Generation of DFA Minimization Problems

Gregor H. C. Sönnichsen

February 3, 2020

Contents

1 Introduction **2**
1.1 Preliminaries . . . 2
1.1.1 Deterministic Finite Automatons . . . 2
1.1.2 Minimal DFAs . . . 3
1.1.3 Isomorphy of DFAs . . . 3
1.1.4 Duplicate states . . . 4
1.1.5 The minimization algorithm . . . 4
1.2 Requirements analysis . . . 5
1.2.1 Example of a DFA minimization task for students . . . 5
1.2.2 Definition and evaluation of possible requirements . . . 6
1.3 Approach and general algorithm . . . 7

2 Building solution DFAs **9**
2.1 Using trial and error . . . 10
2.1.1 Ensuring A_{test} is minimal and $\mathcal{D}(A_{test})$ is correct . . . 10
2.1.2 Ensuring A_{test} is planar . . . 11
2.1.3 Ensuring A_{test} is unused . . . 11
2.1.4 Option 1: Generating A_{test} via Randomness . . . 12
2.1.5 Option 2: Generating A_{test} via Enumeration . . . 12
2.1.6 Ideas for more efficiency . . . 12
2.2 Alternative approach: Building $m(i)$ bottom up . . . 12

3 Extending solution DFAs to task DFAs **13**
3.1 Adding unreachable states . . . 14
3.2 Adding duplicate states . . . 14
3.2.1 Adding duplicate states does not change L . . . 15
3.2.2 Adding duplicate states does not change $\mathcal{D}$ . . . 15

4 Notes on the implementation **17**

5 Conclusion **18**

A List of Figures **19**

B Bibliography **20**

Chapter 1

Introduction

- study computer science
- theoretical informatics
- automata theory
- value of this theory
- typical topics, why typical
- why automation

This work lays out the theory for a program solving this task. As a consequence, parameters, which are sensible as user input, will be incorporated in problem definitions. In addition, when evaluating possible algorithms, we will take their usability in a practical use case into account. Furthermore additional theory will be discussed, to enhance usability.

1.1 Preliminaries

We start with defining preliminary theoretical foundations.

1.1.1 Deterministic Finite Automatons

A 5-tuple $A = (Q, \Sigma, \delta, s, F)$ with Q being a finite set of *states*, Σ a finite set of *alphabet symbols*, $\delta\colon\ Q \times \Sigma \to Q$ a *transition function*, $s \in Q$ a *start state* and $F \subseteq Q$ *final states* is called *deterministic finite automaton* (DFA) [2, p. 46]. From now on $\mathcal{A}$ shall denote the set of all DFAs.

We say $\delta(q, \sigma) = p$ is a transition from q to p using symbol σ. We define the *extended transition function* $\delta^* : Q \times \Sigma^* \to Q$ of a DFA $A = (Q, \Sigma, \delta, s, F)$ as:

- $\delta^*(q, \varepsilon) = q$
- $\delta^*(q, w\sigma) = \delta(\delta^*(q, w), \sigma)$ for all $q \in Q$, $w \in \Sigma^*$, $\sigma \in \Sigma$

Then, the *language* of that DFA is defined as $L(A) = \{\ w \mid \delta^*(w) \in F\ \}$ [2, pp. 49-50. 52].

Given a state $q \in Q$. We call all transitions $\delta(q', \sigma) = q$ *ingoing* transitions of q. All transitions $\delta(q, \sigma) = q'$ are called *outgoing* transitions of q.

We say a state q is *(un-)reachable* in an DFA A, iff there is (no) a word $w \in \Sigma^*$ such that $\delta^*(s, w) = q$. If a transition is of the form $\delta(q, \sigma) = q$, then we say that q has a *loop*.

A DFA is called *complete* iff for all states, every symbol of the alphabet is used on an outgoing transition: $\forall q \in Q \colon \forall \sigma \in \Sigma \colon \exists p \in Q \colon \delta(q, \sigma) = p$. Note, that every incomplete DFA can be converted to a complete one by adding a so called *dead state* [2, p. 67]. The resulting automaton has the same language. We will from now on only work with complete DFAs.

