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Preface

If you’ve taken a few computer science courses, you may now have the feeling that programs can always be written to solve any computational problem. Writing the program may be hard work. For example, it may involve learning a difficult technique. And many hours of debugging. But with enough time and effort, the program can be written.

So it may come as a surprise that this is not the case: there are computational problems for which no program exists. And these are not ill-defined problems — Can a computer fall in love? — or uninteresting toy problems. These are precisely defined problems with important practical applications.

Theoretical computer science can be briefly described as the mathematical study of computation. These notes will introduce you to this branch of computer science by focusing on computability theory and automata theory. You will learn how to precisely define what computation is and why certain computational problems cannot be solved. You will also learn several concepts and techniques that have important applications. Chapter 1 provides a more detailed introduction to this rich and beautiful area of computer science.

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 prerequisites are CS142 (a second course in programming) and
MA211 (a course on discrete mathematics with a focus on writing mathematical proofs).

These notes were typeset using LaTeX (MiKTeX implementation with the TeX-works environment). The paper size and margins are set small to make it easier to read the notes on the relatively small screen of a laptop or tablet. But then, if you’re going to print the notes, don’t print them to “fit the page”. That would give you pages with huge text and tiny margins. Instead, print them double-sided, at “actual size” (100%) and centered. If your favorite Web browser doesn’t allow you to do that, download the notes and print them from a standalone PDF reader such as Adobe Acrobat.

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

Introduction

In this chapter, we introduce the subject of these notes, automata theory and computability theory. We explain what this is and why it is worth studying.

Computer science can be divided into two main branches. One branch is concerned with the design and implementation of computer systems, with a special focus on software. (Computer hardware is the main focus of computer engineering.) This includes not only software development but also research into subjects like operating systems and computer security. This branch of computer science is called *applied computer science*. It can be viewed as the engineering component of computer science.

The other branch of computer science is the mathematical study of computation. One of its main goals is to determine which computational problems can and cannot be solved, and which ones can be solved efficiently. This involves discovering algorithms for computational problems, but also finding mathematical proofs that such algorithms do not exist. This branch of computer science is called *theoretical computer science* or the *theory of computation*.¹ It can be viewed

¹The two main US-based theory conferences are the ACM’s *Symposium on Theory of Comput-
as the science component of computer science.²

To better illustrate what theoretical computer science is, consider the Halting Problem. The input to this computational problem is a program \( P \) written in some fixed programming language. To keep things simple and concrete, let’s limit the problem to C++ programs whose only input is a single text file. The output of the Halting Problem is the answer to the following question: Does the program \( P \) halt on every possible input? In other words, does \( P \) always halt no matter how it is used?

It should be clear that the Halting Problem is both natural and relevant. Software developers already have a tool that determines if the programs they write are correctly written according to the rules of the language they are using. This is part of what the compiler does. It would clearly be useful if software developers also had a tool that could determine if their programs are guaranteed to halt on every possible input.

Unfortunately, it turns out such a tool does not exist. Not that it currently does not exist and that maybe one day someone will invent one. No, it turns out that there is no algorithm that can solve the Halting Problem.

How can something like that be known? How can we know for sure that a computational problem has no algorithms, none, not now, not ever? Perhaps the only way of being absolutely sure of anything is to use mathematics... What this means is that we will define the Halting Problem precisely and then prove a theorem that says that no algorithm can decide the Halting Problem.

Note that this also requires that we define precisely what we mean by an algorithm or, more generally, what it means to compute something. Such a defining (STOC) and the IEEE’s Symposium on Foundations of Computing (FOCS). One of the main European theory conferences is the Symposium on Theoretical Aspects of Computer Science (STACS).

²Note that many areas of computer science have both applied and theoretical aspects. Artificial intelligence is one example. Some people working in AI produce actual systems that can be used in practice. Others try to discover better techniques by using theoretical models.
inition is called a *model of computation*. We want a model that’s simple enough so we can prove theorems about it. But we also want this model to be close enough to real-life computation so we can claim that the theorems we prove say something that’s relevant about real-life computation.

The general model of computation we will study is the *Turing machine*. We won’t go into the details right now but the Turing machine is easy to define and, despite the fact that it is very simple, it captures the essential operations of real-life digital computers.³

Once we have defined Turing machines, we will be able to prove that no Turing machine can solve the Halting Problem. And we will take this as clear evidence that no real-life computer program can solve the Halting Problem.

The above discussion was meant to give you a better idea of what theoretical computer science is. The discussion focused on computability theory, the study of which computational problems can and cannot be solved. It’s useful at this point to say a bit more about why theoretical computer science is worth studying (either as a student or as a researcher).

First, theoretical computer science provides critical guidance to applied computer scientists. For example, because the Halting Problem cannot be solved by any Turing machine, applied computer scientists do not waste their time trying to write programs that solves this problem, at least not in full generality. There are many other other examples, many of which are related to program verification.

Second, theoretical computer science involves concepts and techniques that have found important applications. For example, *regular expressions*, and algorithms that manipulate them, are used in compiler design and in the design of many programs that process input.

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³In fact, the Turing machine was used by its inventor, Alan Turing, as a basic mathematical blueprint for the first digital computers.
Third, theoretical computer science is intellectually interesting, which leads some people to study it just out of curiosity. This should not be underestimated: many important scientific and mathematical discoveries have been made by people who were mainly trying to satisfy their intellectual curiosity. A famous example is number theory, which plays a key role in the design of modern cryptographic systems. The mathematicians who investigated number theory many years ago had no idea that their work would make possible electronic commerce as we know it today.

The plan for the rest of these notes is as follows. The first part of the notes will focus on finite automata, which are essentially Turing machines without memory. The study of finite automata is good practice for the study of Turing machines. But we will also learn about the regular expressions we mentioned earlier. Regular expressions are essentially a way of describing patterns in strings. We will learn that regular expressions and finite automata are equivalent, in the sense that the patterns that can be described by regular expressions are also the patterns that can be recognized by finite automata. And we will learn algorithms that can convert regular expressions into finite automata, and vice-versa. These are the algorithms that are used in the design of programs, such as compilers, that process input. We will also learn how to prove that certain computational problems cannot be solved by finite automata, which also means that certain patterns cannot be described by regular expressions.

Next, we will study context-free grammars, which are essentially an extension of regular expressions that allows the description of more complex patterns. Context-free grammars are needed for the precise definition of modern programming languages and therefore play a critical role in the design of compilers.

The final part of these notes will focus on general Turing machines and will culminate in the proof that certain problems, such as the Halting Problem, cannot be solved by Turing machines.
Chapter 2

Finite Automata

In this chapter, we study a very simple model of computation called a finite automaton. Finite automata are useful for solving certain problems but studying finite automata is also good practice for the study of Turing machines, the general model of computation we will study later in these notes.

2.1 Turing Machines

As explained in the previous chapter, we need to define precisely what we mean by an algorithm, that is, what we mean when we say that something is computable. Such a definition is called a model of computation. As we said, we want a model that’s simple enough so we can prove theorems about it, but a model that’s also close enough to real-life computation so we can claim that the theorems we prove about our model say something that’s relevant about real-life computation.

A first idea for a model of computation is any of the currently popular high-level programming languages. C++, for example. A C++ program consists
of instructions and variables. We could define C++ precisely but C++ is not simple. It has complex instructions such as loops and conditional statements, which can be nested within each other, as well as various other features such as type conversions, parameter passing and inheritance.

A simpler model would be a low-level assembler or machine language. These languages are much simpler. They have no variables, no functions, no types and only very simple instructions. An assembler program is a linear sequence of instructions (no nesting). These instructions directly access data that is stored in memory or in a small set of registers. One of these registers is the program counter, or instruction counter, that keeps track of which instruction is currently being executed. Typical instructions allow you to set the contents of a memory location to a given value, or copy the contents of a memory location to another one. Despite their simplicity, it is widely accepted that anything that can be computed by a C++ program can be computed by an assembler program. The evidence is that we have compilers that translate C++ programs into assembler.

But it is possible to define an even simpler model of computation. In this model, instructions can no longer access memory locations directly by specifying their address. Instead, we have a memory head that points to a single memory location. Instructions can access the data under the memory head and then move the head one location to the right or one location to the left. In addition, there is only one type of instruction in this model. Each instruction specifies, for each possible value that could be stored in the current memory location (the one under the memory head), a new value to be written at that location as well as the direction in which the memory head should be moved. For example, if $a, b, c$ are the possible values that could be stored in each memory location, the table in Figure 2.1 describes one possible instruction. Such a table is called a transition table. A program then consists of a simple loop that executes one of these instructions.
This is a very simple model of computation but we may have gone too far: since the value we write in each memory location depends only on the contents of that memory location, there is no way to copy a value from one memory location to another. To fix this without reintroducing more complicated instructions, we simply add to our model a special register we call the state of the program. Each instruction will now have to consider the current state in addition to the current memory location. A sample transition table is shown in Figure 2.2, assuming that $q_0, q_1, q_2$ are the possible states.

The model we have just described is called the Turing machine. (Each “program” in this model is considered a “machine”.) To complete the description of the model, we need to specify a few more details. First, we restrict our atten-
CHAPTER 2. FINITE AUTOMATA

tion to decision problems, which are computational problems in which the input is a string and the output is the answer to some yes/no question about the input. The Halting Problem mentioned in the previous chapter is an example of a decision problem.

Second, we need to describe how the input is given to a Turing machine, how the output is produced by the machine, and how the machine terminates its computation. For the input, we assume that initially, the memory of the Turing machine contains the input and nothing else. For the output, each Turing machine will have special yes and no states. Whenever one of these states is entered, the machine halts and produces the corresponding output. This takes care of termination too.

Figure 2.3 shows a Turing machine. The control unit consists of the transition table and the state.

The Turing machine is the standard model that is used to study computation mathematically. (As mentioned earlier, the Turing machine was used by its inventor, Alan Turing, as a basic mathematical blueprint for the first digital computers.) The Turing machine is clearly a simple model but it is also relevant
to real-life computations because it is fairly easy to write a C++ program that can simulate any Turing machine, and because Turing machines are powerful enough to simulate typical assembler instructions. This last point will become clearer later in these notes when we take a closer look at Turing machines.

2.2 Introduction to Finite Automata

Before studying general Turing machines, we will study a restriction of Turing machines called finite automata. A finite automaton is essentially a Turing machine without memory. A finite automaton still has a state and still accesses its input one symbol at a time but the input can only be read, not written to, as illustrated in Figure 2.4. We will study finite automata for at least three reasons. First, this will help us understand what can be done with the control unit of a Turing machine. Second, this will allow us to learn how to study computation mathematically. Finally, finite automata are actually useful for solving certain types of problems.
Here are a few more details about finite automata. First, in addition to being read-only, the input must be read from left to right. In other words, the input head can only move to the right. Second, the computation of a finite automaton starts at the beginning of the input and automatically ends when the end of the input is reached, that is, after the last symbol of the input has been read. Finally, some of the states of the automaton are designated as accepting states. If the automaton ends its computation in one of those states, then we say that the input is accepted. In other words, the output is yes. On the other hand, if the automaton ends its computation in a non-accepting state, then the input is rejected — the output is no.

Now that we have a pretty good idea of what a finite automaton is, let’s look at a couple of examples. A valid C++ identifier consists of an underscore or a letter followed by any number of underscores, letters and digits. Consider the problem of determining if an input string is a valid C++ identifier. This is a decision problem.

Figure 2.5 shows the transition table of a finite automaton that solves this problem. As implied by the table, the automaton has three states. State $q_0$ is the start state of the automaton. From that state, the automaton enters state $q_1$ if it the first symbol of the input is an underscore or a letter. The automaton will
remain in state $q_1$ as long as the input consists of underscores, letter and digits. In other words, the automaton finds itself in state $q_1$ if the portion of the string it has read so far is a valid C++ identifier.

On the other hand, the automaton enters state $q_2$ if it has decided that the input cannot be a valid C++ identifier. If the automaton enters state $q_2$, it will never be able to leave. This corresponds to the fact that once we see a character that causes the string to be an invalid C++ identifier, there is nothing we can see later that could fix that. A non-accepting state from which you cannot escape is sometimes called a garbage state.

State $q_1$ is accepting because if the computation ends in that state, then this implies that the entire string is a valid C++ identifier. The start state is not an accepting state because the empty string, the one with no characters, is not a valid identifier.

Let’s look at some sample strings. When reading the string input_file, the automaton enters state $q_1$ and remains there until the end of the string. Therefore, this string is accepted, which is correct. On the other hand, when reading the string input-file, the automaton enters state $q_1$ when it sees the first i but then leaves for state $q_2$ when it encounters the dash. This will cause the string to be rejected, which is correct since dashes are not allowed in C++ identifiers.

A finite automaton can also be described by using a graph. Figure 2.6 shows the transition graph of the automaton for valid C++ identifiers. Each state is represented by a node in this graph. Each edge connects two states and is labeled by an input symbol. If an edge goes from $q$ to $q'$ and is labeled $a$, this indicates that when in state $q$ and reading an $a$, the automaton enters state $q'$. Each such step is called a move or a transition (hence the terms transition table and transition graph). The start state is indicated with an arrow and the accepting states have a double circle.
Figure 2.6: The transition graph of a finite automaton that determines if the input is a valid C++ identifier
2.2. INTRODUCTION TO FINITE AUTOMATA

Figure 2.7: A finite automaton that determines if the input is a correctly formatted phone number

Transition graphs and transition tables provide exactly the same information. But the graphs make it easier to visualize the computation of the automaton, which is why we will draw transition graphs whenever possible. There are some circumstances, however, where it is impractical to draw a graph. We will see examples later.

Let’s consider another decision problem, the problem of determining if an input string is a phone number in one of the following two formats: 7 digits, or 3 digits followed by a dash and 4 digits. Figure 2.7 shows a finite automaton that solves this problem. The transition label \(d\) stands for digit.

In a finite automaton, from every state, there should be a transition for every possible input symbol. This means that the graph of Figure 2.7 is missing many transitions. For example, from state \(q_0\), there is no transition labeled \(-\) and there is no transition labeled by a letter. All those missing transitions correspond to cases in which the input string should be rejected. Therefore, we can have all of those missing transitions go to a garbage state. We chose not to draw those transitions and the garbage state simply to avoid cluttering the diagram unnecessarily.

It is interesting to compare the finite automata we designed in this section with C++ programs that solve the same problems. For example, Figure 2.8 shows an algorithm that solves the C++ identifier problem. The algorithm is
if (end of input) return no
read char c
if (c is not underscore or letter) return no
while (not end of input)
    read char c
    if (c is not underscore, letter or digit) return no
return yes

Figure 2.8: A simple algorithm that determines if the input is a valid C++ identifier

described in pseudocode, which is simpler than C++. But even by looking at pseudocode, the simplicity of finite automata is evident. The pseudocode algorithm uses variables and different types of instructions. The automaton, on the other hand, consists of only states and transitions. This is consistent with what we said earlier, that Turing machines, and therefore finite automata, are a much simpler model of computation that a typical high-level programming language.

At the beginning of this section, we said that finite automata can be useful for solving certain problems. This relies on the fact that finite automata can be easily converted into programs, as shown in Figure 2.9. All that we need to add to this algorithm is a function `start_state()` that returns the start state of the finite automaton, a function `next_state(q, c)` that, for every pair `(q, c)` where `q` is a state and `c` is an input character, returns the next state according to the transition table (or graph) of the finite automaton, and a function `is_accepting(q)` that returns `true` if state `q` is an accepting state.

Therefore, a possible strategy for solving a decision problem is to design a finite automaton and then convert it to a pseudocode algorithm as explained above. In some cases, this can be easier than designing a pseudocode algorithm directly, for several reasons. One is that the simplicity of the finite automa-
q = start_state()
while (not end of input)
    read symbol c
    q = next_state(q, c)
if (is_accepting(q))
    return yes
else
    return no

Figure 2.9: An algorithm that simulates a finite automaton

A finite automaton model can help us focus more clearly on the problem itself, without being distracted by the various features that can be used in a high-level pseudocode algorithm. Another reason is that the computation of a finite automaton can be visualized by its transition graph, making it easier to understand what is going on. Finally, when designing a finite automaton we have to include transitions for every state and every input symbol. This helps to ensure that we consider all the necessary cases. This strategy of designing finite automata and then converting them to algorithms is used in the design of compilers and other programs that perform input processing.

Study Questions

2.2.1. Can finite automata solve problems that high-level pseudocode algorithms cannot?

2.2.2. What are three advantages of finite automata over high-level pseudocode algorithms?
Exercises

2.2.3. Consider the problem of determining if a string is an integer in the following format: an optional minus sign followed by at least one digit. Design a finite automaton for this problem.

2.2.4. Consider the problem of determining if a string is a number in the following format: an optional minus sign followed by at least one digit, or an optional minus sign followed by any number of digits, a decimal point and at least one digit. Design a finite automaton for this problem.

2.2.5. Suppose that a valid C++ identifier is no longer allowed to consist of only underscores. Modify the finite automaton of Figure 2.6 accordingly.

2.2.6. Add optional area codes to the phone number problem we saw in this section. That is, consider the problem of determining if a string is a phone number in the following format: 7 digits, or 10 digits, or 3 digits followed by a dash and 4 digits, or 3 digits followed by a dash, 3 digits, another dash and 4 digits. Design a finite automaton for this problem.

