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Preface

This document contains solutions to the exercises of the course notes *Automata and Computability*. These notes were written for the course CS345 *Automata Theory and Formal Languages* taught at Clarkson University. The course is also listed as MA345 and CS541. The solutions are organized according to the same chapters and sections as the notes.

Here's some advice. Whether you are studying these notes as a student in a course or in self-directed study, your goal should be to understand the material well enough that you can do the exercises on your own. Simply studying the solutions is not the best way to achieve this. It is much better to spend a reasonable amount of time and effort trying to do the exercises yourself before looking at the solutions.

If you can’t do an exercise on your own, you should study the notes some more. If that doesn’t work, seek help from another student or from your instructor. Look at the solutions only to check your answer once you think you know how to do an exercise.

If you needed help doing an exercise, try redoing the same exercise later on your own. And do additional exercises.

If your solution to an exercise is different from the solution in this document, take the time to figure out why. Did you make a mistake? Did you forget some-
thing? Did you discover another correct solution? If you’re not sure, ask for help from another student or the instructor. If your solution turns out to be incorrect, fix it, after maybe getting some help, then try redoing the same exercise later on your own and do additional exercises.

Feedback on the notes and solutions is welcome. Please send comments to alexis@clarkson.edu.
Chapter 1

Introduction

There are no exercises in this chapter.
Chapter 2

Finite Automata

2.1 Turing Machines

There are no exercises in this section.

2.2 Introduction to Finite Automata

2.2.3.

Missing edges go to a garbage state. In other words, the full DFA looks like this:
The transition label *other* means any character that's not a dash or a digit.

Missing edges go to a garbage state.
2.2.5.
CHAPTER 2. FINITE AUTOMATA

2.2.6.
2.2.7.

    starting_state() { return q0 }

    is_accepting(q) { return true iff q is q1 }

    next_state(q, c) {
        if (q is q0)
            if (c is underscore or letter)
                return q1
            else
                return q2
        else if (q is q1)
            if (c is underscore, letter or digit)
                return q1
            else
                return q2
        else // q is q2
            return q2
    }

2.2.8. The following assumes that the garbage state is labeled $q_9$. In the pseudocode algorithm, states are stored as integers. This is more convenient here.

    starting_state() { return 0 }

    is_accepting(q) { return true iff q is 8 }
next_state(q, c) {
    if (q in {0, 1, 2} or {4, 5, 6, 7})
        if (c is digit)
            return q + 1
        else
            return 9
    else if (q is 3)
        if (c is digit)
            return 5
        else if (c is dash)
            return 4
        else
            return 9
    else if (q is 8 or 9)
        return 9
}
2.3. More Examples

2.3.5.

2.3.6. In all cases, missing edges go to a garbage state.

a) 

b)
2.3.7. 

a) 

b) 

c)
2.3. MORE EXAMPLES

2.3.8. In all cases, missing edges go to a garbage state.
b) The idea is for the DFA to remember the last two symbols it has seen.

c) Again, the idea is for the DFA to remember the last two symbols it has seen. We could simply change the accepting states of the previous DFA to \( \{q_{10}, q_{11}\} \). But we can also simplify this DFA by assuming that strings of length less than two are preceded by 00.
2.4. Formal Definition

2.4.5. a) The DFA is \((\{q_0, q_1, q_2, \ldots, q_9\}, \Sigma, \delta, q_0, \{q_8\})\) where \(\Sigma\) is the set of all characters that appear on a standard keyboard and \(\delta\) is defined as follows:

\[
\delta(q_i, c) = \begin{cases} 
q_{i+1} & \text{if } i \notin \{3, 8, 9\} \text{ and } c \text{ is digit} \\
q_9 & \text{if } i \notin \{3, 8, 9\} \text{ and } c \text{ is not digit}
\end{cases}
\]

\[
\delta(q_3, c) = \begin{cases} 
q_4 & \text{if } c \text{ is dash} \\
q_5 & \text{if } c \text{ is digit} \\
q_9 & \text{otherwise}
\end{cases}
\]

\[
\delta(q_8, c) = q_9 \quad \text{for every } c
\]

\[
\delta(q_9, c) = q_9 \quad \text{for every } c
\]
b) The DFA is \((\{q_0, q_1, q_2, q_3\}, \Sigma, \delta, q_0, \{q_2\})\) where \(\Sigma\) is the set of all characters that appear on a standard keyboard and \(\delta\) is defined as follows:

\[
\delta(q_0, c) = \begin{cases} 
q_1 & \text{if } c \text{ is dash} \\
q_2 & \text{if } c \text{ is digit} \\
q_3 & \text{otherwise}
\end{cases}
\]

\[
\delta(q_i, c) = \begin{cases} 
q_2 & \text{if } i \in \{1, 2\} \text{ and } c \text{ is digit} \\
q_3 & \text{if } i \in \{1, 2\} \text{ and } c \text{ is not digit}
\end{cases}
\]

\[
\delta(q_3, c) = q_3 \text{ for every } c
\]

c) The DFA is \((\{q_0, q_1, q_2, \ldots, q_5\}, \Sigma, \delta, q_0, \{q_2, q_4\})\) where \(\Sigma\) is the set of all characters that appear on a standard keyboard and \(\delta\) is defined as follows:

\[
\delta(q_0, c) = \begin{cases} 
q_1 & \text{if } c \text{ is dash} \\
q_2 & \text{if } c \text{ is digit} \\
q_3 & \text{if } c \text{ is decimal point} \\
q_5 & \text{otherwise}
\end{cases}
\]

\[
\delta(q_i, c) = \begin{cases} 
q_2 & \text{if } i \in \{1, 2\} \text{ and } c \text{ is digit} \\
q_3 & \text{if } i \in \{1, 2\} \text{ and } c \text{ is decimal point} \\
q_5 & \text{if } i \in \{1, 2\} \text{ and } c \text{ is not digit or decimal point}
\end{cases}
\]

\[
\delta(q_i, c) = \begin{cases} 
q_4 & \text{if } i \in \{3, 4\} \text{ and } c \text{ is digit} \\
q_5 & \text{if } i \in \{3, 4\} \text{ and } c \text{ is not digit}
\end{cases}
\]

\[
\delta(q_5, c) = q_5 \text{ for every } c
\]
2.4. FORMAL DEFINITION

2.4.6. The idea is for the DFA to remember the last $k$ symbols it has seen. But this is too difficult to draw clearly, so here’s a formal description of the DFA: $(Q, \{0, 1\}, \delta, q_0, F)$ where

\[
Q = \{q_w \mid w \in \{0, 1\}^* \text{ and } w \text{ has length } k\}
\]

\[
q_0 = q_{w_0} \quad \text{where } w_0 = 0^k \quad \text{(that is, a string of } k \text{ 0’s)}
\]

\[
F = \{q_w \in Q \mid w \text{ starts with a } 1\}
\]

and $\delta$ is defined as follows:

\[
\delta(q_{au}, b) = q_{ub}
\]

where $a \in \Sigma$, $u$ is a string of length $k - 1$ and $b \in \Sigma$.

