Foundations of Artificial Intelligence

15. State-Space Search: Best-first Graph Search

Malte Helmert

Universität Basel

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State-Space Search: Overview

Chapter overview: state-space search

- 5.–7. Foundations
- 8.–12. Basic Algorithms
- 13.–19. Heuristic Algorithms
  - 13. Heuristics
  - 14. Analysis of Heuristics
  - 15. Best-first Graph Search
  - 16. Greedy Best-first Search, A*, Weighted A*
  - 17. IDA*
  - 18. Properties of A*, Part I
  - 19. Properties of A*, Part II

15.1 Introduction

Heuristic Search Algorithms

Heuristic Search Algorithms

Heuristic search algorithms use heuristic functions to (partially or fully) determine the order of node expansion.

German: heuristische Suchalgorithmen

- this chapter: short introduction
- next chapters: more thorough analysis

15.2 Best-first Search

Best-first Search

Best-first search is a class of search algorithms that expand the "most promising" node in each iteration.

- decision which node is most promising uses heuristics...
- ...but not necessarily exclusively.

Best-first Search

A best-first search is a heuristic search algorithm that evaluates search nodes with an evaluation function f and always expands a node n with minimal $f(n)$ value.

German: Bestensuche, Bewertungsfunktion

- implementation essentially like uniform cost search
- different choices of f $\rightsquigarrow$ different search algorithms

The Most Important Best-first Search Algorithms

the most important best-first search algorithms:

- $f(n) = h(n.\text{state})$: greedy best-first search
  $\rightsquigarrow$ only the heuristic counts
- $f(n) = g(n) + h(n.\text{state})$: A*
  $\rightsquigarrow$ combination of path cost and heuristic
- $f(n) = g(n) + w \cdot h(n.\text{state})$: weighted A*
  $w \in \mathbb{R}_0^+$ is a parameter
  $\rightsquigarrow$ interpolates between greedy best-first search and A*

German: gierige Bestensuche, A*, Weighted A*

$\rightsquigarrow$ properties: next chapters

What do we obtain with $f(n) := g(n)$?

Best-first Search: Graph Search or Tree Search?

Best-first search can be graph search or tree search.

- now: graph search (i.e., with duplicate elimination), which is the more common case
- Chapter 17: a tree search variant

15.3 Algorithm Details

Reminder: Uniform Cost Search

reminder: uniform cost search

Uniform Cost Search

```
$open$ := new MinHeap ordered by $g$
$open$.insert(make_root_node())
$closed$ := new HashSet
while not $open$.is_empty():
    $n$ := $open$.pop_min()
    if $n$.state $\notin$ $closed$:
        $closed$.insert($n$)
        if is_goal($n$.state):
            return extract_path($n$)
        for each $\langle a, s' \rangle \in$ succ($n$.state):
            $n'$ := make_node($n, a, s'$)
            $open$.insert($n'$)
return unsolvable
```

Best-first Search without Reopening (1st Attempt)

best-first search without reopening (1st attempt)

Best-first Search without Reopening (1st Attempt)

```
$open$ := new MinHeap ordered by $f$
$open$.insert(make_root_node())
$closed$ := new HashSet
while not $open$.is_empty():
    $n$ := $open$.pop_min()
    if $n$.state $\notin$ $closed$:
        $closed$.insert($n$)
        if is_goal($n$.state):
            return extract_path($n$)
        for each $\langle a, s' \rangle \in$ succ($n$.state):
            $n'$ := make_node($n, a, s'$)
            $open$.insert($n'$)
return unsolvable
```

Best-first Search w/o Reopening (1st Attempt): Discussion

Discussion:

This is already an acceptable implementation of best-first search.

two useful improvements:

- discard states considered unsolvable by the heuristic
  $\rightsquigarrow$ saves memory in *open*
- if multiple search nodes have identical f values, use h to break ties (preferring low h)
  - not always a good idea, but often
  - obviously unnecessary if $f = h$ (greedy best-first search)

Best-first Search without Reopening (Final Version)

Best-first Search without Reopening

```
open := new MinHeap ordered by ⟨f, h⟩
if h(init()) < ∞:
    open.insert(make_root_node())
closed := new HashSet
while not open.is_empty():
    n := open.pop_min()
    if n.state ∉ closed:
        closed.insert(n)
        if is_goal(n.state):
            return extract_path(n)
        for each ⟨a, s'⟩ ∈ succ(n.state):
            if h(s') < ∞:
                n' := make_node(n, a, s')
                open.insert(n')
return unsolvable
```

Best-first Search: Properties

properties:

- complete if h is safe (Why?)
- optimality depends on f $\rightsquigarrow$ next chapters

15.4 Reopening

Reopening

- reminder: uniform cost search expands nodes in order of increasing g values

$\rightsquigarrow$ guarantees that cheapest path to state of a node has been found when the node is expanded

- with arbitrary evaluation functions f in best-first search this does not hold in general

$\rightsquigarrow$ in order to find solutions of low cost, we may want to expand duplicate nodes when cheaper paths to their states are found (reopening)

German: Reopening

Best-first Search with Reopening

Best-first Search with Reopening

```
open := new MinHeap ordered by $\langle f, h \rangle$
if $h(\text{init}()) < \infty$:
    open.insert(make_root_node())
distances := new HashTable
while not open.is_empty():
    $n :=$ open.pop_min()
    if distances.lookup($n$.state) = none or $g(n) <$ distances[$n$.state]:
        distances[$n$.state] := $g(n)$
        if is_goal($n$.state):
            return extract_path($n$)
        for each $\langle a, s' \rangle \in$ succ($n$.state):
            if $h(s') < \infty$:
                $n' :=$ make_node($n, a, s'$)
                open.insert($n'$)
return unsolvable
```

$\rightsquigarrow$ *distances* controls reopening and replaces *closed*

15.5 Summary

Summary

- best-first search: expand node with minimal value of evaluation function f
  - $f = h$: greedy best-first search
  - $f = g + h$: A*
  - $f = g + w \cdot h$ with parameter $w \in \mathbb{R}_0^+$: weighted A*
- here: best-first search as a graph search
- reopening: expand duplicates with lower path costs to find cheaper solutions