Foundations of Artificial Intelligence

B6. State-Space Search: Breadth-first Search

Malte Helmert

University of Basel

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State-Space Search: Overview

Chapter overview: state-space search

- B1–B3. Foundations
- B4–B8. Basic Algorithms
  - B4. Data Structures for Search Algorithms
  - B5. Tree Search and Graph Search
  - B6. Breadth-first Search
  - B7. Uniform Cost Search
  - B8. Depth-first Search and Iterative Deepening
- B9–B15. Heuristic Algorithms

B6.1 Blind Search

Blind Search

In Chapters B6–B8 we consider blind search algorithms:

Blind Search Algorithms

Blind search algorithms use no information about state spaces apart from the black box interface.

They are also called uninformed search algorithms.

contrast: heuristic search algorithms (Chapters B9–B15)

Blind Search Algorithms: Examples

examples of blind search algorithms:

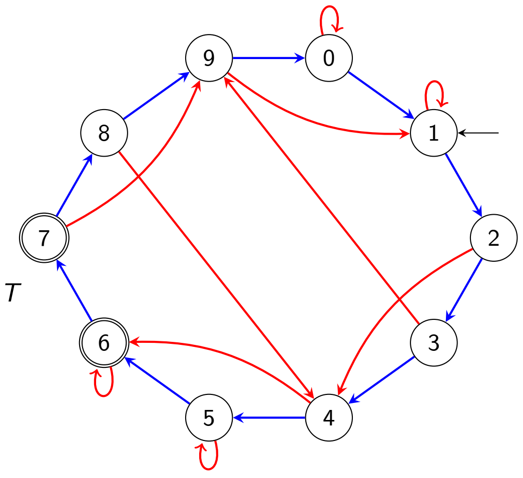
- breadth-first search ($\rightsquigarrow$ this chapter)
- uniform cost search ($\rightsquigarrow$ Chapter B7)
- depth-first search ($\rightsquigarrow$ Chapter B8)
- depth-limited search ($\rightsquigarrow$ Chapter B8)
- iterative deepening search ($\rightsquigarrow$ Chapter B8)

B6.2 Breadth-first Search: Introduction

Running Example: Reminder

bounded inc-and-square:

- $S = \{0, 1, \dots, 9\}$
- $A = \{inc, sqr\}$
- $cost(inc) = cost(sqr) = 1$
- T s.t. for $i = 0, \dots, 9$:
  - $\langle i, inc, (i + 1) \bmod 10\rangle \in T$
  - $\langle i, sqr, i^2 \bmod 10\rangle \in T$
- $s_I = 1$
- $S_G = \{6, 7\}$



Idea

breadth-first search:

- expand nodes in order of generation (FIFO)
  - ⇝ open list is linked list or deque
- we start with an example using graph search

German: Breitensuche

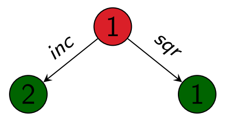
Example: Generic Graph Search with FIFO Expansion

next

open: [1]

closed: { }

Example: Generic Graph Search with FIFO Expansion

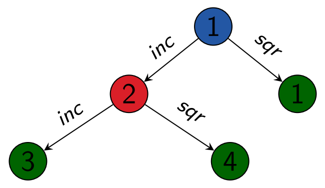


next

open: [2 1]

closed: {1}

Example: Generic Graph Search with FIFO Expansion

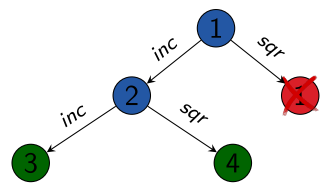


next

open: [1 3 4]

closed: {1, 2}

Example: Generic Graph Search with FIFO Expansion

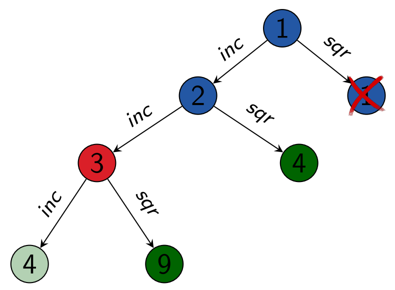


next

open: [3 4]

closed: $\{1, 2\}$

Example: Generic Graph Search with FIFO Expansion

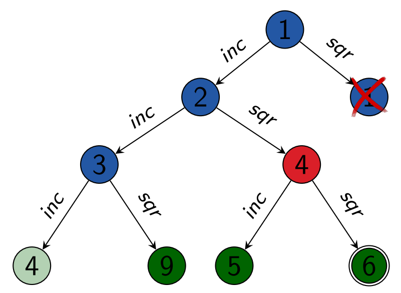


next

open: [4 4 9]

