Example: Romania

On holiday in Romania; currently in Arad.
Flight leaves tomorrow from Bucharest

Formulate goal:
be in Bucharest

Formulate problem:
states: various cities
actions: drive between cities

Find solution:
sequence of cities, e.g., Arad, Sibiu, Fagaras, Bucharest
Example: Romania

Network diagram showing the cities and their connections in Romania.
Problem types

Deterministic, fully observable $\implies$ single-state problem
Agent knows exactly which state it will be in; solution is a sequence

Non-observable $\implies$ conformant problem
Agent may have no idea where it is; solution (if any) is a sequence

Nondeterministic and/or partially observable $\implies$ contingency problem
percepts provide \textit{new} information about current state
solution is a \textit{contingent plan} or a \textit{policy}
often \textit{interleave} search, execution

Unknown state space $\implies$ exploration problem (“online”)
Example: vacuum world

Single-state, start in #5. Solution??

1

2

3

4

5

6

7

8
Example: vacuum world

Single-state, start in #5. Solution??
[Right, Suck]

Conformant, start in \{1, 2, 3, 4, 5, 6, 7, 8\}
e.g., Right goes to \{2, 4, 6, 8\}. Solution??
Example: vacuum world

Single-state, start in #5. Solution??
[Right, Suck]

Conformant, start in \{1, 2, 3, 4, 5, 6, 7, 8\}
e.g., Right goes to \{2, 4, 6, 8\}. Solution??
[Right, Suck, Left, Suck]

Contingency, start in #5
Murphy’s Law: Suck can dirty a clean carpet
Local sensing: dirt, location only.
Solution??
Example: vacuum world

Single-state, start in #5. Solution??
[Right, Suck]

Conformant, start in \{1, 2, 3, 4, 5, 6, 7, 8\}
e.g., Right goes to \{2, 4, 6, 8\}. Solution??
[Right, Suck, Left, Suck]

Contingency, start in #5
Murphy’s Law: Suck can dirty a clean carpet
Local sensing: dirt, location only.
Solution??
[Right, if dirt then Suck]
A problem is defined by four items:

initial state  e.g., “at Arad”

successor function $S(x) =$ set of action–state pairs
  e.g., $S(Arad) = \{\langle Arad \rightarrow Zerind, Zerind \rangle, \ldots \}$

goal test, can be
  explicit, e.g., $x =$ “at Bucharest”
  implicit, e.g., $NoDirt(x)$

path cost (additive)
  e.g., sum of distances, number of actions executed, etc.
  $c(x, a, y)$ is the step cost, assumed to be $\geq 0$

A solution is a sequence of actions
leading from the initial state to a goal state
Selecting a state space

Real world is absurdly complex
⇒ state space must be \textit{abstracted} for problem solving

(Abstract) state = set of real states

(Abstract) action = complex combination of real actions
\hspace{1cm} e.g., “Arad \rightarrow Zerind” represents a complex set
\hspace{1cm} of possible routes, detours, rest stops, etc.

For guaranteed realizability, \textit{any} real state “in Arad”
\hspace{1cm} must get to some real state “in Zerind”

(Abstract) solution =
\hspace{1cm} set of real paths that are solutions in the real world

Each abstract action should be “easier” than the original problem!
Example: vacuum world state space graph

states??
actions??
goal test??
path cost??
Example: vacuum world state space graph

**states??**: integer dirt and robot locations (ignore dirt **amounts** etc.)

**actions??**

**goal test??**

**path cost??**
Example: vacuum world state space graph

**states**: integer dirt and robot locations (ignore dirt amounts etc.)

**actions**: *Left, Right, Suck, NoOp*

**goal test**

**path cost**
Example: vacuum world state space graph

**states??**: integer dirt and robot locations (ignore dirt amounts etc.)

**actions??**: *Left, Right, Suck, NoOp*

**goal test??**: no dirt

**path cost??**
Example: vacuum world state space graph

states??: integer dirt and robot locations (ignore dirt amounts etc.)
actions??: Left, Right, Suck, NoOp
goal test??: no dirt
path cost??: 1 per action (0 for NoOp)
Example: The 8-puzzle