2.4.7.

a) The idea is for the DFA to store the value, modulo 3, of the portion of the number it has seen so far, and then update that value for every additional digit that is read. To update the value, the current value is multiplied by 10, the new digit is added and the result is reduced modulo 3.
(Note that this is exactly the same DFA we designed in an example of this section for the language of strings that have the property that the sum of their digits is a multiple of 3. This is because $10 \mod 3 = 1$ so that when we multiply the current value by 10 and reduce modulo 3, we are really just multiplying by 1. Which implies that the strategy we described above is equivalent to simply adding the digits of the number, modulo 3.)

b) We use the same strategy that was described in the first part, but this time, we reduce modulo $k$. Here’s a formal description of the DFA: $(Q, \Sigma, \delta, q_0, F)$ where

\[
Q = \{q_0, q_1, q_2, \ldots, q_{k-1}\}
\]
\[
\Sigma = \{0, 1, 2, \ldots, 9\}
\]
\[
F = \{q_0\}
\]

and $\delta$ is defined as follows: for every $i \in Q$ and $c \in \Sigma$,

$$\delta(q_i, c) = q_j \quad \text{where} \quad j = (i \cdot 10 + c) \mod k.$$
2.4. FORMAL DEFINITION

2.4.8.

a) The idea is for the DFA to verify, for each input symbol, that the third digit is the sum of the first two plus any carry that was previously generated, as well as determine if a carry is generated. All that the DFA needs to remember is the value of the carry (0 or 1). The DFA accepts if no carry is generated when processing the last input symbol. Here’s a formal description of the DFA, where state $q_2$ is a garbage state: $(Q, \Sigma, \delta, q_0, F)$ where

$$Q = \{q_0, q_1, q_2\}$$

$$\Sigma = \{[abc] \mid a, b, c \in \{0, 1, 2, \ldots, 9\}\}$$

$$F = \{q_0\}$$

and $\delta$ is defined as follows:

$$\delta(q_d, [abc]) = \begin{cases} 
q_0 & \text{if } d \in \{0, 1\} \text{ and } d + a + b = c \\
q_1 & \text{if } d \in \{0, 1\}, d + a + b \geq 10 \text{ and } (d + a + b) \mod 10 = c \\
q_2 & \text{otherwise}
\end{cases}$$

Here’s a transition diagram of the DFA that shows only one of the 1,000 transitions that come out of each state.
b) Since the DFA is now reading the numbers from left to right, it can’t compute the carries as it reads the numbers. So it will do the opposite: for each input symbol, the DFA will figure out what carry it needs from the rest of the numbers. For example, if the first symbol that the DFA sees is \([123]\), the DFA will know that there should be no carry generated from the rest of the numbers. But if the symbol is \([124]\), the DFA needs the rest of the number to generate a carry. And if a carry needs to be generated, the next symbol will have to be something like \([561]\) but not \([358]\). The states of the DFA will be used to remember the carry that is needed from the rest of the numbers. The DFA will accept if no carry is needed for the first position of the numbers (which is given by the last symbol of the input string). Here’s a formal description of the DFA, where state \(q_2\) is a garbage state: \((Q, \Sigma, \delta, q_0, F)\) where

\[
Q = \{q_0, q_1, q_2\}
\]
\[
\Sigma = \{[abc] \mid a, b, c \in \{0, 1, 2, \ldots, 9\}\}
\]
\[
F = \{q_0\}
\]

and \(\delta\) is defined as follows:

\[
\delta(q_0, [abc]) = \begin{cases} q_d & \text{if } d \in \{0, 1\} \text{ and } d + a + b = c \\ q_2 & \text{otherwise} \end{cases}
\]

\[
\delta(q_1, [abc]) = \begin{cases} q_d & \text{if } d \in \{0, 1\}, \ d + a + b \geq 10 \text{ and } \ (d + a + b) \mod 10 = c \\ q_2 & \text{otherwise} \end{cases}
\]

\[
\delta(q_2, [abc]) = q_2, \quad \text{for every } [abc] \in \Sigma
\]
Here's a transition diagram of the DFA that shows only one of the 1,000 transitions that come out of each state.

2.5 Closure Properties

2.5.3. In each case, all we have to do is switch the acceptance status of each state. But we need to remember to do it for the garbage states too.

a)
2.5.4. It is important to include in the pair construction the garbage states of the DFA's for the simpler languages. (This is actually not needed for intersections but it is critical for unions.) In each case, we give the DFA's for the two simpler languages followed by the DFA obtained by the pair construction.
a)

\[
\begin{array}{c}
q_0 \xrightarrow{0,1} q_1 \xrightarrow{1} q_2 \xrightarrow{0,1} q_3 \\
q_0 \xrightarrow{1} q_1 \xrightarrow{0} q_1 \xrightarrow{0,1} q_1 \\
q_0 \xrightarrow{1} q_0 \xrightarrow{0,1} q_0 \\
q_0 \xrightarrow{1} q_{10} \xrightarrow{1} q_{20} \xrightarrow{1} q_{30} \\
q_{00} \xrightarrow{1} q_{10} \xrightarrow{1} q_{20} \xrightarrow{1} q_{30} \\
q_{01} \xrightarrow{0,1} q_{11} \xrightarrow{1} q_{21} \xrightarrow{0,1} q_{31} \\
q_{00} \xrightarrow{0} q_{10} \xrightarrow{0} q_{20} \xrightarrow{0} q_{30} \\
q_{01} \xrightarrow{0,1} q_{11} \xrightarrow{1} q_{21} \xrightarrow{0,1} q_{31} \\
q_{00} \xrightarrow{0} q_{10} \xrightarrow{0} q_{20} \xrightarrow{0} q_{30} \\
q_{01} \xrightarrow{0,1} q_{11} \xrightarrow{1} q_{21} \xrightarrow{0,1} q_{31} \\
\end{array}
\]
b)
d)
2.5.5. In both cases, missing edges go to a garbage state.

