CSCI 2670 Introduction to Theory of Computing

Lecture Note 2
Automata and Languages

Liming Cai, CS@UGA, Fall 2018
Chapter 1. Regular Languages
Chapter 1. Regular Languages

- 1.0 Why languages?
- 1.1 Finite automata
- 1.2 Nondeterminism
- 1.3 Regular expressions
- 1.4 Non-regular languages
1.0 Why languages
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Studying languages is a simple and rigorous way to investigate computational problems.
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(1) computational problems
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(1) computational problems \iff
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(1) computational problems ⇔ decision problems
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(1) computational problems $\iff$ decision problems

(2) decision problems
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Two types of problems
(1) decision problems whose output is TRUE/FALSE (one bit);
(2) search problems whose output can be much longer

Is Sorting a decision or search problem?
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![Graph Diagram]
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the output should be

either \((a, b), (b, f)\),
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the output should be

either $(a, b), (b, f)$, or $(a, e), (e, f)$. 
1.0 Why languages

Consider the following decision problem:

Shortest Path Length

Input: graph \( G = (V, E) \), vertices \( s, t \in V \) and integer \( k \geq 0 \);

Output: TRUE if and only if the shortest path from \( s \) to \( t \) contains \( k \) edges.

For input \( G \), \( s = a \), \( t = f \), and \( k = 2 \) the output should be TRUE; but for input \( G \), \( s = a \), \( t = c \), and \( k = 3 \), the output should be FALSE.

Can an algorithms for Shortest Path Length and for Shortest Path help each other? YES!
1.0 Why languages

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For input $G$, $s = a$, $t = f$, and $k = 2$ the output should be **TRUE**; But for input $G$, $s = a$, $t = c$, and $k = 3$ the output should be **FALSE**.
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For input \( G \):

- \( s = a, t = f, \) and \( k = 2 \)
  - the output should be \( \text{TRUE} \);

But for input \( G \), \( s = a, t = c, \) and \( k = 3 \), the output should be \( \text{FALSE} \).
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For input $G$: $s = a, t = f, \text{ and } k = 2$ the output should be **TRUE**;

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Can an algorithms for **Shortest Path Length** and for **Shortest Path** help each other?

**YES!**
1.0 Why languages

Assume we have an algorithm Oracle $A$ that can decide whether the shortest path between vertices $s$ and $t$ in graph $G$ contains $k$ edges:

$A(G,s,t,k) = \{ Yes \text{ shortest path between } s \text{ and } t \text{ contains } k \text{ edges}, No \text{ otherwise } \}$
1.0 Why languages

Assume we have an algorithm **Oracle A** that can decide whether the shortest path between vertices *s* and *t* in graph *G* contains *k* edges.

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A(G, s, t, k) = \begin{cases} 
\text{Yes} & \text{shortest path between } s \text{ and } t \text{ contains } k \text{ edges} \\
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Assume we have an algorithm **Oracle** $A$ that can decide whether the shortest path between vertices $s$ and $t$ in graph $G$ contains $k$ edges

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1. Input: graph $G$ and two vertices $s$ and $t$;

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   2.1 ask Oracle $A(G, s, t, k)$;
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   2.1 ask Oracle $A(G, s, t, k)$;
   2.2 if $A(G, s, t, k) = \text{Yes}$, set $k_0 = k$; exit from the loop

3. while $G$ contains unmarked edges do
   3.1 pick any unmarked edge $e$ and remove it from $G$;
   3.2 if $A(G, s, t, k_0) = \text{No}$, restore $e$ in $G$ and marked $e$;

4. return (marked edges) (which form a shortest path from $s$ and $t$)
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- We observe that the solution to the decision problem Shortest Path Length is essential to the solution to the search problem Shortest Path.
- In general, the solution to a search problem is underscored by the solution to its corresponding decision problem.
- It suffices to focus on investigating decision problems.
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1.0 Why languages

Now we relate decision problems to languages. There is one-to-one correspondence between the two. Specifically, for every decision problem $\Pi$, we can define a language $L_{\Pi}$ such that any algorithm recognizing the language $L_{\Pi}$ can be used to solve the decision problem $\Pi$; and vice versa.
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For decision problem Shortest Path Length:

Shortest Path Length (abbr. SPL) Input: graph $G = (V, E)$, vertices $s, t \in V$ and integer $k \geq 0$; Output: TRUE if and only if the shortest path from $s$ to $t$ contains $k$ edges.

We define language $L_{SPL} = \{\langle G, s, t, k \rangle :$ shortest path from $s$ to $t$ has $k$ edges in $G\}$ where $\langle G, s, t, k \rangle$ is a string that encodes graph $G$, vertices $s, t$, and integer $k$.

That is, $L_{SPL}$ contains exactly positive instances of decision problem SPL.

Algorithms for SPL can be used to recognize strings in $L_{SPL}$, and vice versa.
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where \( \langle G, s, t, k \rangle \) is a string that encodes graph \( G \), vertices \( s, t \), and integer \( k \).

- That is, \( L_{\text{SPL}} \) contains exactly positive instances of decision problem SPL.

- Algorithms for SPL can be used to recognize strings in \( L_{\text{SPL}} \), and vice versa.
1.0 Why languages

For example, the language \( L_{\text{SPL}} \) contains the strings like \( \langle G_1, A, P, 2 \rangle \), \( \langle G_1, C, L, 3 \rangle \), \( \langle G_2, 1, 4, 3 \rangle \), \( \cdots \) where graphs \( G_1 \) and \( G_2 \) are but not strings like \( \langle G_1, B, S, 3 \rangle \) or \( \langle G_2, 2, 3, 1 \rangle \),
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For example, the language $L_{SPL}$ contains the strings like

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[Diagram of graphs $G_1$ and $G_2$]
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![Graph $G_1$](image1)

![Graph $G_2$](image2)

but not strings like $\langle G_1, B, S, 3 \rangle$ or $\langle G_2, 2, 3, 1 \rangle$, 
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Let \( \Sigma \) be a finite alphabet, e.g., \( \Sigma = \{0, 1\} \);

- we will consider languages \( L \) defined over \( \Sigma \).
- That is \( L \subseteq \Sigma^* \).

We investigate classes of languages by examining different types of computational models that can be programmed to compute them.
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• We investigate classes of languages by examining different types of computational models that can be programmed to compute them.
1.0 Why languages

All such models have the following:

- an read-(from left to right)-only input buffer – called input tape
- a finite set of states, some are accept states
- model accepts a string iff it halts at an accept state

Different models may have different extra memory "facilities" to use.
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1.1 Finite automata

A finite automaton is a mathematical model used to recognize patterns in input strings. It consists of:

1. A finite number of states, some of which are designated as "accept states".
2. It reads one symbol at a time from the input, in a left-to-right manner.
3. The next state is determined by the current state and the symbol just read.
4. The input string is accepted if it ends at an "accept" state.
5. Otherwise, the input is "rejected".

What strings does the FA accept?
1.1 Finite automata

finite automaton that has no extra memory facility.
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![Finite automaton diagram]

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description of state transitions
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description of state transitions

```
(a, 1) =⇒ a
(a, 0) =⇒ b
(b, 0) =⇒ b
(b, 1) =⇒ c
(c, 1) =⇒ a
(c, 0) =⇒ d
(d, 1) =⇒ d
(d, 0) =⇒ d
```

transition function: \( Q \times \Sigma \rightarrow Q \)
where \( Q = \{ a, b, c, d \} \) and \( \Sigma = \{ 0, 1 \} \)
1.1 Finite automata

description of state transitions

\[ (a, 1) \rightarrow a \]
1.1 Finite automata

description of state transitions

\[(a, 1) \rightarrow a \quad (a, 0) \rightarrow b\]
1.1 Finite automata

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(a, 1) \rightarrow a \quad (a, 0) \rightarrow b \quad (b, 0) \rightarrow b \quad (b, 1) \rightarrow c
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description of state transitions

![Diagram of finite automata]

\[(a, 1) \rightarrow a \quad (a, 0) \rightarrow b \quad (b, 0) \rightarrow b \quad (b, 1) \rightarrow c \quad (c, 1) \rightarrow a\]
1.1 Finite automata

description of state transitions

\[(a, 1) \rightarrow a \quad (a, 0) \rightarrow b \quad (b, 0) \rightarrow b \quad (b, 1) \rightarrow c \]

\[(c, 1) \rightarrow a \quad (c, 0) \rightarrow d \]
1.1 Finite automata

description of state transitions

![Finite Automata Diagram]

- $(a, 1) \rightarrow a$  
- $(a, 0) \rightarrow b$  
- $(b, 0) \rightarrow b$  
- $(b, 1) \rightarrow c$
- $(c, 1) \rightarrow a$  
- $(c, 0) \rightarrow d$  
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\[(a, 1) \rightarrow a \quad (a, 0) \rightarrow b \quad (b, 0) \rightarrow b \quad (b, 1) \rightarrow c \]
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transition function: \( Q \times \Sigma \rightarrow Q \)

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1.1 Finite automata

Another FA $M_1$

What strings does $M_1$ accept?
1.1 Finite automata

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Formal definition of FA

Definition 1.5 (page 35)
1.1 Finite automata

Formal definition of FA

**Definition 1.5** (page 35)

A finite automaton is a 5-tuple \((Q, \Sigma, \delta, q_0, F)\), where
1.1 Finite automata

Formal definition of FA

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1. \(Q\) is a finite set called the *states*,
2. \(\Sigma\) is a finite set called the *alphabet*,
3. \(\delta\) is the *transition function*,
4. \(q_0\) is the *start state*, and
5. \(F\) is the *set of accept states*. 


1.1 Finite automata

Formal definition of FA

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1. \(Q\) is a finite set called the *states*,
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3. \(\delta: Q \times \Sigma \rightarrow Q\) is the *transition function*,
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1.1 Finite automata

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1.1 Finite automata
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$$Q = \{ q_0, q_1, q_2 \}, \Sigma = \{ 0, 1 \}, F = \{ q_1 \}$$
1.1 Finite automata

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1.1 Finite automata

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1.1 Finite automata

More FA examples

FA $M_2$ (Figure 1.8 page 37).

$L_{M_2} = \{ w : \text{string } w \text{ ends with symbol } a \}$

FA $M_3$ (Figure 1.10, page 38)

$L_{M_3} = \{ w : \text{string } w \text{ contains even number of } 0 \text{'s} \}$
1.1 Finite automata

More FA examples
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1.1 Finite automata

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1.1 Finite automata

More FA examples

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1.1 Finite automata

FA $M_4$ (Figure 1.12 page 38).
1.1 Finite automata

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$L_{M_4} = \{w : w$ starts and ends with the same symbol$\}$
1.1 Finite automata

FA $M_5$ (Figure 1.13 page 39).
1.1 Finite automata

FA $M_5$ (Figure 1.13 page 39).

$L_{M_5} = \{ w : \text{the sum of symbols in } w \text{ is multiple of } 3 \}$
Example 1.15 page 40, Similar to $M_5$ but modulo $i$ instead of 3,
Example 1.15 page 40, Similar to $M_5$ but modulo $i$ instead of 3,

Can you draw an FA for $i = 4$?
1.1 Finite automata
1.1 Finite automata

Formal definition of FA computation
1.1 Finite automata

Formal definition of FA computation

Let $M = (Q, \Sigma, \delta, q_0, F)$ be a finite automaton.
1.1 Finite automata

Formal definition of FA computation

Let $M = (Q, \Sigma, \delta, q_0, F)$ be a finite automaton.

Let $w = w_1w_2 \ldots w_n$ be a string where each symbol $w_i \in \Sigma$. 
1.1 Finite automata

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Then $M$ accepts $w$ if a sequence states $r_0, r_1, \ldots, r_n$ in $Q$ exist with three conditions:
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1.1 Finite automata

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3. $r_n \in F$.

We say $M$ recognizes language $L$ if

$$L = \{ w : w \in \Sigma^* \text{ and } M \text{ accepts } w \}$$
1.1 Finite automata

Definition 1.16
A language is called a regular language if it can be recognized by some finite automaton.

Some basic questions:
1. Is $\{\epsilon\}$ regular?
2. Is $\Sigma^*$ regular?
3. Is $\{}$ regular?
4. Can two FA recognize the same language?
5. Is any finite language $L$ always regular?
6. Is a single string language regular?
1.1 Finite automata

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1.1 Finite automata

Some suggestions:

- put yourself in the position of an automaton
- have small amount of memory (which is a few states) to use
- scan the input from left to right
- e.g., construct an FA to recognize strings containing an odd number of 1s. Ignore 0s.
- use two different states for odd and even 1s
- let state change if additional 1 is encountered.
1.1 Finite automata

Design Finite Automata

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1.1 Finite automata

e.g., construct an FA to recognize strings containing 001 as a substring.

There are four possibilities:

• have not seen any symbols of the pattern 001
• have seen just a 0
• have seen 00
• have seen 001

You may use 4 states for these 4 possibilities, respectively.
1.1 Finite automata

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Creating languages through regular operations

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CONCATENATION
STAR
1.1 Finite automata

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\( L_1 \) contains all strings with substring 11
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Then

\[
L_1 \cup L_2 = \{ x : x \in L_1 \text{ or } x \in L_2 \}
\]
1.1 Finite automata

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L_1^* = \{\epsilon\} \cup L_1 \cup L_1L_1 \cup L_1L_1L_1 \ldots$
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$L_1^* = \{\epsilon\} \cup L_1 \cup L_1L_1 \cup L_1L_1L_1 \ldots$
\[= \{w_1w_2\ldots w_k : k \geq 0 \text{ and each } x_i \in L_1\}\]
1.1 Finite automata

Intuitively,

- \( L_1 \cup L_2 \) contains strings that are from either \( L_1 \) or \( L_2 \);
- \( L_1 \cdot L_2 \) contains strings consisting of two segments, with the first segment belonging to \( L_1 \) and the second to \( L_2 \);
- \( L_1^* \) contains strings consisting of zero or more segments, each belonging to \( L_1 \).
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1.1 Finite automata

$L_1$ contains all strings with substring 11

$L_2$ contains all strings with substring 000

How to construct an FA to recognize $L_1 \cup L_2$

We may need to use FAs designed for $L_1$ and for $L_2$.

but first, let us construct such $M_1$ and $M_2$. 
1.1 Finite automata

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We may need to use FAs designed for $L_1$ and for $L_2$.

but first, let us construct such $M_1$ and $M_2$. 

1.1 Finite automata

However, given two FAs, one for $L_1$ and another for $L_2$, it may be difficult to simply combine them for the recognition of $L_1 \cup L_2$. e.g., simply put the two starting states together does not work! What seem to be causing the problem? We cannot "rewind the input tape" to read it again.
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1.1 Finite automata

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What seem to be causing the problem?

We cannot “rewind the input tape” to read it again.
1.1 Finite automata

Allow the input string to be checked simultaneously by the two FAs when it is being read. How?

• to combine states from the two FAs, and
• to combine transition functions from the two FAs.

For example, for $\delta(q, 1) = q'$ of $M_1$ and $\gamma(p, 1) = p'$ of $M_2$, we define:

$$\theta([q, p], 1) = [q', p']$$
1.1 Finite automata

Allow the input string to be checked simultaneously by the two FAs when it is being read
1.1 Finite automata

Allow the input string to be checked *simultaneously by the two FAs* when it is being read

How?
1.1 Finite automata

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For example, for $\delta(q, 1) = q'$ of $M_1$ and $\gamma(p, 1) = p'$ of $M_2$,

we define: $\theta([q]_p, 1) = [q']_p$
1.1 Finite automata

Assuming two simpler languages $L_1 = \{ x : x \text{ contains substring } 1 \}$ and $L_2 = \{ x : x \text{ contains substring } 00 \}$ with the corresponding FAs $M_1$ and $M_2$.

$M_1$ has start state $q_0$ and accepting state $q_1$.

$M_2$ has start state $p_0$, state $p_1$, accepting state $p_00$.
1.1 Finite automata

Assuming two simpler languages

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where
1.1 Finite automata

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with the corresponding FAs \( M_1 \) and \( M_2 \). where

\( M_1 \) has start state \( q \) and accepting state \( q_1 \)

\[
\begin{array}{ccc}
0 & 1 \\
q & q & q_1 \\
q_1 & q_1 & q_1 \\
\end{array}
\]
1.1 Finite automata

Assuming two simpler languages

\[ L_1 = \{ x : x \text{ contains substring } 1 \} \]
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with the corresponding FAs \( M_1 \) and \( M_2 \). where

\( M_1 \) has start state \( q \) and accepting state \( q_1 \)

\[
\begin{array}{ccc}
0 & 1 \\
q & q & q_1 \\
q_1 & q_1 & q_1 \\
\end{array}
\]

\( M_2 \) has start state \( p \), state \( p_0 \), accepting state \( p_{00} \)

\[
\begin{array}{ccc}
0 & 1 \\
p & p_0 & p \\
p_0 & p_{00} & p \\
p_{00} & p_{00} & p_{00} \\
\end{array}
\]
1.1 Finite automata

Then the new machine $M$ has 6 states:

$[q \ p],
[q \ p 0],
[q \ p 00],
[q \ 1 \ p],
[q \ 1 \ p 0],
[q \ 1 \ p 00].$

Which are the accepting states?
1.1 Finite automata

\[
\begin{array}{ccc}
M_1 & 0 & 1 \\
q & q & q_1 \\
q_1 & q_1 & q_1 \\
\end{array}
\]

Then the new machine \(M\) has 6 states:

\[
\begin{array}{ccc}
q & p & 0 \\
q_1 & p & 0 \_ \\
q_1 & p & 0 \_ \\
q & 1 & p \\
q_1 & 1 & p \_ \\
q_1 & 1 & p \_ \_ \\
\end{array}
\]

Which are the accepting states?
1.1 Finite automata

\[ M_1 \]

\[
\begin{array}{ccc}
0 & 1 \\
q & q & q_1 \\
q_1 & q_1 & q_1 \\
\end{array}
\]

\[ M_2 \]

\[
\begin{array}{ccc}
0 & 1 \\
p & p_0 & p \\
p_0 & p_{00} & p \\
p_00 & p_{00} & p_{00} \\
\end{array}
\]

Which are the accepting states?
Then the new machine $M$ has 6 states:

$[q_p], [q_{p_0}], [q_{p_{00}}], [q_{1_p}], [q_{1_{p_0}}], [q_{1_{p_{00}}}]$
1.1 Finite automata

\[ M_1 \]
\[
\begin{array}{c|cc}
q & q & q_1 \\
q_1 & q_1 & q_1 \\
\end{array}
\]

\[ M_2 \]
\[
\begin{array}{c|cc}
p & p_0 & p \\
p_0 & p_0 & p_0 \\
p_0 & p_0 & p_0 \\
\end{array}
\]

Then the new machine \( M \) has 6 states: \([q], [q_0], [q], [q_1], [q_1], [q_1]\)

\[
\begin{array}{c|cc}
0 & 1 \\
\end{array}
\]
1.1 Finite automata

$$M_1$$

\[
\begin{array}{ccc}
q & q & q_1 \\
q_1 & q_1 & q_1 \\
\end{array}
\]

$$M_2$$

\[
\begin{array}{ccc}
p & p_0 & p \\
p_0 & p_00 & p \\
p_00 & p_00 & p_00 \\
\end{array}
\]

Then the new machine $$M$$ has 6 states: $$[q_p], [q_{p_0}], [q_{p_00}], [q_1], [q_1], [q_1]$$
1.1 Finite automata

$$M_1$$

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$q$</td>
<td>$q$</td>
<td>$q_1$</td>
</tr>
<tr>
<td>$q_1$</td>
<td>$q_1$</td>
<td>$q_1$</td>
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$$M_2$$

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>$p$</td>
<td>$p_0$</td>
<td>$p$</td>
</tr>
<tr>
<td>$p_0$</td>
<td>$p_{00}$</td>
<td>$p$</td>
</tr>
<tr>
<td>$p_{00}$</td>
<td>$p_{00}$</td>
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</tr>
</tbody>
</table>

Then the new machine $M$ has 6 states: $[q]_p$, $[q]_{p_0}$, $[q]_{p_{00}}$, $[q_1]_p$, $[q_1]_{p_0}$, $[q_1]_{p_{00}}$
1.1 Finite automata

Then the new machine $M$ has 6 states: $\{q, \{q\}, \{q\}, \{q\}, \{q\}, \{q\}\}$
1.1 Finite automata

\[ M_1 \]

\[
\begin{array}{ccc}
0 & 1 \\
q & q & q_1 \\
q_1 & q_1 & q_1 \\
\end{array}
\]

\[ M_2 \]

\[
\begin{array}{ccc}
0 & 1 \\
p & p_0 & p \\
p_0 & p_{00} & p \\
p_{00} & p_{00} & p_{00} \\
\end{array}
\]

Then the new machine \( M \) has 6 states: \([q], [q_0], [q_{00}], [q_1], [p_0], [p_{00}]\)

\[
\begin{array}{ccc}
0 & 1 \\
\begin{bmatrix} q \\ p \end{bmatrix} & \begin{bmatrix} q_0 \\ p_0 \end{bmatrix} & \begin{bmatrix} q_1 \\ p_1 \end{bmatrix} \\
\begin{bmatrix} q \\ p \end{bmatrix} & \begin{bmatrix} q_{00} \\ p_{00} \end{bmatrix} & \begin{bmatrix} q_1 \\ p_1 \end{bmatrix} \\
\begin{bmatrix} q_1 \\ p_0 \end{bmatrix} & \begin{bmatrix} p \\ q_1 \end{bmatrix} & \begin{bmatrix} p_0 \\ q_{00} \end{bmatrix} \\
\begin{bmatrix} q_1 \\ p_0 \end{bmatrix} & \begin{bmatrix} p \\ q_1 \end{bmatrix} & \begin{bmatrix} p_0 \\ q_{00} \end{bmatrix} \\
\begin{bmatrix} q_0 \\ p_0 \end{bmatrix} & \begin{bmatrix} q_{00} \\ p_{00} \end{bmatrix} & \begin{bmatrix} q_1 \\ p_{00} \end{bmatrix} \\
\end{array}
\]

Which are the accepting states?
1.1 Finite automata
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1.1 Finite automata
The technique applies to constructing an FA for $L_1 \cap L_2$. But what would the accepting states be? Seems not applicable to constructing an FA for concatenation $L_1 L_2$. Or can we just "connect" two FAs to form one? What might seem to be the problem?
1.1 Finite automata

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1.2 Nondeterminism

The need for nondeterminism in the computation with FAs, e.g., combining two FAs for $L_1 \cup L_2$, for $L_1 \cap L_2$.