1.1.2 Minimal DFAs

This section closely follows [4, pp. 42-45]. We call a DFA A *minimal*, if there exists no other automaton with the same language using less states. With $\mathcal{A}_{min}$ we shall denote the set of all minimal DFAs.

The *Nerode-relation* $\equiv_L \subseteq \Sigma^* \times \Sigma^*$ of a language L with alphabet Σ is defined as follows:

$$x \equiv_L y \;\Leftrightarrow_{def}\; \forall z \in \Sigma^* \colon (xz \in L \Leftrightarrow yz \in L)$$

The Nerode-relation of a DFA A is the the Nerode-relation of its language: $\equiv_{L(A)}$. If the context makes it clear, than we will shorten the notation of a equivalence class $[x]_{\equiv_L}$ with $[x]$.

The *equivalence class automaton* $A_L = (Q_L, \Sigma_L, \delta_L, s_L, F_L)$ to a regular language L with alphabet Σ is defined as follows:

- $Q_L = \{\ [x] \mid x \in \Sigma^*\ \}$
- $\Sigma_L = \Sigma$
- $\delta_L([x], \sigma) = [x\sigma],\ \forall x \in \Sigma^*,\ \forall \sigma \in \Sigma$
- $s = [\varepsilon]$
- $F = \{\ [x] \mid x \in L\ \}$

Theorem 1. *Given a language L, then the equivalence class automaton A_L is minimal.*

1.1.3 Isomorphy of DFAs

Given two DFAs $A_1 = (Q_1, \Sigma_1, \delta_1, s_1, F_1)$ and $A_2 = (Q_2, \Sigma_2, \delta_2, s_2, F_2)$. We say A_1 and A_2 are *isomorph* ($A_1 \cong A_2$), iff:

- $\Sigma_1 = \Sigma_2$ and
- there exists a bijection $\pi \colon Q_1 \to Q_2$ such that:

  $\pi(s_1) = s_2$

  $\forall q \in Q_1 \colon (q \in F_1 \Longleftrightarrow \pi(q) \in F_2)$

  $\forall q \in Q_1 \colon \forall \sigma \in \Sigma \colon (\pi(\delta_1(q, \sigma)) = \delta_2(\pi(q), \sigma))$

Theorem 2. [4, p. 45] *Every minimal DFA is unique except for isomorphy.*

Corollary 1. *Every minimal DFA A is isomorph to its corresponding equivalence class automaton $A_{L(A)}$.*

1.1.4 Duplicate states

Definition 1 (Duplicate States)**.** [2, p. 154] Two states $q_1, q_2 \in Q$ of a DFA $A = (Q, \Sigma, \delta, s, F)$ are called *duplicates* of each other, iff $d_A(q_1, q_2)$ is true, whereas

$$q_1 \; d_A \; q_2 \;\; \Leftrightarrow_{def} \;\; \forall z \in \Sigma^*\colon \;\; (\delta^*(q_1, z) \in F \Leftrightarrow \delta^*(q_2, z) \in F)$$

Note that the relation d_A is indeed an equivalence relation.

1.1.5 The minimization algorithm

This minimization algorithm requires a complete DFA and works in four major steps, removing essentially states in such a way, that no unreachable and no duplicate states are left.

1. Compute all unreachable states via breadth-first search for example.

```
function ComputeUnreachableStates($A$)
    $U \leftarrow Q \setminus \{s\}$                                  ▷ undiscovered states
    $O \leftarrow \{s\}$                                              ▷ observed states
    $D \leftarrow \{\}$                                               ▷ discovered states
    while $|O| > 0$ do
        $N \leftarrow \{ \; p \mid \exists q \in O \; \sigma \in \Sigma\colon \; \delta(q, \sigma) = p \; \wedge \; p \notin O \cup D \; \}$
        $U \leftarrow U \setminus N$
        $D \leftarrow D \cup O$
        $O \leftarrow N$
    return $U$
```

