Intelligent Agents, Search Problem Formulation and Uninformed Search

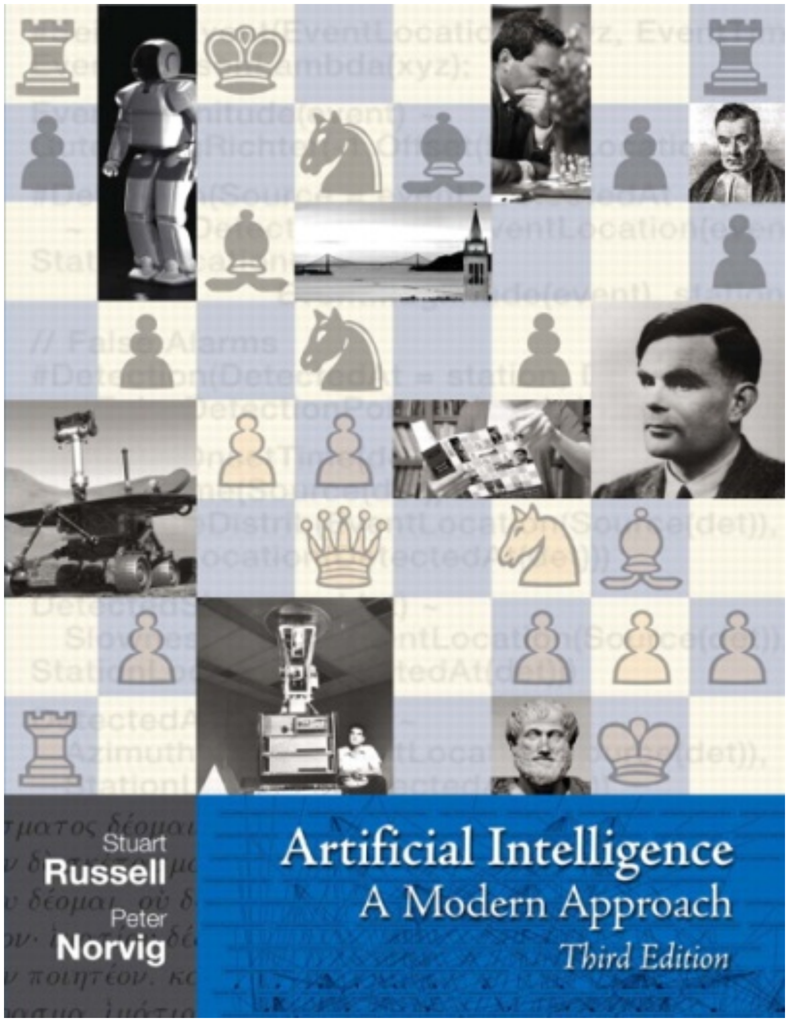
AIMA, Chapters 2 and 3

Reminder – HW due Tuesday

- HW1 is due Tuesday night before 11:59pm.
- Please submit early. 1 second late = 1 late day.
- Verify by this afternoon that you have a Gradescope account for the class. Private post on Piazza if you don't.

- My office hours are Tuesday/Thurs from 3pm-4pm. TAs office hours are on the course web site (still working out space for them)
- No class on Tuesday (I'm traveling to DARPA)

Outline for today's lecture



- *Intelligent Agents (AIMA 2.1-2.3)*
- Task Environments
- Formulating Search Problems
- Uninformed Search *(AIMA 3.1-3.4)*

Thinking humanly	Thinking rationally
Acting humanly	Acting rationally

Review: What is AI?

Views of AI fall into four categories:

Thinking humanly	Thinking rationally
Acting humanly	Acting rationally

We will focus on "acting rationally“

Review: Acting rationally: rational agents

Thinking humanly	Thinking rationally
Acting humanly	Acting rationally

- Rational behavior: doing the right thing
- The right thing: that which is ***expected to maximize goal achievement, given the available information***
- ***Rational agent: An agent is an entity that perceives and acts rationally***

This course is about *effective programming techniques* for designing *rational agents*

Agents

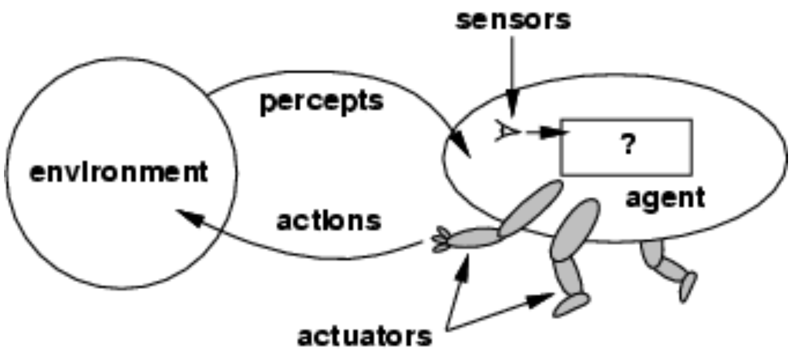
- An ***agent*** is anything that perceives its environment through ***sensors*** and can act on its environment through ***actuators***
- A ***percept*** is the agent's perceptual inputs at any given instance

