

# Theory Of Computation

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### Abstract

The note is taken by studying 18.404J/6.5400 *Theory of Computation* course by professor Michael Sipser of MIT. The course material can be downloaded in [MIT OpenCourseWare](#). Meanwhile, most contents in this note will also be derived from his book *Introduction to the Theory of Computation, third edition*.

The course is divided into 2 parts, computational theory and complexity theory. Computational theory is developed during 1930s - 1950s. It concerns about what is computable. This note will be focused on the first part.

**Example.** Program verification, mathematical truth

**Example (Models of Computation).** Finite automata, Turing machines, ...

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# Chapter 1

## Introduction, Finite Automata, Regular Expressions

The theory of computation begins with a question: What is a computer. The real computer is too complicated to understand, to start with, we use an idealized computer called **computational model**.

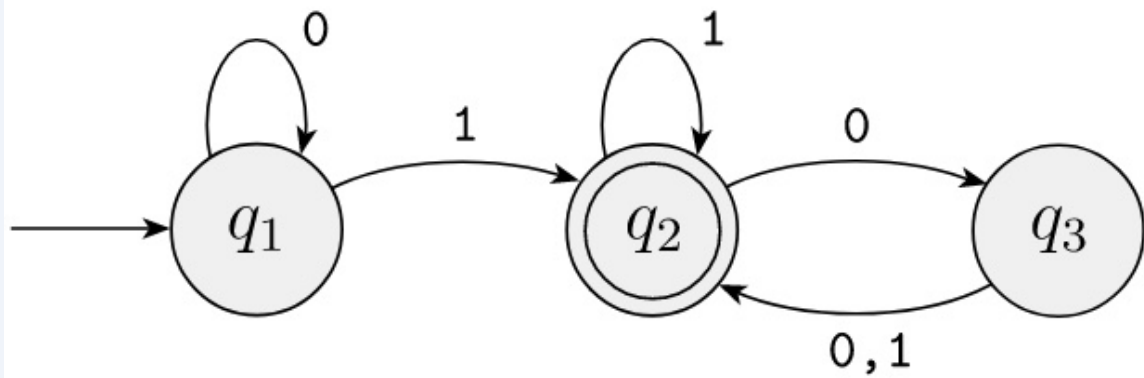
The simplest model among them is **finite state machine** or **finite automaton**.

### 1.1 Finite Automata

Finite automata are good models for computers with an extremely limited amount of memory.

Finite automata and their probabilistic counterpart **Markov chains** are useful tools when we're attempting to recognize patterns in data. Markov chains have even been used to model and predict price changes in financial markets.

**Example (Finite Automata Example).** Here's an example of finite automata:



- The figure is called **state diagram** of  $M_1$ .
- Three **states**:  $q_1$ ,  $q_2$  and  $q_3$ .
- **Start state**:  $q_1$ .
- **Accept state**:  $q_2$ .
- The arrows going from one state to another are called **transitions**.

When the automaton receives an input string such as 1101, it processes that string and produces an output. The output is either **accept** or **reject**:

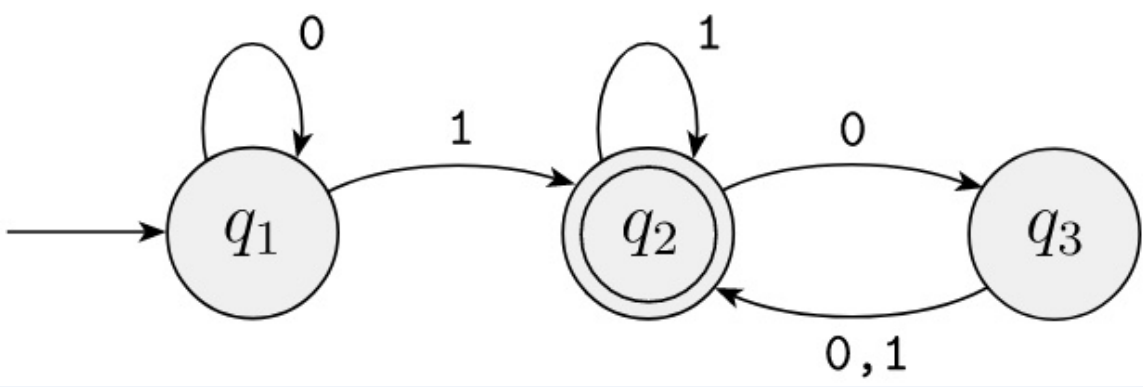
1. Start in state  $q_1$
2. Read 1, follow transition from  $q_1$  to  $q_2$

3. Read 1, follow transition from  $q_2$  to  $q_2$
4. Read 0, follow transition from  $q_2$  to  $q_3$
5. Read 1, follow transition from  $q_3$  to  $q_2$
6. *Accept* because  $M_1$  is in an accept state  $q_2$  at the end of the input

**Definition 1.1.1 (Formal Definition of A Finite Automaton).** A **finite automaton** is a 5-tuple  $(Q, \Sigma, \delta, q_0, F)$ , where

