

# Theory of Computation

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# 1 Finite Automata

## 1.1 Deterministic Finite Automata

A **deterministic finite automaton**<sup>1</sup> (DFA) is a 5-tuple  $(Q, \Sigma, \delta, q_0, F)$  where

- $Q$  is a finite set whose elements are **states**.
- $\Sigma$  is a finite **input alphabet**, whose elements are **input symbols**.
- $\delta: Q \times \Sigma \rightarrow Q$  is the **transition function**.
- $q_0 \in Q$  is the **start state** (or **initial state**).
- $F \subseteq Q$  is the set of **accept states** (or **final states**).

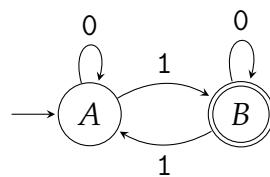
The transition function may be specified using a **transition table**, which has rows indexed by the states and columns indexed by the input symbols, with the entry in the row of  $q$  and column of  $s$  being the value of  $\delta(q, s)$ . See Example 1.1.

A DFA has a graphical representation as a directed graph in which each vertex is a state and each edge is a **transition**. That is, if  $\delta(q_1, s) = q_2$  (where  $q_1$  and  $q_2$  are states and  $s$  is an input symbol), then the graph has an edge labelled  $s$  from the vertex  $q_1$  to the vertex  $q_2$ . It is usual to depict the vertices by circles, with the vertex label (name of the state) written inside the circle, if necessary. The start state is indicated by an arrow without a source entering it, and accept states are indicated by using double-circles. See Example 1.1.

**Example 1.1.** Consider a DFA  $M = (Q, \Sigma, \delta, A, F)$ , where  $Q = \{A, B, C\}$ ,  $\Sigma = \{0, 1\}$ ,  $F = \{B\}$ , and  $\delta$  is as defined by the transition table given below.

$\delta$	0	1
A	A	B
B	B	A

The graphical representation of  $M$  is shown below.



An **input** to a DFA  $M = (Q, \Sigma, \delta, q_0, F)$  is a string over  $\Sigma$  – i.e. a finite sequence of symbols of  $\Sigma$ . If  $w = s_1s_2 \dots s_k$  is an input string, and  $q_1, q_2, \dots, q_k \in Q$  such that

$$\delta(q_0, s_1) = q_1, \delta(q_1, s_2) = q_2, \dots, \delta(q_{k-1}, s_k) = q_k,$$

then  $M$  is in the state  $q_k$  after reading the input  $w$ . If  $q_k \in F$  (i.e.  $q_k$  is an accept state), then  $M$  accepts  $w$ , otherwise it rejects  $w$ . For instance, the DFA  $M$  given in Example 1.1 is in the state  $A$  after reading the input  $0110$ , and is in the state  $B$  after reading  $0100$ . Since  $A \notin F$  and  $B \in F$ , it rejects  $0110$  and accepts  $0100$ .

Given the graphical representation of a DFA  $M$ , to check which state  $M$  is in after reading an input  $w = s_1 \dots s_k$ , simply begin at the start state of  $M$  and follow the arrows labelled  $s_1, \dots, s_k$ . For instance, in Example 1.1, the input  $0110$  corresponds to the sequence of states  $A, A, B, A, A$ , and the input  $0100$  corresponds to the sequence of states  $A, A, B, B, B$  (note

<sup>1</sup>The plural of *automaton* (ɔ:təmətən or ɔ:təmə,tən) is *automata* (ɔ:təmətə).

that in both cases, the first  $A$  is the start state, and only the next four states are the results of transitions).

A **language** over an alphabet  $\Sigma$  is a set of strings over  $\Sigma$ . In particular, the language  $\Sigma^*$  is the set of all strings over  $\Sigma$ . Thus, a language over  $\Sigma$  is any subset of  $\Sigma^*$ . If  $M$  is a DFA with input alphabet  $\Sigma$ , then  $M$  **accepts the language**  $L$  if  $L$  is the set of all strings accepted by  $M$ . For example, the DFA  $M$  in Example 1.1 accepts the language of all binary strings containing an odd number of 1s.