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:**

$$P=[\mathbf{p_0}, \mathbf{p_1}, \ldots, \mathbf{p_t}]$$

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

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*, …**

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

Rational agents

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

Rationality is *not* omniscience

- **Ideal agent: maximizes *actual* performance, but needs to be *omniscient*.**
  - Usually impossible…..
    - — But consider tic-tac-toe agent…
  - Rationality ≠ Guaranteed Success

- **Caveat: computational limitations make *complete rationality* unachievable**

  →design best *program* for given machine resources

- **In Economics:**
  "Bounded Rationality" → "Behavioral Economics"

Rational agents 2

- **Rational Agent: For each possible percept sequence P, a rational agent selects an action a to *maximize* its *performance measure***
- **Performance measure: An objective criterion for success of an agent's behavior, given the evidence provided by the percept sequence.**

Revised:

- **Rational Agent: For the current percept sequence P, a rational agent selects an action a that *maximizes* the *expected value of* its *performance measure***

Outline for today's lecture

- Intelligent Agents
- *Task Environments (AIMA 2.3)*
- Formulating Search Problems

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

Performance measure:

- ?

Environment:

- ?

Actuators:

- ?

Sensors:

- ?

PEAS: Specifying an automated taxi driver

Performance measure:

- safe, fast, legal, comfortable, maximize profits

Environment:

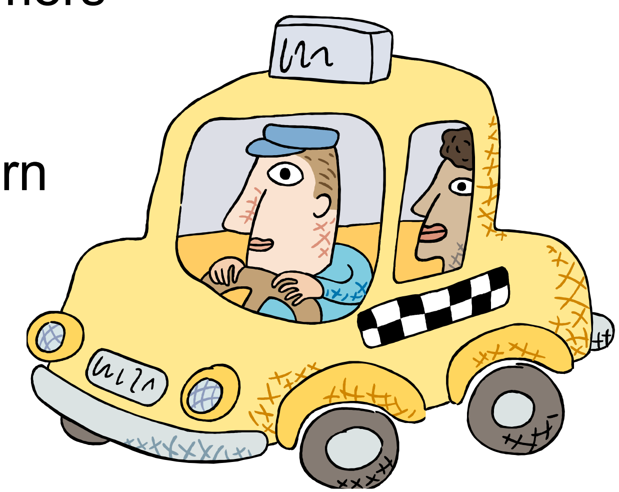
- roads, other traffic, pedestrians, customers

Actuators:

- steering, accelerator, brake, signal, horn

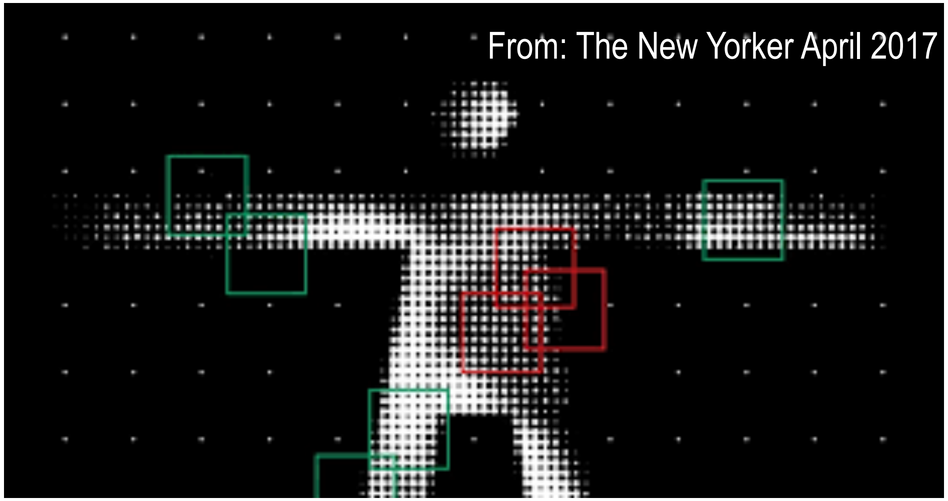
Sensors:

