# HEURISTIC SEARCH I

## Recap

The last lecture introduced

- Basic problem solving techniques:
  - Breadth-first search
  - Depth-first search
- Breadth-first search is complete but expensive.
- Depth-first search is cheap but incomplete
- Can't we do better than this?
- That is what this lecture is about

## Overview

Aims of this lecture:

- show how basic search (depth 1st, breadth 1st) can be improved;
- introduce:
  - *depth limited search;*
  - *iterative deepening*.
- show that even with such improvements, search is hopelessly unrealistic for real problems.

## Algorithmic Improvements

- Are then any *algorithmic* improvements we can make to basic search algorithms that will improve overall performance?
- Try to get *optimality* and *completeness* of breadth 1st search with *space efficiency* of depth 1st.
- Not too much to be done about time complexity :-(

## Depth Limited Search

- Depth first search has some desirable properties — space complexity.
- But if wrong branch expanded (with no solution on it), then it won't terminate.
- Idea: introduce a *depth limit* on branches to be expanded.
- Don't expand a branch below this depth.

- General algorithm for depth limited search:

```
depth limit = max depth to search to;
agenda = initial state;
while agenda not empty do
  take node from front of agenda;
  new nodes = apply operations to node;
  if goal state in new nodes then {
    return solution;
  }
  if depth(node) < depth limit then {
    add new nodes to front of agenda;
  }
}
```

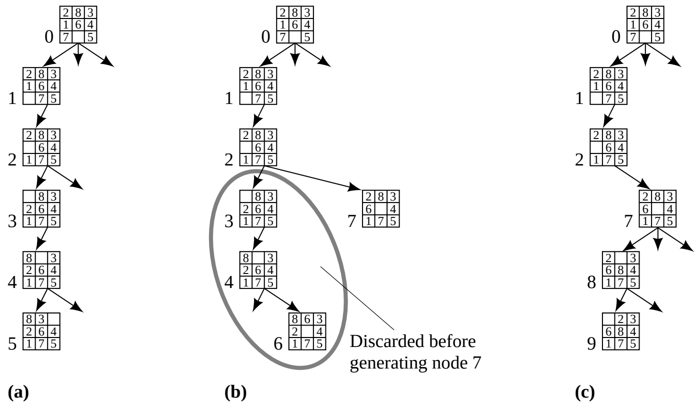
- For the 8-puzzle setup as:

| | | |
|---|---|---|
| 2 | 8 | 3 |
| 1 | 6 | 4 |
| 7 | | 5 |

⇒

| | | |
|---|---|---|
| 1 | 2 | 3 |
| 8 | | 4 |
| 7 | 6 | 5 |

- the search will be as follows:



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- So, when we hit the depth bound, we don't add any more nodes to the agenda.
- Then we pick the next node off the agenda.
- This has the effect of moving the search back to the last node above depth limit that that is "partly expanded".
- This is known as *chronological backtracking*.
- The effect of the depth limit is to force the search of the whole state space down to the limit.
- We get the completeness of breadth-first (down to the limit), with the space cost of depth first.

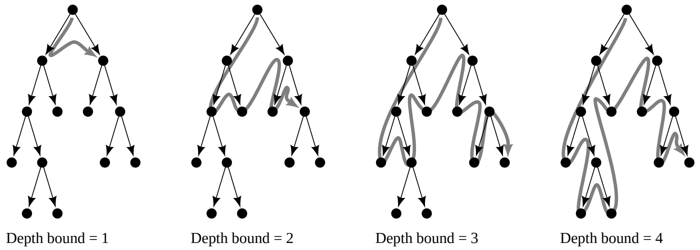
## Iterative Deepening

- Unfortunately, if we choose a max depth for d.l.s. such that shortest solution is longer, d.l.s. is not complete.
- Iterative deepening an ingenious *complete* version of it.
- Basic idea is:
  - do d.l.s. for depth 1; if solution found, return it;
  - otherwise do d.l.s. for depth n; if solution found, return it;
  - otherwise, . . .
- So we *repeat* d.l.s. for all depths until solution found.

- General algorithm for depth limited search:

```
depth limit = 1;
repeat {
  result = depth_limited_search(
    max depth = depth limit;
    agenda = initial node;
  );
  if result contains goal then {
    return result;
  }
  depth limit = depth limit + 1;
} until false; /* i.e., forever */
```

- Calls d.l.s. as subroutine.



