III. Informed Search

- Best-First Search
- Best-First Search for State-Space Graphs
- Cost Functions for State-Space Graphs
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- Cost Functions for AND-OR Graphs
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Best-First Search for AND-OR Graphs
Illustration of Solution Graphs and Solution Bases

Problem-reduction graph:

Solved rest problem
Best-First Search for AND-OR Graphs

Illustration of Solution Graphs and Solution Bases

Problem-reduction graph:

Solution graph for node $s$:

- Solved rest problem

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Best-First Search for AND-OR Graphs

Illustration of Solution Graphs and Solution Bases

Problem-reduction graph:

Solution graph for node $s$:

Solution graph for node $n_2$:

- Solved rest problem
Solution graph for $n_3$: 

```
s
  \rightarrow
  \downarrow
  n_1
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  n_2
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  \rightarrow
  \downarrow
  n_3
```
Solution graph for $n_3$:

Solution base for $s$:
Best-First Search for AND-OR Graphs
Illustration of Solution Graphs and Solution Bases (continued)

Solution graph for $n_3$:

Solution base for $s$:

Solution base for $s$:

Compare: Solution paths and solution bases in a state-space graphs.
Best-First Search for AND-OR Graphs

Properties of Problem-Reduction Graphs

1. $G$ is an implicitly defined directed AND-OR graph.
2. $G$ is acyclic and locally finite.

When searching problem-reduction graphs with the Algorithm GBF,

- the underlying problem-reduction graph $G$ is assumed to be acyclic,
- $f_1$ evaluates solution bases $H$,
- a most promising solution base minimizes $f_1$,
- a most promising solution base is searched among all solution bases maintained by GBF,
- solution bases maintained by GBF are solution bases for $s$ in the explicit part $G_e$ of $G$ with tip nodes in OPEN,
- $f_2$ returns a most informative node in a solution base.
Best-First Search for AND-OR Graphs

Principles of Algorithm GBF

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- the underlying problem-reduction graph $G$ is assumed to be acyclic,
- $f_1$ evaluates solution bases $H$,
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- a most promising solution base is searched \textit{among all solution bases} maintained by GBF,
- solution bases maintained by GBF are solution bases for $s$ in the explicit part $G_e$ of $G$ with tip nodes in OPEN,
- $f_2$ returns a most informative node in a solution base.
Remarks:

- Again, $G$ denotes the explored part of the search space graph.
- When searching AND-OR graphs with the algorithm GBF, only solution bases $H$ need to be considered that have not been considered so far. I.e., only solution bases $H$ with leaf nodes that are goal nodes or nodes in $\text{OPEN}$ and inner nodes in $\text{CLOSED}$ are considered.
- In an AND-OR graph, a node may be part of several solution bases.
- Usually, the evaluation function $f_1(H)$ is based on a heuristic $h(n)$.
- $h(n)$ estimates the optimum cost of solution graphs for the rest problem associated with a node $n$. Ideally, $h(n)$ should consider the probability of the solvability of the problem at node $n$.
- Compared to $f_2(H)$, the evaluation function $f_1(H)$ is usually more important.
- Searching AND-OR graphs with cycles is intricate. Note that the algorithms presented by Martelli and Montanari [1973, 1978], Nilsson [1980], or Pearl [1984] presume graphs without cycles. In the following, we will restrict to acyclic graphs as well.
- In the context of Markov Decision Processes, MDP, and advanced planning algorithms researchers have dealt with AND-OR graphs that contain cycles. [Bonet/Geffner 2005]
Best-First Search for AND-OR Graphs

Algorithm: GBF

Input: 
- $s$. Start node representing the initial problem.
- $\text{successors}(n)$. Returns the successors of node $n$.
- $\text{is\_solved}(n)$. Predicate that is True if $n$ is labeled "solved" or $n$ is a goal node.

Output: A solution graph or the symbol $Fail$. 

$\text{successors}(n)$. Returns the successors of node $n$. 

$\text{is\_solved}(n)$. Predicate that is True if $n$ is labeled "solved" or $n$ is a goal node. 