- cameras, LiDAR, speedometer, GPS



PEAS: Medical diagnosis system

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



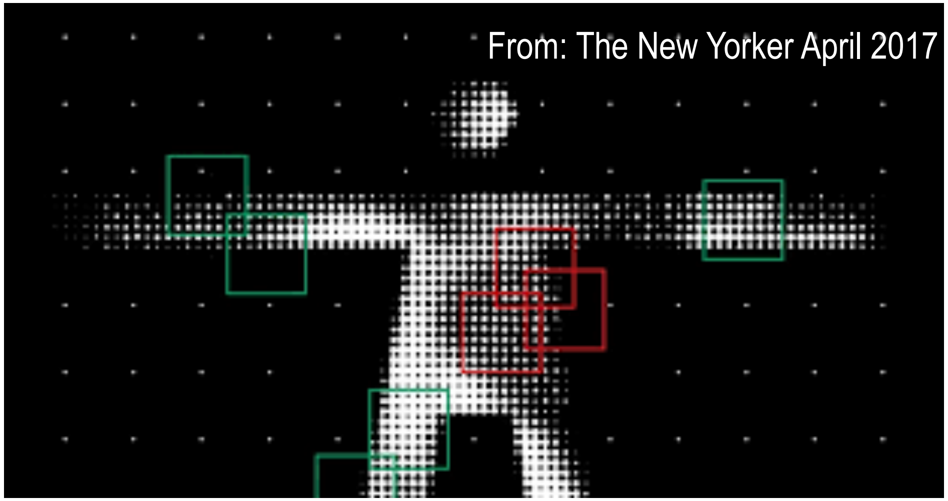
PEAS: Medical diagnosis system

- ***P**erformance measure*: **Healthy patient, minimize costs, lawsuits**

- ***E**nvironment*: **Patient, hospital, staff**

- ***A**ctuators*: **Screen display (form including: questions, tests, diagnoses, treatments, referrals)**

- ***S**ensors*: **Keyboard (entry of symptoms, findings, patient's answers)**



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**

Environment types: Definitions 1

- ***Fully observable*** **(vs. partially observable): An agent's sensors give it access to the complete state of the environment at each point in time.**

- ***Deterministic*** **(vs. stochastic): The next state of the environment is completely determined by the current state and the action executed by the agent.**
  - If the environment is deterministic except for the actions of other agents, then the environment is *strategic*.

- ***Episodic*** **(vs. sequential): The agent's experience is divided into atomic "episodes" during which the agent perceives and then performs a single action, and the choice of action in each episode does not depend on any previous action. (example: classification task)**

Environment types: Definitions 2

- ***Static*** **(vs. dynamic): The environment is unchanged while an agent is deliberating.**
  - The environment is *semidynamic* if the environment itself does not change with the passage of time but the agent's performance score does.
- ***Discrete*** **(vs. continuous): A limited number of distinct, clearly defined percepts and actions.**
- ***Single agent*** **(vs. multiagent): An agent operating by itself in an environment.**

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***

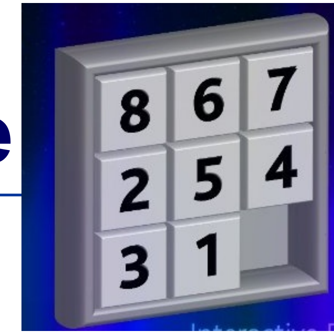
Environment Restrictions for Now

- **We will assume environment is**
  - ***Static***
  - ***Fully Observable***
  - ***Deterministic***
  - ***Discrete***

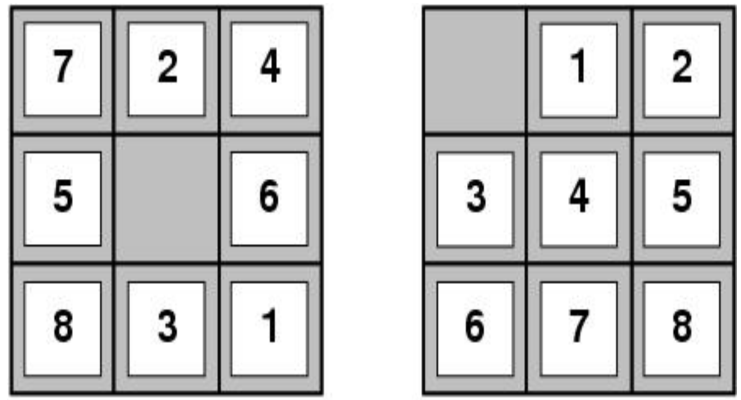
Problem Solving Agents & Problem Formulation