- Nondeterminism is “uncertainty” or “guessing”.
- In FAs, nondeterminism is such that a transition from given (state, symbol) has more than one option, e.g., $\delta(q_0, 1) = \{q_1, q_2\}$.
- In FA, nondeterministic computation results in more than one sequence of states.
1.2 Nondeterminism

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1.2 Nondeterminism

**Nondeterminism**

The need for *nondeterminism* in the computation with FAs

e.g., combining two FAs for $L_1 \cup L_2$, for $L_1L2$.

- nondeterminism is “uncertainty” or “guessing”.
- in FAs, nondeterminism is such that
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- in FA, nondeterministic computation results in *more than one sequences of states.*
1.2 Nondeterminism

Nondeterminism increases convenience in constructing FAs. For example, construct an FA for $L_1 \cup L_2$. More examples: Figure 1.34 (page 52) and Figure 1.36 (page 53).
1.2 Nondeterminism

Nondeterminism increases convenience in constructing FAs
1.2 Nondeterminism

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E.g., construct an FA for $L_1 \cup L_2$
1.2 Nondeterminism

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E.g., Construct an FA for all strings whose third position is a 1
1.2 Nondeterminism

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1.2 Nondeterminism

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   Construct an FA for all strings whose third last position is a 1

More examples: Figure 1.34 (page 52) and Figure 1.36 (page 53)
1.2 Nondeterminism

\[ \text{What are } \epsilon \text{-transitions?} \]

\[ \delta(q, \epsilon) = \{ q_1 \} \]

\[ \text{What does an } \epsilon \text{-transition mean?} \]

\[ \text{\( \epsilon \)-transition makes FA construction convenient.} \]

\[ \text{e.g., FA for concatenation } L_1 L_2. \]

\[ \text{More example: Example 1.38 (page 54)} \]
1.2 Nondeterminism

$\epsilon$-transitions

What are they?

$\delta(q, \epsilon) = \{ q_1 \}$.

What does an $\epsilon$-transition mean?

$\epsilon$-transition makes FA construction convenient.

E.g., FA for concatenation $L_1 L_2$.

More example: Example 1.38 (page 54)
1.2 Nondeterminism

ε-transitions

What are they?
1.2 Nondeterminism

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More example: Example 1.38 (page 54)
1.2 Nondeterminism

Formal Definition of a nondeterministic FA

Definition 1.37 (page 35)

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

1. $Q$ is a finite set called the states,
2. $\Sigma$ is a finite set called the alphabet,
3. $\delta: Q \times \Sigma \rightarrow P(Q)$ is the transition function,
4. $q_0 \in Q$ is the start state, and
5. $F \subseteq Q$ is the set of accept states.

where $\Sigma \epsilon = \Sigma \cup \{\epsilon\}$ and $P(Q)$ is the power set of $Q$, also written as $2^Q$. 
1.2 Nondeterminism

Formal Definition of a nondeterministic FA
1.2 Nondeterminism

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\[
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\]

\(\mathcal{P}(Q)\) is the power set of \(Q\), also written as \(2^Q\).
1.2 Nondeterminism

Let $N = (Q, \Sigma, \epsilon, \delta, q_0, F)$ be a nondeterministic finite automaton. Let $w = w_1w_2...w_n$ be a string where each symbol $w_i \in \Sigma \epsilon$. Then $N$ accepts $w$ if a sequence of states $r_0, r_1, ..., r_n$ exists with three conditions:

1. $r_0 = q_0$;
2. $r_{i+1} \in \delta(r_i, w_{i+1})$, for $i = 0, 1, ..., n-1$;
3. $r_n \in F$.

We say $N$ recognizes language $L$ if $L = \{w : w \in \Sigma^* \text{ and } N \text{ accepts } w\}$.
1.2 Nondeterminism

Formal definition of computation with NFA
1.2 Nondeterminism

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1.2 Nondeterminism

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1.2 Nondeterminism

Examples of NFAs (NFA $N_1$ in example 1.38, page 54)

The formal definition of $N_1$ is $(Q, \Sigma, \delta, q_1, F)$, where $Q = \{q_1, q_2, q_3, q_4\}$, $\Sigma = \{0, 1\}$, $q_1$ is the start state, $F = \{q_4\}$ and $\delta$ is given as:

- $0 \in q_1 \rightarrow \{q_1\}$
- $1 \in q_1 \rightarrow \{q_1, q_2\}$
- $\epsilon \in q_2 \rightarrow \emptyset$
- $\epsilon \in q_3 \rightarrow \emptyset$
- $\epsilon \in q_3 \rightarrow \{q_4\}$
- $\epsilon \in q_4 \rightarrow \emptyset$
- $0 \in q_4 \rightarrow \{q_4\}$
- $1 \in q_4 \rightarrow \{q_4\}$

What language does it accept?
1.2 Nondeterminism

Examples of NFAs (NFA $N_1$ in example 1.38, page 54)

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$$
\begin{array}{c|ccc}
 & 0 & 1 & \epsilon \\
\hline
q_1 & \{q_1\} & \{q_1, q_2\} & \emptyset \\
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$$

What language does it accept?
1.2 Nondeterminism

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What language does it accept?
1.2 Nondeterminism

Are NFAs more powerful than DFAs?

Actually, NFAs are not more powerful than DFAs.
1.2 Nondeterminism

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Are there languages recognized by NFAs but not by DFAs?

Actually, NFAs are not more powerful than DFAs.
1.2 Nondeterminism

The classes of languages recognized by NFAs and by DFAs are the same! This is because $\Sigma \subseteq \Sigma^*$, and $\delta(q, a) = p$ can be redefined as $\delta(q, a) = \{p\}$.

To see the other way around, we only need to show that for every NFA, there is a DFA accepting the same language.
1.2 Nondeterminism

Equivalence of NFA and DFA
1.2 Nondeterminism

Equivalence of NFA and DFA

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1.2 Nondeterminism

Equivalence of NFA and DFA

- The classes of languages recognized by NFAs and by DFAs are the same!

First the class of languages recognized by DFAs can be recognized by NFAs as well.
1.2 Nondeterminism

Equivalence of NFA and DFA

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Equivalence of NFA and DFA

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• To see the other way around is also true, we only need to show
1.2 Nondeterminism

Equivalence of NFA and DFA

- The classes of languages recognized by NFAs and by DFAs are the same!

First the class of languages recognized by DFAs can be recognized by NFAs as well.

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- To see the other way around is also true, we only need to show that for every NFA, there is a DFA accepting the same language.
1.2 Nondeterminism

Theorem 1.39

Every NFA has an equivalent DFA.

Proof idea
To use a DFA to "simulate the NFA's computation"

How: keep tracking on all the transitions of the NFA
- assume the NFA has \( k \) states in total
- given state \( q \) and symbol \( a \), transiting to a subset of \( k \) states
- make each such subset to single state in the new DFA,
1.2 Nondeterminism

**Theorem 1.39** (page 55) *Every NFA has an equivalent DFA.*
1.2 Nondeterminism

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1.2 Nondeterminism

E.g., Consider NFA

\[ \delta(p, 0) = \{ p \}, \delta(p, 1) = \{ p, q \}, \delta(q, 0) = \emptyset, \delta(q, 1) = \emptyset. \]

What language does it accept?

Is transition \[ \delta(q, 0) = p \] needed?

Can you design a DFA for this language?

Define a DFA with states \[ \emptyset, \{ p \}, \{ q \}, \{ p, q \} \] with new transition function

\[ \Delta(\{ p \}, 0) = \{ p \}, \Delta(\{ p \}, 1) = \{ p, q \}, \Delta(\{ q \}, 0) = \emptyset, \Delta(\{ q \}, 1) = \emptyset, \Delta(\{ p, q \}, 0) = \{ p \}, \Delta(\{ p, q \}, 1) = \{ p, q \} \]

What does it look like?
1.2 Nondeterminism

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Can you design a DFA for this language?

Define a DFA with states $[\emptyset]$, $[p]$, $[q]$, and $[p, q]$ with new transition function $\Delta$
1.2 Nondeterminism

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\begin{align*}
\delta(p, 0) &= \{p\}, & \delta(p, 1) &= \{p, q\}, & \delta(q, 0) &= \emptyset, & \delta(q, 1) &= \emptyset.
\end{align*}
\]

What language does it accept? Is transition \(\delta(q, 0) = p\) needed?

Can you design a DFA for this language?

Define a DFA with states \([\emptyset]\), \([p]\), \([q]\), and \([p, q]\) with new transition function \(\Delta\)

\[
\Delta([p], 0) = [p],
\]
E.g., Consider NFA

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1.2 Nondeterminism

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Define a DFA with states \([\emptyset], [p], [q],\) and \([p, q]\) with new transition function \(\Delta\)

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\Delta([p], 0) &= [p], \quad \Delta([p], 1) = [p, q], \quad \Delta([q], 0) = [\emptyset],
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1.2 Nondeterminism

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\[ \Delta([p, q], 0) = [p], \]

What does it look like?
1.2 Nondeterminism

E.g., Consider NFA

\[
\delta(p, 0) = \{p\}, \delta(p, 1) = \{p, q\}, \delta(q, 0) = \emptyset, \delta(q, 1) = \emptyset.
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What language does it accept? Is transition \( \delta(q, 0) = p \) needed?

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Define a DFA with states \([\emptyset]\), \([p]\), \([q]\), and \([p, q]\) with new transition function \( \Delta \)

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\begin{align*}
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\Delta([p], 1) &= [p, q], \\
\Delta([q], 0) &= [\emptyset], \\
\Delta([q], 1) &= [\emptyset], \\
\Delta([p, q], 0) &= [p], \\
\Delta([p, q], 1) &= [p, q].
\end{align*}
\]
1.2 Nondeterminism

E.g., Consider NFA

![NFA Diagram]

\[ \delta(p, 0) = \{p\}, \delta(p, 1) = \{p, q\}, \delta(q, 0) = \emptyset, \delta(q, 1) = \emptyset. \]

What language does it accept? Is transition \( \delta(q, 0) = p \) needed?

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Define a DFA with states \([\emptyset]\), \([p]\), \([q]\), and \([p, q]\) with new transition function \( \Delta \)

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\begin{align*}
\Delta([p], 0) &= [p], & \Delta([p], 1) &= [p, q], & \Delta([q], 0) &= [\emptyset], & \Delta([q], 1) &= [\emptyset] \\
\Delta([p, q], 0) &= [p], & \Delta([p, q], 1) &= [p, q]
\end{align*}
\]

What does it look like?
1.2 Nondeterminism

NFA to DFA conversion further explained:

Consider again NFA on input string 011:

\[ q_1 \]

\[ q_1 = 0 \rightarrow q_1 \]

\[ q_1 = 1 \rightarrow q_1, q_2 \]

\[ q_1, q_2 = \epsilon \rightarrow q_3 \]

\[ q_1, q_2 = 1 \rightarrow q_1, q_2, q_4 \]

We can represent these branchings on string 011 deterministically:

\[ q_1 \]

\[ q_1 = 0 \rightarrow q_1 \]

\[ q_1 = 1 \rightarrow q_1, q_2 \]

with $E(q_1, q_2) = q_1, q_2, q_3$

states reachable from $\{ q_1, q_2 \}$ via $\epsilon$-transitions.
1.2 Nondeterminism

NFA to DFA conversion further explained:

consider again NFA on input string 011
1.2 Nondeterminism

NFA to DFA conversion further explained:

NFA on input string 011:

\[ \{ q_1 \} \xrightarrow{0} \]

Diagram:

- \( q_1 \rightarrow 1 \rightarrow q_2 \rightarrow \varepsilon \rightarrow q_3 \rightarrow 1 \rightarrow q_4 \)
- Transitions:
  - \( q_1 \xrightarrow{0,1} q_1 \)
  - \( q_2 \xrightarrow{1} q_2 \)
  - \( q_3 \xrightarrow{0, \varepsilon} q_3 \)
  - \( q_4 \xrightarrow{0,1} q_4 \)

States reachable via \( \varepsilon \)-transitions:

- Treat as \( \{ q_1, q_2 \} \)
- States reachable:
  - \( \{ q_1, q_2, q_3 \} \)
  - \( \{ q_1, q_2, q_3, q_4 \} \)
1.2 Nondeterminism

NFA to DFA conversion further explained:

Consider again NFA on input string 011:

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

\[ \{q_1, q_2\} \xrightarrow{\varepsilon} \{q_1, q_2, q_3\} \]

\[ \{q_1, q_2, q_3\} \xrightarrow{1} \{q_1, q_2, q_3, q_4\} \]

Using the set of states reachable via \(\varepsilon\)-transitions.
1.2 Nondeterminism

NFA to DFA conversion further explained:

consider again NFA on input string 011

\{ q_1 \} \xrightarrow{0} \{ q_1 \} \xrightarrow{1} \{ q_1, q_2 \}
1.2 Nondeterminism

NFA to DFA conversion further explained:

consider again NFA
on input string 011

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

Using

\[
E(\{ q_1, q_2 \}) = \{ q_1, q_2, q_3 \}
\]
1.2 Nondeterminism

NFA to DFA conversion further explained:

consider again NFA on input string 011

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

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

\[
\{ q_1 \} \xrightarrow{0, \varepsilon} \{ q_3 \} \xrightarrow{1} \{ q_4 \}
\]

We can represent these branchings on string 011 deterministically:

\[
\begin{align*}
\{ q_1 \} & \xrightarrow{0} \{ q_1 \} \xrightarrow{1} \{ q_1, q_2 \} \\
q_1 & \xrightarrow{1} \{ q_1, q_2 \}
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\{q_1\} & \xrightarrow{0} \{q_1\} \xrightarrow{1} \{q_1, q_2\} \\
q_1 & \xrightarrow{1} \{q_1, q_2\} \\
q_2 & \xrightarrow{1} \emptyset
\end{align*}
\]

\[
\text{We can represent these branchings on string } 011 \\
\text{deterministically:}
\]

\[
\begin{align*}
\{q_1\} & \xrightarrow{0} \{q_1\} \xrightarrow{1} \{q_1, q_2\} \\
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\]
1.2 Nondeterminism

NFA to DFA conversion further explained:

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q_2
1.2 Nondeterminism

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q_2 & \xrightarrow{1} \emptyset \\
q_2 & \xrightarrow{\epsilon} \{q_3\}
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\{q_1\} &\xrightarrow{0}\{q_1\} \xrightarrow{1}\{q_1, q_2\} \\
q_1 &\xrightarrow{1}\{q_1, q_2\} \\
q_2 &\xrightarrow{0}\emptyset \\
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\]

We can represent these branchings on string 011 deterministically:
Nondeterminism

NFA to DFA conversion further explained:

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\{q_1\} & \xrightarrow{0} \{q_1\} \xrightarrow{1} \{q_1, q_2\} \\
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\]

We can represent these branchings on string 011 deterministically:

\[
[q_1] \xrightarrow{0}
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1.2 Nondeterminism

NFA to DFA conversion further explained:

consider again NFA
on input string 011

\( \{q_1\} \xrightarrow{0} \{q_1\} \xrightarrow{1} \{q_1, q_2\} \)
\( q_1 \xrightarrow{1} \{q_1, q_2\} \)
\( q_2 \xrightarrow{1} \emptyset \)
\( q_2 \xrightarrow{\epsilon} \{q_3\} \xrightarrow{1} \{q_4\} \)

We can represent these branchings on string 011 deterministically:

\([q_1] \xrightarrow{0} [q_1]\)
1.2 Nondeterminism

NFA to DFA conversion further explained:

Consider again NFA on input string 011

- \{q_1\} \xrightarrow{0} \{q_1\} \xrightarrow{1} \{q_1, q_2\}
  - \{q_1\} \xrightarrow{0} \{q_1, q_2\}
  - q_1 \xrightarrow{1} \{q_1, q_2\}
  - q_2 \xrightarrow{1} \emptyset
  - q_2 \xrightarrow{\varepsilon} \{q_3\} \xrightarrow{1} \{q_4\}

We can represent these branchings on string 011 deterministically:

\[ [q_1] \xrightarrow{0} [q_1] \xrightarrow{1} [q_1, q_2] \]
1.2 Nondeterminism

NFA to DFA conversion further explained:

Consider again NFA on input string 011

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\end{align*}
\]

We can represent these branchings on string 011 deterministically:

\[
[q_1] \xrightarrow{0} [q_1] \xrightarrow{1} [q_1, q_2] \xrightarrow{\text{with } E(q_1, q_2)} [q_1, q_2, q_3]
\]
1.2 Nondeterminism

NFA to DFA conversion further explained:

consider again NFA
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\begin{align*}
\{q_1\} & \xrightarrow{0} \{q_1\} \xrightarrow{1} \{q_1, q_2\} \\
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using \( E(\{q_1, q_2\}) = \{q_1, q_2, q_3\} \), states reachable from \{q_1, q_2\} via \( \epsilon \)-transitions
1.2 Nondeterminism

But how exactly is the new transition \( \Delta \) defined?

- \( Q' = \mathcal{P}(Q) \), consider all \( 2^k \) states – if the NFA has \( k \) states in \( Q \);
- let \( R \in Q' \) (i.e., \( R \subseteq Q \)), \( \Delta(R, a) = \bigcup_{r \in R} \delta(r, a) = \{ q : q \in \delta(r, a), \text{for some } r \in R \} \)

\[
\Delta(\{p, q\}, 0) = \delta(p, 0) \cup \delta(q, 0) = \{p\} \cup \emptyset = \{p\}
\]

\[
\Delta(\{p, q\}, 1) = \delta(p, 1) \cup \delta(q, 1) = \{p, q\} \cup \emptyset = \{p, q\}
\]

that is:

\[
\Delta([p, q], 0) = [p], \quad \Delta([p, q], 1) = [p, q]
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1.2 Nondeterminism

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1.2 Nondeterminism

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1.2 Nondeterminism

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$$

* e.g.,

$$
\Delta(\{p, q\}, 0) = \delta(p, 0) \cup \delta(q, 0) = \{p\} \cup \emptyset = \{p\}
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1.2 Nondeterminism

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\[\Delta(\{p, q\}, 0) = \delta(p, 0) \cup \delta(q, 0) = \{p\} \cup \emptyset = \{p\}\]

\[\Delta(\{p, q\}, 1) = \delta(p, 1) \cup \delta(q, 1) = \{p, q\} \cup \emptyset = \{p, q\}\]

that is: $\Delta([p, q], 0) = [p]$,
1.2 Nondeterminism

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e.g.,

$$\Delta(\{p, q\}, 0) = \delta(p, 0) \cup \delta(q, 0) = \{p\} \cup \emptyset = \{p\}$$

$$\Delta(\{p, q\}, 1) = \delta(p, 1) \cup \delta(q, 1) = \{p, q\} \cup \emptyset = \{p, q\}$$

that is: $\Delta([p, q], 0) = [p]$, $\Delta([p, q], 1) = [p, q]$
1.2 Nondeterminism

Now include $\epsilon$-transitions. But again what does an $\epsilon$-transition mean?, e.g., $\delta(p, \epsilon) = \{q\}$ if a state can reach state $p$ on some string, it can also reach $q$ on the same string.