closed: $\{1, 2, 3\}$

Example: Generic Graph Search with FIFO Expansion

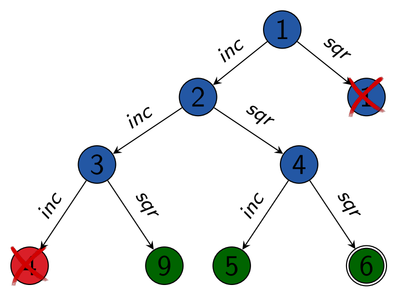


next

open: [4 9 5 6]

closed: $\{1, 2, 3, 4\}$

Example: Generic Graph Search with FIFO Expansion

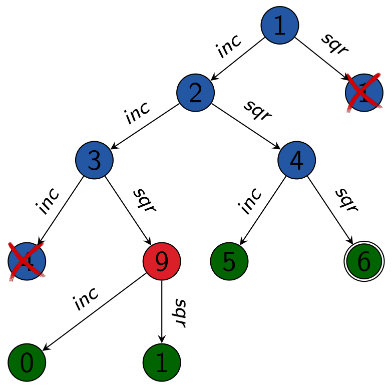


next

open: [9 5 6]

closed: $\{1, 2, 3, 4\}$

Example: Generic Graph Search with FIFO Expansion

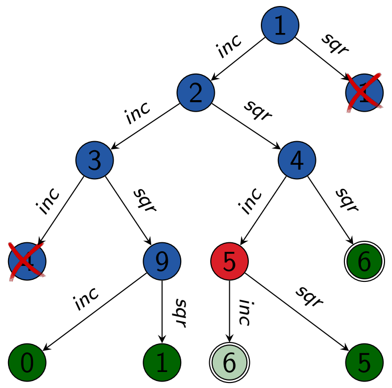


next

open: [5 6 0 1]

closed: $\{1, 2, 3, 4, 9\}$

Example: Generic Graph Search with FIFO Expansion

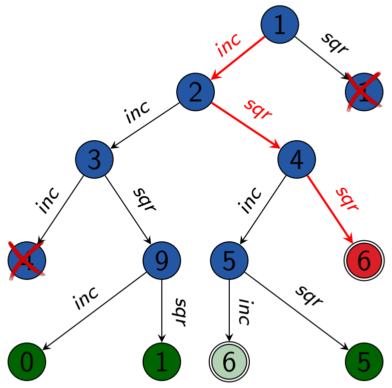


next

open: [6 0 1 6 5]

closed: $\{1, 2, 3, 4, 5, 9\}$

Example: Generic Graph Search with FIFO Expansion



next

open: [0 1 6 5]

closed: $\{1, 2, 3, 4, 5, 6, 9\}$

Observations from Example

breadth-first search behaviour:

- state space is searched layer by layer

$\rightsquigarrow$ shallowest goal node is always found first

Breadth-first Search: Tree Search or Graph Search?

Breadth-first search can be performed

- without duplicate elimination (as a tree search)
  $\rightsquigarrow$ BFS-Tree
- or with duplicate elimination (as a graph search)
  $\rightsquigarrow$ BFS-Graph

(BFS = breadth-first search).

$\rightsquigarrow$ We consider both variants.

B6.3 BFS-Tree

Reminder: Generic Tree Search Algorithm

reminder from Chapter B5:

Generic Tree Search

```
open := new OpenList
open.insert(make_root_node())
while not open.is_empty():
    n := open.pop()
    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
```

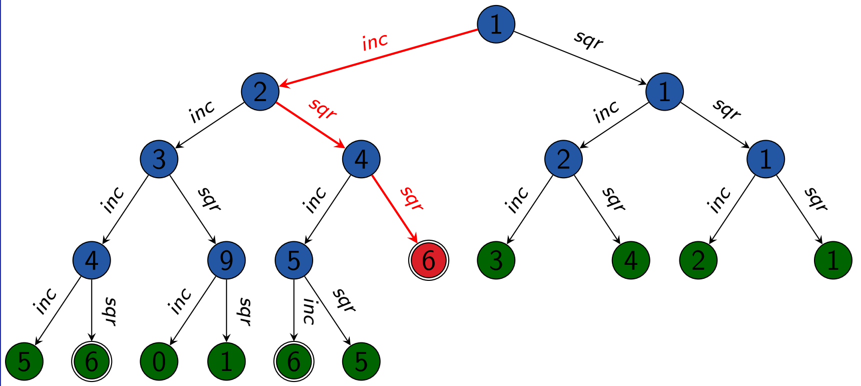
BFS-Tree (1st Attempt)