1.  $Q$  is a finite set called **state**
2.  $\Sigma$  is a finite set called the **alphabet**
3.  $\delta : Q \times \Sigma \Rightarrow Q$  is the **transition function**
4.  $q_0 \in Q$  is the **start state**
5.  $F \subseteq Q$  is the **set of accept state**

**Example (Revisit Finite Automata Example).** Let's revisit the finite automata example  $M_1$  and see from the formal definition perspective:



We can describe  $M_1$  formally by writing  $M_1 = (Q, \Sigma, \delta, q_1, F)$ , where

1.  $Q = \{q_1, q_2, q_3\}$
2.  $\Sigma = \{0, 1\}$
3.  $\delta$  is described as

	0	1
$q_1$	$q_1$	$q_2$
$q_2$	$q_3$	$q_2$
$q_3$	$q_2$	$q_2$

4.  $q_1$  is the start state
5.  $F = \{q_2\}$

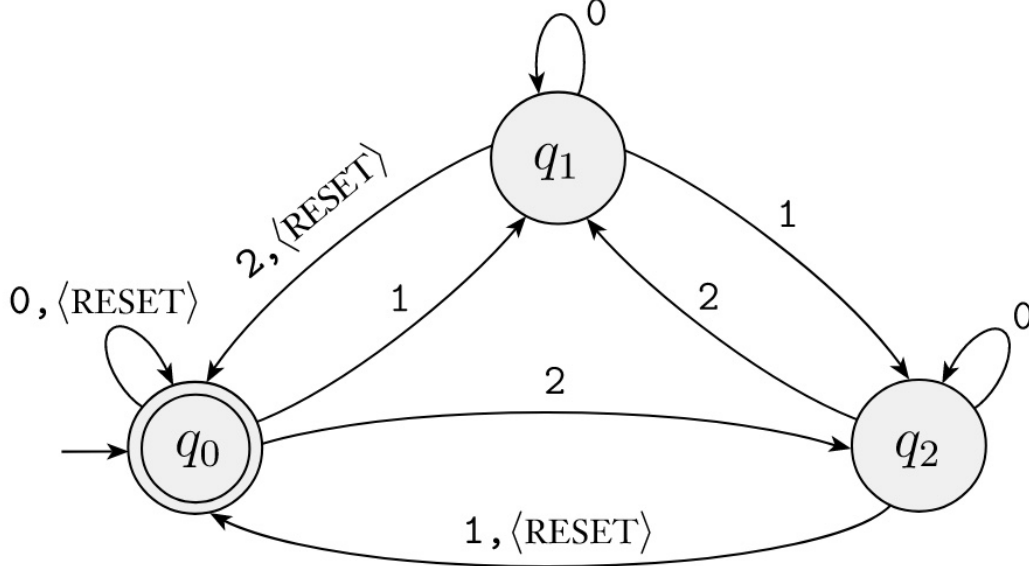
If  $A$  is the set of all strings that machine  $M$  accepts, we say that  $A$  is the **language of machine  $M$**  and write  $L(M) = A$ . We say that  **$M$  recognizes  $A$**  or that  **$M$  accepts  $A$** . Here because *accept* has different meaning, we use *recognize* for the language.

**Remark.** A machine may accept several strings, but it always recognizes only one language. If the machine accepts no strings, it still recognizes one language – namely, the empty language  $\emptyset$ .

**Example (Revisit Finite Automata Example: Language).** In our example, the language set  $A$  can be represented as:

$A = \{\omega \mid \omega \text{ contains at least one 1 and an even number of 0s follow the last 1}\}.$   
Then  $L(M_1) = A$ , or equivalently,  $M_1$  recognizes  $A$ .

**Example.** When describing such a machine:



The alphabet  $\Sigma = \{1, 2, 3, \langle RESET \rangle\}$ , we treat  $\langle RESET \rangle$  as a single symbol.

The machine keeps a running count of the sum of the numerical input symbols it reads, modulo 3. Every time it receives  $\langle RESET \rangle$  symbol, it resets the count to 0. It accepts if the sum is 0 modulo 3.

## 1.2 Formal Definition of Computation

Let  $M = (Q, \Sigma, \delta, q_0, F)$  be a FA and let  $\omega = \omega_1\omega_2\cdots\omega_n$  be a string where each  $\omega_i$  is a member of alphabet  $\Sigma$ . Then  $M$  **accepts**  $\omega$  if a sequence of state  $r_0, r_1, \dots, r_n$  in  $Q$  exists with three conditions:

1.  $r_0 = q_0$  (machine starts at initial state)
2.  $\delta(r_i, \omega_{i+1}) = r_{i+1}$  (machine goes from state to state following the transition function)
3.  $r_n \in F$  (machine accepts its input if it ends up in an accept state)

We say that  $M$  recognizes language  $A$  if  $A = \{\omega \mid M \text{ accepts } \omega\}$

**Note.**  $A$  is the language,  $\omega$  is the accepted string.  $A$  is the set of all instances of  $\omega$ .

We say a machine "accepts" a string, and a machine "recognizes" a language.