2.2.7. Convert the finite automaton of Figure 2.6 into a high-level pseudocode algorithm by using the technique explained in this section. That is, write pseudocode for the functions starting_state(), next_state(q, c) and is_accepting(q) of Figure 2.9.

2.2.8. Repeat the previous exercise for the finite automaton of Figure 2.7. (Don’t forget the garbage state.)
2.3 Formal Definition

In this section, we define precisely what we mean by a finite automaton. This is necessary for proving mathematical statements about finite automata and for writing programs that manipulate finite automata.

From the discussion of the previous section, it should be clear that a finite automaton consists of four things:

- A finite set of states.
- A special state called the starting state.
- A subset of states called accepting states.
- A transition table or graph that specifies a next state for every possible pair (state, input character).

Actually, to be able to specify all the transitions, we also need to know what the possible input symbols are. This information should also be considered part of the finite automaton:

- A set of possible input symbols.

We can also define what it means for a finite automaton to accept a string: run the algorithm of Figure 2.9 and accept if the algorithm returns yes.

The above definition of a finite automaton and its operation should be pretty clear. But it has a couple of problems. The first one is that it doesn’t say exactly what a transition table or graph is. That wouldn’t be too hard to fix but the second problem with the above definition is more serious: the operation of the finite automaton is defined in terms of a high-level pseudocode algorithm. For this definition to be complete, we would need to also define what those algorithms are. But recall that we are interested in finite automata mainly because
they are supposed to be easy to define. Finite automata are not going to be simpler than another model if their definition includes a definition of that other model.

In the rest of this section, we will see that it is possible to define a finite automaton and its operation without referring to either graphs or algorithms. This will be our formal definition of a finite automaton, in the sense that it is precise and complete. The above definition, in terms of a graph and an algorithm, will be considered an informal definition.

The formal definition of a finite automaton will be done as a sequence of definitions. The purpose of most of these is only to define useful terms.

**Definition 2.1** An alphabet is a finite set whose elements are called symbols.

This definition allows us to talk about the “input alphabet” of a finite automaton instead of having to say the “set of possible input symbols” of a finite automaton. In this context, symbols are sometimes also called letters or characters, as we did in the previous section.

**Definition 2.2** A deterministic finite automaton (DFA) is a 5-tuple \((Q, \Sigma, \delta, q_0, F)\) where

1. \(Q\) is a finite set of states.\(^1\)
2. \(\Sigma\) is an alphabet called the input alphabet.
3. \(\delta : Q \times \Sigma \rightarrow Q\) is the transition function.
4. \(q_0 \in Q\) is the starting state.

---

\(^1\)It would be more correct to say that \(Q\) is a finite set whose elements are called states, as we did in the definition of an alphabet. But this shorter style is easier to read.
5. $F \subseteq Q$ is the set of accepting states.

Note that this definition is for deterministic finite automata. We will encounter another type of finite automata later in these notes.

**Example 2.3** Consider the DFA shown in Figure 2.6. Here is what this DFA looks like according to the formal definition. The DFA is $\left( \{q_0, q_1, q_2\}, \Sigma, \delta, q_0, \{q_1\} \right)$ where $\Sigma$ is the set of all characters that appear on a standard keyboard and $\delta$ is defined as follows:

\[
\delta(q_0, c) = \begin{cases} 
q_1 & \text{if } c \text{ is an underscore or a letter} \\
q_2 & \text{otherwise}
\end{cases}
\]

\[
\delta(q_1, c) = \begin{cases} 
q_1 & \text{if } c \text{ is an underscore, a letter or a digit} \\
q_2 & \text{otherwise}
\end{cases}
\]

\[
\delta(q_2, c) = q_2, \text{ for every } c \in \Sigma.
\]

When a DFA is described as a 5-tuple, as in the formal definition, we call this a formal description of the DFA. In a formal description, the transition function is often described by a set of equations, as in the previous example. An alternative is a table, as shown in Figure 2.5. But equations are often more concise and easier to understand.

As we saw earlier, DFA’s can also be described by transition graphs, as shown in Figure 2.6. Compared with formal descriptions, transition graphs have the advantage of helping us visualize the computation of the automaton. But there are situations where transition graphs are not practical. In those cases, we resort to a formal description. We will see an example in the next section.
We now define what it means for a DFA to accept its input string. Without referring to an algorithm. Instead, we will only talk about the sequence of states that the DFA goes through while processing its input string.

**Definition 2.4** A string over an alphabet $A$ is a finite sequence of symbols from $A$.

The length of a string is the number of symbols it contains. Note that a string can be empty: the empty string has length 0 and contains no symbols. In these notes, we will use $\varepsilon$ to denote the empty string.

**Definition 2.5** Let $M = (Q, \Sigma, \delta, q_0, F)$ be a DFA and let $w = w_1 \cdots w_n$ be a string of length $n$ over $\Sigma$.² Let $r_0, r_1, \ldots, r_n$ be the sequence of states defined by

\[
\begin{align*}
    r_0 &= q_0 \\
    r_i &= \delta(r_{i-1}, w_i), \text{ for } i = 1, \ldots, n.
\end{align*}
\]

Then $M$ accepts $w$ if and only if $r_n \in F$.

Note how the sequence of states is defined by only referring to the transition function, without referring to an algorithm that computes that sequence of states.

Each DFA solves a problem by accepting some strings and rejecting the others. Another way of looking at this is to say that the DFA recognizes a set of strings, those that it accepts.

**Definition 2.6** A language over an alphabet $A$ is a set of strings over $A$.

**Definition 2.7** The language recognized by a DFA $M$ (or the language of $M$) is the following set:

\[ L(M) = \{ w \in \Sigma^* \mid w \text{ is accepted by } M \} \]

²It is understood here that $w_1, \ldots, w_n$ are the individual symbols of $w$. 
where \( \Sigma \) is the input alphabet of \( M \) and \( \Sigma^* \) denotes the set of all strings over \( \Sigma \).

The languages that are recognized by DFA's are called regular.

**Definition 2.8** A language is regular if it is recognized by some DFA.

Many interesting languages are regular but we will soon learn that many others are not. Those languages require algorithms that are more powerful than DFA's.

**Study Questions**

2.3.1. What is the advantage of the formal definition of a DFA over the informal definition presented at the beginning of this section?

2.3.2. What is an alphabet?

2.3.3. What is a DFA?

2.3.4. What is a string?

2.3.5. What does it mean for a DFA to accept a string?

2.3.6. What is a language?

2.3.7. What does it mean for a language to be recognized by a DFA?

2.3.8. What is a regular language?
Exercises

2.3.9. Give a formal description of the DFA of Figure 2.7. (Don’t forget the garbage state.)

2.3.10. Give a formal description of the DFA of Exercise 2.2.3.

2.3.11. Give a formal description of the DFA of Exercise 2.2.4.

2.4 More Examples

The examples of DFA’s we have seen so far, in the text and in the exercises, have been inspired by real-world applications. We now take a step back and consider what else can DFA’s do. We will see several languages that may not have obvious applications but that illustrate basic techniques that are useful in the design of DFA’s.

Unless otherwise specified, in the examples of this section the input alphabet is \{0, 1\}.

Example 2.9 Figure 2.10 shows a DFA for the language of strings that start with 1.

Example 2.10 Now consider the language of strings that end in 1. One difficulty here is that there is no mechanism in a DFA that allows us to know whether the symbol we are currently looking at is the last symbol of the input string. So we have to always be ready, as if the current symbol was the last one. What this means is that after reading every symbol, we have to be in an accept state if and only if the portion of the input string we’ve seen so far is in the language.

\[3\]To paraphrase a well-known quote attributed to Jeremy Schwartz, “Read every symbol as if it were your last. Because one day, it will be.”
Figure 2.10: A DFA for the language of strings that start with 1

Figure 2.11 shows a DFA for this language. Strings that begin in 1 lead to state $q_1$ while strings that begin in 0 lead to state $q_2$. Further 0’s and 1 cause the DFA to move between these states as needed.

Notice that the starting state is not an accepting state because the empty string, the string of length 0 that contains no symbols, does not end in 1. But then, states $q_0$ and $q_2$ play the same role in the DFA: they’re both non-accepting states and the transitions coming out of them lead to the same states. This implies that these states can be merged to get the slightly simpler DFA shown in Figure 2.12.

**Example 2.11** Consider the language of strings of length at least two that begin and end with the same symbol. A DFA for this language can be obtained by combining the ideas of the previous two examples, as shown in Figure 2.13

**Example 2.12** Consider the language of strings that contain the string 001 as a substring. What this means is that the symbols 0, 0, 1 occur consecutively within the input string. For example, the string 0100110 is in the language but 0110110 is not.
Figure 2.11: A DFA for the language of strings that end in 1

Figure 2.12: A simpler DFA for the language of strings that end in 1
Figure 2.13: A DFA for the language of strings of length at least two that begin and end with the same symbol
Figure 2.14 shows a DFA for this language. The idea is that the DFA remembers the longest prefix of 001 that ends the portion of the input string that has been seen so far. For example, initially, the DFA has seen nothing, so the starting state corresponds to the empty string. If the DFA then sees a 0, it moves to state \( q_1 \). If it then sees a 1, then the portion of the input string that the DFA has seen so far ends in 01, which is not a prefix of 001. So the DFA goes back to state \( q_0 \).

**Example 2.13** Consider the language of strings that contain an even number of 1’s. Initially, the number of 1’s is 0, which is even. After seeing the first 1, that number will be 1, which is odd. After seeing each additional 1, the DFA will toggle back and forth between even and odd. This idea leads to the DFA shown in Figure 2.15. Note how the input symbol 0 never affects the state of the DFA. We say that in this DFA, and with respect to this language, the symbol is neutral.

**Example 2.14** The above example can be generalized. A number is even if it is a multiple of 2. So consider the language of strings that contain a number of 1’s that’s a multiple of 3. The idea is to count modulo 3, as shown in Figure 2.16.
2.4. MORE EXAMPLES

Figure 2.15: A DFA for the language of strings that contain an even number of 1's

Figure 2.16: A DFA for the language of strings that contain a number of 1's that's a multiple of 3
Example 2.15 We can generalize this even further. For every number \( k \geq 2 \), consider the language of strings that contain a number of 1’s that’s a multiple of \( k \). Note that this defines an infinite number of languages, one for every possible value of \( k \). Each one of those languages is regular since, for every \( k \geq 2 \), a DFA can be constructed to count modulo \( k \), as shown in Figure 2.17.

Example 2.16 Let’s go back the modulo 3 counting example and generalize it in another way. Suppose that the input alphabet is now \( \{0, 1, 2, \ldots, 9\} \) and consider the language of strings that have the property that the sum of their digits is a multiple of 3. For example, \( 315 \) is in the language because \( 3 + 1 + 5 = 9 \) is a multiple of 3. The idea is still to count modulo 3 but there are now more cases to consider, as shown in Figure 2.18.

Example 2.17 Now let’s go all out and combine the generalizations of the last two examples. That is, over the alphabet \( \{0, 1, 2, \ldots, 9\} \), for every number \( k \), let’s consider the language of strings that have the property that the sum of their digits is a multiple of \( k \). Once again, the idea is to count modulo \( k \). For example, Figure 2.19 shows the DFA for \( k = 4 \).
It should be pretty clear that a DFA exists for every \( k \). But the transition diagram would be difficult to draw and it would likely be ambiguous. This is an example where we are better off describing the DFA “in words”, that is, by giving a formal description. Here it is: the DFA is \((Q, \Sigma, \delta, q_0, F)\) 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 \( c \in \Sigma \),

\[
\delta(q_i, c) = q_j, \quad \text{where } j = (i + c) \mod k.
\]
Figure 2.19: A DFA for the language of strings whose digits add to a multiple of 4
2.4. MORE EXAMPLES

Figure 2.20: DFA’s for the languages $\Sigma^*$, $\emptyset$ and $\{\epsilon\}$

important languages $\Sigma^*$ (the language of all strings), $\emptyset$ (the empty language) and $\{\epsilon\}$ (the language that contains only the empty string). The DFA’s are shown in Figure 2.20.

Exercises

2.4.1. Modify the DFA of Figure 2.13 so that strings of length 1 are also accepted.

2.4.2. Give DFA’s for the following languages. In all cases, the alphabet is $\{0, 1\}$.

   a) The language of strings of length at least two that begin with 0 and end in 1.

   b) The language of strings of length at least two that have a 1 as their second symbol.

   c) The language of strings of length at least $k$ that have a 1 in position $k$. Do this in general, for every $k \geq 1$. (You did the case $k = 2$ in part (b).)

2.4.3. Give DFA’s for the following languages. In all cases, the alphabet is $\{0, 1\}$.

   a) The language of strings of length at least two whose first two symbols are the same.
b) The language of strings of length at least two whose last two symbols are the same.

c) The language of strings of length at least two that have a 1 in the second-to-last position.

d) The language of strings of length at least \( k \) that have a 1 in position \( k \) from the end. Do this in general, for every \( k \geq 1 \). (You did the case \( k = 2 \) in part (c).)

2.4.4. Give DFA’s for the following languages. In all cases, the alphabet is \{0, 1\}.

a) The language of strings that contain at least one 1.

b) The language of strings that contain exactly one 1.

c) The language of strings that contain at least two 1’s.

d) The language of strings that contain less than two 1’s.

e) The language of strings that contain at least \( k \) 1’s. Do this in general, for every \( k \geq 0 \). (You did the case \( k = 2 \) in part (c).)

2.4.5. Give DFA’s for the following languages. In both cases, the alphabet is the set of digits \{0, 1, 2, \ldots, 9\}.

a) The language of strings that represent a multiple of 3. For example, the string 036 is in the language because 36 is a multiple of 3.

b) The generalization of the previous language where 3 is replaced by any number \( k \geq 2 \).

2.4.6. This exercise asks you to show that DFA’s can add, at least when the numbers are presented in certain ways. Consider the alphabet that consists of symbols of the form \([abc]\) where \( a, b \) and \( c \) are digits. For example,
and are two of the symbols in this alphabet. If \( w \) is a string of digits, let \( n(w) \) denote the number represented by \( w \). For example, if \( w \) is the string 428, then \( n(w) \) is the number 428. Now give DFA’s for the following languages.

a) The language of strings of the form \([x_0y_0z_0]\) \([x_1y_1z_1]\) \(\cdots\) \([x_ny_nz_n]\) such that
\[
n(x_n \cdots x_1x_0) + n(y_n \cdots y_1y_0) = n(z_n \cdots z_1z_0).
\]
For example, \([279][864][102]\) is in the language because \(182 + 67 = 249\). (This language corresponds to reading the numbers from right to left and position by position. Note that this is how we “read” numbers when we add them by hand.)

b) The language of strings of the form \([x_ny_nz_n]\) \(\cdots\) \([x_1y_1z_1]\) \([x_0y_0z_0]\) such that
\[
n(x_n \cdots x_1x_0) + n(y_n \cdots y_1y_0) = n(z_n \cdots z_1z_0).
\]
For example, \([102][864][279]\) is in the language because \(182 + 67 = 249\). (This time, the numbers are read from left to right.)

2.5 Closure Properties

In the previous section, we considered the language of strings that contain the substring 001 and designed a DFA that recognizes it. The DFA is shown again in Figure 2.21. Suppose that we are now interested in the language of strings that do not contain the substring 001. Is that language regular?
CHAPTER 2. FINITE AUTOMATA

A quick glance at the DFA should reveal a solution: since strings that contain 001 end up in state 001 while strings that do not contain 001 end up in one of the other states, all we have to do is switch the acceptance status of every state in the above DFA to obtain a DFA for this new language. So the answer is, yes, the new language is regular.

This new language is the complement of the first one.\(^4\) And the above technique should work for any regular language \(L\): by switching the accepting states of a DFA for \(L\), we should get a DFA for \(\overline{L}\).

In a moment, we will show in detail that the complement of a regular language is always regular. This is an example of what is called a closure property.

**Definition 2.19** A set is closed under an operation if applying that operation to elements of the set results in an element of the set.

For example, the set of natural numbers is closed under addition and multiplication but not under subtraction or division because \(2 - 3\) is negative and \(1/2\) is not even an integer. The set of integers is closed under addition, subtraction

\(^4\)Note that to define precisely what is meant by the complement of a language, we need to know the alphabet over which the language is defined. If \(L\) is a language over \(\Sigma\), then its complement is defined as follows: \(\overline{L} = \{w \in \Sigma^* \mid w \notin L\}\). In other words, \(\overline{L} = \Sigma^* - L\).
and multiplication but not under division. The set of rational numbers is closed under those four operations but not under the square root operation since $\sqrt{2}$ is not a rational number.\(^5\)

**Theorem 2.20** The class of regular languages is closed under complementation.

**Proof** Suppose that $A$ is regular and let $M$ be a DFA for $A$. We construct a DFA $M'$ for $\overline{A}$.

Let $M'$ be the result of switching the accepting status of every state in $M$. More precisely, if $M = (Q, \Sigma, \delta, q_0, F)$, then $M' = (Q, \Sigma, \delta, q_0, Q - F)$. We claim that $L(M') = \overline{A}$.

