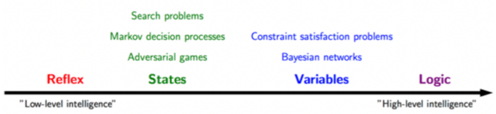
Goal-based agents 有目标的搜索

- **Reflex agents**: use a mapping from states to actions (lookup).
- **Goal-based agents**: problem solving agents or planning agents.



- Agents work towards a goal.
- Agents consider the impact of actions on future states, which means that their job is to identify the action or series of actions that lead to the goal.
- Formalized as a search through possible solutions.

Problem solving as search

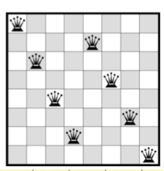
1. **Define the problem through:**
   (a) Goal formulation
   (b) Problem formulation
2. **Solving the problem as a 2-stage process:**
   (a) Search: "mental" or "offline" exploration of several possibilities
   (b) Execute the solution found

Problem formulation

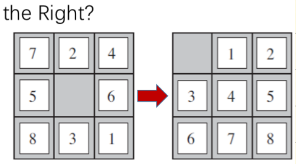
- **Initial state**: the state in which the agent starts.
- **States**: all states reachable from the initial by any sequence of actions. **(State space)**
- **Actions**: possible actions available to the agent. At a state *s*, *Actions*(*s*) returns the set of actions that can be executed in state *s*. **(Action space)**
- **Transition model**: a description of what each action does *Results*(*s*, *a*).
- **Goal test**: determine if a given state is a goal state.
- **Path cost**: function that assigns a numeric cost to each path w.r.t. performance measure.

Formulation: 8-queen problem

- **States**: all arrangements of 8 queens on the board.
- **Initial state**: no queen on the board.
- **Actions**: add a queen to any empty square.
- **Transition**: updated board.
- **Goal test**: 8 queens on board without attacked?

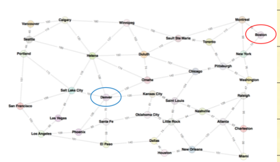


- **States**: any configuration of the 8 tiles on the 3x3 grid
- **Initial state**: any state (e.g., the configuration of the Left).
- **Actions**: move Left, Right, Up or Down.
- **Transition**: Given a state and an action, returns resulting state.
- **Goal state**: the configuration of the Right?
- **Path cost**: #moves.



Formulation: Routing problem

- **States**: In City where City ∈ {New York, San Francisco, Denver,...}.
- **Initial state**: In Boston
- **Actions**: walk to the adjacent city.
- **Transition**: new city.
- **Goal test**: In Denver
- **Path cost**: path length in kilometers.



State space vs. Search space

- **State space**: a *physical* configuration
- **Search space**: an *abstract* configuration represented by a search tree or graph of possible solutions.
- **Search tree** **models the sequence of actions**.
  - Root: initial state
  - Branches: actions
  - Nodes: results from actions. A node has: parent, children, depth, path cost, associated state in the state space.
- **Expand**: A function that given a node, creates all children nodes

Search Space Regions

- The search space is divided into three regions:
  - 1. **Explored** (a.k.a. Closed List, Visited Set)
  - 2. **Frontier** (a.k.a. Ready list, Open List, the Fringe)
  - 3. **Unexplored**.
- The **essence of search** is moving nodes from regions (3) to (2) to (1), and the essence of search strategy is deciding the order of such moves.

搜索空间有三部分:
①已搜索 ②前沿子 ③未搜索

Tree search

```
function TREE-SEARCH(initialState, goalTest)
    returns SUCCESS or FAILURE :

    initialize frontier with initialState

    while not frontier.isEmpty():
        state = frontier.remove()

        if goalTest(state):
            return SUCCESS(state)

        for neighbor in state.neighbors():
            frontier.add(neighbor)

    return FAILURE
```

Graph Search

```
function GRAPH-SEARCH(initialState, goalTest)
    returns SUCCESS or FAILURE :

    initialize frontier with initialState
    explored = Set.new()

    while not frontier.isEmpty():
        state = frontier.remove()
        explored.add(state)

        if goalTest(state):
            return SUCCESS(state)

        for neighbor in state.neighbors():
            if neighbor not in frontier ∪ explored:
                frontier.add(neighbor)

    return FAILURE
```

能避免重复搜索同一个节点
(即重复状态)

Search Strategies

- 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 it exists?
  - **Time complexity**: # nodes generated/expanded.
  - **Space complexity**: maximum # nodes in memory.
  - **Optimality**: Does it always find the least-cost solution?