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- Note that in iterative deepening, we *re-generate nodes on the fly*.

  Each time we do call on depth limited search for depth $d$, we need to regenerate the tree to depth $d-1$.
- Isn't this inefficient?
- Tradeoff *time* for *memory*.
- In general we might take a *little* more time, but we save a *lot* of memory.
- Now for breadth-first search to level $d$:

$$\begin{aligned} N_{bf} &= 1 + b + b^2 + b \qquad (1)\\ &= \frac{b^{d+1}-1}{b-1} \qquad (2)\end{aligned}$$

- In contrast a complete depth-limited search to level $j$:

$$N^j_{df} = \frac{b^{j+1}-1}{b-1} \qquad (3)$$

- (This is just a breadth-first search to depth $j$.)
- In the worst case, then we have to do this to depth $d$, so expanding:

$$\begin{aligned} N_{id} &= \sum_{j=0}^{d} \frac{b^{j+1}-1}{b-1} \qquad (4)\\ &\vdots \qquad (5)\\ &= \frac{b^{d+2}-2b-bd+d+1}{(b-1)^2} \qquad (6)\end{aligned}$$

- For large $d$:

$$\frac{N_{id}}{N_{bf}} = \frac{b}{b-1} \qquad (7)$$

- So for high branching and relatively deep goals we do a small amount more work.
- Example: Suppose $b = 10$ and $d = 5$.

  Breadth first search would require examining $111,111$ nodes, with memory requirement of $100,000$ nodes.

  Iterative deepening for same problem: $123,456$ nodes to be searched, with memory requirement only $50$ nodes.

  Takes 11% longer in this case.

- For the 8-puzzle setup as:

| | | |
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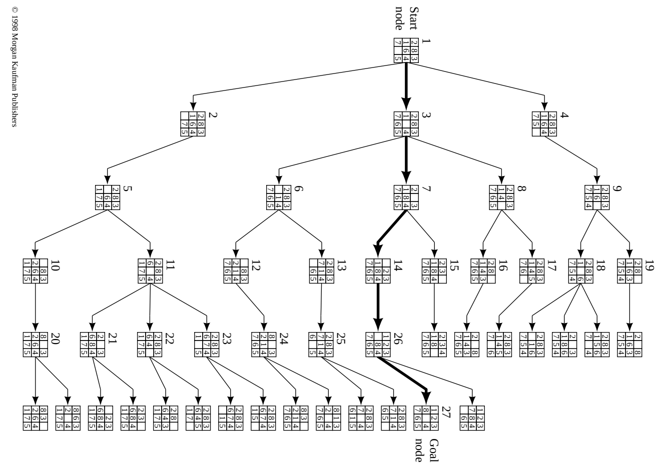
⇒

| | | |
|---|---|---|
| 1 | 2 | 3 |
| 8 | | 4 |
| 7 | 6 | 5 |

- What would iterative deepening search look like?
- Well, it would explore the search space:



- In the following way.
- States would be expanded in the order:
  1. 1
  2. 1, 2, 3, 4
  3. 1, 2, 5, 3, 6, 7, 8, 4, 9.
  4. 1, 2, 5, 10, 11, 3, 6, 13, 13, 7, 14, 15, 8, 16, 17, 4, 9, 18, 19.
  5. . . .
- Note that these are the states *visited*, not the nodes on the agenda.

## Bi-directional Search

- Suppose we search from *the goal state backwards* as well as from *initial state forwards*.
- Involves determining *predecessor* nodes to goal, and then looking at predecessor nodes to this, . . .
- Rather than doing one search of $b^d$, we do *two* $b^{d/2}$ searches.
- *Much* more efficient.

- Example:

  Suppose $b = 10$, $d = 6$.

  Breadth first search will examine nodes.

  Bidirectional search will examine nodes.
- Can combine different search strategies in different directions.
- For large $d$, is still impractical!

## Summary

- This lecture has looked at some more efficient techniques than breadth first and depth first search.
  - depth-limited search;
  - iterative-deepening search; and
  - bidirectional search.
- These all improve on depth-first and breadth-first search.
- However, all fail for big enough problems (too large state space).
- Next lecture, we will look at approaches that cut down the size of the state-space that is searched.