2. Remove all unreachable states and their transitions.

```
function RemoveUnreachableStates($A, U$)
    for $q$ in $U$ do
        if $q \in F$ then
            $F \leftarrow F \; \{q\}$
        $\delta \leftarrow \delta \setminus \{ \; ((q_1, \sigma), q_2) \in \delta \mid q_1 = q \vee q_2 = q \; \}$
    return $A$
```

3. Compute all non-duplicate states ($\neg d_A(p, q)$) via the MinimizationMark-algorithm.

```
function MinimizationMark($A$)
    $M \leftarrow \{(p, q), (q, p) \mid p \in F, q \notin F\}$
    do
        $M' \leftarrow \{(p, q) \mid (p, q) \notin M \wedge \exists \sigma \in \Sigma\colon (\delta(p, \sigma), \delta(q, \sigma)) \in M\}$
        $M \leftarrow M \cup M'$
    while $M' \neq \emptyset$
```

```
7:     return $M$
```

4. Merge all duplicate state pairs, which are exactly those, that are not in $\neg d_A$.

```
function MinimizationMerge($A, \neg d_A$)
    compute $d_A$
    while $d_A \neq \emptyset$ do
        $(p, q) \in d_A$
        $d_A \leftarrow d_A \setminus \{(p, q)\}$
        if $p \neq q$ then
            exchange all occurrences of $q$ in $A$ and $d_A$ by $p$
    return $A$
```

Theorem 3. *The minimization algorithm computes a minimal DFA to its input DFA.*

The definition of this DFA minimization algorithm is inspired by Schöning [4, p. 46].

When looking at MinimizationMark, one notes, that it computes distinct subsets of $Q \times Q$ on the way. Indeed, one could write the algorithm in such a way, that these subsets are explicitly computed in form of a function $m\colon \mathbb{N} \to \mathcal{P}(Q \times Q)$:

```
function $m$-MinimizationMark($(Q, \Sigma, \delta, s, F)$)
    $i \leftarrow 0$
    $m(0) \leftarrow \{(p, q), (q, p) \mid p \in F, q \notin F\}$
    do
        $i \leftarrow i + 1$
        $m(i) \leftarrow \{(p, q) \mid (p, q) \notin \bigcup m(\cdot) \wedge \exists \sigma \in \Sigma\colon (\delta(p, \sigma), \delta(q, \sigma)) \in m(i-1)\}$
    while $m(i) \neq \emptyset$
    return $\bigcup m(\cdot)$
```

Using this redefinition, we can easier refer to the state pairs marked in a certain iteration. We will use both variants in exchange.

We will denote the number of iterations done by MinimizationMark on an DFA A as $\mathcal{D}(A)$. Note that $\mathcal{D}(A) = \max n \in \mathbb{N} \mid m(n) \neq \emptyset$.

1.2 Requirements analysis

1.2.1 Example of a DFA minimization task for students

- present a typical task and its solution (text, image, table)
- name its elements
- clarify two parts: solution, task
- clarify four parts from task to solution: find unreachables, delete them, find duplicates, merge them
- what are the difficulties of this tasks?

We will call the minimal automaton *solution DFA* (A_{sol}) and its extension with duplicate and unreachable states *task DFA* (A_{task}).

heuristic:

- $h \colon \mathcal{A} \times \mathcal{A} \to \mathbb{R}^+$
- $h(A_{min}, A_{task}) = studentfriendliness$

1.2.2 Definition and evaluation of possible requirements

Dismissed:

- $h(A_{sol}, A_{task}) = |Q_{task}| \ / \ |Q_{sol}|$
- number of transitions
- max degree of a node (Why not this?)
- Does GraphViz have a heuristic?

Accepted solution DFA criteria:

-> minimal

-> number of states

-> number of MinimizationMark iterations ($\mathcal{D}(A_{sol})$)

-> alphabet size

-> number of accepting states

-> planarity (can be checked in $O(|Q_{sol}|)$)

-> A_{sol} is unused (regarding all previously generated solution DFAs)

Definition 2 (Unused DFAs)**.** A DFA A is *unused* regarding a set of *used DFAs* U, if A is not isomorph to any DFA in U.