In particular, time and space complexity are measured regarding:

- b – maximum branching factor of the search tree (actions per state).
- d – depth of the solution.
- m – maximum depth of the state space (may be ∞) (also noted sometimes D).

Two kinds of search: **Uninformed** and **Informed**.

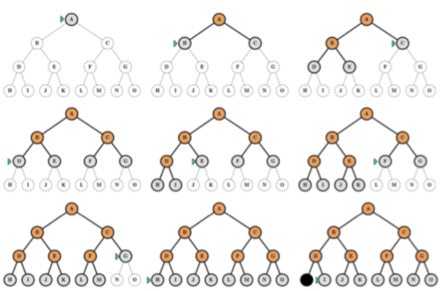
Uninformed Search

无任何领域知识

- Use **no** domain knowledge.
- **Strategies:**
  1. Breadth-first search (BFS): Expand shallowest node
  2. Depth-first search (DFS): Expand deepest node
  3. Depth-limited search (DLS): Depth first with depth limit
  4. Iterative-deepening search (IDS): DLS with increasing limit
  5. Uniform-cost search (UCS): Expand least cost node

Breadth-first Search (BFS)

- BFS: Expand **shallowest** first.



Pseudo-code

```
function GRAPH-SEARCH(initialState, goalTest)
    returns SUCCESS or FAILURE :

    initialize frontier with initialState
    explored = Set.new()

    while not frontier.isEmpty():
        state = frontier.remove()
        explored.add(state)

        if goalTest(state):
            return SUCCESS(state)

        for neighbor in state.neighbors():
            if neighbor not in frontier ∪ explored:
                frontier.add(neighbor)

    return FAILURE
```

```
function BREADTH-FIRST-SEARCH(initialState, goalTest)
    returns SUCCESS or FAILURE :

    frontier = Queue.new(initialState)
    explored = Set.new()

    while not frontier.isEmpty():
        state = frontier.dequeue()
        explored.add(state)

        if goalTest(state):
            return SUCCESS(state)

        for neighbor in state.neighbors():
            if neighbor not in frontier ∪ explored:
                frontier.enqueue(neighbor)

    return FAILURE
```

BFS: PF Metrics

- **Complete:** Yes (if b is finite)
- **Time:** $1 + b + b^2 + b^3 + \cdots + b^d = O(b^d)$
- **Space:** $O(b^d)$
- **Optimal:** Yes (if cost = 1 per step).
- **Implementation:** frontier: FIFO (Queue)

BFS: PF Metrics

How bad is BFS?

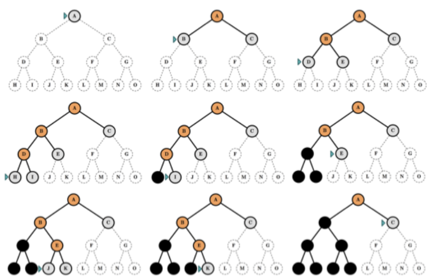
Time and Memory requirements for breadth-first search for a branching factor b=10; 1 million nodes per second; 1,000 bytes per node.

Depth	Nodes	Time	Memory
2	110	.11 milliseconds	107 kilobytes
4	11,110	11 milliseconds	10.6 megabytes
6	10^6	1.1 seconds	1 gigabyte
8	10^8	2 minutes	103 gigabytes
10	10^{10}	3 hours	10 terabytes
12	10^{12}	13 days	1 petabyte
14	10^{14}	3.5 years	99 petabytes
16	10^{16}	350 years	10 exabytes

Memory requirement + exponential time complexity are the biggest handicaps of BFS!

Depth-first Search (DFS)

- DFS: Expand **deepest** first.



