



An Introduction to Artificial Intelligence

— Lecture Notes in Progress —

Prof. Dr. Karl Stroetmann

February 25, 2017

These lecture notes, their \LaTeX sources, and the programs discussed in these lecture notes are all available at

<https://github.com/karlstroetmann/Artificial-Intelligence>.

In particular, the lecture notes are found in the directory **Lecture-Notes** in the file **artificial-intelligence.pdf**. The lecture notes are subject to continuous change. Provided the program **git** is installed on your computer, the repository containing the lecture notes can be cloned using the command

```
git clone https://github.com/karlstroetmann/Artificial-Intelligence.git.
```

Once you have cloned the repository, the command

```
git pull
```

can be used to load the current version of these lecture notes from **github**. As this is the first time that I give these lectures, these lecture notes are very incomplete and will be changed frequently during the semester.

Contents

1	Introduction	2
1.1	What is Artificial Intelligence?	2
1.2	Literature	4
2	Search	5
2.1	The Sliding Puzzle	8
2.2	Breadth First Search	10
2.2.1	A Queue Based Implementation of Breadth First Search	12
2.3	Depth First Search	15
2.3.1	Getting Rid of the Parent Dictionary	16
2.3.2	A Recursive Implementation of Depth First Search	16
2.4	Iterative Deepening	18
2.4.1	A Recursive Implementation of Iterative Deepening	19
2.5	Bidirectional Breadth First Search	20
2.6	The A* Search Algorithm	22
2.7	Bidirectional A* Search	27
2.8	Iterative Deepening A* Search	27
2.9	The A*-IDA* Search Algorithm	31
3	Constraint Satisfaction	34
3.1	Formal Definition of Constraint Satisfaction Problems	34
3.1.1	Example: Map Coloring	35
3.1.2	Example: The Eight Queens Puzzle	36
3.1.3	Applications	38
3.2	Brute Force Search	39
3.3	Backtracking Search	41
3.4	Constraint Propagation	43
3.5	Local Search	47

Chapter 1

Introduction

1.1 What is Artificial Intelligence?

Before we start to dive into the subject of **Artificial Intelligence** we have to answer the following question:

What is *Artificial Intelligence*?

Historically, there have been a number of different answers to this question [3]. We will look at these different answers and discuss them.

1. *Artificial Intelligence* is the study of creating machines that think like humans.

As we have a working prototype of intelligence, namely humans, it is quite natural to try to build machines that work in a way similar to humans, thereby creating artificial intelligence. As a first step in this endeavor we would have to study how humans actually think and thus we would have to study the brain. Unfortunately, as of today, no one really knows how the brain works. Although there are branches of science devoted to studying the human thought processes and the human brain, namely **cognitive science** and **computational neuroscience**, this approach has not proven to be fruitful for creating thinking machines, the reason being that the current understanding of the human thought processes is just not sufficient.

2. *Artificial Intelligence* is the science of machines that act like people.

Since we do not know how humans think, we cannot build machines that think like people. Therefore, the next best thing might be to build machines that act and behave like humans. Actually, the **Turing Test** is based on this idea: Turing suggested that if we want to know whether we have succeeded in building an intelligent machine, we should place it at the other end of chat line. If we cannot distinguish the computer from a human, then we have succeeded at creating intelligence.

However, with respect to the kind of Artificial Intelligence that is needed in industry, this approach isn't very useful. To illustrate the point, consider an analogy with aerodynamics: In aerodynamics we try to build planes that fly fast and efficiently, not planes that flap their wings like birds do, as the later approach has failed historically, e.g. **Daedalus and Icarus**.

3. *Artificial Intelligence* is the science of creating machines that think logically.

The idea with this approach is to create machines that are based on **mathematical logic**. If a goal is given to these machines, then these machines use logical reasoning in order to deduce those actions that need to be performed in order to best achieve the given goals. Unfortunately, this approach had only limited success: In playing games the approach was quite successful for dealing with games like checkers or chess. However, the approach was mostly unsuccessful for dealing with many real world problems. There were two main reasons for its failure:

- (a) In order for the logical approach to be successful, the environment has to be **completely** described by mathematical axioms. It has turned out that our knowledge of the real world is often not sufficient to completely describe the environment via axioms.

- (b) Even if we have complete knowledge, it often turns out that describing every possible case via logic formulae is just unwieldy. Consider the following formula:

$$\forall x : (\text{bird}(x) \rightarrow \text{flies}(x))$$

The problem with this formula is that although it appears to be common sense, there are a number of counter examples:

- i. Penguins, Emus, and ostriches don't fly.
However, if we put a penguin into a plane, it turns out the penguin will fly.
- ii. Birds that are too young do not fly.
- iii. Birds with clapped wings do not fly.
- iv. ...

Trying to model all eventualities with logic has turned out to be too unwieldy to be practical.

- (c) In real life situations we often deal with *uncertainty*. Classical logic does not perform well when it has to deal with uncertainties.

4. *Artificial Intelligence* is the science of creating machines that act rationally.

All we really want is to build machines that, given the knowledge we have, try to *optimize the expected results*: In our world, there is lots of uncertainty. We cannot hope to create machines that always make the decisions that turn out to be optimal. What we can hope is to create machines that will make decisions that turn out to be good on average. For example, suppose we try to create a program for asset management: We cannot hope to build a machine that always buys the best company share in the stock market. Rather, our goal should be to build a program that maximizes our expected profits in the long term.

It has turned out that the main tool needed for this approach is not mathematical logic but rather *numerical analysis* and *mathematical statistics*. The shift from logic to numerical analysis and statistics has been the most important reason for the success of Artificial Intelligence in the recent years. Another important factor is the *enhanced performance of modern hardware*.

Now that we have clarified the notion of artificial intelligence, we should set its goals. As we can never achieve more than what we aim for, we have every reason to be ambitious here. For example, my personal vision of Artificial Intelligence goes like this: Imagine 70 years from now you (not feeling too well) have a conversation with *Siri*. Instead of asking Siri for the best graveyard in the vicinity, you think about all the sins you have committed. As Siri has accompanied you for your whole life, she knows about these sins better than you. Hence, the conversation with Siri works out as follows:

You (with trembling voice):

Hey Siri, does God exist?

Siri (with the voice of Darth Vader):

Your voice seems troubled, let me think ...

After a small pause which almost drains the battery of your phone completely, Siri gets back with a soothing announcement:

You don't have to worry any more, I have fixed the problem. He is dead now.

May *The Force* be with us on achieving our goals!

1.2 Literature

The main sources of these lecture notes are the following:

1. A course on artificial intelligence that was offered on the EDX platform. The course materials are available at

<http://ai.berkeley.edu/home.html>.

2. The book

Introduction to Artificial Intelligence

written by Stuart Russel and Peter Norvig [3].

3. A course on artificial that is offered on [Udacity](#). The title of the course is

[Intro to Artificial Intelligence](#)

and the course is given by [Peter Norvig](#), who is director of research at Google and [Sebastian Thrun](#), who is the chairman of [Udacity](#).

The programs presented in these lecture notes have been tested with version 2.6 of [SETLX](#).

Chapter 2

Search

In this chapter we discuss various *search algorithms*. First, we define the notion of a *search problem*. As one of the examples, we will discuss the *sliding puzzle*. Then we introduce various algorithms for solving search problems. In particular, we present

1. breadth first search,
2. depth first search,
3. iterative deepening,
4. bidirectional breadth first search,
5. A* search,
6. bidirectional A* search,
7. iterative deepening A* search, and
8. A*-IDA* search.

Definition 1 (Search Problem) A *search problem* is a tuple of the form

$$\mathcal{P} = \langle Q, \text{nextStates}, \text{start}, \text{goal} \rangle$$

where

1. Q is the set of states, also known as the *state space*.
2. nextStates is a function taking a state as input and returning the set of those states that can be reached from the given state in one step, i.e. we have

$$\text{nextStates} : Q \rightarrow 2^Q.$$

The function nextStates gives rise to the *transition relation* R , which is a relation on Q , i.e. $R \subseteq Q \times Q$. This relation is defined as follows:

$$R := \{ \langle s_1, s_2 \rangle \in Q \times Q \mid s_2 \in \text{nextStates}(s_1) \}.$$

If either $\langle s_1, s_2 \rangle \in R$ or $\langle s_2, s_1 \rangle \in R$, then s_1 and s_2 are called *neighboring states*.

3. start is the *start state*, hence $\text{start} \in Q$.
4. goal is the *goal state*, hence $\text{goal} \in Q$.

Sometimes, instead of a single goal there is a set of goal states G .

A **path** is a list $[s_1, \dots, s_n]$ such that $\langle s_i, s_{i+1} \rangle \in R$ for all $i \in \{1, \dots, n-1\}$. The **length** of this path is defined as the length of the list. A path $[s_1, \dots, s_n]$ is a **solution** to the search problem P iff the following conditions are satisfied:

1. $s_1 = \text{start}$, i.e. the first element of the path is the start state.
2. $s_n = \text{goal}$, i.e. the last element of the path is the goal state.

A path $p = [s_1, \dots, s_n]$ is a **minimal solution** to the search problem \mathcal{P} iff it is a solution and, furthermore, the length of p is minimal among all other solutions. \diamond

Remark: In the literature, a **state** is often called a **node**. In these lecture notes, I will also refer to states as nodes. \diamond

Example: We illustrate the notion of a search problem with the following example, which is also known as the **missionaries and cannibals problem**: Three missionaries and three infidels have to cross a river that runs from the west to the east. Initially, they are on the northern shore. There is just one small boat and that boat has only room for at most two passengers. Both the missionaries and the infidels can steer the boat. However, if at any time the missionaries are confronted with a majority of infidels on either shore of the river, then the missionaries have a problem.

```

1  problem := [m, i] |-> m > 0 && m < i;
2
3  noProblemAtAll := [m, i] |-> !problem(m, i) && !problem(3 - m, 3 - i);
4
5  nextStates := procedure(s) {
6      [m, i, b] := s;
7      if (b == 1) { // The boat is on the northern shore.
8          return { [m - mb, i - ib, 0]
9                  : mb in {0 .. m}, ib in {0 .. i}
10                 | mb + ib in {1, 2} && noProblemAtAll(m - mb, i - ib)
11               };
12      } else {
13          return { [m + mb, i + ib, 1]
14                  : mb in {0 .. 3 - m}, ib in {0 .. 3 - i}
15                 | mb + ib in {1, 2} && noProblemAtAll(m + mb, i + ib)
16               };
17      }
18  };
19  start := [3, 3, 1];
20  goal := [0, 0, 0];

```

Figure 2.1: The missionary and cannibals problem codes as a search problem.

Figure 2.1 shows a formalization of the missionaries and cannibals problem as a search problem. We discuss this formalization line by line.

1. Line 1 defines the auxiliary function **problem**.

If m is the number of missionaries on a given shore, while i is the number of infidels on that same shore, then $\text{problem}(m, i)$ is **true** iff the missionaries have a problem on that shore.

2. Line 3 defines the auxiliary function **noProblemAtAll**.

If m is the number of missionaries on the northern shore and i is the number of infidels on that shore, then the expression $\text{noProblemAtAll}(m, i)$ is true, if there is no problem for the missionaries on either shore.

The implementation of this function uses the fact that if m is the number of missionaries on the northern shore, then $3 - m$ is the number of missionaries on the southern shore. Similarly, if i is the number of infidels on the northern shore, then the number of infidels on the southern shore is $3 - i$.

3. Line 5 to 18 define the function `nextStates`. A state s is represented as a triple of the form

$$s = [m, i, b] \quad \text{where } m \in \{0, 1, 2, 3\}, i \in \{0, 1, 2, 3\}, b \in \{0, 1\}.$$

Here m is the number of missionaries on the northern shore, i is the number of infidels on the northern shore, and b is the number of boats on the northern shore.

- (a) Line 6 extracts the components m , i , and b from the state s .
- (b) Line 7 checks whether the boat is on the northern shore.
- (c) If this is the case, then the states reachable from the given state s are those states where `mb` missionaries and `ib` infidels cross the river. After `mb` missionaries and `ib` infidels have crossed the river and reached the southern shore, $m - mb$ missionaries and $i - ib$ infidels remain on the northern shore. Of course, after the crossing the boat is no longer on the northern shore. Therefore, the new state has the form

$$[m - mb, i - ib, 0].$$

This explains line 8.

- (d) Since the number `mb` of missionaries leaving the northern shore can not be greater than the number m of all missionaries on the northern shore, we have the condition

$$mb \in \{0, \dots, m\}.$$

There is a similar condition for the number of infidels crossing:

$$ib \in \{0, \dots, i\}.$$

This explains line 9.

- (e) Furthermore, we have to check that the number of persons crossing the river is at least 1 and at most 2. This explains the condition

$$mb + im \in \{1, 2\}.$$

Finally, there should be no problem in the new state on either shore. This is checked using the expression

$$\text{noProblemAtAll}(m - mb, i - ib).$$

These two checks are performed in line 10.

4. If the boat is on the southern shore instead, then the missionaries and the infidels will be crossing the river from the southern shore to the northern shore. Therefore, the number of missionaries and infidels on the northern shore is now increased. Hence, in this case the new state has the form

$$[m - mb, i - ib, 0].$$

As the number of missionaries on the southern shore is $3 - m$ and the number of infidels on the southern shore is $3 - i$, `mb` is now a member of the set $\{0, \dots, 3 - m\}$, while `ib` is a member of the set $\{0, \dots, 3 - i\}$.