Accepted task DFA criteria:

-> $L(A_{sol}) = L(A_{task})$

-> $\mathcal{D}(A_{sol}) = \mathcal{D}(A_{task})$

-> number of duplicate states

-> number of unreachable states

-> alphabet size

-> planarity (can be checked in $O(|Q_{task}|)$)

-> completeness (for MinimizationMark-algorithm to work)

1.3 Approach and general algorithm

In this work we will first build the solution DFA (step 1), and - based on that - the task DFA by adding duplicate and unreachable states (step 2). Both steps will fulfill all criteria chosen above and are covered in depth in chapter 2 respectively chapter 3.

It follows that $\mathcal{D}$ and L of both DFAs will be set when building A_{sol}. As a consequence we need to ensure that adding duplicate and unreachable state does neither change $\mathcal{D}(A_{task})$ nor $L(A_{task})$ in comparison to A_{sol}. We will do this during the discussion of step 2.

Here follow problem definitions for the two steps, which specify all needed informations. **Gregor:** Hidden formulation here

Definition 3 (BuildNewMinimalDFA)**.**

Given:

$q, a, f, m_{min}, m_{max} \in \mathbb{N}$,

$p \in \{0, 1\}$

Request:

Let $A_{sol} = (Q, \Sigma, \delta, s, F)$ be a DFA, such that

$|Q| = q$, $|\Sigma| = a$, $|F| = f$,

$m_{min} \leq \mathcal{D}(A_{sol}) \leq m_{max}$,

A_{sol} is planar iff $p = 1$ and

the language of $L(A)$ is unequal to any DFA used before.

Return A_{sol}, if it exists, $\perp$ otherwise.

Definition 4 (ExtendMinimalDFA)**.**

Given:

$A_{sol} = (Q, \Sigma, \delta, s, F) \in \mathcal{A}_{min}$,

$p \in \{0, 1\}$,

$d, u \in \mathbb{N}$

Request:

A DFA $A_{task} = (Q', \Sigma', \delta', s', F')$ with reachable duplicate states $q_1 \dots q_d$ and unreachable states $p_1 \dots p_u$, such that

$Q = Q' \cup \{q_1, \dots q_d, p_1 \dots p_u\}$,

$\Sigma = \Sigma'$, $s = s'$,

$F \subseteq F'$,

A_{task} is planar iff $p = 1$,

$L(A_{sol}) = L(A_{task})$ and $\mathcal{D}(A_{sol}) = \mathcal{D}(A_{task})$.

The main algorithm will then simply be:

```
1: function GenerateDFAMinimizationProblem($q, a, f, m_{min}, m_{max}, p_1, p_2, d, u$)
```

```
2:  $A_{sol} \leftarrow \textsc{BuildNewMinimalDFA}(q, a, f, m_{min}, m_{max}, p_1)$
3:  $A_{task} \leftarrow \textsc{ExtendMinimalDFA}(A_{sol}, p_2, d, u)$
4:  **return** $A_{sol}, A_{task}$
```

Chapter 2

Building solution DFAs

Gregor: argue that and why we make A sol complete

We want an algorithm for DFA generation that fulfills the following conditions:

-> minimal

-> number of states

-> number of MinimizationMark iterations ($\mathcal{D}(A_{sol})$)

-> alphabet size

-> number of accepting states

-> planarity (can be checked in $O(|Q_{sol}|)$)

-> A_{sol} is unused (regarding all previously generated solution DFAs)

Definition 5 (BuildNewMinimalDFA)**.**

Given:

$q, a, f, m_{min}, m_{max} \in \mathbb{N}$,

$p \in \{0, 1\}$

Request:

Let $A_{sol} = (Q, \Sigma, \delta, s, F)$ be a DFA, such that

$|Q| = q$, $|\Sigma| = a$, $|F| = f$,

$m_{min} \leq \mathcal{D}(A_{sol}) \leq m_{max}$,

A_{sol} is planar iff $p = 1$ and

the language of $L(A)$ is unequal to any DFA used before.

Return A_{sol}, if it exists, $\perp$ otherwise.