**Definition 1.2.1 (Regular Language).** A language is called a **regular language** if some finite automaton recognizes it.

**Example.** Let  $B = \{\omega \mid \omega \text{ has even number of 1s}\}$   
 $B$  is a regular language.

**Example.** Let  $C = \{\omega \mid \omega \text{ has equal numbers of 0s and 1s}\}$   
 $C$  is not a regular language.

## 1.3 Regular Expressions

### 1.3.1 Regular Operations

**Definition 1.3.1.** Let  $A$  and  $B$  be languages, we define the regular operations **union**, **concatenation**, and **star** as follows:

- Union:  $A \cup B = \{x | x \in A \vee x \in B\}$
- Concatenation:  $A \circ B = \{xy | x \in A \wedge y \in B\}$
- Star:  $A^* = \{x_1 x_2 \cdots x_k | k \geq 0 \wedge x_i \in A\}$

Notice that  $\epsilon$  (empty language) always belongs to  $A^*$ .

**Example.**  $\Sigma^*1$  is the language end with 1

**Remark.** Show finite automata equivalent to regular expressions.

### 1.3.2 Closure Properties

**Theorem 1.3.1.** The class of regular language is closed under the union operation.  
In other words, if  $A_1$  and  $A_2$  are regular languages, so is  $A_1 \cup A_2$ .

**Proof.** Let  $M_1 = \{Q_1, \Sigma, \delta_1, q_1, F_1\}$  recognize  $A_1$ .

Let  $M_2 = \{Q_2, \Sigma, \delta_2, q_2, F_2\}$  recognize  $A_2$ . (assuming in the same alphabet to make the proof simple)

Construct  $M = (Q, \Sigma, \delta, q_0, F)$  recognizing  $A_1 \cup A_2$ .

$M$  should accept input  $w$  if either  $M_1$  or  $M_2$  accepts  $w$ .

Component of  $M$ :

- $Q = Q_1 \times Q_2$
- $q_0 = (q_1, q_2)$
- $\delta((q, r), a) = (\delta_1(q, a), \delta_2(r, a))$
- $F = (F_1 \times Q_2) \cup (Q_1 \times F_2)$
- not  $F = \underline{F_1} \times \underline{F_2}$  (this gives intersection!)

■

**Example (What is close?).** Positive integers close under addition but not close under subtraction.

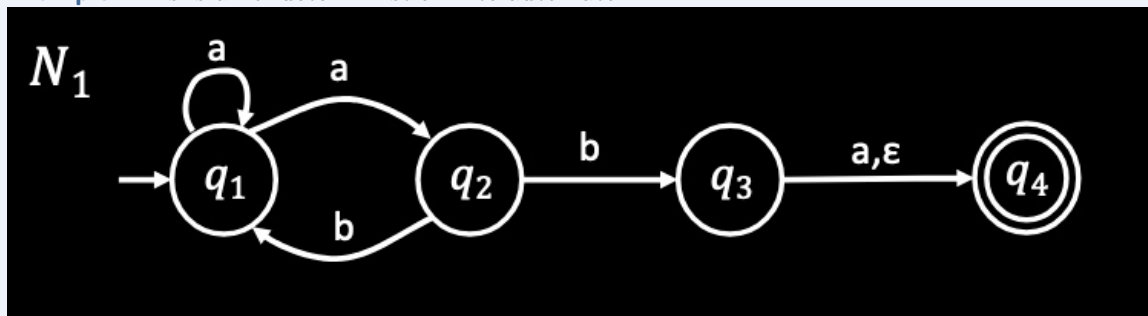
**Theorem 1.3.2.** The class of regular language is closed under the concatenation operation.  
In other words, if  $A_1$  and  $A_2$  are regular languages then so is  $A_1 \circ A_2$ .

## Chapter 2

# Nondeterminism, Closure Properties, Regular Expressions $\rightarrow$ Finite Automata

### 2.1 Nondeterminism

**Example.** This is a nondeterministic finite automaton:



What's the difference with what we saw in the last lecture:

- in  $q_1$ , when accepting an  $a$ , you can either stay in  $q_1$  or go to  $q_2$
- in  $q_1$ , if getting  $b$  then there's nowhere to go
- ...

Example inputs

- **ab (accept )**
- **aa (reject )**

New features of nondeterminism:

- multiple paths possible (0, 1 or many at each step)
- $\epsilon$ -transition is a "free" move without reading input
- Accept input if some path leads to accept state (acceptance overrules rejection) (if one of possible ways to go accepts, then accepts)

Nondeterminism doesn't correspond to a physical machine we can build, however it is useful mathematically.