**Note.** Although we say simply that  $M$  accepts  $L$ , this means not only that every string in  $L$  is accepted by  $M$ , but also that every string *not* in  $L$  is *rejected* by  $M$ .

**Exercise 1.1.** Construct a DFA that accepts all binary strings with an even number of 0s.

*Solution.*

**Exercise 1.2.** Construct a DFA that accepts all strings over the alphabet {a, b} that begin in aab.

*Solution.*

Observe that two of the states of the DFA given in the solution of Exercise 1.2 are states that, once entered, cannot be left – i.e. every transition out of such each of these states is into that state itself. Such a state is a **trap state**. One of these two trap states is an accept states – which indicates that any input that leads to this state is accepted regardless of what the rest of the input contains – while the other trap state is a non-accept state – which indicates that any input leading to this state is *permanently* rejected and that no further “correction” can be made to get the input accepted.

## 1.2 Nondeterministic Finite Automata

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

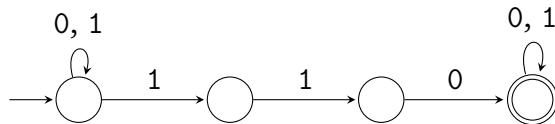
- $Q$  is a finite set of states.
- $\Sigma$  is a finite input alphabet.
- $\delta: Q \times (\Sigma \cup \{\epsilon\}) \rightarrow 2^Q$  is the transition function.
- $q_0 \in Q$  is the start state.
- $F \subseteq Q$  is the set of accept states.

Note that the transition function has codomain  $2^Q$ , the power set of  $Q$ . That is, each transition of a nondeterministic finite automaton is from one state into possibly several states or even to no state. The interpretation of this is that at each step, for a given input, the machine may have many options of the state to transition to, and an input string is accepted if there is at least one path from the start state to an accept state with arrows labelled by the input. More formally, an input  $s_1 \dots s_n$  is accepted by an NFA  $M = (Q, \Sigma, \delta, q_0, F)$ , if and only if there exist states  $q_1, \dots, q_k \in Q$ , with  $q_k \in F$ , such that

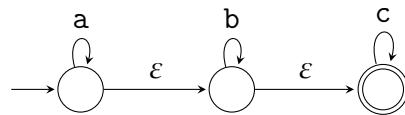
$$q_1 \in \delta(q_0, s_1), q_2 \in \delta(q_1, s_2), \dots, q_k \in \delta(q_{k-1}, s_n).$$

A transition labelled by  $\varepsilon$ , i.e. a transition of the form  $\delta(q, \varepsilon)$ , is an **epsilon transition**, and does not consume an input symbol. An NFA also has a graphical representation similar to that of a DFA.

**Example 1.2.** The NFA shown below accepts all binary strings that contain 110 as a (contiguous) substring.



**Example 1.3.** The NFA shown below accepts all strings over the alphabet  $\{a, b, c\}$  in which the symbols appear in alphabetical order.



### 1.3 Conversion of NFA to DFA

Trivially, a deterministic finite automaton can be considered as a nondeterministic finite automaton. That is, NFAs are at least as powerful as DFAs, in the sense that any language accepted by a DFA is also accepted by an NFA. Now we will see that conversely, NFAs are not strictly more powerful than DFAs. Any NFA can be converted to an equivalent DFA<sup>2</sup>, by the **subset construction**. Each transition of an NFA is from one state to a set of states, whereas any transition of a DFA is from one state to a single state. The main idea of the subset construction is to consider each set of states of an NFA as a single state of a DFA. The conversion procedure is described below.