2.1 Using trial and error

We will develop an algorithm that makes partly use of the trial-and-error paradigm to find matching DFAs. The approach here is as follows:

Firstly a *test* DFA A_{test} is generated by use of either randomness or enumeration. Alphabet size and number of (final) states will already be correct. On this DFA then tests will be executed, to check if it is minimal, planar (if wished) and unused. If this is the case, A_{test} will be returned, if not, new test DFAs are generated until all tests pass.

By constructing test DFAs with already correct alphabet size and number of (final) states we are able to subdivide the search space of DFAs in advance into much smaller pieces.

Gregor: How much smaller?

```
1: function BuildNewMinimalDFA (
       $q, a, f, m_{min}, m_{max} \in \mathbb{N}$,
       $p \in \{0, 1\}$
       )
2:     while True do
3:         generate DFA $A_{test}$ with $|Q|, |\Sigma|, |F|$ matching $q, a, f$
4:         if $A_{test}$ not minimal or not $m_{min} \leq \mathcal{D}(A_{test}) \leq m_{max}$ then
5:             continue
6:         if $p = 1$ and $A_{test}$ is not planar then
7:             continue
8:         if $A_{test}$ was used before then
9:             continue
10:        return $A_{test}$
```

We will complete this algorithm by resolving how the tests in lines 4, 6 and 8 work and by showing two methods for generation of test automatons.

2.1.1 Ensuring A_{test} is minimal and $\mathcal{D}(A_{test})$ is correct

In order to test, whether A_{test} is minimal, we could simply use the minimization algorithm and compare the resulting DFA and A_{test} using an isomorphy test. However it is sufficient to ensure, that no duplicate or unreachable states exist.

To get $\mathcal{D}(A_{test})$, we have to run MinimizationMark entirely anyway. Hence we can combine the test for duplicate states with computing the DFAs $\mathcal{D}$-value:

```
1: function HasDuplicateStates($A$)
2:     $depth \leftarrow 0$
3:     $M \leftarrow \{(p, q), (q, p) \mid p \in F, q \notin F\}$
4:     do
5:         $depth \leftarrow depth + 1$
6:         $M' \leftarrow \{(p, q) \mid (p, q) \notin M \wedge \exists \sigma \in \Sigma\colon (\delta(p, \sigma), \delta(q, \sigma)) \in M\}$
7:         $M \leftarrow M \cup M'$
8:     while $M' \neq \emptyset$
9:     $hasDupl \leftarrow |\{(p, q) \mid p \neq q \wedge (p, q) \notin M\}| > 0$
10:    return $hasDupl, depth$
```

Since MinimizationMark computes all non-duplicate state pairs $\neg d_A$, we test in line 9, whether there is a pair of distinct states not in $\neg d_A$.

Regarding the unreachable states, we can just use ComputeUnreachableStates and test whether the computed set is empty:

```
1: function HasUnreachableStates($A$)
2:     return |ComputeUnreachableStates($A$)| $> 0$
```

Gregor: Is there a more efficient method? Since we actually need to know of only one unreachable state.

2.1.2 Ensuring A_{test} is planar

There exist several algorithms for planarity testing of graphs. In this work, the library *pygraph*[1] has been used, which implements the Hopcroft-Tarjan planarity algorithm. More information on this can be found for example in this [3] introduction from William Kocay. The original paper describing the algorithm is [1].

2.1.3 Ensuring A_{test} is unused

In our requirements we stated, that we wanted the generated solution DFA to be unused with regards to all previous generated solution DFAs. This implies the need of a database, that allows saving single DFAs and loading DFAs. We name this database *DB1*. Assuming the database is relational, the following scheme is proposed:

$$|Q_A| \quad |\Sigma_A| \quad |F_A| \quad \mathcal{D}(A) \quad \mathit{isPlanar}(A) \quad \mathit{encode}(A)$$

With this scheme we can fetch once all DFAs matching the search parameters. Thus we need not fetch all used DFAs every time, but only those that are relevant. Afterwards we must only check whether any isomorphy test on the current test DFA and one of the fetched DFAs is positive. If any test DFA passes all tests and is going to be returned, then we have to save that DFA in the database.