This implies that the set of states that can be transited to should be extended through $\epsilon$-transitions:

$$E(R) = \{q: q \text{ is reachable from } R \text{ via zero or more } \epsilon - \text{transitions}\}$$

New transition:

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1.2 Nondeterminism

Proof of Theorem 1.39

Let $N = (Q, \Sigma, \epsilon, \delta, q_0, F)$ be an NFA recognizing language $L$. We construct a DFA $M = (Q', \Sigma, \Delta, q'_0, F')$ to recognize the same language $L$.

1. $Q'$ contains $2^k$ states, one for each subset of $Q$.
2. Let $p_R \in Q'$, where $R \subseteq Q$ representing a subset of $Q$ define $\Delta(p_R, a) = p_S$, where $S = \{q : q \in \delta(r, a), \text{for some } r \in R\}$.
3. $q'_0 = p\{q_0\}$
4. $F' = \{p_R : R \text{ contains an accepting state of } N\}$.
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Let $p_R \in Q'$, where $R \subseteq Q$ representing a subset of $Q$ define $\Delta(p_R, a) = p_S$, where $S = \{q : q \in E(\delta(r, a))$, for some $r \in R\}$.

$q_0' = p_{E(S)}$ where $E(S)$ includes all the states in $S$ and those reachable through the $\epsilon$ transitions from the states in $S$.

Apparently $M$ simulates the computation of $N$ on any input string and accepts it if and only if $N$ accepts it.
1.2 Nondeterminism

When $\epsilon$ transitions are involved
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1.2 Nondeterminism

- Example
  - the DFA has states $\emptyset$, \{1\}, \{2\}, \{3\}, \{1, 2\}, \{1, 3\}, \{2, 3\}, \{1, 2, 3\}
  - and the new transition function $\Delta$
    - $\Delta(\{1\}, a) = \emptyset$
    - $\Delta(\{1\}, b) = \{2\}$
    - $\Delta(\{2\}, a) = \{2, 3\}$
    - $\Delta(\{2\}, b) = \{3\}$
    - $\Delta(\{3\}, a) = E(\{1\}) = \{1, 3\}$
    - $\Delta(\{3\}, b) = \emptyset$
    - $\Delta(\{1, 2\}, a) = \{2, 3\}$
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1.2 Nondeterminism

Example

Diagram of a nondeterministic finite automaton with states 1, 2, and 3, transitions labeled with symbols a, b, and ε.
1.2 Nondeterminism

Example

\[\begin{array}{c}
\text{1} \\
\text{2} \\
\text{3}
\end{array}\]

\[\begin{array}{c}
\text{∅} \\
\{1\} \\
\{2\} \\
\{1,2\} \\
\{3\} \\
\{1,3\} \\
\{2,3\} \\
\{1,2,3\}
\end{array}\]

Transition function \( \Delta \):

- \( \Delta(\{1\},a) = \emptyset \)
- \( \Delta(\{1\},b) = \{2\} \)
- \( \Delta(\{2\},a) = \{2\}, \{3\} \)
- \( \Delta(\{2\},b) = \{3\} \)
- \( \Delta(\{3\},a) = \{1\}, \{3\} \)
- \( \Delta(\{3\},b) = \emptyset \)
- \( \Delta(\{1,2\},a) = \{1\}, \{2\}, \{3\} \)
- \( \Delta(\{1,2\},b) = \{2\} \)
- \( \Delta(\{1,3\},a) = \{1\}, \{3\} \)
- \( \Delta(\{1,3\},b) = \emptyset \)
- \( \Delta(\{2,3\},a) = \{2\}, \{3\} \)
- \( \Delta(\{2,3\},b) = \emptyset \)
- \( \Delta(\{1,2,3\},a) = \{1\}, \{2\}, \{3\} \)
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1.2 Nondeterminism

Example

- the DFA has states
1.2 Nondeterminism

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1.2 Nondeterminism

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1.2 Nondeterminism

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1.2 Nondeterminism

Steps to convert an NFA to DFA:
• determine the states for the DFA
• determine the start and accepting states
• determine the transition function, pay attention to $\epsilon$-transitions
• simplify the DFA by removing unnecessary states

Corollary 1.40 (page 56)
A language is regular if and only if some NFA recognizes it.

We have established the equivalence between regular languages and NFAs.
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Theorem 1.45
The class of regular languages is closed under the union operation. That is, if \( L_1 \) and \( L_2 \) are regular, so is \( L_1 \cup L_2 \).

Theorem 1.46
The class of regular languages is closed under the concatenation operation. That is, if \( L_1 \) and \( L_2 \) are regular, so is \( L_1L_2 \).

Theorem 1.49
The class of regular languages is closed under the star operation. That is, if \( L \) is regular, so is \( L^* \).

Note: \( L^* = \{ \epsilon \} \cup L \cup LL \cup \ldots \)
1.2 Nondeterminism

Properties of regular languages under some operations
1.2 Nondeterminism

Properties of regular languages under some operations

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Theorem 1.45 (page 59)
The class of regular languages is closed under the union operation.

Proof: Construct an NFA to recognize $L_1 \cup L_2$.

[Drawing is not a formal proof]
1.2 Nondeterminism

Properties of regular languages under some operations
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![Diagram of NFAs and NFA](image-url)
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Proof:
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but drawing pictures is not a formal proof
Properties of regular languages under some operations

Theorem 1.45 (page 59)

*The class of regular languages is closed under the union operation.*

(What does it mean that a class is closed under certain operation?)

**Proof:**

construct an NFA to recognize $L_1 \cup L_2$.

but drawing pictures is not a formal proof

So how to prove?
1.2 Nondeterminism

Let $w = w_1 w_2 ... w_n \in L_1 \cup L_2$, where $w_i \in \Sigma$.

Then $w \in L_1$ or $w \in L_2$.

Assume $w \in L_1$ (the case of $w \in L_2$ can be proved similarly).

Assume $N_1$ recognizes $L_1$; then $w$ is accepted by $N_1$.

There must be a sequence of states $r_0 r_1 ... r_n$, such that

- $r_0$ is the start state of $N_1$,
- $r_{i+1} \in \delta_1(r_i, w_{i+1})$, $i = 0, 1, ..., n - 1$,
- $r_n$ is an accept state of $N_1$.

On the combined NFA $N$, $w$ can be written as $\epsilon w_1 ... w_n$.

According to the construction of $N$, it is clear the sequence of states of $N_0 r_2 ... r_n$ accepts $w = \epsilon w_1 ... w_n$ because

- $r_0 \in \Delta(r, \epsilon)$,
- $r_{i+1} \in \Delta(r_i, w_{i+1})$, $i = 0, 1, ..., n - 1$,
- $r_n$ is an accept state of $N_1$.

So $N$ accepts $w$.

Is that all? What else are needed to be done?
1.2 Nondeterminism

1. Let \( w = w_1 w_2 \ldots w_n \in L_1 \cup L_2 \), where \( w_i \in \Sigma_e \).
1.2 Nondeterminism

1. Let \( w = w_1w_2 \ldots w_n \in L_1 \cup L_2 \), where \( w_i \in \Sigma \epsilon \)

2. Then \( w \in L_1 \) or \( w \in L_2 \).
1.2 Nondeterminism

1. Let $w = w_1w_2 \ldots w_n \in L_1 \cup L_2$, where $w_i \in \Sigma_e$

2. Then $w \in L_1$ or $w \in L_2$.

3. Assume $w \in L_1$ (the case of $w \in L_2$ can be proved similarly.)
1.2 Nondeterminism

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2. Then \( w \in L_1 \) or \( w \in L_2 \).
3. Assume \( w \in L_1 \) (the case of \( w \in L_2 \) can be proved similarly.)
4. Assume \( N_1 \) recognizes \( L_1 \); then \( w \) is accepted by \( N_1 \).
1.2 Nondeterminism

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4. Assume \( N_1 \) recognizes \( L_1 \); then \( w \) is accepted by \( N_1 \).

5. There must be a sequence of states \( r_0 r_1 \ldots r_n \), such that
   - \( r_0 \) is the start state of \( N_1 \),
   - \( r_{i+1} \in \delta_1(r_i, w_{i+1}) \), \( i = 0, 1, \ldots, n - 1 \)
   - \( r_n \) is an accept state of \( N_1 \).

6. On the combined NFA \( N \), \( w \) can be written as \( \epsilon w_1 \ldots w_n \).

7. According to the construction of \( N \), it is clear the sequence of states of \( r_0 r_2 \ldots r_n \) accepts \( w = \epsilon w_1 \ldots w_n \) because
   - \( r_0 \in \Delta(r, \epsilon) \),
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Is that all? What else are needed to be done?
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1. Let $w = w_1w_2 \ldots w_n \in L_1 \cup L_2$, where $w_i \in \Sigma^*$

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7. According to the construction of \( N \), it is clear the sequence of states of \( N \)
   \( \overline{r}r_0r_2 \ldots r_n \) accepts \( w = \epsilon w_1 \ldots w_n \) because
1.2 Nondeterminism

1. Let $w = w_1w_2 \ldots w_n \in L_1 \cup L_2$, where $w_i \in \Sigma_\epsilon$

2. Then $w \in L_1$ or $w \in L_2$.

3. Assume $w \in L_1$ (the case of $w \in L_2$ can be proved similarly.)

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7. According to the construction of $N$, it is clear the sequence of states of $N$
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1.2 Nondeterminism

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Is that all? What else are needed to be done?
1.2 Nondeterminism

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8. So $N$ accepts $w$.

Is that all? What else are needed to be done?
1.2 Nondeterminism

We actually need to prove:

for any $w \in \Sigma^*$, $w \in L_1 \cup L_2$ if and only if $N$ accepts $w$. That is

1. if $w \in L_1 \cup L_2$ then $N$ accepts $w$;
2. if $w \not\in L_1 \cup L_2$ then $N$ does not accept $w$.

We have just proved Part (1). Part (2) can be restated as:

2. if $N$ accepts $w$, then $w \in L_1 \cup L_2$.

Example of language union and combined NFA.
1.2 Nondeterminism

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1.2 Nondeterminism

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1.2 Nondeterminism

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1.2 Nondeterminism

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Example of language union and combined NFA.
1.2 Nondeterminism

Theorem 1.46

The class of regular languages is closed under the concatenation operation.

Proof: construct an NFA to recognize $L_1 L_2$.

How to prove?

Example of language concatenation and combined NFA.
1.2 Nondeterminism

**Theorem 1.46** (page 60)

The class of regular languages is closed under the concatenation operation.

Proof: construct an NFA to recognize $L_1 \cdot L_2$.

How to prove?

Example of language concatenation and combined NFA.
1.2 Nondeterminism

**Theorem 1.46** (page 60)

*The class of regular languages is closed under the concatenation operation.*
1.2 Nondeterminism

**Theorem 1.46** (page 60)

*The class of regular languages is closed under the concatenation operation.*

**Proof:** construct an NFA to recognize $L_1 L_2$. 

![Diagram of NFA construction](image)
Theorem 1.46 (page 60)

*The class of regular languages is closed under the concatenation operation.*

**Proof:** construct an NFA to recognize $L_1L_2$.

How to prove?
1.2 Nondeterminism

**Theorem 1.46** (page 60)

The class of regular languages is closed under the concatenation operation.

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How to prove?

Example of language concatenation and combined NFA.
1.2 Nondeterminism

\[ L^* = \{ \epsilon \} \cup L \cup L_2 \cup L_3 \cup ... \]

where \( L_k = L_{k-1} \), for \( k \geq 1 \).

Example:
\( \Sigma = \{ 0, 1 \} \).

\( L = \{ w : w \text{ contains pattern '11' and no other 1's} \} \).

\( L^* = \{ w : w = \epsilon \text{ or } w = w_1 ... w_k, \text{ for some } w_1, w_2, ..., w_k \in L, \text{ for some } k \geq 1 \} \).

That is: every string in \( L^* \) contains \( k \) copies of pattern '11' and no other 1's, for some \( k \geq 0 \).

DFA for \( L \) is the red portion only.

NFA for \( L^* \) is with the additional green portions.
1.2 Nondeterminism

\[ L^* = \{ \epsilon \} \cup L \cup L^2 \cup L^3 \cup \ldots \quad \text{where} \quad L^k = LL^{k-1}, \quad k \geq 1 \]
1.2 Nondeterminism

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1.2 Nondeterminism

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DFA for \( L \) is the red portion only.
1.2 Nondeterminism

$$L^* = \{\epsilon\} \cup L \cup L^2 \cup L^3 \cup \ldots$$ \quad \text{where } L^k = LL^{k-1}, \ k \geq 1

Example: \(\Sigma = \{0, 1\}\). \(L = \{w : w \text{ contains pattern '11' and no other 1's}\}\)

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That is: every string in \(L^*\) contains \(k\) copies of pattern '11' and no other 1's, for some \(k \geq 0\).

DFA for \(L\) is the red portion only.

NFA for \(L^*\) is with the additional green portions.
1.2 Nondeterminism

\[ L^* = \{ \epsilon \} \cup L \cup L^2 \cup L^3 \cup \ldots \quad \text{where} \quad L^k = LL^{k-1}, \ k \geq 1 \]

Example: \( \Sigma = \{0, 1\} \). \( L = \{ w : w \text{ contains pattern '11' and no other 1's} \} \)

\[ L^* = \{ w : w = \epsilon \text{ or } w = w_1 \ldots w_k, \text{ for some } w_1 \in L, \ldots, w_k \in L, \text{ for some } k \geq 1 \} \]

That is: every string in \( L^* \) contains \( k \) copies of pattern '11' and no other 1's, for some \( k \geq 0 \).

DFA for \( L \) is the red portion only.

NFA for \( L^* \) is with the additional green portions.
1.2 Nondeterminism

NFA for $L^*$ can be written as:

- $w_1 = 00110$
- $w_2 = 0011$
- $w_3 = 1100$

State transitions:

- $q_0 \Rightarrow \epsilon$
- $q_1 \Rightarrow 0$
- $q_1 \Rightarrow 0$
- $q_2 \Rightarrow 1$
- $q_3 \Rightarrow 0$
- $q_3 \Rightarrow \epsilon$
- $q_1 \Rightarrow 0$
- $q_1 \Rightarrow 0$
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1.2 Nondeterminism

NFA for $L^*$ is with the additional green portions.
NFA for $L^*$ is with the additional green portions.
1.2 Nondeterminism

NFA for $L^*$ is with the additional green portions.

To recognize string $w = 0011000111100$
1.2 Nondeterminism

NFA for $L^*$ is with the additional green portions.

To recognize string $w = 001100111100$

$w$ can be written as $w_1w_2w_3$, for $w_1 = 00110, w_2 = 0011, w_3 = 1100$
1.2 Nondeterminism

NFA for \( L^* \) is with the additional green portions.

To recognize string \( w = 001100111100 \)

\( w \) can be written as \( w_1w_2w_3 \), for \( w_1 = 00110, w_2 = 0011, w_3 = 1100 \)

state transitions:

\[
\begin{align*}
q_0 & \Rightarrow^\epsilon q_1 \Rightarrow^0 q_1 \Rightarrow^0 q_1 \Rightarrow^1 q_2 \Rightarrow^1 q_3 \Rightarrow^0 q_3 \Rightarrow^\epsilon q_1 \Rightarrow^0 q_1 \\
& \Rightarrow^0 q_1 \Rightarrow^1 q_2 \Rightarrow^1 q_3 \Rightarrow^\epsilon q_1 \Rightarrow^1 q_2 \Rightarrow^1 q_3 \Rightarrow^0 q_3 \Rightarrow^0 q_3
\end{align*}
\]
Theorem 1.49 (page 62)

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

Proof

Construct an NFA to recognize \( L^* \).

How to prove?

Math induction on \( n \) for \( w \in L^n \).

• When \( n = 0 \), we have \( w = \epsilon \) and \( N \) accepts \( \epsilon \);

• Assume for all \( w \in L^k \), \( N \) accepts \( w \);

• Now if \( w \in L^{k+1} \), \( w \) can be written as \( w = xy \) where \( x \in L^k \), \( y \in L^k \).

• By assumption \( N \) accepts \( x \);

• \( x \) arrives at some accept state \( q_{acc} \) in \( N \);

• Because of \( \epsilon \)-transition from \( q_{acc} \) to the start state of \( N_1 \), \( xy \) also arrives at some accept state of \( N \). So \( N \) accepts \( w \).

Example of language star and combined NFA.
1.2 Nondeterminism

Theorem 1.49 (page 62)
1.2 Nondeterminism

**Theorem 1.49** (page 62)

*The class of regular languages is closed under the star operation.*
1.2 Nondeterminism

**Theorem 1.49** (page 62)

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

**Proof** construct an NFA to recognize $L^*$. 

![Diagram of NFAs](image-url)
1.2 Nondeterminism

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How to prove?
1.2 Nondeterminism

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- when $n = 0$, we have $w = \epsilon$ and $N$ accepts $\epsilon$;
1.2 Nondeterminism

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Proof

construct an NFA to recognize $L^*$. 

How to prove ? 

math induction on $n$ for $w \in L^n$

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Proof construct an NFA to recognize $L^*$. 

How to prove? math induction on $n$ for $w \in L^n$

• when $n = 0$, we have $w = \epsilon$ and $N$ accepts $\epsilon$;
• assume for all $w \in L^k$, $N$ accepts $w$;
• now if $w \in L^{k+1}$, $w$ can be written as $w = xy$ where $x \in L^k$, $y \in L$. 
1.2 Nondeterminism

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- by assumption $N$ accepts $x$; $x$ arrives at some accept state $q_{acc}$ in $N$;
1.2 Nondeterminism

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- because of $\epsilon$-transition from $q_{acc}$ to the start state of $N_1$, $xy$ also arrives at some accept state of $N$. So $N$ accepts $w$. 
1.2 Nondeterminism

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\begin{figure}
\centering
\includegraphics[width=\textwidth]{nfa_diagram}
\caption{Example of language star and combined NFA.}
\end{figure}

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Example of language star and combined NFA.
1.3 Regular Expressions

- Natural languages are too vague for language definition.
- FAs are precise but not succinct for language definition.
- Regular expressions are used to define regular languages.
1.3 Regular Expressions

Regular expressions

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Regular expressions

- Natural languages are too vague for language definition.
- FAs are precise but not succinct for language definition.
- Regular expressions are used to define regular languages.
For example, a language in which each string contains either substring 11 or 001, i.e., each string can have "anything" as prefix, "anything" as suffix, and contain 11 or 001 in between such set of strings can be expressed as

$$(1 \cup 0)^*(11 \cup 001)(1 \cup 0)^*$$

Another example: a language whose strings have symbol a in the third last position.

$$(a \cup b)^*a(a \cup b)(a \cup b)$$
1.3 Regular Expressions

For example,

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1.3 Regular Expressions

Notations for regular expressions:

1. Use 0 to represent \{0\}, and 1 for \{1\};
2. Use * to represent "repeats", e.g., 1* = \{\epsilon, 1, 11, ...\};
3. Use ∪ for 'OR', e.g., 1 ∪ 0 represents \{0, 1\};
4. Use ◦ for 'concatenation', e.g., 0 ◦ 1* represents \{0, 01, 011, 0111, ...\}, often ◦ can be removed: 01*
5. Use '(', ')' whenever needed (as in arithmetic expressions).
1.3 Regular Expressions

Notations for regular expressions
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1.3 Regular Expressions

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4. Use $\circ$ for ’concatenation’,
   e.g., $0 \circ 1^*$ represents \{0, 01, 011, 0111, \ldots \},
1.3 Regular Expressions

Notations for regular expressions

1. Use 0 to represent \{0\}, and 1 for \{1\};
2. Use $\ast$ to represent “repeats”, e.g., $1\ast = \{\epsilon, 1, 11, \ldots \}$;
3. Use $\cup$ for 'OR', e.g., $1 \cup 0$ represents $\{0, 1\}$
4. Use $\circ$ for 'concatenation',
   e.g., $0 \circ 1\ast$ represents $\{0, 01, 011, 0111, \ldots \}$,
   often $\circ$ can be removed: $01\ast$
1.3 Regular Expressions

Notations for regular expressions

1. Use 0 to represent \{0\}, and 1 for \{1\};
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   often \circ can be removed: \01^*
5. Use '(, ' whenever needed (as in arithmetic expressions).
1.3 Regular Expressions

More examples:
\[(1 \cup 0)^*\]
represents language \(\{00, 01, 10, 11\}\)
\[(0 \cup 1)^* = \{\epsilon, 0, 1, 00, 01, 10, 11, 000, 001, \ldots\} = \Sigma^* \]
where \(\Sigma = \{0, 1\}\)
\[(0 \cup 1)^* \circ 1 \circ 1 \circ 1 (1 \cup 0)^*\], or simply \(\Sigma^* 111 \Sigma^* 0 \Sigma^* 0 \cup 1 \Sigma^* 1 \cup 1 \cup 0\)
\[(0 \cup \epsilon)^* = 01^* \cup 1^*\]
\[(0 \cup \epsilon)(1 \cup \epsilon) = \{\epsilon, 1, 0, 01\}\]
\[\emptyset^* = \emptyset\]
1.3 Regular Expressions

More examples:
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\[(1 \cup 0) \circ (1 \cup 0)\] represents language
1.3 Regular Expressions

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\[(0 \cup \epsilon)^*1 = 01^* \cup 1^*\]

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\[1^*\emptyset = \emptyset\]
1.3 Regular Expressions

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\(\emptyset^* = \text{?}\)
1.3 Regular Expressions

Definition 1.52

A regular expression $R$ is one of the followings:

1. A symbol $a \in \Sigma$ the alphabet
2. $\epsilon$
3. $\emptyset$
4. $(R_1 \cup R_2)$, where $R_1, R_2$ are regular expressions
5. $(R_1 \circ R_2)$, where $R_1, R_2$ are regular expressions
6. $(R_1^*)$, where $R_1$ is a regular expression.