Let  $M = (Q, \Sigma, \delta, q_0, F)$  be an NFA (without epsilon transitions). Define a DFA  $D_M = (Q', \Sigma, \delta', q'_0, F')$  as follows:

1. Every set of states of the NFA  $M$  becomes a single state of the DFA  $D_M$ . That is,  $Q' = 2^Q$ .
2. The start state of  $D_M$  is the singleton set containing the start state of  $M$ . That is,  $q'_0 = \{q_0\}$ .
3. The transition function  $\delta'$  of  $D_M$  is given by

$$\delta'(\{q_1, \dots, q_k\}, s) = \bigcup_{i=1}^k \delta(q_i, s).$$

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<sup>2</sup>Two finite automata are **equivalent** if the language accepted by them is the same

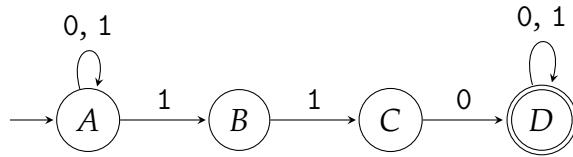
That is, given a state  $q'$  of  $D_M$ , which is a set of states of the NFA  $M$ , and an input symbol  $s \in \Sigma$ , for each state  $q \in q'$   $\delta(q, s)$  is some set of states of  $M$ . Combine all these sets  $\delta(q, s)$  for  $q \in q'$  (via union) to get  $\delta'(q', s)$ .

4. Each state of  $D_M$  that contains at least one accept state of  $M$  becomes an accept state. That is,

$$F' = \{ q' \in Q' \mid q' \cap F \neq \emptyset \}.$$

If  $M$  has epsilon transitions, then  $\delta'(\{q_1, \dots, q_k\}, s)$  will contain, in addition to the states described above, the states of  $M$  that can be reached from each state in  $\delta(q_i, s)$  via any sequence epsilon transitions. Similarly,  $q'_0$  will be the set of all states of  $M$  that can be reached from  $q_0$  via (a sequence of) epsilon transitions.

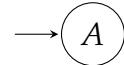
**Example 1.4.** Consider the NFA given in Example 1.2.



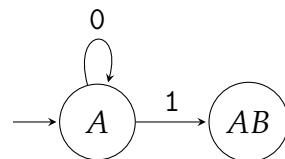
Here, the initial state is  $q_0 = A$ , and the set of accept states is  $F = \{D\}$ . Now, the equivalent DFA  $D_M$  will  $2^4 = 16$  states, namely  $\emptyset, \{A\}, \{B\}, \{C\}, \{D\}, \{A, B\}, \{A, C\}, \dots, \{A, B, C, D\}$ . For the sake of simplicity, we will denote these as  $\emptyset, A, B, C, D, AB, AC, \dots, ABCD$ .

Note that many of these states may be **unreachable** – i.e. there will be no path from the start state to them. We will not include them in the graphical representation of  $D_M$ , even though, formally, they are part of  $D_M$ . To find all the **reachable** (i.e. not unreachable) states, we will begin with the start state, and iteratively add the other states while computing the transitions from the current states corresponding to each input symbol.

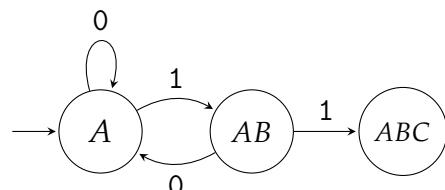
1. Initially, we have only the start state,  $A$ .



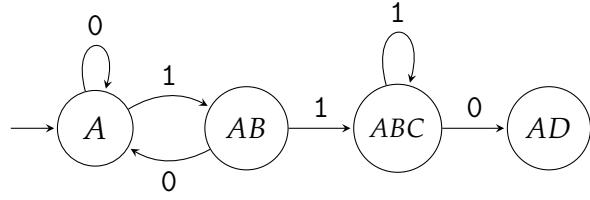
2. Next,  $\delta'(A, 0) = \delta(A, 0) = \{A\}$  (written as just  $A$ ) and  $\delta'(A, 1) = \delta(A, 1) = \{A, B\}$  (written as just  $AB$ ).