AIMA 3.1-3.2

Example search problem: 8-puzzle



- **Formulate *goal***
  - Pieces to end up in order as shown…

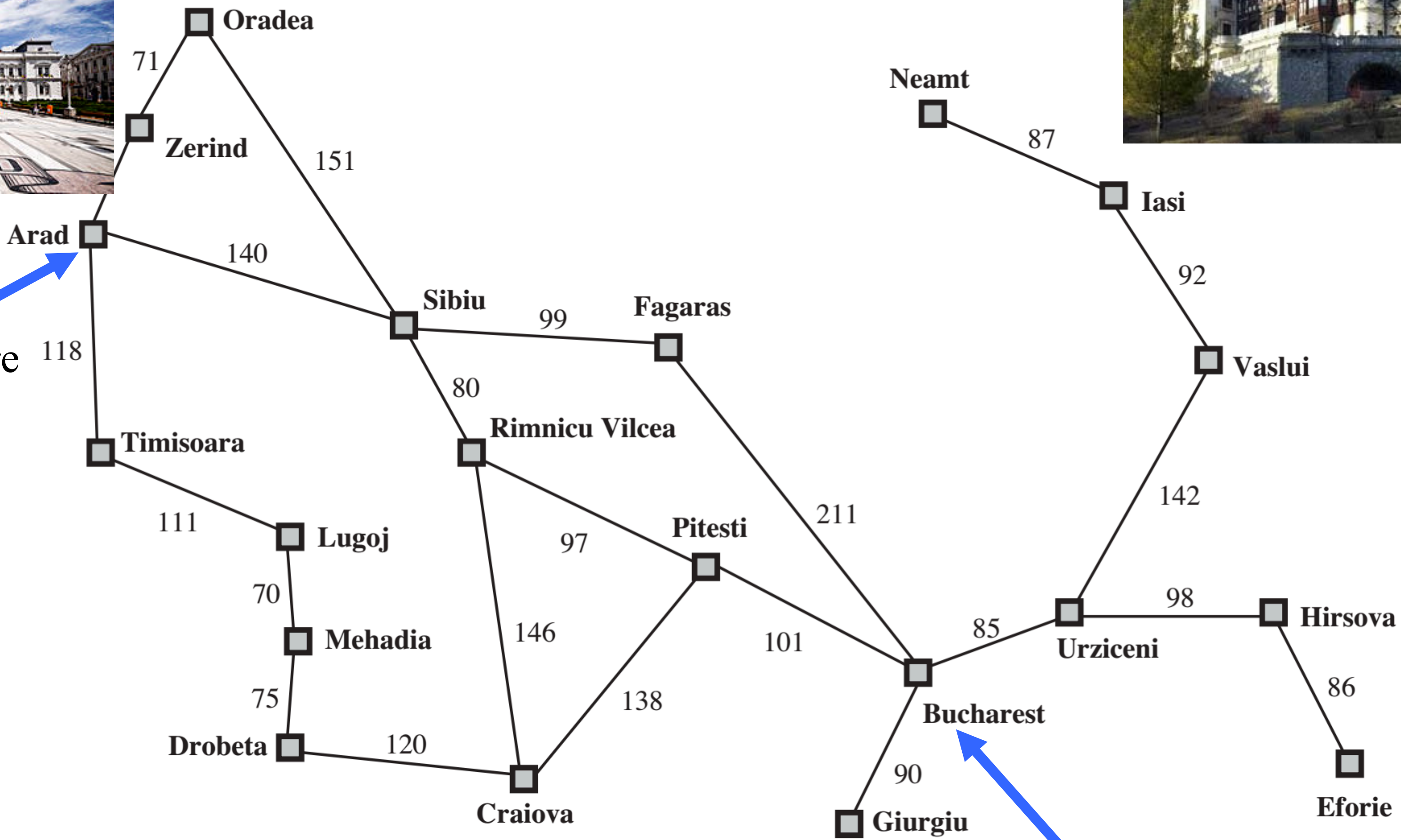


Start State   Goal State

- **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



You are here

You need to be here

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*.**

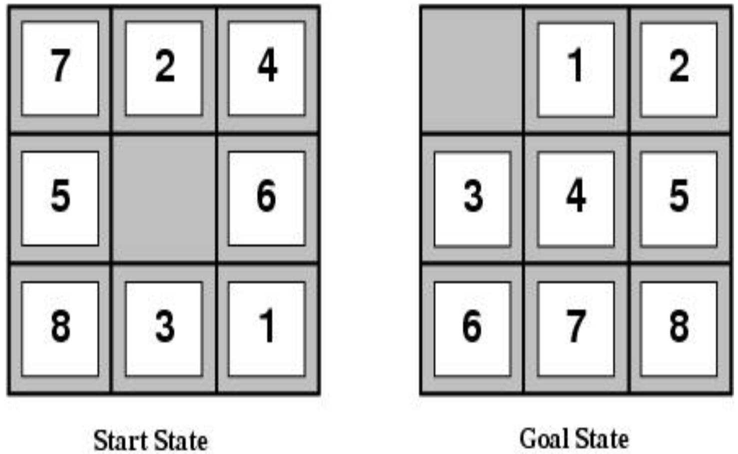
Art: Formulating a Search Problem

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*

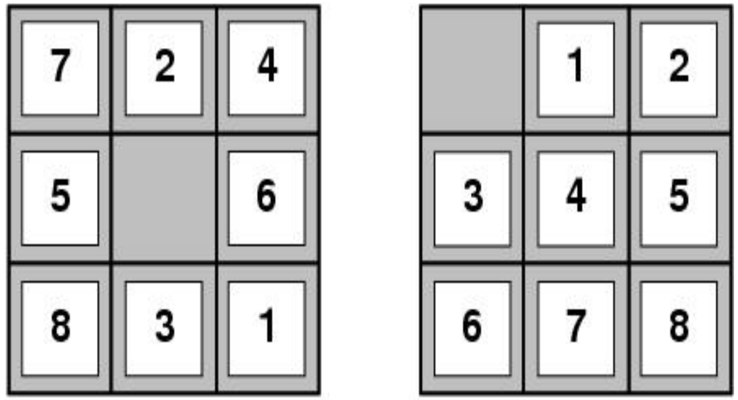
Formulation greatly affects combinatorics of search space and therefore speed of search

Example: 8-puzzle



- States??
- Initial state??
- Actions??
- Transition Model??
- Goal test??
- Path cost??

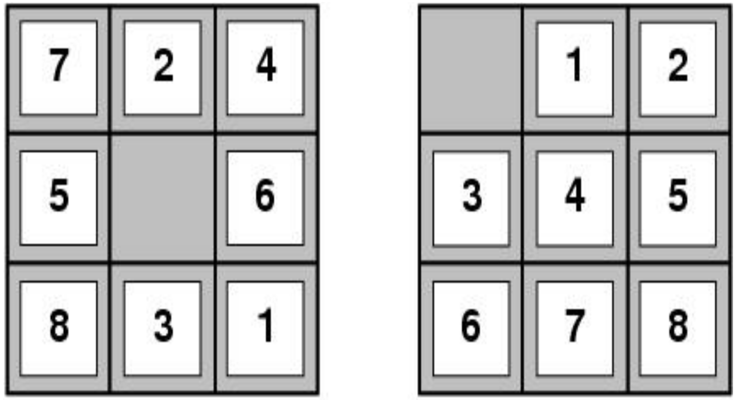
Example: 8-puzzle



Start State   Goal State

- States??
- Initial state??
- Actions??
- Transition Model??
- Goal test??
- Path cost??