5. Finally the start state and the goal state are defined in line 19 and line 20.

The code in Figure 2.1 does not define the set of states Q of the search problem. The reason is that, in order to solve the problem, we do not need to define this set. If we wanted to, we could define the set of states as follows:

```
States := { [m,i,b] : m in {0..3}, i in {0..3}, b in {0,1} | noProblemAtAll(m, i) };
```

Figure 2.2 shows a graphical representation of the transition relation of the missionaries and cannibals puzzle. In that figure, for every state both the northern and the eastern shore are shown. The start state is covered with a blue ellipse, while the goal state is covered with a green ellipse. The figure clearly shows that the problem is solvable and that there is a solution involving just 11 crossings of the river. \diamond

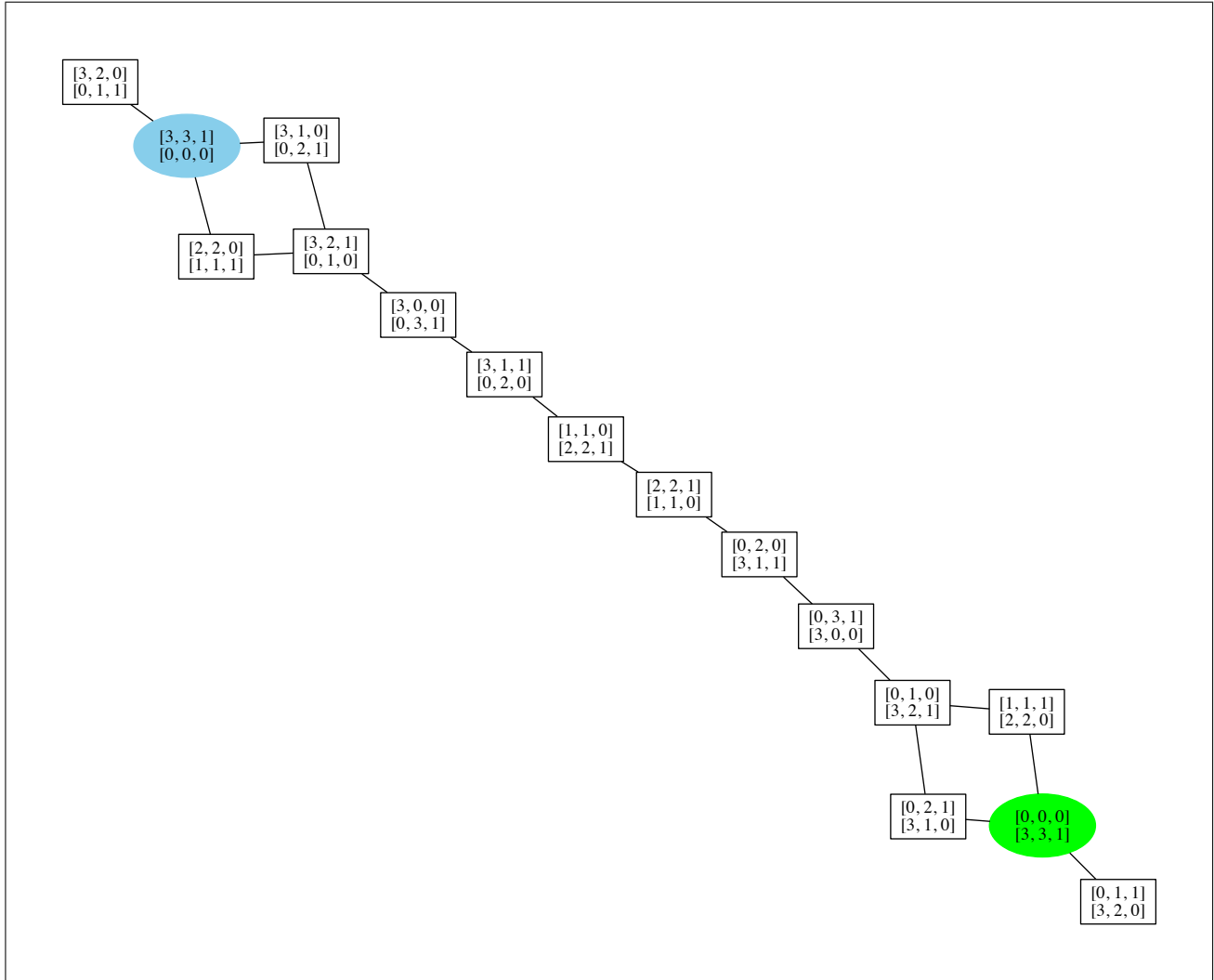


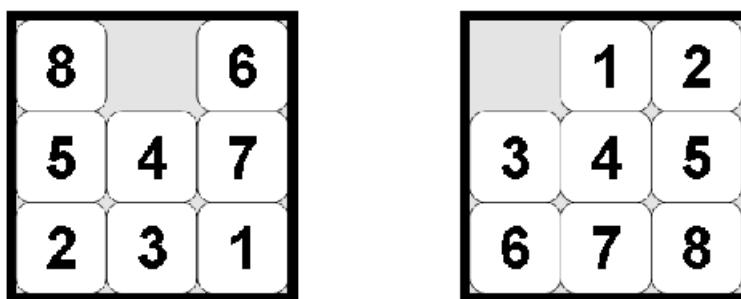
Figure 2.2: A graphical representation of the missionaries and cannibals problem.

2.1 The Sliding Puzzle

The 3×3 sliding puzzle uses a square board of length 3. This board is subdivided into $3 \times 3 = 9$ squares of length 1. Of these 9 squares, 8 are occupied with square tiles that are numbered from 1 to 8. One square remains empty. Figure 2.3 on page 2.3 shows two possible states of this sliding puzzle. The 4×4 **sliding puzzle** is similar to the 3×3 sliding puzzle but it is played on a square board of length 4 instead. The 4×4 sliding puzzle is also known as the **15 puzzle**, while the 3×3 puzzle is called the **8 puzzle**.

In order to solve the 3×3 sliding puzzle shown in Figure 2.3 we have to transform the state shown on the left of Figure 2.3 into the state shown on the right of this figure. The following operations are permitted when transforming a state of the sliding puzzle:

1. If a tile is to the left of the free square, this tile can be moved to the right.
2. If a tile is to the right of the free square, this tile can be moved to the left.
3. If a tile is above the free square, this tile can be moved down.
4. If a tile is below the free square, this tile can be moved up.

Figure 2.3: The 3×3 sliding puzzle.

In order to get a feeling for the complexity of the sliding puzzle, you can check the page

<http://mypuzzle.org/sliding>.

The sliding puzzle is much more complex than the missionaries and cannibals problem because the state space is much larger. For the case of the 3×3 sliding puzzle, there are 9 squares that can be positioned in $9!$ different ways. It turns out that only half of these positions are reachable from a given start state. Therefore, the effective number of states for the 3×3 sliding puzzle is

$$9!/2 = 181,440.$$

This is already a big number, but 181,440 states can still be stored in a modern computer. However, the 4×4 sliding puzzle has

$$16!/2 = 10,461,394,944,000$$

different states reachable from a given start state. If a state is represented as matrix containing 16 numbers and we store every number using just 4 bits, we still need $16 \cdot 4 = 64$ bits or 8 bytes for every state. Hence we would need a total of

$$(16!/2) \cdot 8 = 83,691,159,552,000$$

bytes to store every state. We would thus need about 84 Terabytes to store the set of all states. As few computers are equipped with this kind of memory, it is obvious that we won't be able to store the entire state space in memory.

Figure 2.4 shows how the 3×3 sliding puzzle can be formulated as a search problem. We discuss this program line by line.

1. `findTile` is an auxiliary procedure that takes a `number` and a `state` and returns the row and column where the tile labeled with `number` can be found.

Here, a state is represented as a list of lists. For example, the states shown in Figure 2.3 are represented as shown in line 26 and line 30. The empty tile is coded as 0.

2. `moveDir` takes a `state`, the `row` and the `column` where to find the empty square and a direction in which the empty square should be moved. This direction is specified via the two variables `dx` and `dy`. The tile at the position $\langle \text{row} + \text{dx}, \text{col} + \text{dy} \rangle$ is moved into the position $\langle \text{row}, \text{col} \rangle$, while the tile at position $\langle \text{row} + \text{dx}, \text{col} + \text{dy} \rangle$ becomes empty.
3. Given a `state`, the procedure `newStates` computes the set of all states that can be reached in one step from `state`. The basic idea is to find the position of the empty tile and then try to move the empty tile in all possible directions. If the empty tile is found at position $[\text{row}, \text{col}]$ and the direction of the movement is given as $[\text{dx}, \text{dy}]$, then in order to ensure that the empty tile can be moved to the position $[\text{row} + \text{dx}, \text{col} + \text{dy}]$, we have to ensure that both

$$\text{row} + \text{dx} \in \{1, \dots, n\} \quad \text{and} \quad \text{col} + \text{dy} \in \{1, \dots, n\}$$

```

1  findTile := procedure(number, state) {
2      n := #state;
3      L := [1 .. n];
4      for (row in L, col in L | state[row][col] == number) {
5          return [row, col];
6      }
7  };
8  moveDir := procedure(state, row, col, dx, dy) {
9      state[row + dx][col + dy] := state[row][col];
10     state[row][col] := 0;
11     return state;
12 };
13 nextStates := procedure(state) {
14     n := #state;
15     [row, col] := findTile(0, state);
16     newStates := [];
17     directions := [ [1, 0], [-1, 0], [0, 1], [0, -1] ];
18     L := [1 .. n];
19     for ([dx, dy] in directions) {
20         if (row + dx in L && col + dy in L) {
21             newStates += [ moveDir(state, row, col, dx, dy) ];
22         }
23     }
24     return newStates;
25 };
26 start := [ [8, 0, 6],
27            [5, 4, 7],
28            [2, 3, 1]
29 ];
30 goal := [ [0, 1, 2],
31           [3, 4, 5],
32           [6, 7, 8]
33 ];

```

Figure 2.4: The 3×3 sliding puzzle.

hold, where n is the size of the board.

Next, we want to develop an algorithm that can solve puzzles of the kind described so far. The most basic algorithm to solve search problems is **breadth first search**. We discuss this algorithm next.

2.2 Breadth First Search

Informally, breadth first search, abbreviated as BFS, works as follows:

1. Given a search problems $\langle Q, \text{nextStates}, \text{start}, \text{goal} \rangle$, we initialize a set **Frontier** to contain the state **start**.

In general, **Frontier** contains those states that have just been discovered and whose successors have not yet been seen.

2. As long as the set **Frontier** does not contain the state **goal**, we recompute this set by adding all states to it that can be reached in step from a state in **Frontier**. Then, the states that had been previously present in **Frontier** are removed. These old states are then saved into a set **Visited**.

In order to avoid loops, an implementation of breadth first search keeps track of those states that have been visited. These states are collected in a set **Visited**. Once a state has been added to the set **Visited**, it will never be revisited again. Furthermore, in order to keep track of the path leading to the goal, we have a dictionary **Parent**. For every state s that is in **Frontier**, **Parent**[s] is the state that caused s to be added to the set **Frontier**, i.e. we have

$$s \in \text{nextStates}(\text{Parent}[s]).$$

```

1  search := procedure(start, goal, nextStates) {
2      Frontier := { start };
3      Visited  := {}; // set of nodes that have been expanded
4      Parent   := {};
5      while (Frontier != {}) {
6          NewFrontier := {};
7          for (s in Frontier, ns in nextStates(s) | !(ns in Visited)) {
8              NewFrontier += { ns };
9              Parent[ns]  := s;
10             if (ns == goal) {
11                 return pathTo(goal, Parent);
12             }
13         }
14         Visited  += Frontier;
15         Frontier := NewFrontier;
16     }
17 };

```

Figure 2.5: Breadth first search.

Figure 2.5 on page 11 shows an implementation of breadth first search in SETLX. We discuss this implementation line by line:

1. **Frontier** is the set of all those states that have been encountered but whose neighbours have not yet been explored. Initially, it contains the state **start**.
2. **Visited** is the set of all those states, all whose neighbours have already been added to the set **Frontier**. In order to avoid infinite loops, these states must not be visited again.
3. **Parent** is a dictionary keeping track of the state leading to a given state.
4. As long as the set **Frontier** is not empty, we add all neighbours of states in **Frontier** that have not yet been visited to the set **NewFrontier**. When doing this, we keep track of the path leading to a new state **ns** by storing its parent in the dictionary **Parent**.
5. If the new state happens to be the state **goal**, we return a path leading from **start** to **goal**. The procedure **pathTo()** is shown in Figure 2.6 on page 12.
6. After we have collected all successors of states in **Frontier**, the states in the set **Frontier** have been visited and are therefore added to the set **Visited**, while the **Frontier** is updated to **NewFrontier**.

The procedure call **pathTo(state, Parent)** constructs a path reaching from **start** to **state** in reverse by looking up the parent states.

If we try breadth first search to solve the missionaries and cannibals problem, we immediately get the solution shown in Figure 2.7. 15 nodes had to be expanded to find this solution. To keep this in perspective, we note that Figure 2.2 shows that the entire state space contains 16 states. Therefore, with the exception of one state, we have inspected all the states. This is a typical behaviour for breadth first search.

```

1  pathTo := procedure(state, Parent) {
2      Path := [];
3      while (state != om) {
4          Path += [state];
5          state := Parent[state];
6      }
7      return reverse(Path);
8  };

```

Figure 2.6: The procedure `pathTo()`.

1	MMM	KKK	B	~~~~~		
2				> KK >		
3	MMM	K		~~~~~		KK B
4				< K <		
5	MMM	KK	B	~~~~~		K
6				> KK >		
7	MMM			~~~~~		KKK B
8				< K <		
9	MMM	K	B	~~~~~		KK
10				> MM >		
11	M	K		~~~~~	MM	KK B
12				< M K <		
13	MM	KK	B	~~~~~	M	K
14				> MM >		
15		KK		~~~~~	MMM	K B
16				< K <		
17		KKK	B	~~~~~	MMM	
18				> KK >		
19		K		~~~~~	MMM	KK B
20				< K <		
21		KK	B	~~~~~	MMM	K
22				> KK >		
23				~~~~~	MMM	KKK B

Figure 2.7: A solution of the missionaries and cannibals problem.

Next, let us try to solve the 3×3 sliding puzzle. It takes less about 9 seconds to solve this problem on my computer¹, while 181439 states are touched. Again, we see that breadth first search touches nearly all the states reachable from the start state.

2.2.1 A Queue Based Implementation of Breadth First Search

In the literature, for example in Figure 3.11 of Russell & Norvig [3], breadth first search is often implemented using a **queue** data structure. Figure 2.8 on page 13 shows an implementation of breadth first search that uses a queue to store the set **Frontier**. However, when we run this version, it turns out that the solution of the 3×3 sliding puzzle needs about 58 seconds, which is a lot slower than our set based implementation that has been presented in Figure 2.5.

¹ I happen to own an iMac from 2011. This iMac is equipped with 16 Gigabytes of main memory and a quad core 2.7 GHz “Intel Core i5” processor. I suspect this to be the I5-2500S (Sandy Bridge) processor.

```

1  search := procedure(start, goal, nextStates) {
2      Queue := [ start ];
3      Visited := {};
4      Parent := {};
5      while (Queue != []) {
6          state := Queue[1];
7          Queue := Queue[2..];
8          if (state == goal) {
9              return pathTo(state, Parent);
10         }
11         Visited += { state };
12         newStates := nextStates(state);
13         for (ns in newStates | !(ns in Visited) && Parent[ns] == om) {
14             Parent[ns] := state;
15             Queue += [ ns ];
16         }
17     }
18 };

```

Figure 2.8: A queue based implementation of breadth first search.

The solution of the 3×3 sliding puzzle that is found by breadth first search is shown in Figure 2.9 and Figure 2.10.

We conclude our discussion of breadth first search by noting the two most important properties of breadth first search.

1. Breadth first search is *complete*: If there is a solution to the given search problem, then breadth first search is going to find it.
2. The solution found by breadth first search is *optimal*, i.e. it is the shortest possible solution.

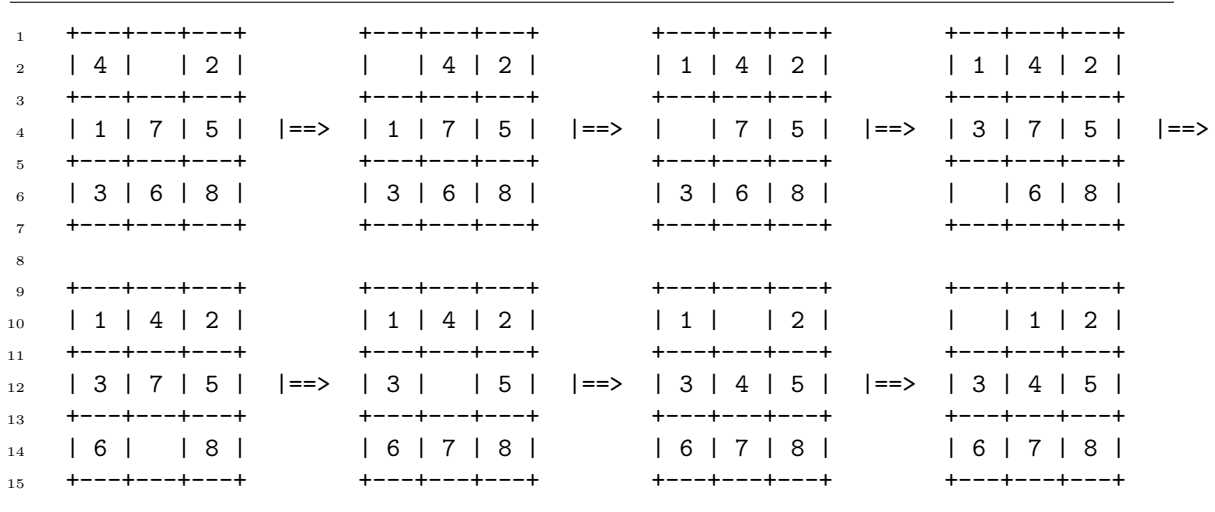
Proof: Both of these claims can be shown simultaneously. Consider the implementation of breadth first search shown in Figure 2.5. An easy induction on the number of iterations of the **while** loop shows that after n iterations of the **while** loop, the set **Frontier** contains exactly those states that have a distance of n to the state **start**. This claim is obviously true before the first iteration of the while loop as in this case, **Frontier** only contains the state **start**. In the induction step we assume the claim is true after n iterations. Then, in the next iteration all states that can be reached in one step from a state in **Frontier** are added to the new **Frontier**, provided there is no shorter path to these states. There is a shorter path to these states if these states are already a member of the set **Visited**. Hence, the claim is true after $n + 1$ iterations also.