To prove that, suppose that $w \in A$. Then, in $M$, $w$ leads to an accepting state. This implies that in $M'$, $w$ leads to the same state but this state is non-accepting in $M'$. Therefore, $M'$ rejects $w$.

A similar argument shows that if $w \notin A$, then $M'$ accepts $w$. Therefore, $L(M') = \overline{A}$. \(\square\)

Note that the proof of this closure property is constructive: it establishes the existence of a DFA for $\overline{A}$ by providing an algorithm that constructs that DFA. Proofs of existence are not always constructive. But when they are, the algorithms they provide are often useful.

At this point, it is natural to wonder if the class of regular languages is closed under other operations. A natural candidate is the union operation: if $A$ and $B$

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\(^5\)The proof of this fact is a nice example of a proof by contradiction and of the usefulness of basic number theory. Suppose that $\sqrt{2}$ is a rational number. Let $a$ and $b$ be positive integers such that $\sqrt{2} = a/b$. Since fractions can be simplified, we can assume that $a$ and $b$ have no common factors (other than 1). Now, the fact that $\sqrt{2} = a/b$ implies that $2 = a^2/b^2$ and that $2b^2 = a^2$. Therefore, $a$ is even and 4 divides $a^2$. But then, 4 must also divide $2b^2$, which implies that 2 divides $b$. Therefore, 2 divides both $a$ and $b$, contradicting the fact that $a$ and $b$ have no common factors.
are two languages over $\Sigma$, then the union of $A$ and $B$ is $A \cup B = \{w \in \Sigma^* \mid w \in A \text{ or } w \in B\}$.

For example, consider the language of strings that contain either a number of 0’s that’s even or a number of 1’s that’s even. Call this language $L$. It turns out that $L$ is the union of two languages we are familiar with:

$$L = L_1 \cup L_2$$

where

$$L_1 = \{w \in \{0, 1\}^* \mid w \text{ contains an even number of 0’s}\}$$

and

$$L_2 = \{w \in \{0, 1\}^* \mid w \text{ contains an even number of 1’s}\}$$

In particular, we already know how to construct DFA’s for $L_1$ and $L_2$. These DFA’s are the first two shown in Figure 2.22.

Now, a DFA for $L$ can be designed by essentially simulating the DFA’s for $L_1$ and $L_2$ in parallel. That is, let $M_1$ and $M_2$ be the DFA’s for $L_1$ and $L_2$. The DFA for $L$, which we will call $M$, will “store” the current state of both $M_1$ and $M_2$, and update these states according to the transition functions of these DFA’s. This can be implemented by having each state of $M$ be a pair that combines a state of $M_1$ with a state of $M_2$. The result is the third DFA shown in Figure 2.22.

The 0 transitions in $M$ toggle the first state in each pair between $q_0$ and $q_1$ (and between columns) while having no effect on the second state (and the

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6 We could also consider the union of languages that are defined over different alphabets. In that case, the alphabet for the union would be the union of the two underlying alphabets: if $A$ is a language over $\Sigma_1$ and $B$ is a language over $\Sigma_2$, then $A \cup B = \{w \in (\Sigma_1 \cup \Sigma_2)^* \mid w \in A \text{ or } w \in B\}$. In these notes, we will normally consider only the union of languages over the same alphabet because this keeps things simpler and because this is probably the most common situation that occurs in practice.
Figure 2.22: A DFA for the language of strings that contain an even number of 0’s, a DFA for the language of strings that contain an even number of 1’s, and a DFA for the union of these two languages.
row). This is consistent with the fact that 0 transitions toggle the state in $M_1$ and have no effect in $M_2$. The 1 transitions in $M$ toggle the second state in each pair between $r_0$ and $r_1$ (and between rows) while having no effect on the first state (and the column). This is consistent with the fact that 1 transitions toggle the state in $M_2$ and have no effect in $M_1$.

The accepting states of $M$ are those pairs that have $q_0$ has their first or $r_0$ as their second state. This is correct since $M$ should accept the input whenever either $M_1$ or $M_2$ accepts.

The above idea can be generalized to show that the union of any two regular languages is always regular.

**Theorem 2.21** The class of regular languages is closed under union.

**Proof** Suppose that $A_1$ and $A_2$ are regular and let $M_1$ and $M_2$ be DFA’s for these languages. We construct a DFA $M$ that recognizes $A_1 \cup A_2$.

The idea, as explained above, is that $M$ is going to simulate $M_1$ and $M_2$ in parallel. More precisely, if after reading a string $w$, $M_1$ would be in state $r_1$ and $M_2$ would be in state $r_2$, then $M$, after reading the string $w$, will be in state $(r_1, r_2)$.

Here are the full details. Suppose that $M_i = (Q_i, \Sigma, \delta_i, q_i, F_i)$, for $i = 1, 2$. Then let $M = (Q, \Sigma, \delta, q_0, F)$ where

$$Q = Q_1 \times Q_2$$

$$q_0 = (q_1, q_2)$$

$$F = \{(r_1, r_2) \mid r_1 \in F_1 \text{ or } r_2 \in F_2\}$$

and $\delta$ is defined as follows: for every $r_1 \in Q_1$, $r_2 \in Q_2$ and $a \in \Sigma$,

$$\delta((r_1, r_2), a) = (\delta_1(r_1, a), \delta_2(r_2, a))$$.
Because the start state of $M$ consists of the start states of $M_1$ and $M_2$, and because $M$ updates its state according to the transition functions of $M_1$ and $M_2$, it should be clear that after reading a string $w$, $M$ will be in state $(r_1, r_2)$ where $r_1$ and $r_2$ are the states that $M_1$ and $M_2$ would be in after reading $w$. Now, if $w \in A_1 \cup A_2$, then either $r_1 \in F_1$ or $r_2 \in F_2$, which implies that $M$ accepts $w$. The reverse is also true. Therefore, $L(M) = A_1 \cup A_2$. □

**Corollary 2.22** The class of regular languages is closed under intersection.

**Proof** In the proof of the previous theorem., change the definition of $F$ as follows:

$$F = \{(r_1, r_2) \mid r_1 \in F_1 \text{ and } r_2 \in F_2\}.$$ 

In other words, $F = F_1 \times F_2$. □

So we now know that the class of regular languages is closed under the three

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7 We could provide more details here, if we thought our readers needed them. The idea is to refer to the details in the definition of acceptance. Suppose that $w = w_1 \cdots w_n$ is a string of length $n$ and that $r_0, r_1, \ldots, r_n$ is the sequence of states that $M_1$ goes through while reading $w$. This means that $r_0 = q_1$ and that, for $i = 1, \ldots, n$,

$$r_i = \delta(r_{i-1}, w_i).$$

Suppose that $s_0, s_1, \ldots, s_n$ is the sequence of states that $M_2$ goes through while reading $w$. Again, this means that $s_0 = q_2$ and that, for $i = 1, \ldots, n$,

$$s_i = \delta(s_{i-1}, w_i).$$

Then $(r_0, s_0), (r_1, s_1), \ldots, (r_n, s_n)$ has to be the sequence of states that $M$ goes through while reading $w$ because $(r_0, s_0) = (q_1, q_2) = q_0$ and, for $i = 1, \ldots, n$,

$$(r_i, s_i) = (\delta_1(r_{i-1}, w_i), \delta_2(s_{i-1}, w_i)) = \delta((r_{i-1}, s_{i-1}), w_i).$$

Therefore, if after reading $w$, $M_1$ is in state $r_n$ and $M_2$ is in state $s_n$, then $M$ is in state $(r_n, s_n)$. 

We end this section with another operation that's specific to languages. If $A$ and $B$ are two languages over $\Sigma$, then the *concatenation* of $A$ and $B$ is

$$AB = \{x \ y \in \Sigma^* \mid x \in A \text{ and } y \in B\}.$$ 

That is, the concatenation of $A$ and $B$ consists of those strings we can form, in all possible ways, by taking a string from $A$ and appending to it a string from $B$.

For example, suppose that $A$ is the language of strings that consist of an even number of 0’s (no 1’s) and that $B$ is the language of strings that consist of an odd number of 1’s (no 0’s). That is,

$$A = \{0^k \mid k \text{ is even}\}$$

$$B = \{1^k \mid k \text{ is odd}\}$$

Then $AB$ is the language of strings that consist of an even number of 0’s followed by an odd number of 1’s:

$$AB = \{0^i \ 1^j \mid i \text{ is even and } j \text{ is odd}\}.$$ 

Here's another example that will demonstrate the usefulness of both the union and concatenation operations. Let $N$ be the language of numbers defined in Exercise 2.2.4: strings that consist of an optional minus sign followed by at least one digit, or an optional minus sign followed by any number of digits, a decimal point and at least one digit. Let $D^*$ denote the language of strings that consist of any number of digits. Let $D^+$ denote the language of strings that
consist of at least one digit. Then the language $N$ can be defined as follows:

$$ N = \{\epsilon, -\}D^+ \cup \{\epsilon, -\}D^* \{.\} D^+. $$

In other words, a language that took 33 words to describe can now be defined with a mathematical expression that’s about half a line long. In addition, the mathematical expression helps us visualize what the strings of the language look like.

The obvious question now is whether the class of regular languages is closed under concatenation? And whether we can prove this closure property constructively.

Closure under concatenation is trickier to prove than closure under complementation and closure under union. In many cases, it is easy to design a DFA for the concatenation of two particular languages. For example, Figure 2.23 shows a DFA for the language $AB$ mentioned above. (As usual, missing transitions go to a garbage state.) This DFA is essentially a DFA for $A$, on the left, connected to a DFA for $B$, on the right. As soon as the DFA on the left sees a 1 while in its accepting state, the computation switches over to the DFA on the right.

The above example suggests an idea for showing that the concatenation of
two regular languages is always regular. Suppose that $M_1$ and $M_2$ are DFA’s for $A$ and $B$. We want a DFA for $AB$ to accept a string in $A$ followed by a string in $B$. That is, a string that goes from the start state of $M_1$ to an accepting state of $M_1$, followed by a string that goes from the start state of $M_2$ to an accepting state of $M_2$. So what about we add to each accepting state of $M_1$ all the transitions that come out of the starting state of $M_2$? This is illustrated by Figure 2.24. (The new transitions are shown in a dashed pattern.) This will cause the accepting states of $M_1$ to essentially act as if they were the start state of $M_2$.

But there is a problem with this idea: the accepting states of $M_1$ may now have multiple transitions labeled by the same symbol. In other words, when the DFA reaches an accepting state of $M_1$, it may not know whether to continue computing in $M_1$ or whether to switch to $M_2$. And this is the key difficulty in proving closure under concatenation: given a string $w$, how can a DFA determine where to split $w$ into $x$ and $y$ so that $x \in A$ and $y \in B$? In the next chapter, we
2.5. CLOSURE PROPERTIES

will develop the tools we need to solve this problem.

Study Questions

2.5.1. What does it mean for a set to be closed under a certain operation?

2.5.2. What is the concatenation of two languages?

Exercises

2.5.3. Give DFA’s for the complement of each of the languages of Exercise 2.4.2.

2.5.4. Each of the following languages is the union or intersection of two simpler languages. In each case, give DFA’s for the two simpler languages and then use the pair construction from the proof of Theorem 2.21 to obtain a DFA for the more complex language. In all cases, the alphabet is \{0, 1\}.

   a) The language of strings of length at least two that have a 1 in their second position and also contain at least one 0.

   b) The language of strings that contain at least two 1’s or at least two 0’s.

   c) The language of strings that contain at least two 1’s and at most one 0.

   d) The language of strings that contain at least two 1’s and an even number of 0’s.

2.5.5. Give DFA’s for the following languages. In all cases, the alphabet is \{0, 1, \#\}.

   a) The language of strings of the form $0^i \# 1^j$ where $i$ is even and $j \geq 2$. 
b) The language of strings of the form $0^i 1^j$ where $i$ is even and $j \geq 2$. 


Chapter 3

Nondeterministic Finite Automata

So far, all our finite automata have been deterministic. This means that each one of their moves is completely determined by the current state and the current input symbol. In this chapter, we learn that finite automata can be nondeterministic. Nondeterministic finite automata are a useful tool for showing that languages are regular. They are also a good introduction to the important concept of nondeterminism.

3.1 Introduction

In this section, we introduce the concept of a nondeterministic finite automaton (NFA) through some examples. In the next section, we will formally define what we mean.

Consider again the language of strings that contain the substring 001. Figure 3.1 shows the DFA we designed in the previous chapter for this language.

Now consider the finite automaton of Figure 3.2. This automaton is not a DFA for two reasons. First, some transitions are missing. For example, state $q_1$
Figure 3.1: A DFA for the language of strings that contain the substring 001

Figure 3.2: An NFA for the language of strings that contain the substring 001
3.1. INTRODUCTION

has no transition labeled 1. If the NFA is in that state and the next input symbol is a 1, we consider that the NFA is stuck. It can’t finish reading the input string and is unable to accept it.

Second, some states have multiple transitions for the same input symbol. In the case of this NFA, there are two transitions labeled 0 coming out of state $q_0$. What this means is that when in that state and reading a 0, the NFA has a choice: it can stay in state $q_0$ or move to state $q_1$.

How does the NFA make that choice? We simply consider that if there is an option that eventually leads the NFA to accept the input string, the NFA will choose that option. In this example, if the input string contains the substring 001, the NFA will wait in state $q_0$ until it reaches an occurrence of the substring 001 (there may be more than one), move to the accepting state as it reads the substring 001, and then finish reading the input string while looping in the accepting state.

On the other hand, if the input string does not contain the substring 001, then the NFA will do something, but whatever it does will not allow it to reach the accepting state. That’s because to move from the start state to the accepting state requires that the symbols 0, 0 and 1 occur consecutively in the input string.

Here’s another example. Consider the language of strings that contain either a number of 0’s that’s even or a number of 1’s that’s even. In the previous chapter, we observed that this language is the union of two simpler languages and then used the pair construction to obtain the DFA of Figure 2.22.

An NFA for this language is shown in Figure 3.3. It combines the DFA’s of the two simpler languages in a much simpler way than the pair construction.

This NFA illustrates another feature that distinguishes NFA’s from DFA’s: transitions that are labeled $\epsilon$. The NFA can use these $\epsilon$ transitions without reading any input symbols. This particular NFA has two $\epsilon$ transitions, both coming out of the start state. This means that in its start state, the NFA has two options: it
Figure 3.3: An NFA for the language of strings that contain either a number of 0’s that’s even or a number of 1’s that’s even.

...can move to either state $q_{10}$ or state $q_{20}$. And it makes that choice before reading the first symbol of the input string.

This NFA operates as described earlier: given multiple options, if there is one that eventually leads the NFA to accept the input string, the NFA will choose that option. In this example, if the number of 1’s in the input string is even but the number of 0’s is not, the NFA will choose to move to state $q_{10}$. If instead the number of 0’s is even but the number of 1’s is not, the NFA will choose to move to state $q_{20}$. If both the number of 0’s and the number of 1’s are even, the NFA will choose to move to either state $q_{10}$ or $q_{20}$, and eventually accept either way. If neither the number of 0’s nor the number of 1’s is even, then the NFA will not be able to accept the input string.

Here’s one more example. Consider the language of strings of length at least 3 that have a 1 in position 3 from the end. We can design a DFA for this language...
Figure 3.4: A DFA for the language of strings of length at least 3 that have a 1 in position 3 from the end by having the DFA remember the last three symbols it has seen, as shown in Figure 3.4. The start state is $q_{000}$, which corresponds to assuming that the input string is preceded by 000. This eliminates special cases while reading the first two symbols of the input string.

Figure 3.5 shows an NFA for the same language. This NFA is surprisingly simpler than the DFA. If the input string does contain a 1 in position 3 from the end, the NFA will wait in the start state until it reaches that 1 and then move to the accepting state as it reads the last three symbols of the input string.

On the other hand, if the input string does not contain a 1 in position 3 from the end, then the NFA will either fall short of reaching the accepting state or it will reach it before having read the last symbol of the input string. In that case, it will be stuck, unable to finish reading the input string. Either way, the input string will not be accepted.
Figure 3.5: An NFA for the language of strings of length at least 3 that have a 1 in position 3 from the end

This example makes two important points. One is that NFA’s can be much simpler than DFA’s that recognize the same language and, consequently, it can be much easier to design an NFA than a DFA. Second, we consider that an NFA accepts its input string only if it is able to read the entire input string.

To summarize, an NFA is a finite automaton that may have missing transitions, multiple transitions coming out of a state for the same input symbol, and transitions labeled $\epsilon$ that can be used without reading any input symbol. An NFA accepts a string if there is a way for the NFA to read the entire string and end up in an accepting state.

Earlier, we said that when confronted with multiple options, we consider that the NFA makes the right choice: if there is an option that eventually leads to acceptance, the NFA will choose it. Now, saying that the NFA makes the right choice, if there is one, does not explain how the NFA makes that choice. One way to look at this is to simply pretend that the NFA has the magical ability to make the right choice…

Of course, real computers aren’t magical. In fact, they’re deterministic. So a more realistic way of looking at the computation of an NFA is to imagine that the NFA explores all the possible options, looking for one that will allow it to accept the input string. So it’s not that NFA’s are magical, it’s that they are...
somewhat misleading: when we compare the NFA of Figure 3.5 with the DFA of Figure 3.4, the NFA looks much simpler but, in reality, it hides a large amount of computation.