(a)

(b) The dashed state and edge could be deleted.
Chapter 3

Nondeterministic Finite Automata

3.1 Introduction

3.1.3.

a)
b) 

\[ q_0 \xrightarrow{0,1} q_1 \xrightarrow{0} q_3 \xrightarrow{1} q_2 \]


c) 

\[ q_0 \xrightarrow{0,1} q_1 \xrightarrow{1} q_2 \]

d) 

\[ q_0 \xrightarrow{0,1} q_1 \xrightarrow{0,1} q_2 \xrightarrow{0,1} \ldots \xrightarrow{0,1} q_k \]

e) 

\[ q_0 \xrightarrow{1} q_1 \xrightarrow{0} q_0 \]
3.2. Formal Definition

3.2.1.  

a) The NFA is \((Q, \{0, 1\}, \delta, q_0, F)\) where

\[
Q = \{q_0, q_1, q_2, q_3\} \\
F = \{q_3\}
\]

and \(\delta\) is defined by the following table

<table>
<thead>
<tr>
<th>(\delta)</th>
<th>0</th>
<th>1</th>
<th>(\varepsilon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q_0)</td>
<td>(q_0)</td>
<td>(q_0, q_1)</td>
<td>(-)</td>
</tr>
<tr>
<td>(q_1)</td>
<td>(q_2)</td>
<td>(q_2)</td>
<td>(-)</td>
</tr>
<tr>
<td>(q_2)</td>
<td>(q_3)</td>
<td>(q_3)</td>
<td>(-)</td>
</tr>
<tr>
<td>(q_3)</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
</tbody>
</table>
b) The NFA is \((Q, \{0, 1\}, \delta, q_0, F)\) where

\[
\begin{align*}
Q &= \{q_0, q_1, q_2, q_3\} \\
F &= \{q_3\}
\end{align*}
\]

and \(\delta\) is defined by the following table:

<table>
<thead>
<tr>
<th>(\delta)</th>
<th>0</th>
<th>1</th>
<th>(\epsilon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q_0)</td>
<td>(q_1)</td>
<td>(q_0)</td>
<td>-</td>
</tr>
<tr>
<td>(q_1)</td>
<td>(q_2)</td>
<td>-</td>
<td>(q_0)</td>
</tr>
<tr>
<td>(q_2)</td>
<td>-</td>
<td>(q_3)</td>
<td>(q_1)</td>
</tr>
<tr>
<td>(q_3)</td>
<td>(q_3)</td>
<td>(q_3)</td>
<td>-</td>
</tr>
</tbody>
</table>

3.2.2.

The NFA accepts because the last two sequences end in the accepting state.
3.2. FORMAL DEFINITION

3.2.3.

The NFA accepts because the last three sequences end in the accepting state.
3.3 Equivalence with DFA’s
3.3. EQUIVALENCE WITH DFA'S

3.3.3.

a)

\[
\begin{array}{c|cc}
\delta' & 0 & 1 \\
\hline
q_0 & q_1 & - \\
q_1 & q_1 & q_1, q_2 \\
q_2 & - & - \\
q_1, q_2 & q_1 & q_1, q_2 \\
\end{array}
\]

The start state is \( \{q_0\} \). The accepting states are \( q_2 \) and \( \{q_1, q_2\} \). (As usual, the symbol \(-\) represents the state \( \emptyset \). That state is a garbage state.)

b)

\[
\begin{array}{c|ccc}
\delta' & 0 & 1 \\
\hline
q_0 & q_0, q_1 & q_0, q_2 \\
q_1 & q_3 & - \\
q_2 & - & q_3 \\
q_3 & - & - \\
q_0, q_1 & q_0, q_1, q_3 & q_0, q_2 \\
q_0, q_2 & q_0, q_1 & q_0, q_2, q_3 \\
q_0, q_1, q_3 & q_0, q_1, q_3 & q_0, q_2 \\
q_0, q_2, q_3 & q_0, q_1 & q_0, q_2, q_3 \\
\end{array}
\]
The start state is \( \{q_0\} \). The accepting states are \( q_3, \{q_0, q_1, q_3\} \) and \( \{q_0, q_2, q_3\} \).

c)

\[
\begin{array}{c|cc}
\delta' & 0 & 1 \\
\hline
q_0 & q_0 & q_0, q_1 \\
q_1 & q_2 & q_2 \\
q_2 & - & - \\
q_0, q_1 & q_0, q_2 & q_0, q_1, q_2 \\
q_0, q_2 & q_0 & q_0, q_1 \\
q_0, q_1, q_2 & q_0, q_2 & q_0, q_1, q_2 \\
\end{array}
\]

The start state is \( \{q_0\} \). The accepting states are \( q_2, \{q_0, q_2\} \) and \( \{q_0, q_1, q_2\} \).

d)

\[
\begin{array}{c|cc}
\delta' & 0 & 1 \\
\hline
q_0 & q_0 & q_1 \\
q_1 & q_1 & - \\
\end{array}
\]

The start state is \( \{q_0\} \). The accepting state is \( \{q_1\} \). (The given NFA was almost a DFA. All that was missing was a garbage state and that’s precisely what the algorithm added.)
3.3. EQUIVALENCE WITH DFA'S

3.3.4.

a)

\[
\begin{array}{c|cc}
\delta' & 0 & 1 \\
\hline
q_0 & q_1 & - \\
q_1 & q_1 & q_1, q_2 \\
q_2 & - & - \\
q_{1,2} & q_1 & q_1, q_2 \\
\end{array}
\]

The start state is \( E(\{q_0\}) = \{q_0\} \). The accepting states are \( q_2 \) and \( \{q_1, q_2\} \).

b)

\[
\begin{array}{c|ccc}
\delta' & 0 & 1 \\
\hline
q_0 & q_0, q_1, q_2 & q_0, q_1, q_2 \\
q_1 & q_3 & - \\
q_2 & - & q_3 \\
q_3 & - & - \\
q_{0,1,2} & q_0, q_1, q_2, q_3 & q_0, q_1, q_2, q_3 \\
q_{0,1,2,3} & q_0, q_1, q_2, q_3 & q_0, q_1, q_2, q_3 \\
\end{array}
\]

The start state is \( E(\{q_0\}) = \{q_0, q_1, q_2\} \). The accepting states are \( q_3 \) and \( \{q_0, q_1, q_2, q_3\} \).
3.4 Closure Properties

3.4.2. Suppose that $M_i = (Q_i, \Sigma, \delta_i, q_i, F_i)$, for $i = 1, 2$. Without loss of generality, assume that $Q_1$ and $Q_2$ are disjoint. Then $N = (Q, \Sigma, \delta, q_0, F)$ where

\[
Q = Q_1 \cup Q_2 \\
q_0 = q_1 \\
F = F_2
\]

and $\delta$ is defined as follows:

\[
\delta(q, \epsilon) = \begin{cases} 
\{q_2\} & \text{if } q \in F_1 \\
\emptyset & \text{otherwise}
\end{cases}
\]

\[
\delta(q, a) = \{\delta_i(q, a)\}, \quad \text{if } q \in Q_i \text{ and } a \in \Sigma.
\]

3.4.3. Suppose that $M = (Q_1, \Sigma, \delta_1, q_1, F_1)$. Let $q_0$ be a state not in $Q_1$. Then $N = (Q, \Sigma, \delta, q_0, F)$ where

\[
Q = Q_1 \cup \{q_0\} \\
F = F_1 \cup \{q_0\}
\]

and $\delta$ is defined as follows:

\[
\delta(q, \epsilon) = \begin{cases} 
\{q_1\} & \text{if } q \in F_1 \cup \{q_0\} \\
\emptyset & \text{otherwise}
\end{cases}
\]

\[
\delta(q, a) = \{\delta_1(q, a)\}, \quad \text{if } q \neq q_0 \text{ and } a \in \Sigma.
\]
3.4.4.

a) In the second to last paragraph of the proof, it is claimed that $w = x_1 \cdots x_{k+1}$, with each $x_i \in A$. It is true that $x_1, \ldots, x_k$ are all in $A$ because they must lead from the start state to one of the original accepting states of $M$. But this is not true for $x_{k+1}$: that string could lead back to the start state instead of leading to one of the original accepting states of $M$. In that case, $x_{k+1}$ might not be in $A$ and we wouldn’t be able to conclude that $w$ is in $A^*$.

b) Consider the following DFA for the language of strings that contain at least one 1:

![DFA Diagram]

If we used this idea, we would get the following NFA:

![NFA Diagram]

This NFA accepts strings that contain only 0’s. These strings are not in the language $L(M)^*$. Therefore, $L(N) \neq L(M)^*$.