Now, if there is a path from **start** to **goal**, there must also be a shortest path. Assume this path has a length of k . Then, **goal** is reached in the iteration number k and the shortest path is returned. \square

The fact that breadth first search is both complete and the path returned is optimal is rather satisfying. However, breadth first search still has a big downside that makes it unusable for many problems: If the **goal** is far from the **start**, breadth first search will use a lot of memory because it will store a large part of the state space in the set **Visited**. In many cases, the state space is so big that this is not possible. For example, it is impossible to solve the more interesting cases of the 4×4 sliding puzzle.

1	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
2	8 6		8 6		5 8 6		5 8 6
3	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
4	5 4 7	==>	5 4 7	==>	4 7	==>	2 4 7
5	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
6	2 3 1		2 3 1		2 3 1		3 1
7	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
8							
9	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
10	5 8 6		5 8 6		5 8 6		5 8
11	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
12	2 4 7	==>	2 4 7	==>	2 4	==>	2 4 6
13	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
14	3 1		3 1		3 1 7		3 1 7
15	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
16							
17	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
18	5 8		5 8		2 5 8		2 5 8
19	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
20	2 4 6	==>	2 4 6	==>	4 6	==>	4 6
21	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
22	3 1 7		3 1 7		3 1 7		3 1 7
23	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
24							
25	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
26	2 5 8		2 5 8		2 5 8		2 5
27	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
28	4 1 6	==>	4 1 6	==>	4 1	==>	4 1 8
29	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
30	3 7		3 7		3 7 6		3 7 6
31	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
32							
33	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
34	2 5		2 5		4 2 5		4 2 5
35	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
36	4 1 8	==>	4 1 8	==>	1 8	==>	1 8
37	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
38	3 7 6		3 7 6		3 7 6		3 7 6
39	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
40							
41	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
42	4 2 5		4 2 5		4 2 5		4 2
43	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
44	1 7 8	==>	1 7 8	==>	1 7	==>	1 7 5
45	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+
46	3 6		3 6		3 6 8		3 6 8
47	+---+---+---+		+---+---+---+		+---+---+---+		+---+---+---+

Figure 2.9: The first 24 steps in the solution of the 3×3 sliding puzzle.

Figure 2.10: The last 7 steps in the solution of the 3×3 sliding puzzle.

2.3 Depth First Search

To overcome the memory limitations of breadth first search, the **depth first search** algorithm has been developed. The basic idea is to replace the queue of Figure 2.8 by a stack. The resulting algorithm is shown in Figure 2.11 on page 15. Basically, in this implementation, a path is searched to its end before trying an alternative. This way, we might be able to find a **goal** that is far away from **start** without exploring the whole state space.

```

1  search := procedure(start, goal, nextStates) {
2      Stack := [ start ];
3      Parent := {};
4      while (Stack != []) {
5          state := Stack[-1];
6          Stack := Stack[..-2];
7          if (state == goal) {
8              return pathTo(state, Parent);
9          }
10         newStates := nextStates(state);
11         for (ns in newStates | ns != start && Parent[ns] == om) {
12             Parent[ns] := state;
13             Stack      += [ns];
14         }
15     }
16 };
```

Figure 2.11: The depth first search algorithm.

Actually, it is not necessary to understand the details of the implementation shown in Figure 2.11 on page 15. The reason is that the recursive implementation of depth first search that is presented in the following subsection is superior to the implementation shown in Figure 2.11 on page 15. When we test the implementation shown above with the 3×3 sliding puzzle, it takes about 96 seconds to find a solution. The solution that is found has a length of 41,553 steps. As the shortest path from **start** to **goal** has 31 steps, the solution found by depth first search is very far from optimal. All this is rather disappointing news. The only good news is that there is no longer a need to keep the set **Visited** around. However, we still have to maintain the set **Parent**. If we

were more ambitious, we could eliminate the use of this dictionary also, but the resulting implementation would be rather unwieldy. Fortunately, we will be able to get rid of the set `Parent` with next to no effort when we develop a recursive implementation of depth first search in the following subsection.

2.3.1 Getting Rid of the Parent Dictionary

It can be argued that the implementation of depth first search discussed previously is not really depth first search because it uses the dictionary `Parent`. As states are only added to `Parent` and never removed, at the end of the search this dictionary will contain all states that have been visited. This defeats the most important advantage of depth first search which is the fact that it should only store the current path that is investigated. Therefore, it has been suggested (for example compare Russel and Norvig [3]) that instead of storing single states, the stack should store the full paths leading to these states. This leads to the implementation shown in Figure 2.12 on page 16.

```

1  search := procedure(start, goal, nextStates) {
2      Stack := [ [start] ];
3      while (Stack != []) {
4          Path := Stack[-1];
5          Stack := Stack[..-2];
6          state := Path[-1];
7          if (state == goal) {
8              return Path;
9          }
10         newStates := nextStates(state);
11         for (ns in newStates | !(ns in Path)) {
12             Stack += [ Path + [ns] ];
13         }
14     }
15 };

```

Figure 2.12: An path-based implementation of depth first search.

Unfortunately, it turns out that the paths get very long and hence need a lot of memory to be stored and this fact defeats the main idea of this implementation. As a result, the procedure `search` that is given in Figure 2.12 on page 16 is not able to solve the instance of the 3×3 sliding puzzle that was shown in Figure 2.3 on page 9.

Exercise 1: Assume that a single state can be stored using 8 bytes. Furthermore, assume that the top of the stack in the procedure `search` contains a list of length n . How many bytes are at least needed to store all the states that are put on the stack? How big is this memory if $n = 10,000$?

- (a) **Note** that the question only asks for the memory needed to store the states. The memory needed to store the stack itself and the various lists on the stack comes on top of the memory needed to store the states. However, to answer this exercise correctly, you should ignore this type of memory.
- (b) If we only know that the path on top of the stack has a length of n , then this fact does not tell us the actual size of the stack. However, it does provide a lower bound on the size of the stack and a lower bound is all that is needed. ◇

2.3.2 A Recursive Implementation of Depth First Search

Sometimes, the depth first search algorithm is presented as a recursive algorithm, since this leads to an implementation that is slightly shorter and more easy to understand. What is more, we no longer need the dictionary `Parent` to record the parent of each node. The resulting implementation is shown in Figure 2.13 on page 17.

```

1  search := procedure(start, goal, nextStates) {
2      return dfs(start, goal, nextStates, [start]);
3  };
4  dfs := procedure(state, goal, nextStates, Path) {
5      if (state == goal) {
6          return Path;
7      }
8      newStates := nextStates(state);
9      for (ns in newStates | !(ns in Path)) {
10         result      := dfs(ns, goal, nextStates, Path + [ns]);
11         if (result != om) {
12             return result;
13         }
14     }
15 };

```

Figure 2.13: A recursive implementation of depth first search.

The only purpose of the procedure `search` is to call the procedure `dfs`, which needs one additional argument. This argument is called `Path`. The idea is that `Path` is a path leading from the state `start` to the current `state` that is the first argument of the procedure `dfs`. Of course, on the first invocation of `dfs`, the parameter `state` is equal to `start` and therefore `Path` is initialized as the list containing only `start`.

The implementation of `dfs` works as follows:

1. If `state` is equal to `goal`, our search is successful. Since by assumption the list `Path` is a path connecting `start` and `state` and we have checked that `state` is equal to `goal`, we can return `Path` as our solution.
2. Otherwise, `newStates` is the set of states that are reachable from `state` in one step. Any of the states `ns` in this set could be the next state on a path that leads to `goal`. Therefore, we try recursively to reach `goal` from every state `ns`. Note that we have to change `Path` to the list

`Path + [ns]`

when we call the procedure `dfs` recursively. This way, we retain the invariant of `dfs` that the list `Path` is a path connecting `start` with `state`.

3. We still have to avoid running in circles. In the recursive version of depth first search, this is achieved by checking that the state `ns` is not already a member of the list `Path`. In the non-recursive version of depth first search, we had used the set `Parent` instead. The current implementation no longer has a need for the dictionary `Parent`. This is very fortunate since it reduces the memory requirements of depth first search considerably.
4. If one of the recursive calls of `dfs` returns a list, this list is a solution to our search problem and hence it is returned. However, if instead the undefined value `om` is returned, the `for` loop needs to carry on and test the other successors of `state`.
5. Note that the recursive invocation of `dfs` returns `om` if the end of the `for` loop is reached and no solution has been returned so far. The reason is that there is no `return` statement at the end of the procedure `dfs`. Hence, if the last line of the procedure `dfs` is reached, `om` is returned by default.

For the 3×3 puzzle, it takes about 2 seconds to compute the solution. In this case, the length of the solution is still 3653 steps, which is unsatisfying. The good news is that this program does not need much memory. The only variable that uses considerable memory is the variable `Path`. If we can somehow keep the list `Path` short, then the recursive version of depth first search uses only a tiny fraction of the memory needed by breadth first search.

2.4 Iterative Deepening

The fact that the recursive version of depth first search took just 2 seconds to find a solution is very impressive. The question is whether it might be possible to force depth first search to find the shortest solution. The answer to this question leads to an algorithm that is known as **iterative deepening**. The main idea behind iterative deepening is to run depth first with a *depth limit* d . This limit enforces that a solution has at most a length of d . If no solution is found at a depth of d , the new depth $d + 1$ can be tried next and the process can be continued until a solution is found. The program shown in Figure 2.14 on page 18 implements this strategy. We proceed to discuss the details of this program.

```

1  search := procedure(start, goal, nextStates) {
2      limit := 1;
3      while (true) {
4          Path := depthLimitedSearch(start, goal, nextStates, limit);
5          if (Path != om) { return Path; }
6          limit += 1;
7      }
8  };
9  depthLimitedSearch := procedure(start, goal, nextStates, limit) {
10     Stack := [ [start] ];
11     while (Stack != []) {
12         Path := Stack[-1];
13         Stack := Stack[..-2];
14         state := Path[-1];
15         if (state == goal) { return Path; }
16         if (#Path >= limit) { continue; }
17         for (ns in nextStates(state) | !(ns in Path)) {
18             Stack += [ Path + [ns] ];
19         }
20     }
21 };

```

Figure 2.14: Iterative deepening implemented in SETLX.

1. The procedure `search` initializes the variable `limit` to 1 and tries to find a solution to the search problem that has a length that is less than or equal to `limit`. If a solution is found, it is returned. Otherwise, the variable `limit` is incremented by one and a new instance of depth first search is started. This process continues until either
 - a solution is found or
 - the sun rises in the west.
2. The procedure `depthLimitedSearch` implements depth first search but takes care to compute only those paths that have a length of at most `limit`. The implementation shown in Figure 2.14 is stack based. In this implementation, the stack contains paths leading from `start` to the state at the end of a given path. Hence it is similar to the implementation of depth first search shown in Figure 2.11 on page 15.
3. The stack is initialized to contain the path `[start]`.
4. In the `while`-loop, the first thing that happens is that the `Path` on top of the stack is removed from the stack. The state at the end of this `Path` is called `state`. If this `state` happens to be the `goal`, a solution to the search problem has been found and this solution is returned.

5. Otherwise, we check the length of **Path**. If this length is greater than or equal to the **limit**, the **Path** can be discarded as we have already checked that it does not end in the **goal**.
6. Otherwise, the neighbours of **state** are computed. For every neighbour **ns** of **state** that has not yet been encountered in **Path**, we extend **Path** to a new list that ends in **ns**.
7. This process is iterated until the **Stack** is exhausted.

The nice thing about the program presented in this section is the fact that it does not use much memory. The reason is that the stack can never have a size that is longer than **limit** and therefore the overall memory that is needed can be bounded by $\mathcal{O}(\text{limit}^2)$. However, when we run this program to solve the 3×3 sliding puzzle, the algorithm takes about 42 minutes. There are two reasons for this:

1. First, it is quite wasteful to run the search for a depth limit of 1, 2, 3, \dots all the way up to 31. Essentially, all the computations done with a limit less the 31 are essentially wasted.
2. Given a state s that is reachable from the **start**, there often is a huge number of different paths that lead from **start** to s . The version of iterative deepening presented in this section tries all of these paths and hence needs a large amount of time.

Exercise 2: Assume the set of states Q is defined as

$$Q := \{\langle a, b \rangle \mid a \in \mathbb{N} \wedge b \in \mathbb{N}\}.$$

Furthermore, the states **start** and **goal** are defined as

$$\text{start} := \langle 0, 0 \rangle \quad \text{and} \quad \text{goal} := \langle n, n \rangle \text{ where } n \in \mathbb{N}.$$

Next, the function **nextStates** is defined as

$$\text{nextStates}(\langle a, b \rangle) := \{\langle a + 1, b \rangle, \langle a, b + 1 \rangle\}.$$

Finally, the search problem \mathcal{P} is defined as

$$\mathcal{P} := \langle Q, \text{nextStates}, \text{start}, \text{goal} \rangle.$$

Given a natural number n , compute the number of different solutions of this search problem and prove your claim. \diamond

Exercise 3: If there is no solution, the implementation of iterative deepening that is shown in Figure 2.14 does not terminate. The reason is that the function **depthLimitedSearch** does not distinguish between the following two reasons for failure:

1. It can fail to find a solution because the depth limit is reached.
2. It can also fail if it has tried all paths without hitting the depth limit but the **Stack** is exhausted.

Improve the implementation of iterative deepening so that it will always terminate eventually, provided the state space is finite. \diamond

2.4.1 A Recursive Implementation of Iterative Deepening

If we implement iterative deepening recursively, then we know that the call stack is bounded by the length of the shortest solution. Figure 2.15 on page 20 shows a recursive implementation of iterative deepening. This implementation has several nice features:

1. The path that is computed no longer requires the dictionary **Parent** as it is built incrementally in the argument **Path** of the procedure **dfsLimited**.
2. Similarly, there is no longer a need to keep the dictionary **Distance**.

Unfortunately, the running time of the recursive implementation of iterative deepening is still quite big: On my computer, the recursive implementation takes about 36 minutes.

```

1  search := procedure(start, goal, nextStates) {
2      limit := 1;
3      while (true) {
4          result := dfsLimited(start, goal, nextStates, [start], limit);
5          if (result != om) {
6              return result;
7          }
8          limit += 1;
9      }
10 };
11 dfsLimited := procedure(state, goal, nextStates, Path, limit) {
12     if (state == goal) {
13         return Path;
14     }
15     if (limit == 0) {
16         return; // limit exceeded
17     }
18     for (ns in nextStates(state) | !(ns in Path)) {
19         result := dfsLimited(ns, goal, nextStates, Path + [ns], limit - 1);
20         if (result != om) {
21             return result;
22         }
23     }
24 };

```

Figure 2.15: A recursive implementation of iterative deepening.