Without the parentheses, evaluation of a regular expression is done in the precedence order: star, then concatenation, then union.

Also we use $R^+$ for $R^*$. For example, $1^+ = \{1, 11, 111, ...\}$. 
1.3 Regular Expressions

Formal Definition of a Regular Expression

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1.3 Regular Expressions

Formal Definition of a Regular Expression

**Definition 1.52** (page 64)
1.3 Regular Expressions

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Without the parentheses, evaluation of a regular expression is done in the precedence order: star, then concatenation, then union.

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1.3 Regular Expressions

Additional special cases, where $R$ is a regular expression already:

- $R \cup \epsilon = ?$
- $R \circ \epsilon = ?$
- $R \cup \emptyset = ?$
- $R \circ \emptyset = ?$

More examples:

\{ $w$: $w$ starts with 0 and has even length or starts with 1 and has odd length \}

Answer: $0((1 \cup 0)(1 \cup 0))^* (1 \cup 0) \cup 1 ((1 \cup 0)(1 \cup 0))^*$
1.3 Regular Expressions

Additional special cases, where $R$ is a regular expression already

More examples:

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1.3 Regular Expressions

Additional special cases, where \( R \) is a regular expression already

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1.3 Regular Expressions

Additional special cases, \textit{where} $R$ is a regular expression already

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1.3 Regular Expressions

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Additional special cases, where $R$ is a regular expression already

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Answer:

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$0((1 \cup 0)(1 \cup 0))^*(1 \cup 0)$
1.3 Regular Expressions

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Answer:

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1.3 Regular Expressions

Additional special cases, where $R$ is a regular expression already

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More examples:

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Answer:

$0((1 \cup 0)(1 \cup 0))^*(1 \cup 0) \cup 1$
1.3 Regular Expressions

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Answer:

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1.3 Regular Expressions

Theorem 1.54
A language is regular if and only if some regular expression describes it.

The theorem has two directions (stated in the following lemmas.)

Lemma 1.55
If a language is described by a regular expression, then it is regular.

Lemma 1.60
If a language is regular, then it is described by a regular expression.
1.3 Regular Expressions

**Theorem 1.54** (page 66)

A language is regular if and only if some regular expression describes it.
1.3 Regular Expressions

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**Lemma 1.55** (page 67)

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1.3 Regular Expressions

Theorem 1.54 (page 66)
A language is regular if and only if some regular expression describes it.

The theorem has two directions (stated in the following lemmas.)

Lemma 1.55 (page 67)
If a language is described by a regular expression, then it is regular.

Lemma 1.60 (page 69)
If a language is regular, then it is described by a regular expression.
1.3 Regular Expressions

Lemma 1.55

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

proof idea

• Convert a regular expression $R$ to an NFA;
• by following constructing rules of regular expressions;
• to assemble NFAs in a bottom up fashion.

First, try an example. Given regular expression:

$((ab)^* \cup (ba)^*)^*(aaa)^*$

build an NFA to recognize the described language.
1.3 Regular Expressions

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1.3 Regular Expressions

In general, given regular expression $R$,

• build NFAs for "atomic regular expressions" in $R$,

• assemble these NFAs into a larger NFA for $R$ according to how the rules used to "assemble" $R$.

That is

• prove all atomic regular expressions have corresponding NFAs;

• prove if all sub-regular expressions in $R$ have corresponding NFAs;

then $R$ has a corresponding NFA.

Use structural induction.
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Use structural induction
1.3 Regular Expressions

1.3.1 Mathematical Induction

Re-examine mathematical induction

Let $N = \{1, 2, ..., \}$ be the set of natural numbers. How do you define $N$ more rigorously?

Define elements in $N$ inductively:

1. $1 \in N$
2. For any $x \in N$, $x + 1 \in N$
3. Only elements generated with rules (1) and (2) belong to $N$

Claim: for every $y \in N$, $y \leq y^2$.

Prove using structural induction (mathematical induction for $N$).

Let $y$ be any element in $N$.

If $y = 1$, $1 \leq 1^2$; so $y \leq y^2$;

otherwise, there is $x \in N$ such that $y = x + 1$ assume $x^2 \geq x$ then $y^2 = (x + 1)^2 = x^2 + 2x + 1 \geq x + 2x + 1 = x + 1 = y$.

Therefore the claim is true.
1.3 Regular Expressions

Re-examine mathematical induction
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\[ N = \{1, 2, \ldots, \} \] is the set of natural numbers.
1.3 Regular Expressions

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1.3 Regular Expressions

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Prove using structural induction (mathematical induction for \( N \)).

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Assume \( x^2 \geq x + 1 \) then \( y^2 = (x + 1)^2 = x^2 + 2x + 1 \geq x + 1 = y \)

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Example: Let set $T$ be defined with following (inductive rules)

1. $3 \in T$;
2. for any $x \in T$, $3x \in T$;
3. only elements generated with rules (1) and (2) belong to $T$.

What is $T$?

Claim: every $x \in T$ is a power of 3?

We prove the claim by following how each element in $T$ was created.

Let $y$ be any element in $T$.

If $y = 3$, then $y = 3^1$, a power of 3.

Otherwise, $y = 3x$ for some $x \in T$.

Assume $x$ is a power of 3, i.e., $x = 3^k$ for some integer $k$;
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Therefore, all elements in $T$ are powers of 3.
Where is the "structure"? 

This is about the structure of how an element in the set is created: e.g.,

\[ T = \{ 3, 3 \times 3, 3 \times 3 \times 3, \ldots \} \]

So to prove certain property \( P \) holds for every element in \( T \), it suffices to show that every time a new element was included to the set, it has the property \( P \). So the idea of structural induction proof is to proceed in the same inductive way that \( T \) was defined. e.g., for \( 3 \times 3 \times 3 \) it belongs to \( T \) because \( 3 \times 3 \) already belongs to \( T \), since \( 3 \times 3 \) belongs to \( T \), it already have property \( P \), to prove \( 3 \times 3 \times 3 \) also has the same property.
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- Since $3 \times 3$ belongs to $T$, it already have property $P$.
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this is about the structure of how an element in the set is created:

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• \( 3 \times 3 \times 3 \) belongs to \( T \) because \( 3 \times 3 \) already belongs to \( T \)
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So the idea of structural induction proof is to proceed in the same inductive way that $T$ was defined.

e.g., for $3 \times 3 \times 3$

• it belongs to $T$ because $3 \times 3$ already belongs to $T$
Where is the “structure”? 
this is about the structure of how an element in the set is created:
edg., \( T = \{3, 3 \times 3, 3 \times 3 \times 3, \ldots \} \)

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1.3 Regular Expressions

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1.3 Regular Expressions

Here is the definition for regular expressions:

1. $a \in \Sigma$, the alphabet

2. $\epsilon$

3. $\emptyset$

4. $(R_1 \cup R_2)$, where $R_1, R_2$ are regular expressions

5. $(R_1 \circ R_2)$, where $R_1, R_2$ are regular expressions

6. $(R_1^*)$, where $R_1$ is a regular expression.

We can redefine it in a slightly different way:

The set $R$ of regular expressions is defined inductively:

1. For any $a \in \Sigma$, $a \in R$;

2. $\epsilon \in R$;

3. $\emptyset \in R$;

4. If $R_1, R_2 \in R$, then $(R_1 \cup R_2) \in R$;

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Lemma 1.55

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

Proof: (Using structural induction)

Recall $R$ is a regular expression if $R$ is one of the followings:

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6. $(R_1^*)$, where $R_1$ is a regular expression.

Let language $L$ be described by regular expression $R$.

- If $R = a$ for some $a \in \Sigma$, we can construct an NFA to recognize exactly strings described by $a$.
- Similar arguments for $R = \epsilon$, $R = \emptyset$; ...
- If $R = (R_1 \cup R_2)$, where $R_1, R_2$ are regular expressions.
  Assume $R_1, R_2$ describe regular languages $L_1, L_2$, respectively
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  Thus, $R$ describes a regular language.
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Let language \( L \) be described by regular expression \( R \).

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More examples of building NFAs from regular expressions.

Building an NFA for regular expression 

\((a \cup b)^*aba\), (Figure 1.59, page 69)

to determine how the expression is composed,
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to determine how the expression is composed, then to construct NFAs bottom-up

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1.3 Regular Expressions

Lemma 1.60 (page 69)

If a language is regular, it is described by a regular expression.

Proof idea:
• A regular language is recognized by some DFA;
• Convert the DFA to a generalized NFA (GNFA);
• Repeatedly simplify the GNFA until it contains only two states;
• The two-state GNFA is actually a regular expression.
1.3 Regular Expressions

How about the other direction?
1.3 Regular Expressions

How about the other direction?

**Lemma 1.60** (page 69)

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1.3 Regular Expressions

- a single accept state;
- only out-going transitions from start state;
- only incoming transitions to accept state;
- one transition from one state to every other state, and from one to itself, excluding start and accept states;
- start and accept states are not the same.

transition edges can have regular expressions, instead of single symbol
1.3 Regular Expressions

GNFA
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1.3 Regular Expressions

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GNFA
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1.3 Regular Expressions

- Add a new start state $S_{\text{start}}$.
- Add a new accept state $S_{\text{accept}}$.
- Remove state $S_2$ and compensate it with regular expression $01^*0$ on a new transition from $S_1$ to $S_1$.
- On the self-loop, combine $1$ with $01^*0$, resulting in $1 \cup 01^*0$.
- Remove state $S_1$ and compensate it with regular expression $\epsilon(1 \cup 01^*0)^*\epsilon$.
- Only $S_{\text{start}}$ and $S_{\text{accept}}$ remain, with $\epsilon(1 \cup 01^*0)^*\epsilon$ on the transition.
- Simplify $\epsilon(1 \cup 01^*0)^*\epsilon$ as $(1 \cup 01^*0)^*$, the desired regular expression.
1.3 Regular Expressions

- add a new start state $S_{\text{start}}$;
1.3 Regular Expressions

- add a new start state $S'_{\text{start}}$;
- add a new accept state $S'_{\text{accept}}$;

\[
\begin{array}{c}
S_1 \\
\downarrow  \\
\bullet \\
\downarrow \\
S_2
\end{array}
\]

a DFA

\[
\begin{array}{ccc}
0 & & 1 \\
& \uparrow & \\
S_1 & & S_2 \\
\downarrow & & \downarrow \\
0 & & 1
\end{array}
\]
1.3 Regular Expressions

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- on the self-loop, combine 1 with $01^*0$, resulting in $1 \cup 01^*0$;
- remove state $S_1$ and compensate it with regular expression $\epsilon (1 \cup 01^*0)^* \epsilon$.
1.3 Regular Expressions

- add a new start state $S'_{start}$;
- add a new accept state $S'_{accept}$;
- remove state $S_2$ and compensate it with regular expression $01^*0$ on a new transition from $S_1$ to $S_1$;
- on the self-loop, combine 1 with $01^*0$, resulting in $1 \cup 01^*0$;
- remove state $S_1$ and compensate it with regular expression $\epsilon(1 \cup 01^*0)^*\epsilon$;
- only $S'_{start}$ and $S'_{accept}$ remain, with $\epsilon(1 \cup 01^*0)^*\epsilon$ on the transition;
1.3 Regular Expressions

- add a new start state $S_{\text{start}}$;
- add a new accept state $S_{\text{accept}}$;
- remove state $S_2$ and compensate it with regular expression $01^*0$ on a new transition from $S_1$ to $S_1$;
- on the self-loop, combine 1 with $01^*0$, resulting in $1 \cup 01^*0$;
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- simplify $\epsilon(1 \cup 01^*0)^*\epsilon$ as $(1 \cup 01^*0)^*$, the desired regular expression.
1.3 Regular Expressions

General steps (given regular language $L$ that is recognized by DFA $M$):

- $M$ $\Rightarrow$ GNFA with $k$ states
- $\Rightarrow$ GNFA with $k - 1$ states
- $\Rightarrow$ ...
- $\Rightarrow$ GNFA with 2 states
- $\Rightarrow$ regular expression

The critical step is to construct an equivalent GNFA with one fewer state when $k > 2$, where $q_{rip}$ is removed and compensated for it with regular expression $(R_1)(R_2)\ast(R_3)\cup(R_4)$.
1.3 Regular Expressions

General steps (given regular language $L$ that is recognized by DFA $M$)

- DFA $M$ $\Rightarrow$ GNFA with $k$ states
- GNFA with $k-1$ states
- $\ldots$
- GNFA with 2 states $\Rightarrow$ regular expression

The critical step is to construct an equivalent GNFA with one fewer state when $k > 2$. Where $q$ is removed and compensated for it with regular expression $(R_1)(R_2)^* (R_3) \cup (R_4)$. 
1.3 Regular Expressions

General steps (given regular language $L$ that is recognized by DFA $M$)

DFA $M$
1.3 Regular Expressions

General steps (given regular language $L$ that is recognized by DFA $M$)

DFA $M \Rightarrow$ GNFA with $k$ states

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where $q_{rip}$ is removed and compensate for it with regular expression

\[(R_1)(R_2)^* (R_3) \cup (R_4)\]
1.3 Regular Expressions

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DFA $M \Rightarrow$ GNFA with $k$ states $\Rightarrow$ GNFA with $k - 1$ states

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1.3 Regular Expressions

General steps (given regular language \( L \) that is recognized by DFA \( M \))

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\text{DFA } M \Rightarrow \text{GNFA with } k \text{ states} \Rightarrow \text{GNFA with } k - 1 \text{ states} \\
\Rightarrow \ldots \text{ GNFA with 2 states} \Rightarrow \text{regular expression}
\]
1.3 Regular Expressions

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where $q_{rip}$ is removed and compensate for it with regular expression

$$(R_1)(R_2)^*(R_3) \cup (R_4)$$
1.3 Regular Expressions

Actually accomplished in the following steps:

• remove \( q_\text{rip} \) and drop transitions from \( q_i \) to \( q_\text{rip} \) and from \( q_\text{rip} \) to \( q_j \);

• compensate with a transition from \( q_i \) to \( q_j \) with regular expression \((R_1)(R_2)^* (R_3)\);

• combine the two transitions from \( q_i \) to \( q_j \), resulting in \((R_1)(R_2)^* (R_3) \cup (R_4)\).
1.3 Regular Expressions

Actually accomplished in the following steps:

- Remove $q_{\text{rip}}$ and drop transitions from $q_i$ to $q_{\text{rip}}$ and from $q_{\text{rip}}$ to $q_j$;
- Compensate with a transition from $q_i$ to $q_j$ with regular expression $(R_1)(R_2)^* (R_3) \cup (R_4)$;
- Combine the two transitions from $q_i$ to $q_j$, resulting in $(R_1)(R_2)^* (R_3) \cup (R_4)$.

**Figure 1.63**
Constructing an equivalent GNFA with one fewer state
1.3 Regular Expressions

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1.3 Regular Expressions
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Alternative way to view removal of a state from a GNFA
1.3 Regular Expressions

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To show that every regular language $L$ can be described with a regular expression, we prove it by construction. So we need

• a formal definition of GNFA; and
• an algorithm to derive from GNFA a regular expression that can describe the given language $L$. 

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To show that every regular language $L$ can be described with a regular expression, we prove it \textit{by construction}.

So we need

- a formal definition of GNFA; and

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  the given language $L$.
A generalized NFA is a 5-tuple \((Q, \Sigma, \delta, q_{\text{start}}, q_{\text{accept}})\), where

1. \(Q\) is the finite set of states;
2. \(\Sigma\) is the input alphabet;
3. \(\delta\) is transition function:
   \((Q - \{q_{\text{accept}}\}) \times (Q - \{q_{\text{start}}\}) \rightarrow \mathbb{R}\);
4. \(q_{\text{start}}\) is the start state;
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where \(\mathbb{R}\) is the set of regular expressions.

The GNFA accepts a string \(w = w_1w_2...w_k\), where \(w_i \in \Sigma^*\) if there is a sequence of states \(q_0q_1...q_k\) such that

1. \(q_0 = q_{\text{start}}\)
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3. \(w_i \in \text{set of strings represented by regular expression } R_i, \) where
   \(R_i = \delta(q_{i-1}, q_i)\), for all \(i = 1, 2, ..., k\).
1.3 Regular Expressions

**Definition 1.64 (page 73)**
A generalized NFA is a 5-tuple \((Q, \Sigma, \delta, q_{\text{start}}, q_{\text{accept}})\), where

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   \[
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   \]
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\[
(1) \quad q_0 = q_{start}
\]
1.3 Regular Expressions

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1.3 Regular Expressions

Formally define this GNFA

- \( Q = \{ q_{\text{start}}, q_{\text{accept}}, q_{\text{up}}, q_{\text{down}} \} \)
- \( \delta(q_{\text{start}}, q_{\text{up}}) = \text{ab}^* \), \( \delta(q_{\text{start}}, q_{\text{down}}) = \emptyset \), \( \delta(q_{\text{start}}, q_{\text{accept}}) = b \)
- \( \delta(q_{\text{up}}, q_{\text{up}}) = \text{aa} \), \( \delta(q_{\text{up}}, q_{\text{accept}}) = \text{ab} \cup \text{ba} \)
- \( \delta(q_{\text{up}}, q_{\text{down}}) = \text{a}^* \)

Is string \( w = \text{abbbaaaaabbbbb} \) accepted?

Rewrite \( w = \text{abbbaaaaabbbbb} \)

- \( w_1 = \text{abbb} \in \delta(q_{\text{start}}, q_{\text{up}}) \)
- \( w_2 = \text{aa} \in \delta(q_{\text{up}}, q_{\text{up}}) \)
- \( w_3 = \text{aaa} \in \delta(q_{\text{up}}, q_{\text{down}}) \)
- \( w_4 = \text{bbbb} \in \delta(q_{\text{down}}, q_{\text{accept}}) \)

Sequence of states \( q_{\text{start}} q_{\text{up}} q_{\text{up}} q_{\text{down}} q_{\text{accept}} \) allows \( w \) to be accepted.
1.3 Regular Expressions

Formally define this GNFA

\[ Q = \{ q_{\text{start}}, q_{\text{accept}}, q_{\text{up}}, q_{\text{down}} \} \]

\[ \delta(q_{\text{start}}, q_{\text{up}}) = ab^* , \]
1.3 Regular Expressions

Formally define this GNFA

- \( Q = \{ q_{\text{start}}, q_{\text{accept}}, q_{\text{up}}, q_{\text{down}} \} \)
- \( \delta(q_{\text{start}}, q_{\text{up}}) = ab^* \), \( \delta(q_{\text{start}}, q_{\text{down}}) = \emptyset \),

Is string \( w = \text{abbbaaaaabbbbb} \) accepted?
1.3 Regular Expressions

Formally define this GNFA

- $Q = \{q_{\text{start}}, q_{\text{accept}}, q_{\text{up}}, q_{\text{down}}\}$
- $\delta(q_{\text{start}}, q_{\text{up}}) = ab^*$,
- $\delta(q_{\text{start}}, q_{\text{down}}) = \emptyset$,
- $\delta(q_{\text{start}}, q_{\text{accept}}) = b$, 

Is string $w = abbbaaaaabbbbb$ accepted?