Note: Once a node is expanded, it is removed from memory asap all its children are explored.

Pseudo-code

```
function BREADTH-FIRST-SEARCH(initialState, goalTest)
    returns SUCCESS or FAILURE :

    frontier = Queue.new(initialState)
    explored = Set.new()

    while not frontier.isEmpty():
        state = frontier.dequeue()
        explored.add(state)

        if goalTest(state):
            return SUCCESS(state)

        for neighbor in state.neighbors():
            if neighbor not in frontier ∪ explored:
                frontier.enqueue(neighbor)

    return FAILURE
```

```
function DEPTH-FIRST-SEARCH(initialState, goalTest)
    returns SUCCESS or FAILURE :

    frontier = Stack.new(initialState)
    explored = Set.new()

    while not frontier.isEmpty():
        state = frontier.pop()
        explored.add(state)

        if goalTest(state):
            return SUCCESS(state)

        for neighbor in state.neighbors():
            if neighbor not in frontier ∪ explored:
                frontier.push(neighbor)

    return FAILURE
```

DFS: PF Metrics

- **Complete:**
  No: fails in infinite-depth spaces, spaces with loops.
  Modify to avoid repeated states along path: complete in finite spaces
- **Time:** $1 + b + b^2 + b^3 + \cdots + b^m = O(b^m)$
  bad if m is much larger than d
  but if solutions are dense, may be much faster than BFS.
- **Space:** $O(bm)$ **linear space complexity!** (needs to store only a single path from the root to a leaf node, **along with the remaining unexpanded sibling nodes for each node on the path, hence the m factor.**)
- **Optimal:** No
- **Implementation:** fringe: LIFO (Stack)

How bad is DFS?

Time and Memory requirements for breadth-first search for a branching factor b=10; 1 million nodes per second; 1,000 bytes per node.

Recall for BFS...

Depth	Nodes	Time	Memory
2	110	.11 milliseconds	107 kilobytes
4	11,110	11 milliseconds	10.6 megabytes
6	10^6	1.1 seconds	1 gigabyte
8	10^8	2 minutes	103 gigabytes
10	10^{10}	3 hours	10 terabytes
12	10^{12}	13 days	1 petabyte
14	10^{14}	3.5 years	99 petabytes
16	10^{16}	350 years	10 exabytes

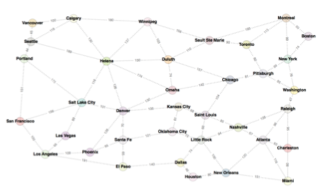
Depth =16.

We go down from 10 exabytes in BFS to 156 kilobytes in DFS!

Depth-limited Search (DLS)

限定DFS搜索深度

- DFS with depth limit l (nodes at level l has no successors).
- Select some limit in depth to explore with DFS
- If we know some knowledge about the problem, may be we don't need to go to a full depth.



Idea: any city can be reached from another city in at most l steps with l < 36.

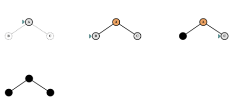
Iterative deepening Search (IDS)

不断加深DFS深度

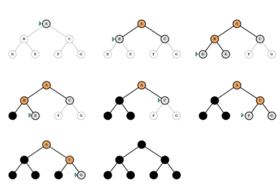
- Combines the benefits of BFS and DFS.
- Idea: Iteratively increase the search limit until the depth of the shallowest solution d is reached.
- Applies **DLS with increasing limits**.
- The algorithm will stop if a solution is found or if DLS returns a failure (no solution).
- Because most of the nodes are on the bottom of the search tree, it not a big waste to iteratively re-generate the top
- Let' s take an example with a depth limit between 0 and 3.

- Limit = 0

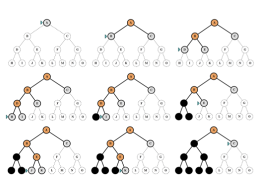
- Limit = 1



- Limit = 2



- Limit = 3



Uniform-cost Search (UCS)

- The arcs in the search graph may have weights (different cost attached). How to leverage this information?
- BFS will find the shortest path which may be costly.
- We want the **cheapest** not shallowest solution.
- Modify BFS: Prioritize by cost not depth → **Expand node *n* with the lowest path cost *g*(*n*)**
- Explores increasing costs.

