1 handout: slides
check your Wildcat Pass before coming to campus
email for grades, Piazza
Search
This particular pattern of molecules known as a 'human being' has evolved an amazing depth of consciousness: an ability to internally model the reality beyond the senses, to imagine futures that have never happened, to use language, to use rationality to build and test theories about our universe, to become self-aware. —Jeff Lieberman (artist, roboticist)
The ability to think is perhaps the most distinctive of human capacities. Typically, thinking involves mentally representing some aspects of the world (including aspects of ourselves) and manipulating these representations or beliefs so as to yield new beliefs, where the latter may aid in accomplishing a goal. —Edward E. Smith (Psychology, U Michigan)

The ability to solve problems is one of the most important manifestations of human thinking. ... We might therefore suspect that problem solving depends on general cognitive abilities that can potentially be applied to an essentially unlimited range of domains. —Keith Holyoak (Psychology, UCLA)
Formalizing Problem Solving

**State:** hypothetical world state
**Operators:** actions that modify world
**Goal:** desired state or test

Representation

VW search space
VW state space
MC representation
Basic Algorithms
open ← an ordered list containing just the initial state.

Loop

If open is empty,
then return failure.

Node ← Pop(open).

If Node is a goal,
then return Node (or path to it).
else

Children ← Expand (Node).
Add Children to front of open.
Assume branching factor $b$ and solution at depth $d$.

Completeness:
- Time:
- Space:

Admissibility:
Breadth-First Search

open ← an ordered list containing just the initial state.

Loop
  If open is empty,
    then return failure.
  Node ← Pop(open).
  If Node is a goal,
    then return Node (or path to it).
  else
    Children ← Expand (Node).
    Add Children to end of open.
Assume branching factor $b$ and solution at depth $d$.

Completeness:

Time:

Space:

Admissibility:
open $\leftarrow$ an ordered list containing just the initial state.

Loop

If open is empty,
   then return failure.

$Node \leftarrow \text{Pop(open)}$.

If $Node$ is a goal,
   then return $Node$ (or path to it).
else
   $Children \leftarrow \text{Expand}(Node)$.
   Merge $Children$ into open, keeping sorted by path cost.
1. Check for cycles with ancestors
2. Maintain closed list (hash table) to detect duplicates
<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Time</th>
<th>Space</th>
<th>Complete</th>
<th>Admissible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth-first</td>
<td>$b^m$</td>
<td>$bm$</td>
<td>If $m \geq d$</td>
<td>No</td>
</tr>
<tr>
<td>Breadth-first</td>
<td>$b^d$</td>
<td>$b^d$</td>
<td>Yes</td>
<td>If ops cost 1</td>
</tr>
<tr>
<td>Uniform-cost</td>
<td>$b^d$</td>
<td>$b^d$</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

branching factor $b$
maximum depth $m$
solution depth $d$
Assume $b = 10$; 100,000 nodes/sec; 100 bytes/node.

<table>
<thead>
<tr>
<th>Sol. depth</th>
<th>Nodes</th>
<th>Time</th>
<th>Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11</td>
<td>.11 msec</td>
<td>1.1 Kb</td>
</tr>
<tr>
<td>2</td>
<td>111</td>
<td>1.1 msec</td>
<td>11 Kb</td>
</tr>
<tr>
<td>4</td>
<td>11,111</td>
<td>.11 sec</td>
<td>1 Mb</td>
</tr>
<tr>
<td>6</td>
<td>$10^6$</td>
<td>11 sec</td>
<td>111 Mb</td>
</tr>
<tr>
<td>8</td>
<td>$10^8$</td>
<td>18 min</td>
<td>11 Gb</td>
</tr>
<tr>
<td>10</td>
<td>$10^{10}$</td>
<td>31 hours</td>
<td>1 Tb</td>
</tr>
<tr>
<td>12</td>
<td>$10^{12}$</td>
<td>128 days</td>
<td>111 Tb</td>
</tr>
<tr>
<td>14</td>
<td>$10^{14}$</td>
<td>35 yrs</td>
<td>11 Pb</td>
</tr>
</tbody>
</table>
Search Conundrum

Breadth-first uses $b^d$ space

but complete and admissible

Depth-first complete only if $\text{limit} > d$, not admissible

but $bd$ space

How can we get the best of both?
A Clever Algorithm
for $d = 1$ to $\infty$ do
  depth-first search to level $d$
  if it succeeds
    then return solution

Could this possibly be efficient?
Assume branching factor $b$ and solution at depth $d$.

Completeness:

Time:

Space:

Admissibility:
### Nodes Generated by IDS

**b = 2**

<table>
<thead>
<tr>
<th>d</th>
<th>at d</th>
<th>in prev.</th>
<th>total</th>
<th>IDS</th>
<th>% of opt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>100.0</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>133.3</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>3</td>
<td>7</td>
<td>11</td>
<td>157.1</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>16</td>
<td>31</td>
<td>57</td>
<td>183.9</td>
</tr>
</tbody>
</table>

**b = 10**

<table>
<thead>
<tr>
<th>d</th>
<th>at d</th>
<th>in prev.</th>
<th>total</th>
<th>IDS</th>
<th>% of opt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>100.0</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>1</td>
<td>11</td>
<td>12</td>
<td>109.1</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>11</td>
<td>111</td>
<td>123</td>
<td>110.8</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>10000</td>
<td>1111</td>
<td>11,111</td>
<td>12,345</td>
</tr>
</tbody>
</table>
\[ b^d + 2b^{d-1} + 3b^{d-2} + \ldots + (d - 1)b^2 + db \]

\[ \approx b^d \left( \frac{b}{b - 1} \right)^2 \]
EOLQs
Please write down the most pressing question you have about the course material covered so far and put it in the box on your way out.

Thanks!