3.4.5. One proof is to notice that $A^+ = AA^*$. Since the class of regular languages
is closed under star and concatenation, we also get closure under the plus operation.

An alternative proof is to modify the construction that was used for the star operation. The only change is that a new start state should not be added. The argument that this construction works is almost the same as before. If \( w \in A^+ \), then \( w = x_1 \cdots x_k \) with \( k \geq 1 \) and each \( x_i \in A \). This implies that \( N \) can accept \( w \) by going through \( M \) \( k \) times, each time reading one \( x_i \) and then returning to the start state of \( M \) by using one of the new \( \epsilon \) transitions (except after \( x_k \)).

Conversely, if \( w \) is accepted by \( N \), then it must be that \( N \) uses the new \( \epsilon \) “looping back” transitions \( k \) times, for some number \( k \geq 0 \), breaking \( w \) up into \( x_1 \cdots x_{k+1} \), with each \( x_i \in A \). This implies that \( w \in A^+ \). Therefore, \( L(N) = A^+ \).

3.4.6. Suppose that \( L \) is regular and that it is recognized by a DFA \( M \) that doesn’t have exactly one accepting state.

If \( M \) has no accepting states, then simply add one and make all the transitions leaving that state go back to itself. Since this new accepting state is unreachable from the start state, the new DFA still recognizes \( L \) (which happens to be the empty set).

Now suppose that \( M \) has more than one accepting state. For example, it may look like this:
3.4. CLOSURE PROPERTIES

Then $M$ can be turned into an equivalent NFA $N$ with a single accepting state as follows:

That is, we add a new accepting state, an $\epsilon$ transition from each of the old accepting states to the new one, and we make the old accepting states non-accepting.

We can show that $L(N) = L(M)$ as follows. If $w$ is accepted by $M$, then $w$ leads to an old accepting state, which implies that $N$ can accept $w$ by using one of the new $\epsilon$ transitions. If $w$ is accepted by $N$, then the reading of $w$ must finish with one of the new $\epsilon$ transitions. This implies that in $M$, $w$ leads to one of the old accepting states, so $w$ is accepted by $M$.

3.4.7. Suppose that $L$ is recognized by a DFA $M$. Transform $N$ into an equivalent NFA with a single accepting state. (The previous exercise says that this can be done.) Now reverse every transition in $N$: if a transition labeled $a$ goes
from $q_1$ to $q_2$, make it go from $q_2$ to $q_1$. In addition, make the accepting state become the start state, and switch the accepting status of the new and old start states. Call the result $N'$.

We claim that $N'$ recognizes $L^\mathcal{R}$. If $w = w_1 \cdots w_n$ is accepted by $N'$, it must be that there is a path through $N'$ labeled $w$. But then, this means that there was a path labeled $w_n \cdots w_1$ through $N$. Therefore, $w$ is the reverse of a string in $L$, which means that $w \in L^\mathcal{R}$. It is easy to see that the reverse is also true.
Chapter 4

Regular Expressions

4.1 Introduction

4.1.5.

a) \((- \cup \epsilon)DD^*\)
b) \((- \cup \epsilon)DD^* \cup (- \cup \epsilon)D^* \cdot DD^*\)
c) \(_\cup (\_ \cup \cup \cup \cup \cup \cup \cup \cup \cup \cup \cup L \cup D) \cup (\_ \cup \cup \cup \cup \cup \cup \cup \cup \cup \cup \cup L \cup D)^* \cup L(\_ \cup \cup \cup \cup \cup \cup \cup \cup \cup \cup \cup L \cup D)^*\)
d) \(D^7 \cup D^{10} \cup D^3 - D^4 \cup D^3 - D^3 - D^4\)

4.2 Formal Definition

There are no exercises in this section.
4.3 More Examples

4.3.1. \( 0 \cup 1 \cup 0\Sigma^*0 \cup 1\Sigma^*1 \).

4.3.2.
   a) \( 0\Sigma^*1 \).
   b) \( \Sigma1\Sigma^* \).
   c) \( \Sigma^{k-1}1\Sigma^* \).

4.3.3.
   a) \( (00 \cup 11)\Sigma^* \).
   b) \( \Sigma^*(00 \cup 11) \).
   c) \( \Sigma^*1\Sigma \).

4.3.4.
   a) \( \Sigma^*1\Sigma^* \).
   b) \( 0^*10^* \).
   c) \( \Sigma^*1\Sigma^*1\Sigma^* \).
   d) \( 0^* \cup 0^*10^* \).
   e) \( (\Sigma^*1)^k\Sigma^* \).

4.3.5.
   a) \( \varepsilon \cup 1\Sigma^* \cup \Sigma^*0 \).
   b) \( \varepsilon \cup \Sigma \cup \Sigma\Sigma^* \).
   c) \( (\varepsilon \cup \Sigma)^{k-1} \cup \Sigma^{k-1}0\Sigma^* \). Another solution: \( \cup_{i=0}^{k-1}\Sigma^i \cup \Sigma^{k-1}0\Sigma^* \).
4.3. MORE EXAMPLES

4.3.6.

a) \(01\Sigma^* \cup 11\Sigma^*0\Sigma^*\).

b) \(\Sigma^*1\Sigma^*1\Sigma^* \cup \Sigma^*0\Sigma^*0\Sigma^*\).

c) One way to go about this is to focus on the first two 1’s that occur in the string and then list the ways in which the 0 in the string can relate to those two 0’s. Here’s what you get:

\[11^+ \cup 011^+ \cup 101^+ \cup 11^+01^*\.

d) Let \(E_0 = (1^*01^*0)^*1^*\) and \(D_0 = (1^*01^*0)^*1^*01^*\). The regular expression \(E_0\) describes the language of strings with an even number of 0’s while \(D_0\) describes the language of strings with an odd number of 0’s. Then the language of strings that contain at least two 1’s and an even number of 0’s can be described as follows:

\[E_01E_01E_0 \cup E_01D_01D_0 \cup D_01E_01D_0 \cup D_01D_01E_0\.