So why are we interested in NFA’s if they aren’t a realistic model of computation? One answer is that they are useful. We will soon learn that there is a simple algorithm that can convert any NFA into an equivalent DFA, that is, one that recognizes the same language. And for some languages, it can be much easier to design an NFA than a DFA. This means that for those languages, it is much easier to design an NFA and then convert it to a DFA than to design the DFA directly.

Another reason for studying NFA’s is that they are a good introduction to the concept of nondeterminism. In the context of finite automata, NFA’s are no more powerful than DFA’s: they do not recognize languages that can’t already be recognized by DFA’s. But in other contexts, nondeterminism seems to result in additional computational power.

Without going into the details, here’s the most famous example. Algorithms are generally considered to be efficient if they run in polynomial time. There is a wide variety of languages that can be recognized by polynomial-time algorithms. But there are also many others that can be recognized by nondeterministic polynomial-time algorithms but for which no deterministic polynomial-time algorithm is known. It is widely believed that most of these languages cannot be recognized by deterministic polynomial-time algorithms. After decades of effort, researchers are still unable to prove this but their investigations have led to deep insights into the complexity of computational problems.¹

¹What we are referring to here is the famous P vs NP problem and the theory of NP-completeness. Let P be the class of languages that can be recognized by deterministic algorithms that run in polynomial time. Let NP be the class of languages that can be recognized by nondeterministic algorithms that run in polynomial time. Then proving that there are languages that can be recognized by nondeterministic polynomial-time algorithms but not by deterministic
Study Questions

3.1.1. What is an NFA?

3.1.2. What does it mean for an NFA to accept a string?

Exercises

3.1.3. Give NFA’s for the following languages. Each NFA should respect the specified limits on the number of states and transitions. (Transitions labeled with two symbols count as two transitions.) In all cases, the alphabet is \{0, 1\}.

   a) The language of strings of length at least two that begin with 0 and end in 1. No more than three states and four transitions.

   b) The language of strings of length at least two whose last two symbols are the same. No more than four states and six transitions.

   c) The language of strings of length at least two that have a 1 in the second-to-last position. No more than three states and five transitions.

   d) The language of strings of length at least \(k\) that have a 1 in position \(k\) from the end. Do this in general, for every \(k \geq 1\). No more than...
3.2 FORMAL DEFINITION

$k + 1$ states and $2k + 1$ transitions. (You did the case $k = 2$ in the previous part.)

e) The language of strings that contain exactly one 1. No more than two states and three transitions.

3.2 Formal Definition

In this section, we formally define what an NFA is. As was the case with DFA’s, a formal definition is necessary for proving mathematical statements about NFA’s and for writing programs that manipulate NFA’s.

As explained in the previous section, an NFA is a DFA that can have missing transitions, multiple transitions coming out of a state for the same input symbol, and transitions labeled $\epsilon$. The first two features can be captured by having the transition function return a set of states: $\delta(q, a)$ will be the set of options available to the NFA from state $q$ when reading symbol $a$. Note that this set can be empty. Transitions labeled $\epsilon$ can be described by extending the transition function: $\delta(q, \epsilon)$ will be the set of states that can be reached from state $q$ by $\epsilon$ transitions.

**Definition 3.1** A nondeterministic finite automaton (NFA) is a 5-tuple $(Q, \Sigma, \delta, q_0, F)$ where

1. $Q$ is a finite set of states.

2. $\Sigma$ is an alphabet called the input alphabet.

3. $\delta : Q \times (\Sigma \cup \epsilon) \rightarrow P(Q)$ is the transition function.

4. $q_0 \in Q$ is the starting state.
Figure 3.6: An NFA for the language of strings that contain the substring 001.

\[
\begin{array}{c|ccc}
\delta & 0 & 1 & \epsilon \\
\hline
q_0 & \{q_0, q_1\} & \{q_0\} & \emptyset \\
q_1 & \{q_2\} & \emptyset & \emptyset \\
q_2 & \emptyset & \{q_3\} & \emptyset \\
q_3 & \{q_3\} & \{q_3\} & \emptyset \\
\end{array}
\]

Figure 3.7: The transition function of the NFA of Figure 3.6.

5. \( F \subseteq Q \) is the set of accepting states.

Example 3.2 Consider the NFA shown in Figure 3.6. Here is the formal description of this NFA: 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 table shown in Figure 3.7.

Example 3.3 Consider the NFA shown in Figure 3.8. This NFA is
3.2. FORMAL DEFINITION

Figure 3.8: An NFA for the language of strings that contain either a number of 0’s that’s even or a number of 1’s that’s even.

\((Q, \{0, 1\}, \delta, q_0, F)\) where

\[
Q = \{q_0, q_{10}, q_{11}, q_{20}, q_{21}\}
\]

\[
F = \{q_{10}, q_{20}\}
\]

and \(\delta\) is defined by the table shown in Figure 3.9. Note that in this table, we omitted the braces and used a dash (\(-\)) instead of the empty set symbol (\(\emptyset\)). We will often do that to avoid cluttering the tables.

We now define what it means for an NFA to accept an input string. We first do this for NFA’s that don’t contain any \(\varepsilon\) transitions.

In the case of DFA’s (see Definition 2.5), we were able to talk about the sequence of states that the DFA goes through while reading the input string. That was because that sequence was unique. But in the case of NFA’s, there may
be multiple sequences of states for each input string, depending on how many options the NFA has.

For example, consider the NFA of Figure 3.6. While reading the string \( w = 0001 \), the NFA could go through any of the following four sequences of states:

\[
\begin{array}{c|ccc}
\delta & 0 & 1 & \epsilon \\
\hline
q_0 & - & - & q_{10}, q_{20} \\
q_{10} & q_{10} & q_{11} & - \\
q_{11} & q_{11} & q_{10} & - \\
q_{20} & q_{21} & q_{20} & - \\
q_{21} & q_{20} & q_{21} & - \\
\end{array}
\]

Figure 3.9: The transition function of the NFA of Figure 3.8.

Two of those sequences end prematurely because the NFA is stuck, unable to read the next input symbol. The first sequence allows the NFA to read the entire input string but it ends in a non-accepting state. We consider that the NFA accepts because one of these four sequences, the third one, allows the NFA to read the entire input string and end in an accepting state.
3.2. **FORMAL DEFINITION**

**Definition 3.4** Let \( N = (Q, \Sigma, \delta, q_0, F) \) be an NFA without \( \epsilon \) transitions and let \( w = w_1 \cdots w_n \) be a string of length \( n \) over \( \Sigma \). Then \( N \) accepts \( w \) if and only if there is a sequence of states \( r_0, r_1, \ldots, r_n \) such that

\[
\begin{align*}
    r_0 &= q_0 \quad \text{(3.1)} \\
    r_i &\in \delta(r_{i-1}, w_i), \quad \text{for } i = 1, \ldots, n \quad \text{(3.2)} \\
    r_n &\in F. \quad \text{(3.3)}
\end{align*}
\]

Equations 3.1 and 3.2 assert that the sequence of states \( r_0, r_1, \ldots, r_n \) is one of the possible sequences of states that the NFA may go through while reading (all of) \( w \). Equation 3.3 says that this sequence of states leads to an accepting state.

We now define acceptance for NFA's that may contain \( \epsilon \) transitions. This is a little trickier. Figure 3.10 shows another NFA for the language of strings that contain the substring 001. Consider again the string \( w = 0001 \). The NFA accepts this string because it could go through the following sequence of states as it reads \( w \):

![NFA Diagram](image)

Figure 3.10: Another NFA for the language of strings that contain the substring 001
For the NFA to go through this sequence of states, the NFA needs to essentially “insert” an $\varepsilon$ between the first and second symbols of $w$. That is, it needs to view $w$ as $0\varepsilon001$.

Another possible sequence of states is

$$
\begin{array}{cccccc}
q_0 & \xrightarrow{0} & q_1 & \xrightarrow{0} & q_2 & \xrightarrow{1} q_3 \\
& & \varepsilon & & & \\
\end{array}
$$

In this case, the NFA inserts an $\varepsilon$ between the second and third symbols of $w$. That is, it views $w$ as $00\varepsilon01$.

A definition of acceptance for NFA’s with $\varepsilon$ transitions can be based on this idea of inserting $\varepsilon$ into the input string. Note that inserting $\varepsilon$ into a string does not change its “value”; that is, as strings, we have that $0001 = 0\varepsilon001 = 00\varepsilon01$. (In fact, for every string $x$, $x\varepsilon = \varepsilon x = x$. We say that $\varepsilon$ is an neutral element with respect to concatenation of strings.)

**Definition 3.5** Let $N = (Q, \Sigma, \delta, q_0, F)$ be an NFA and let $w = w_1 \cdots w_n$ be a string of length $n$ over $\Sigma$. Then $N$ accepts $w$ if and only if $w$ can be written as $y_1 \cdots y_m$, with $y_i \in \Sigma \cup \{\varepsilon\}$, for every $i = 1, \ldots, m$, and there is a sequence of states $r_0, r_1, \ldots, r_m$ such that

$$
\begin{align*}
  r_0 &= q_0 & (3.4) \\
  r_i &\in \delta(r_{i-1}, y_i), \quad \text{for } i = 1, \ldots, m & (3.5) \\
  r_m &\in F. & (3.6)
\end{align*}
$$

Note that in this definition, $m$ could be greater than $n$. In fact, $m - n$ equals the number of $\varepsilon$ transitions that the NFA needs to use to go through the sequence
of states $r_0, \ldots, r_m$ as it reads $w$. Once again, Equations 3.4 and 3.5 assert that this sequence of states is one of the possible sequences of states the NFA may go through while reading $w$, and Equation 3.6 says that this sequence of states leads to an accepting state.

**Exercises**

3.2.1. Give a formal description of the NFA of Figure 3.5.

3.2.2. Give a formal description of the NFA of Figure 3.10.

3.2.3. Consider the NFA of Figure 3.6. There are three possible sequences of states that this NFA could go through while reading all of the string 001001. What are they? Does the NFA accept this string?

3.2.4. Consider the NFA of Figure 3.10. There are seven possible sequences of states that this NFA could go through while reading all of the string 001001. What are they? Indicate where $\epsilon$’s need to be inserted into the string. Does the NFA accept this string?

### 3.3 Equivalence with DFA’s

Earlier in this chapter, we mentioned that there is a simple algorithm that can convert any NFA into an *equivalent* DFA, that is, one that recognizes the same language. In this section, we are going to learn what this algorithm is. Since DFA’s are just a special case of NFA’s, this will show that DFA’s and NFA’s recognize the same class of languages.

Consider the NFA of Figure 3.11. This NFA recognizes the language of strings that end in 1. It’s not the simplest possible NFA for this language, but if an
algorithm is going to be able to convert NFA's into DFA's, it has to be able to handle any NFA.

Now consider the input string \( w = 1101101 \). The diagram of Figure 3.12 shows all the possible ways in which the NFA could process this string. This diagram is called the \textit{computation tree} of the NFA on string \( w \). The nodes in this tree are labeled by states. The root of the tree (shown at the top) represents the beginning of the computation. Edges show possible moves that the NFA can make. For example, from the start state, the NFA has two options when reading symbol 1: stay in state \( q_0 \) or go to state \( q_1 \).

Some nodes in the computation tree are dead ends. For example, the node labeled \( q_1 \) at level 1 is a dead end because there is no 1 transition coming out of state \( q_1 \). (Note that the top level of a tree is considered to be level 0.)

The nodes at each level of the computation tree show all the possible states that the NFA could be in after reading a certain portion of the input string. For example, level 4 has nodes labeled \( q_0, q_1, q_0, q_1 \). These are the states that the NFA could be in after reading \( 1101 \).

The nodes at the bottom level show the states that the NFA could be in after reading the entire string. We can see that this NFA accepts this input string because the bottom level contains the accepting state \( q_1 \).
Figure 3.12: The computation tree of the NFA of Figure 3.11 on input string 1101101
Computation trees help us visualize all the possible ways in which an NFA can process a particular input string. But they also suggest a way of simulating NFAs: as we read the input string, we can move down the computation tree, figuring out what nodes occur at each of its levels. And we don’t need to remember the entire tree, only the nodes at the current level, the one that corresponds to the last input symbol that was read.\(^2\) For example, in the computation tree of Figure 3.12, after reading the string 1101, we would have figured out that the current level of the computation tree consists of states \(q_0, q_1, q_0, q_1\).

How would a DFA carry out this simulation? In the only other simulation we have seen so far, the pair construction of Theorem 2.21, the DFA \(M\) simulates the DFA’s \(M_1\) and \(M_2\) by keeping track of the state in which each of these DFA’s would be. Each of the states of \(M\) is a pair that combined a state of \(M_1\) with a state of \(M_2\).

In our case, we would have each state of the DFA that simulates an NFA be the sequence of states that appear at the current level of the computation tree of the NFA on the input string. However, as the computation tree of Figure 3.12 clearly indicates, the number of nodes at each level can grow. For example, if an NFA has two options at each move, which is certainly possible, then the bottom level of the tree would contain \(2^n\) nodes, where \(n\) is the length of the input string. This implies that there may be an infinite number of possible sequences of states that can appear at any level of the computation tree. Since the DFA has a finite number of states, it can’t have a state for each possible sequence.

A solution to this problem comes from noticing that most levels of the tree of Figure 3.12 contain a lot of repetition. And we only want to determine if an accepting state occurs at the bottom level of the tree, not how many times

\(^2\)Some of you may recognize that this is essentially a breadth-first search. At Clarkson, this algorithm and other important graph algorithms are normally covered in the courses CS344 Algorithms and Data Structures and CS447 Computer Algorithms.
3.3. EQUIVALENCE WITH DFA’S

it occurs, or how many different ways it can be reached from the start state. Therefore, as it reads the input string, the DFA only needs to remember the set of states that occur at the current level of the tree (without repetition). This corresponds to pruning the computation tree by eliminating duplicate subtrees, as shown in Figure 3.13. The pruning locations are indicated by dots (⋯).

Another way of looking at this is to say that as it reads the input string, the DFA simulates the NFA by keeping track of the set of states that the NFA could currently be in. If the NFA has \( k \) states, then there are \( 2^k \) different sets of states. Since \( k \) is a constant, \( 2^k \) is also a constant. This implies that the DFA can have a state for each set of states of the NFA.

Here are the details of the simulation, first for the case of NFA’s without \( \epsilon \) transitions.

**Theorem 3.6** Every NFA without \( \epsilon \) transitions has an equivalent DFA.

**Proof** Suppose that \( N = (Q, \Sigma, \delta, q_0, F) \) is an NFA without \( \epsilon \) transitions. As explained above, we construct a DFA \( M \) that simulates \( N \) by keeping track of the set of states that \( N \) could currently be in. More precisely, each state of \( M \) will be a set of states of \( N \). If after reading a string \( w \), \( R \) is the set of states that \( N \) could be in, then \( M \) will be in state \( R \).

We need to specify the start state, the accepting states and the transition function of \( M \). Initially, \( N \) can only be in its start state so the start state of \( M \) will be \( \{q_0\} \).

NFA \( N \) accepts a string \( w \) if and only if the set of states it could be in after reading \( w \) includes at least one accepting state. Therefore, the accepting states of \( M \) will be those sets \( R \) that contain at least one state from \( F \).

If \( R \) is the set of states that \( N \) can currently be in, then after reading one more symbol \( a \), \( N \) could be in any state that can be reached from a state in \( R \) by
Figure 3.13: The computation tree of Figure 3.12 with duplicate subtrees removed
3.3. EQUIVALENCE WITH DFA'S

a transition labeled $a$. That is, $N$ could be in any state in the following set:

$$\{q \in Q \mid q \in \delta(r, a), \text{ for some } r \in R\}.$$ 

Therefore, from state $R$, $M$ will have a transition labeled $a$ going to the state that corresponds to that set.

To summarize, the DFA $M$ is $(Q', \Sigma, \delta', q'_0, F')$ where

$$Q' = \mathcal{P}(Q)$$

$$q'_0 = \{q_0\}$$

$$F' = \{R \subseteq Q \mid R \cap F \neq \emptyset\}$$

and $\delta'$ is defined as follows: for every $R \subseteq Q$ and $a \in \Sigma$,

$$\delta'(R, a) = \bigcup_{r \in R} \delta(r, a)$$

From the above description of $M$, it should be clear that $L(M) = L(N)$. \hfill \Box

**Example 3.7** Let’s construct a DFA that simulates the NFA of Figure 3.11. We get $M = (Q', \{0, 1\}, \delta', q'_0, F')$ where

$$Q' = \{\emptyset, \{q_0\}, \{q_1\}, \{q_0, q_1\}\}$$

$$q'_0 = \{q_0\}$$

$$F' = \{\{q_1\}, \{q_0, q_1\}\}$$

and $\delta'$ is defined by the table shown in Figure 3.14.