$f_1(H)$. Evaluation function for solution bases. 

$f_2(H)$. Selection function for OPEN-nodes in a solution base. 

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Best-First Search for AND-OR Graphs

\[ \text{GBF}(s, \text{successors}, \text{is\_solved}, f_1, f_2) \]

1. \textit{insert}(s, OPEN); \textit{add\_node}(s, G_e); \quad \text{// } G_e \text{ is the explored part of } G. \\
2. \textbf{LOOP} \\
3. \quad \text{IF } (\text{OPEN} = \emptyset) \text{ THEN RETURN(} \text{Fail}; \\
4.a \\
4.b \\
5. \\
6. \textbf{ENDLOOP}
Best-First Search for AND-OR Graphs

\[ \text{GBF}(s, \text{successors}, \text{is\_solved}, f_1, f_2) \]

1. \( \text{insert}(s, \text{OPEN}); \ \text{add\_node}(s, G_e); \) // \( G_e \) is the explored part of \( G \).
2. \text{LOOP}
3. \text{IF} (\text{OPEN} = \emptyset) \text{ THEN } \text{RETURN}(\text{Fail});
4.a \( H = \text{min\_solution\_base}(s, G_e, f_1); \) // Find most prom. sol. base in \( G_e \).
4.b \( n = f_2(H); \) // Find most informative non-goal node in \( H \).
    \( \text{remove}(n, \text{OPEN}); \ \text{push}(n, \text{CLOSED}); \)
5.

\[ \text{IF} \ \text{is\_solved}(n) \text{ \ THEN } \text{RETURN}(\text{compute\_solution\_graph}(G_e)); \]

6. \text{ENDLOOP}
Best-First Search for AND-OR Graphs

\[ \text{GBF}(s, \text{successors}, \text{is\_solved}, f_1, f_2) \]

1. \textit{insert}(s, \text{OPEN}); \textit{add\_node}(s, G_e); \quad \text{\textit{// \(G_e\) is the explored part of \(G\).}}
2. \textbf{LOOP}
3. \quad \textbf{IF} (\text{OPEN} = \emptyset) \textbf{THEN} \text{RETURN}(\text{Fail});
4. \qquad \text{a} \quad H = \text{min\_solution\_base}(s, G_e, f_1); \quad \text{\textit{// Find most prom. sol. base in \(G_e\).}}
4. \qquad \text{b} \quad n = f_2(H); \quad \text{\textit{// Find most informative non-goal node in \(H\).}}
\quad \textit{remove}(n, \text{OPEN}); \quad \textit{push}(n, \text{CLOSED});
5. \quad \textbf{FOREACH} \quad n' \ \text{IN} \ \text{successors}(n) \ \textbf{DO}

\quad \quad \textit{insert}(n', \text{OPEN}); \quad \textit{add\_node}(n', G_e);
\quad \quad \textit{add\_backpointer}(n', n);
\quad \quad \textbf{IF} \ \text{is\_solved}(n') \ \textbf{THEN} \ \text{\textit{propagate\_label}(n')};
\quad \quad \quad \textbf{IF} \ \text{is\_solved}(s) \ \text{THEN} \ \text{RETURN}(\text{compute\_solution\_graph}(G_e));
\quad \quad \textbf{ENDIF}
\quad \textbf{ENDDO}
6. \textbf{ENDLOOP}
Best-First Search for AND-OR Graphs \([\text{BF, BF}^*, \text{GBF}^*]\)

\[\text{GBF}(s, \text{successors, is\_solved, } f_1, f_2)\]