4.3.7.

a) \((00)^*\#11^*\).

b) \((00)^*11^*\).
4.4 Converting Regular Expressions into DFA's

4.4.1.

a) 

\[ q_6 \xrightarrow{\varepsilon} q_2 \xrightarrow{\varepsilon} q_0 \xrightarrow{0} q_1 \]

\[ q_5 \xrightarrow{\varepsilon} q_3 \xrightarrow{1} q_4 \]

b) 

\[ q_5 \xrightarrow{\varepsilon} q_4 \xrightarrow{\varepsilon} q_0 \xrightarrow{0} q_1 \]

\[ q_6 \xrightarrow{\varepsilon} q_2 \xrightarrow{\varepsilon} q_3 \xrightarrow{1} q_3 \xrightarrow{\varepsilon} q_6 \xrightarrow{0} q_7 \]
4.4.2. Two new cases must be added to the first definition of Section 4.2:

7. \( R = (R_1 \cap R_2) \), where each \( R_i \) is a regular expression over \( \Sigma \).

8. \( R = (\overline{R_1}) \), where \( R_1 \) is a regular expression over \( \Sigma \).

Two new cases must also be added to the second definition of that section:
7. \( L(R_1 \cap R_2) = L(R_1) \cap L(R_2) \).
8. \( L(R_1) = \overline{L(R_1)} \).

To show that these extended regular expressions can only describe regular languages, all we need to do is show that these regular expressions can be converted into NFA's by extending the theorem of Section 4.4 as follows:

If \( R = R_1 \cap R_2 \), or if \( R = \overline{R_1} \), then recursively convert \( R_1 \) and \( R_2 \) into NFA's \( N_1 \) and \( N_2 \), convert these NFA's into DFA's \( M_1 \) and \( M_2 \), and then combine or transform these DFA's into a DFA \( M \) for \( L(R) \) by using the constructions we used to prove the closure results of Section 2.5.
4.5.1. a) We first add a new accepting state:

![Diagram](image)

We then remove state $q_1$:

![Diagram](image)

We remove state $q_2$:

$$01^*1(0 \cup 01^*1)^*1$$

The final regular expression is

$$(01^*1(0 \cup 01^*1)^*1)(\varepsilon \cup 01^*1(0 \cup 01^*1)^*)$$
b) First, we add a new accepting state:

![Diagram](attachment:image.png)

Then, we notice that state $q_2$ cannot be used to travel between the other two states. So we can just remove it:

![Diagram](attachment:image.png)

We remove state $q_1$:

![Diagram](attachment:image.png)

The final regular expression is $(0 \cup 0^+1)^*0^+$. 
4.6 Precise Description of the Algorithm

4.6.1. The GNFA is \((Q, \{a, b, c\}, \delta, q_0, F)\) where

\[
Q = \{q_0, q_1, q_2\} \\
F = \{q_2\}
\]

and \(\delta\) is defined by the following table:

<table>
<thead>
<tr>
<th>(\delta)</th>
<th>(q_0)</th>
<th>(q_1)</th>
<th>(q_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q_0)</td>
<td>(a \cup b^+ c)</td>
<td>(b)</td>
<td>(c \cup b^+ a)</td>
</tr>
<tr>
<td>(q_1)</td>
<td>(c)</td>
<td>(b)</td>
<td>(a)</td>
</tr>
<tr>
<td>(q_2)</td>
<td>(b)</td>
<td>(c)</td>
<td>(a)</td>
</tr>
</tbody>
</table>

4.6.2. The GNFA is \((Q, \{a, b, c\}, \delta, q_0, F)\) where

\[
Q = \{q_0, q_2\} \\
F = \{q_2\}
\]

and \(\delta\) is defined by the following table:

<table>
<thead>
<tr>
<th>(\delta)</th>
<th>(q_0)</th>
<th>(q_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(q_0)</td>
<td>(a \cup b^+ c)</td>
<td>(c \cup b^+ a)</td>
</tr>
<tr>
<td>(q_2)</td>
<td>(b \cup cb^* c)</td>
<td>(a \cup cb^* a)</td>
</tr>
</tbody>
</table>
Chapter 5

Nonregular Languages

5.1 Some Examples

5.1.1. Suppose that \( L = \{0^n1^{2n} \mid n \geq 0\} \) is regular. Let \( M \) be a DFA that recognizes \( L \) and let \( n \) be the number of states of \( M \).

Consider the string \( w = 0^n1^{2n} \). As \( M \) reads the 0’s in \( w \), \( M \) goes through a sequence of states \( q_0, q_1, q_2, \ldots, q_n \). Because this sequence is of length \( n + 1 \), there must be a repetition in the sequence.

Suppose that \( q_i = q_j \) with \( i < j \). Then the computation of \( M \) on \( w \) looks like this:

This implies that the string \( 0^i0^{n-j}1^{2n} = 0^{n-(j-i)}1^{2n} \) is also accepted. But
since this string no longer has exactly $n$ 0's, it cannot belong to $L$. This contradicts the fact that $M$ recognizes $L$. Therefore, $M$ cannot exist and $L$ is not regular.

5.1.2. Suppose that $L = \{0^i1^j \mid 0 \leq i \leq 2j\}$ is regular. Let $M$ be a DFA that recognizes $L$ and let $n$ be the number of states of $M$.

Consider the string $w = 0^{2n}1^n$. As $M$ reads the first $n$ 0's in $w$, $M$ goes through a sequence of states $q_0, q_1, q_2, \ldots, q_n$. Because this sequence is of length $n + 1$, there must be a repetition in the sequence.