The entries in this table were computed as follows. First, $\delta'(\emptyset, a) = \emptyset$ because an empty union gives an empty set. (This is consistent with the fact that no states can be reached from any of the states in an empty set.) Then $\delta'(\{q_0\}, a) =$
### Definition 3.8

The extension of a set of states $R$, denoted $E(R)$, is the set of states

$$E(R) = \{ s \in \Sigma^+ \mid \exists r \in R, \exists a \in \Sigma, r \rightarrow a r \}$$

where $\Sigma$ is the alphabet, $\rightarrow$ is the transition relation of the NFA, and $s$ is any string in $\Sigma^*$. The extension $E(R)$ includes all states reachable from states in $R$ through any number of transitions.

### Figure 3.14

The transition function of the DFA that simulates the NFA of Figure 3.11

<table>
<thead>
<tr>
<th>$\delta'$</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>${q_0}$</td>
<td>${q_0}$</td>
<td>${q_0, q_1}$</td>
</tr>
<tr>
<td>${q_1}$</td>
<td>${q_0}$</td>
<td>$\emptyset$</td>
</tr>
<tr>
<td>${q_0, q_1}$</td>
<td>${q_0}$</td>
<td>${q_0, q_1}$</td>
</tr>
</tbody>
</table>

### Figure 3.15

The transition diagram of the DFA. Note that state $\{q_1\}$ cannot be reached from the start state. This means that it can be removed from the DFA. And if state $\{q_1\}$ is removed, then state $\emptyset$ also becomes unreachable from the start state. So it can be removed too. This leaves us with the DFA of Figure 3.16. Note that apart from the names of the states, this DFA is identical to the DFA that we directly designed in the previous chapter (see Figure 2.12).
Figure 3.15: The DFA that simulates the NFA of Figure 3.11

Figure 3.16: A simplified DFA that simulates the NFA of Figure 3.11
Figure 3.17: An NFA for the language of strings that contain the substring 001 that can be reached from any state in $R$ by using any number of $\varepsilon$ transitions (none included).³

Example 3.9 Figure 3.17 shows an NFA for the language of strings that contain the substring 001. In this NFA, we have the following:

$$E(\{q_0\}) = \{q_0\}$$
$$E(\{q_1\}) = \{q_0, q_1\}$$
$$E(\{q_2\}) = \{q_0, q_1, q_2\}$$
$$E(\{q_2, q_3\}) = \{q_0, q_1, q_2, q_3\}.$$  

³This can be defined more formally as follows: $E(R)$ is the set of states $q$ for which there is a sequence of states $r_0, \ldots, r_k$, for some $k \geq 0$, such that

$$r_0 \in R$$
$$r_i \in \delta(r_{i-1}, \varepsilon), \quad \text{for } i = 1, \ldots, k$$
$$r_k = q.$$
Theorem 3.10 Every NFA has an equivalent DFA.

Proof Suppose that \( N = (Q, \Sigma, \delta, q_0, F) \) is an NFA. We construct a DFA \( M \) that simulates \( N \) pretty much as in the proof of the previous theorem. In particular, if \( R \) is the set of states that \( N \) could be in after reading a string \( w \) and using any number of \( \epsilon \) transitions, then \( M \) will be in state \( R \).

One difference from the previous theorem is that \( M \) will not start in state \( \{q_0\} \) but in state \( E(\{q_0\}) \). This will account for the fact that \( N \) can use any number of \( \epsilon \) transitions even before reading the first input symbol.

The other difference is that from state \( R \), \( M \) will have a transition labeled \( a \) going to state

\[
\{q \in Q \mid q \in E(\delta(r, a))\}, \text{ for some } r \in R.
\]

This will account for the fact that \( N \) can use any number of \( \epsilon \) transitions after reading each input symbol (including the last one).

This is what we get: \( M = (Q', \Sigma, \delta', q'_0, F') \) where

\[
Q' = \mathcal{P}(Q)
\]
\[
q'_0 = E(\{q_0\})
\]
\[
F' = \{R \subseteq Q \mid R \cap F \neq \emptyset\}
\]

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

\[
\delta'(R, a) = \bigcup_{r \in R} E(\delta(r, a)), \text{ for } R \subseteq Q \text{ and } a \in \Sigma.
\]

It should be clear that \( L(M) = L(N) \).

Example 3.11 Let's construct a DFA that simulates the NFA of Figure 3.17. The easiest way to do this by hand is usually to start with the transition table and proceed as follows:
<table>
<thead>
<tr>
<th>$\delta'$</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_0$</td>
<td>$q_0, q_1$</td>
<td>$q_0$</td>
</tr>
<tr>
<td>$q_1$</td>
<td>$q_0, q_1, q_2$</td>
<td>$-$</td>
</tr>
<tr>
<td>$q_2$</td>
<td>$-$</td>
<td>$q_3$</td>
</tr>
<tr>
<td>$q_3$</td>
<td>$q_3$</td>
<td>$q_3$</td>
</tr>
<tr>
<td>$q_0, q_1$</td>
<td>$q_0, q_1, q_2$</td>
<td>$q_0$</td>
</tr>
<tr>
<td>$q_0, q_1, q_2$</td>
<td>$q_0, q_1, q_2$</td>
<td>$q_0, q_3$</td>
</tr>
<tr>
<td>$q_0, q_3$</td>
<td>$q_0, q_1, q_3$</td>
<td>$q_0, q_3$</td>
</tr>
<tr>
<td>$q_0, q_1, q_3$</td>
<td>$q_0, q_1, q_2, q_3$</td>
<td>$q_0, q_3$</td>
</tr>
<tr>
<td>$q_0, q_1, q_2, q_3$</td>
<td>$q_0, q_1, q_2, q_3$</td>
<td>$q_0, q_3$</td>
</tr>
</tbody>
</table>

Figure 3.18: The transition function of the DFA that simulates the NFA of Figure 3.17

1. Compute $\delta'\left(\{r\}, a\right) = E(\delta(r, a))$ for the individual states $r$ of the NFA. Those values are shown in the top half of Figure 3.18.

2. Identify the start state. In this case it’s $E(\{q_0\}) = \{q_0\}$.

3. Add states as needed (to the bottom half of the table) until no new states are introduced. The value of the transition function for these states is computed from the values in the top half of the table by taking advantage of the following fact:

$$\delta'(R, a) = \bigcup_{r \in R} E(\delta(r, a)) = \bigcup_{r \in R} \delta'\left(\{r\}, a\right).$$
3.3. EQUIVALENCE WITH DFAS

Figure 3.19: A DFA that simulates the NFA of Figure 3.17

Note that in this table, we omitted the braces and used a dash (−) instead of the empty set symbol (∅).

All that we have left to do now is to identify the accepting states of the DFA. In this case, they’re the sets of states that contain \( q_3 \), the accepting state of the NFA.

Figure 3.19 shows the transition diagram of the DFA. Note that the three accepting states can be merged since all the transitions coming out of these states stay within this group of states. If we merged these states, then this DFA would be identical to the DFA we designed in the previous chapter (see Figure 2.14). □
Figure 3.20: An NFA for the language of strings that contain either a number of 0’s that’s even or a number of 1’s that’s even.

Example 3.12 Let’s construct a DFA that simulates the NFA of Figure 3.20. Figure 3.21 shows the transition table of the DFA. The start state is $E(\{q_0\}) = \{q_0, q_{10}, q_{20}\}$, which is why this state is the first one that appears in the bottom half of the table. The accepting states are all the states that contain either $q_{10}$ or $q_{20}$, the two accepting states of the NFA.

Note that states $\{q_0, q_{10}, q_{20}\}$ and $\{q_{10}, q_{20}\}$ could be merged since they are both accepting and their transitions lead to exactly the same states. If we did that, then we would find that this DFA is identical to the DFA we designed in the previous chapter by using the pair construction algorithm (see Figure 2.22).

By the way, since the NFA has 5 states, in principle, the DFA has $2^5 = 32$ states. But as the transition table indicates, there are only 5 states that are reachable from the start state.
### Figure 3.21: The transition function of the DFA that simulates the NFA of Figure 3.20

<table>
<thead>
<tr>
<th>$\delta'$</th>
<th>0</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_0$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$q_{10}$</td>
<td>$q_{10}$</td>
<td>$q_{11}$</td>
</tr>
<tr>
<td>$q_{11}$</td>
<td>$q_{11}$</td>
<td>$q_{10}$</td>
</tr>
<tr>
<td>$q_{20}$</td>
<td>$q_{21}$</td>
<td>$q_{20}$</td>
</tr>
<tr>
<td>$q_{21}$</td>
<td>$q_{20}$</td>
<td>$q_{21}$</td>
</tr>
<tr>
<td>$q_0, q_{10}, q_{20}$</td>
<td>$q_{10}, q_{21}$</td>
<td>$q_{11}, q_{20}$</td>
</tr>
<tr>
<td>$q_{10}, q_{21}$</td>
<td>$q_{10}, q_{20}$</td>
<td>$q_{11}, q_{21}$</td>
</tr>
<tr>
<td>$q_{11}, q_{20}$</td>
<td>$q_{11}, q_{21}$</td>
<td>$q_{10}, q_{20}$</td>
</tr>
<tr>
<td>$q_{10}, q_{20}$</td>
<td>$q_{10}, q_{21}$</td>
<td>$q_{11}, q_{20}$</td>
</tr>
<tr>
<td>$q_{11}, q_{21}$</td>
<td>$q_{11}, q_{20}$</td>
<td>$q_{10}, q_{21}$</td>
</tr>
</tbody>
</table>
In this section, we used the technique described in the proofs of Theorems 3.6 and 3.10 to convert three NFA’s into equivalent DFA’s. Does that mean that these proofs are constructive? Yes but with one caveat: in the proof of Theorem 3.10, we didn’t specify how to compute the extension of a set of states. This is essentially what is called a graph reachability problem. We will learn a graph reachability algorithm later in these notes.

Another observation. A language is regular if it is recognized by some DFA. This is the definition. But now we know that every NFA can be simulated by a DFA. We also know that a DFA is a special case of an NFA. Therefore, we get the following alternate characterization of regular languages:

**Corollary 3.13** A language is regular if and only if it is recognized by some NFA.

**Study Questions**

3.3.1. In an NFA, what is the extension of a state?

**Exercises**

3.3.2. Draw the computation tree of the NFA of Figure 3.6 on the input string 001001. Prune as needed.

3.3.3. By using the algorithm of this section, convert into DFA’s the NFA’s of Figures 3.22 and 3.23.

3.3.4. By using the algorithm of this section, convert into DFA’s the NFA’s of Figure 3.24.
Figure 3.22: NFA's for Exercise 3.3.3 (part 1 of 2)
d)

Figure 3.23: NFA’s for Exercise 3.3.3 (part 2 of 2)

a)

Figure 3.24: NFA’s for Exercise 3.3.4
3.4 Closure Properties

In Section 2.5, we proved that the class of regular languages is closed under complementation, union and intersection. We also discussed closure under concatenation, realized that this was more difficult to establish, and announced that we would learn the necessary tools in this chapter.

Well, that tool is the NFA. We saw a hint of that in the NFA of Figure 3.3. That NFA recognized the union of two languages and was designed as a combination of DFA's for those two languages. Now that we know that every NFA can be simulated by a DFA, this gives us another way of showing that the class of regular languages is closed under union.

**Theorem 3.14** The class of regular languages is closed under union.

**Proof** Suppose that $A_1$ and $A_2$ are regular and let $M_1$ and $M_2$ be DFA's for these languages. We construct an NFA $N$ that recognizes $A_1 \cup A_2$.

The idea is illustrated in Figure 3.25. We add to $M_1$ and $M_2$ a new start state that we connect to the old start states with $\epsilon$ transitions. This gives the NFA the option of processing the input string by using either $M_1$ or $M_2$. If $w \in A_1 \cup A_2$, then $N$ will choose the appropriate DFA and accept. And if $N$ accepts, it must be that one of the DFA's accepts $w$. Therefore, $L(N) = A_1 \cup A_2$.

The NFA can be described more precisely as follows. 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. (Otherwise, rename the states so the two sets become disjoint.) Let $q_0$ be a state not in $Q_1 \cup Q_2$. Then $N = (Q, \Sigma, \delta, q_0, F)$ where

$$Q = Q_1 \cup Q_2 \cup \{q_0\}$$

$$F = F_1 \cup F_2$$
Figure 3.25: An NFA for the union of two regular languages
and \( \delta \) is defined as follows:

\[
\delta(q, \epsilon) = \begin{cases} 
\{q_1, q_2\} & \text{if } q = q_0 \\
\emptyset & \text{otherwise}
\end{cases}
\]

\[
\delta(q, a) = \begin{cases} 
\{\delta_i(q, a)\} & \text{if } q \in Q_i \text{ and } a \in \Sigma \\
\emptyset & \text{if } q = q_0 \text{ and } a \in \Sigma.
\end{cases}
\]

In the previous chapter, we proved closure under union by using the pair construction. And we observed that the construction could be easily modified to prove closure under intersection. We can’t do this here: there is no known simple way to adapt the above construction for the case of intersection. But we can still easily prove closure under intersection by using De Morgan’s Law.

**Corollary 3.15** The class of regular languages is closed under intersection.

**Proof** Suppose that \( A_1 \) and \( A_2 \) are two languages. Then

\[
A_1 \cap A_2 = \overline{A_1 \cup A_2}.
\]

If \( A_1 \) and \( A_2 \) are regular, then \( \overline{A_1} \) and \( \overline{A_2} \) are regular, \( \overline{A_1 \cup A_2} \) is regular, and then so is \( \overline{A_1 \cup A_2} \). This implies that \( A_1 \cap A_2 \) is regular. \( \square \)

Let’s now turn to concatenation. Figure 2.24 illustrates one possible idea: connect DFA’s \( M_1 \) and \( M_2 \) in series by adding transitions so that the accepting states of \( M_1 \) act as the start state of \( M_2 \). By using \( \epsilon \) transitions, we can simplify this a bit.

**Theorem 3.16** The class of regular languages is closed under concatenation.
Figure 3.26: An NFA for the concatenation of two regular languages

**Proof** Suppose that \( A_1 \) and \( A_2 \) are regular and let \( M_1 \) and \( M_2 \) be DFA's for these languages. We construct an NFA \( N \) that recognizes \( A_1A_2 \).

The idea is illustrated in Figure 3.26. We add to the accepting states of \( M_1 \) \( \epsilon \) transitions to the start state of \( M_2 \). This gives \( N \) the option of “switching” to \( M_2 \) every time it enters one of the accepting states of \( M_1 \). We also make the accepting states of \( M_1 \) non-accepting.

Let’s make sure this really works. Suppose that \( w \in A_1A_2 \). That is, \( w = xy \) with \( x \in A_1 \) and \( y \in A_2 \). Then after reading \( x \), \( N \) will be in one of the accepting states of \( M_1 \). From there, it can use one of the new \( \epsilon \) transitions to move to the start state of \( M_2 \). The string \( y \) will then take \( N \) to one of the accepting states of \( M_2 \), causing \( N \) to accept \( w \).

Conversely, if \( w \) is accepted by \( N \), it must be that \( N \) uses one of the new \( \epsilon \) transitions. This means that \( w = xy \) with \( x \in A_1 \) and \( y \in A_2 \). Therefore, \( L(N) = A_1A_2 \).

The formal description of \( N \) is left as an exercise. \[ \square \]

We end this section by considering another operation on languages. If \( A \) is a
language over $\Sigma$, then the star of $A$ is the language

$$A^* = \{x_1 \cdots x_k \mid k \geq 0 \text{ and each } x_i \in A\}.$$ 

That is, $A^*$ consists of those strings we can form, in all possible ways, by taking any number of strings from $A$ and concatenating them together.\(^4\) Note that $\varepsilon$ is always in the star of a language because, by convention, $x_1 \cdots x_k = \varepsilon$ when $k = 0$.

For example, $\{0\}^*$ is the language of all strings that contain only 0’s: $\{\varepsilon, 0, 00, 000, \ldots\}$. And $\{0, 1\}^*$ is the language of all strings that can be formed with 0’s and 1’s: $\{\varepsilon, 0, 1, 00, 01, 10, 11, 000, \ldots\}$. Note that this definition of the star operation is consistent with our use of $\Sigma^*$ to denote the set of all strings over the alphabet $\Sigma$.

**Theorem 3.17** The class of regular languages is closed under the star operation.

**Proof** Suppose that $A$ is regular and let $M$ be a DFA that recognizes this languages. We construct an NFA $N$ that recognizes $A^*$.

The idea is illustrated in Figure 3.27. From each of the accepting states of $M$, we add $\varepsilon$ transitions that loop back to the start state.

We also need to ensure that $\varepsilon$ is accepted by $N$. One idea is to simply make the start state of $M$ an accepting state. But this doesn’t work, as one of the exercises asks you to demonstrate. A better idea is to add a new start state with an $\varepsilon$ transition to the old start state and make the new start state an accepting state.

If $w = x_1 \cdots x_k$ with each $x_i \in A$, then $N$ 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 $\varepsilon$ transitions (except after $x_k$).

\(^4\)The language $A^*$ is also sometimes called the *Kleene closure* of $A$. 
Conversely, if \( w \) is accepted by \( N \), then it must be that either \( w = \epsilon \) or 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 \( x_i \in A \). In either case, this implies that \( w \in A^* \). Therefore, \( L(N) = A^* \).