2.5 Bidirectional Breadth First Search

Breadth first search first visits all states that have a distance of 1 from start, then all states that have a distance of 2, then of 3 and so on until finally the goal is found. If the shortest path from **start** to **goal** is d , then all states that have a distance of at most d will be visited. In many search problems, the number of states grows exponentially with the distance. i.e. there is a *branching factor* b such that the set of all states that have a distance of at most d from **start** is roughly

$$1 + b + b^2 + b^3 + \dots + b^d = \frac{b^{d+1} - 1}{b - 1} = \mathcal{O}(b^d).$$

At least this is true in the beginning of the search. As the size of the memory that is needed is the most constraining factor when searching, it is important to cut down this size. One simple idea is to start searching both from the node **start** and the node **goal** simultaneously. The justification is that we can hope that the path starting from **start** and the path starting from **goal** will meet in the middle and hence they will both have a size of approximately $d/2$. If this is the case, only

$$2 \cdot \frac{b^{d/2} - 1}{b - 1}$$

nodes need to be explored and even for modest values of b this number is much smaller than

$$\frac{b^{d+1} - 1}{b - 1}$$

which is the number of nodes expanded in breadth first search. For example, assume that the branching factor $b = 2$ and that the length of the shortest path leading from **start** to **goal** is 40. Then we need to explore

$$2^{40} - 1 = 1,099,511,627,775$$

in breadth first search, while we only have to explore

$$2^{40/2} - 1 = 1,048,575$$

with bidirectional depth first search. While it is certainly feasible to keep a million states in memory, keeping a trillion states in memory is impossible on most devices.

```

1  search := procedure(start, goal, nextStates) {
2      FrontierA := { start };
3      VisitedA  := {}; // set of nodes expanded starting from start
4      ParentA   := {};
5      FrontierB := { goal };
6      VisitedB  := {}; // set of nodes expanded starting from goal
7      ParentB   := {};
8      while (FrontierA != {} && FrontierB != {}) {
9          VisitedA += FrontierA;
10         VisitedB += FrontierB;
11         NewFrontier := {};
12         for (s in FrontierA, ns in nextStates(s) | !(ns in VisitedA)) {
13             NewFrontier += { ns };
14             ParentA[ns] := s;
15             if (ns in VisitedB) {
16                 return combinePaths(ns, ParentA, ParentB);
17             }
18         }
19         FrontierA := NewFrontier;
20         NewFrontier := {};
21         for (s in FrontierB, ns in nextStates(s) | !(ns in VisitedB)) {
22             NewFrontier += { ns };
23             ParentB[ns] := s;
24             if (ns in VisitedA) {
25                 return combinePaths(ns, ParentA, ParentB);
26             }
27         }
28         FrontierB := NewFrontier;
29     }
30 };

```

Figure 2.16: Bidirectional breadth first search.

Figure 2.16 on page 21 shows the implementation of bidirectional breadth first search. Essentially, we have to copy the breadth first program shown in Figure 2.5. Let us discuss the details of the implementation.

1. The variable **FrontierA** is the frontier that starts from the state **start**, while **FrontierB** is the frontier that starts from the state **goal**.
2. **VisitedA** is the set of states that have been visited starting from **start**, while **VisitedB** is the set of states that have been visited starting from **goal**.
3. For every state s that is in **FrontierA**, **ParentA**[s] is the state that caused s to be added to the set **FrontierA**. Similarly, for every state s that is in **FrontierB**, **ParentB**[s] is the state that caused s to be added to the set **FrontierB**.
4. The bidirectional search keeps running for as long as both sets **FrontierA** and **FrontierB** are non-empty and a path has not yet been found.

5. Initially, the **while** loop adds the frontier sets to the visited sets as all the neighbours of the frontier sets will now be explored.
6. Then the **while** loop computes those states that can be reached from **FrontierA** and have not been visited from **start**. If a state **ns** is a neighbour of a state **s** from the set **FrontierA** and the state **ns** has already been encountered during the search that started from **goal**, then a path leading from **start** to **goal** has been found and this path is returned. The function **combinePaths** that computes this path by combining the path that leads from **start** to **ns** and then from **ns** to **goal** to is shown in Figure 2.17 on page 22.
7. Next, the same computation is done with the role of the states **start** and **goal** exchanged.

On my computer, bidirectional breadth first search solves the 3×3 sliding puzzle in less than a second! However, bidirectional breadth first search is still not able to solve the 4×4 sliding puzzle since the portion of the search space that needs to be computed is just too big to fit into memory.

```

1  combinePaths := procedure(node, ParentA, ParentB) {
2      Path1 := pathTo(node, ParentA);
3      Path2 := pathTo(node, ParentB);
4      return Path1[.-2] + reverse(Path2);
5  };

```

Figure 2.17: Combining two paths.

2.6 The A* Search Algorithm

Up to now, all the search algorithms we have discussed were essentially blind. Given a state s and all of its neighbours, they had no idea which of the neighbours they should pick because they had no conception which of these neighbours might be more promising than the other neighbours. If a human tries to solve a problem, she usually will develop a feeling that certain states are more favourable than other states because they seem to be closer to the solution. In order to formalise this procedure, we next define the notion of a *heuristic*.

Definition 2 (Heuristic) Given a search problem

$$\mathcal{P} = \langle Q, \text{nextStates}, \text{start}, \text{goal} \rangle,$$

a *heuristic* is a function

$$h : Q \rightarrow \mathbb{R}$$

that computes an approximation of the distance of a given state s to the goal state goal . The heuristic is *admissible* if it always underestimates the true distance, i.e. if the function

$$d : Q \rightarrow \mathbb{R}$$

computes the true distance of a state s to the goal, then we must have

$$h(s) \leq d(s) \quad \text{for all } s \in Q.$$

Hence, the heuristic is admissible iff it is *optimistic*: An admissible heuristic must never overestimate the distance to the goal, but it is free to underestimate this distance.

Finally, the heuristic h is called *consistent* iff we have

$$h(\text{goal}) = 0 \quad \text{and} \quad h(s_1) \leq 1 + h(s_2) \quad \text{for all } s_2 \in \text{neighbours}(s_1). \quad \diamond$$

Let us explain the idea behind the notion of consistency. First, if we are already at the goal, the heuristic should notice this and hence return $h(\text{goal}) = 0$. Secondly, assume we are at the state s_1 and s_2 is a neighbour of s_1 , i.e. we have that

$$s_2 \in \text{nextStates}(s_1).$$

Now if our heuristic h assumes that the distance of s_2 from the **goal** is $h(s_2)$, then the distance of s_1 from the **goal** can be at most $1 + h(s_2)$ because starting from s_1 we can first go to s_2 in one step and then from s_2 to **goal** in $h(s_2)$ steps for a total of $1 + h(s_2)$ steps. Of course, it is possible that there exists a cheaper path from s_1 leading to the **goal** than the one that visits s_2 first. Hence we have the inequality

$$h(s_1) \leq 1 + h(s_2).$$

Theorem 3 Every consistent heuristic is also admissible.

Proof: Assume that the heuristic h is consistent. Assume further that $s \in Q$ is some state such that there is a path p from s to the **goal**. Assume this path has the form

$$p = [s_n, s_{n-1}, \dots, s_1, s_0], \quad \text{where } s_n = s \text{ and } s_0 = \text{goal}.$$

Then the length of p is n and we have to show that $h(s) \leq n$. In order to prove this claim, we show that we have

$$h(s_k) \leq k \quad \text{for all } k \in \{0, 1, \dots, n\}.$$

This claim is shown by induction on k .

B.C.: $k = 0$.

We have $h(s_0) = h(\text{goal}) = 0 \leq 0$ because the fact that h is consistent implies $h(\text{goal}) = 0$.

I.S.: $k \mapsto k + 1$.

We have to show that $h(s_{k+1}) \leq k + 1$ holds. This is shown as follows:

$$\begin{aligned} h(s_{k+1}) &\leq 1 + h(s_k) && \text{because } h \text{ is consistent} \\ &\leq 1 + k && \text{because } h(s_k) \leq k \text{ by induction hypotheses} \end{aligned}$$

This concludes the proof. □

It is natural to ask whether the last theorem can be reversed, i.e. whether every admissible heuristic is also consistent. The answer to this question is negative since there are *some contorted* heuristics that are admissible but that fail to be consistent. However, in practice it turns out that most admissible heuristics are also consistent. Therefore, when we construct consistent heuristics later, we will start with admissible heuristics, since these are easy to find. We will then have to check that these heuristics are also consistent.

Examples: In the following, we will discuss several heuristics for the sliding puzzle.

1. The simplest heuristic that is admissible is the function $h(s) := 0$. Since we have

$$0 \leq 1 + 0,$$

this heuristic is obviously consistent, but this heuristic is too trivial to be of any use.

2. The next heuristic is the *number of misplaced tiles* heuristic. For a state s , this heuristic counts the number of tiles in s that are not in their final position, i.e. that are not in the same position as the corresponding tile in **goal**. For example, in Figure 2.3 on page 9 in the state depicted to the left, only the tile with the label 4 is in the same position as in the state depicted to the right. Hence, there are 7 misplaced tiles.

As every misplaced tile must be moved at least once and every step in the sliding puzzle moves at most one tile, it is obvious that this heuristic is admissible. It is also consistent. First, the **goal** has no misplaced tiles, hence its heuristic is 0. Second, in every step of the sliding puzzle only one tile is moved. Therefore the number of misplaced tiles in two neighbouring state can differ by at most one.

We will later see that the number of misplaced tiles heuristic is very crude and therefore not particularly useful.

3. The *Manhattan heuristic* improves on the previous heuristic. For two points $\langle x_1, y_1 \rangle, \langle x_2, y_2 \rangle \in \mathbb{R}^2$ the *Manhattan distance* of these points is defined as

$$d_1(\langle x_1, y_1 \rangle, \langle x_2, y_2 \rangle) := |x_1 - x_2| + |y_1 - y_2|.$$

If we associate *Cartesian coordinates* with the tiles of the sliding puzzle such that the tile in the upper left corner has coordinates $\langle 1, 1 \rangle$ and the coordinates of the tile in the lower right corner is $\langle 3, 3 \rangle$, then the Manhattan distance of two positions measures how many steps it takes to move a tile from the first position to the second position if we are only allowed to move the tile horizontally or vertically. To compute the Manhattan heuristic for a state s with respect to the **goal**, we first define the position $\text{pos}(t, s)$ for all tiles $t \in \{1, \dots, 8\}$ in a given state s as follows:

$$\text{pos}(t, s) = \langle \text{row}, \text{col} \rangle \stackrel{\text{def}}{\iff} s[\text{row}][\text{col}] = t,$$

i.e. given a state s , the expression $\text{pos}(t, s)$ computes the Cartesian coordinates of the tile t with respect to s . Then we can define the Manhattan heuristic h for the 3×3 puzzle as follows:

$$h(s) := \sum_{t=1}^8 d_1(\text{pos}(t, s), \text{pos}(t, \text{goal})).$$

The Manhattan heuristic measure the number of moves that would be needed if we wanted to put every tile of s into its final positions and if we were allowed to slide tiles over each other. Figure 2.18 on page 24 shows how the Manhattan distance can be computed. The code given in that figure works for a general $n \times n$ sliding puzzle. It takes two states **stateA** and **stateB** and computes the Manhattan distance between these states.

- (a) First, the size **n** of the puzzle is computed by checking the number of rows of **stateA**.
- (b) Next, the **for** loop iterates over all rows and columns of **stateA** that do not contain a blank tile. Remember that the blank tile is coded using the number 0. The tile at position $\langle \text{rowA}, \text{colA} \rangle$ in **stateA** is computed using the expression **stateA**[**rowA**][**colA**] and the corresponding position $\langle \text{rowB}, \text{colB} \rangle$ of this tile in state **stateB** is computed using the function **findTile**.
- (c) Finally, the Manhattan distance between the two positions $\langle \text{rowA}, \text{colA} \rangle$ and $\langle \text{rowB}, \text{colB} \rangle$ is added to the **result**.

```

1  manhattan := procedure(stateA, stateB) {
2      n := #stateA;
3      L := [1 .. n];
4      result := 0;
5      for (rowA in L, colA in L | stateA[rowA][colA] != 0) {
6          [rowB, colB] := findTile(stateA[rowA][colA], stateB);
7          result += abs(rowA - rowB) + abs(colA - colB);
8      }
9      return result;
10 };
```

Figure 2.18: The Manhattan distance between two states.

The Manhattan distance is admissible. The reason is that if $s_2 \in \text{nextStates}(s_1)$, then there can be only one tile t such that the position of t in s_1 is different from the position of t in s_2 . Furthermore, this position differs by either one row or one column. Therefore,

$$|h(s_1) - h(s_2)| = 1$$

and hence $h(s_1) \leq 1 + h(s_2)$. □

Now we are ready to describe how the A* algorithm uses its heuristic. The basic idea is that the A* search algorithm works similar to the queue based version of breadth first search, but instead of using a simple queue, a priority queue is used instead. The priority $f(s)$ of every state s is given as

$$f(s) := g(s) + h(s),$$

where $g(s)$ computes the length of the path leading from **start** to s and $h(s)$ is the heuristical estimate of the distance from s to **goal**. The details of the A* algorithm are given in Figure 2.19 on page 25 and discussed below.

```

1  aStarSearch := procedure(start, goal, nextStates, heuristic) {
2      Parent   := {};                               // back pointers, represented as dictionary
3      Distance := { [start, 0] };
4      estGoal  := heuristic(start, goal);
5      Estimate := { [start, estGoal] }; // estimated distances
6      Frontier := { [estGoal, start] }; // priority queue
7      while (Frontier != {}) {
8          [stateEstimate, state] := fromB(Frontier);
9          if (state == goal) {
10             return pathTo(state, Parent);
11          }
12          stateDist := Distance[state];
13          for (neighbour in nextStates(state)) {
14             oldEstimate := Estimate[neighbour];
15             newEstimate := stateDist + 1 + heuristic(neighbour, goal);
16             if (oldEstimate == om || newEstimate < oldEstimate) {
17                 Parent[neighbour] := state;
18                 Distance[neighbour] := stateDist + 1;
19                 Estimate[neighbour] := newEstimate;
20                 Frontier += { [newEstimate, neighbour] };
21                 if (oldEstimate != om) {
22                     Frontier -= { [oldEstimate, neighbour] };
23                 }
24             }
25         }
26     }
27 };

```

Figure 2.19: The A* search algorithm.

The function `aStarSearch` takes 4 parameters:

1. **start** is a state. This state represents the start state of the search problem.
2. **goal** is the goal state.
3. **nextStates** is a function that takes a state as a parameter. For a state s ,

`nextStates(s)`

computes the set of all those states that can be reached from s in a single step.

4. **heuristic** is a function that takes two parameters. For two states s_1 and s_2 , the expression

`heuristic(s_1, s_2)`

computes an estimate of the distance between s_1 and s_2 .

The function `aStarSearch` maintains 5 variables that are crucial for the understanding of the algorithm.

1. **Parent** is a dictionary associating a parent state with those states that have already been encountered during the search, i.e. we have

$$\text{Parent}[s_2] = s_1 \Rightarrow s_2 \in \text{nextStates}(s_1).$$

Once the goal has been found, this dictionary is used to compute the path from **start** to **goal**.