### 2.2 NFA



**Definition 2.2.1.** A **nondeterministic finite automaton** is a 5-tuple  $Q, \Sigma, \delta, q_0, F$ , where

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

In which,  $\Sigma_\epsilon$  is a shorthand of  $\Sigma \cup \{\epsilon\}$ .  $P(Q)$  means the power set of  $Q$  which can be represented as  $P(Q) = \{R \mid R \subseteq Q\}$ , which is the set which contains all the subset of  $Q$ .

**Example.** Check the [NFA example](#), we can write transition function such as:

- $\delta(q_1, a) = \{q_1, q_2\}$
- $\delta(q_1, b) = \emptyset$

Ways to think about nondeterminism:

Computational view: Fork new parallel thread and accept if any thread leads to an accept state.

Mathematical view: Tree with branches, accept if any branch leads to an accept state.

Magical: Guess at each nondeterministic step which way to go. Machine always makes the right guess that leads to accepting, if possible.

**Theorem 2.2.1.** If an NFA recognizes  $A$  then  $A$  is regular.

**Proof.** By showing how to convert an NFA to an equivalent DFA.

Let NFA  $M = (Q, \Sigma, \delta, q_0, F)$  recognize  $A$ , we're going to construct DFA  $M' = (Q', \Sigma, \delta', q'_0, F')$  recognizing  $A$ .

IDEA: DFA  $M'$  keeps track of the subset of possible states in NFA  $M$ .

Construct of  $M'$ :

- $Q' = P(Q)$  (States of  $M'$  is the power set of  $Q$ )
- $\delta'(R, a) = \{q \mid q \in \delta(r, a) \text{ for some } r \in R\}$  ( $R \in Q'$ )
- $q'_0 = \{q_0\}$
- $F' = \{R \in Q' \mid R \text{ intersects } F\}$

■

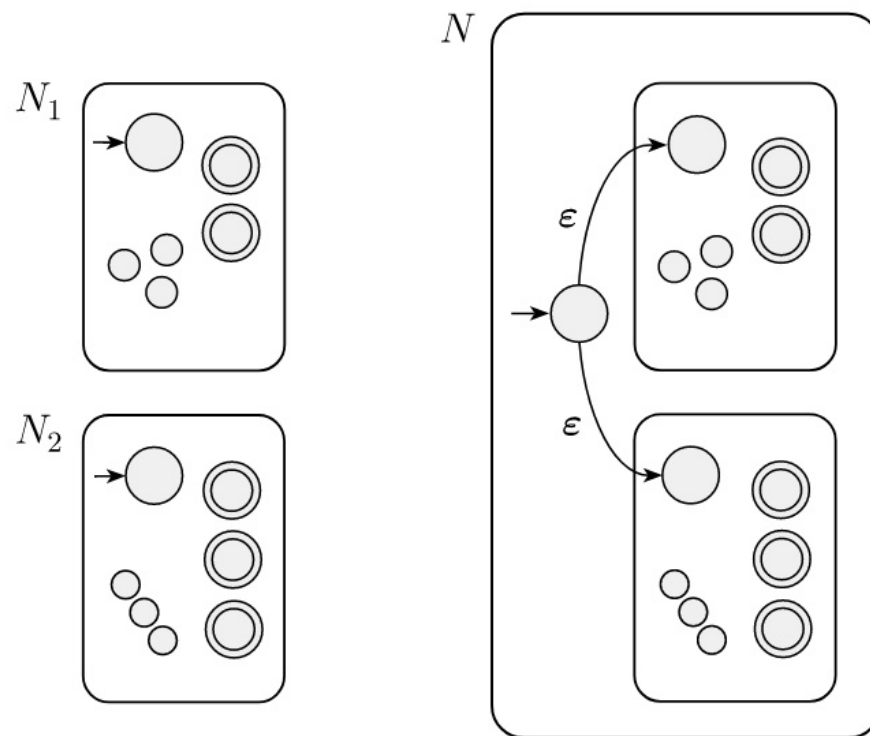
**Remark.** If  $M$  has  $n$  states, how many states does  $M'$  have by this construction?

The answer is  $2^n$ .

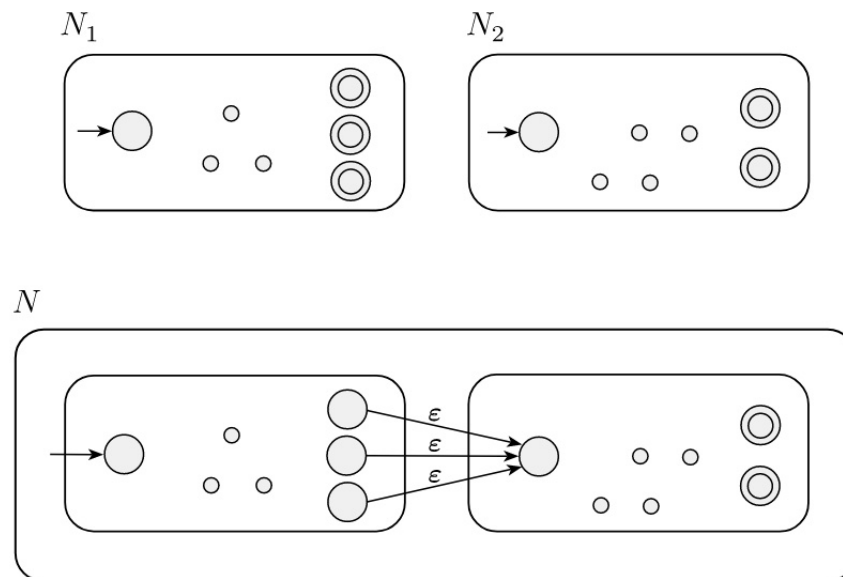
Return to [Union Closure Property](#) and [Concatenation Closure Property](#) by constructing an NFA to prove.