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)***

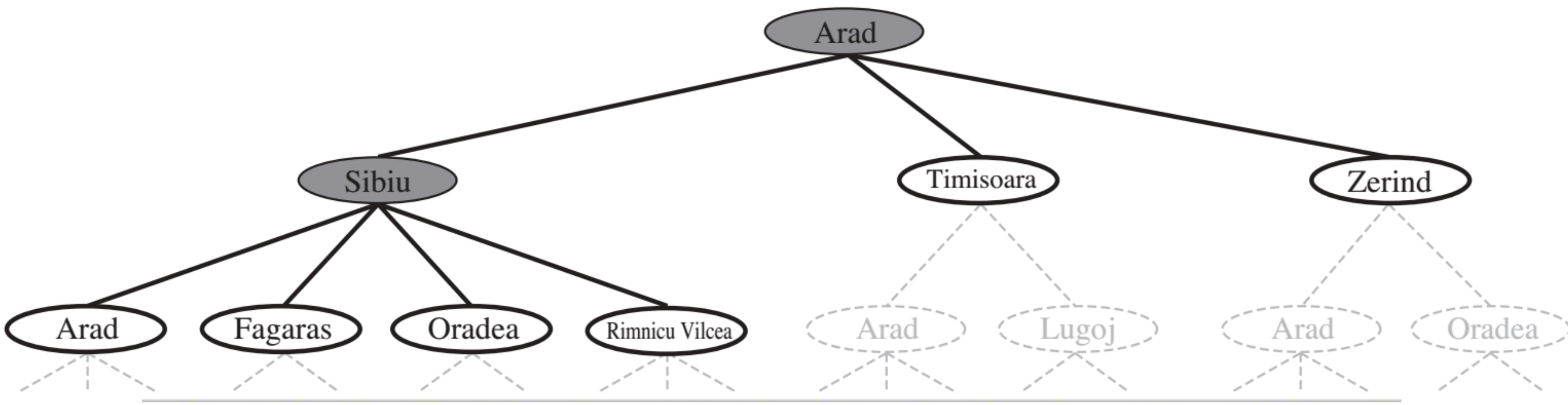
Useful Concepts

- ***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 *problem*

do

if **the frontier is empty** then return ***failure***

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

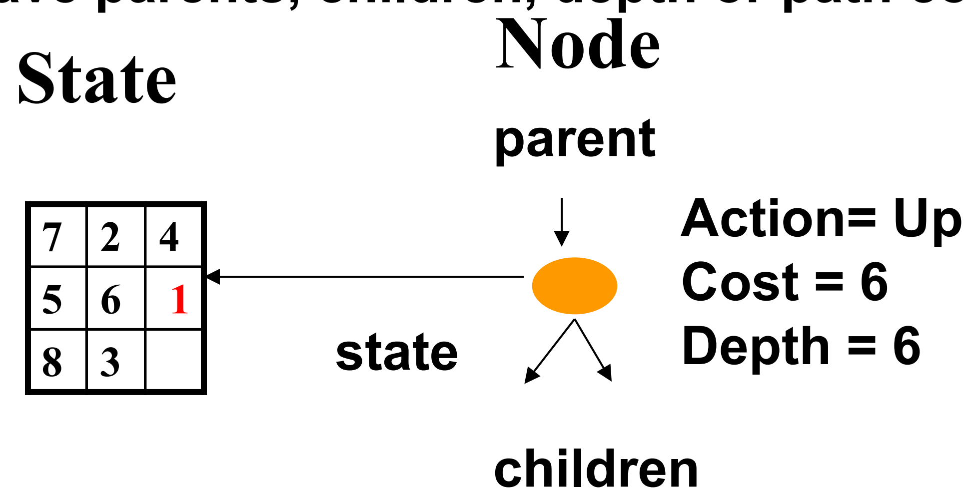