2. **Distance** is a dictionary. For every state s that is encountered during the search, this dictionary records the length of the shortest path from **start** to s .
3. **Estimate** is a dictionary. For every state s encountered in the search, $\text{Estimate}[s]$ is an estimate of the length that a path from **start** to **goal** would have if it would pass through the state s . This estimate is calculated using the equation

$$\text{Estimate}[s] = \text{Distance}[s] + \text{heuristic}(s, \text{goal}).$$

Instead of recalculating this sum every time we need it, we store it in the dictionary **Estimate**. This increases the efficiency of the algorithm.

4. **Frontier** is a **priority queue**. The elements of **Frontier** are pairs of the form

$$[d, s] \quad \text{such that} \quad d = \text{Estimate}[s],$$

i.e. if $[d, s] \in \text{Frontier}$, then the state s has been encountered in the search and it is estimated that a path leading from **start** to **goal** and passing through s would have a length of d .

Now that we have established the key variables, the A* algorithm runs in a **while** loop that does only terminate if either a solution is found or the priority queue **Frontier** is exhausted.

1. First, the **state** with the smallest estimated distance for a path running from **start** to **goal** and passing through **state** is chosen from the priority queue **Frontier**. Note that the call to `fromB` does not only return the pair

$$[\text{stateEstimate}, \text{state}]$$

from **Frontier** that has the lowest value of **stateEstimate**, but also removes this pair from the priority queue.

2. Now if this **state** is the **goal** a solution has been found. Hence, in this case the solution is returned and the function `aStarSearch` terminates.
3. Otherwise, we check the length of the path leading from **start** to **state**. This length is stored in **stateDist**. Effectively, this is the distance between **start** and **state**.
4. Next, we have a loop that iterates over all neighbours of **state**.

- (a) For every **neighbour** we check the estimated length of a solution passing through **neighbour** and store this length in **oldEstimate**. Note that **oldEstimate** is undefined, i.e. it has the value `om`, if we haven't yet encountered the node **neighbour** in our search.
- (b) If a solution would go from **start** to **state** and from there proceed to **neighbour**, the estimated length of this solution would be

$$\text{stateDist} + 1 + \text{heuristic}(\text{neighbour}, \text{goal}).$$

Therefore this value is stored in **newEstimate**.

- (c) Next, we need to check whether this new solution that first passes through **state** and then proceeds to **neighbour** is better than the previous solution that passes through **neighbour**. This check is done by comparing **newEstimate** and **oldEstimate**. Note that we have to take care of the fact that there might be no valid **oldEstimate**.

In case the new solution seems to be better than the old solution, we have to update the **Parent** dictionary, the **Distance** dictionary, and the **Estimate** dictionary. Furthermore, we have to update the priority queue **Frontier**. Here, we have to take care to remove the previous entry for the state **neighbour** if it exists, which is the case if **oldEstimate** is not **om**.

It can be shown that the A* search algorithm is complete and that the computed solution is optimal. The A* algorithm has been discovered by Hart, Nilsson, and Raphael and was first published in 1968 [1]. However, there was subtle bug in the first publication which was corrected in 1972 [2].

When we run A* on the 3×3 sliding puzzle, it takes about 17 seconds to solve the instance shown in Figure 2.3 on page 9. If we just look at the time, this seems to be disappointing. However, the good news is that now only 10061 states are touched in the search for a solution. This is more than a tenfold reduction when compared with breadth first search. The fact that the running time is, nevertheless, quite high results from the complexity of computing the Manhattan distance.

2.7 Bidirectional A* Search

So far, the best search algorithm we have encountered is bidirectional breadth first search. However, in terms of memory consumption, the A* algorithm also looks very promising. Hence, it might be a good idea to combine these two algorithms. Figure 2.20 on page 28 shows the resulting program. This program relates to the A* algorithm shown in Figure 2.19 on page 25 as the algorithm for bidirectional search shown in Figure 2.16 on page 21 relates to breadth first search shown in Figure 2.5 on page 11. Hence, we will not discuss the details any further.

When we run bidirectional A* search for the 3×3 sliding puzzle shown in Figure 2.3 on page 9, the program takes 2 second but only uses 2,963 states. Therefore, I have tried to solve the 4×4 sliding puzzle shown in Figure 2.21 on page 29 using bidirectional A* search. A solution of 44 steps was found in less than 58 seconds. Only 20,624 states had to be processed to compute this solution! None of the other algorithms presented so far was able to compute the solution.

2.8 Iterative Deepening A* Search

So far, we have combined A* search with bidirectional search and achieved good results. When memory space is too limited for bidirectional A* search to be possible, we can instead combine A* search with *iterative deepening*. The resulting search technique is known as *iterative deepening A* search* and is commonly abbreviated as IDA*. Figure 2.22 on page 29 shows an implementation of IDA* in SETLX. We proceed to discuss this program.

1. As in the A* search algorithm, the function `idaStarSearch` takes four parameters.
 - (a) **start** is a state. This state represents the start state of the search problem.
 - (b) **goal** is the goal state.
 - (c) **nextStates** is a function that takes a state s as a parameter and computes the set of all those states that can be reached from s in a single step.
 - (d) **heuristic** is a function that takes two parameters s_1 and s_2 , where s_1 and s_2 are states. The expression

$$\text{heuristic}(s_1, s_2)$$

computes an estimate of the distance between s_1 and s_2 . It is assumed that this estimate is optimistic.

2. The function `idaStarSearch` initializes **limit** to be an estimate of the distance between **start** and **goal**. As we assume that the function **heuristic** is optimistic, we know that there is no path from **start** to **goal** that is shorter than **limit**. Hence, we start our search by assuming that we might find a path that has a length of **limit**.

```

1  aStarSearch := procedure(start, goal, nextStates, heuristic) {
2      ParentA   := {};                               ParentB   := {};
3      DistanceA := { [start, 0] };                     DistanceB := { [goal, 0] };
4      estimate  := heuristic(start, goal);
5      EstimateA := { [start, estimate] }; EstimateB := { [goal, estimate] };
6      FrontierA := { [estimate, start] }; FrontierB := { [estimate, goal] };
7      while (FrontierA != {} && FrontierB != {}) {
8          [guessA, stateA] := first(FrontierA);
9          stateADist      := DistanceA[stateA];
10         [guessB, stateB] := first(FrontierB);
11         stateBDist      := DistanceB[stateB];
12         if (guessA <= guessB) {
13             FrontierA -= { [guessA, stateA] };
14             for (neighbour in nextStates(stateA)) {
15                 oldEstimate := EstimateA[neighbour];
16                 newEstimate := stateADist + 1 + heuristic(neighbour, goal);
17                 if (oldEstimate == om || newEstimate < oldEstimate) {
18                     ParentA[neighbour] := stateA;
19                     DistanceA[neighbour] := stateADist + 1;
20                     EstimateA[neighbour] := newEstimate;
21                     FrontierA += { [newEstimate, neighbour] };
22                     if (oldEstimate != om) { FrontierA -= { [oldEstimate, neighbour] }; }
23                 }
24                 if (DistanceB[neighbour] != om) {
25                     return combinePaths(neighbour, ParentA, ParentB);
26                 }
27             }
28         } else {
29             FrontierB -= { [guessB, stateB] };
30             for (neighbour in nextStates(stateB)) {
31                 oldEstimate := EstimateB[neighbour];
32                 newEstimate := stateBDist + 1 + heuristic(start, neighbour);
33                 if (oldEstimate == om || newEstimate < oldEstimate) {
34                     ParentB[neighbour] := stateB;
35                     DistanceB[neighbour] := stateBDist + 1;
36                     EstimateB[neighbour] := newEstimate;
37                     FrontierB += { [newEstimate, neighbour] };
38                     if (oldEstimate != om) { FrontierB -= { [oldEstimate, neighbour] }; }
39                 }
40                 if (DistanceA[neighbour] != om) {
41                     return combinePaths(neighbour, ParentA, ParentB);
42                 }
43             }
44         }
45     }
46 };

```

Figure 2.20: Bidirectional A* search.

- Next, we start a loop. In this loop, we call the function `search` to compute a path from `start` to `goal` that has a length of at most `limit`. This function `search` uses A* search and is described in detail below. Now there are two cases:

```

1  start := [ [ 1, 2, 0, 4 ],
2             [ 14, 7, 12, 10 ],
3             [ 3, 5, 6, 13 ],
4             [ 15, 9, 8, 11 ]
5             ];
6  goal  := [ [ 1, 2, 3, 4 ],
7             [ 5, 6, 7, 8 ],
8             [ 9, 10, 11, 12 ],
9             [ 13, 14, 15, 0 ]
10            ];

```

Figure 2.21: A start state and a goal state for the 4×4 sliding puzzle.

```

1  idaStarSearch := procedure(start, goal, nextStates, heuristic) {
2      limit := heuristic(start, goal);
3      while (true) {
4          Path := search(start, goal, nextStates, 0, limit, [start], heuristic);
5          if (isList(Path)) {
6              return Path;
7          }
8          limit := Path;
9      }
10 };
11 search := procedure(state, goal, nextStates, distance, limit, Path, heuristic) {
12     total := distance + heuristic(state, goal);
13     if (total > limit) {
14         return total;
15     }
16     if (state == goal) {
17         return Path;
18     }
19     smallest := mathConst("Infinity");
20     for (ns in nextStates(state) | !(ns in Path) ) {
21         result := search(ns, goal, nextStates, distance + 1, limit,
22                         Path + [ ns ], heuristic);
23         if (isList(result)) {
24             return result;
25         }
26         smallest := min([result, smallest]);
27     }
28     return smallest;
29 };

```

Figure 2.22: Iterative deepening A* search.

- (a) **search** does find a path. In this case, this path is returned in the variable **Path** and this variable is a list. This list is returned as the solution to the search problem.
- (b) **search** is not able to find a path within the given **limit**. In this case, search will not return a path but instead it will return a number. This number will specify the minimal length that any path leading from **start** to **goal** needs to have. This number is then used to update the **limit** which is

used for the next invocation of **search**.

Note that the fact that **search** is able to compute this new **limit** is a significant enhancement of iterative deepening. While we had to test every single possible length in iterative deepening, now the fact that we can intelligently update the **limit** results in a considerable saving of computation time.

We proceed to discuss the function **search**. This function takes 7 parameters, which we describe next.

1. **state** is a state. Initially, **state** is the **start** state. However, on recursive invocations of **search**, **state** is some state such that we have already found a path from **start** to **state**.
2. **goal** is another state. The purpose of the recursive invocations of **search** is to find a path from **state** to **goal**.
3. **nextStates** is a function that takes a state s as input and computes the set of states that are reachable from s in one step.
4. **distance** is the distance between **start** and **state**. It is also the length of the list **Path** described below.
5. **limit** is the maximal length of the path from **start** to **goal**.
6. **Path** is a path from **start** to **state**.
7. **heuristic**(s_1, s_2) computes an *estimate* of the distance between s_1 and s_2 . It is assumed that this estimate is optimistic, i.e. the value returned by **heuristic**(s_1, s_2) is less or equal than the true distance between s_1 and s_2 .

We proceed to describe the implementation of the function **search**.

1. As **distance** is the length of **Path** and the heuristic is assumed to be optimistic, i.e. it always underestimates the true distance, if we want to extend **Path**, then the best we can hope for is to find a path from **start** to **goal** that has a length of

$$\text{distance} + \text{heuristic}(\text{state}, \text{goal}).$$

This length is computed and saved in the variable **total**.

2. If **total** is bigger than **limit**, it is not possible to find a path from **start** to **goal** passing through **state** that has a length of at most **limit**. Hence, in this case we return **total** to communicate that the limit needs to be increased to have at least a value of **total**.
3. If we are lucky and have found the **goal**, the **Path** is returned.
4. Otherwise, we iterate over all nodes reachable from **state** that have not already been visited by **Path**. If **ns** is a node of this kind, we extend the **Path** so that this node is visited next. The resulting path is

$$\text{Path} + [\text{ns}].$$

Next, we recursively start a new search starting from the node **ns**. If this search is successful, the resulting path is returned. Otherwise, the search returns the minimum distance that is needed to reach the state **goal** from the state **ns**. If this distance is smaller than the distance returned from previous nodes which is stored in the variable **smallest**, this variable is updated accordingly. This way, if the **for** loop is not able to return a path leading to **goal**, the variable **smallest** contains the minimum distance that is needed to reach **goal** by a path that extends the given **Path**.

Note: At this point, a natural question is to ask whether the **for** loop should collect all paths leading to **goal** and then only return that path that is shortest. However, this is not necessary: Every time the function **search** is invoked it is already guaranteed that there is no path that is shorter than the parameter **limit**. Therefore, if **search** is able to find a path that has a length of at most **limit**, this path is already known to be optimal.

Iterative deepening A* is a complete search algorithm that does find an optimal path, provided that the employed heuristic is optimistic. On the instance of the 3×3 sliding puzzle shown on Figure 2.3 on page 9, this algorithm takes about 2.6 seconds to solve the puzzle. For the 4×4 sliding puzzle, the algorithm takes about 518 seconds. Although this is more than the time needed by bidirectional A* search, the good news is that the IDA* algorithm does not need much memory since basically only the path discovered so far is stored in memory. Hence, IDA* is a viable alternative if the available memory is not sufficient to support the bidirectional A* algorithm.

2.9 The A*-IDA* Search Algorithm

So far, from all of the algorithms we have tried, the bidirectional A* search has performed best. However, bidirectional A* search is only feasible if sufficient memory is available. While IDA* requires more time, its memory consumption is much lower than the memory consumption of bidirectional A*. Hence, it is natural to try to combine these two algorithms. Concretely, the idea is to run an A* search from the **start** node until memory is more or less exhausted. Then, we start IDA* from the **goal** node and search until we find any of the nodes discovered by the A* search that had been started from the **start** node.

```

1  aStarIdaStarSearch := procedure(start, goal, nextStates, heuristic, size) {
2      Parent      := {};
3      Distance    := { [start, 0] };
4      est         := heuristic(start, goal);
5      Estimate    := { [start, est] };
6      Frontier    := { [est, start] };
7      while (#Distance < size && Frontier != {}) {
8          [guess, state] := first(Frontier);
9          if (state == goal) {
10             return pathTo(state, Parent);
11         }
12         stateDist := Distance[state];
13         Frontier -= { [guess, state] };
14         for (neighbour in nextStates(state)) {
15             oldEstimate := Estimate[neighbour];
16             newEstimate := stateDist + 1 + heuristic(neighbour, goal);
17             if (oldEstimate == om || newEstimate < oldEstimate) {
18                 Parent[neighbour] := state;
19                 Distance[neighbour] := stateDist + 1;
20                 Estimate[neighbour] := newEstimate;
21                 Frontier += { [newEstimate, neighbour] };
22                 if (oldEstimate != om) {
23                     Frontier -= { [oldEstimate, neighbour] };
24                 }
25             }
26         }
27     }
28     [s, P] := deepeningSearch(goal, start, nextStates, heuristic, Distance);
29     return pathTo(s, Parent) + P;
30 };

```

Figure 2.23: The A*-IDA* search algorithm, part I.

An implementation of the A*-IDA* algorithm is shown in Figure 2.23 on page 31 and Figure 2.24 on page 33. We begin with a discussion of the procedure `aStarIdaStarSearch`.