**Proof: Closure Properties Union.**  $N_1$  corresponds to the DFA  $M_1$  recognizes  $A_1$ , and  $N_2$  corresponds to an input of DFA  $M_2$  who recognizes  $A_2$ .

We can construct an NFA like following:

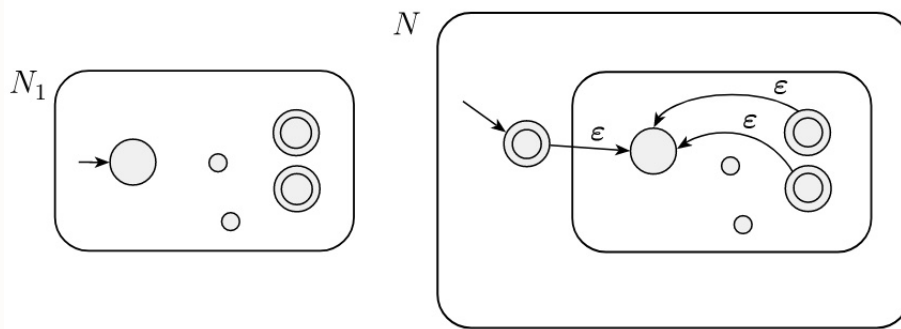


**Proof: Closure Properties Concat.** Similar with the last one, this one constructs an NFA recognizes  $A_1A_2$ :



**Theorem 2.2.2 (Closure Under Star).** If  $A$  is a regular language, so is  $A^*$ .

**Proof.** Given DFA  $M$  recognizing  $A$ , construct NFA  $M'$  recognizing  $A^*$ .



**Remark.**  $M'$  have  $n + 1$  states in this construction.

**Theorem 2.2.3.** If  $R$  is regular expression and  $A = L(R)$  then  $A$  is regular.

That is to say: A language is regular and only if some regular expression describes it.

This theorem has two directions:

**Lemma 2.2.1.** If a language is described by a regular expression, then it is regular

**Proof.** IDEA: Say that we have a regular expression  $R$  describing some language  $A$ . We show how to convert  $R$  into an NFA recognizing  $A$ .

When  $R$  is atomic, we can easily construct NFA for:

- $R = a$  for some  $a \in \Sigma$
- $R = \epsilon$
- $R = \emptyset$

When  $R$  is composite, as we have already constructed for them (closure properties).

**Note.** This proof works in a recursive way.

**Lemma 2.2.2.** If a language is regular, then it is described by a regular expression.

**Proof.** This will be proved in next lecture.

**Note.** Before going to prove this theorem, I need to make some clarifications here.

- **Regular language:** if some finite automaton recognizes a language, then it is called regular language.
- We say a machine recognizes a language if the language is the set contains all the string that can run the machine into an accept state.

Also we need the definition of **regular expression** here:

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**Definition 2.2.2.** Say that  $R$  is a **regular expression** if  $R$  is

1.  $a$  for some  $a$  in the alphabet  $\Sigma$
2.  $\epsilon$
3.  $\emptyset$
4.  $R_1 \cup R_2$  where  $R_1$  and  $R_2$  are regular expressions
5.  $R_1 \circ R_2$  where  $R_1$  and  $R_2$  are regular expressions
6.  $R_1^*$  where  $R_1$  is a regular expression

## Chapter 3

# The Regular Pumping Lemma, Finite Automata $\rightarrow$ Regular Expressions, CFGs

### 3.1 GNFA

Let's go back to [the Lemma in the previous lecture](#):

**Theorem 3.1.1** (DFA  $\rightarrow$  Regular Expressions). If a language is regular, then it is described by a regular expression.

In another word, if  $A$  is regular then  $A = L(R)$  for some regular exp  $R$ .