if **node contains goal state** then return ***solution***

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!**

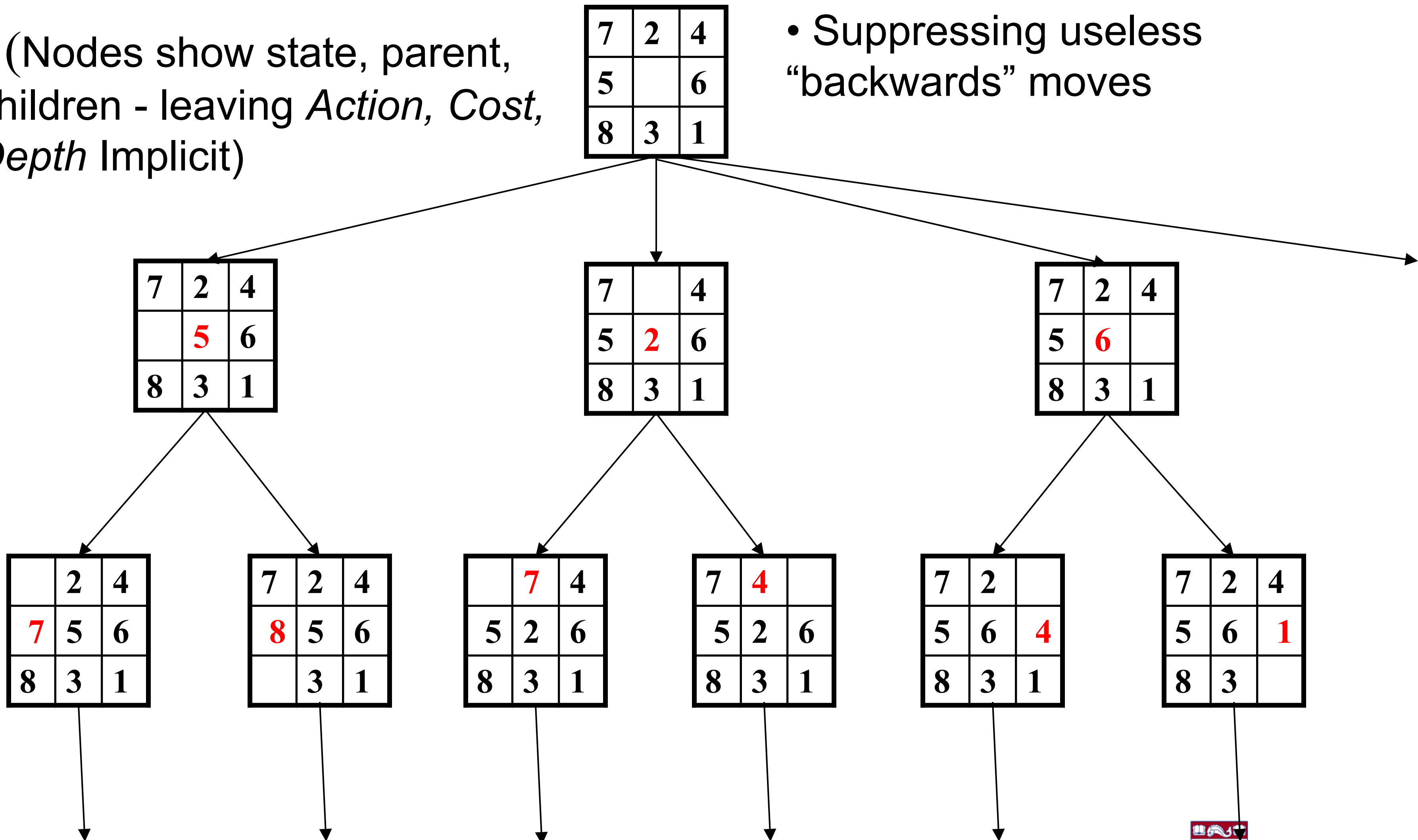


- **The EXPAND function**
  - uses the Actions and Transition Model to create the corresponding states
    - —creates new nodes,
    - —fills in the various fields