Rewrite $w = abbbaaaaabbbbb$

$w_1 = abbb \in \delta(q_{\text{start}}, q_{\text{up}})$,

$w_2 = aa \in \delta(q_{\text{up}}, q_{\text{up}})$,

$w_3 = aaa \in \delta(q_{\text{up}}, q_{\text{down}})$,

$w_4 = bbbbb \in \delta(q_{\text{down}}, q_{\text{accept}})$

Sequence of states $q_{\text{start}} \rightarrow q_{\text{up}} \rightarrow q_{\text{up}} \rightarrow q_{\text{down}} \rightarrow q_{\text{accept}}$ allows $w$ to be accepted.
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Is string \( w = abbbaaaaabbbbb \) accepted?

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\( w_4 = bbb \in \delta(q_{\text{down}}, q_{\text{accept}}) \)

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......
1.3 Regular Expressions

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......

Is string $w = abbbaaaaabbbbb$ accepted? Rewrite $w = abbbaaaaabbbbb$

$w_1 = abbb \in \delta(q_{\text{start}}, q_{\text{up}})$,
1.3 Regular Expressions

Formally define this GNFA

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$w_1 = abbb \in \delta(q_{\text{start}}, q_{\text{up}})$, $w_2 = aa \in \delta(q_{\text{up}}, q_{\text{up}})$,
1.3 Regular Expressions

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\( w_1 = abbb \in \delta(q_{\text{start}}, q_{\text{up}}), w_2 = aa \in \delta(q_{\text{up}}, q_{\text{up}}), w_3 = aaa \in \delta(q_{\text{up}}, q_{\text{down}}) \),
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Is string $w = abbbaaaaaabbbbbb$ accepted? Rewrite $w = abbbaaaaaabbbbbb$

- $w_1 = abbb \in \delta(q_{\text{start}}, q_{\text{up}})$,
- $w_2 = aa \in \delta(q_{\text{up}}, q_{\text{up}})$,
- $w_3 = aaa \in \delta(q_{\text{up}}, q_{\text{down}})$,
- $w_4 = bbbbbb \in \delta(q_{\text{down}}, q_{\text{accept}})$
1.3 Regular Expressions

Formally define this GNFA

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1.3 Regular Expressions
Algorithm to convert DFA $M$ to a 2-state GNFA.
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**Algorithm** to convert DFA $M$ to a 2-state GNFA.

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1.3 Regular Expressions

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$\text{CONVERT}(G)$:

1. Let $k$ be the number of states in $G$;
2. If $k = 2$, a single transition from $q_{\text{start}}$ to $q_{\text{accept}}$ with $R$

   return $(R)$ and stop.
1.3 Regular Expressions

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1.3 Regular Expressions

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   set $\delta'(q_i, q_j) = R_1 R_2 \ast R_3 \cup R_4$, 

1.3 Regular Expressions

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1.3 Regular Expressions

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1. Let $k$ be the number of states in $G$;
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   \[ \text{return} \ (R) \] and stop.
3. Select a state $q_{\text{rip}}$, for every pair of states $q_i, q_j$ that
   are not $q_{\text{rip}}$, or start, or accept state,
   set $\delta'(q_i, q_j) = R_1 R_2 \ast R_3 \cup R_4,$
   where $R_1 = \delta(q_i, q_{\text{rip}})$, $R_2 = \delta(q_{\text{rip}}, q_{\text{rip}})$,
   $R_3 = \delta(q_{\text{rip}}, q_j)$, $R_4 = \delta(q_i, q_j)$
   $\delta'$ is the same as $\delta$ for the remaining parts
4. Let $G' = (Q - \{q_{\text{rip}}\}, \Sigma, \delta', q_{\text{start}}, q_{\text{accept}})$
5. Call $\text{CONVERT}(G')$. 

1.3 Regular Expressions

Claim: for any $G$, Convert($G$) returns a regular expression that describes the language $L$.

Proof: We prove the claim by induction on $k$, the number of states in $G$:

basis: $k = 2$. The GNAF is equivalent to the DFA $M$; the regular expression returned by $G$ describes $L$. The claim is true.

assumption: Convert($G$) returns a regular expression that describes language $L$ when $G$ has $k-1$ states.

induction: $G$ has $k$ states. We show that $G'$, the GNFA as the result of removing some state $q$ from $G$, recognizes the same language as $G$ does. By assumption, Convert($G'$) returns a regular expression that describes language $L$; thus, Convert($G$) returns a regular expression that describes language $L$. The claim is proved.
1.3 Regular Expressions

**Claim**: for any $G$, $\text{CONVERT}(G)$ returns a regular expression that describes the language $L$. 
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- **assumption:** $\text{CONVERT}(G)$ returns a regular expression that describes language $L$ when $G$ has $k - 1$ states.
1.3 Regular Expressions

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- **induction:** $G$ has $k$ states. We show that $G'$, the GNFA as the result of removing some state $q_{\text{rip}}$ from $G$, recognizes the same language as $G$ does.

  By assumption, $\text{CONVERT}(G')$ returns a regular expression that describes language $L$;
Claim: for any $G$, $\text{Convert}(G)$ returns a regular expression that describes the language $L$.

Proof: We prove the claim by induction on $k$, the number of states in $G$:

basis: $k = 2$. The GNAF is equivalent to the DFA $M$; the regular expression returned by $G$ describes $L$. The claim is true.

assumption: $\text{Convert}(G)$ returns a regular expression that describes language $L$ when $G$ has $k - 1$ states.

induction: $G$ has $k$ states. We show that $G'$, the GNFA as the result of removing some state $q_{ri}$ from $G$, recognizes the same language as $G$ does.

   By assumption, $\text{Convert}(G')$ returns a regular expression that describes language $L$;
   thus, $\text{Convert}(G)$ returns a regular expression that describes language $L$. The claim is proved.
1.3 Regular Expressions

Claim: for any $G$, $\text{Convert}(G)$ returns a regular expression that describes the language $L$.

Proof: We prove the claim by induction on $k$, the number of states in $G$:

**basis**: $k = 2$. The GNAF is equivalent to the DFA $M$; the regular expression returned by $G$ describes $L$. The claim is true.

**assumption**: the claim is true when $G$ has $k-1$ states.

**induction**: $G$ has $k$ states. We show removing state $q_{rip}$ still allows the recognition of the same language.

Let $w$ be accepted by the $k$ state GNFA $G$, with path $q_{start}, q_1, q_2, ..., q_{accept}$.

**Case 1.** $q_{rip}$ does not occur in the path. The claim is true.

**Case 2.** $q_{rip}$ occurred in the path. Let $q_i = q_{rip}$. $\text{Convert}(G)$ step 3 guarantees $w$ can be accepted by the reduced GNFA $G'$ of $k-1$ states, with the path $q_{start}, q_1, ..., q_{i-1}, q_{i+1}, ..., q_{accept}$.

So $G$ and $G'$ accepts the same set of strings. By assumption, $\text{Convert}(G')$ returns a regular expression that describes language $L$; thus, $\text{Convert}(G)$ returns a regular expression that describes language $L$. The claim is proved.
1.3 Regular Expressions

**Claim**: for any $G$, $\text{CONVERT}(G)$ returns a regular expression that describes the language $L$.
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*Proof:* We prove the claim by induction on $k$, the number of states in $G$:
1.3 Regular Expressions

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1.3 Regular Expressions

**Claim:** for any $G$, $\text{CONVERT}(G)$ returns a regular expression that describes the language $L$.

**Proof:** We prove the claim by induction on $k$, the number of states in $G$:

**basis:** $k = 2$. The GNAF is equivalent to the DFA $M$; the regular expression returned by $G$ describes $L$. The claim is true.

**assumption:** the claim is true when $G$ has $k - 1$ states.
1.3 Regular Expressions

**Claim**: for any $G$, $\text{CONVERT}(G)$ returns a regular expression that describes the language $L$.

**Proof**: We prove the claim by *induction on $k$*, the number of states in $G$:

- **basis**: $k = 2$. The GNAF is equivalent to the DFA $M$; the regular expression returned by $G$ describes $L$. The claim is true.

- **assumption**: the claim is true when $G$ has $k - 1$ states.

- **induction**: $G$ has $k$ states. We show removing state $q_{rip}$ still allows the recognition of the same language.
1.3 Regular Expressions

Claim: for any $G$, $\text{CONVERT}(G)$ returns a regular expression that describes the language $L$.

Proof: We prove the claim by induction on $k$, the number of states in $G$:

basis: $k = 2$. The GNAF is equivalent to the DFA $M$; the regular expression returned by $G$ describes $L$. The claim is true.

assumption: the claim is true when $G$ has $k - 1$ states.

induction: $G$ has $k$ states. We show removing state $q_{\text{rip}}$ still allows the recognition of the same language.
Let $w$ be accepted by the $k$ state GNFA $G$, with path
$q_{\text{start}}, q_1, q_2, \ldots, q_{\text{accept}}$
1.3 Regular Expressions

Claim: for any $G$, $\text{CONVERT}(G)$ returns a regular expression that describes the language $L$.

Proof: We prove the claim by induction on $k$, the number of states in $G$:

basis: $k = 2$. The GNAF is equivalent to the DFA $M$; the regular expression returned by $G$ describes $L$. The claim is true.

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Let $w$ be accepted by the $k$ state GNFA $G$, with path $q_{\text{start}}, q_1, q_2, \ldots, q_{\text{accept}}$

Case 1. $q_{\text{rip}}$ does not occur in the path. The claim is true.
1.3 Regular Expressions

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Claim: for any $G$, $\text{CONVERT}(G)$ returns a regular expression that describes the language $L$.

Proof: We prove the claim by induction on $k$, the number of states in $G$:

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Case 1. $q_{\text{rip}}$ does not occur in the path. The claim is true.

Case 2. $q_{\text{rip}}$ occurred in the path. Let $q_i = q_{\text{rip}}$
1.3 Regular Expressions

**Claim:** for any $G$, $\text{CONVERT}(G)$ returns a regular expression that describes the language $L$.

**Proof:** We prove the claim by induction on $k$, the number of states in $G$:

**basis:** $k = 2$. The GNAF is equivalent to the DFA $M$; the regular expression returned by $G$ describes $L$. The claim is true.

**assumption:** the claim is true when $G$ has $k - 1$ states.

**induction:** $G$ has $k$ states. We show removing state $q_{\text{rip}}$ still allows the recognition of the same language.

Let $w$ be accepted by the $k$ state GNFA $G$, with path $q_{\text{start}}, q_1, q_2, \ldots, q_{\text{accept}}$

**Case 1.** $q_{\text{rip}}$ does not occur in the path. The claim is true.

**Case 2.** $q_{\text{rip}}$ occurred in the path. Let $q_i = q_{\text{rip}}$.

$\text{CONVERT}(G')$ step 3 guarantees $w$ can be accepted by the reduced GNFA $G'$ of $k - 1$ states, with the path $q_{\text{start}}, q_1, \ldots, q_{i-1}, q_{i+1}, \ldots, q_{\text{accept}}$.
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$$q_{\text{start}}, q_1, q_2, \ldots, q_{\text{accept}}$$

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Case 2. $q_{\text{rip}}$ occurred in the path. Let $q_i = q_{\text{rip}}$

$\text{CONVERT}(G')$ step 3 guarantees $w$ can be accepted by the reduced GNFA $G'$ of $k − 1$ states, with the path

$$q_{\text{start}}, q_1, \ldots, q_i − 1, q_i + 1, \ldots, q_{\text{accept}}$$

So $G$ and $G'$ accepts the same set of strings.
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So $G$ and $G'$ accepts the same set of strings

By assumption, $\text{CONVERT}(G')$ returns a regular expression that describes language $L$;
thus, $\text{CONVERT}(G)$ returns a regular expression that describes language $L$. The claim is proved.
1.3 Regular Expressions

Examples:

• Convert the 2-state DFA to an equivalent regular expression.

• Convert the 3-state DFA to a regular expression.
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1.4 Non-Regular Languages

To answer the following related questions:

• How powerful is a DFA (NFA)?

• What problems may (not) be defined as regular languages?

• What makes an FA (not) powerful?

• What languages cannot be recognized by FAs?
1.4 Non-Regular Languages

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1.4 Non-Regular Languages

Revisit the case of matching parentheses in arithmetic expressions. FAs do not seem to be able to do matching.

More examples:

\( L_1 = \{ w \mid w \text{ contains the same number of 1 and 0} \} \).

\( L_2 = \{ 0^k 1^k \mid k \geq 0 \} \).

\( L_3 = \{ w \mid w \in \Sigma^* \text{ and } w \text{ is a palindrome} \} \).

If FAs cannot recognize these languages, they are not regular languages.

What makes these languages non-regular?
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1.4 Non-Regular Languages

Consider $L_2 = \{0^k1^k : k \geq 0\}$.

Assume some NFA $M$ recognizes the language. It has $|Q| = 8$ states: \{blue, black, green, red, pink, gray, violet, orange\}.

Also assume string $w = 00000111$. $w$ is accepted by $M$ with a sequence of 11 states $q_0, q_1, \ldots, q_{10}$ because $|w| = 10$. 

\[
\begin{array}{cccccccc}
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & \\
\end{array}
\]
Consider \( L_2 = \{0^k1^k : k \geq 0\} \)

A portion of NFA

\[\begin{array}{c}
q_0 \\
q_1 \\
q_2 \\
q_3 \\
q_4 \\
q_5 \\
q_6 \\
q_7 \\
q_8 \\
q_9 \\
q_{10}
\end{array}\]
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Also assume string \( w = 0^51^5 \).
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\[
w = 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1
\]
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a sequence of 11 states \( q_0, q_1, \ldots, q_{10} \) because \(|w| = 10\).

\[
\begin{array}{cccccccc}
\text{\textcolor{blue}{q}_0} & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1
\end{array}
\]
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\[
\begin{array}{cccccccc}
  w & = & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
  q_0 & q_1
\end{array}
\]
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$w = \begin{array}{cccccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2
\end{array}$
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\[
\begin{align*}
w &= 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 1 \ 1 \ 1 \ 1 \\
q_0 &\ q_1 \ q_2 \ q_3
\end{align*}
\]
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$w = \begin{array}{cccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 
\end{array}$
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\[
\begin{align*}
w & = 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 1 \ 1 \ 1 \ 1 \\
q_0 & q_1 q_2 q_3 q_4 q_5
\end{align*}
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$w = 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 1 \ 1 \ 1 \ 1$

\begin{align*}
q_0 & \quad q_1 & \quad q_2 & \quad q_3 & \quad q_4 & \quad q_5 & \quad q_6 \\
\end{align*}
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\[
w = 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 1 \ 1 \ 1 \ 1
\]
\[
q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7
\]
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\[
\begin{array}{cccccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_0
\end{array}
\]
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0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 \\
\end{array}
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\[ w = \begin{array}{cccccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10}
\end{array} \]
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\[
\begin{align*}
w &= 0 0 0 0 0 1 1 1 1 1 \\
q_0 & q_1 q_2 q_3 q_4 q_5 q_6 q_7 q_8 q_9 q_{10} \\
q_0
\end{align*}
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\[ w = \begin{array}{cccccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
\end{array} \]

\[ \begin{array}{ccccccccccc}
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 \\
\end{array} \]
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\[
\begin{array}{cccccccc}
w = & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2
\end{array}
\]
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0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10}
\end{array}$

$\begin{array}{cccc}
q_0 & q_1 & q_2 & q_3
\end{array}$
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\[
\begin{array}{cccccccccc}
 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
 q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
 q_0 & q_1 & q_2 & q_3 & q_4 \\
\end{array}
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$$w = \begin{array}{cccccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10}
\end{array}$$

$$\begin{array}{cccccc}
q_0 & q_1 & q_2 & q_3 & q_4 & q_5
\end{array}$$
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\[
w = \begin{array}{cccccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10}
\end{array}
\]

\[
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6
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\[
\begin{array}{cccccccccc}
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\
\end{array}
\]
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\[
w = \begin{array}{cccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8
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$w = \begin{array}{ccccccccccc} 
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9
\end{array}$
1.4 Non-Regular Languages

Consider \( L_2 = \{0^k1^k : k \geq 0\} \)

Assume some NFA \( M \) recognizes the language. It has \( |Q| = 8 \) states: 
\{\text{blue}, \text{black}, \text{green}, \text{red}, \text{pink}, \text{gray}, \text{violet}, \text{orange}\}\)

Also assume string \( w = 0^51^5 \). \( w \) is accepted by \( M \) with 
a sequence of 11 states \( q_0, q_1, \ldots, q_{10} \) because \( |w| = 10 \).

\[
\begin{array}{cccccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10}
\end{array}
\]
1.4 Non-Regular Languages

Consider $L_2 = \{0^k1^k : k \geq 0\}$

Assume some NFA $M$ recognizes the language. It has $|Q| = 8$ states: 
\{blue, black, green, red, pink, gray, violet, orange\}

Also assume string $w = 0^51^5$. $w$ is accepted by $M$ with a sequence of 11 states $q_0, q_1, \ldots, q_{10}$ because $|w| = 10$.

\[
\begin{array}{cccccccccc}
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0
\end{array}
\]
1.4 Non-Regular Languages

Consider $L_2 = \{0^k1^k : k \geq 0\}$

Assume some NFA $M$ recognizes the language. It has $|Q| = 8$ states: 
\{blue, black, green, red, pink, gray, violet, orange\}

Also assume string $w = 0^51^5$. $w$ is accepted by $M$ with a sequence of 11 states $q_0, q_1, \ldots, q_{10}$ because $|w| = 10$.

\[
\begin{array}{cccccccccc}
  w &=& 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \\
  q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
  q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_9 & q_{10} \\
  q_0 & q_1 \\
\end{array}
\]
1.4 Non-Regular Languages

Consider \( L_2 = \{0^k1^k : k \geq 0\} \)

Assume some NFA \( M \) recognizes the language. It has \( |Q| = 8 \) states: 
\{blue, black, green, red, pink, gray, violet, orange\}

Also assume string \( w = 0^51^5 \). \( w \) is accepted by \( M \) with a sequence of 11 states \( q_0, q_1, \ldots, q_{10} \) because \( |w| = 10 \).

\[
\begin{array}{cccccccccc}
& 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2
\end{array}
\]
1.4 Non-Regular Languages

Consider $L_2 = \{0^k1^k : k \geq 0\}$

Assume some NFA $M$ recognizes the language. It has $|Q| = 8$ states: \{blue, black, green, red, pink, gray, violet, orange\}

Also assume string $w = 0^51^5$. $w$ is accepted by $M$ with a sequence of 11 states $q_0, q_1, \ldots, q_{10}$ because $|w| = 10$.

$$w = \begin{array}{cccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
q_0 & q_1 & q_2 & q_3
\end{array}$$
1.4 Non-Regular Languages

Consider \( L_2 = \{0^k1^k : k \geq 0\} \)

Assume some NFA \( M \) recognizes the language. It has \( |Q| = 8 \) states: \{blue, black, green, red, pink, gray, violet, orange\}

Also assume string \( w = 0^51^5 \). \( w \) is accepted by \( M \) with a sequence of 11 states \( q_0, q_1, \ldots, q_{10} \) because \( |w| = 10 \).

\[
\begin{array}{ccccccccc}
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & & & & & & \\
\end{array}
\]
1.4 Non-Regular Languages

Consider $L_2 = \{0^k1^k : k \geq 0\}$

Assume some NFA $M$ recognizes the language. It has $|Q| = 8$ states: 
{$\text{blue, black, green, red, pink, gray, violet, orange}$} 

Also assume string $w = 0^51^5$. $w$ is accepted by $M$ with 
a sequence of 11 states $q_0, q_1, \ldots, q_{10}$ because $|w| = 10$.