Start State

Goal State

slides from Russell and Norvig

states??
actions??
goal test??
path cost??
Example: The 8-puzzle

states??: integer locations of tiles (ignore intermediate positions)
actions??
goal test??
path cost??
Example: The 8-puzzle

states??: integer locations of tiles (ignore intermediate positions)
actions??: move blank left, right, up, down (ignore unjamming etc.)
goal test??
path cost??
Example: The 8-puzzle

Start State

Goal State

states??: integer locations of tiles (ignore intermediate positions)
actions??: move blank left, right, up, down (ignore unjamming etc.)
goal test??: = goal state (given)
path cost??
**Example: The 8-puzzle**

Start State

```
7 2 4
5 6
8 3 1
```

Goal State

```
1 2 3
4 5 6
7 8
```

*states??*: integer locations of tiles (ignore intermediate positions)

*actions??*: move blank left, right, up, down (ignore unjamming etc.)

*goal test??*: = goal state (given)

*path cost??*: 1 per move

[Note: optimal solution of $n$-Puzzle family is NP-hard]
Example: robotic assembly

states??: real-valued coordinates of robot joint angles
parts of the object to be assembled

actions??: continuous motions of robot joints

goal test??: complete assembly with no robot included!

path cost??: time to execute

Chapter 3
Tree search algorithms

Basic idea:
- offline, simulated exploration of state space
- by generating successors of already-explored states
  (a.k.a. expanding states)

```
function TREE-SEARCH(problem, strategy) returns a solution, or failure
    initialize the search tree using the initial state of problem
    loop do
        if there are no candidates for expansion then return failure
        choose a leaf node for expansion according to strategy
        if the node contains a goal state then return the corresponding solution
        else expand the node and add the resulting nodes to the search tree
    end
```
Tree search example
Tree search example
Tree search example
A state is a (representation of) a physical configuration
A node is a data structure constituting part of a search tree
includes parent, children, depth, path cost $g(x)$
States do not have parents, children, depth, or path cost!

The \texttt{Expand} function creates new nodes, filling in the various fields and using the \texttt{SuccessorFn} of the problem to create the corresponding states.
Implementation: general tree search

**function** Tree-Search( `problem`, `fringe`) **returns** a solution, or failure

`fringe ← Insert(Make-Node(Initial-State[problem]), fringe)`

**loop do**

  **if** `fringe` is empty **then return** failure

  `node ← Remove-Front(fringe)`

  **if** Goal-Test(`problem`, State(`node`)) **then return** `node`

  `fringe ← InsertAll(Expand(`node`, `problem`), fringe)`

**function** Expand( `node`, `problem`) **returns** a set of nodes

`successors ← the empty set`

**for each** `action`, `result` in Successor-Fn(`problem`, State[`node`]) **do**

  `s ← a new Node`

  Parent-Node[`s`] ← `node`; Action[`s`] ← `action`; State[`s`] ← `result`

  Path-Cost[`s`] ← Path-Cost[`node`] + Step-Cost(`node`, `action`, `s`)

  Depth[`s`] ← Depth[`node`] + 1

  add `s` to `successors`

**return** `successors`
A strategy is defined by picking the **order of node expansion**

Strategies are evaluated along the following dimensions:
- **completeness**—does it always find a solution if one exists?
- **time complexity**—number of nodes generated/expanded
- **space complexity**—maximum number of nodes in memory
- **optimality**—does it always find a least-cost solution?

Time and space complexity are measured in terms of
- \( b \)—maximum branching factor of the search tree
- \( d \)—depth of the least-cost solution
- \( m \)—maximum depth of the state space (may be \( \infty \))
Uninformed search strategies

Uninformed strategies use only the information available in the problem definition

Breadth-first search

Uniform-cost search

Depth-first search

Depth-limited search

Iterative deepening search
Breadth-first search

Expand shallowest unexpanded node

**Implementation:**

`fringe` is a FIFO queue, i.e., new successors go at end

![Diagram of a tree with nodes A, B, C, D, E, F, G and an arrow pointing to A, indicating the breadth-first search order.](image)
Breadth-first search