8-Puzzle *Search Tree*

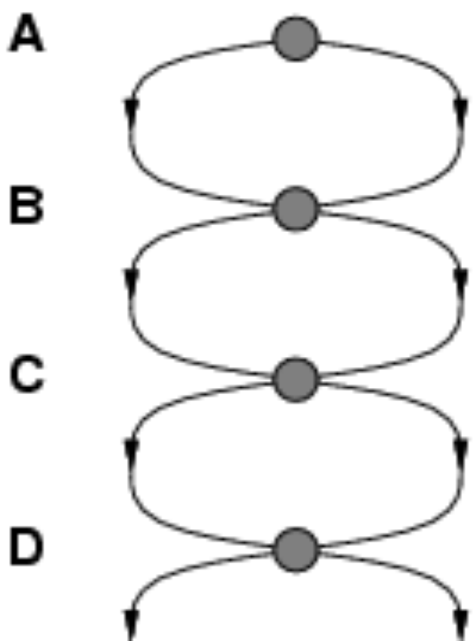
- (Nodes show state, parent, children - leaving *Action, Cost, Depth* Implicit)

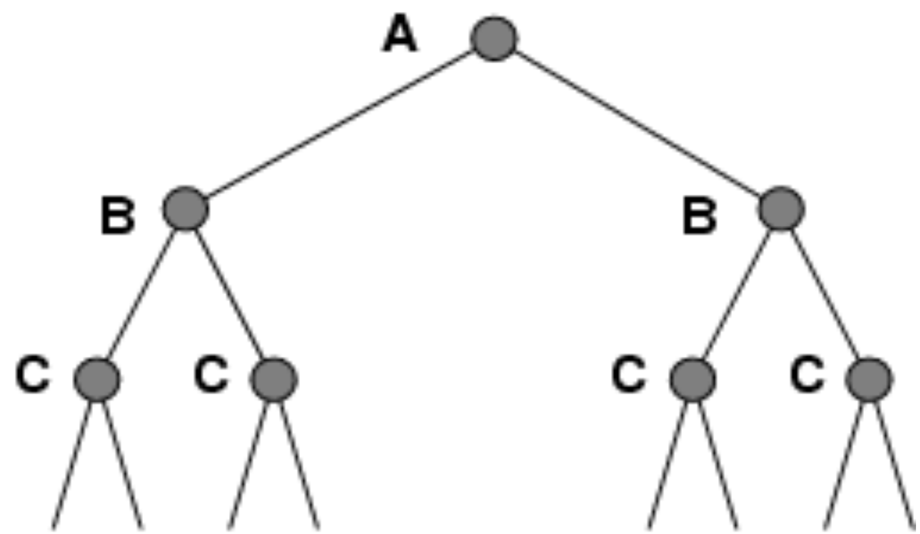
- Suppressing useless "backwards" moves



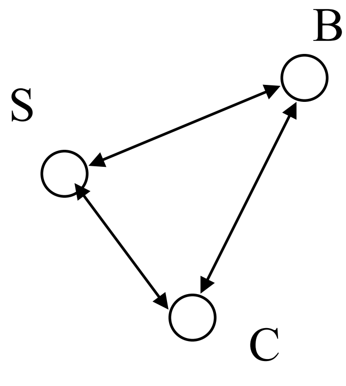
Problem: Repeated states

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

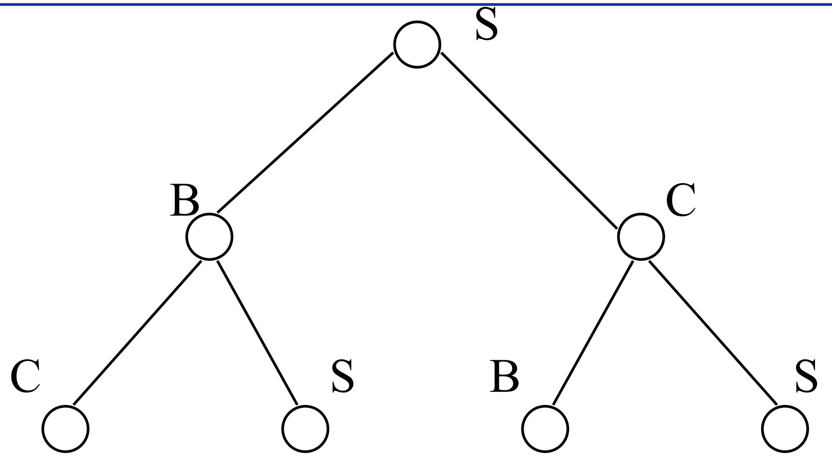




Solution: Graph Search!