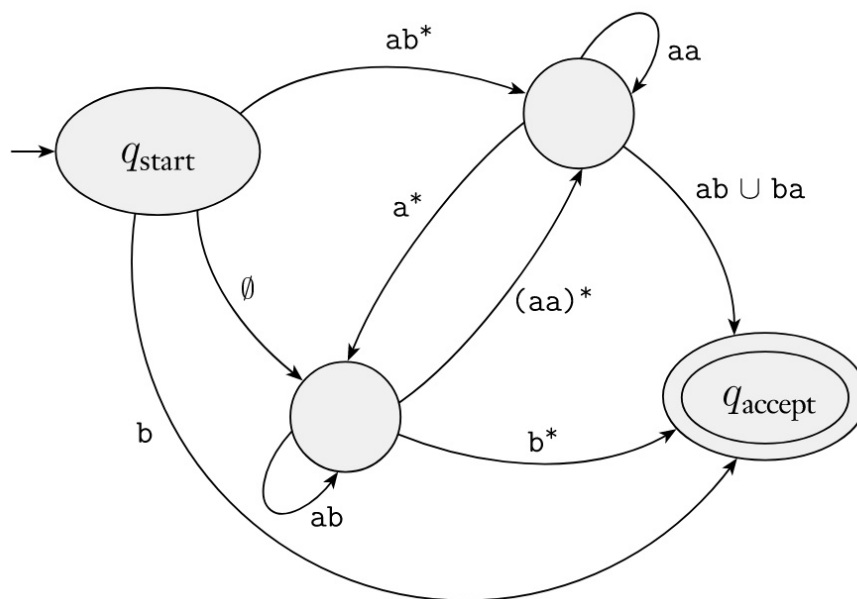
**Proof.** IDEA: Give conversion DFA  $M \rightarrow R$  We need new tool: Generalized NFA ■

**Definition 3.1.1** (Generalized NFA). A Generalized nondeterministic Finite Automaton(GNFA) is similar to an NFA, but allows regular expressions as transition labels.

The formal definition is that a **generalized nondeterministic finite automaton** is a 5-tuple,  $(Q, \Sigma, \delta, q_{start}, q_{accept})$ , where

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

**Example** (Example of GNFA). Similar with NFA but transitions allow regular expressions



Now we're going to covert GNFA to regular expressions to proof [the Lemma](#).  
For convenience, we will assume (we can easily modify the machine to achieve):

- One accept state, separate from the start state.
- One arrow from each state to each state, except
  - only exiting the start state
  - only entering the accept state

**Lemma 3.1.1 (GNFA  $\rightarrow$  Regular Expressions).** Every GNFA  $G$  has an equivalent regular expression  $R$ .

**Proof.** By induction(recursion) on the number of states  $k$  of  $G$ .

Basis( $k = 2$ ):  $G$  can only looks like:

$G = \text{start} \xrightarrow{r} \text{accept}$

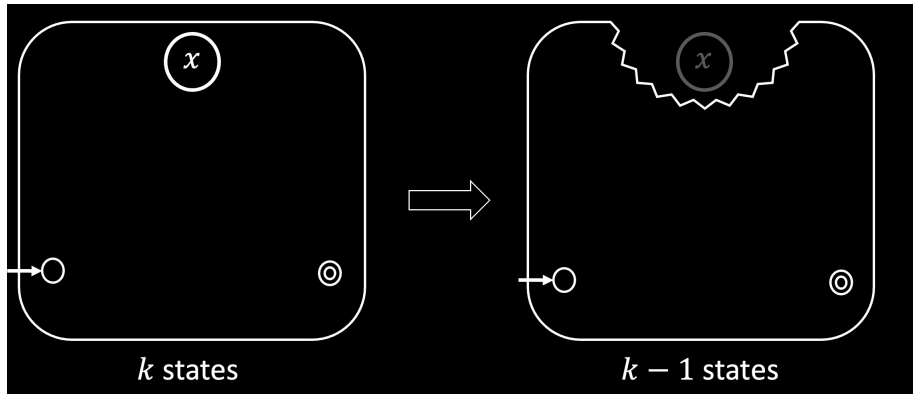
In this case,  $R = r$ .

Induction step( $k > 2$ ): Assume Lemma true for  $k - 1$  states and prove for  $k$  states

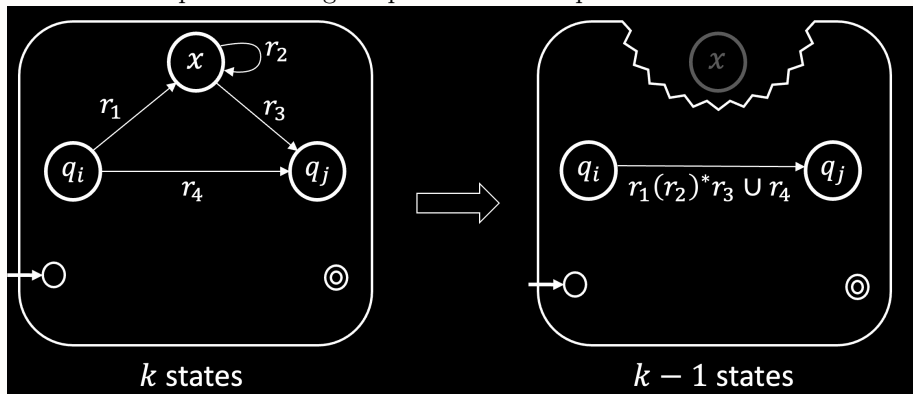
IDEA: Convert  $k$ -state GNFA to equivalent  $(k - 1)$ -state GNFA

1. First we pick any state  $x$  except the start and accept states.
2. Remove  $x$ .
3. Repair the damage by recovering all paths that went through  $x$ .
4. Make the indicated change for each pair of states  $q_i, q_j$ .