$w =$ \begin{align*} 
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 &  
\end{align*}
1.4 Non-Regular Languages

Consider $L_2 = \{0^k1^k : k \geq 0\}$

Assume some NFA $M$ recognizes the language. It has $|Q| = 8$ states:

\{blue, black, green, red, pink, gray, violet, orange\}

Also assume string $w = 0^51^5$. $w$ is accepted by $M$ with a sequence of 11 states $q_0, q_1, \ldots, q_{10}$ because $|w| = 10$.

\[
\begin{array}{ccccccccccc}
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q \\
\end{array}
\]
1.4 Non-Regular Languages

Consider \( L_2 = \{0^k1^k : k \geq 0\} \)

Assume some NFA \( M \) recognizes the language. It has \(|Q| = 8\) states: \{blue, black, green, red, pink, gray, violet, orange\}

Also assume string \( w = 0^51^5 \). \( w \) is accepted by \( M \) with a sequence of 11 states \( q_0, q_1, \ldots, q_{10} \) because \(|w| = 10\).

\[
\begin{array}{cccccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q & q_7
\end{array}
\]
1.4 Non-Regular Languages

Consider $L_2 = \{0^k1^k : k \geq 0\}$

Assume some NFA $M$ recognizes the language. It has $|Q| = 8$ states:
{blue, black, green, red, pink, gray, violet, orange}

Also assume string $w = 0^51^5$. $w$ is accepted by $M$ with a sequence of 11 states $q_0, q_1, \ldots, q_{10}$ because $|w| = 10$.

$w = \begin{array}{cccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q & q_7
\end{array}$
1.4 Non-Regular Languages

Consider $L_2 = \{0^k1^k : k \geq 0\}$

Assume some NFA $M$ recognizes the language. It has $|Q| = 8$ states:
\{blue, black, green, red, pink, gray, violet, orange\}

Also assume string $w = 0^51^5$. $w$ is accepted by $M$ with a sequence of 11 states $q_0, q_1, \ldots, q_{10}$ because $|w| = 10$.

\[
\begin{array}{cccccccccc}
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q & q_7 & q & q & q_{10} \\
\end{array}
\]
1.4 Non-Regular Languages

Consider $L_2 = \{0^k1^k : k \geq 0\}$

Assume some NFA $M$ recognizes the language. It has $|Q| = 8$ states: 
{
  \text{\textit{blue}}, \text{\textit{black}}, \text{\textit{green}}, \text{\textit{red}}, \text{\textit{pink}}, \text{\textit{gray}}, \text{\textit{violet}}, \text{\textit{orange}}
}

Also assume string $w = 0^51^5$. $w$ is accepted by $M$ with a sequence of 11 states $q_0, q_1, \ldots, q_{10}$ because $|w| = 10$.

\begin{align*}
w &= 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \\
q_0 \quad q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6 \quad q_7 \quad q_8 \quad q_9 \quad q_{10} \\
q_0 \quad q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6 \quad q_7 \quad q_8 \quad q_9 \quad q_{10} \\
q_0 \quad q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q \quad q_7 \quad q \quad q_9 \quad q_{10}
\end{align*}
1.4 Non-Regular Languages

Consider \( L_2 = \{0^k1^k : k \geq 0 \} \)

Assume some NFA \( M \) recognizes the language. It has \(|Q| = 8\) states: 
\{blue, black, green, red, pink, gray, violet, orange\}

Also assume string \( w = 0^51^5 \). \( w \) is accepted by \( M \) with a sequence of 11 states \( q_0, q_1, \ldots, q_{10} \) because \(|w| = 10\).

\[
\begin{array}{ccccccccccc}
0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q & q_7 & q & q_9 & q_{10}
\end{array}
\]

A portion of NFA \( M \)
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0 \rightarrow q_1 \rightarrow q_2 \rightarrow q_3 \rightarrow q_4 \rightarrow q_5 \rightarrow q_6 \rightarrow q_7 \rightarrow q_8 \rightarrow q_9 \rightarrow 0000011111$

$q_0 \rightarrow q_1 \rightarrow q_2 \rightarrow q_3 \rightarrow q_4 \rightarrow q_5 \rightarrow q_6 \rightarrow q_7 \rightarrow q_8 \rightarrow q_9 \rightarrow 000001111111$

More accept paths?

By the way, can you give a regular expression for these strings?

So $M$ accepts strings like $w' = 0\overline{5}1\overline{7}$, $0\overline{5}1\overline{9}$, $0\overline{5}1\overline{3}$, etc.

$M$ does not exactly recognize $L_2$. Contradicts.
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.
1.4 Non-Regular Languages

From this portion of $\mathcal{M}$, we can derive some other strings accepted by $\mathcal{M}$. We find accept paths:

$q_0$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0 \quad q_1$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0 \quad q_1 \quad q_2$
From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0 \quad q_1 \quad q_2 \quad q_3$
From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0$  $q_1$  $q_2$  $q_3$  $q_4$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0 \quad q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0 \quad q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6 \quad q_7$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8$$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0 \quad q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6 \quad q_7 \quad q_8 \quad q_9$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0 \quad q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6 \quad q_7 \quad q_8 \quad q_9 \quad q_{10}$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$ 0000011111

By the way, can you give a regular expression for these strings? So $M$ accepts strings like $w' = 0^517$, $0^519$, $0^513$, etc.

$M$ does not exactly recognize $L_2$. Contradicts.
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$ 0000011111

$q_0$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$ 0000011111

$q_0$ $q_1$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \ 0000011111$

$q_0 \ q_1 \ q_2$

By the way, can you give a regular expression for these strings? So $M$ accepts strings like $w' = 0517$, $0519$, $0513$, etc.

$M$ does not exactly recognize $L_2$. Contradicts.
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \ 0000011111$

$q_0 \ q_1 \ q_2 \ q_3$
From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \ 000001111111$

$q_0 \ q_1 \ q_2 \ q_3 \ q_4$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$ 0000011111 

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0 \quad q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6 \quad q_7 \quad q_8 \quad q_9 \quad q_{10} \quad \text{0000011111}$

$q_0 \quad q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6$
From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0$  $q_1$  $q_2$  $q_3$  $q_4$  $q_5$  $q_6$  $q_7$  $q_8$  $q_9$  $q_{10}$  0000011111

$q_0$  $q_1$  $q_2$  $q_3$  $q_4$  $q_5$  $q_6$  $q_7$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0$  $q_1$  $q_2$  $q_3$  $q_4$  $q_5$  $q_6$  $q_7$  $q_8$  $q_9$  $q_{10}$  0000011111

$q_0$  $q_1$  $q_2$  $q_3$  $q_4$  $q_5$  $q_6$  $q_7$  $q_8$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \ 0000011111$

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_7$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0 \rightarrow q_1 \rightarrow q_2 \rightarrow q_3 \rightarrow q_4 \rightarrow q_5 \rightarrow q_6 \rightarrow q_7 \rightarrow q_8 \rightarrow q_9 \rightarrow q_{10} \rightarrow q_0 \rightarrow q_1 \rightarrow q_2 \rightarrow q_3 \rightarrow q_4 \rightarrow q_5 \rightarrow q_6 \rightarrow q_7 \rightarrow q_7 \rightarrow q_8$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$ 0000011111

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_7$ $q_8$ $q_9$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$ 0000011111

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_7$ $q_8$ $q_9$ $q_{10}$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \ 0000011111$

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \ 000001111111$
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$ $0000011111$

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_7$ $q_8$ $q_{9}$ $q_{10}$ $000001111111$

More accept paths?
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$$q_0, q_1, q_2, q_3, q_4, q_5, q_6, q_7, q_8, q_9, q_{10} \quad 0000011111$$

$$q_0, q_1, q_2, q_3, q_4, q_5, q_6, q_7, q_7, q_8, q_9, q_{10} \quad 000001111111$$

More accept paths?

By the way, can you give a regular expression for these strings?
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$. We find accept paths:

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$ 0000011111

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_{7}$ $q_{8}$ $q_9$ $q_{10}$ 000001111111

More accept paths?

By the way, can you give a regular expression for these strings?

So $M$ accepts strings like $w' = 0^51^7$, $0^51^9$, $0^51^3$, etc.
1.4 Non-Regular Languages

From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$ 00000111111

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_7$ $q_8$ $q_9$ $q_{10}$ 000001111111

More accept paths?

By the way, can you give a regular expression for these strings?

So $M$ accepts strings like $w' = 0^51^7$, $0^51^9$, $0^51^3$, etc.

$M$ does not exactly recognize $L_2$. Contradicts.
From this portion of $M$, we can derive some other strings accepted by $M$.

We find accept paths:

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$ 0000011111

$q_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_7$ $q_8$ $q_9$ $q_{10}$ 00000111111

More accept paths?

By the way, can you give a regular expression for these strings?

So $M$ accepts strings like $w' = 0^51^7$, $0^51^9$, $0^51^3$, etc.

$M$ does not exactly recognize $L_2$. Contradicts.
1.4 Non-Regular Languages

We conclude the following:

- If $M$ recognizes language $L$ and accepts a string $w \in L$, where $|w| \geq |Q|$; the accept path for $w$ in $M$ contains a pair of same state.

- The substring on the transitions between this pair of states can be skipped or repeated multiple times; ("pumped").

- Strings as result of pumping are also accepted by $M$.

- However, if we can show pumped strings are NOT desired by $L$, we show $M$ does NOT recognize exactly $L$, a contradiction.
1.4 Non-Regular Languages

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  000001
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1.4 Non-Regular Languages

We consider another example $L_1 = \{w : w \text{ contains the same number of 1's and 0's} \}$. Is $L_1$ regular? We now try to use the same trick to disprove.

- Assume NFA $M$ recognizes $L_1$.
- Pick a string $w \in L_1$ which has length $\geq |Q|$,
- $M$ accepts $w$ with a path of states, including a pair of same states.
- We hope $w$ can be pumped, resulted in $w'$ such that
  1) the $w'$ is also accepted by $M$,
  2) but $w'$ does not contain the same number of 0's and 1's

However, statement (2) may not always be true.
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1.4 Non-Regular Languages

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1.4 Non-Regular Languages

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1.4 Non-Regular Languages

\[ Q_0, Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, Q_7, Q_8, Q_9, Q_{10} \]

Conclusion: \( M \) accepts strings \( 001(1010)^*101 \) \( \subseteq L_1 \), No contradiction!
1.4 Non-Regular Languages

conclusion: $M$ accepts strings $\{101\}^* \subseteq L_1$, No contradiction!
1.4 Non-Regular Languages

\[ |Q| = 8, \ |w| = 10, \]

\[ w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \]
1.4 Non-Regular Languages

\[ |Q| = 8, \ |w| = 10, \]

\[ w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \]

\[ q_0 \]

\[ \text{conclusion: } M \text{ accepts strings } \{001, 1010\} \subseteq L_1, \text{ No contradiction!} \]
1.4 Non-Regular Languages

$|Q| = 8, |w| = 10,$

$w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1$

$q_0 \ q_1$

Conclusion: $M$ accepts strings $001(1010)^*101 \subseteq L_{\epsilon}$, No contradiction!
1.4 Non-Regular Languages

\[ |Q| = 8, \ |w| = 10, \]

\[ w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \]

\[ q_0 \ \ q_1 \ \ q_2 \]

\[ M \text{ accepts strings } 0011010101 \subseteq L_1, \text{ No contradiction!} \]
1.4 Non-Regular Languages

\[ |Q| = 8, \ |w| = 10, \]

\[ w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \]

\[
\begin{array}{cccc}
q_0 & q_1 & q_2 & q_3 \\
\end{array}
\]

Conclusion: \( M \) accepts strings \( 001(1010) \), No contradiction!
1.4 Non-Regular Languages

\[ |Q| = 8, \, |w| = 10, \]

\[ w = 0 \, 0 \, 1 \, 1 \, 0 \, 1 \, 0 \, 1 \, 0 \, 1 \]

\[ q_0 \, q_1 \, q_2 \, q_3 \, q_4 \]

Conclusion: \( M \) accepts strings \( 001(1010) \star 101 \subseteq L_1 \), No contradiction!
1.4 Non-Regular Languages

\[ |Q| = 8, \ |w| = 10, \]

\[ w = \begin{array}{cccccccc}
0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5
\end{array} \]

conclusion: \( M \) accepts strings \( 001(1010)^*101 \), No contradiction!
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0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 \\
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1.4 Non-Regular Languages

\[ |Q| = 8, \ |w| = 10, \]

\[ w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \]

\begin{align*}
q_0 & \quad q_1 & \quad q_2 & \quad q_3 & \quad q_4 & \quad q_5 & \quad q_6 & \quad q_7 \\
\end{align*}

Conclusion: \( M \) accepts strings \( 001(1010)^*101 \subseteq L_1 \), No contradiction!
1.4 Non-Regular Languages

$|Q| = 8, |w| = 10,$

\[ w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \]

<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_0$</td>
<td>$q_1$</td>
<td>$q_2$</td>
<td>$q_3$</td>
<td>$q_4$</td>
<td>$q_5$</td>
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1.4 Non-Regular Languages

$|Q| = 8$, $|w| = 10,$

$w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1$

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9$

Conclusion: $M$ accepts strings $001(1010)^*101 \subseteq L_1$, No contradiction!
1.4 Non-Regular Languages

\[ |Q| = 8, \; |w| = 10, \]

\[ w = 0 \; 0 \; 1 \; 1 \; 0 \; 1 \; 0 \; 1 \; 0 \; 1 \]

\[ q_0 \; q_1 \; q_2 \; q_3 \; q_4 \; q_5 \; q_6 \; q_7 \; q_8 \; q_9 \; q_{10} \]

Conclusion: \( M \) accepts strings \( 001(1010)^*101 \subset L_1 \), no contradiction!
1.4 Non-Regular Languages

\[ |Q| = 8, \ |w| = 10, \]

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$q_0 \ q_1$
1.4 Non-Regular Languages

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\[ w = \begin{array}{cccccccccc}
0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
q_0 & q_1 & q_2
\end{array} \]

Conclusion: $M$ accepts strings $001(1010)^*101 \subseteq L_1$, No contradiction!
1.4 Non-Regular Languages

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\[ q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \]

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1.4 Non-Regular Languages

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\[|Q| = 8, \ |w| = 10,\]

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\[q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10}\]

\[q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6\]
1.4 Non-Regular Languages

\[ |Q| = 8, \quad |w| = 10, \]

\[ w = 0 \quad 0 \quad 1 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1 \]

q0  q1  q2  q3  q4  q5  q6  q7  q8  q9  q10
q0  q1  q2  q3  q4  q5  q6  q7
1.4 Non-Regular Languages

$|Q| = 8$, $|w| = 10,$

$$w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1$$

$$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10}$$

$w \subseteq L_1$, No contradiction!
1.4 Non-Regular Languages

\[ |Q| = 8, \ |w| = 10, \]

\[ w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \]

\[ q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \]

Conclusion: \( M \) accepts strings \( 0011010101 \subseteq L_1 \), no contradiction!
1.4 Non-Regular Languages

$|Q| = 8$, $|w| = 10,$

$w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1$

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10}$

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10}$

conclusion: $M$ accepts strings $001(1010)^*101 \subseteq L_1$, No contradiction!
|Q| = 8, \(|w| = 10, \\

w = 0 0 1 1 0 1 0 1 0 1 \\
q_0 q_1 q_2 q_3 q_4 q_5 q_6 q_7 q_8 q_9 q_{10} \\
q_0 q_1 q_2 q_3 q_4 q_5 q_6 q_7 q_8 q_9 q_{10} \\
q_0 

\text{Conclusion: } M \text{ accepts strings } 001(1010)^* \subseteq L_1, \text{ No contradiction!}
1.4 Non-Regular Languages

\[ |Q| = 8, \ |w| = 10, \]

\[ w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1 \]

\[ q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \]

\[ q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \]

\[ q_0 \ q_1 \]

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0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 \\
\end{array}$

Conclusion: $M$ accepts strings $001(1010)^*101 \subseteq L_1$, No contradiction!
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\[
q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10}
\]

\[
q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10}
\]

\[
q_0 \ q_1 \ q_2 \ \boxed{q}
\]
1.4 Non-Regular Languages

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\[ q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \]

\[ q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \]

\[ q_0 \ q_1 \ q_2 \ q \ q_4 \]

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1.4 Non-Regular Languages

|Q| = 8, |w| = 10,

w = 0 0 1 1 0 1 0 1 0 1

\[
\begin{array}{cccccccccccc}
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q & q_4 & q_5 & q
\end{array}
\]

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1.4 Non-Regular Languages

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$w = 0 \ 0 \ 1 \ 1 \ 0 \ 1 \ 0 \ 1 \ 0 \ 1$

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10}$

$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10}$

$q_0 \ q_1 \ q_2 \ \textcolor{blue}{q} \ q_4 \ q_5 \ q_6$
1.4 Non-Regular Languages

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0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10}
\end{array} \]

Conclusion: \( M \) accepts strings \( 001(1010)^*101 \subseteq L_1 \), No contradiction!
1.4 Non-Regular Languages

$|Q| = 8$, $|w| = 10,$

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$q_0 \ q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10}$

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1.4 Non-Regular Languages

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q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q & q_4 & q_5 & q_6 & q & q_8 & q_9
\end{array}$

Conclusion: $M$ accepts strings $0011010101 \subseteq L_1$, No contradiction!
1.4 Non-Regular Languages

$|Q| = 8, \ |w| = 10,$

$w = \begin{array}{cccccccccc}
0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q & q_4 & q_5 & q_6 & q & q_8 & q_9 & q_{10}
\end{array}$

conclusion: $M$ accepts strings $001(1010)^*101 \subseteq L_1$, No contradiction!
1.4 Non-Regular Languages

$|Q| = 8$, $|w| = 10$,

$$w = \begin{array}{ccccccccccc}
0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
q_0 & q_1 & q_2 & q & q_4 & q_5 & q_6 & q & q_8 & q_9 & q_{10} \\
\end{array}$$

conclusion: $M$ accepts strings $001(1010)^*101$
1.4 Non-Regular Languages

$|Q| = 8, \ |w| = 10,$

\[
\begin{array}{cccccccccccc}
  w &=& 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
  q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
  q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
  q_0 & q_1 & q_2 & q & q_4 & q_5 & q_6 & q & q_8 & q_9 & q_{10}
\end{array}
\]

conclusion: $M$ accepts strings $001(1010)^*101 \subseteq L_1$, No contradiction!
1.4 Non-Regular Languages

We will have to choose a different word, but any word in $L_1$ may seem difficult.

Strings described by regular expression $01010110100101010101000101110100010101010111 \times 101011110$ are all in $L_1$.

What should we do? Actually, the previous trick should apply not just the whole string $w$ but to any long substring as well!
1.4 Non-Regular Languages

We will have to choose a different word, but any word in $L_1$ may seem difficult

01010110100101010101000101110100010101011110
1.4 Non-Regular Languages

We will have to choose a different word, but any word in $L_1$ may seem difficult

0101011010010101010100010111010001010101011110
0101011010010101010100010(111010001010)∗101011110
010101101001010101010101010100010111010001010101011110
1.4 Non-Regular Languages

We will have to choose a different word, but any word in \( L_1 \) may seem difficult

\[
\begin{align*}
0101011010010101010100010111010001010101011110 \\
01010110100101010101000101110100010101011110 \\
\end{align*}
\]

strings described by regular expression

\[
0101011010010101010101010101000101110100010101011110(111010001010)*101011110
\]

are all in \( L_1 \).
1.4 Non-Regular Languages

We will have to choose a different word, but any word in $L_1$ may seem difficult

    01010110100101010100010111010001010101011110
    01010110100101010100010111010001010101011110

strings described by regular expression

    010101101001010101000101110100010110100010101011110

are all in $L_1$.

What should we do?
1.4 Non-Regular Languages

We will have to choose a different word, but any word in $L_1$ may seem difficult

\[
010101101001010101001011110100010101010101111000101011110
0101011010010101010100010111010010101011110
\]

strings described by regular expression

\[
010101101001010101010100010111010010101011110(111010001010)^*101011110
\]

are all in $L_1$.

What should we do?

Actually, the previous trick should apply not just the whole string $w$ but to any long substring as well!
1.4 Non-Regular Languages

Assume $|Q| = 8$. Consider string $w = 00000000001111111111 \in L_1$ (because it contains the same number of 0's and 1's). and substring $1111111111$ in $w$ (of length 10).