A more concrete specification of this proceeding is shown below, embedded in the main algorithm:

```
1: function BuildNewMinimalDFA ($q, a, f, m_{min}, m_{max}, p$)
2:     $l \leftarrow$ all DFAs in DB1 matching $q, a, f, m_{min}, m_{max}, p$
3:     while True do
4:         ...
5:         for $A$ in $l$ do
6:             if $A_{test}$ is isomorph to $A$ then
7:                 continue
8:         save $A_{test}$ and its respective properties in DB1
9:         return $A_{test}$
```

[1]`https://github.com/jciskey/pygraph`

2.1.4 Option 1: Generating A_{test} via Randomness

2.1.5 Option 2: Generating A_{test} via Enumeration

DB2 - Enumeration Progress |Q| |Σ| f t finished
f and t are the encoded final states respectively transitions enumeration progresses for the given |Q| and |Σ| (and f in case of t). With this table the enumeration room is split into smaller pieces.

The enumeration algorithm

```
function BuildNewMinimalDFA ($q, a, f, m_{min}, m_{max}, p$)
    $l \leftarrow$ load based on all parameters
    $e \leftarrow$ load enumeration progress for $q, a, f, p$
    while True do
        if $e$ is finished then
            save $e$
            return $\perp$
        $A_L \leftarrow$ next DFA based on $e$
        if $A_L$ not minimal then
            continue
        if $p = 1$ and $A_L$ is not planar then
            continue
        if $A_L$ isomorph to any DFA in $l$ matching with $q, a, f, m_{min}, m_{max}, p$ then
            continue
        save $e$
        save $l \cup A_L$
        return $A_L$
```

2.1.6 Ideas for more efficiency

incrementing final state binary faster in enum-alternative
speed up isomorphy test
rewrite everything in C
solve P vs NP

2.2 Alternative approach: Building $m(i)$ bottom up

Build m from m-MinimizationMark iteratively. (Why would this basically result in running MinimizationMark all the time?)

Chapter 3

Extending solution DFAs to task DFAs

We have the following requirements for this stage:

-> $L(A_{sol}) = L(A_{task})$

-> $\mathcal{D}(A_{sol}) = \mathcal{D}(A_{task})$

-> number of duplicate states

-> number of unreachable states

-> alphabet size

-> planarity (can be checked in $O(|Q_{task}|)$)

-> completeness (for MinimizationMark-algorithm to work)

In order to fulfill these requirements when adding new elements to a given minimal automaton A_{sol}, we can simply look at the kind of elements removed by the minimization algorithm. We will show for each class of addable elements, that they do not change the DFAs language and its $\mathcal{D}$-value.

What kind of elements are removed from a DFA, if the minimization algorithm is applied to it?

1. unreachable states

2. duplicate states

As requirement for the new DFAs we have completeness, so whenever we add a new state, we have to ensure it has a transition for every alphabet symbol in the end. Furthermore, since unreachable states are removed first in the minimization algorithm, we may assume that every state, that is duplicated, is reachable.

Gregor: Adding unreachable states is essentially just talking about that special equivalence class. Think and tell more about this

3.1 Adding unreachable states

From step 1 of the minimization algorithm we can deduce option 1. Unreachable states can easily be added to a DFA by just adding non-start states with no ingoing transitions (see definition of unreachability). Number and nature of outgoing transitions may be arbitrary.

Lemma 1. *Adding unreachable states to a DFA does not change its language.*

Proof. The language of a DFA $A = (Q, \Sigma, \delta, s, F)$ is defined as $L(A) = \{\ w \mid w \in \Sigma^* \wedge \delta^*(s, w) \in F\ \}$. For any unreachable state q there exists no word $v \in \Sigma^*$ such that $\delta^*(s, v) = q$. Thus such a state cannot be the cause for any word to be in $L(A)$. □

Lemma 2. *Adding unreachable states to a DFA does not change its $\mathcal{D}$-value in the context of the minimization algorithm.*

Proof. Since unreachable states are eliminated from the input DFA in the first place, when applying the minimization algorithm to it, we get the same DFA for the MinimizationMark-algorithm, as if we had not added any unreachable states. □

3.2 Adding duplicate states

Gregor: hidden definition: correct duplication

Step 2 and 3 of the minimization algorithm are concerned with detection and elimination of duplicate states. How do we add duplicate states to a DFA?