Expand shallowest unexpanded node

**Implementation:**

*fringe* is a FIFO queue, i.e., new successors go at end
Breadth-first search

Expand shallowest unexpanded node

**Implementation:**
*fringe* is a FIFO queue, i.e., new successors go at end

```

A
/|
/ |
B C
/|
/ |
D E
/|
/ |
F G
```

Chapter 35
Breadth-first search

Expand shallowest unexpanded node

**Implementation:**

*fringe* is a FIFO queue, i.e., new successors go at end
Properties of breadth-first search

Complete??
Properties of breadth-first search

**Complete??** Yes (if $b$ is finite)

**Time??**
Properties of breadth-first search

Complete? Yes (if $b$ is finite)

Time? $1 + b + b^2 + b^3 + \ldots + b^d + b(b^d - 1) = O(b^{d+1})$, i.e., exp. in $d$

Space?
Properties of breadth-first search

Complete?? Yes (if $b$ is finite)

Time?? $1 + b + b^2 + b^3 + \ldots + b^d + b(b^d - 1) = O(b^{d+1})$, i.e., exp. in $d$

Space?? $O(b^{d+1})$ (keeps every node in memory)

Optimal??
Properties of breadth-first search

**Complete**? Yes (if \( b \) is finite)

**Time**? \( 1 + b + b^2 + b^3 + \ldots + b^d + b(b^d - 1) = O(b^{d+1}) \), i.e., exp. in \( d \)

**Space**? \( O(b^{d+1}) \) (keeps every node in memory)

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

**Space** is the big problem; can easily generate nodes at 100MB/sec so 24hrs = 8640GB.
Uniform-cost search

Expand least-cost unexpanded node

**Implementation:**

\[ \text{fringe} = \text{queue ordered by path cost, lowest first} \]

Equivalent to breadth-first if step costs all equal

**Complete??** Yes, if step cost \( \geq \epsilon \)

**Time??** \# of nodes with \( g \leq \) cost of optimal solution, \( O(b^{[C^*/\epsilon]}) \)

where \( C^* \) is the cost of the optimal solution

**Space??** \# of nodes with \( g \leq \) cost of optimal solution, \( O(b^{[C^*/\epsilon]}) \)

**Optimal??** Yes—nodes expanded in increasing order of \( g(n) \)
Depth-first search

Expand deepest unexpanded node

Implementation:

fringe = LIFO queue, i.e., put successors at front

A

B

C

D

E

F

G

H

I

J

K

L

M

N

O
Depth-first search

Expand deepest unexpanded node

**Implementation:**

fringe = LIFO queue, i.e., put successors at front
Depth-first search

Expand deepest unexpanded node

**Implementation:**

fringe = LIFO queue, i.e., put successors at front
Depth-first search

Expand deepest unexpanded node

**Implementation:**

\[ fringe = \text{LIFO queue, i.e., put successors at front}\]
Depth-first search

Expand deepest unexpanded node

**Implementation:**

\[ \text{fringe} = \text{LIFO queue, i.e., put successors at front} \]
Depth-first search

Expand deepest unexpanded node

**Implementation:**

\(\text{fringe} = \text{LIFO queue, i.e., put successors at front}\)
Depth-first search

Expand deepest unexpanded node

**Implementation:**

fringe = LIFO queue, i.e., put successors at front
Depth-first search

Expand deepest unexpanded node

**Implementation:**

*fringe* = LIFO queue, i.e., put successors at front
Depth-first search

Expand deepest unexpanded node

**Implementation:**

*fringe* = LIFO queue, i.e., put successors at front
Depth-first search

Expand deepest unexpanded node

Implementation:

\( fringe = \text{LIFO queue, i.e., put successors at front} \)
Depth-first search

Expand deepest unexpanded node

**Implementation:**

*fringe* = LIFO queue, i.e., put successors at front
Depth-first search

Expand deepest unexpanded node

**Implementation:**

fringe = LIFO queue, i.e., put successors at front
Properties of depth-first search

Complete??
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**
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??**
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?? \(O(bm)\), i.e., linear space!

Optimal??
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?? \( O(bm) \), i.e., linear space!