Therefore, strings described by regular expression $0000000000111(1111)^*$ are also in $L_1$! But numbers of 1's and 0's are different, Contradicts.

So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000011111111111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).
Assume $|Q| = 8$.
Consider string $w = 00000000011111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)
1.4 Non-Regular Languages

Assume $|Q| = 8$. Consider string $w = 00000000111111111111 \in L_1$ (because it contains the same number of 0’s and 1’s).

And substring 1111111111 in $w$ (of length 10)

```
1 1 1 1 1 1 1 1 1 1
```
1.4 Non-Regular Languages

Assume $|Q| = 8$. Consider string $w = 000000000111111111 \in L_1$ (because it contains the same number of 0's and 1's).

and substring 1111111111 in $w$ (of length 10)

```
   1  1  1  1  1  1  1  1  1  1
```

Therefore, strings described by regular expression $000000000111(1111)^*111$ are also in $L_1$! But numbers of 1's and 0's are different, Contradicts. So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 0000000001111111111 \in L_1$ (because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

1 1 1 1 1 1 1 1 1 1

Therefore, strings described by regular expression $000000000111(1111)^*111$ are also in $L_1$.

But numbers of 1’s and 0’s are different, Contradicts.

So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 \\
\end{array}
\]
Assume $|Q| = 8$.
Consider string $w = 0000000001111111111 \in L_1$ (because it contains the same number of 0's and 1's).

and substring $1111111111$ in $w$ (of length 10)

$$1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1$$

$p_0 \ q_1 \ q_2 \ q_3$

Therefore, strings described by regular expression $0000000000111(1111)^*111$ are also in $L_1$

But numbers of 1's and 0's are different, Contradicts.

So $L_1$ is not a regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000011111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{ccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4
\end{array}
\]

Therefore, strings described by regular expression

\[0000000001111(1111)\]

are also in $L_1$!

But numbers of 1’s and 0’s are different, Contradicts.

So $L_1$ is not regular language.
Assume $|Q| = 8$.
Consider string $w = 00000000011111111111 \in L_1$ (because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccc}
& 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & & & & \\
\end{array}
\]
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6
\end{array}
\]

Therefore, strings described by regular expression
0000000000111(1111)*111
are also in $L_1$!
But numbers of 1’s and 0’s are different,
Contradicts.

So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 000000000011111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 \\
\end{array}
\]

Therefore, strings described by regular expression

\[
0000000000111(1111)^*111
\]

are also in $L_1$!

But numbers of 1’s and 0’s are different, Contradicts.

So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

```
1 1 1 1 1 1 1 1 1 1
p_0 q_1 q_2 q_3 q_4 q_5 q_6 q_7 q_8
```

Therefore, strings described by regular expression

$$0000000000111(1111)^*111$$

are also in $L_1$!

But numbers of 1’s and 0’s are different, Contradicts.

So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{ccccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 \\
\end{array}
\]

Therefore, strings described by regular expression $000000000011(1111)^* 11$ are also in $L_1$!

But numbers of 1’s and 0’s are different, Contradicts.
So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000011111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

1 1 1 1 1 1 1 1 1 1
$p_0 \quad q_1 \quad q_2 \quad q_3 \quad q_4 \quad q_5 \quad q_6 \quad q_7 \quad q_8 \quad q_9 \quad q_{10}$

Therefore, strings described by regular expression
000000000111(1111)∗111
are also in $L_1$
But numbers of 1’s and 0’s are different, Contradicts.
So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000011111111111 \in L_1$ (because it contains the same number of 0’s and 1’s).

and substring $1111111111$ in $w$ (of length 10)

$$
\begin{array}{cccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
p_0 \\
\end{array}
$$

Therefore, strings described by regular expression $000000000111(1111)^*111$ are also in $L_1$.

But numbers of 1’s and 0’s are different, Contradicts.

So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
p_0 & q_1
\end{array}
\]

Therefore, strings described by regular expression $0000000000111(1111)^*_111$ are also in $L_1$.
But numbers of 1’s and 0’s are different, Contradicts.

So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

1 1 1 1 1 1 1 1 1 1
$p_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$
$p_0$ $q_1$ $q_2$
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000011111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10}
\end{array}
\]

Therefore, strings described by regular expression

$00000000011(1111)^* 111$

are also in $L_1$!

But numbers of 1’s and 0’s are different, Contradicts.

So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 0000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\begin{align*}
&1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \\
p_0 & q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7 \ q_8 \ q_9 \ q_{10} \\
p_0 & q_1 \ q_2 \ q_3 \ q_4
\end{align*}

Therefore, strings described by regular expression $0000000001111(1111)^\star 111$ are also in $L_1$.
But numbers of 1’s and 0’s are different, Contradicts.

So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000011111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

```
   1 1 1 1 1 1 1 1 1 1
   p0 q1 q2 q3 q4 q5 q6 q7 q8 q9 q10
   p0 q1 q2 q3 q4 q5
```
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 0000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring $1111111111$ in $w$ (of length 10)

\[
\begin{array}{cccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6
\end{array}
\]
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10}
\end{array}
\]

Therefore, strings described by regular expression $0000000000111(1111)^*111$ are also in $L_1$.
But numbers of 1’s and 0’s are different, Contrads.
So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$
(because it contains the same number of 0's and 1's).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10}
\end{array}
\]
1.4 Non-Regular Languages

Assume $|Q| = 8$. Consider string $w = 00000000011111111111 \in L_1$ (because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\begin{array}{ccccccccccc}
& 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10}
\end{array}

Therefore, strings described by regular expression $0000000001111(1111)\ast111$ are also in $L_1$. But numbers of 1’s and 0’s are different, Contradicts. So $L_1$ is not regular language.
Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
P_0 & Q_1 & Q_2 & Q_3 & Q_4 & Q_5 & Q_6 & Q_7 & Q_8 & Q_9 & Q_{10}
\end{array}
\]
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

Therefore, strings described by regular expression
0000000000111(1111)$^*$
are also in $L_1$.
But numbers of 1’s and 0’s are different, Contradicts.
So $L_1$ is not regular language.
Assume $|Q| = 8$.
Consider string $w = 00000000011111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).
and substring 1111111111 in $w$ (of length 10)

1 1 1 1 1 1 1 1 1 1
$p_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$
$p_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$
$p_0$ $q_1$

Therefore, strings described by regular expression $000000000111(1111)^*111$ are also in $L_1$.
But numbers of 1’s and 0’s are different, Contradicts.
So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$. Consider string $w = 0000000001111111111111$ $\in L_1$ (because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
p_0 & q_1 & q_2 \\
p_0 & q_1 & q_2
\end{array}
\]

Therefore, strings described by regular expression $000000000111(1111)^*$ are also in $L_1$! Numbers of 1’s and 0’s are different, contradicts. So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 000000000111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

1 1 1 1 1 1 1 1 1 1

$p_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$

$p_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$

$p_0$ $q_1$ $q_2$ $q$

Therefore, strings described by regular expression $0000000001111(1111)^*111$
are also in $L_1$.
But numbers of 1’s and 0’s are different, Contradicts.
So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 000000000011111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_{10} \\
p_0 & q_1 & q_2 & q & q_4 \\
\end{array}
\]

Therefore, strings described by regular expression $0000000000111(1111)\ast 111$
are also in $L_1$! But numbers of 1’s and 0’s are different, Contradicts.
So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$. Consider string $w = 0000000001111111111 \in L_1$ (because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

$$
\begin{array}{cccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
Q_0 & Q_1 & Q_2 & Q_3 & Q_4 & Q_5 & Q_6 & Q_7 & Q_8 & Q_9 & Q_{10}
\end{array}
$$

Therefore, strings described by regular expression $00000000011(111)^\ast$ are also in $L_1$. But numbers of 1’s and 0’s are different, Contradicts. So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 0000000001111111111$ ∈ $L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

```
1 1 1 1 1 1 1 1 1 1
p_0 q_1 q_2 q_3 q_4 q_5 q_6 q_7 q_8 q_9 q_{10}
p_0 q_1 q_2 q_3 q_4 q_5 q_6 q_7 q_8 q_9 q_{10}
p_0 q_1 q_2 q q_4 q_5 q_6
```

Therefore, strings described by regular expression $000000000111(1111)^*$ are also in $L_1$.
But numbers of 1’s and 0’s are different, Contradicts.
So $L_1$ is not a regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$. Consider string $w = 0000000001111111111 \in L_1$ (because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccccc}
   & p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & \\
\end{array}
\]

Therefore, strings described by regular expression $000000000111(1111)^*111$ are also in $L_1$.

But numbers of 1’s and 0’s are different, Contradicts.

So $L_1$ is not regular language.
1.4 Non-Regular Languages

Assume $|Q| = 8$. Consider string $w = 00000000001111111111 \in L_1$ (because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

1 1 1 1 1 1 1 1 1 1
$p_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$
$p_0$ $q_1$ $q_2$ $q_3$ $q_4$ $q_5$ $q_6$ $q_7$ $q_8$ $q_9$ $q_{10}$
$p_0$ $q_1$ $q_2$ $q$ $q_4$ $q_5$ $q_6$ $q$ $q_8$
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 0000000001111111111 \in L_1$
(because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

```
1 1 1 1 1 1 1 1 1 1
p_0 q_1 q_2 q_3 q_4 q_5 q_6 q_7 q_8 q_{10}
p_0 q_1 q_2 q_3 q_4 q_5 q_6 q_7 q_8 q_{10}
p_0 q_1 q_2 q q_4 q_5 q_6 q q_8 q_9
```
1.4 Non-Regular Languages

Assume $|Q| = 8$.
Consider string $w = 00000000001111111111 \in L_1$ (because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

$$
\begin{array}{cccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
p_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10} \\
p_0 & q_1 & q_2 & q & q_4 & q_5 & q_6 & q & q_8 & q_9 & q_{10} \\
p_0 & q_1 & q_2 & q & q_4 & q_5 & q_6 & q & q_8 & q_9 & q_{10}
\end{array}
$$

Therefore, strings described by regular expression $00000000001111111111^*111$ are also in $L_1$!
But numbers of 1’s and 0’s are different, Contradicts.
So $L_1$ is not regular language.
Assume $|Q| = 8$.

Consider string $w = 00000000001111111111 \in L_1$ (because it contains the same number of 0’s and 1’s).

and substring 1111111111 in $w$ (of length 10)

\[
\begin{array}{cccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
\mathcal{P}_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6 & q_7 & q_8 & q_9 & q_{10}
\end{array}
\]

Therefore, strings described by regular expression

\[
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1.4 Non-Regular Languages

• The trick we used takes advantage of an important property of regular languages.
• Such a property is formally summarized into a Pumping Lemma (for regular languages).
• Once we define and prove the Pumping lemma, we can use it e.g., to prove some languages are not regular languages.
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The Pumping Lemma For Regular Languages

Theorem 1.70 (Pumping lemma) (page 78)

If \( A \) is a regular language, then there is a number \( p \) (called pumping length) where, for any string \( s \in A \) of \(|s| \geq p\), \( s \) can be written as \( s = xyz \), such that

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1.4 Non-Regular Languages

The pumping lemma illustrated:

$s \in L$

$s = xyz \in L$

$xy^3z \in L$
1.4 Non-Regular Languages

Pumping lemma illustrated:

\[ s = \overbrace{0101010010000010010010010101001010010}^p \in L \]
1.4 Non-Regular Languages

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\[ s \in L \]

\[ s = 010101001000001001001001010010010010101 \]

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\[ s \in L \]
1.4 Non-Regular Languages

Pumping lemma illustrated:

\[ s = 010101001000001001001001010010010010 \]

\[ s \in L \]

\[ s = 010101001000 \text{ blue bar} \]

\[ = p \]

\[ q \]

\[ q \]

\[ s = xyz \in L \]
1.4 Non-Regular Languages

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Proof idea:

• Assume some DFA accepts language $A$, $p = |Q|$;
• $|s| \geq p$, at least $p + 1$ states in the accepting sequence;
• the first $p + 1$ states must contain a repetition (Pigeonhole principle);
• name the substring "between" repetition of the state $y$;
• denote substring before $y$ with $x$ and substring after $y$ with $z$. 
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Proof:

Let $M = (Q, \Sigma, \delta, q_0, F)$ be a DFA that recognizes $A$ and $p = |Q|$.

Let $s = s_1s_2...s_n$, $n \geq p$; where $s_i \in \Sigma$, $1 \leq i \leq n$.

Let $q_0, q_1,..., q_n$ be the states on the path to accept $s$.

Among the first $p + 1$ states, two must be the same: $q_j = q_l$, $j < l \leq p$.

$s_1s_2...s_js_{j+1}...s_ls_{l+1}...s_p...s_n$ $q_0q_1...q_{j-1}q_j...q_{l-1}q_l...q_p...q_n$

Let $x = s_1...s_j$, $y = s_{j+1}...s_l$, and $z = s_{l+1}...s_n$.

So (1) $M$ accepts $xy^iz$ for every $i \geq 0$; (proved by induction, later)

(2) $|y| > 0$ because $j < l$;

(3) $|xy| \leq p$ because $xy = s_1...s_l$, $l \leq p$.
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```
 s_1 s_2 \ldots s_j s_{j+1} \ldots s_l \ldots s_p \ldots s_n
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\]
\[
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  q_0 & q_1 & \ldots & q_{j-1} & q_j & \ldots & q_{l-1} & q_l & \ldots & q_p & \ldots & q_n
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**Proof:**

Let $M = (Q, \Sigma, \delta, q_0, F)$ be a DFA that recognizes $A$ and $p = |Q|$. Let $s = s_1s_2 \ldots s_n$, $n \geq p$; where $s_i \in \Sigma$, $1 \leq i \leq n$

Let $q_0, q_1, \ldots, q_n$ be the states on the path to accept $s$

Among the first $p + 1$ states, two must be the same: $q_j = q_l$, $j < l \leq p$

$s_1 \ s_2 \ \ldots \ s_j \ s_{j+1} \ \ldots \ s_l \ \ldots \ s_p \ \ldots \ s_n$
$q_0 \ q_1 \ \ldots \ q_{j-1} \ q_j \ \ldots \ q_{l-1} \ q_l \ \ldots \ q_p \ \ldots \ q_n$

Let $x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

So (1) $M$ accepts $xy^iz$ for every $i \geq 0$; (proved by induction, later)
1.4 Non-Regular Languages

Theorem 1.70 (Pumping lemma) (page 78)
If $A$ is a regular language, then there is a number $p$ (called pumping length) where, for any string $s \in A$ of $|s| \geq p$, $s$ can be written as $s = xyz$, such that

1. for each $i \geq 0$, $xy^iz \in A$,
2. $|y| > 0$, and
3. $|xy| \leq p$

Proof:

Let $M = (Q, \Sigma, \delta, q_0, F)$ be a DFA that recognizes $A$ and $p = |Q|$. Let $s = s_1s_2 \ldots s_n$, $n \geq p$; where $s_i \in \Sigma$, $1 \leq i \leq n$

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Among the first $p + 1$ states, two must be the same: $q_j = q_l$, $j < l \leq p$

\[
\begin{align*}
    s_1 & s_2 & \ldots & s_j & s_{j+1} & \ldots & s_l & \ldots & s_p & \ldots & s_n \\
    q_0 & q_1 & \ldots & q_{j-1} & q_j & \ldots & q_{l-1} & q_l & \ldots & q_p & \ldots & q_n
\end{align*}
\]

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1.4 Non-Regular Languages

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Among the first $p + 1$ states, two must be the same: $q_j = q_l$, $j < l \leq p$

\[
\begin{array}{cccccccc}
  s_1 & s_2 & \ldots & s_j & s_{j+1} & \ldots & s_l & \ldots & s_p & \ldots & s_n \\
  q_0 & q_1 & \ldots & q_{j-1} & q_j & \ldots & q_{l-1} & q_l & \ldots & q_p & \ldots & q_n
\end{array}
\]

Let $x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

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1.4 Non-Regular Languages

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Let $q_0, q_1, \ldots, q_n$ be the states on the path to accept $s$. Among the first $p + 1$ states, two must be the same: $q_j = q_l$, $j < l \leq p$.

Let $x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

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1.4 Non-Regular Languages

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$$
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s_1 & s_2 & \ldots & s_j & s_{j+1} & \ldots & s_l & \ldots & s_p & \ldots & s_n \\
q_0 & q_1 & \ldots & q_{j-1} & q_j & \ldots & q_{l-1} & q_l & \ldots & q_p & \ldots & q_n \\
\end{array}
$$

Let $x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

So (1) $M$ accepts $xy^iz$ for every $i \geq 0$; (proved by induction, later) (2) $|y| > 0$ because $j < l$; (3) $|xy| \leq p$ because $xy = s_1 \ldots s_l$, $l \leq p$. 
1.4 Non-Regular Languages

To prove (1) $M$ accepts $xy^iz$ for every $i \geq 0$, we restate it as

Claim: For every $i \geq 0$, there is an accept path for $xy^iz$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

Basis: $i = 0$, $xy^iz = xz = s_1s_j\ldots s_{l+1}\ldots s_n$ that is accepted with path $q_0q_1\ldots q_{j-1}q_jq_{l+1}\ldots q_p\ldots q_n$. The claim is true.

Basis: $i = 1$, $xy^iz = xyz = s_1\ldots s_{j+1}...s_{l+1}\ldots s_n$, accepted with path $q_0q_1\ldots q_{j-1}q_jq_{l+1}\ldots q_p\ldots q_n$. The claim is true.

Assumption: assume that for $i = k \geq 1$, the claim is true.

Induction: $xy^{k+1}z = xy^kz$; by the assumption, substring $y^k$ invokes transitions from $y_j$ to $y_l$, the following $y$ will invoke transitions from $y_l$ (which is $y_j$) to $y_l$, and continue to the accept state $q_n$.

So the claim is proved.
1.4 Non-Regular Languages

To prove (1) $M$ accepts $xy^i z$ for every $i \geq 0$, we restate it as

Claim: For every $i \geq 0$, there is an accept path for $xy^i z$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

Basis $i = 0$, $xy^0 z = xz$ that is accepted with path $q_0 q_1 \ldots q_{j-1} q_j q_{l+1} \ldots q_p \ldots q_n$. The claim is true.

Basis $i = 1$, $xy^1 z = xyz$; by the assumption, substring $y^1$ invokes transitions from $y_j$ to $y_l$, the following $y$ will invoke transitions from $y_l$ (which is $y_j$) to $y_l$, and continue to the accept state $q_n$. So the claim is proved.
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Proof (by induction on $i$)

Basis $i = 0$, $xy^0 z = xz$ that is accepted with path $q_0 q_1 ... q_{j-1} q_j q_{j+1} ... q_{p} ... q_{n}$.
The claim is true.

Basis $i = 1$, $xy^1 z = xyz$ accepted with path $q_0 q_1 ... q_{j-1} q_j q_{j+1} ... q_{p} ... q_{n}$. The claim is true.