Consider the properties a duplicate state, say q_d, must have. It is in particular duplicate to *another* state, we call it q_o. Since we add only one state for now, q_d, we can assume that q_o is part of the solution DFA. We call the new, by q_d extended DFA, A.

Outgoing transitions We know that q_d, q_o are duplicates, iff $\forall \sigma \in \Sigma$: $[\delta(q_d, \sigma)]_{d_A} = [\delta(q_o, \sigma)]_{d_A}$. Thus, when adding some q_d, we have to choose for each symbol $\sigma \in \Sigma$ at least one transition from the following set:

$$P_\sigma = \{\ ((q_d, \sigma), p) \mid p \in [\delta(q_o, \sigma)]_{d_A}\ \}$$

Since the solution DFA is complete, we know that every $P_\sigma \neq \emptyset$.

Gregor: Why does this not affect the eq. class of any other state?

Ingoing transitions The ingoing transitions of q_d are not directly restricted through the duplicateness of q_d and q_o.

First of all, we know, that q_o is reachable. We then need to give q_d at least one ingoing transition. Doing this, we have to ensure, that any state s, that gets such an outgoing transition to q_d remains in its solution equivalence class.

Thus a fitting state s has to have a transition to some state in $[q_d]_{d_A} = [q_o]_{d_A}$ already. So, given a state s with $((s, \sigma), t)$ and $t \in [q_o]_{d_A}$, we can add $((s, \sigma), q_d)$.

But this would make our new DFA a NFA. As a consequence we have to remove the original transition $((s, \sigma), t)$ each time we add an ingoing transition for a newly created duplicate state.

So we have to choose at least one transition of

$$\{ \ ((s,\sigma), q_d) \mid \delta(s,\sigma) \in [q_o]_{d_A} \ \}$$

If a $((s,\sigma), q_d)$ is chosen, remove $((s,\sigma), t)$. This leads us to the requirement, that any q_o has to have at least 2 ingoing transitions.

Gregor: Talk somewhere about eq. automaton and extending it. An eq. class of reach. q's can be max. $|\Sigma|$ big. From this can compute the max. number of dupl. states which can be added.

3.2.1 Adding duplicate states does not change L

p. 159 Hopcroft

3.2.2 Adding duplicate states does not change $\mathcal{D}$

Lemma 3.

$$\begin{aligned} \mathcal{D}(A) = \ & n \Rightarrow \\ & n = \max_{n \in \mathbb{N}} \ \exists p, q \in Q \ \ \exists w \in \Sigma^* : \\ & \qquad |w| = n - 1 \wedge (\delta^*(p,w) \in F \Leftrightarrow \delta^*(q,w) \notin F) \end{aligned}$$

Proof. Via direct proof.

Assume m-MinimizationMark(A) has done n iterations (so $\mathcal{D}(A) = n$). We then know, that

- $\forall i \in [0, n-1] \colon m(i) \neq \emptyset$
- $m(n) = \emptyset$

m-MinimizationMark(A) terminates iff $m(i) = \emptyset$. If the first point would not hold, then the algorithm would have stopped before.

Since the algorithm did n iterations, the internal variable i must be n at the end of the last iteration. The terminating condition is $m(i) \neq \emptyset$; thus follows the second point.

Lemma 4.

$$\begin{aligned} (p,q) \in m(k) \Longleftrightarrow \exists w \in \Sigma^* \colon |w| = n - 1 \ \wedge & \\ & (\delta^*(p,w) \in F \Leftrightarrow \delta^*(q,w) \notin F) \end{aligned}$$

Following this lemma (which can easily be proved by induction) we know that there exists at least one word $w \in \Sigma^*$ with $|w| = n - 1$ such that for two $p, q \in Q \colon (\delta^*(p,w) \in F \wedge \delta^*(q,w) \notin F)$.

There cannot be any two states $p', q' \in Q$ and a word $w' \in \Sigma^*$ with $|w'| \geq n-1$ fulfilling this property. We could write w' as $u'v'$ with $|v'| = n$. Then (p,q) should be in $m(n)$, which is contradictory.