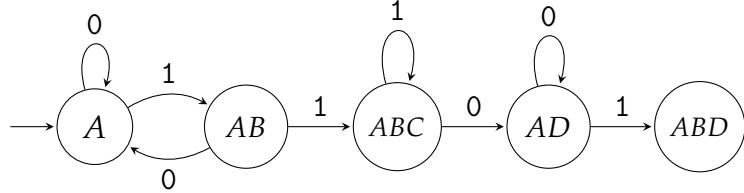
3. Now,  $\delta'(AB, 0) = \delta(A, 0) \cup \delta(B, 0) = \{A\} \cup \emptyset = \{A\}$  (i.e.  $A$ ) and  $\delta'(AB, 1) = ABC$ .



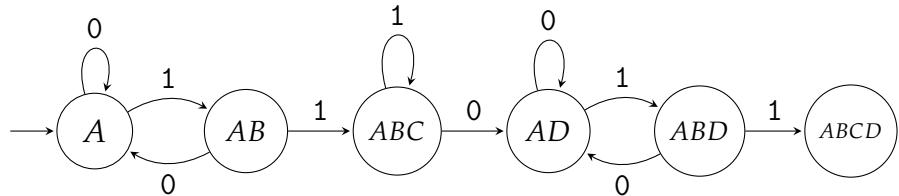
4. Similarly,  $\delta'(ABC, 0) = AD$  and  $\delta'(ABC, 1) = ABC$ .



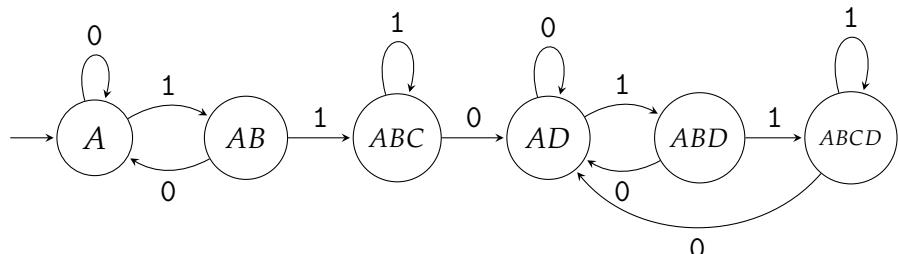
5. Similarly,  $\delta'(AD, 0) = AD$  and  $\delta'(AD, 1) = ABD$ .



6. Similarly,  $\delta'(ABD, 0) = AD$  and  $\delta'(ABD, 1) = ABCD$ .

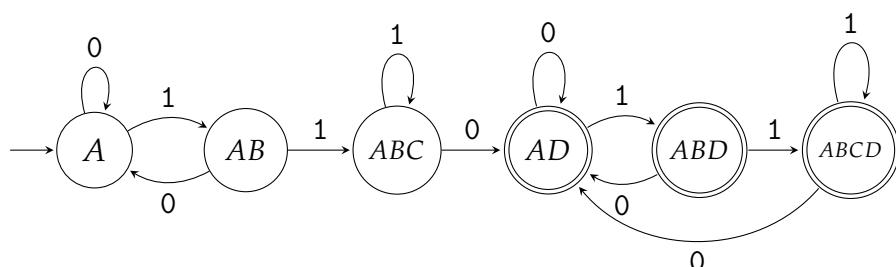


7. Finally,  $\delta'(ABCD, 0) = AD$  and  $\delta'(ABCD, 1) = ABCD$ .

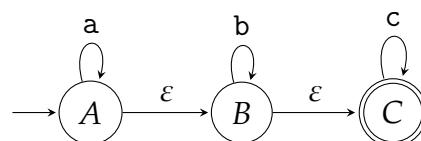


As no new state is added in this step, all the other states (not shown here) are unreachable.

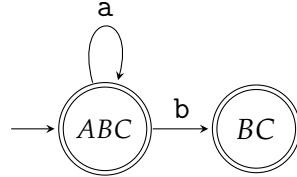
Now, the states  $AD$ ,  $ABD$ , and  $ABCD$  all contain  $D$ , which is the only accept state of the original NFA. Hence, these states are accept state of the DFA.



