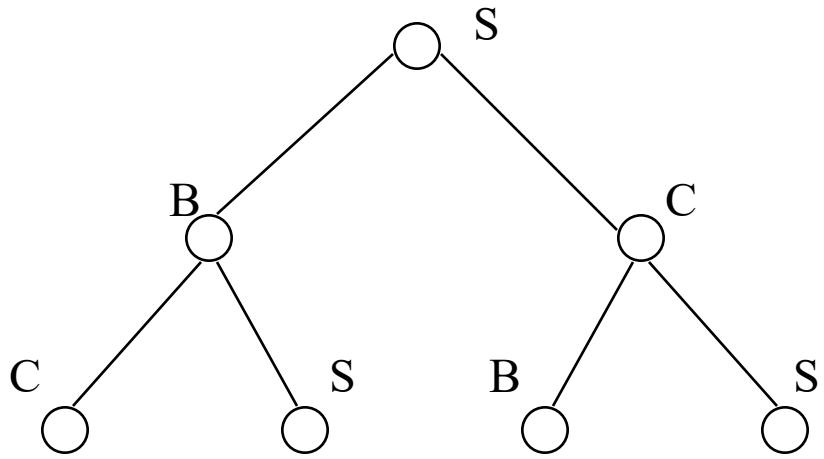




Solution: Graph Search!



State Space



Search Tree

Graph search

- Simple Mod from tree search*: Check to see if a node has been visited before adding to search queue*
  - must keep track of all possible states (can use a lot of memory)
  - e.g., 8-puzzle problem, we have 9!/2 ≈182K states

Graph Search vs Tree Search

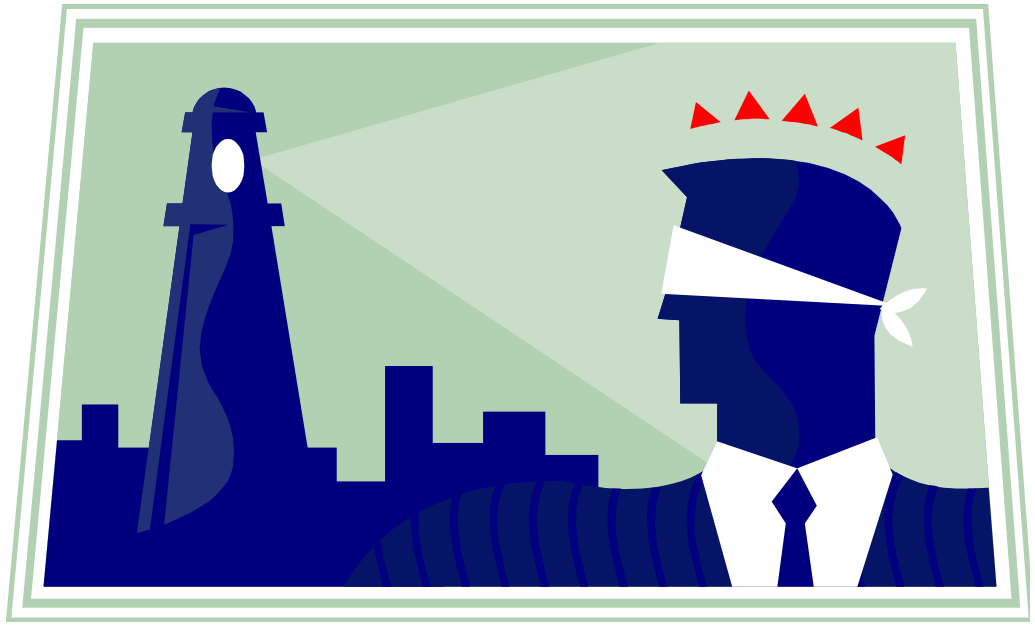
```
function TREE-SEARCH(problem) returns a solution, or failure
    initialize the frontier using the initial state of problem
    loop do
        if the frontier is empty then return failure
        choose a leaf node and remove it from the frontier
        if the node contains a goal state then return the corresponding solution
        expand the chosen node, adding the resulting nodes to the frontier
```

```
function GRAPH-SEARCH(problem) returns a solution, or failure
    initialize the frontier using the initial state of problem
    initialize the explored set to be empty
    loop do
        if the frontier is empty then return failure
        choose a leaf node and remove it from the frontier
        if the node contains a goal state then return the corresponding solution
        add the node to the explored set
        expand the chosen node, adding the resulting nodes to the frontier
            only if not in the frontier or explored set
```

Figure 3.7 An informal description of the general tree-search and graph-search algorithms. The parts of GRAPH-SEARCH marked in bold italic are the additions needed to handle repeated states.

Uninformed Search Strategies

AIMA 3.3-3.4



Uninformed search strategies:

AKA “Blind search”

Uses only information available in problem definition

Informally:

Uninformed search: All non-goal nodes in frontier look equally good

Informed search: Some non-goal nodes can be ranked above others.

