Foundations of Artificial Intelligence

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

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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

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

Best-first Search

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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

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

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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

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($n$.state)
        **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)

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

Discussion:

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

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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 $\langle f, h \rangle$
**if** $h(\text{init}()) < \infty$:
    $open$.insert(make_root_node())
$closed$ := **new** HashSet
**while not** $open$.is_empty():
    $n$ := $open$.pop_min()
    **if** $n$.state $\notin$ $closed$:
        $closed$.insert($n$.state)
        **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
```

Best-first Search: Properties

properties:

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

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

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

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

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