In the following example, this is how we remove a state  $x$ :



Then we replace the original paths with new paths:



We're already done, because DFAs are a type of GNFA. ■

## 3.2 Non-Regular Languages

How do we show a language is not regular?

- To show a language is regular we give a DFA.
- To show a language is not regular, we must give a proof (It is not enough to say that you couldn't find a DFA for it, therefore the language is not regular).

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

1. B has equal numbers of 0 and 1  
Intuition: B is not regular because DFAs cannot count unboundedly.
2. C has equal numbers of 01 and 10 substrings.  
0101  $\notin C$   
0110  $\in C$   
Intuition: C is not regular because DFAs cannot count unboundedly. (Wrong! Actually, C is regular!)

Moral: You need a proof.

## 3.3 Pumping Lemma

Pumping lemma is the method for proving non-regularity.

**Lemma 3.3.1 (Pumping Lemma).** For every regular language A, there's a number  $p$  (the "pumping length") such that if  $s \in A$  and  $|s| \geq p$  then  $s = xyz$  where

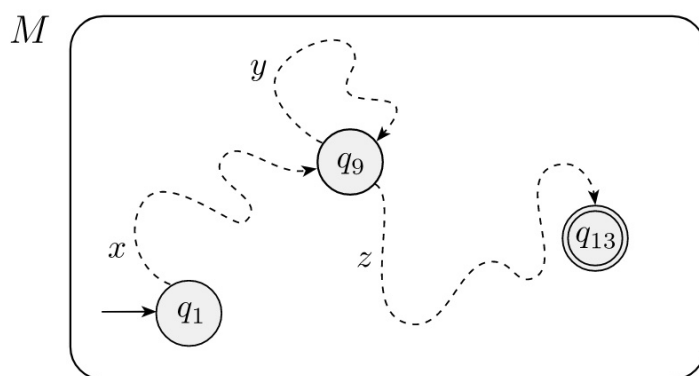
1.  $xy^iz \in A$  for all  $i \geq 0$      $y^i = yy \cdots y$  (i number of y)
2.  $y \neq \epsilon$
3.  $|xy| \leq p$

**Remark.**  $|s|$  means the length of the string  $s$ .

Informally:  $A$  is regular  $\rightarrow$  every long string in  $A$  can be pumped and the result stays in  $A$ .

**Proof.** Let DFA  $M$  recognize  $A$ . Let  $p$  be the number of states in  $M$ . Pick  $s \in A$  where  $|s| \geq p$ .

When you have a too long string, you inevitably have to revisit the same state again and again, forming the struct as following:



This is also known as The Pigeonhole Principle. ■

**Example (Prove Non-regularity).** Let  $D = \{0^k 1^k | k \geq 0\}$

**Proof.** Show:  $D$  is not regular

Proof by Contradiction:

Assume that  $D$  is regular, applying pumping lemma, let  $s = 0^p 1^p \in D$ .

Pumping lemma says that can divide  $s = xyz$  satisfying the 3 conditions.

But  $xyyz$  has excess 0s and thus  $xyyz \notin D$  contradicting the pumping lemma. ■

**Example.** Let  $F = \{ww | w \in \Sigma^*\}$ , Say  $\Sigma^* = \{0, 1\}$

**Proof.** Assume  $F$  is regular.

Try  $s = 0^p 10^p 1 \in F$ , show cannot be pumped  $s = xyz$  satisfying the 3 conditions. ■

Variant: Combine closure properties with the pumping lemma.

**Example.** Let  $B = \{w | w \text{ has equal number of 0s and 1s}\}$ .

**Proof.** Assume that  $B$  is regular.

We know that  $0^* 1^*$  is regular so  $B \cap 0^* 1^*$  is regular (closure under intersection).

But  $D = B \cap 0^* 1^*$  and we already showed  $D$  is not regular. Contradiction! ■

## 3.4 Context Free Grammars

It is a stronger computation model.



## Chapter 4

# Pushdown Automata, $\text{CFG} \leftrightarrow \text{PDA}$

### 4.1 CFG: Context Free Grammars

Using FA and regular expressions, some language such as  $\{0^n 1^n | n \geq 0\}$  can not be described.

**Context-free grammars** is a more powerful method of describing languages. Such grammar can describe certain features that have a recursive structure, which makes them useful in a variety of applications.

An important application of CFG occurs in the specification and compilation of programming languages. A number of methodologies facilitate the construction of a **parser** once a CFG is available. Some tools even automatically generate the parser from the grammar.