1. The procedure takes 5 arguments.

- (a) **start** and **goal** are nodes. The procedure tries to find a path connecting **start** and **goal**.
 - (b) **nextStates** is a function that takes a state s as input and computes the set of states that are reachable from s in one step.
 - (c) **heuristic** computes an *estimate* of the distance between s_1 and s_2 . It is assumed that this estimate is optimistic, i.e. the value returned by **heuristic**(s_1, s_2) is less or equal than the true distance between s_1 and s_2 .
 - (d) **size** is the maximal number of states that the A* search is allowed to explore before the algorithm switches over to IDA* search.
2. The basic idea behind the A*-IDA* algorithm is to first use A* search to find a path from **start** to **goal**. If this is successfully done without visiting more than **size** nodes, the algorithm terminates and returns the path that has been found. Otherwise, the algorithm switches over to an IDA* search that starts from **goal** and tries to connect **goal** to any of the nodes that have been encountered during the A* search. To this end, the procedure **aStarIdaStarSearch** maintains the following variables.

- (a) **Parent** is a dictionary associating a parent state with those states that have already been encountered during the search, i.e. we have

$$\text{Parent}[s_2] = s_1 \Rightarrow s_2 \in \text{nextStates}(s_1).$$

Once the goal has been found, this dictionary is used to compute the path from **start** to **goal**.

- (b) **Distance** is a dictionary that remembers for every state s that is encountered during the A* search the length of the shortest path from **start** to s .
- (c) **Estimate** is a dictionary. For every state s encountered in the A* search, **Estimate**[s] is an estimate of the length that a path from **start** to **goal** would have if it would pass through the state s . This estimate is calculated using the equation

$$\text{Estimate}[s] = \text{Distance}[s] + \text{heuristic}(s, \text{goal}).$$

Instead of recalculating this sum every time we need it, we store it in the dictionary **Estimate**.

- (d) **Frontier** is a **priority queue**. The elements of **Frontier** are pairs of the form

$$[d, s] \quad \text{such that} \quad d = \text{Estimate}[s],$$

i.e. if $[d, s] \in \text{Frontier}$, then the state s has been encountered in the A* search and it is estimated that a path leading from **start** to **goal** and passing through s would have a length of d .

- 3. The A* search runs exactly as discussed previously. The only difference is that the **while** loop is terminated once the dictionary **Distance** has more than **size** entries. If we are lucky, the A* search is already able to find the **goal** and the algorithm terminates.
- 4. Otherwise, the procedure **deepeningSearch** is called. This procedure starts an iterative deepening A* search from the node **goal**. This search terminates as soon as a state is found that has already been encountered during the A* search. The set of these nodes is given to the procedure **deepeningSearch** via the parameter **Distance**. The procedure **deepeningSearch** returns a pair. The first component of this pair is the state s . This is the state in **Distance** that has been reached by the IDA* search. The second component is the path P that leads from the node s to the node **goal** but that does not include the node s . In order to compute a path from **start** to **goal**, we still have to compute a path from **start** to s . This path is then combined with the path P and the resulting path is returned.

Iterative deepening A*-IDA* is a complete search algorithm. On the instance of the 3×3 sliding puzzle shown on Figure 2.3 on page 9, this algorithm takes about 1.4 seconds to solve the puzzle. For the 4×4 sliding puzzle, if the algorithm is allowed to visit at most 3 000 states, the algorithm takes less than 9 seconds. However, there is one caveat: A*-IDA* search is not *guaranteed* to find an optimal path, although in practise it often does.

```

1  deepeningSearch := procedure(g, s, nextStates, heuristic, Distance) {
2      limit := 0;
3      while (true) {
4          Path := search(g, s, nextStates, 0, limit, heuristic, [g], Distance);
5          if (isList(Path)) {
6              return Path;
7          }
8          limit := Path;
9      }
10 };
11 search := procedure(g, s, nextStates, d, l, heuristic, Path, Dist) {
12     total := d + heuristic(g, s);
13     if (total > l) {
14         return total;
15     }
16     if (Dist[g] != om) {
17         return [g, Path[2..]];
18     }
19     smallest := mathConst("Infinity");
20     for (ns in nextStates(g) | !(ns in Path)) {
21         result := search(ns, s, nextStates, d+1, l, heuristic, [ns]+Path, Dist);
22         if (isList(result)) {
23             return result;
24         }
25         smallest := min([smallest, result]);
26     }
27     return smallest;
28 };

```

Figure 2.24: The A*-IDA* search algorithm, part II.

Exercise 4: Assume that you have 3 water buckets: The first bucket can hold 12 liters of water, the second bucket can hold 8 liters, while the last bucket can hold 3 liters. There are three types of action:

1. A bucket can be completely filled.
2. A bucket can be completely emptied.
3. The content of one bucket can be poured into another bucket. Then, there are two cases.
 - (a) If the second bucket has enough free space for all the water in the first bucket, then the first bucket is emptied and all the water from the first bucket is poured into the second bucket.
 - (b) However, if there is not enough space in the second bucket, then the second bucket is filled completely, while the water that does not fit into the second bucket remains in the first bucket.

Your goal is to measure out exactly one liter. Write a program that computes a plan to achieve this goal. ◇

Chapter 3

Constraint Satisfaction

In this chapter we discuss algorithms for solving *constraint satisfaction problems*. This chapter is structured as follows:

1. The first section defines the notion of a constraint satisfaction problem. In order to illustrate this concept, two examples of constraint satisfaction problems are presented. After that, we discuss applications of constraint satisfaction problems.
2. The simplest algorithm to solve a constraint satisfaction problem is via *brute force search*. The idea behind brute force search is to test all possible variable assignments.
3. In most cases, the number of variable assignments is too big to be enumerated completely. *Backtracking search* improves on brute force search by mixing the generation of assignments with the testing of the constraints. In most cases, this approach can drastically improve the performance of the search algorithm.
4. Backtracking search can be refined by using *constraint propagation* and by using the *most restricted variable* heuristic.
5. Finally, *local search* is a completely different approach to solve constraint satisfaction problems.

3.1 Formal Definition of Constraint Satisfaction Problems

Formally, we define a *constraint satisfaction problem* as a triple

$$\mathcal{P} := \langle \text{Vars}, \text{Values}, \text{Constraints} \rangle$$

where

1. **Vars** is a set of strings which serve as *variables*,
2. **Values** is a set of *values* for the variables in **Vars**.
3. **Constraints** is a set of formulae from *first order logic*. Each of these formulae is called a *constraint* of \mathcal{P} .

In order to be able to interpret these formulae, we need a *first order structure* $\mathcal{S} = \langle \mathcal{U}, \mathcal{J} \rangle$. Here, \mathcal{U} is the *universe* of \mathcal{S} and we will assume that this universe is identical to the set **Values**. The second component \mathcal{J} is the *interpretation* of the function symbols and predicate symbols that are used in the constraints. In what follows we assume that this interpretation is understood from the context of the constraint satisfaction problem \mathcal{P} .

In the following, the abbreviation CSP is short for *constraint satisfaction problem*. Given a CSP

$$\mathcal{P} = \langle \text{Vars}, \text{Values}, \text{Constraints} \rangle,$$

a *variable assignment* for \mathcal{P} is a function

$A : \text{Vars} \rightarrow \text{Values}$.

A variable assignment A is a *solution* of the CSP \mathcal{P} if, given the assignment A , all constraints of \mathcal{P} are satisfied. Finally, a *partial variable assignment* B for \mathcal{P} is a function

$B : \text{Vars} \rightarrow \text{Values} \cup \{\Omega\}$.

Hence, a partial variable assignment does not assign values to all variables. Instead, it assigns values only to a subset of the set Vars . The *domain* $\text{dom}(B)$ of a partial variable assignment B is the set of those variables that are assigned a value different from Ω , i.e. we define

$\text{dom}(B) := \{x \in \text{Vars} \mid B(x) \neq \Omega\}$.

We proceed to illustrate the definitions given so far with two examples.

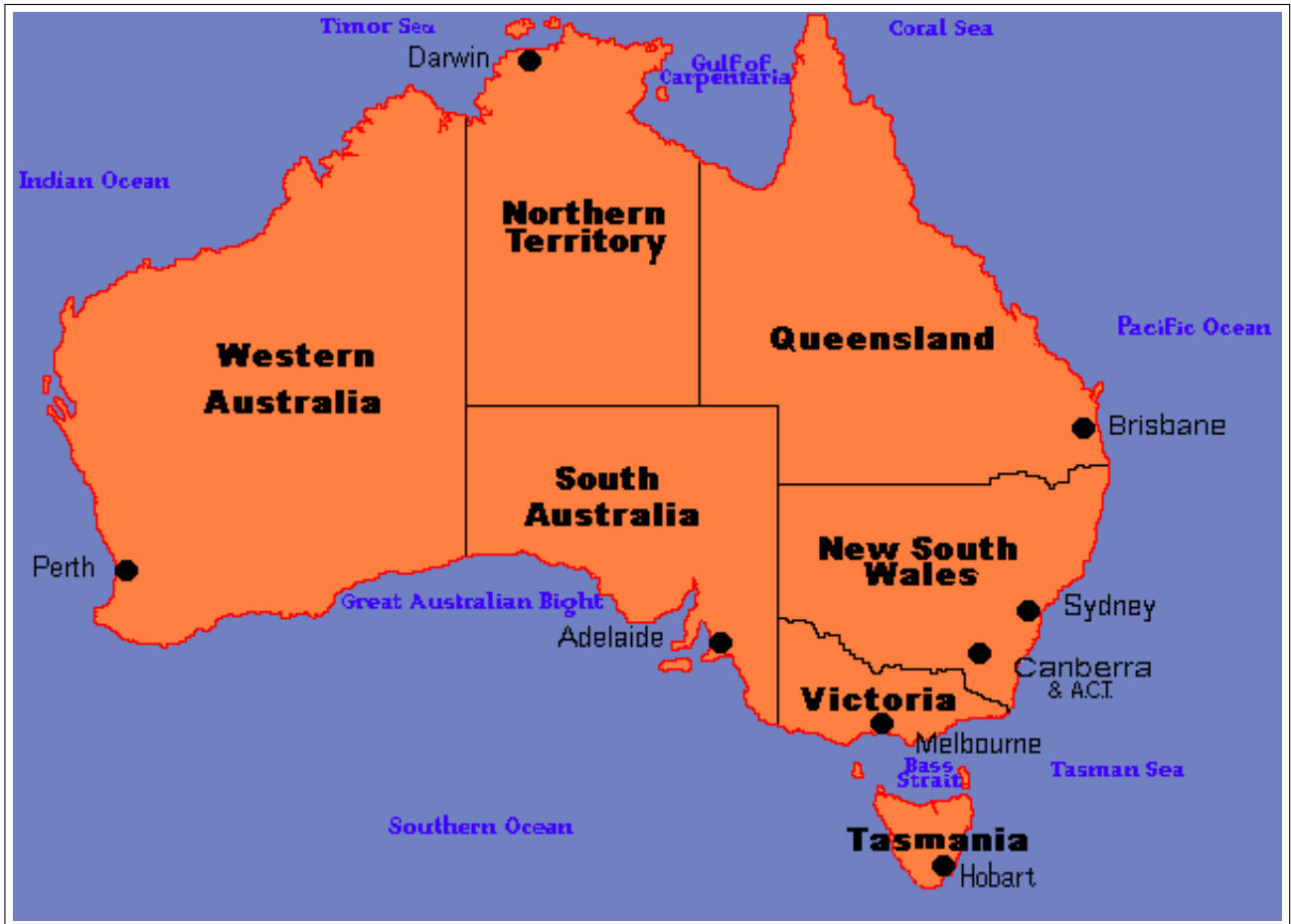


Figure 3.1: A map of Australia.

3.1.1 Example: Map Coloring

In *map colouring* a map showing different state borders is given and the task is to colour the different states such that no two states that have a common border share the same colour. Figure 3.1 on page 35 shows a map of Australia. There are seven different states in Australia:

1. Western Australia, abbreviated as WA,
2. Northern Territory, abbreviated as NT,

3. South Australia, abbreviated as SA,
4. Queensland, abbreviated as Q,
5. New South Wales, abbreviated as NSW,
6. Victoria, abbreviated as V, and
7. Tasmania, abbreviated as T.

Figure 3.1 would certainly look better if different states had been coloured with different colours. For the purpose of this example let us assume that we have only three colours available. The question then is whether it is possible to colour the different states in a way that no two neighbouring states share the same colour. This problem can be formalized as a constraint satisfaction problem. To this end we define:

1. **Vars** := {WA, NT, SA, Q, NSW, V, T},
2. **Values** := {red, green, blue},
3. **Constraints** := {WT ≠ NT, WT ≠ SA, NT ≠ SA, NT ≠ Q, SA ≠ Q, SA ≠ NSW, SA ≠ V, V ≠ T}

Then $\mathcal{P} := \langle \text{Vars}, \text{Values}, \text{Constraints} \rangle$ is a constraint satisfaction problem. If we define the assignment A such that

1. $A(\text{WA}) = \text{blue}$,
2. $A(\text{NT}) = \text{red}$,
3. $A(\text{SA}) = \text{green}$,
4. $A(\text{Q}) = \text{blue}$,
5. $A(\text{NSW}) = \text{red}$,
6. $A(\text{V}) = \text{blue}$,
7. $A(\text{T}) = \text{red}$,

then you can check that the assignment A is indeed a solution to the constraint satisfaction problem \mathcal{P} .

3.1.2 Example: The Eight Queens Puzzle

The **eight queens problem** asks to put 8 queens onto a chessboard such that no queen can attack another queen. In **chess**, a queen can attack all pieces that are either in the same row, the same column, or the same diagonal. If we want to put 8 queens on a chessboard such that no two queens can attack each other, we have to put exactly one queen in every row: If we would put more than one queen in a row, the queens in that row can attack each other. If we would leave a row empty, then, given that the other rows contain at most one queen, there would be less than 8 queens on the board. Therefore, in order to model the eight queens problem as a constraint satisfaction problem, we will use the following set of variables:

$$\text{Vars} := \{V_1, V_2, V_3, V_4, V_5, V_6, V_7, V_8\},$$

where for $i \in \{1, \dots, 8\}$ the variable V_i specifies the column of the queen that is placed in row i . As the columns run from one to eight, we define the set **Values** as

$$\text{Values} := \{1, 2, 3, 4, 5, 6, 7, 8\}.$$

Next, let us define the constraints. There are three different types of constraints.

1. We have constraints that express that no two queens positioned in different rows share the same column. To capture these constraints, we define

$$\text{SameRow} := \{V_i \neq V_j \mid i \in \{1, \dots, 8\} \wedge j \in \{1, \dots, 8\} \wedge j < i\}.$$

Here the condition $i < j$ ensures that, for example, we have the constraint $V_2 \neq V_1$ but not the constraint $V_1 \neq V_2$, as the latter would be redundant if the former is already given.

2. We have constraints that express that no two queens positioned in different rows share the same rising diagonal. To capture these constraints, we define

$$\text{SameRising} := \{i + V_i \neq j + V_j \mid i \in \{1, \dots, 8\} \wedge j \in \{1, \dots, 8\} \wedge j < i\}.$$

3. We have constraints that express that no two queens positioned in different rows share the same falling diagonal. To capture these constraints, we define

$$\text{SameFalling} := \{i - V_i \neq j - V_j \mid i \in \{1, \dots, 8\} \wedge j \in \{1, \dots, 8\} \wedge j < i\}.$$

Then, the set of constraints is defined as

$$\text{Constraints} := \text{SameRow} \cup \text{SameRising} \cup \text{SameFalling}$$

and the eight queens problem can be stated as the constraint satisfaction problem

$$\mathcal{P} := \langle \text{Vars}, \text{Values}, \text{Constraints} \rangle.$$

If we define the assignment A such that

$$A(1) := 4, A(2) := 8, A(3) := 1, A(4) := 2, A(5) := 6, A(6) := 2, A(7) := 7, A(8) := 5,$$

then it is easy to see that this assignment is a solution of the eight queens problem. This solution is shown in Figure 3.2 on page 37.