1. \(\text{insert}(s, \text{OPEN}); \ \text{add\_node}(s, G_e); \ // \ G_e \text{ is the explored part of } G.\)
2. \ loops
3. \text{IF} (\text{OPEN} = \emptyset) \text{THEN} \text{RETURN}(\text{Fail});
4.a \(H = \text{min\_solution\_base}(s, G_e, f_1); \ // \text{Find most prom. sol. base in } G_e.\)
4.b \(n = f_2(H); \ // \text{Find most informative non-goal node in } H.\)
   \(\text{remove}(n, \text{OPEN}); \ \text{push}(n, \text{CLOSED});\)
5. \text{FOREACH } n' \text{ IN } \text{successors}(n) \text{ DO}
   \text{IF} (n' \in \text{OPEN OR } n' \in \text{CLOSED}) \ // \text{Instance of } n' \text{ seen before?}
   \text{THEN} \ // \text{Use old instance of } n' \text{ instead.}
   \quad n' = \text{retrieve}(n', \text{OPEN} \cup \text{CLOSED});
   \text{ELSE} \ // n' encodes an instance of a new state.
   \quad \text{insert}(n', \text{OPEN}); \ \text{add\_node}(n', G_e);
   \text{ENDIF}
   \text{add\_backpointer}(n', n);
   \text{IF } \text{is\_solved}(n') \ // \text{Is } n' \text{ goal node or labeled solvable?}
   \text{THEN}
   \quad \text{propagate\_label}(n');
   \quad \text{IF } \text{is\_solved}(s) \ \text{THEN} \ \text{RETURN}(\text{compute\_solution\_graph}(G_e));
   \text{ENDIF}
\text{ENDDO}
6. \text{ENDLOOP}
Finding dead ends can be handled in the same way as finding goal nodes.

\[
\text{IF } ( \bot (n') \text{ OR } \text{is\_labeled}(n') ) \quad \text{// Is } n' \text{ unsolvable?}
\]

\[
\text{THEN}
\]

\[
\text{propagate\_label}(n'); \text{IF } \text{is\_unsolvable}(s) \text{ THEN RETURN}(\text{Fail});
\]

\[
\text{ENDIF}
\]

The expansion of nodes in $G$ can be implemented with or without occurrence check:

(a) With occurrence check. If an already existing rest problem is encountered, only an additional link is added to $G_e$. As a consequence, $G_e$ is a subgraph of the underlying search space graph $G$.

(b) Without occurrence check. Each successor becomes a new node, irrespective of duplicate rest problems. As a consequence, $G_e$ corresponds to an AND-OR tree that can be considered as an unfolding of the underlying search space graph $G$.

Therefore, using an occurrence check or not can be seen as different ways of modeling a problem.

The construction of solution bases depends strongly on the structure of the evaluation function $f_1$. In the general case, an individual construction of all possible solution bases plus an individual computation of the $f_1$-values cannot be avoided. However, if $f_1$ can be stated in a recursive manner using specific functions, computation of the minimum $f_1$ value and computation of a most promising solution base can be done very efficiently.
Best-First Search for AND-OR Graphs

Illustration of GBF

The underlying AND-OR graph of the following GBF illustration.
Illustration of GBF

- $f_1(H)$ Evaluates solution bases $H$ in regard to their edge count. Answers the question: What does the solution associated with $H$ cost?
- $f_2(H)$ Returns the node with a most expensive rest problem in $H$. Answers the question: What node to expand next?
- $h(n)$ Estimates the number of edges for the rest problem at node $n.$
Remarks:

- The evaluation function $f_1(H)$ estimates the total number of edges of a solution graph extending solution base $H$. Obviously, $f_1(H)$ will be based on the heuristic $h(n)$.

- Rationale for $f_1$. Searching the smallest solution may quickly lead to a first solution graph. Keyword: Small-is-Quick Principle

- Rationale for $f_2$. A possible estimation error of $h$, which allegedly claims an unsolvable rest problem as a solvable one, should be detected earliest. Since it is reasonable to assume that the estimation error is proportional to the cost estimate, we pick a most expensive rest problem first.

- Recall that the complete AND-OR graph is neither given nor manageable for real-world problems.
1. $s$ is expanded and moved to CLOSED.
Best-First Search for AND-OR Graphs

Illustration of GBF (continued)

1. $s$ is expanded and moved to CLOSED.

Possible solution bases:

- $f_1(H) = 6 + 1 = 7$
- $f_1(H) = 4 + 1 = 5$
- $f_1(H) = 3 + 1 = 4$

Most promising solution base $H$
2. Expansion of the node $n \in (\text{OPEN} \cap H)$.