The formal description of \( N \) is left as an exercise. \( \square \)

**Study Questions**

3.4.1. What is the star of a language?

**Exercises**

3.4.2. Give a formal description of the NFA of the proof of Theorem 3.16.

3.4.3. Give a formal description of the NFA of the proof of Theorem 3.17.

3.4.4. The proof of Theorem 3.17 mentions the idea illustrated in Figure 3.28. From each of the accepting states of \( M \), we add \( \epsilon \) transitions that loop back to the start state. In addition, we make the start state of \( M \) accepting to ensure that \( \epsilon \) is accepted.
3.4. CLOSURE PROPERTIES

3.4.5. For every language $A$ over alphabet $\Sigma$, let

$$A^+ = \{x_1 \cdots x_k \mid k \geq 1 \text{ and each } x_i \in \Sigma^*\}.$$

Show that the class of regular languages is closed under the “plus” operation.

3.4.6. Show that a language is regular if and only if it can be recognized by some NFA with at most one accepting state.

3.4.7. If $w = w_1 \cdots w_n$ is a string of length $n$, let $w^R$ denote the reverse of $w$, that is, the string $w_n \cdots w_1$. The reverse $L^R$ of a language $L$ is defined as the language of strings $w^R$ where $w \in L$. Show that the class of regular languages is closed under reversal, that is, show that if $L$ is regular, then $L^R$ is also regular.
Chapter 4

Regular Expressions

In the previous two chapters, we studied two types of machines that recognize languages. In this chapter, we approach languages from a different angle: instead of recognizing them, we will describe them. We will learn that regular expressions allow us to describe languages precisely and, often, concisely. We will also learn that regular expressions are powerful enough to describe any regular language, that regular expressions can be easily converted to DFA’s, and that it is often easier to write a regular expression than to directly design a DFA or an NFA. This implies that regular expressions are useful not only for describing regular languages but also as a tool for obtaining DFA’s for these languages.

4.1 Introduction

Many of you are probably already familiar with regular expressions. For example, in the Unix or Linux operating systems, when working at the prompt (on a console or terminal) we can list all the PDF files in the current directory (folder) by using the command `ls *.pdf`. The string `ls` is the name of the command.
The string ∗.pdf is a regular expression. In Unix regular expressions, the star (\*) represents any string. So this command is asking for a list of all the files whose name consists of any string followed by the characters .pdf.

Another example is \texttt{rm project1\.*}. This removes all the files associated with Project 1, that is, all the files that have the name \texttt{project1} followed by any extension.

Regular expressions are convenient. They allow us to precisely and concisely describe many interesting patterns in strings. But note that a regular expression corresponds to a set of strings, those strings that possess the pattern. Therefore, regular expressions describe languages.

In the next section, we will define precisely what we mean by a regular expression. Our regular expressions will be a little different from Unix regular expressions. In the meantime, here are two examples that illustrate both the style of regular expressions we will use as well as the usefulness of regular expressions.

\textbf{Example 4.1} Consider the language of valid C++ identifiers. Recall that these are strings that begin with an underscore or a letter followed by any number of underscores, letters and digits. Figure 4.1 shows the DFA we designed earlier for this language. This DFA is not very complicated but a regular expression is even simpler. Let \textit{D} stand for any digit and \textit{L} for any letter. Then the valid C++ identifiers can be described as follows:

\[(\_ \cup L)(\_ \cup L \cup D)^*\].

This expression says that an identifier is an underscore or a letter followed by any number of underscores, letters and digits. Note how the star is used not to represent any string but as an \textit{operator} that essentially means “any number of”.

(It’s short for \textit{list}.)
Figure 4.1: A DFA for the set of valid C++ identifiers
We can make the regular expression more precise be defining what we mean with the symbols $L$ and $D$. Here too, regular expressions can be used:

$$L = a \cup b \cup c \cup \cdots \cup Z$$
$$D = 0 \cup 1 \cup 2 \cup \cdots \cup 9$$

Example 4.2 Consider the language of correctly formatted phone numbers. As before, what we mean are strings that consists of 7 digits, or 3 digits followed by a dash and 4 digits. Figure 4.2 shows the DFA we designed earlier for this language. Recall that in this DFA, the transition label $d$ stands for digit. For this language, we can give a regular expression that is not only simpler than the DFA but also much more concise:

$$D^7 \cup D^3 - D^4.$$ 

An integer $i$ used as an exponent essentially means “$i$ times”.

Compared to the description in words, the regular expression is much more concise since that description used 16 words. In addition, the regular expression allows us to better visualize the strings in the language.
4.2. FORMAL DEFINITION

Study Questions

4.1.1. What are three frequent advantages of regular expressions over descriptions in words (in a natural language such as English)?

4.1.2. What is a potential advantage of regular expressions over DFA’s?

4.1.3. What do a star and an integer exponent mean in a regular expression?

4.1.4. What does the union operator (∪) mean in a regular expression?

Exercises

4.1.5. Give regular expressions for the languages of the first four exercises of Section 2.2. (Note that ϵ can be used in a regular expression.)

4.2 Formal Definition

In this section, we formally define what a regular expression is and what a regular expression means, that is, the language that a regular expression describes.

Definition 4.3 We say that R is a regular expression over alphabet Σ if R is of one of the following forms:

1. $R = a$, where $a \in \Sigma$.

2. $R = \epsilon$.

3. $R = \emptyset$.

4. $R = (R_1 \cup R_2)$, where each $R_i$ is a regular expression over $\Sigma$. 
5. \( R = (R_1 \circ R_2) \), where each \( R_i \) is a regular expression over \( \Sigma \).

6. \( R = (R_1^* \) ), where \( R_1 \) is a regular expression over \( \Sigma \).

Note that, to be precise, these are fully parenthesized regular expressions. But parentheses can be omitted. In that case, we assume that the operations are left associative and that they have the following order of precedence: \( \ast \), then \( \circ \), then \( \cup \). In addition, the concatenation operator \( \circ \) is usually omitted: \( R_1R_2 \). So, for example,
\[
0 \cup 01 \cup 1^* = (0 \cup (01)) \cup (1^*)
\]
and
\[
0 \cup 01^* = 0 \cup (0(1^*)).
\]

**Definition 4.4** Suppose that \( R \) is a regular expression over \( \Sigma \). The language described by \( R \) (or the language of \( R \)) is defined as follows:

1. \( L(a) = \{a\}, \) if \( a \in \Sigma \).

2. \( L(\varepsilon) = \{\varepsilon\} \).

3. \( L(\emptyset) = \emptyset \).

4. \( L(R_1 \cup R_2) = L(R_1) \cup L(R_2) \).

5. \( L(R_1R_2) = L(R_1)L(R_2) \).

6. \( L(R_1^*) = L(R_1)^* \).

These are the basic regular expressions we will use in these notes. When convenient, we will augment them with the following “abbreviations”. If \( \Sigma = \).
\{a_1, \ldots, a_k\} is an alphabet, then \(\Sigma\) denotes the regular expression \(a_1 \cup \cdots \cup a_k\). If \(R\) is a regular expression, then \(R^+\) denotes the regular expression \(RR^*\), so that

\[
L(R^+) = L(R)L(R)^*
= \{x_1 \cdots x_k \mid k \geq 1 \text{ and each } x_i \in L(R)\}
= L(R)^+.
\]

If \(R\) is a regular expression and \(k\) is a positive integer, then \(R^k\) denotes \(R\) concatenated with itself \(k\) times.

### 4.3 More Examples

In this section, we give several additional examples of regular expressions. In fact, we give regular expressions for almost all the languages of the examples of Section 2.4. The regular expressions will not be necessarily much simpler than DFA’s or NFA’s for these languages, but they will be more concise.

**Example 4.5** In all of these examples, the alphabet is \(\Sigma = \{0, 1\}\).

1. The regular expression \(\Sigma^*\) describes the language of all strings over \(\Sigma\). In other words, \(L(\Sigma^*) = \Sigma^*\).

2. The language of all strings that begin with 1 is described by the regular expression \(1\Sigma^*\).

3. The language of all strings that end in 1 is described by \(\Sigma^*1\).

4. The language of strings of length at least two that begin and end with the same symbol is described by \(0\Sigma^*0 \cup 1\Sigma^*1\).
5. The language of strings that contain the substring 001 is described by \( \Sigma^*001\Sigma^* \).

6. The language of strings that contain an even number of 1's is described by \((0^*10^*1)^*0^*\).

7. The language of strings that contain a number of 1's that's a multiple of \( k \) is described by \(((0^*1)^k)^*0^*\).

\[ \square \]

**Example 4.6** If \( R \) is a regular expression, then

\[
L(R \cup \emptyset) = L(R) \\
L(R\emptyset) = \emptyset \\
L(R\epsilon) = L(R)
\]

In addition, \( L(\epsilon^*) = \{\epsilon\} \) and

\[
L(\emptyset^*) = \emptyset^* \\
= \{x_1 \cdots x_k \mid k \geq 0 \text{ and each } x_i \in \emptyset\} \\
= \{\epsilon\}
\]

since, as we said earlier, by convention, \( x_1 \cdots x_k = \epsilon \) when \( k = 0 \). \( \square \)

**Exercises**

4.3.1. Give a regular expression for the language of strings that begin and end with the same symbol. (Note that the strings may have length one.) The alphabet is \( \Sigma = \{0, 1\} \).
4.3.2. Give regular expressions for the languages of Exercise 2.4.2.

4.3.3. Give regular expressions for the languages of Exercise 2.4.3.

4.3.4. Give regular expressions for the languages of Exercise 2.4.4.

4.3.5. Give regular expressions for the complement of each of the languages of Exercise 2.4.2.

4.3.6. Give regular expressions for the languages of Exercise 2.5.4.

4.3.7. Give regular expressions for the languages of Exercise 2.5.5.

4.4 Converting Regular Expressions into DFA’s

In this section, we show that the languages that are described by regular expressions are all regular. And the proof of this result will be constructive: it will provide an algorithm for converting regular expression into NFA’s, which can then be converted into DFA’s by using the algorithm of the previous chapter. Combined with the fact that it is often easier to write a regular expression than to design a DFA or an NFA, this implies that regular expressions are useful as a tool for obtaining DFA’s for many languages.

**Theorem 4.7** If a language is described by a regular expression, then it is regular.

**Proof** Suppose that \( R \) is a regular expression. We construct an NFA \( N \) that recognizes \( L(R) \).

The construction is recursive. There are six cases that correspond to the six cases of Definition 4.3. If \( R = a \), where \( a \in \Sigma \), if \( R = \epsilon \), or if \( R = \emptyset \), then \( N \) is one of the NFA’s shown in Figure 4.3. These are the base cases.
If \( R = R_1 \cup R_2 \), if \( R = R_1 R_2 \), or if \( R = R_1^* \), then first recursively convert \( R_1 \) and \( R_2 \) into \( N_1 \) and \( N_2 \) and then combine or transform these NFA's into an NFA \( N \) for \( L(R) \) by using the constructions we used to prove the closure results of Section 3.4.

**Example 4.8** Recall the regular expression for the language of valid C++ identifiers:

\[
(\_ \cup L)(\_ \cup L \cup D)^*.
\]

Let's convert this regular expression into an NFA.

Figures 4.4 and 4.5 show the various steps. Step 1 shows the basic NFA's. Step 2 shows an NFA for \( \_ \cup L \). The NFA for \( \_ \cup L \cup D \) is similar. Step 3 shows an NFA for \( (\_ \cup L \cup D)^* \). Figure 4.5 shows the final result, the concatenation of the NFA's from Steps 2 and 3.

Note that we treated \( L \) and \( D \) as symbols even though they really are unions of symbols. What this means is that transitions labeled \( L \) and \( D \) are actually multiple transitions, one for each letter or digit.

**Exercises**

4.4.1. By using the algorithm of this section, convert the following regular expressions into NFA's. In all cases, the alphabet is \( \Sigma = \{0, 1\} \).

a) \( 0^* \cup 1^* \).
Figure 4.4: The conversion of the regular expression \((\_ \cup L)(\_ \cup L \cup D)^*\).
Figure 4.5: An NFA for the regular expression \((\_ \cup L)(\_ \cup L \cup D)^*\).
b) $0 \Sigma^* 0$.

c) $0^* 10^*$.

d) $(11)^*$.

4.4.2. Extend regular expressions by adding intersection and complementation operators, as in $R_1 \cap R_2$ and $\overline{R_1}$. Revise the formal definitions of Section 4.2 and then show that these extended regular expressions can only describe regular languages. (In other words, these extended regular expressions are no more powerful than the basic ones.)

4.5 Converting DFA’s into Regular Expressions

In the previous section, we learned that regular expressions can be converted into DFA’s. And we said that this was useful because it is often easier to write a regular expression than to design a DFA directly. Compiler-design tools, for example, take advantage of this fact: they take as input regular expressions that specify elements of a programming language and then convert those expressions into DFA’s that are eventually turned into code that is incorporated into a compiler. Another example is the standard library of the programming language JavaScript, which allows programmers to specify input string patterns by using regular expressions.

One question that then arises is whether this strategy of writing a regular expression and then converting it into a DFA applies to every regular language. In other words, are there languages that have DFA’s but no regular expression? If so, we would have to design DFA’s directly for those languages.

In this section and the next one, we will show that the answer is no: every language that has a DFA also has a regular expression. This shows that the
above strategy of writing regular expressions and converting them into DFA's is not more limited than the alternative of designing DFA's directly.

Once again, the proof of this result will be constructive: it will provide an algorithm that converts DFA’s into equivalent regular expressions. In principle, this algorithm could be useful. For example, there are languages for which it is easier to design a DFA directly than to write a regular expression. If what we needed for such a language was a regular expression, then it might be easier to design a DFA and convert it into a regular expression than to write a regular expression directly.

So we want an algorithm that converts DFA’s into regular expressions. Where should we start? Let’s start small. Let’s start with the smallest possible DFA’s and see how we can convert them into regular expressions.

There are two DFA’s that have only one state:

To keep things concrete, we’re assuming that the input alphabet \( \Sigma \) is \{0, 1\}. These DFA’s can be easily converted into regular expressions: \( \Sigma^* \) and \( \emptyset \). This was probably too easy to teach us much about the algorithm.

So let’s consider a DFA with two states:
A regular expression for this DFA can be written by allowing the input string to leave and return to the start state any number of times, and then go to the accepting state and stay there. There are two basic ways to leave the start state and return to it: either by reading a 0 or by reading a string of the form $11^*0$. There is only one way of going to the accepting state and staying there: by reading a string of the form $11^*$. So the resulting regular expression is $(0 \cup 11^*0)^*11^*$.

Here's another two-state DFA:

In this case, the regular expression is simpler: $(0 \cup 11^*0)^*$.

It could also be that both states of a two-state DFA are accepting, or that neither state is accepting. Those cases are easy to deal with: $\Sigma^*$ and $\emptyset$.

Now, it could be that some of the transitions are missing and that others are labeled by multiple symbols. For example,

In this case, there is only one way to leave the start state and return to it: by reading a string of the form $(0 \cup 1)^*0$. This leads to the regular expression $((0 \cup 1)^*0)(0 \cup 1)^*$. 
So transitions labeled with multiple symbols are easy to deal with. But any of the transitions in a two-state DFA can be missing. This would lead to a large number of cases. It would be much more convenient if we could come up with a single “formula” that covers all the cases.

This can be done by considering that missing transitions are actually there but labeled by the regular expression $\emptyset$. This makes sense because the set of symbols that allow us to use a missing transition is empty. In addition, we can consider that transitions labeled with multiple symbols are actually labeled by the union of those symbols. This too makes sense since that’s the regular expression that describes the set of symbols that allow us to use that transition. If we transform the previous DFA in this way, we get

\[
\begin{align*}
\emptyset & \quad 1 \\
0 \cup 1 & \quad 0
\end{align*}
\]

This DFA has the following general form:

In this DFA, each transition is labeled by a regular expression. That regular expression describes the set of strings that must be read for that transition to be used. Using our earlier reasoning, the set of strings accepted by this general
DFA is described by the following regular expression:

\[(R_1 \cup (R_2)(R_3)^*(R_4))^*(R_2)(R_3)^*\].

It is possible to double-check that the above regular expression is correct by considering all the ways in which any of the transitions could be labeled by the empty set. This would make extensive use of the following basic properties of regular expressions: \(R \cup \emptyset = \emptyset \cup R = R\), \(R\emptyset = \emptyset R = \emptyset\) and \(\emptyset^* = \{\varepsilon\}\).

Another possible general form for a two-state DFA is

\[
\begin{array}{c}
R_1 \\
\downarrow \\
R_2 \\
\downarrow \\
R_3 \\
\end{array}
\]

Again, using our earlier reasoning, this corresponds to the regular expression

\[(R_1 \cup (R_2)(R_3)^*(R_4))^*\].

So we now know how to handle any two-state DFA. Let’s move on to a DFA with three states, such as the one shown in Figure 4.6. To make things more interesting, the input alphabet is now \(\{a, b, c\}\). Coming up with a regular expression for this DFA seems much more complicated than for DFA’s with two states. So here’s an idea that may at first seem a little crazy: what about we try to remove the middle state of the DFA? If this could be done, then the DFA would have two states and we already know how to handle that.