Suppose that $q_i = q_j$ with $i < j$. Then the computation of $M$ on $w$ looks like this:

```
Now consider going twice around the loop. This implies that the string $0^i0^{2(j-i)}0^{2n-j}1^n = 0^{2n+(j-i)}1^n$ is also accepted. But since this string has more than $2n$ 0's, it does not belong to $L$. This contradicts the fact that $M$ recognizes $L$. Therefore, $M$ cannot exist and $L$ is not regular.

5.1.3. Suppose that $L = \{ww^R \mid w \in \{0,1\}^*\}$ is regular. Let $M$ be a DFA that recognizes $L$ and let $n$ be the number of states of $M$.

Consider the string $w = 0^n110^n$. As $M$ reads the first $n$ 0's of $w$, $M$ goes through a sequence of states $q_0, q_1, q_2, \ldots, q_n$. Because this sequence is of length $n + 1$, there must be a repetition in the sequence.

Suppose that $q_i = q_j$ with $i < j$. Then the computation of $M$ on $w$ looks like this:
This implies that the string $0^i 0^{n-j} 110^n = 0^{n-(j-i)} 110^n$ is also accepted. But this string does not belong to $L$. This contradicts the fact that $M$ recognizes $L$. Therefore, $M$ cannot exist and $L$ is not regular.

### 5.2 The Pumping Lemma

#### 5.2.1. Let $L = \{0^i 1^j \mid i \leq j\}$. Suppose that $L$ is regular. Let $p$ be the pumping length. Consider the string $w = 0^p 1^p$. Clearly, $w \in L$ and $|w| \geq p$. Therefore, according to the Pumping Lemma, $w$ can be written as $xyz$ where

1. $|xy| \leq p$.
2. $y \neq \varepsilon$.
3. $xy^kz \in L$, for every $k \geq 0$.

Condition (1) implies that $y$ contains only 0’s. Condition (2) implies that $y$ contains at least one 0. Therefore, the string $xy^2z$ does not belong to $L$ because it contains more 0’s than 1’s. This contradicts Condition (3) and implies that $L$ is not regular.

#### 5.2.2. Let $L = \{1^i \# 1^j \# 1^{i+j}\}$. Suppose that $L$ is regular. Let $p$ be the pumping length. Consider the string $w = 1^p \# 1^p \# 1^{2p}$. Clearly, $w \in L$ and $|w| \geq p$. Therefore, according to the Pumping Lemma, $w$ can be written as $xyz$ where
1. $|xy| \leq p$.
2. $y \neq \varepsilon$.
3. $xy^kz \in L$, for every $k \geq 0$.

Since $|xy| \leq p$, we have that $y$ contains only 1’s from the first part of the string. Therefore, $xy^2z = 1^{p+|y|} \# 1^p \# 1^2p$. Because $|y| \geq 1$, this string cannot belong to $L$. This contradicts the Pumping Lemma and shows that $L$ is not regular.

5.2.3. Let $L$ be the language described in the exercise. Suppose that $L$ is regular. Let $p$ be the pumping length. Consider the string $w = 1^p \# 2^p \# 3^p$. Clearly, $w \in L$ and $|w| \geq p$. Therefore, according to the Pumping Lemma, $w$ can be written as $xyz$ where

1. $|xy| \leq p$.
2. $y \neq \varepsilon$.
3. $xy^kz \in L$, for every $k \geq 0$.

Since $|xy| \leq p$, we have that $y$ contains only 1’s from the first part of the string. Therefore, $xy^2z = 1^{p+|y|} \# 1^p \# 1^2p$. In other words, since $|y| \geq 1$, the first number in this string was changed but not the other two, making impossible for the sum of the first two numbers to equal the third. Therefore, $xy^2z$ is not in $L$. This contradicts the Pumping Lemma and shows that $L$ is not regular.

5.2.4. What is wrong with this proof is that we cannot assume that $p = 1$. All that the Pumping Lemma says is that $p$ is positive. We cannot assume anything else about $p$. For example, if we get a contradiction for the case $p = 1$, then we haven’t really contradicted the Pumping Lemma because it may be that $p$ has another value.
Chapter 6

Context-Free Languages

6.1 Introduction

6.1.6.

a)

\[ I \rightarrow SN \]
\[ S \rightarrow - \mid \varepsilon \]
\[ N \rightarrow DN \mid D \]
\[ D \rightarrow 0 \mid \cdots \mid 9 \]
b)

\[
\begin{align*}
R & \rightarrow SN_1 | SN_0 N_1 \\
S & \rightarrow - | \epsilon \\
N_0 & \rightarrow DN_0 | \epsilon \\
N_1 & \rightarrow DN_0 \\
D & \rightarrow 0 | \cdots | 9
\end{align*}
\]

\[
\begin{align*}
I & \rightarrow _R1 | LR_0 \\
R_0 & \rightarrow _R0 | LR_0 | DR_0 | \epsilon \\
R_1 & \rightarrow R_0 LR_0 | R_0 DR_0 \\
L & \rightarrow a | \cdots | z | A | \cdots | Z \\
D & \rightarrow 0 | \cdots | 9
\end{align*}
\]

6.2 Formal Definition of CFG’s

There are no exercises in this section.
6.3. More Examples

6.3.1.

a) 

\[ S \rightarrow 0S0 \mid 1 \]

b) 

\[ S \rightarrow 0S0 \mid 1S1 \mid \varepsilon \]

c) 

\[ S \rightarrow 0S11 \mid \varepsilon \]

d) Here’s one solution:

\[ S \rightarrow ZS1 \mid \varepsilon \]

\[ Z \rightarrow 0 \mid \varepsilon \]

Here’s another one:

\[ S \rightarrow 0S1 \mid T \]

\[ T \rightarrow T1 \mid \varepsilon \]
6.3.2.

\[
S \rightarrow 1S1 | \#T \\
T \rightarrow 1T1 | \#
\]

6.3.3.

a) 

\[
0 : S_1 \rightarrow 0 \\
0^* : S_2 \rightarrow S_1S_2 | \epsilon \\
1 : S_3 \rightarrow 1 \\
1^* : S_4 \rightarrow S_3S_4 | \epsilon \\
0^* \cup 1^* : S_5 \rightarrow S_2 | S_4
\]

The start variable is \( S_5 \).

b) 

\[
0 : S_1 \rightarrow 0 \\
0^* : S_2 \rightarrow S_1S_2 | \epsilon \\
1 : S_3 \rightarrow 1 \\
0^*1 : S_4 \rightarrow S_2S_3 \\
0^*10 : S_5 \rightarrow S_4S_1
\]

The start variable is \( S_5 \).
6.4. AMBIGUITY AND PARSE TREES

c)

\[
1 : S_1 \rightarrow 1 \\
11 : S_2 \rightarrow S_1 S_1 \\
(11)^* : S_3 \rightarrow S_2 S_3 | \epsilon
\]

The start variable is \( S_3 \).

6.3.4.

\[
S \rightarrow (S) S | [S] S | \{S\} S | \epsilon
\]

6.3.5. A string of properly nested parentheses is either ( ) or a string of the form \((u)v\) where \(u\) and \(v\) are either empty or strings of properly nested parentheses. Here's a grammar that paraphrases this definition:

\[
S \rightarrow (U) U | ()
\]

\[
U \rightarrow S | \epsilon
\]

Here's an alternative that essentially incorporates the rules for \( U \) into the rules for \( S \):

\[
S \rightarrow (S) S | () S | (S) | ()
\]

6.4 Ambiguity and Parse Trees

6.4.4. Two parse trees in the first grammar:
The unique parse tree in the second grammar:
6.5. A Pumping Lemma

6.5.1. Let \( L \) denote that language and suppose that \( L \) is context-free. Let \( p \) be the pumping length. Consider the string \( w = 0^p 1^p 0^p \). Clearly, \( w \in L \) and \( |w| \geq p \). Therefore, according to the Pumping Lemma, \( w \) can be written as \( uvxyz \) where

1. \( vy \neq \epsilon \).