![Diagram](image)

- **Node on OPEN**
- **Node on CLOSED**
- **Solved rest problem**

**previous most promising solution base**

$h = 6$
$h = 4$
$c = 0$
2. Expansion of the node $n \in (\text{OPEN} \cap H)$.

\[
\begin{array}{c}
\text{s} \\
h = 6 \\
\text{h} = 4 \\
c = 0
\end{array}
\]

Possible solution bases:

\[
\begin{array}{c}
f_1(H) = 7 \\
s \\
\text{f} = 6 \\
\text{Most promising solution base } H
\end{array}
\]

\[
\begin{array}{c}
f_1(H) = 5 \\
s \\
\text{f} = 6 \\
\text{Most promising solution base } H
\end{array}
\]

\[
\begin{array}{c}
f_1(H) = 7 \\
s \\
\text{f} = 6 \\
\text{Most promising solution base } H
\end{array}
\]
3. Expansion of the node $n \in (\text{OPEN} \cap \text{H})$.
Best-First Search for AND-OR Graphs

Illustration of GBF (continued)

3. Expansion of the node \( n \in (\text{OPEN} \cap H) \).

Possible solution bases:

- \( f_1(H) = 7 \)
- \( f_1(H) = 7 \)
- \( f_1(H) = 9 \)
4. Based on $f_2(n)$: expansion of some node $n \in (\text{OPEN} \cap H)$. 
4. Based on $f_2(n)$: expansion of some node $n \in (\text{OPEN} \cap H)$.

Solution bases:
5. Expansion of the node \( n \in (\text{OPEN} \cap H) \).
5. Expansion of the node \( n \in (\text{OPEN} \cap H) \).

A solution graph \( H \):
5. Expansion of the node \( n \in (\text{OPEN} \cap H) \).

A solution graph \( H \):

\[ f_1 = 9 \]
\[ f_1 = 8 \]
\[ f_1 = 3 \]
\[ f_1 = 2 \]
\[ 6 \]
\[ 0 \]
Best-First Search for AND-OR Graphs

Multiple Accounting of a Node

- Node on OPEN
- Node on CLOSED
- Solved rest problem

---

Diagram:

- Node on OPEN
- Node on CLOSED
- Solved rest problem

---

Node on OPEN:
- $n_1$
- $n_2$
- $n_3$
- $n_4$
- $n_5$

Node on CLOSED:
- $h = 10$
- $c = 0$

Solved rest problem:
- $h = 5$

---

$h = 5$

---

$h = 10$

---

$c = 0$

---

Node on OPEN: $s$

---

Node on CLOSED: $n_1$

---

Solved rest problem: $n_5$
Best-First Search for AND-OR Graphs

Multiple Accounting of a Node

- Node on OPEN
- Node on CLOSED
- Solved rest problem

$n_1$ start node

Duplicate count

\[ C_G(n_1) \]

True count
Best-First Search for AND-OR Graphs
Multiple Accounting of a Node

\[
C_G(n_1) \quad \begin{array}{ll}
\text{duplicate count} & 19 \\
\text{true count} & 24
\end{array}
\]
Best-First Search for AND-OR Graphs

Multiple Accounting of a Node

- Node on OPEN
- Node on CLOSED
- Solved rest problem

\[ C_G(n_1) \]

<table>
<thead>
<tr>
<th>duplicate count</th>
<th>(a)</th>
<th>(b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>true count</td>
<td>19</td>
<td>14</td>
</tr>
</tbody>
</table>
Remarks:

- The minimum cost contribution of node $n_2$ to a solution is not constant, depending on the multiple accounting of node $n_3$.
- Q. Which approach is to be preferred—simple computation of $f_1$ (∼multiple accounting) or true accounting?
In general, the first solution found by Algorithm GBF may not be optimum with respect to the evaluation function $f_1$.