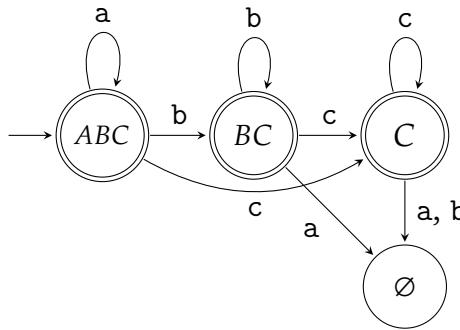
**Example 1.5.** Consider the NFA given in Example 1.2.



Here, the start state is  $A$ , but  $B$  can be reached from  $A$  via an epsilon transition, and  $C$  can be reached from  $B$  via an epsilon transition. Hence, the start state of the converted DFA will be  $ABC$ , which will also be an accept state, since it contains  $C$ , an accept state of the original NFA. Next,  $\delta(A, a) = A$ ,  $\delta(B, a) = \delta(C, a) = \emptyset$ . But  $B$  and  $C$  can be reached from  $A$  by epsilon transitions. Therefore,  $\delta'(ABC, a) = ABC$ . Similarly,  $\delta'(ABC, b) = BC$ , which will also be an accept state. Similarly,  $\delta'(ABC, c) = C$ , also an accept state.



But now,  $\delta(B, a) = \delta(C, a) = \emptyset$ . Hence,  $\delta'(BC, a) = \emptyset$ . Note that  $\emptyset$  will be state from which there are no transitions into any other states – i.e. it is a trap state. Hence,  $\delta'(\emptyset, a) = \delta'(\emptyset, b) = \emptyset$ . Proceeding thus, we find that  $\delta'(BC, b) = BC$ ,  $\delta'(BC, c) = C$ ,  $\delta'(C, a) = \delta'(C, b) = \emptyset$ , and  $\delta'(C, c) = C$ .



## 1.4 Product Construction

If  $L_1$  and  $L_2$  are languages over the same alphabet  $\Sigma$ , and  $M_1$  and  $M_2$ , respectively, are the NFAs accepting them, then the **intersection** of  $L_1$  and  $L_2$ ,

$$L_1 \cap L_2 = \{ w \in \Sigma^* \mid w \in L_1 \text{ and } w \in L_2 \}$$

is accepted by the product of  $M_1$  and  $M_2$ , defined as follows: Let  $M_1 = (Q_1, \Sigma, \delta_1, q_{10}, F_1)$  and  $M_2 = (Q_2, \Sigma, \delta_2, q_{20}, F_2)$ . Then their **product**  $M_1 \times M_2 = (Q, \Sigma, \delta, q_0, F)$ , where

- (i)  $Q = Q_1 \times Q_2$ , the Cartesian product of  $Q_1$  and  $Q_2$ . That is, each state of  $M_1 \times M_2$  is a pair of states, the first from  $M_1$  and the second from  $M_2$ .
- (ii) For each  $q_1 \in Q_1$ ,  $q_2 \in Q_2$ , and  $s \in \Sigma$ ,  $\delta((q_1, q_2), s) = (\delta_1(q_1, s), \delta_2(q_2, s))$ .
- (iii)  $q_0 = (q_{10}, q_{20})$ .
- (iv)  $F = F_1 \times F_2$ .

## 2 Regular Expressions

A **regular expression (RE)** over an alphabet  $\Sigma$  is an expression consisting of one or more of the symbols in  $\Sigma$  or  $\epsilon$  or  $\emptyset$ , one or both of the operators  $+$  and  $*$ , and parentheses  $($  and  $)$ , whose syntax is defined recursively as follows:

1. For each  $s \in \Sigma$ ,  $s$  is a regular expression, and  $\epsilon$  and  $\emptyset$  are regular expressions.
2. If  $r$  is a regular expression, then so is  $(r)^*$ .
3. If  $r_1$  and  $r_2$  are regular expressions, then so are  $r_1 + r_2$  and  $(r_1)(r_2)$ .

**Note.** If  $r$  is a single symbol (i.e.  $r \in \Sigma$ ), then  $(r)^*$  can also be written as  $r^*$ ;  $(r)(r')$  can also be written as  $r(r')$ ; and  $(r')(r)$  can also be written as  $(r')r$ .