~~breadth-first search without duplicate elimination (1st attempt):~~

~~**BFS-Tree (1st Attempt)**~~

```
~~open := new Deque~~
~~open.push_back(make_root_node())~~
~~while not open.is_empty():~~
~~    n := open.pop_front()~~
~~    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.push_back($n'$)~~
~~return unsolvable~~
```

Running Example: BFS-Tree (1st Attempt)



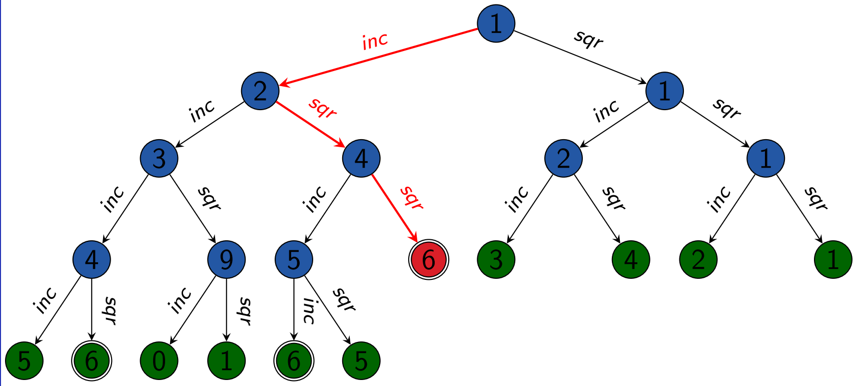
Opportunities for Improvement

- In a BFS, the first generated goal node is always the first expanded goal node. (Why?)

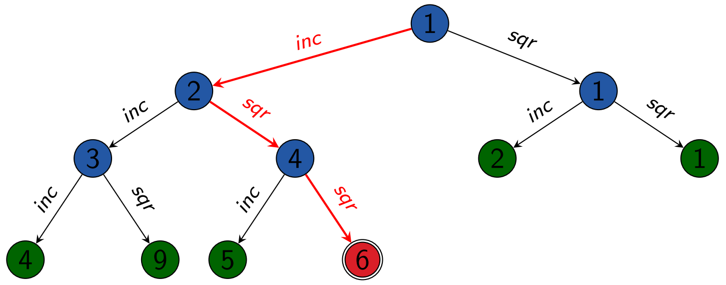
⇝ It is more efficient to perform the goal test upon generating a node (rather than upon expanding it).

⇝ How much effort does this save?

BFS-Tree without Early Goal Tests



BFS-Tree with Early Goal Tests



BFS-Tree (2nd Attempt)

breadth-first search without duplicate elimination (2nd attempt):

BFS-Tree (2nd Attempt)

```
open := new Deque
open.push_back(make_root_node())
while not open.is_empty():
    n := open.pop_front()
    ~~if is_goal(n.state):~~
        ~~return extract_path(n)~~
    for each $\langle a, s' \rangle \in$ succ(n.state):
        $n'$ := make_node(n, a, $s'$)
        if is_goal($s'$):
            return extract_path($n'$)
        open.push_back($n'$)
return unsolvable
```

BFS-Tree (2nd Attempt): Discussion

Where is the bug?

BFS-Tree (Final Version)

breadth-first search without duplicate elimination (final version):

BFS-Tree

```
if is_goal(init()):
    return $\langle\rangle$
open := new Deque
open.push_back(make_root_node())
while not open.is_empty():
    n := open.pop_front()
    for each $\langle a, s' \rangle \in$ succ(n.state):
        $n'$ := make_node(n, a, $s'$)
        if is_goal($s'$):
            return extract_path($n'$)
        open.push_back($n'$)
return unsolvable
```

B6.4 BFS-Graph

Reminder: Generic Graph Search Algorithm

reminder from Chapter B5:

Generic Graph Search

```
$open$ := new OpenList
$open$.insert(make_root_node())
$closed$ := new ClosedList
while not $open$.is_empty():
    $n$ := $open$.pop()
    if $closed$.lookup($n$.state) = none:
        $closed$.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
```

Adapting Generic Graph Search to Breadth-First Search

Adapting the generic algorithm to breadth-first search:

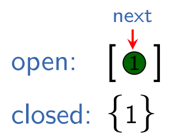
- similar adaptations to BFS-Tree (deque as open list, early goal tests)
- as closed list does not need to manage node information, a set data structure suffices
- for the same reasons why early goal tests are a good idea, we should perform duplicate tests against the closed list and updates of the closed lists as early as possible

BFS-Graph (Breadth-First Search with Duplicate Elim.)