Important preconditions for (provably) finding optimum solution graphs in AND-OR-graphs by general best-first algorithms:

1. The cost estimate underlying $f_1$ must be optimistic, i.e., underestimating costs or overestimating merits.
   
   In particular, the true cost of a cheapest solution graph $H$ extending a solution base $H$ exceeds its $f_1$-value: $C_H(s) \geq f_1(H)$.

2. The termination in case of success ($is\_solved(s) = True$) must be delayed.
   
   In particular, there is no call to $solved\_labeling$ after node expansion, but each time when determining a most promising solution base $H$.

Algorithm GBF with delayed termination is called Algorithm GBF*.
Best-First Search for AND-OR Graphs

Optimality of Algorithm GBF

In general, the first solution found by Algorithm GBF may not be optimum with respect to the evaluation function $f_1$.

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**Best-First Search for AND-OR Graphs**

\[ \mathbf{GBF}^*(s, \text{successors}, \text{is\_solved}, f_1, f_2) \]

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2. \textbf{LOOP}
3. \textbf{IF} (\text{OPEN} = \emptyset) \textbf{THEN} RETURN(\text{Fail});
4. \quad a \quad H = \textit{min\_solution\_base}(s,G_e,f_1); \quad // Find most prom. sol. base in G_e.
   \quad \rightarrow \textit{solved\_labeling}(H); \quad // Is H a solution graph?
   \quad \rightarrow \textbf{IF} \text{is\_solved}(s) \textbf{THEN} RETURN(H); \quad // Delayed termination.
4. \quad b \quad n = f_2(H); \quad // Find most informative non-goal node in H.
   \quad \textit{remove}(n, \text{OPEN}); \quad \textit{push}(n, \text{CLOSED});
5. \quad \textbf{FOREACH} \ n' \ \textbf{IN} \ \text{successors}(n) \ \textbf{DO}
   \quad \textbf{IF} (\ n' \in \text{OPEN} \ \text{OR} \ n' \in \text{CLOSED} \ ) \ \textbf{THEN} \ \textbf{USE} \ \text{old} \ \text{instance} \ \text{of} \ \text{n'} \ \text{instead}.
   \quad \textbf{ELSE} \ \textbf{IF} \ \text{n'} \ \text{encodes} \ \text{an} \ \text{instance} \ \text{of} \ \text{a} \ \text{new} \ \text{state}.
   \quad \quad \text{insert}(n', \text{OPEN}); \quad \text{add\_node}(n',G_e);
   \quad \textbf{ENDIF}
   \quad \text{add\_backpointer}(n',n);
   \quad \rightarrow \textbf{IF} \text{is\_solved}(n')\text{THEN}\text{RETURN}(\text{Fail});
   \quad \rightarrow \textbf{THEN}
   \quad \rightarrow \quad \textit{propagate\_label}(n'); \quad \text{IF} \text{is\_solved}(s) \text{THEN} \text{RETURN}(\text{compute\_solution\_graph}(G_e));
   \quad \rightarrow \textbf{ENDIF}
   \quad \textbf{ENDIF}
   \quad \textbf{ENDDO}
6. \textbf{ENDLOOP}
5. Expansion of the node $n \in (\text{OPEN} \cap \text{H})$. 

![Diagram showing the expansion of a node with $h = 6$ and $c = 0$. The node is marked as being on the OPEN list. There are child nodes with $h = 2$ and $c = 0$, which are marked as solved rest problem nodes. The diagram also shows the previous most promising solution base.]
5. Expansion of the node $n \in (\text{OPEN} \cap H)$.

Solution base / graph:
6. Expansion of the node \( n \in (\text{OPEN} \cap H) \).
6. Expansion of the node $n \in (\text{OPEN} \cap H)$.