**Example 2.1.** The following are some regular expressions over  $\Sigma = \{0, 1\}$ :

$$0 + 1, \quad 0(0 + 1), \quad (0 + 1)^*110(0 + 1)^*, \quad 1^*0^* + 0^*1^*, \quad 0^*10^*(0^*10^*1)^*0^*, \quad 0(0 + 1)^*0 + 1(0 + 1)^*1$$

Each RE represents or generates a particular language. To rigorously define the language generated by an RE, we will first define some operations on languages.

Let  $L_1$  and  $L_2$  be two languages over the same alphabet  $\Sigma$ . Recall that this means  $L_1$  and  $L_2$  are sets of strings of symbols in  $\Sigma$ , i.e.  $L_1, L_2 \subseteq \Sigma^*$ .

1. The **union** of  $L_1$  and  $L_2$  is  $L_1 \cup L_2$ , defined as their union as sets.

$$L_1 \cup L_2 = \{ w \in \Sigma^* \mid w \in L_1 \text{ or } w \in L_2 \}$$

2. The **concatenation** of  $L_1$  and  $L_2$  is  $L_1 L_2$ , the language of all strings obtained by concatenating a string of  $L_1$  with a string of  $L_2$ .

$$L_1 L_2 = \{ w_1 w_2 \mid w_1 \in L_1, w_2 \in L_2 \}$$

3. The **Kleene star**<sup>3</sup> of  $L_1$  is  $L_1^*$ , the language of all strings obtained by concatenating any finite number of strings of  $L_1$  together.

$$\begin{aligned} L_1^* &= \{ w_1 w_2 \dots w_n \mid w_i \in L_1, i = 1, \dots, n, n \in \mathbb{N}_0 \} \\ &= \{ \epsilon \} \cup L_1 \cup L_1 L_1 \cup L_1 L_1 L_1 \cup \dots \end{aligned}$$

The language generated by an RE can now be recursively defined as follows:

1. The language generated by the RE  $s$ , where  $s \in \Sigma$  (a single symbol), is  $\{s\}$  and the language generated by the RE  $\epsilon$  is  $\epsilon$ .
2. The language generated by the RE  $\emptyset$  is the empty language  $\emptyset = \{\}$ . Note that this language does *not* contain the empty string!
3. If  $r_1$  and  $r_2$  are two REs over the same alphabet  $\Sigma$ , that generate languages  $L_1$  and  $L_2$ , respectively, then
  - (i) the RE  $r_1 + r_2$  generates the language  $L_1 + L_2$
  - (ii) the RE  $(r_1)(r_2)$  generates the language  $L_1 L_2$
  - (iii) the RE  $(r_1)^*$  generates the language  $L_1^*$ .

**Example 2.2.** Let  $\Sigma = \{0, 1\}$ .

1. The RE  $0 + 1$  generates the language  $\{0, 1\}$ .
2. The RE  $0(0 + 1)$  generates the language  $\{00, 01\}$ .
3. The RE  $(0 + 1)^*110(0 + 1)^*$  generates the language of all binary strings containing 110 as a substring.
4. The RE  $0^*1^* + 1^*0^*$  generates the language of all binary strings that are either a string of (zero or more) 0s followed by a string of 1s, or a string of 1s followed by a string of 0s.

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<sup>3</sup>Named after the mathematician Stephen Cole Kleene, pronounced **klay-nee** ('kleini).

**Exercise 2.1.** Let  $\Sigma = \{0, 1\}$ .

1. What is the language generated by  $0(0 + 1)^*0 + 1(0 + 1)^*1$ ?
2. What is the language generated by  $0^*10^*(0^*10^*1)^*0^*$ ?