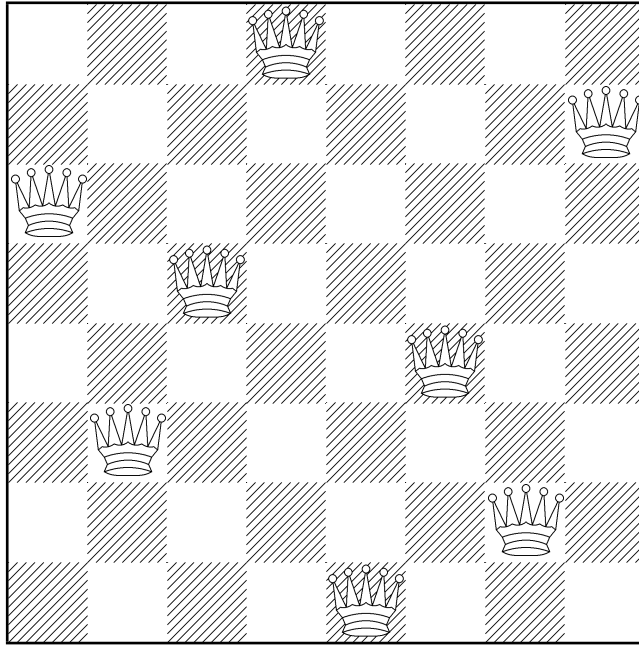


Figure 3.2: A solution of the eight queens problem.

Later, when we implement procedures to solve CSPs, we will represent variable assignments and partial variable assignments as binary relations. For example, A would then be represented as the relation

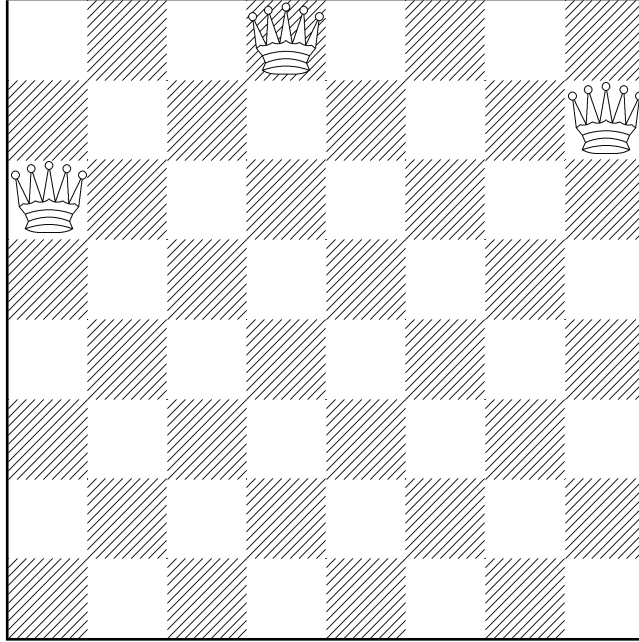
$$A = \{\langle V_1, 4 \rangle, \langle V_2, 8 \rangle, \langle V_3, 1 \rangle, \langle V_4, 2 \rangle, \langle V_5, 6 \rangle, \langle V_6, 2 \rangle, \langle V_7, 7 \rangle, \langle V_8, 5 \rangle\}.$$

If we define

$$B := \{\langle V_1, 4 \rangle, \langle V_2, 8 \rangle, \langle V_3, 1 \rangle\},$$

then B is a partial assignment and $\text{dom}(B) = \{V_1, V_2, V_3\}$. This partial assignment is shown in Figure 3.3 on page 38.

Figure 3.4 on page 38 shows a SETLX program that can be used to create the eight queens puzzle as a CSP. The code shown in this figure is more general than the eight queens puzzle: Given a natural number n ,

Figure 3.3: The partial assignment $\{\langle V_1, 4 \rangle, \langle V_2, 8 \rangle, \langle V_3, 1 \rangle\}$.

the function call `queensCSP(n)` creates a constraint satisfaction problem \mathcal{P} that generalizes the eight queens problem to the problem of putting n queens on a board of size n times n .

```

1  queensCSP := procedure(n) {
2    Variables  := { "V$i$" : i in {1..n} };
3    Values     := { 1 .. n };
4    Constraints := {};
5    for (i in [2..n], j in [1..i-1]) {
6      Constraints += { "V$i$ != V$j$" };
7      Constraints += { "$i$ + V$i$ != $j$ + V$j$" };
8      Constraints += { "$i$ - V$i$ != $j$ - V$j$" };
9    }
10   return [Variables, Values, Constraints];
11 };

```

Figure 3.4: SETLX code to create the CSP representing the eight-queens puzzle.

The beauty of **constraint programming** is the fact that we will be able to develop a so called *constraint solver* that takes as input a CSP like the one produced by the program shown in Figure 3.4 and that is then capable of computing a solution.

3.1.3 Applications

Besides the toy problems discussed so far, there are a number of industrial applications of constraint satisfaction problems. The most important application seem to be variants of **scheduling problems**. A simple example of a scheduling problem is the problem of generating a time table for a school. A school has various teachers, each of which can teach some subjects but not others. Furthermore, there are a number of classes that must be taught in different subjects. The problem is then to assign teachers to classes and to create a time table.

3.2 Brute Force Search

The most straightforward algorithm to solve a CSP is to test all possible combinations of assigning values to variables. If there are n different values that can be assigned to k variables, this amounts to checking n^k different assignments. For example, for the eight queens problem there are 8 variables and 8 possible values leading to

$$8^8 = 16,777,216$$

different assignments that need to be tested. Given the clock speed of modern computers, checking a million assignments per second is plausible. Hence, this approach would be able to solve the eight queens problem in about 15 minutes. The approach of testing all possible combinations is known as *brute force search*. An implementation is shown in Figure 3.5 on page 39.

```

1  solve := procedure(csp) {
2      [Variables, Values, Constraints] := csp;
3      return brute_force_search({}, Variables, Values, Constraints);
4  };
5  brute_force_search := procedure(Assignment, Variables, Values, Constraints) {
6      if (Variables == {}) {
7          if (check_all_constraints(Assignment, Constraints)) {
8              return Assignment;
9          }
10         return;
11     }
12     var := from(Variables);
13     for (value in Values) {
14         NewAss := Assignment + { [var, value] };
15         result := brute_force_search(NewAss, Variables, Values, Constraints);
16         if (result != om) {
17             return result;
18         }
19     }
20 };

```

Figure 3.5: Solving a CSP via brute force search.

The procedure `solve` gets a constraint satisfaction problem `csp` as its input. This `csp` is given a triple. The sole purpose of `search` is to extract the components of this triple and then calls the procedure `brute_force_search` with the corresponding arguments.

The function `brute_force_search` takes four arguments.

1. **Assignment** is a partial assignment of values to variables. Initially, this assignment will be empty. Every recursive call of `brute_force_search` adds the assignment of one variable to the given assignment.
2. **Variables** is the set of variables of the CSP that is to be solved. This set contains only those variables that have not yet been assigned a value.
3. **Values** is the set of values of this CSP.
4. **Constraints** is the corresponding set of constraints.

The implementation of `brute_force_search` works as follows:

1. If all variables have been assigned a value, the set **Variables** will be empty. Then we test whether all constraints are satisfied. This is done using the auxiliary procedure `check_all_constraints` that is shown

in Figure 3.6 on page 40. If the current **Assignment** does indeed satisfy all constraints, it is a solution and is returned.

If, instead, some constraint is not satisfied, then the procedure returns the undefined value Ω .

2. If the assignment is not yet complete, we pick a variable **var** from the set of **Variables** that still have no value assigned. Then, for every possible **value** in the set **Values**, we augment the current partial **Assignment** to the new assignment

Assignment + { [var, value] }.

Then, the algorithm recursively tries to find a solution for this new partial assignment. If this recursive call succeeds, the solution is returned. Otherwise, the next **value** is tried.

```

21  check_all_constraints := procedure(Assignment, Constraints) {
22      for (f in Constraints) {
23          Vars := collectVars(f);
24          if (!eval_constraint(Assignment, f, Vars)) {
25              return false;
26          }
27      }
28      return true;
29  };
30  eval_constraint := procedure(Assignment, Formula, Vars) {
31      for (v in Vars) {
32          execute("$v$ := $Assignment[v]$");
33      }
34      return eval(Formula);
35  };

```

Figure 3.6: Auxiliary procedures for brute force search.

The function `check_all_constraints` takes a complete variable **Assignment** as its first input. The second input is the set of **Constraints**. For all constraints **f**, it computes the set of variables **Vars** occurring in **f**. Then the constraint **f** is evaluated. If the evaluation of any of the constraints returns **false**, the function returns **false**. Otherwise, **true** is returned.

The procedure `eval_constraint` takes a partial **Assignment**, a **Formula** that is supposed to be a constraint, and the set of variables **Vars** that occur in **Formula**. Its purpose is to evaluate **Formula** using the **Assignment**. In order for this to be possible we have to assume that

$\text{var}(\text{Formula}) \subseteq \text{dom}(\text{Assignment})$,

i.e. all variables occurring in **Formula** have a value assigned in **Assignment**.

The **Formula** is evaluated by first assigning the value prescribed in **Assignment** to all variables **v** occurring in **Vars**. Once these assignments have been executed in the **for**-loop, the **Formula** can be evaluated using the procedure `eval`, which is one of the predefined procedures in SETLX.

When I tested this brute force search with the eight queens problem, it took about 510 seconds to compute a solution. In contrast, the seven queens problem only took 45 seconds. As we have

$$\frac{8^8}{7^7} \approx 20.3 \quad \frac{510}{45} \approx 11.3$$

this shows that the computation time does indeed grow with the number of possible assignments that have to be checked. However, the correspondence is not exact. The reason is that we stop our search as soon as a solution is found. If we are lucky and the given CSP is easy to solve, this might happen when we have checked only a small portion of the space of possible assignments.

3.3 Backtracking Search

One simple approach to solve a CSP is via *backtracking*. Figure 3.7 on page 41 shows a simple CSP solver that employs backtracking. We discuss this program next.

```

1  solve := procedure(csp) {
2      [Vars, Vals, Constrs] := csp;
3      csp := [Vars, Vals, { [f, collectVars(f)] : f in Constrs }];
4      check {
5          return bt_search({}, csp);
6      }
7  };
8  bt_search := procedure(Assignment, csp) {
9      [Variables, Values, Constraints] := csp;
10     if (#Assignment == #Variables) {
11         return Assignment;
12     }
13     var := select_unassigned_variable(Assignment, Variables);
14     for (value in Values) {
15         check {
16             if (is_consistent(var, value, Assignment, Constraints)) {
17                 return bt_search(Assignment + { [var, value] }, csp);
18             }
19         }
20     }
21     backtrack;
22 };

```

Figure 3.7: A backtracking CSP solver.

The procedure `solve` takes a constraint satisfaction problem `csp` as input and tries to find a solution.

1. First, the `csp` is split into its components.
2. Next, for every constraint `f` of the given `csp`, we compute the set of variables that are used in `f`. These variables are then stored together with the constraint `f` and the correspondingly modified data structure is stored in `csp` and is called an *augmented CSP*.

The reason to compute and store these variables is efficiency: When we later check whether a constraint `f` is satisfied for a partial variable assignment B , we only need to check the constraint `f` iff all of its variables are members of the domain of B .

3. Next, we call the procedure `bt_search` to compute a solution of `csp`. This procedure is enclosed in a `check`-block. Conceptually, this `check`-block is the same as if we had enclosed the call to `bt_search` in a `try-catch`-block as shown below:

```

try {
    return bt_search({}, csp);
} catch(e) {}

```

The point is that the procedure `bt_search` either returns a solution or, if it is not able to find a solution, it throws a special kind of exception, a so called *backtrack exception*. The `check`-block ensures that this exception is silently discarded. It is just a syntactical convenience that is more concise than using `try` and `catch`.

Next, we discuss the procedure `bt_search`. This procedure gets a partial assignment `Assignment` as input together with an augmented `csp`. This partial assignment is *consistent* with `csp`: If `f` is a constraint of `csp` such that all the variables occurring in `f` are members of `dom(Assignment)`, then evaluating `f` using `Assignment` yields `true`. Initially, this partial assignment is empty and hence trivially consistent. The idea is to extend this partial assignment until it is a complete assignment that satisfies all constraints of the given `csp`.

1. First, the augmented `csp` is split into its components.
2. Next, if `Assignment` is already a complete variable assignment, it is a solution of `csp` and this solution is returned. Since `Assignment` is represented as a binary relation, `Assignment` is complete if its size is the same as the size of `Variables`.
3. Otherwise, we have to extend the partial `Assignment`. In order to do so, we first have to select a variable `var` that has not yet been assigned a value. This is done using the auxiliary procedure `select_unassigned_variable` that is shown in Figure 3.8 on page 42 and will be discussed later.
4. Next, it is tried to assign a `value` to the selected variable `var`. It is checked whether this assignment would be consistent using the procedure `is_consistent`. If the partial assignment turns out to be consistent, the partial assignment is extended to the new partial assignment

`Assignment + { [var, value] }.`

Then, the procedure `bt_search` is called recursively to complete this new partial assignment. If this is successful, the resulting assignment is a solution that is returned. Otherwise, the recursive call of `bt_search` will instead raise an exception. This exception is muted by the `check`-block that surrounds the call to `bt_search`. In that case, the `for`-loop generates a new possible `value` that can be assigned to the variable `var`. If all possible values have been tried and none was successful, the `for`-loop ends and the `backtrack`-statement is executed. Effectively, this statement raises an exception that is caught by one of `check`-blocks.

```

1  select_unassigned_variable := procedure(Assignment, Variables) {
2      return rnd({ v : v in Variables | Assignment[v] == om });
3  };
4  is_consistent := procedure(var, value, Assignment, Constraints) {
5      NewAssignment := Assignment + { [var, value] };
6      for ([Formula, Vars] in Constraints | var in Vars) {
7          if (Vars <= domain(NewAssignment)) {
8              if (!eval_constraint(NewAssignment, Formula, Vars)) {
9                  return false;
10             }
11         }
12     }
13     return true;
14 };

```

Figure 3.8: Auxiliary procedures for the CSP solver shown in Figure 3.7

We still need to discuss the implementation of the auxiliary procedures shown in Figure 3.8 on page 42.

1. The procedure `select_unassigned_variable` takes a partial `Assignment` and the set of all `Variables`. It randomly selects a variable `v` such that

$$v \notin \text{dom}(\text{Assignment})$$

which is the case if `Assignment[v] = Ω` .

It is certainly possible to be more clever here. We will later show that it is beneficial to select a variable that is a *most constrained variable*, i.e. a variable such that the number of values that can be assigned to this variable while still having a consistent assignment is minimal.

2. The procedure `is_consistent` takes a variable `var`, a value, a partial `Assignment` and a set of `Constraints`. It is assumed that `Assignment` is *partially consistent* with respect to the set `Constraints`, i.e. for every formula `f` occurring in `Constraints` such that $\text{vars}(f) \subseteq \text{dom}(\text{Assignment})$ the formula `f` evaluates to `true` using `Assignment`. The purpose of `is_consistent` is to check, whether the extended assignment

$$\text{NewAssignment} := \text{Assignment} \cup \{\{\text{var}, \text{value}\}\}$$

that assigns `value` to the variable `var` is still partially consistent with `Constraints`. To this end, the `for-loop` iterates over all `Formula` in `Constraints`. However, we only have to check those `Formula` that contain the variable `var` and, furthermore, have all their variables occurring in $\text{dom}(\text{NewAssignment})$. The reasoning is as follows:

- (a) If `var` does not occur in `Formula`, then adding `var` to `Assignment` cannot change the result of evaluating `Formula` and as `Assignment` is assumed to be partially consistent with respect to `Formula`, `NewAssignment` is also partially consistent with respect to `Formula`.
- (b) If $\text{dom}(\text{NewAssignment}) \not\subseteq \text{Vars}$, then `Formula` can not be evaluated anyway.