Returned solution graph $H$: $s$
Best-First Search for AND-OR Graphs

Illustration of GBF* (continued)

6. Expansion of the node \( n \in (\text{OPEN} \cap H) \).

Returned solution graph \( H \):
Relation between GBF and BF

Algorithm GBF applied to a state-space graph will simulate Algorithm BF. (if the evaluation function $f$ in BF is order preserving)
Relation between GBF and BF

Algorithm GBF applied to a state-space graph will simulate Algorithm BF. (if the evaluation function \( f \) in BF is order preserving) [S:III Evaluation of State-Space Graphs]

The key difference between GBF and BF:

GBF  Solution bases are graphs. (clear due to nature of the problem)

BF   Solution bases are paths. (clear due to nature of the problem)
Relation between GBF and BF

Algorithm GBF applied to a state-space graph will simulate Algorithm BF. (if the evaluation function $f$ in BF is order preserving)

The key difference between GBF and BF:

**GBF** Solution bases are graphs. (clear due to nature of the problem)

GBF The most promising solution base is searched among all possible solution bases in $G_e$, the explored part of the search space graph.

**BF** Solution bases are paths. (clear due to nature of the problem)

BF At each point in time the union of the considered solution bases forms a tree with root $s$. The tree structure is maintained by always discarding the inferior path of two paths leading to the same node. The most promising solution base is searched among all paths in this tree.
Relation between GBF and BF

Algorithm GBF applied to a state-space graph will simulate Algorithm BF. (if the evaluation function \( f \) in BF is order preserving)  

The key difference between GBF and BF:

**GBF**  Solution bases are graphs. (clear due to nature of the problem)

**GBF**  The most promising solution base is searched among all possible solution bases in \( G_e \), the explored part of the search space graph.

**BF**  Solution bases are paths. (clear due to nature of the problem)

**BF**  At each point in time the union of the considered solution bases forms a tree with root \( s \). The tree structure is maintained by always discarding the inferior path of two paths leading to the same node. The most promising solution base is searched among all paths in this tree.
Relation between GBF and BF

Algorithm GBF applied to a state-space graph will simulate Algorithm BF. (if the evaluation function $f$ in BF is order preserving) [S:III Evaluation of State-Space Graphs]

The key difference between GBF and BF:

**GBF**  
Solution bases are graphs. (clear due to nature of the problem)

**GBF**  
The most promising solution base is searched among all possible solution bases in $G_e$, the explored part of the search space graph.

**BF**  
Solution bases are paths. (clear due to nature of the problem)

**BF**  
At each point in time the union of the considered solution bases forms a tree with root $s$. The tree structure is maintained by always discarding the inferior path of two paths leading to the same node. The most promising solution base is searched among all paths in this tree.

**BF**  
The discarding of a path (solution base) is *irrevocable*. 
Remarks:

- (Under BF) the tree formed by the union of all solution bases is also called *traversal tree*. It is defined by the backpointers that are set by the Algorithm BF.

- (Under BF) the decision to discard an inferior path (solution base) is based on a single parameter, usually a cost value, which is maintained at the respective OPEN node.

- Under BF the cost value assigned to a node is unique. Under GBF, however, a node can be used in different solution bases and may get assigned different cost values for different solution bases at the same time.

- Under BF there is a 1:1 relationship between expansion candidates (the nodes on OPEN) and solution bases (the paths that start at $s$ and end at some node on OPEN). Put another way, each node on OPEN represents a solution base, and there is no solution base without a corresponding OPEN node.

- (Under BF) the term “irrevocable” means that an inferior path from $s$ so some $n$ will never become part of solution that also contains the node $n$. Irrevocability has wide-ranging consequences, which may be both crucial and reasonable, depending on the search problem at hand.
Relation between GBF and BF

Irrevocability is not Amenable to Problem Reduction Graphs

[Irrevocability in State-Space Graphs]

The following equivalence does not generally hold for problem reduction graphs:

“Solution base $H_1$ can be completed to a solution”

$\iff$

“Solution base $H_2$ can be completed to a solution.”
The illustrated solution bases $H_1$, $H_2$, do not fulfill the equivalence. They share the continuation at node $n_4$, and let us assume that $H_2$ is inferior to $H_1$: $f_1(H_1) < f_1(H_2)$. However, $H_2$ cannot be discarded since at a later point in time the problem associated with node $n_3$ may turn out to be unsolvable. If we discarded $H_2$, GBF would miss the only possible solution.