*Solution.*

## 2.1 Conversion of NFA to RE

Any nondeterministic finite automaton can be converted to an equivalent<sup>4</sup> regular expression. The conversion procedure involves first reducing the given NFA, by eliminating one state at a time, to intermediate finite automata of a new kind, until just one start state and one accept state remain. A **generalised (nondeterministic) finite automaton (GFA or GNFA)** is a finite automaton in which the arrows are labelled by REs, and a transition along this arrow is made if the next few characters of the input match the RE. That is, if the arrow from state  $q_1$  to state  $q_2$  is labelled by the regular expression  $r$ , and the unread part of the input when  $q_1$  is reached is  $s_1s_2 \dots s_n$ , then a transition can be made to  $q_2$  if  $s_1s_2 \dots s_i$  is a string generated by  $r$  for some  $i \leq k$ . Trivially, every NFA is a GFA, since any single symbol or  $\epsilon$  is an RE, and a transition of an NFA consists of reading one symbol and moving along one arrow, or reading no symbol (i.e. an empty string) and making an epsilon transition.

The procedure for converting an NFA to RE is as follows. Let  $M = (Q, \Sigma, \delta, q_0, F)$  be an NFA. Furthermore, assume that  $q_0$  has no arrows entering it and  $F$  contains a single state  $q_f$  with no arrows leaving it – in both cases, even self-loops are not allowed<sup>5</sup>. Now, iteratively reduce  $M$  by eliminating one state other than  $q_0$  and  $q_f$  at a time as given below:

1. Let  $q$  be any state different from  $q_0$  and  $q_f$ , and let  $r$  be the label on the self-loop on  $q$ .
2. For each state  $q_1 \neq q$  with a transition into  $q$  labelled  $r_1$ , and each state  $q_2 \neq q$  into which there is a transition from  $q$  labelled  $r_2$ , let  $r_{12} = r_1r^*r_2$  (suitably parenthesised), where  $r$  is the regular expression on the self-loop on  $q$  (if  $q$  has no self-loop, then this is just  $r_1r_2$ ).
3. If there is no arrow from  $q_1$  to  $q_2$ , add an arrow labelled  $r_{12}$ . If an arrow already exists from  $q_1$  to  $q_2$ , replace its label, say  $r'$ , by  $r' + r_{12}$ .
4. Delete  $q$ .

When  $q_0$  and  $q_f$  are the only states remaining, the label on the arrow from  $q_0$  to  $q_f$  is the RE equivalent to the NFA  $M$ .

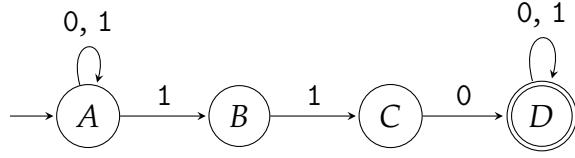
*Note.* The order in which the states are eliminated does not matter, although the REs obtained may differ (but be equivalent) according to the order followed.

**Example 2.3.** Consider the NFA given in Example 1.2.

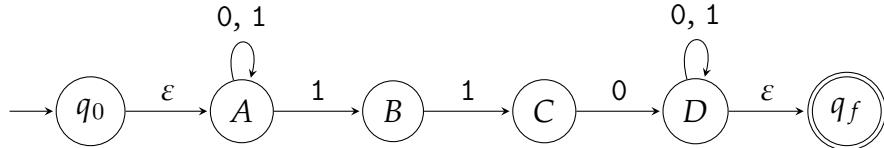
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<sup>4</sup>An RE equivalent to an NFA is one that generates the language accepted by the NFA.

<sup>5</sup>It is easy to see that any NFA can be converted to an equivalent NFA satisfying this condition by using epsilon transitions. If  $q_0$  has an arrow entering it, then make a new start state  $q'_0$  with an epsilon transition into  $q_0$ , which will no longer be the start state. Similarly, if  $q_f$  has an arrow leaving it, make it a non-accept state and add a new accept state  $q'_f$  with an epsilon transition into it from  $q_f$ . If  $M$  has multiple accept states, make all of them non-accept states, and add a new accept state  $q_f$  with an epsilon transition into it from each of the old accept states.