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

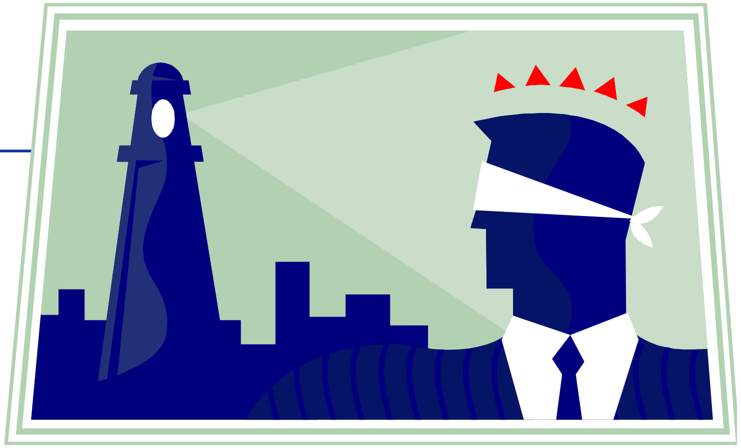
Graph Search vs Tree Search

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

- **<u>Implementation:</u>**
  - *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 return 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 then
           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 inserte*
queue only after test
see if it is a goal st

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 SOLUTION(node)
  frontier <- a FIFO queue with node as the only element
  loop do
    if EMPTY?(frontier) then return 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 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*

From Figure 3.11 Breadth-first search (ignores loops, repeated nodes)

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!!*

Search Conundrum

- **Breadth-first**
  - ☑ Complete,
  - ☑ Optimal
  - ☒ *but* uses $O(b^d)$ space
- **Depth-first**
  - ☒ Not complete *unless m is bounded*
  - ☒ Not optimal
  - ☒ Uses $O(b^m)$ time; terrible if m >> d
  - ☑ *but* only uses $O(\boldsymbol{b*m})$ ***space***

How can we get the best of both?

Depth-limited search: A building block

- **Depth-First search *but with depth limit ℓ.***
  - i.e. nodes at depth ℓ *have no successors.*
  - No infinite-path problem!

- **If $\ell = d$ (by luck!), then optimal**
  - But:
    - —**If $\ell < d$ then incomplete** ☹
    - —**If $\ell > d$ then not optimal** ☹

- **Time complexity:** $O(b^l)$
- **Space complexity:** $O(bl)$ ☺

Iterative deepening search

- **A general strategy to find best depth limit *l*.**
  - **Key idea: use *Depth-limited search* as subroutine, with increasing *l*.**

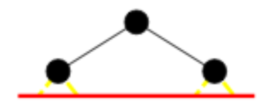
```
For l = 0 to ∞ do
        depth-limited-search to level l
        if it succeeds
              then return solution
```

  - ***Complete & optimal*: Goal is always found at depth *d*, the depth of the shallowest goal-node.**

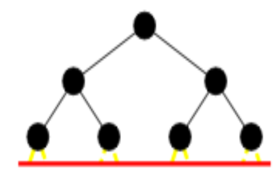
Could this possibly be efficient?

Nodes constructed at each deepening

- **Depth 0: 0 (Given the node, doesn't *construct* it.)**



- **Depth 1: b^1 nodes**



- **Depth 2: b nodes + b^2 nodes**
- **Depth 3: b nodes + b^2 nodes + b^3 nodes**
- **…**

Total nodes constructed:

- Depth 0: 0 (Given the node, doesn't *construct* it.)
- Depth 1: $b^1 = b$ nodes
- Depth 2: b nodes + b^2 nodes
- Depth 3: b nodes + b^2 nodes + b^3 nodes
- …

Suppose the first solution is the last node at depth 3:

Total nodes constructed:

3*b nodes + **2***b^2 nodes + **1***b^3 nodes

ID search, Evaluation II: Time Complexity

- **More generally, the time complexity is**
  - $(d)b + (d-1)b^2 + \ldots + (1)b^d = O(b^d)$

- ***As efficient in terms of O(…)*** **as Breadth First Search:**
  - $b + b^2 + \ldots + b^d = O(b^d)$

ID search, Evaluation III

- **Complete: YES (no infinite paths)** ☺
- **Time complexity:** $O(b^d)$
- **Space complexity:** $O(bd)$ ☺
- **Optimal: YES if step cost is 1.** ☺

Summary of algorithms

Criterion	Breadth-First	Depth-First	Depth-limited	Iterative deepening
Complete?	**YES**	**NO**	**NO**	**YES**
Time	b^d	b^m	b^l	b^d
Space	b^d	bm	bl	bd
Optimal?	**YES**	**NO**	**NO**	**YES**