限定只搜索n个节点
使cost g(n)最小

UCS: Pseudo-code

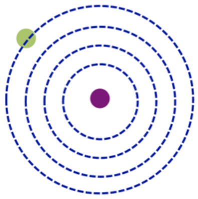
```
function BREADTH-FIRST-SEARCH(initialState, goalTest)
    returns SUCCESS or FAILURE :

    frontier = Queue.new(initialState)
    explored = Set.new()

    while not frontier.isEmpty():
        state = frontier.dequeue()
        explored.add(state)

        if goalTest(state):
            return SUCCESS(state)

        for neighbor in state.neighbors():
            if neighbor not in frontier ∪ explored:
                frontier.enqueue(neighbor)

    return FAILURE
```

```
function UNIFORM-COST-SEARCH(initialState, goalTest)
    returns SUCCESS or FAILURE : /* Cost f(n) = g(n) */

    frontier = Heap.new(initialState)
    explored = Set.new()

    while not frontier.isEmpty():
        state = frontier.deleteMin()
        explored.add(state)

        if goalTest(state):
            return SUCCESS(state)

        for neighbor in state.neighbors():
            if neighbor not in frontier ∪ explored:
                frontier.insert(neighbor)
            else if neighbor in frontier:
                frontier.decreaseKey(neighbor)

    return FAILURE
```

Cost: $f(n) = depth(n)$ 即为BFS
Cost: $f(n) = -depth(n)$ 即为DFS

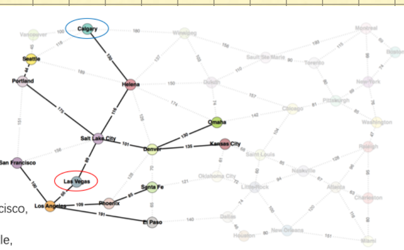
UCS: PF Metrics

- **Complete:** Yes, if solution has a finite cost.
- **Time:**
  - Suppose C^*: cost of the optimal solution.
  - Every action costs at least ϵ (bound on the cost).
  - The effective depth is roughly C^*/ϵ (how deep the cheapest solution could be).
  - $O(b^{C^*/\epsilon})$
- **Space:** # of nodes with $g \leq$ cost of optimal solution, $O(b^{C^*/\epsilon})$
- **Optimal:** Yes.
- **Implementation:** frontier = queue ordered by path cost *g*(*n*), lowest first = Heap!
- **While complete and optimal, UCS explores the space in every direction because no information is provided about the goal!**



UCS

Start: Las Vegas
Goal: Calgary

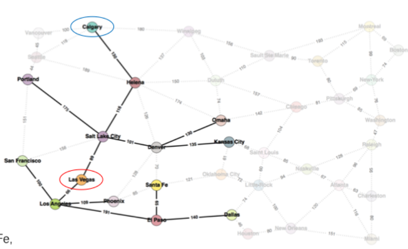


Order of Visit: Las Vegas, Los Angeles, Salt Lake City, San Francisco, Phoenix, Denver, Helena, El Paso, Santa Fe, Portland, Seattle, Omaha, Kansas City, Calgary.

Example using the map

BFS

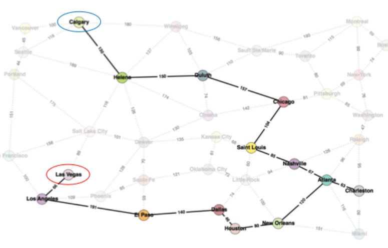
Start: Las Vegas
Goal: Calgary



Order of Visit: Las Vegas, Los Angeles, Salt Lake City, El Paso, Phoenix, San Francisco, Denver, Helena, Portland, Dallas, Santa Fe, Kansas City, Omaha, Calgary.

DFS

Start: Las Vegas
Goal: Calgary



Order of Visit: Las Vegas, Los Angeles, El Paso, Dallas, Houston, New Orleans, Atlanta, Charleston, Nashville, Saint Louis, Chicago, Duluth, Helena, Calgary.