Optimal?? No
Depth-limited search

= depth-first search with depth limit \( l \),
i.e., nodes at depth \( l \) have no successors

Recursive implementation:

```plaintext
function Depth-Limited-Search(problem, limit) returns soln/fail/cutoff
    Recursive-DLS(Make-Node(Initial-State[problem]), problem, limit)

function Recursive-DLS(node, problem, limit) returns soln/fail/cutoff
    cutoff-occurred? ← false
    if Goal-Test(problem, State[node]) then return node
    else if Depth[node] = limit then return cutoff
    else for each successor in Expand(node, problem) do
        result ← Recursive-DLS(successor, problem, limit)
        if result = cutoff then cutoff-occurred? ← true
        else if result ≠ failure then return result
    if cutoff-occurred? then return cutoff else return failure
```

Chapter 360

Slides from Russell and Norvig
Iterative deepening search

function Iterative-Deepening-Search(problem) returns a solution

inputs: problem, a problem

for depth ← 0 to ∞ do
    result ← Depth-Limited-Search(problem, depth)
    if result ≠ cutoff then return result
end
Iterative deepening search \( l = 0 \)
Iterative deepening search $l = 1$
Iterative deepening search $l = 2$

Limit = 2
Iterative deepening search $l = 3$

Limit = 3

Slides from Russell and Norvig
Properties of iterative deepening search

Complete??
Properties of iterative deepening search

*Complete*?? Yes

*Time*??
Properties of iterative deepening search

**Complete** Yes

**Time** \[(d + 1)b^0 + db^1 + (d - 1)b^2 + \ldots + b^d = O(b^d)\]

**Space**
Properties of iterative deepening search

Complete?? Yes

Time?? \((d + 1)b^0 + db^1 + (d - 1)b^2 + \ldots + b^d = O(b^d)\)

Space?? \(O(bd)\)

Optimal??
Properties of iterative deepening search

**Complete** Yes

**Time** $(d + 1)b^0 + db^1 + (d - 1)b^2 + \ldots + b^d = O(b^d)$

**Space** $O(bd)$

**Optimal** Yes, if step cost = 1

Can be modified to explore uniform-cost tree

Numerical comparison for $b = 10$ and $d = 5$, solution at far right leaf:

\[
N(\text{IDS}) = 50 + 400 + 3,000 + 20,000 + 100,000 = 123,450 \\
N(\text{BFS}) = 10 + 100 + 1,000 + 10,000 + 100,000 + 999,990 = 1,111,100
\]

IDS does better because other nodes at depth $d$ are not expanded

BFS can be modified to apply goal test when a node is generated
## Summary of algorithms

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Breadth-First</th>
<th>Uniform-Cost</th>
<th>Depth-First</th>
<th>Depth-Limited</th>
<th>Iterative Deepening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete?</td>
<td>Yes*</td>
<td>Yes*</td>
<td>No</td>
<td>Yes, if ( l \geq d )</td>
<td>Yes</td>
</tr>
<tr>
<td>Time</td>
<td>( b^{d+1} )</td>
<td>( b^{\lfloor C^*/\epsilon \rfloor} )</td>
<td>( b^m )</td>
<td>( b^l )</td>
<td>( b^d )</td>
</tr>
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<td>( b^{d+1} )</td>
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<td>( b^l )</td>
<td>( b^d )</td>
</tr>
<tr>
<td>Optimal?</td>
<td>Yes*</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes*</td>
</tr>
</tbody>
</table>
Repeated states

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

Chapter 372

Slides from Russell and Norvig
function Graph-Search (problem, fringe) returns a solution, or failure

    closed ← an empty set
    fringe ← Insert(Make-Node(Initial-State[problem]), fringe)

loop do
    if fringe is empty then return failure
    node ← Remove-Front(fringe)
    if Goal-Test(problem, State[node]) then return node
    if State[node] is not in closed then
        add State[node] to closed
        fringe ← InsertAll(Expand(node, problem), fringe)
    end
Summary

Problem formulation usually requires abstracting away real-world details to define a state space that can feasibly be explored.

Variety of uninformed search strategies

Iterative deepening search uses only linear space and not much more time than other uninformed algorithms.

Graph search can be exponentially more efficient than tree search.