Search Strategies

Review: Strategy = order of tree expansion

- Implemented by different queue structures (LIFO, FIFO, priority)

Dimensions for evaluation

- *Completeness-* always find the solution?
- *Optimality* - finds a least cost solution (lowest path cost) first?
- *Time complexity* - # of nodes generated *(worst case)*
- ***Space complexity*** **- # of nodes simultaneously in memory** *(worst case)*

Time/space complexity variables

- *b, maximum branching factor* of search tree
- *d, depth* of the shallowest goal node
- *m*, maximum length of any path in the state space (potentially ∞)

Introduction to *space* complexity

You know about:

- "Big O" notation
- *Time complexity*

Space complexity is analogous to time complexity

Units of space are arbitrary

- Doesn't matter because Big O notation ignores constant multiplicative factors
- Plausible Space units:
  - One Memory word
  - Size of any fixed size data structure
    - For example, size of fixed size node in search tree

Review: Breadth-first search

Idea:

- Expand *shallowest* unexpanded node

Implementation:

- *frontier* is FIFO (First-In-First-Out) Queue:
  - Put successors at the *end* of *frontier* successor list.

Image credit: Dan Klein and Pieter Abbeel
http://ai.berkeley.edu

Breadth-first search (simplified)

```
function BREADTH-FIRST-SEARCH(problem) returns a solution, or failure
    node ← a node with STATE = problem.INITIAL-STATE, PATH-COST = 0
    if problem.GOAL-TEST(node.STATE) then return SOLUTIO
    frontier ← a FIFO queue with node as the only element
    explored ← an empty set
    loop do
        if EMPTY?(frontier) then retur failure
        node ← POP(frontier)  /* chooses the shallowest node in frontier */
        add node.STATE to explored
        for each action in problem.ACTIONS(node.STATE) do
            child ← CHILD-NODE(problem, node, action)
            if child.STATE is not in explored or frontier the
                if problem.GOAL-TEST(child.STATE) then return SOLUTION(child)
                frontier ← INSERT(child, frontier)
```

Position within queue of new items determines search strategy

Subtle: *Node inserted into queue only after testing to see if it is a goal state*

Properties of breadth-first search

Complete? Yes (if b is finite)

Time Complexity? $1+b+b^2+b^3+\ldots+b^d = O(b^d)$

Space Complexity? $O(b^d)$ (keeps every node in memory)

Optimal? Yes, if cost = 1 per step
(not optimal in general)

b: maximum branching factor of search tree
d: depth of the least cost solution
m: maximum depth of the state space (∞)

Exponential Space (and time) Not Good…

- Exponential complexity uninformed search problems *cannot* be solved for any but the smallest instances.
- *(Memory* requirements are a bigger problem than *execution* time.)

DEPTH	NODES	TIME	MEMORY
2	**110**	**0.11 milliseconds**	**107 kilobytes**
4	**11110**	**11 milliseconds**	**10.6 megabytes**
6	**10^6**	**1.1 seconds**	**1 gigabytes**
8	**10^8**	**2 minutes**	**103 gigabytes**
10	**10^{10}**	**3 hours**	**10 terabytes**
12	**10^{12}**	**13 days**	**1 petabytes**
14	**10^{14}**	**3.5 years**	**99 petabytles**

Fig 3.13 Assumes b=10, 1M nodes/sec, 1000 bytes/node

Review: Depth-first search

Idea:

- Expand *deepest* unexpanded node

Implementation:

- *frontier* is LIFO (Last-In-First-Out) Queue:
  - Put successors at the *front* of *frontier* successor list.

Image credit: Dan Klein and Pieter Abbeel
http://ai.berkeley.edu

Properties of depth-first search

Complete? No: fails in infinite-depth spaces, spaces with loops

- Modify to avoid repeated states along path
  → complete in finite spaces

Time? $O(b^m)$: terrible if m is much larger than d

- but if solutions are dense, may be much faster than breadth-first

Space? $O(b*m)$, i.e., linear space!

Optimal? No

b: maximum branching factor of search tree
d: depth of the least cost solution
m: maximum depth of the state space (∞)

Depth-first vs Breadth-first

Use depth-first if

- *Space is restricted*
- There are many possible solutions with long paths and wrong paths are usually terminated quickly
- Search can be fine-tuned quickly

Use breadth-first if

- *Possible infinite paths*
- Some solutions have short paths
- Can quickly discard unlikely paths

Outline for today's lecture

Formulating Search Problems – An Example

Search Fundamentals

Introduction to Uninformed Search

- Review of Breadth first and Depth-first search

Iterative deepening search (AIMA 3.4.4-5)

- *Strange Subroutine: Depth-limited search*
- *Depth-limited search + iteration = WIN!!*