To be able to remove state \(q_1\) from the DFA, we need to consider all the ways in which state \(q_1\) can be used to travel through the DFA. For example, state \(q_1\) can be used to go from state \(q_0\) to state \(q_2\). The DFA does that while reading a
string of the form $bb^*a$. The eventual removal of state $q_1$ can be compensated for by adding the option $bb^*a$ to the transition that goes directly from $q_0$ to $q_2$, as shown in Figure 4.7. Then, instead of going from $q_0$ to $q_2$ through $q_1$ while reading a string of the form $bb^*a$, we can now go directly from $q_0$ to $q_2$ while reading that same string.

Note that the resulting automaton is no longer a DFA because it now contains a transition that is labeled by a regular expression and that regular expression is not just $\emptyset$ or a union of symbols. But the meaning of this should be pretty clear: if a transition is labeled $R$, then that transition can be used while reading any string in the language described by $R$. In the next section, we will take the time to formally define this new kind of automaton and how it operates.

Another possibility that needs to be considered is that state $q_1$ can also be used to travel from state $q_0$ back to state $q_0$. The DFA does that while reading a string of the form $bb^*c$. Once again, the removal of state $q_1$ can be compensated for by adding to the transition that goes directly from $q_0$ back to $q_0$, as shown in Figure 4.8.

To be able to fully remove $q_1$ from the DFA, this compensation operation needs...
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Figure 4.7: Preparing to remove state $q_1$

Figure 4.8: Preparing to remove state $q_1$ (continued)
to be performed for every pair of states other than \( q_1 \). Once this is done and \( q_1 \) is removed, the result is the two-state automaton shown in Figure 4.9. And we already know how to convert a two-state automaton to a regular expression.

Here’s a general description of the compensation operation. Consider the top automaton of Figure 4.10. State \( q_1 \) is the one we want to remove. That state can be used to travel from \( q_2 \) to \( q_3 \) while reading a string of the form \((R_2)(R_3)^*(R_4)\). So we can compensate for the eventual removal of \( q_1 \) by adding the option \((R_2)(R_3)^*(R_4)\) to the transition going directly from \( q_2 \) to \( q_3 \), as shown in the second automaton of Figure 4.10.

Note that in Figure 4.10, transitions are labeled by regular expressions, not individual symbols. This allows us to deal with missing transitions and transitions labeled with multiple symbols, as explained earlier.

In Figure 4.10, it could also be that \( q_2 \) and \( q_3 \) are the same state. In that case, the transition going from \( q_2 \) to \( q_3 \) would be a loop.

Now, not all DFA’s with three states are similar to the DFA of Figure 4.6. For example, it could be that state \( q_1 \) is also an accepting state, as shown in Figure 4.11. Removing state \( q_1 \) would be problematic.

A solution is to modify the DFA so it has only one accepting state. This can be done by adding a new accepting state, new \( \epsilon \) transitions from the old accepting
4.5. CONVERTING DFA’S INTO REGULAR EXPRESSIONS

Figure 4.10: The compensation operation

Figure 4.11: A three-state DFA with two accepting states
states to the new one, and removing the accepting status of the old accepting states, as shown in Figure 4.12. Once the new accepting state is added, we can remove states \( q_1 \) and \( q_2 \), one by one, as before, and end up, once again, with an automaton with two states. The result is shown in Figure 4.13. The first automaton is the result of removing \( q_2 \). The second automaton is the result of removing \( q_1 \). That automaton is of the form

\[
R_1 = a \cup ca^*b \cup (b \cup ca^*c)(b \cup aa^*c)^*(c \cup aa^*b)
\]

and

\[
R_2 = ca^* \cup (b \cup ca^*c)(b \cup aa^*c)^*(\epsilon \cup aa^*).
\]
4.5. CONVERTING DFA'S INTO REGULAR EXPRESSIONS

Figure 4.13: Removing states \( q_2 \) and \( q_1 \) (in that order) from the automaton of Figure 4.12
This automaton is easy to convert into a regular expression: \((R_1)^*(R_2)\).

It’s interesting to note that the removal of states \(q_1\) and \(q_2\) from the automaton of Figure 4.12 resulted in a very simple two-state automaton. This is not an accident: when we add a new accepting state to an automaton in the way we described, the resulting two-state automaton is always of the form

\[
\begin{array}{c}
R_1 \\
\quad
\end{array}
\quad
\begin{array}{c}
\quad
R_2
\end{array}
\]

To see why, consider again Figure 4.10, which illustrates the compensation operation. If the new accepting state is involved in a compensation operation, it must be as state \(q_3\) because the new accepting state has no outgoing transitions. But then, it’s clear that the compensation operation does not add outgoing transitions to that state. Therefore, in the final two-state automaton, the new accepting state will not have any outgoing transitions. Because this results in a simpler two-state automaton, we will always add a new accepting state to the original automaton, even when it only has one accepting state.

In an automaton with three states, it could also be that the start state is an accepting state. But that’s not a problem since adding a new accepting state will turn the start state into a non-accepting state so we are back to the previous case.

So we now know how to handle any automaton with three states: add a new accepting state and then remove the two states that are not the start state or the new accepting state. This results in a simple two-state automaton that’s easy to convert to a regular expression.

What about an automaton with four states? We can simply use the same strategy: add a new accepting state and then remove the three states that are
not the start state or the new accepting state. And clearly, this can be extended to automata with any number of states. Here’s a complete description of the algorithm:

1. If the automaton has no accepting states, output $\emptyset$.

2. Add a new accepting state, together with new $\varepsilon$ transitions from the old accepting states to the new one. Remove the accepting status of the old accepting states.

3. Remove each state, one by one, except for the start state and the accepting state. This results in an automaton of the following form:

$$
\begin{array}{c}
\text{R}_1 \\
\text{R}_2
\end{array}
$$

4. Output $(R_1)^*(R_2)$.

This description of the algorithm is fairly informal. We will make it more precise in the next section.

**Exercises**

4.5.1. By using the algorithm of this section, convert into regular expressions the NFA’s of Figure 4.14.
Figure 4.14: NFA's for Exercise 4.5.1
4.6 Precise Description of the Algorithm

We now give a precise description of the algorithm of the previous section. Such a description is needed to carefully prove that the algorithm works. Or to code the algorithm.

The key step in the algorithm is the removal of each state other than the start state and the accepting state. This can be done by using the compensation operation we described in the previous section. In general, suppose we want to remove state $q_1$. Let $q_2$ and $q_3$ be two other states and consider the transitions that go from $q_2$ to $q_3$ either directly or through $q_1$, as shown in the first automaton of Figure 4.15. To compensate for the eventual removal of state $q_1$, we add the regular expression $(R_2)(R_3)^*(R_4)$ to the transition that goes directly from $q_2$ to $q_3$, as shown in the second automaton of Figure 4.15.

Note that the description of the compensation operation assumes that there is
exactly one transition going from a state to each other state. This is not the case in every finite automaton since there can be no transitions or multiple transitions going from one state to another. So the first step of the algorithm should actually be to transform the automaton so it has exactly one transition going from each state to every other state. This is easy to do, as explained in the previous section. If there is no transition from $q_1$ to $q_2$, add one labeled $\emptyset$. If there are multiple transitions labeled $a_1, \ldots, a_k$ going from $q_1$ to $q_2$, replace those transitions by a single transition labeled $a_1 \cup \cdots \cup a_k$.

In addition, as mentioned earlier, the compensation operation turns the automaton into one whose transitions are labeled by regular expressions. To be able to describe precisely this operation, and to convince ourselves that it works correctly, we need to define precisely this new type of automaton and how it operates. Here’s one way of doing it.

**Definition 4.9** A generalized nondeterministic finite automaton (GNFA) is a 5-tuple $(Q, \Sigma, \delta, q_0, F)$ where

1. $Q$ is a finite set of states.
2. $\Sigma$ is an alphabet called the input alphabet.
3. $\delta : Q \times Q \rightarrow \mathcal{R}$ is the transition function, where $\mathcal{R}$ is the set of all regular expressions over $\Sigma$.
4. $q_0 \in Q$ is the starting state.
5. $F \subseteq Q$ is the set of accepting states.

The only difference between this definition and that of an ordinary NFA is the specification of the transition function. In an NFA, the transition function takes a state and a symbol, or $\varepsilon$, and gives us a set of possible next states. In
contrast, in a GNFA, the transition function takes a pair of states and gives us the regular expression that labels the transition going from the first state to the second one. Note how this neatly enforces the fact that in a GNFA, there is exactly one transition going from each state to every other state.

**Example 4.10** Consider the NFA shown in Figure 4.16. This NFA is almost a GNFA. In fact, only two things prevent it from being a GNFA: there is no transition from $q_0$ to $q_0$ and there are two transitions going from $q_0$ to $q_1$ (one labeled 0, the other labeled 1). To turn this NFA into a GNFA, all we need to do is add a transition labeled $\emptyset$ from $q_0$ to $q_0$ and merge the two transitions going from $q_0$ to $q_1$ into a single transition labeled $0 \cup 1$.

Here is a formal description of the resulting GNFA: the GNFA is $(\{q_0, q_1\}, \{0, 1\}, \delta, q_0, \{q_2\})$ where $\delta$ is defined by the table shown in Figure 4.17.

We now define how a GNFA operates; that is, we define what it means for a GNFA to accept a string. The idea is that a string $w$ is accepted if the GNFA reads a sequence of strings $y_1, \ldots, y_k$ with the following properties:

1. This sequence of strings takes the GNFA through a sequence of states $r_0, r_1, \ldots, r_k$. 
2. This first state $r_0$ is the start state of the GNFA.

3. The last state $r_k$ is an accepting state.

4. The reading of each string $y_i$ is a valid move, in the sense that $y_i$ is in the language of the regular expression that labels the transition going from $r_{i-1}$ to $r_i$.

5. The concatenation of all the $y_i$'s corresponds to $w$.

All of this can be said more concisely, and more precisely, as follows:

**Definition 4.11** Let $N = (Q, \Sigma, \delta, q_0, F)$ be a GNFA and let $w$ be a string of length $n$ over $\Sigma$. Then $N$ accepts $w$ if and only if $w$ can be written as $y_1 \cdots y_k$, with each $y_i \in \Sigma^*$, and there is a sequence of states $r_0, r_1, \ldots, r_k$ such that

$$r_0 = q_0$$

$$y_i \in \delta(r_{i-1}, r_i), \text{ for } i = 1, \ldots, k$$

$$r_k \in F.$$
the state to be removed. For every other pair of states $q_2$ and $q_3$, let

$$
R_1 = \delta(q_2, q_3)
$$

$$
R_2 = \delta(q_2, q_1)
$$

$$
R_3 = \delta(q_1, q_1)
$$

$$
R_4 = \delta(q_1, q_3)
$$

as illustrated by the first automaton of Figure 4.15. Change to $R_1 \cup (R_2)(R_3)^*(R_4)$ the label of the transition that goes directly from $q_2$ to $q_3$, as shown in the second automaton of Figure 4.15. That is, set $\delta(q_2, q_3)$ to $R_1 \cup (R_2)(R_3)^*(R_4)$. Once all pairs $q_2$ and $q_3$ have been considered, remove state $q_1$ and all adjacent transitions (those that come into, or come out of, $q_1$).

And here’s a proof that this works:

**Lemma 4.12** If the state removal step is applied to GNFA $N$, then the resulting GNFA still recognizes $L(N)$.

**Proof** Let $N'$ be the GNFA that results from removing state $q_1$ from GNFA $N$. Suppose that $w \in L(N)$. If $w$ can be accepted by $N$ without traveling through state $q_1$, then $w$ is accepted by $N'$. Now suppose that to accept $w$, $N$ must travel through $q_1$. Suppose that in one such instance, $N$ reaches $q_1$ from $q_2$ and that it goes to $q_3$ after leaving $q_1$, as shown in the first automaton of Figure 4.15. Then $N$ travels from $q_2$ to $q_3$ by reading strings $y_1, \ldots, y_k$ such that

$$
y_1 \in L(R_2)
$$

$$
y_i \in L(R_3), \quad \text{for } i = 2, \ldots, k - 1
$$

$$
y_k \in L(R_4).
$$

This implies that $y_1 \cdots y_k \in L((R_2)(R_3)^*(R_4))$. In $N'$, the transition going directly
from $q_2$ to $q_3$ is now labeled $R_1 \cup (R_2)(R_3)^*(R_4)$. This implies that $N'$ can move directly from $q_2$ to $q_3$ by reading $y_1 \cdots y_k$. And this applies to every instance in which $N'$ goes through $q_1$ while reading $w$. Therefore, $N'$ still accepts $w$.

Now suppose that $w \in L(N')$. If $w$ can be accepted by $N'$ without using one of the relabeled transitions, then $w$ is accepted by $N$. Now suppose that to accept $w$, $N'$ must use one of the relabeled transitions. Suppose that in one such instance, $N'$ travels from $q_2$ to $q_3$ on a transition labeled $R_1 \cup (R_2)(R_3)^*(R_4)$, as shown in the second automaton of Figure 4.15. If $N'$ goes from $q_2$ to $q_3$ by reading a string $y \in L(R_1)$, then $N$ could have done the same. If instead $N'$ goes from $q_2$ to $q_3$ by reading a string $y \in L((R_2)(R_3)^*(R_4))$, then it must be that $y = y_1 \cdots y_k$ with

$$
\begin{align*}
y_1 &\in L(R_2) \\
y_i &\in L(R_3), \quad \text{for } i = 2, \ldots, k-1 \\
y_k &\in L(R_4).
\end{align*}
$$

This implies that $N$ can go from $q_2$ to $q_3$ while reading $y$ as long as it does it by going through $q_1$ while reading $y_1, \ldots, y_k$. This applies to every instance in which $N'$ uses a relabeled transition while reading $w$. Therefore, $N$ accepts $w$ and this completes the proof that $L(N') = L(N)$. □

So we now know for sure that the state removal step works. As described in the previous section, this step is repeated for every state except for the start state and the new accepting state. As explained in the previous section, this always results in a two-state GNFA of the following form:
We are now ready to describe the entire conversion algorithm and prove its correctness. The algorithm can actually convert arbitrary NFA’s, not just DFA’s.

**Theorem 4.13** If a language is regular, then it can be described by a regular expression.

**Proof** Suppose that $L$ is a regular language and that NFA $N$ recognizes $L$. We construct a regular expression $R$ that describes $L$ by using the following algorithm:

1. If $N$ has no accepting states, set $R = \emptyset$ and stop.

2. Transform $N$ into a GNFA. This can be done as follows. For every pair of states $q_1$ and $q_2$, if there is no transition from $q_1$ to $q_2$, add one labeled $\emptyset$. If there are multiple transitions labeled $a_1, \ldots, a_k$ going from $q_1$ to $q_2$, replace those transitions by a single transition labeled $a_1 \cup \cdots \cup a_k$.

3. Add a new accepting state to $N$, add new $\varepsilon$ transitions from the old accepting states to the new one and remove the accepting status of the old accepting states.

4. One by one, remove every state other than the start state or the accepting state. This can be done as follows. Let $q_1$ be the state to be removed. For
every other pair of states $q_2$ and $q_3$, let

$$R_1 = \delta(q_2, q_3)$$
$$R_2 = \delta(q_2, q_1)$$
$$R_3 = \delta(q_1, q_1)$$
$$R_4 = \delta(q_1, q_3)$$

as illustrated by the first automaton of Figure 4.15. Change to $R_1 \cup (R_2)(R_3)^*(R_4)$ the label of the transition that goes directly from $q_2$ to $q_3$, as shown in the second automaton of Figure 4.15. That is, set

$$\delta(q_2, q_3) = R_1 \cup (R_2)(R_3)^*(R_4).$$

Once all pairs $q_2$ and $q_3$ have been considered, remove state $q_1$.

5. The resulting GNFA is of the form

Set $R = (R_1)^*(R_2)$.

It is not hard to see that this algorithm is correct, mainly because each transformation of $N$ preserves the fact that $N$ recognizes $L$. In the case of the state removal step, this was established by the lemma. □
Exercises

4.6.1. Give a formal description of the GNFA of Figure 4.8.

4.6.2. Give a formal description of the GNFA of Figure 4.9.
Chapter 5

Nonregular Languages

In this chapter, we show that not all languages are regular. In other words, we show that there are languages that can’t be recognized by finite automata or described by regular expressions. We will learn to prove that particular languages are nonregular by using a general result called the Pumping Lemma.

5.1 Some Examples

So far in these notes, we have seen many examples of regular languages. In this section, we discover our first examples of nonregular languages. In all cases, the alphabet is \( \{0, 1\} \).

**Example 5.1** Consider the language of strings of the form \( 0^n1^n \), where \( n \geq 0 \). Call it \( L \). We know that languages such as \( \{0^i1^j \mid i,j \geq 2\} \) and \( \{0^i1^j \mid i \equiv j \pmod{3}\} \) are regular. But here we want to determine if \( i = j \). One strategy a DFA could attempt to use is to count the number of 0’s, count the number of 1’s and then verify that the two numbers are the same.
As we have seen before, one way that a DFA can count 0’s is to move to a different state every time a 0 is read. For example, if the initial state of the DFA is $q_0$, then the DFA could go through states $q_0, q_1, q_2, \ldots, q_n$ as it reads $n$ 0’s. Counting from 0 to $n$ requires $n + 1$ different states, and $n$ can be arbitrary large. But a DFA only has a finite number of states! If $n$ is greater than or equal to that number, then the DFA doesn’t have enough states to implement this strategy.