2. \( uv^kxy^kz \in L \), for every \( k \geq 0 \).

There are two cases to consider. First, suppose that either \( v \) or \( y \) contains more than one type of symbol. Then \( uv^2xy^2z \notin L \) because that string is not even in \( 0^*1^*0^* \).

Second, suppose that \( v \) and \( y \) each contain only one type of symbol. The string \( w \) consists of three blocks of \( p \) symbols and \( v \) and \( y \) can touch at most two of those blocks. Therefore, \( uv^2xy^2z = 0^{p+i}1^{p+j}0^{p+k} \) where at least one of \( i, j, k \) is greater than 0 and at least one of \( i, j, k \) is equal to 0. This implies that \( uv^2xy^2z \notin L \).

In both cases, we have that \( uv^2xy^2z \notin L \). This is a contradiction and proves that \( L \) is not context-free.

6.5.2. Let \( L \) denote that language and suppose that \( L \) is context-free. Let \( p \) be the pumping length. Consider the string \( w = a^pb^pc^p \). Clearly, \( w \in L \) and \( |w| \geq p \). Therefore, according to the Pumping Lemma, \( w \) can be written as \( uvxyz \) where

1. \( vy \neq \epsilon \).
2. \( uv^kxy^kz \in L \), for every \( k \geq 0 \).
There are three cases to consider. First, suppose that either \( v \) or \( y \) contains more than one type of symbol. Then \( uv^2xy^2z \notin L \) because that string is not even in \( a^*b^*c^* \).

In the other two cases, \( v \) and \( y \) each contain only one type of symbol. The second case is when \( v \) consists of a’s. Then, since \( y \) cannot contain both b’s and c’s, \( uv^2xy^2z \) contains more a’s than b’s or more a’s than c’s. This implies that \( uv^2xy^2z \notin L \).

The third case is when \( v \) does not contain any a’s. Then \( y \) can’t either. This implies that \( uv^0xy^0z \) contains less b’s than a’s or less c’s than a’s. Therefore, \( uv^0xy^0z \notin L \).

In all cases, we have that \( uv^kxy^kz \notin L \) for some \( k \geq 0 \). This is a contradiction and proves that \( L \) is not context-free.

6.5.3. Let \( L \) denote that language and suppose that \( L \) is context-free. Let \( p \) be the pumping length. Consider the string \( w = 1^p \# 1^p \# 1^{2p} \). Clearly, \( w \in L \) and \( |w| \geq p \). Therefore, according to the Pumping Lemma, \( w \) can be written as \( uvxyz \) where

1. \( vy \neq \varepsilon \).

2. \( uv^kxy^kz \in L \), for every \( k \geq 0 \).

There are several cases to consider. First, suppose that either \( v \) or \( y \) contains a \#. Then \( uv^2xy^2z \notin L \) because it contains too many \#'s.

For the remaining cases, assume that neither \( v \) nor \( y \) contains a \#. Note that \( w \) consists of three blocks of 1’s separated by \#'s. This implies that \( v \) and \( y \) are each completely contained within one block and that \( v \) and \( y \) cannot contain 1’s from all three blocks.
6.5. A PUMPING LEMMA

The second case is when \( v \) and \( y \) don’t contain any 1’s from the third block. Then \( uv^2xy^2z = 1^{p+i} \# 1^{p+j} \# 1^{2p} \) where at least one of \( i, j \) is greater than 0. This implies that \( uv^2xy^2z \notin L \).

The third case is when \( v \) and \( y \) don’t contain any 1’s from the first two blocks. Then \( uv^2xy^2z = 1^p \# 1^p \# 1^{2p+i} \) where \( i > 0 \). This implies that \( uv^2xy^2z \notin L \).

The fourth case is when \( v \) consists of 1’s the first block and \( y \) consists of 1’s the third block. Then \( uv^2xy^2z = 1^{p+i} \# 1^p \# 1^{2p+j} \) where both \( i, j \) are greater than 0. This implies that \( uv^2xy^2z \notin L \) because the first block is larger than the second block.

The fifth and final case is when \( v \) consists of 1’s the second block and \( y \) consists of 1’s the third block. Then \( uv^0xy^0z = 1^p \# 1^{p-i} \# 1^{2p-j} \) where both \( i, j \) are greater than 0. This implies that \( uv^2xy^2z \notin L \) because the second block is smaller than the first block.

In all cases, we have a contradiction. This proves that \( L \) is not context-free.

6.5.4. Let \( L \) denote that language and suppose that \( L \) is context-free. Let \( p \) be the pumping length. Consider the string \( w = 0^p 1^{2p} 0^p \). Clearly, \( w \in L \) and \( |w| \geq p \). Therefore, according to the Pumping Lemma, \( w \) can be written as \( uvxyz \) where

1. \( |vxy| \leq p \).
2. \( vy \neq \varepsilon \).
3. \( uv^ky^kz \in L \), for every \( k \geq 0 \).

The string \( w \) consists of three blocks of symbols. Since \( |vxy| \leq p \), \( v \) and \( y \) are completely contained within two consecutive blocks. Suppose that \( v \)
and $y$ are both contained within a single block. Then $uv^2xy^2z$ has additional symbols of one type but not the other. Therefore, this string is not in $L$.

Now suppose that $v$ and $y$ touch two consecutive blocks, the first two, for example. Then $uv^0xy^0z = 0^{p-i}1^{2p-j}0^p$ where $1 \leq i, j < p$. This string is clearly not in $L$. The same is true for the other blocks.

Therefore, in all cases, we have that $w$ cannot be pumped. This contradicts the Pumping Lemma and proves that $L$ is not context-free.

6.5.5. Let $L$ denote that language and suppose that $L$ is context-free. Let $p$ be the pumping length. Consider the string $w = 1^p \#1^p \#1^p$. Clearly, $w \in L$ and $|w| \geq p$. Therefore, according to the Pumping Lemma, $w$ can be written as $uvxyz$ where

1. $vy \neq \epsilon$.
2. $uv^kxy^kz \in L$, for every $k \geq 0$.

There are several cases to consider. First, suppose that either $v$ or $y$ contains a $\#$. Then $uv^2xy^2z \notin L$ because it contains too many $\#$’s.

For the remaining cases, assume that neither $v$ or $y$ contains a $\#$. Note that $w$ consists of three blocks of 1’s separated by $\#$’s. This implies that $v$ and $y$ are each completely contained within one block and that $v$ and $y$ cannot touch all three blocks.

The second case is when $v$ and $y$ are contained within the first two blocks. Then $uv^2xy^2z = 1^{p+i} \#1^{p+j} \#1^p$ where at least one of $i, j$ is greater than 0. This implies that $uv^2xy^2z \notin L$.

The third case is when $v$ and $y$ are both within the third block. Then $uv^2xy^2z = 1^p \#1^p \#1^{p+i}$ where $i > 0$. This implies that $uv^2xy^2z \notin L$. 