□

Theorem 4. *Adding duplicate states to an automaton A does not increase the number of iterations in the* MinimizationMark*-algorithm for A.*

Proof. Proof per contradiction.

Let's assume adding a duplicate state q_d to a given automaton $A = (Q, \Sigma, \delta, s, F)$ results in an automaton $A' = (Q', \Sigma, \delta', s, F')$ whereas $\mathcal{D}(A) < \mathcal{D}(A')$.

Concerning A' we can say the following:

- $Q' = Q \cup \{q_d\}$
- $\exists q_o \in Q\colon\ d'_A(q_o, q_d)$

Let us furthermore say that $\mathcal{D}(A) = i$ and $\mathcal{D}(A') = j$.

Lemma 5.

$$\begin{aligned} \mathcal{D}(A) = \ & n \Rightarrow \\ & n = \max_{n \in \mathbb{N}} \ \exists p, q \in Q \ \ \exists w \in \Sigma^*\colon \\ & \qquad |w| = n - 1 \wedge (\delta^*(p, w) \in F \Leftrightarrow \delta^*(q, w) \notin F) \end{aligned}$$

According to this lemma there must be a pair $s, t \in Q'$ to which exists a word $w \in \Sigma'^*$, $|w| = j - 1$, such that $\delta'^*(s, w) \in F' \Leftrightarrow \delta'^*(t, w) \notin F'$.

Let us split w as $w = uv$, whereas $u, v \in \Sigma'^*$ and $|v| = i$, which is exactly one symbol longer than the longest minimization word of A. We can formulate the following statement:

$$\text{There must exist } p, q \in Q' \text{ such that } \delta'^*(p, v) \in F' \Leftrightarrow \delta'^*(q, v) \notin F'. \tag{3.1}$$

Gregor: hidden formulations here

We can therefore state, that $\neg(p \in Q \wedge q \in Q)$, because else $\mathcal{D}(A)$ would be higher than i too.

Since q_d is the only new state in A' compared to A, we can conclude that at least one of both states must be q_d. Since $p = q_d = q$ is contradictory (**Gregor:** why?), we can conclude that exactly one of both states p, q is q_d and that the other one is not.

W.l.o.g. we say $q = q_d$ and $p \in Q' \setminus \{q_d\} = Q$ and reformulate our statement above:

$$\text{There must exist a } p \in Q \text{ such that } \delta'^*(p, v) \in F' \Leftrightarrow \delta'^*(q_d, v) \notin F'. \tag{3.2}$$

Gregor: hidden formulations here

Since for $q_o \in Q$ the relation $d_{A'}(q_o, q_d)$ is given, we know per definition of $d_{A'}$ that $\forall z \in \Sigma'^*\colon \delta'^*(q_o, z) \in F \Leftrightarrow \delta'^*(q_d, z) \in F$.

This implies in combination with statement 2.2, that for p, q_o the word $v \in \Sigma'^*$ would fulfill $\delta'^*(p, v) \in F' \Leftrightarrow \delta'^*(q_o, v) \notin F'$ too. But this is contradictory to $p, q \notin Q$.

Gregor: hidden lemma here

$\square$

Gregor: hidden old 'systematic study of how to extend minimal DFAs'

Chapter 4

Notes on the implementation

Chapter 5

Conclusion

What happens, if we change start and accepting states?
What happens, if we add transitions only?

dfa specific planarity test?
use planarity test information for better drawing?

Appendix A

List of Figures

Appendix B

Bibliography

Bibliography

[1] John Hopcroft and Robert Tarjan. Efficient planarity testing. *J. ACM*, 21(4):549–568, October 1974.

[2] John E. Hopcroft, Rajeev Motwani, and Jeffrey D. Ullman. *Introduction to automata theory, languages, and computation - (2. ed.).* Addison-Wesley series in computer science. Addison-Wesley-Longman, 2001.

[3] William Kocay. The hopcroft-tarjan planarity algorithm. October 1993.

[4] Uwe Schöning. *Theoretische Informatik - kurzgefasst.* Spektrum, Akad. Verl, Heidelberg Berlin, 2001.