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1.4 Non-Regular Languages

To prove (1) $M$ accepts $xy^i z$ for every $i \geq 0$, we restate it as

Claim: For every $i \geq 0$, there is an accept path for $xy^i z$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

$\begin{align*}
s_1 & \ s_2 & \ldots & s_j & s_{j+1} & \ldots & s_l & \ldots & s_p & \ldots & s_n
\end{align*}$
1.4 Non-Regular Languages

To prove (1) \( M \) accepts \( xy^iz \) for every \( i \geq 0 \), we restate it as

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Proof (by induction on \( i \))

\[
\begin{align*}
& s_1 \ s_2 \ \ldots \ s_j \ s_{j+1} \ \ldots \ s_l \ \ldots \ s_p \ \ldots \ s_n \\
& q_0 \ q_1 \ \ldots \ q_{j-1}
\end{align*}
\]
1.4 Non-Regular Languages

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\[
s_1 \ s_2 \ \ldots \ s_j \ s_{j+1} \ \ldots \ s_l \ \ldots \ s_p \ \ldots \ s_n
\]
\[
q_0 \ q_1 \ \ldots q_{j-1} \ q_j \ \ldots \ q_{l-1} \ q_l
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$$q_0 \ q_1 \ \ldots q_{j-1} \ q_j \ \ldots \ q_{l-1} \ q_l \ \ldots \ q_p \ \ldots \ q_n$$
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$$q_0 \ q_1 \ \ldots \ q_{j-1} \ q_j \ \ldots \ q_{l-1} \ q_l \ \ldots \ q_p \ \ldots \ q_n$$

$x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$. 
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\[ s_1 \ s_2 \ \ldots \ \ s_j \ s_{j+1} \ \ldots \ \ s_l \ \ldots \ \ s_p \ \ldots \ \ s_n \]
\[ q_0 \ q_1 \ \ldots \ q_{j-1} \ q_j \ \ldots \ q_{l-1} \ q_l \ \ldots \ q_p \ \ldots \ q_n \]

$x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

**Basis** $i = 0$, $xy^0z$
1.4 Non-Regular Languages

To prove (1) $M$ accepts $xy^iz$ for every $i \geq 0$, we restate it as

Claim: For every $i \geq 0$, there is an accept path for $xy^iz$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

\[ s_1 \ s_2 \ \ldots \ s_j \ s_{j+1} \ \ldots \ s_l \ \ldots \ s_p \ \ldots \ s_n \]
\[ q_0 \ q_1 \ \ldots q_{j-1} \ q_j \ \ldots \ q_{l-1} \ q_l \ \ldots \ q_p \ \ldots \ q_n \]
\[ x = s_1 \ldots s_j, \ y = s_{j+1} \ldots s_l, \text{ and } z = s_{l+1} \ldots s_n. \]

Basis $i = 0$, $xy^0z = xy^0z$
1.4 Non-Regular Languages

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\[
s_1 \ s_2 \ \ldots \ s_j \ s_{j+1} \ \ldots \ s_l \ \ldots \ s_p \ \ldots \ s_n
q_0 \ q_1 \ \ldots q_{j-1} \ q_j \ \ldots q_{l-1} \ q_l \ \ldots q_p \ \ldots q_n
\]

$x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

Basis $i = 0$, $xy^0z = xy^0z = xz$
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Proof (by induction on $i$)

\[ \begin{array}{cccccccccc}
s_1 & s_2 & \ldots & s_j & s_{j+1} & \ldots & s_l & \ldots & s_p & \ldots & s_n \\
q_0 & q_1 & \ldots & q_{j-1} & q_j & \ldots & q_{l-1} & q_l & \ldots & q_p & \ldots & q_n \\
x = s_1 \ldots s_j, & y = s_{j+1} \ldots s_l, & \text{and} & z = s_{l+1} \ldots s_n.
\end{array} \]

Basis $i = 0$, $xy^iz = xy^0z = xz = s_1 \ldots s_j s_{l+1} \ldots s_n$
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Proof (by induction on $i$)

$$
s_1 \ s_2 \ \ldots \ \ s_j \ s_{j+1} \ \ldots \ \ s_l \ \ldots \ \ s_p \ \ldots \ \ s_n
q_0 \ q_1 \ \ldots q_{j-1} \ q_j \ \ldots q_{l-1} \ q_l \ \ldots q_p \ \ldots q_n
$$

$x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

**Basis** $i = 0$, $xy^0z = xz = s_1 \ldots s_js_{l+1} \ldots s_n$

that is accepted with path $q_0q_1 \ldots q_{j-1}$
1.4 Non-Regular Languages

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Claim: For every $i \geq 0$, there is an accept path for $xy^iz$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

$$s_1 s_2 \ldots s_j s_{j+1} \ldots s_l \ldots s_p \ldots s_n$$
$$q_0 q_1 \ldots q_{j-1} q_j \ldots q_{l-1} q_l \ldots q_p \ldots q_n$$

$x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

Basis $i = 0$, $xy^iz = xy^0z = xz = s_1 \ldots s_js_{l+1} \ldots s_n$
that is accepted with path $q_0q_1 \ldots q_{j-1}q_jq_{l+1} \ldots q_p \ldots q_n$. 
1.4 Non-Regular Languages

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Proof (by induction on $i$)

\[
s_1 \ s_2 \ \ldots \ s_j \ s_{j+1} \ \ldots \ s_l \ \ldots \ s_p \ \ldots \ s_n
\]
\[
q_0 \ q_1 \ \ldots \ q_{j-1} \ q_j \ \ldots \ q_{l-1} \ q_l \ \ldots \ q_p \ \ldots \ q_n
\]

$x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

Basis $i = 0$, $xy^0z = xz = s_1 \ldots s_js_{l+1} \ldots s_n$

that is accepted with path $q_0q_1 \ldots q_{j-1}q_jq_{l+1} \ldots q_p \ldots q_n$.

The claim is true.
To prove (1) $M$ accepts $xy^iz$ for every $i \geq 0$, we restate it as

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Proof (by induction on $i$)

\begin{align*}
& s_1 \ s_2 \ \ldots \ s_j \ s_{j+1} \ \ldots \ s_l \ \ldots \ s_p \ \ldots \ s_n \\
& q_0 \ q_1 \ \ldots q_{j-1} \ q_j \ \ldots \ q_{l-1} \ q_l \ \ldots \ q_p \ \ldots \ q_n \\
& x = s_1 \ldots s_j, \ y = s_{j+1} \ldots s_l, \text{ and } z = s_{l+1} \ldots s_n.
\end{align*}

Basis $i = 0$, $xy^iz = xy^0z = xz = s_1 \ldots s_j s_{l+1} \ldots s_n$
that is accepted with path $q_0 q_1 \ldots q_{j-1} q_j q_{l+1} \ldots q_p \ldots q_n$.
The claim is true.

Basis $i = 1$, $xy^i z$
1.4 Non-Regular Languages

To prove (1) $M$ accepts $xy^i z$ for every $i \geq 0$, we restate it as

Claim: For every $i \geq 0$, there is an accept path for $xy^i z$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

\[
\begin{align*}
&\begin{array}{cccccccccccc}
s_1 & s_2 & \ldots & s_j & s_{j+1} & \ldots & s_l & \ldots & s_p & \ldots & s_n \\
q_0 & q_1 & \ldots & q_{j-1} & q_j & \ldots & q_{l-1} & q_l & \ldots & q_p & \ldots & q_n \\
\end{array}
\end{align*}
\]

$x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

**Basis $i = 0$,** $xy^i z = xy^0 z = xz = s_1 \ldots s_j s_{l+1} \ldots s_n$

that is accepted with path $q_0 q_1 \ldots q_{j-1} q_j q_{l+1} \ldots q_p \ldots q_n$.

The claim is true.

**Basis $i = 1$,** $xy^i z = xy^1 z$
To prove (1) $M$ accepts $xy^iz$ for every $i \geq 0$, we restate it as

**Claim:** For every $i \geq 0$, there is an accept path for $xy^iz$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

**Proof (by induction on $i$)**

\[
\begin{align*}
&\quad s_1 \ s_2 \ \ldots \ s_j \ s_{j+1} \ \ldots \ s_l \ \ldots \ s_p \ \ldots \ s_n \\
&\quad q_0 \ q_1 \ \ldots q_{j-1} \ q_j \ \ldots \ q_{l-1} \ q_l \ \ldots \ q_p \ \ldots \ q_n \\
&x = s_1 \ldots s_j, \ y = s_{j+1} \ldots s_l, \text{ and } z = s_{l+1} \ldots s_n.
\end{align*}
\]

**Basis $i = 0$,** $xy^0z = xy^0z = xz = s_1 \ldots s_js_{l+1} \ldots s_n$

that is accepted with path $q_0q_1 \ldots q_{j-1}q_jq_{l+1} \ldots q_p \ldots q_n$. The claim is true.

**Basis $i = 1$,** $xy^1z = xy^1z = xyz = s$
1.4 Non-Regular Languages

To prove (1) $M$ accepts $xy^i z$ for every $i \geq 0$, we restate it as

Claim: For every $i \geq 0$, there is an accept path for $xy^i z$
in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

\[ s_1 \ s_2 \ \ldots \ s_j \ s_{j+1} \ \ldots \ s_l \ \ldots \ s_p \ \ldots \ s_n \]
\[ q_0 \ q_1 \ \ldots q_{j-1} \ q_j \ \ldots q_{l-1} \ q_l \ \ldots q_p \ \ldots q_n \]
\[ x = s_1 \ldots s_j, \ y = s_{j+1} \ldots s_l, \text{ and } z = s_{l+1} \ldots s_n. \]

Basis $i = 0$, $xy^i z = xy^0 z = xz = s_1 \ldots s_j s_{l+1} \ldots s_n$
that is accepted with path $q_0 q_1 \ldots q_{j-1} q_j q_{l+1} \ldots q_p \ldots q_n$. The claim is true.

Basis $i = 1$, $xy^i z = xy^1 z = xy z = s \in A$, accepted with path
\[ q_0 q_1 \ldots q_{j-1} \]
1.4 Non-Regular Languages

To prove (1) $M$ accepts $xy^i z$ for every $i \geq 0$, we restate it as

Claim: For every $i \geq 0$, there is an accept path for $xy^i z$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

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Basis $i = 1$, $xy^1 z = xyz = s \in A$, accepted with path $q_0 q_1 \ldots q_{j-1} q_j q_{j+1} \ldots q_l q_{l+1} \ldots q_p \ldots q_n$. The claim is true.
1.4 Non-Regular Languages

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\begin{align*}
&\begin{array}{cccccccc}
s_1 & s_2 & \ldots & s_j & s_{j+1} & \ldots & s_l & \ldots & s_p & \ldots & s_n \\
q_0 & q_1 & \ldots & q_{j-1} & q_j & \ldots & q_{l-1} & q_l & \ldots & q_p & \ldots & q_n \\
x = s_1 \ldots s_j, & y = s_{j+1} \ldots s_l, & \text{and} & z = s_{l+1} \ldots s_n.
\end{array}
\end{align*}

Basis $i = 0$, $xy^iz = xy^0z = xz = s_1 \ldots s_j s_{l+1} \ldots s_n$

that is accepted with path $q_0 q_1 \ldots q_{j-1} q_j q_{l+1} \ldots q_p \ldots q_n$.

The claim is true.

Basis $i = 1$, $xy^iz = xy^1z = xyz = s \in A$, accepted with path

$q_0 q_1 \ldots q_{j-1} q_j q_{j+1} \ldots q_{l} q_{l+1} \ldots q_p \ldots q_n$. The claim is true.

Assumption: assume that for $i = k \geq 1$, the claim is true.
1.4 Non-Regular Languages

To prove (1) $M$ accepts $xy^iz$ for every $i \geq 0$, we restate it as

Claim: For every $i \geq 0$, there is an accept path for $xy^iz$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

\[
\begin{align*}
&\quad s_1 s_2 \ldots s_j s_{j+1} \ldots s_l \ldots s_p \ldots s_n \\
&\quad q_0 q_1 \ldots q_{j-1} q_j \ldots q_{l-1} q_l \ldots q_p \ldots q_n \\
&\quad x = s_1 \ldots s_j, \ y = s_{j+1} \ldots s_l, \text{ and } z = s_{l+1} \ldots s_n.
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Basis $i = 1$, $xy^1z = xy^1z = xyz = s \in A$, accepted with path $q_0 q_1 \ldots q_{j-1} q_j q_{j+1} \ldots q_l q_{l+1} \ldots q_p \ldots q_n$. The claim is true.

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Induction: $xy^{k+1}z$
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Claim: For every $i \geq 0$, there is an accept path for $xy^iz$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

\[
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  q_0 & q_1 & \ldots & q_{j-1} & q_j & \ldots & q_{l-1} & q_l & \ldots & q_p & \ldots & q_n \\
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$x = s_1 \ldots s_j$, $y = s_{j+1} \ldots s_l$, and $z = s_{l+1} \ldots s_n$.

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Basis $i = 1$, $xy^1z = xyz = s \in A$, accepted with path $q_0 q_1 \ldots q_{j-1} q_j q_{j+1} \ldots q_l q_{l+1} \ldots q_p \ldots q_n$. The claim is true.

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\[
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Induction: $xy^{k+1} z = xy^k y z$; by the assumption, substring $y^k$ invokes transitions from $y_j$ to $y_l$, the following $y$ will invoke transitions from $y_l$ (which is $y_j$) to $y_l$, and continue to the accept state $q_n$. 

To prove (1) $M$ accepts $xy^iz$ for every $i \geq 0$, we restate it as

Claim: For every $i \geq 0$, there is an accept path for $xy^iz$ in which substring $y^i$ invokes transitions from $q_j$ to the same state $q_l$.

Proof (by induction on $i$)

Basis $i = 0$, $xy^0z = xz = s_1 \ldots s_j s_{l+1} \ldots s_n$ that is accepted with path $q_0q_1 \ldots q_{j−1}q_j q_{l+1} \ldots q_p \ldots q_n$. The claim is true.

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Assumption: assume that for $i = k \geq 1$, the claim is true.

Induction: $xy^{k+1}z = xysz$; by the assumption, substring $y^k$ invokes transitions from $y_j$ to $y_l$, the following $y$ will invoke transitions from $y_l$ (which is $y_j$) to $y_l$, and continue to the accept state $q_n$.

So the claim is proved.
1.4 Non-Regular Languages

The Pumping lemma exists without referring at all to non-regular languages. So we first look at its applications in regular languages. Let $\Sigma = \{a, b\}$. Define $L = \{s : s = a^k \text{ or } s = a^k b^3, k \geq 3\}$. So $L$ contains strings like $aaa, aaaa, aaabbb, aaaaaabbb$, etc. Now we apply the Pumping lemma to $L$.

• assume pumping length $p = 7$.

How do we know this is okay?

• choose $s = aaaaaabbb$, such that $|s| = 8 > p = 7$.

• according to the lemma, $s = xyz$, for some substrings $x, y, z$.

• (1) $y$ can be all $a$'s, or (2) $a$'s followed by $b$'s, or (3) all $b$'s;

• The lemma is correct because case (1) would allow pumped strings to belong to $L$ as well.

If we were asked to prove $L$ is not regular, we would have to show that none of the above 3 cases allow pumped strings to belong to $L$. 
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Example 1.73 (page 80)

Claim: $L_2 = \{0^k1^k : k \geq 0\}$ is not a regular language.

Proof: (use proof by contradiction) Assume $L_2$ is a regular language.

According to the Pumping Lemma, there is a number $p$, pumping length.

Choose string $s = 0^p1^p \in L_2$. Thus $|s| = 2p \geq p$.

According to the Pumping Lemma, $s = xyz$, such that

(1) $xy^iz \in L_2$, for every $i \geq 0$

(2) $|y| > 0$

(3) $|xy| \leq p$

From (2) and (3) we conclude that $y = 0^k$, for some $k \geq 1$; $x = 0^l$, for some $l \geq 0$; $z = 0^{p-l-k}1^p$.

From (1), we conclude string $xy0z \in L_2$. That is $0^l0^01^p0^{p-l-k}1^p \in L_2$.

But such string is abnormal, NOT in the format $0^k1^k$. Contradicts!

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From (1), we conclude string \( xy^0z \in L_2 \). That is \( 0^l0^0 \times 0^p-l-k1^p \times 0^p-k1^p = 0^p-k1^p \in L_2 \).
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From (2) and (3) we conclude that
$y = 0^k$, for some $k \geq 1$;
$x = 0^l$, for some $l \geq 0$;
$z = 0^{p-l-k}1^p$;

From (1), we conclude string $xy^0z \in L_2$. That is $0^l0^0\times k0^{p-l-k}1^p = 0^{p-k}1^p \in L_2$.

But such string is abnormal, NOT in the format $0^k1^k$. Contradicts!
So $L_2$ is not a regular language.
Alternatively, we may choose $s = 0^{p_2}1^{p_2}$ (assuming $p$ is even).

- Because $|s| = p_2 + p_2 \geq p$, we can apply the lemma to $s$;
- thus $s = xyz$ for some substrings $x, y, z$ such that $|y| > 0$ and $|xy| \leq p$.

There are three possible cases for what $y$ may be:

1. $y = 0^k$ for some $k \geq 1$, $x = 0^l$ for some $l \geq 0$, $z = 0^{p_2-k-l}$

2. $y = 0^k1^l$, $x = 0^{p_2-k}$, $z = 1^{p_2-l}$, for some $k \geq 1$, $l \geq 1$

3. $y = 1^k$, $z = 1^l$, $x = 0^{p_2-k-l}$, for some $k \geq 1$, $l \geq 0$

Now we need to show that for every one of the 3 cases, pumping $y$ will lead to creating strings NOT in the format of $0^k1^k$.

But the lemma says that such abnormal strings belong to $L_2$. Contradicts.
1.4 Non-Regular Languages

Alternatively, we may choose $s = 0^{\frac{p}{2}} 1^{\frac{p}{2}}$ (assuming $p$ is even)
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Now we need to show that for every one of the 3 cases, pumping \( y \) will lead to creating strings NOT in the format of \( 0^k 1^k \).

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Example: Prove that language of two repeat strings \( L = \{ww : w \in \{0, 1\}^*\} \) is not regular.

The most critical step is to identify such a string \( s \in L \) such that pumping its prefix of at most \( p \) symbols would result in abnormal strings of form \( ww \).

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Often we create abnormal strings by making multiple copies of $y$. But it may not work on the following example:

$L = \{0^i 1^j : \text{positive integers } i > j\}$

To prove $L$ is not regular, we assume it is regular. Then by the lemma, there is a number $p$, the pumping length;

Selecting string $s = 0^p + 1^p$, by the lemma $s = xyz$, for some substrings $x, y, z$;

$|xy| \leq p$, and $|y| > 0$;

Because $|xy| \leq p$, $y = 0^k$ for some $k \geq 1$ and $x = 0^l$ for some $l \geq 0$.

$s = 0^l 0^k 0^p + 1^p - l - k 1^p = 0^{p+k} + 1^p$.

Pumping up $0^k$ would only add more 0's, NOT creating abnormal strings.

Pumping down will work!
1.4 Non-Regular Languages

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- **Pumping down** will work!
1.4 Non-Regular Languages

Pumping down strings $= \ell_0 k_0 p + 1 - \ell - k_1 p$.

New string $\ell(0) k p + 1 - \ell - k_1 p$, let $i = 0$.

By the lemma new string $\ell(0) k p + 1 - \ell - k_1 p = \ell p + 1 - k_1 p \in L$.

However, the number of 0's is NOT $\geq$ that of 1's in $\ell p + 1 - k_1 p$, because $k \geq 1$.

Contradicts!
1.4 Non-Regular Languages

Pumping down string \( s = 0^l 0^k 0^{p+1-l-k} 1^p \).
1.4 Non-Regular Languages

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1.4 Non-Regular Languages

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1.4 Non-Regular Languages

Further questions concerning the Pumping Lemma and NFAs:

• In proving the Pumping Lemma, we assume a DFA $M$ for language $A$.
  Would an NFA work well for the proof?

• The pumping lemma underscores the fundamental limitation of FAs, the capability of such a machine equal that of a constant-memory algorithm;

• Loops (self-loops or not) in an NFA allows to accept a infinite number of strings;
1.4 Non-Regular Languages

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Additional notes for regular expressions

1. In conversion from regular languages to regular expressions, we used DFA. Can you use NFA instead?

2. Regular expressions: operations and simplification
   - Every regular expression describes a set of strings;
   - Operations star $\star$, concatenation $\circ$, and union $\cup$ are used to make larger regular expressions;
   - Let $A, B, C$ be regular expressions; where $A = \{a_1, a_2, \ldots\}$, $B = \{b_1, b_2, \ldots\}$, and $C = \{c_1, c_2, \ldots\}$.
   - Then $(A \cup B) \circ C = ?$
   - $(A \cup B) \star = ?$
   - Is $(A \circ B) \star$ the same as $(A \cup B) \star$ or $A \star \circ B \star$?
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1.4 Non-Regular Languages

- Every language is a subset of $\Sigma^*$ for some finite alphabet $\Sigma$.
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- Let $A$ and $B$ be two languages. If $A \subseteq B$ and $A$ is regular, should $B$ be regular? If $A \subseteq B$ and $B$ is regular, should $A$ be regular?
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  If $A \subseteq B$ and $B$ is regular, should $A$ be regular?
• If $A$ is regular, should $\overline{A}$ be regular?
• If $A$ and $B$ are both regular, should $A \cap B$ be regular?
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Finite Automata
- FA, alphabet, transition, states
- Computation of strings with FA
- Regular languages
  - Design of FA diagrams for regular languages

Nondeterminism
- Difference between DFA and NFA
- Design of FA diagrams
- Equivalence between NFA to DFA
- Regular languages are closed under $\cup$, $\circ$, $\ast$
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  - basic notations and composition rules for regular expression
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  - converting regular expressions to NFA
  - converting DFA to regular expressions

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  - pumping lemma (principle)
  - pumping lemma (theorem)
  - proofs for non-regular languages
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