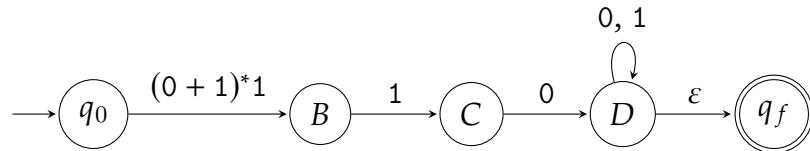


The start state  $A$  has two arrows entering it and the accept state  $D$  has two arrows leaving it (in each case, self-loops labelled 0 and 1). Therefore, we first add a new start state  $q_0$  with an epsilon transition into  $A$  (no longer a start state), and a new accept state  $q_f$  with an epsilon transition into it from  $D$ , which will be made a non-accept state.

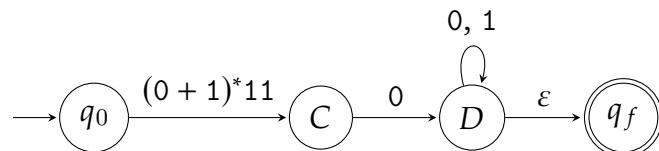


Now we eliminate the non-initial and non-accept states one by one.

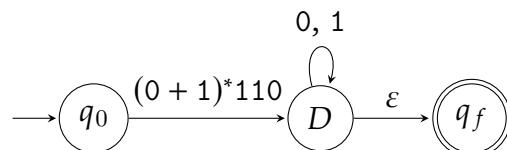
1. If we choose to eliminate  $A$  first, we first note that there is one arrow, labelled  $\epsilon$ , coming into  $A$  from  $q_0$ , and one arrow, labelled  $q$ , going from  $A$  into  $B$ . Also, there are self-loops on  $A$  labelled 0 and 1. Therefore, we add an arrow from  $q_0$  to  $B$  labelled  $\epsilon(0+1)^*1 = (0+1)^*1$ , and then delete  $A$ .



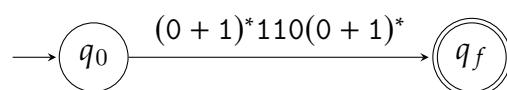
2. Next, if we wish to eliminate  $B$ , we replace the arrow from  $q_0$  to  $B$  labelled  $(0+1)^*1$  and the arrow labelled 1 from  $B$  to  $C$  by the arrow  $(0+1)^*11$  from  $q_0$  to  $C$ .



3. Similarly, we may eliminate  $C$  next.

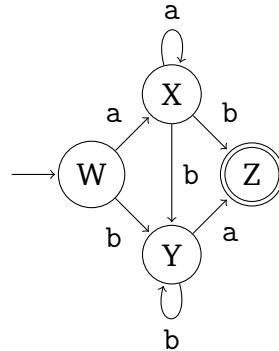


4. Finally, we eliminate  $D$ .



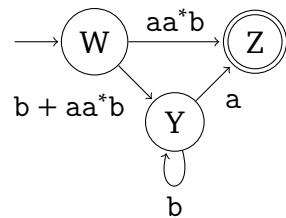
Thus, an RE equivalent to the given NFA is  $(0+1)^*110(0+1)^*$ . We easily verify that indeed, this is an equivalent RE. The original NFA accepts all binary strings containing the substring 110. Every such string can be written as some binary string (i.e. a string generated by  $(0+1)^*$ ), followed by 110, (generated by 110) followed by any binary string (generated by  $(0+1)^*$ )).

**Example 2.4.** Consider the NFA shown below.

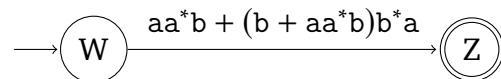


This NFA is already in the form necessary to apply the conversion procedure, as the start state  $W$  has no arrows entering it, and there is a unique accept state  $Z$  with no arrows leaving it.

1. There is only one arrow from a different state entering  $X$ , which is from  $W$ , there are two arrows leaving  $X$ , which are to  $Y$  and  $Z$ , and there is a self-loop on  $X$  labelled  $a$ . On eliminating  $X$ , we get the following GFA.



2. Next, we eliminate  $Y$ .



Thus, the equivalent RE is  $aa^*b + (b + aa^*b)b^*a$ .

**Exercise 2.2.** Convert the NFA given below to an RE.