This argument shows that this particular strategy of counting the number of 0’s by using different states is not going to lead to a DFA that recognizes the language $L$. It’s hard to imagine how a DFA could recognize $L$ without counting the number of 0’s. But because we can’t think of a way doesn’t mean that one doesn’t exist. To prove that $L$ is not regular, we need a more general argument, one that shows that no DFA, using any strategy whatsoever, can recognize this language.

Such an argument can be constructed by considering the states that a DFA goes through as it reads the 0’s of a string of the form $0^n1^n$. Not every DFA counts 0’s but every DFA goes through states as it reads the input.

So suppose that $M$ recognizes $L$. Consider a string $w$ of the form $0^n1^n$. As $M$ reads the 0’s of $w$, it goes through a sequence of states $r_0, r_1, r_2, \ldots, r_n$. Choose $n$ to be equal to the number of states of $M$. Then there must be a repetition in the sequence.

Suppose that $r_i = r_j$ with $i < j$. Then the computation of $M$ on $w$ is as shown in Figure 5.1. That is, after reading $i$ 0’s, the DFA enters state $r_i$. After reading an additional $j-i$ 0’s, for a total of $j$ 0’s, the DFA returns to state $r_i$. From there, after reading the rest of $w$, which equals $0^{n-j}1^n$, the DFA reaches an accepting state.\(^1\)

\(^1\)Strictly speaking, when reading $0^{n-j}1^n$ from state $r_i$, $M$ will actually continue in the loop until the first 1 is read. The diagram of Figure 5.1 is only meant to illustrate the fact that after reading $0^{n-j}1^n$ from $r_i$, the DFA eventually reaches an accepting state.
Now, what Figure 5.1 makes clear is that \( M \) accepts not only \( w \) but also the string \( 0^i0^{n-j}1^n \), which is simply \( w \) with \( j-i \) 0’s removed. This string is accepted by \( M \) because after reading \( 0^i \), the DFA enters state \( r_i \). From there, after reading \( 0^{n-j}1^n \), the DFA again reaches the same accepting state that was reached when reading \( w \). In other words, when reading this string, \( M \) simply skips the loop shown in Figure 5.1.

But \( 0^i0^{n-j}1^n \) is not in \( L \) because it contains less 0’s than 1’s. So we have found a string that is accepted by \( M \) but does not belong to \( L \). This contradicts the fact that \( M \) recognizes \( L \) and shows that a DFA that recognizes \( L \) cannot exist. Therefore, \( L \) is not regular.

The argument we developed in this example can be used to show that other languages are not regular.

**Example 5.2** Let \( L \) be the language of strings of the form \( 0^i1^j \) where \( i \leq j \). Once again, suppose that \( L \) is regular. Let \( M \) be a DFA that recognizes \( L \) and let \( n \) be the number of states of \( M \).

Consider the string \( w = 0^n1^n \). As \( M \) reads the 0’s in \( w \), \( M \) goes through a sequence of states \( r_0, r_1, r_2, \ldots, r_n \). Because this sequence is of length \( n+1 \), there must be a repetition in the sequence.
Suppose that \( r_i = r_j \) with \( i < j \).\(^2\) Then the computation of \( M \) on \( w \) is once again as shown in Figure 5.1. And, once again, this implies that the string \( 0^i0^{n-j}1^n \) is also accepted. But since the number of 0’s has been reduced, this string happens to be in \( L \). So there is no contradiction...

So by skipping the loop, we get a string that is still in the language. Let’s try something else: let’s go around the loop twice. This corresponds to reading the string \( 0^i0^{j-i}0^{j-i}0^{n-j}1^n = 0^{n+(j-i)}1^n \). This string is also accepted by \( M \). However, since this string has more 0’s than 1’s, it is not in \( L \). This contradicts the fact that \( M \) recognizes \( L \). Therefore, \( M \) cannot exist and \( L \) is not regular. □

What this last example shows is that sometimes going around the loop more than once is the way to obtain a contradiction and make the argument work.

Here’s another example.

**Example 5.3** Let \( L \) be the language of strings of the form \( ww \) where \( w \) is any string over the alphabet is \( \{0,1\} \). Suppose that \( L \) is regular. Let \( M \) be a DFA that recognizes \( L \) and let \( n \) be the number of states of \( M \).

Consider the string \( w = 0^n0^n \). As \( M \) reads the 0’s in the first half of \( w \), \( M \) goes through a sequence of states \( r_0, r_1, r_2, \ldots, r_n \). Because this sequence is of length \( n + 1 \), there must be a repetition in the sequence.

Suppose that \( r_i = r_j \) with \( i < j \). Then the computation of \( M \) on \( w \) is as shown in Figure 5.2. This implies that the string \( 0^{2n-(j-i)} \) is also accepted. Unfortunately, we cannot conclude that this string is not in \( L \). In fact, if \( j - i \) is even, then this string is in \( L \) because the total number of 0’s would still be even.

\(^2\)Note that these \( i \) and \( j \) are not the same \( i \) and \( j \) that were used to define the language. It may have been clearer use different names in the definition of the language, for example, by saying that \( L \) is the language of strings of the form \( 0^s1^t \) where \( s \leq t \). But at some point, you start running out of convenient names. So you can just view the \( i \) and \( j \) in the definition of \( L \) as being local to that definition, just as in programming, variables can be local to a function, which allows you to reuse their names for other purposes outside of that function.
To fix this argument, note that if the string is still in $L$ after we delete some 0’s from its first half, it’s because the middle of the string will have shifted to the right. So we just need to pick a string $w$ whose middle cannot move…

Let $w = 0^n 10^n 1$. As before, we get a repetition within the first block of 0’s, as shown in Figure 5.3. This implies that the string $0^{n-(j-i)} 10^n 1$ is also accepted by $M$. If this string was in $L$, since its second half ends in 1, its first half would also have to end in 1. But then, the two halves would not be equal. So this string cannot be in $L$, which contradicts the fact that $M$ recognizes $L$. Therefore, $M$ does not exist and $L$ is not regular. $\square$

This last example makes the important point that the string $w$, that is, the string that we focus the argument on, sometimes has to be chosen carefully. In fact, this choice can sometimes be a little tricky.
Exercises

5.1.1. Show that the language \{0^n1^{2n} \mid n \geq 0\} is not regular.

5.1.2. Show that the language \{0^i1^j \mid 0 \leq i \leq 2j\} is not regular.

5.1.3. If \(w\) is a string, let \(w^R\) denote the reverse of \(w\). That is, if \(w = w_1 \cdots w_n\), then \(w^R = w_n \cdots w_1\). Show that the language \{ww^R \mid w \in \{0, 1\}^*\} is not regular.

5.2 The Pumping Lemma

In the previous section, we showed that three different languages are not regular. Each example involved its own particular details but all three arguments followed the same pattern and had a lot of details in common. In this section, we will isolate the common portion of these arguments and turn it into the proof of a general result about regular languages. In this way, the common details won’t need to be repeated each time we want to show that a language is not regular.

In all three examples, the proof that \(L\) is not regular went as follows. Suppose that \(L\) is regular. Let \(M\) be a DFA that recognizes \(L\) and let \(n\) be the number of states of \(M\).

Choose a string \(w \in L\) of length at least \(n\). (The choice of \(w\) depends on \(L\).) As \(M\) reads the first \(n\) symbols of \(w\), \(M\) goes through a sequence of states \(r_0, r_1, r_2, \ldots, r_n\). Because this sequence is of length \(n + 1\), there must be a repetition in the sequence.

Suppose that \(r_i = r_j\) with \(i < j\). Then the computation of \(M\) on \(w\) is as shown in Figure 5.4. More precisely, if \(w = w_1 \cdots w_m\), then \(x = w_1 \cdots w_i\), \(y = w_{i+1} \cdots w_j\) and \(z = w_{j+1} \cdots w_m\).
The fact that the reading of \( y \) takes \( M \) from state \( r_i \) back to state \( r_i \) implies that the strings \( xz \) and \( xy^2z \) are also accepted by \( M \). (In fact, it is also true that \( xy^kz \) is accepted by \( M \) for every \( k \geq 0 \).)

In each of the examples of the previous section, we then observed that one of the strings \( xz \) or \( xy^2z \) does not belong to \( L \). (The details depend on \( x, y, z \) and \( L \).) This contradicts the fact that \( M \) recognizes \( L \). Therefore, \( M \) cannot exist and \( L \) is not regular.

To summarize, the argument starts with a language \( L \) that is assumed to be regular and a string \( w \in L \) that is long enough. It then proceeds to show that \( w \) can be broken into three pieces, \( w = xyz \), such that \( xy^kz \in L \), for every \( k \geq 0 \).

There is more to it, though. In all three examples of the previous section, we also used the fact that the string \( y \) occurs within the first \( n \) symbols of \( w \). This is because a repetition is guaranteed to occur while \( M \) is reading the first \( n \) symbols of \( w \). This is useful because it gives us some information about the contents of \( y \). For example, in the case of the language \( \{0^n1^n\} \), this told us that \( y \) contained only 0’s, which meant that \( xz \) contained less 0’s than 1’s.

In addition, the above also implicitly uses the fact that \( y \) is not empty. And this is absolutely critical since, otherwise, \( xz \) would equal \( w \) and the fact that \( xz \) is accepted by \( M \) could not possibly lead to a contradiction.

So a more complete summary of the above argument is as follows. The argu-
ment starts with a language $L$ that is assumed to be regular and a string $w \in L$ that is long enough. It then proceeds to show that $w$ can be broken into three pieces, $w = xyz$, such that

1. The string $y$ can be pumped, in the sense that $xy^kz \in L$, for every $k \geq 0$.
2. The string $y$ occurs towards the beginning of $w$.
3. The string $y$ is nonempty.

In other words, the above argument proves the following result, which is called the Pumping Lemma:

**Theorem 5.4 (Pumping Lemma)** If $L$ is a regular language, then there is a number $p > 0$, called the pumping length, such that if $w \in L$ and $|w| \geq p$, then $w$ can be written as $xyz$ where

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

In a moment, we are going to see how the Pumping Lemma can be used to simplify proofs that languages are not regular. But first, here's a clean write-up of the proof of the Pumping Lemma.

**Proof** Let $L$ be a regular and let $M$ be a DFA that recognizes $L$. Let $p$ be the number of states of $M$. Now, suppose that $w$ is any string in $L$ with $|w| \geq p$. As $M$ reads the first $p$ symbols of $w$, $M$ goes through a sequence of states $r_0, r_1, r_2, \ldots, r_p$. Because this sequence is of length $p + 1$, there must be a repetition in the sequence.
Suppose that $r_i = r_j$ with $i < j$. Then the computation of $M$ on $w$ is as shown in Figure 5.4. In other words, if $w = w_1 \cdots w_m$, let $x = w_1 \cdots w_i$, $y = w_{i+1} \cdots w_j$ and $z = w_{j+1} \cdots w_m$. Clearly, $w = xyz$. In addition, $|xy| = j \leq p$ and $|y| = j - i > 0$, which implies that $y \neq \varepsilon$.

Finally, the fact that the reading of $y$ takes $M$ from state $r_i$ back to state $r_i$ implies that the string $xyz$ is accepted by $M$, and thus belongs to $L$, for every $k \geq 0$. \H

We now see how the Pumping Lemma can be used to prove that languages are not regular.

**Example 5.5** Let $L$ be the language $\{0^n1^n \mid n \geq 0\}$. Suppose that $L$ is regular. Let $p$ be the pumping length given by the Pumping Lemma. Consider the string $w = 0^p1^p$. 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. $xyz^k \in L$, 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 $xz$ cannot belong to $L$ because it contains less 0’s than 1’s. This contradicts Condition (3). So it must be that our initial assumption was wrong: $L$ is not regular. \H

It is interesting to compare this proof that $\{0^n1^n\}$ is not regular with the proof we gave in the first example of the previous section. The new proof is shorter
but, perhaps more importantly, it doesn’t need to establish that the string $y$ can be pumped. Those details are now hidden in the proof of the Pumping Lemma.\(^3\)

Here’s another example.

**Example 5.6** Let $L$ be the language of strings of the form $ww$. Suppose that $L$ is regular. Let $p$ be the pumping length given by the Pumping Lemma. Consider the string $w = 0^p1^p1$. 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. $y \neq \epsilon$.
3. $xy^kz \in L$, for every $k \geq 0$.

Condition (1) implies that $y$ contains only 0’s from the first half of $w$. Condition (2) implies that $y$ contains at least one 0. Therefore, $xz$ is of the form $0^i1^p1$ where $i < p$. This string is not in $L$, contradicting Condition (3). This implies that $L$ is not regular. \(\square\)

Here’s an example for a language of a different flavor.

**Example 5.7** Let $L$ be the language $\{1^{n^2} | n \geq 0\}$. That is, $L$ consists of strings of 1’s whose length is a perfect square. Suppose that $L$ is regular. Let $p$ be the pumping length. Consider the string $w = 1^{p^2}$. 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. $y \neq \epsilon$.

\(^3\)Yes, this is very similar to the idea of abstraction in software design.
3. $xy^kz \in L$, for every $k \geq 0$.

Consider the string $xy^2z$, which is equal to $1^{p^2+|y|}$. Since $|y| \geq 1$, for this string to belong to $L$, it must be that $p^2 + |y| \geq (p + 1)^2$, the first perfect square greater than $p^2$. But $|y| \leq p$ implies that $p^2 + |y| \leq p^2 + p = p(p + 1) < (p + 1)^2$. Therefore, $xy^2z$ does not belong to $L$, which contradicts the Pumping Lemma and shows that $L$ is not regular.

Here’s an example that shows that the Pumping Lemma must be used carefully.

**Example 5.8** Let $L$ be the language $\{1^n \mid n \text{ is even}\}$. Suppose that $L$ is regular. Let $p$ be the pumping length. Consider the string $w = 1^{2p}$. Clearly, $w \in L$ and $|w| \geq p$. Therefore, according to the Pumping Lemma, $w$ can be written as $xy^kz$ where

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

Let $y = 1$. Then $xz = 1^{2p-1}$ is of odd length and cannot belong to $L$. This contradicts the Pumping Lemma and shows that $L$ is not regular.

Of course, this doesn’t make sense because we know that $L$ is regular. So what did we do wrong in this “proof”? What we did wrong is that we chose the value of $y$. We can’t do that. All that we know about $y$ is what the Pumping Lemma says: $w = xyz$, $|xy| \leq p$, $y \neq \epsilon$ and $xy^kz \in L$, for every $k \geq 0$. This does not imply that $y = 1$.

To summarize, when using the Pumping Lemma to prove that a language is not regular, we are free to choose the string $w$ and the number $k$. But we cannot choose the number $p$ or the strings $x$, $y$ and $z$. \qed
One final example.

**Example 5.9** Let $L$ be the language of strings that contain an equal number of 0’s and 1’s. We could show that this language is nonregular by using the same argument we used for $\{0^n1^n\}$. However, there is a simpler proof. The key is to note that

$$L \cap 0^*1^* = \{0^n1^n\}.$$  

If $L$ was regular, then $\{0^n1^n\}$ would also be regular because the intersection of two regular languages is always regular. But $\{0^n1^n\}$ is not regular, which implies that $L$ cannot be regular. \hfill $\square$

This example shows that closure properties can also be used to show that languages are not regular. In this case, the fact that $L$ is nonregular became a direct consequence of the fact that $\{0^n1^n\}$ is nonregular.

Note that it is not correct to say that the fact that $\{0^n1^n\}$ is a subset of $L$ implies that $L$ is nonregular. Because the same argument would also imply that $\{0,1\}^*$ is nonregular. In other words, the fact that a language contains a non-regular language does not imply that the larger language is nonregular. What makes a language is nonregular is not the fact that it contains certain strings: it’s the fact that it contains certain strings while excluding certain others.

**Exercises**

5.2.1. Use the Pumping Lemma to show that the language $\{0^i1^j \mid i \leq j\}$ is not regular.

5.2.2. Use the Pumping Lemma to show that the language $\{1^i#1^j#1^{i+j}\}$ is not regular. The alphabet is $\{1,\#\}$. 
5.2.3. Exercise 2.4.6 asked you to show that DFA’s can add when the numbers are presented in a particular way. In contrast, this exercise asks you to show that DFA’s cannot add when the numbers are presented in a more usual way. That is, consider the language of strings of the form $x \# y \# z$ where $x$, $y$ and $z$ are strings of digits that, when viewed as numbers, satisfy the equation $x + y = z$. For example, the string $123\#47\#170$ is in this language because $123 + 47 = 170$. The alphabet is $\{0, 1, \ldots, 9, \#\}$. Use the Pumping Lemma to show that this language is not regular.

5.2.4. Let $L$ be the language of strings that start with $0$. What is wrong with the following “proof” that $L$ is not regular?

Suppose that $L$ is regular. Let $p$ be the pumping length. Suppose that $p = 1$. Consider the string $w = 01^p$. 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 $|xy| \leq p = 1$, it must be that $|y| \leq 1$. Since $y \neq \varepsilon$, it must be that $y = 0$. Therefore, $xz = 1^p \notin L$. This contradicts the Pumping Lemma and shows that $L$ is not regular.
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