The fourth case is when \( v \) consists of 1’s from the first block and \( y \) consists of 1’s from the third block. This case cannot occur since \(|vxy| \leq p|\).

The fifth and final case is when \( v \) consists of 1’s from the second block and \( y \) consists of 1’s from the third block. Then \( uv^2xy^2z = 1^p \# 1^{p+i} \# 1^{p^2+j} \) where both \( i, j \) are greater than 0. Now, \( p(p + i) \geq p(p + 1) = p^2 + p \). On the other hand, \( p^2 + j < p^2 + p \) since \( j = |y| < |vxy| \leq p \). Therefore, \( p(p + i) \neq p^2 + j \). This implies that \( uv^2xy^2z \notin L \).

In all cases, we have a contradiction. This proves that \( L \) is not context-free.

### 6.6 Proof of the Pumping Lemma

There are no exercises in this section.

### 6.7 Closure Properties

6.7.1. (Partial solution.) Suppose that \( L_1 \) and \( L_2 \) are context-free languages. Let \( G_1 \) and \( G_2 \) be CFG’s for these languages. Without loss of generality, assume that the two grammars have no variables in common. (Otherwise, rename variables to ensure that.) Let \( S_1 \) and \( S_2 \) be the start variables of \( G_1 \) and \( G_2 \), respectively. Then, let \( G \) be the CFG that contains all the variables and rules of \( G_1 \) and \( G_2 \) plus a new start variable \( S \) and the following rule: \( S \rightarrow S_1 \mid S_2 \).

We now prove that \( L(G) = L_1 \cup L_2 \). That is, we show that \( G \) can derive all the strings in \( L_1 \cup L_2 \) and only those. Suppose that \( w \in L_1 \). Then \( w \) can be derived from \( S_1 \). A derivation of \( w \) in \( G \) would start with the rule \( S \rightarrow S_1 \).
and then derive \( w \) from \( S_1 \). Similarly if \( w \in L_2 \). Therefore, in either case, \( w \) can be derived in \( G \).

To show that \( G \) only derives strings in \( L_1 \cup L_2 \), suppose that \( w \) can be derived in \( G \). Then it must be that one of the \( S \) rules was used at the beginning of the derivation. If \( S \rightarrow S_1 \) was used, then all of \( w \) can be derived from \( S_1 \), which implies that \( w \in L_1 \). Similarly, if the other \( S \) rule was used, then \( w \in L_2 \). Therefore, \( w \in L_1 \cup L_2 \), which shows that \( G \) only derives strings in \( L_1 \cup L_2 \). This completes the proof that \( L(G) = L_1 \cup L_2 \) and that the class of CFL's is closed under union.

6.7.2. Here's a CFG for the language \( \{a^i b^j c^k \mid i \neq j \text{ or } j \neq k \} \):

\[
S \rightarrow TC \mid AU \\
T \rightarrow aTb \mid aA \mid bB \quad (a^i b^j, \; i \neq j) \\
U \rightarrow bUc \mid bB \mid cC \quad (b^j c^k, \; j \neq k) \\
A \rightarrow aA \mid \epsilon \quad (a^*) \\
B \rightarrow bB \mid \epsilon \quad (b^*) \\
C \rightarrow cC \mid \epsilon \quad (c^*)
\]

Now, the complement of \( \{a^n b^n c^n \mid n \geq 0 \} \) is

\[
\overline{a^*b^*c^*} \cup \{a^i b^j c^k \mid i \neq j \text{ or } j \neq k \}.
\]

The language on the left is regular and, therefore, context-free. We have just shown that the language on the right is context-free. Therefore, the complement of \( \{a^n b^n c^n \mid n \geq 0 \} \) is context-free because the union of two CFL's is always context-free.

6.7.3. Suppose that \( w = xy \) where \( |x| = |y| \) but \( x \neq y \). Focus on one of the
positions where $x$ and $y$ differ. It must be the case that $x = u_1 au_2$ and $y = v_1 bv_2$, where $|u_1| = |v_1|$, $|u_2| = |v_2|$, $a, b \in \{0, 1\}$ and $a \neq b$. This implies that $w = u_1 au_2 v_1 bv_2$. Now, notice that $|u_2 v_1| = |v_2| + |u_1|$. We can then split $u_2 v_1$ differently, as $s_1 s_2$ where $|s_1| = |u_1|$ and $|s_2| = |v_2|$. This implies that $w = u_1 as_1 s_2 bv_2$ where $|u_1| = |s_1|$ and $|s_2| = |v_2|$. The idea behind a CFG that derives $w$ is to generate $u_1 as_1$ followed by $s_2 bv_2$. Here’s the result:

$$
S \rightarrow T_0 T_1 \mid T_1 T_0 \\
T_0 \rightarrow AT_0 A \mid 0 \quad (u0s, \ |u| = |s|) \\
T_1 \rightarrow AT_1 A \mid 1 \quad (u1s, \ |u| = |s|) \\
A \rightarrow 0 \mid 1
$$

Now, the complement of $\{ww \mid w \in \{0, 1\}^*\}$ is

$$
\{w \in \{0, 1\}^* \mid |w| \text{ is odd} \} \cup \{xy \mid x, y \in \{0, 1\}^*, |x| = |y| \text{ but } x \neq y\}
$$

The language on the left is regular and, therefore, context-free. We have just shown that the language on the right is context-free. Therefore, the complement of $\{ww \mid w \in \{0, 1\}^*\}$ is context-free because the union of two CFL’s is always context-free.
6.8 Pushdown Automata

6.8.2. One possible solution is to start with a CFG for this language and then simulate this CFG with a stack algorithm. Here’s a CFG for this language:

\[
\begin{align*}
S & \rightarrow 0S1 \\
S & \rightarrow \varepsilon
\end{align*}
\]
Now, here’s a single-scan stack algorithm that simulates this CFG:

```
push S on the stack
while (stack not empty)
    if (top of stack is S)
        nondeterministically choose to replace S by 0S1 (with 0 at the top of the stack) or to delete S
    else // top of stack is 0 or 1
        if (end of input)
            reject
        read next input symbol c
        if (c equals top of stack)
            pop stack
        else
            reject
    if (end of input)
        accept
else
    reject
```
Another solution is a more direct algorithm:

```plaintext
if (end of input)
    accept
initialize stack to empty
read next char c
while (c is 0)
    push 0 on the stack
    if (end of input)  // some 0's but no 1's
        reject
read next char c
while (c is 1)
    if (stack empty)  // more 1's than 0's
        reject
    pop stack
    if (end of input)
        if (stack empty)
            accept
        else
            reject  // more 0's than 1's
    read next char c
reject  // 0's after 1's
```

6.9 Deterministic Algorithms for CFL’s

6.9.3. Let $L$ be the language of strings of the form $ww$. We know that $L$ is not context-free. If $\overline{L}$ was a DCFL, then $L$ would be also be a DCFL because that class is closed under complementation. This would contradict the fact that $L$ is not even context-free.
Chapter 7

Turing Machines

7.1 Introduction