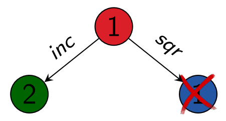
BFS-Graph

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

BFS-Graph: Example



BFS-Graph: Example

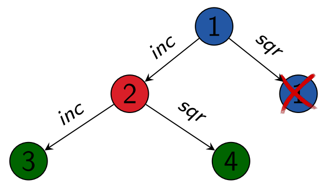


next

open: [2]

closed: $\{1,2\}$

BFS-Graph: Example

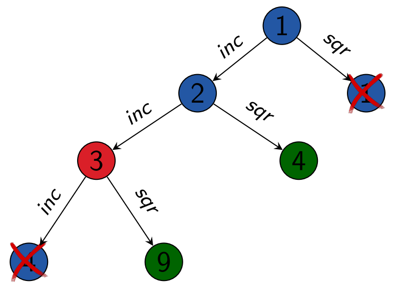


next

open: [3 4]

closed: $\{1, 2, 3, 4\}$

BFS-Graph: Example

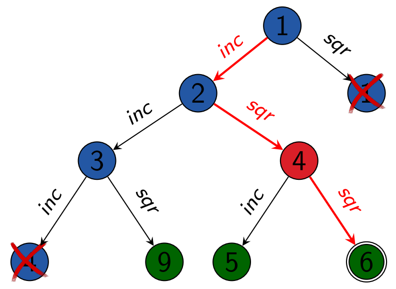


next

open: [4 9]

closed: $\{1, 2, 3, 4, 9\}$

BFS-Graph: Example



next

open: [9 5]

closed: $\{1, 2, 3, 4, 5, 6, 9\}$

B6.5 Properties of Breadth-first Search

Properties of Breadth-first Search

Properties of Breadth-first Search:

- BFS-Tree is semi-complete, but not complete. (Why?)
- BFS-Graph is complete. (Why?)
- BFS (both variants) is optimal
  if all actions have the same cost (Why?),
  but not in general (Why not?).
- complexity: next slides

Breadth-first Search: Complexity

The following result applies to both BFS variants:

Theorem (time complexity of breadth-first search)

Let b be the branching factor and d be the minimal solution length of the given state space. Let $b \geq 2$.

Then the time complexity of breadth-first search is

$$1 + b + b^2 + b^3 + \cdots + b^d = O(b^d)$$

Reminder: we measure time complexity in generated nodes.

It follows that the space complexity of both BFS variants also is $O(b^d)$ (if $b \geq 2$). (Why?)

Breadth-first Search: Example of Complexity

example: $b = 13$; 100 000 nodes/second; 32 bytes/node

Rubik's cube:

- branching factor: ≈ 13
- typical solution length: 18

d	nodes	time	memory
4	30 940	0.3 s	966 KiB
6	$5.2 \cdot 10^6$	52 s	159 MiB
8	$8.8 \cdot 10^8$	147 min	26 GiB
10	10^{11}	17 days	4.3 TiB
12	10^{13}	8 years	734 TiB
14	10^{15}	1 352 years	121 PiB
16	10^{17}	$2.2 \cdot 10^5$ years	20 EiB
18	10^{20}	$38 \cdot 10^6$ years	3.3 ZiB

BFS-Tree or BFS-Graph?

Which is better, BFS-Tree or BFS-Graph?

advantages of BFS-Graph:

- complete
- much (!) more efficient if there are many duplicates

advantages of BFS-Tree:

- simpler
- less overhead (time/space) if there are few duplicates

Conclusion

BFS-Graph is usually preferable, unless we know that there is a negligible number of duplicates in the given state space.

B6.6 Summary

Summary

- blind search algorithm: use no information except black box interface of state space
- breadth-first search: expand nodes in order of generation
  - search state space layer by layer
  - can be tree search or graph search
  - complexity $O(b^d)$ with branching factor b, minimal solution length d (if $b \geq 2$)
  - complete as a graph search; semi-complete as a tree search
  - optimal with uniform action costs