Now if any of the `Formula` evaluates to `false`, then `NewAssignment` is not partially consistent and we can immediately return `false`. Otherwise, `true` is returned.

3.4 Constraint Propagation

Once we choose a value for a variable, this choice influences the values that are still available for other variables. For example, suppose we place the queen in row 1 in the second column, then no other queen can be placed in that column. Additionally, the queen in row 2 can then not be placed in any of the first three columns. It turns out that elaborating this idea can enhance the performance of backtracking search considerably. Figure 3.9 on page 44 shows an implementation of *constraint propagation*.

In order to implement constraint propagation, it is necessary to administer the values that can be used to instantiate the different variables separately, i.e. for every variable `v` we need to know which values are admissible for `v`. To this end, we need a dictionary that contains the set of possible values for every variable `v`. Initially, this dictionary assigns the set `Values` to every variable. These sets will shrink once we start to assign values to variables.

1. The procedure `solve` receives a `csp`. This `csp` is first split into its components.
2. The first task of `solve` is to create the dictionary `ValuesPerVar`. Given a variable `v`, this dictionary assigns the set of values that can be used to instantiate this variable. Initially, this set is the same for all variables and is equal to `Values`.
3. Next, for every constraint `f`, the dictionary `AnnotatedConstraints` attaches the variables occurring in a constraint `f` to `f`.
4. These two dictionaries are then combined with the set of `Variables` into a triple that is used as the argument to the call of `bt_search`.

The procedure `bt_search` is called with a partial `Assignment` that is guaranteed to be consistent and a `csp`. It tries to complete `Assignment` and thereby computes a solution to the `csp`.

1. First, it decomposes the `csp` into its components:
 - (a) `Values` is a dictionary assigning to every variable `v` the set of values that can be used to instantiate `v`. On recursive invocations of `bt_search` these sets will shrink.
 - (b) `Constraints` is a dictionary that assigns to every constraint `f` the set of variables occurring in `f`.

```

1  solve := procedure(csp) {
2      [Variables, Values, Constrs] := csp;
3      ValuesPerVar      := { [v, Values] : v in Variables };
4      AnnotatedConstraints := { [f, collectVars(f)] : f in Constrs };
5      csp                := [Variables, ValuesPerVar, AnnotatedConstraints];
6      check {
7          return bt_search({}, csp);
8      }
9  };
10 bt_search := procedure(Assignment, csp) {
11     [Variables, Values, Constraints] := csp;
12     if (#Assignment == #Variables) {
13         return Assignment;
14     }
15     x := most_constrained_variable(Assignment, Values);
16     for (val in Values[x]) {
17         check {
18             if (is_consistent(x, val, Assignment, Constraints)) {
19                 NewVals := propagate(x, val, Assignment, Constraints, Values);
20                 csp      := [Variables, NewVals, Constraints];
21                 return bt_search(Assignment + { [x, val] }, csp);
22             }
23         }
24     }
25     backtrack;
26 };

```

Figure 3.9:

2. If the partial `Assignment` is already complete, i.e. if it assigns a value to every variable, then a solution to the given `csp` has been found and this solution is returned.
3. Otherwise, we choose a variable `x` such that the number of values that can still be used to instantiate `x` is minimal. This variable is computed using the procedure `most_constrained_variable` that is shown in Figure 3.10 on page 45.
4. Next, all values that are still available for `x` are tried. Note that since `Values[x]` is, in general, smaller than the set of all values of the `csp`, the `for`-loop in this version of backtracking search is more efficient than the version discussed in the previous section.
5. If it is consistent to assign `val` to the variable `x`, we propagate the consequences of this assignment using the procedure `propagate` shown in Figure 3.10 on page 45. This procedure updates the values that are still allowed for the variables of the `csp` once the value `val` has been assigned to the variable `x`.
6. Finally, the partial variable `Assignment` is updated to include the assignment of `val` to `x` and the recursive call to `bt_search` tries to complete this new assignment.

Figure 3.10 on page 45 show the implementation of the procedures `most_constrained_variable` and `propagate`. The procedure `most_constrained_variable` takes a partial `Assignment` and a dictionary `Values` returning the set of allowed values for all variables as input.

1. First, this procedure computes the set of `Unassigned` variables. For every variable `x` that has not yet been assigned a value in `Assignment` this set contains the pair `[x, U]`, where `U` is the set of allowable values for the variable `x`.

```

1  most_constrained_variable := procedure(Assignment, Values) {
2      Unassigned := { [x, U] : [x, U] in Values | Assignment[x] == om };
3      minSize    := min({ #U : [x, U] in Unassigned });
4      return rnd({ x : [x, U] in Unassigned | #U == minSize });
5  };
6  propagate := procedure(x, v, Assignment, Constraints, Values) {
7      NewAssignment := Assignment + { [x, v] };
8      Values[x]      := { v };
9      for ([Formula, Vars] in Constraints | x in Vars) {
10         y := arb(Vars - { x }); // Assume binary constraints!!!
11         if (!(y in domain(NewAssignment))) {
12             NewValues := Values[y];
13             for (w in Values[y]) {
14                 A2 := NewAssignment + { [y, w] };
15                 if (!eval_constraint(A2, Formula, Vars)) {
16                     NewValues -= { w };
17                 }
18             }
19             if (NewValues == {}) { backtrack; }
20             Values[y] := NewValues;
21         }
22     }
23     return Values;
24 };

```

Figure 3.10: Constraint Propagation.

2. Next, it computes from all unassigned variables x the number of values $\#U$ that can be assigned to x . From these numbers, the minimum is computed and stored in `minSize`.
3. Finally, the set of variables that are maximally constrained is computed. These are all those variables x such that `Values[x]` has size `minSize`. From these variables, a random variable is returned.

The function `propagate` takes the following inputs:

- (a) x is a variable.
- (b) v is a value that is assigned to the variable x .
- (c) `Assignment` is a partial assignment that contains only assignments for variables that are different from x .
- (d) `Constraints` is a set of annotated constraints, i.e. this set contains pairs of the form `[Formula, Vars]`, where `Formula` is a constraint and `Vars` is the set of variables occurring in `Formula`.
- (e) `Values` is a dictionary assigning sets of values to the different variables.

The function `propagate` updates the dictionary `Values` by taking into account the consequences of assigning the value v to the variable x .

1. The partial `Assignment` is updated to `NewAssignment`, where `NewAssignment` maps x to v .
2. As x now has the value of v , the corresponding entry in the dictionary `Values` is changed accordingly.
3. Next, `propagate` iterates over all `Constraints` such that x occurs in `Formula`.

4. The implementation of `propagate` shown in Figure 3.10 on page 45 assumes that all constraints are *binary constraints*, i.e. if `Formula` is a constraint, then `Formula` contains exactly two different variables. As one of these variables is `x`, the other variable is called `y`.
5. If the variable `y` has already been assigned a value, then there is nothing to do because we already know that the assignment `NewAssignment` is consistent. This is ensured by the previous call to the function `is_consistent` in the body of the procedure `bt_search`.
However, if `y` is still unassigned, it is necessary to update `Values[y]`.
6. To this end, all values `w` in `Values[y]` are tested. If it turns out that assigning the value `w` to the variable `y` violates the constraint `Formula`, then `Values[y]` must not contain the value `w` and, accordingly, this value is removed from `Values[y]`.
7. If it turns out that `Values[y]` has been reduced to the empty set, then this means that the partial assignment `NewAssignment` can not be completed. Hence, the search has to **backtrack**.

I have tested the program described in this section using the n queens puzzle. I have found that the time needed to solve ten instances of 16 queens problem went down from 72 seconds to just 5 seconds. The procedure is even able to solve the 32 queens problem, taking about 4 seconds on average, while the version of backtracking search that does not use constraint propagation took more than 3 minutes on average.

Exercise 5: There are many different versions of the *zebra puzzle*. The version below is taken from *Wikipedia*. The puzzle reads as follows:

1. There are five houses.
2. The Englishman lives in the red house.
3. The Spaniard owns the dog.
4. Coffee is drunk in the green house.
5. The Ukrainian drinks tea.
6. The green house is immediately to the right of the ivory house.
7. The Old Gold smoker owns snails.
8. Kools are smoked in the yellow house.
9. Milk is drunk in the middle house.
10. The Norwegian lives in the first house.
11. The man who smokes Chesterfields lives in the house next to the man with the fox.
12. Kools are smoked in the house next to the house where the horse is kept.
13. The Lucky Strike smoker drinks orange juice.
14. The Japanese smokes Parliaments.
15. The Norwegian lives next to the blue house.
16. Who drinks water?
17. Who owns the zebra?

In order to solve the puzzle, we also have to know the following facts:

1. Each of the five houses is painted in a *different* color.
2. The inhabitants of the five houses are of *different* nationalities,

3. they own **different** pets,
4. they drink **different** beverages, and
5. they smoke **different** brands of cigarettes.

Formulate the zebra puzzle as a constraint satisfaction problem and solve the puzzle using the program discussed in this section. You should also try to solve the puzzle using the program given in the previous section. Compare the results. \diamond

3.5 Local Search

There is another approach to solve constraint satisfaction problems. This approach is known as **local search**. The basic idea is simple: Given a constraint satisfaction problem \mathcal{C} of the form

$$\mathcal{C} := \langle V, C, D \rangle,$$

local search works as follows:

1. Initialize the values of the variables in V randomly.
2. If all constraints are satisfied, return the solution.
3. For every variable $x \in V$, count the number of unsatisfied constraints that involve the variable x .
4. Set **maxNum** to be the biggest number of unsatisfied constraints for a single variable.
5. Compute the set **maxVars** of those variables that have **maxNum** unsatisfied constraints.
6. Randomly choose a variable x from the set **maxVars**.
7. Find a value $d \in D$ such that by assigning d to the variable x , the number of unsatisfied constraints is minimized.
If there is more than one value d with this property, choose the value d randomly from those values that minimize the number of unsatisfied constraints.
8. Goto step 2 and repeat until a solution is found.

Figure 3.11 on page 48 shows an implementation of these ideas in SETLX. Instead of solving an arbitrary constraint satisfaction problem, the program solves the n queens problem. We proceed to discuss this program line by line.

1. The procedure **solve** takes one parameter **n**, which is the size of the chess board. If the computation is successful, **solve(n)** returns a list of length **n**. Lets call this list **Queens**. For every row $r \in \{1, \dots, n\}$, the value **Queens[r]** specifies that the queen that resides in row r is positioned in column **Queens[r]**.
2. The **for** loop initializes the positions of the queens to random values from the set $\{1, \dots, n\}$. Effectively, for every row on the chess board, this puts a queen in a random column.
3. The variable **iteration** counts the number of times that we need to reassign a queen in a given row.
4. All the remaining statements are surrounded by a **while** loop that is only terminated once a solution has been found.
5. The variable **Conflicts** is a set of pairs of the form $[c, r]$, where c is the number of times the queen in row r is attacked by other queens. Hence, c is the same as the number of unsatisfied conflicts for the variable specifying the column of the queen in row r .
6. **maxNum** is the maximum of the number of conflicts for any row.

```

1  solve := procedure(n) {
2      Queens := [];
3      for (row in [1 .. n]) {
4          Queens[row] := rnd({1 .. n});
5      }
6      iteration := 0;
7      while (true) {
8          Conflicts := { [numConflicts(Queens, row), row] : row in [1 ..n] };
9          [maxNum, _] := last(Conflicts);
10         if (maxNum == 0) {
11             return Queens;
12         }
13         if (iteration % 10 != 0) { // avoid infinite loops
14             row := rnd({ row : [num, row] in Conflicts | num == maxNum });
15         } else {
16             row := rnd({ 1 .. n });
17         }
18         Conflicts := {};
19         for (col in [1 .. n]) {
20             Board := Queens;
21             Board[row] := col;
22             Conflicts += { [numConflicts(Board, row), col] };
23         }
24         [minNum, _] := first(Conflicts);
25         Queens[row] := rnd({ col : [num, col] in Conflicts | num == minNum });
26         iteration += 1;
27     }
28 };

```

Figure 3.11: Solving the n queens problem using local search.

7. If this number is 0, then all constraints are satisfied and the list `Queens` is a solution to the n queens problem.
8. Otherwise, we compute those rows that exhibit the maximal number of conflicts. From these rows we select one `row` arbitrarily.
9. The reason for enclosing the assignment to `row` in an `if` statement is explained later. On a first reading of this program, this `if` statement should be ignored.
10. Now that we have identified the `row` where the number of conflicts is biggest, we need to reassign `Queens[row]`. Of course, when reassigning this variable, we would like to have fewer conflicts after the reassignment. Hence, we test all columns to find the best column that can be assigned for the queen in the given `row`. This is done in a `for` loop that runs over all possible columns. The set `Conflicts` that is maintained in this loop is a set of pairs of the form $[k, c]$ where k is the number of times the queen in `row` would be attacked if it would be placed in column c .
11. We compute the minimum number of conflicts that is possible for the queen in `row` and assign it to `minNum`.
12. From those columns that minimize the number of violated constraints, we choose a column randomly and assign it for the specified `row`.

There is a technical issue, that must be addressed: It is possible there is just one row that exhibits the maximum number of conflicts. It is further possible that, given the placements of the other queens, there is just one optimal

column for this row. In this case, the procedure `solve` would loop forever. To avoid this case, every 10 iterations we pick a random row to change.

```

1  numConflicts := procedure(Queens, row) {
2      n      := #Queens;
3      result := 0;
4      for (r in {1 .. n} | r != row) {
5          if ( Queens[r] == Queens[row]           ||
6              r - Queens[r] == row - Queens[row] ||
7              r + Queens[r] == row + Queens[row]
8          )
9              { result += 1; }
10     }
11     return result;
12 };

```

Figure 3.12: The procedure `numConflicts`.

The procedure `numConflicts` shown in Figure 3.12 on page 49 implements the function `numConflicts`. Given a board `Queens` that specifies the positions of the queens on the board and a `row`, this function computes the number of ways that the queen in `row` is attacked by other queens. If all queens are positioned in different rows, then there are only three ways left that a queen can be attacked by another queen.

1. The queen in row `r` could be positioned in the same column as the queen in `row`.
2. The queen in row `r` could be positioned in the same falling or rising diagonal as the queen in `row`. These diagonals are specified by the linear equations given in line 6 and 7 of Figure 3.12.

Using the program discussed in this section, the n queens problem can be solved for a $n = 1000$ in 30 minutes. As the memory requirements for local search are small, even much higher problem sizes can be tackled if sufficient time is available.

Bibliography

- [1] Peter Hart, Nils Nilsson, and Bertram Raphael. A formal basis for the heuristic determination of minimum cost paths. *IEEE Transactions on Systems Science and Cybernetics SSC4*, 4(2):100–107, 1968.
- [2] Peter Hart, Nils Nilsson, and Bertram Raphael. Correction to “A formal basis for the heuristic determination of minimum cost paths”. *SIGART Newsletter*, 37:28–29, 1972.
- [3] Stuart Russell and Peter Norvig. *Artificial Intelligence: A Modern Approach*. Pearson Education Limited, 3rd edition, 2014.