**Example (CFG example).** The following CFG we call  $G_1$ :

$$\begin{aligned}A &\rightarrow 0A1 \\A &\rightarrow B \\B &\rightarrow \#\end{aligned}$$

Shorthand:

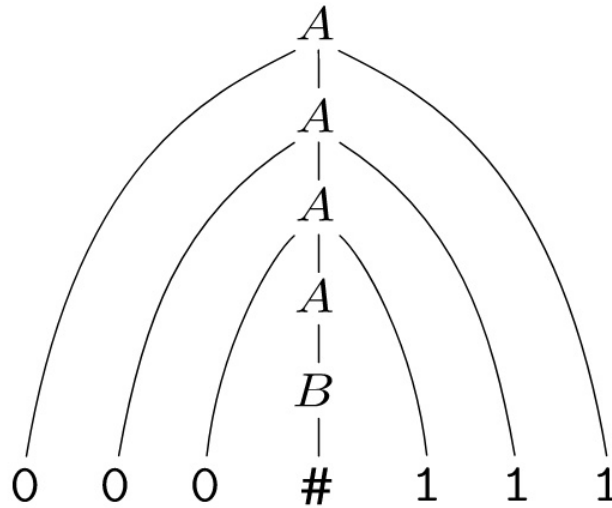
$$\begin{aligned}A &\rightarrow 0A1|B \\B &\rightarrow \#\end{aligned}$$

- It contains a collection of **substitution rules**, also called **productions**.
- Left side: **variable**, capital letters
- Right side: **terminals**, analogous to the input alphabet and often represented by lowercase letters, numbers or special symbols
- In this example,  $G_1$ 's variables are  $A$  and  $B$ , its terminals are 0, 1 and  $\#$ .

Example of using  $G_1$  to generate string 000#111:

$$A \Rightarrow 0A1 \Rightarrow 00A11 \Rightarrow 000A111 \Rightarrow 000B111 \Rightarrow 000\#111$$

The above information can be shown in a **parse tree**:



**Definition 4.1.1 (CFG).** A **context-free grammar** is a 4-tuple  $(V, \Sigma, R, S)$ , where

1.  $V$  is a finite set called the **variables**
2.  $\Sigma$  is a finite set, disjoint from  $V$ , called the **terminals**
3.  $R$  is a finite set of **rules**, with each rule being a variable and a string of variables and terminals (rule form:  $V \rightarrow (V \cup \Sigma)^*$ )
4.  $S \in V$  is the start variable

For  $u, v \in (V \cup \Sigma)^*$  write

1.  $u \Rightarrow v$  if can go from  $u$  to  $v$  with one substitution step in  $G$ .
  2.  $u \xRightarrow{*} v$  if can go from  $u$  to  $v$  with some number of substitution steps in  $G$ .
- $u \Rightarrow u_1 \Rightarrow u_2 \Rightarrow \dots \Rightarrow u_k = v$  is called a derivation of  $v$  from  $u$ .

**Definition 4.1.2 (Context Free Language).** Given  $L(G) = \{w | w \in \Sigma^* \text{ and } S \xRightarrow{*} w\}$

$A$  is a Context Free Language(CFL) if  $A = L(G)$  for some CFG  $G$ .

**Example.** We have 2 set of rules here:

$C_1$ :

$$\begin{aligned} B &\rightarrow 0B1 | \epsilon \\ B1 &\rightarrow 1B \\ 0B &\rightarrow B0 \end{aligned}$$

$C_2$ :

$$\begin{aligned} S &\rightarrow 0S | S1 \\ R &\rightarrow RR \end{aligned}$$

$C_1$  is not a CFG, because the left side is not pure variable, it has "context".

$C_2$ , on the other hand, even though we can not derive a string with all terminals, but it does not violate the rule, so  $C_2$  is a CFG.

**Example (CFG).**  $G_2$ :

$$E \rightarrow E + T|T$$

$$T \rightarrow T \times F|F$$

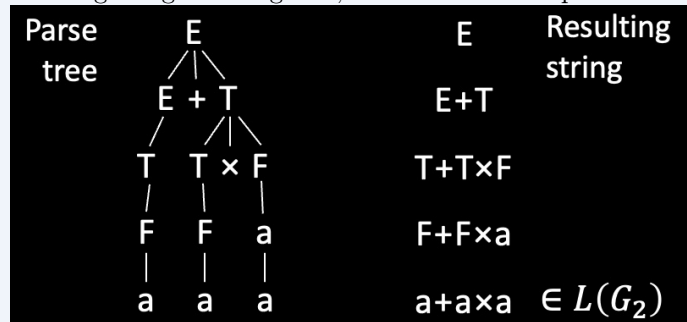
$$F \rightarrow (E)|_a$$

$$V = \{E, T, F\}$$
$$\Sigma = \{+, \times, (, ), a\}$$

$R =$  the 6 rules above

$$S = E$$

Showing the generating tree, it even shows the precedence of the operator  $\times$  is higher than  $+$ :



If a string has 2 different parse trees then it is derived **ambiguously** and we say that the grammar is ambiguous.

**Example** (Ambiguity).  $G_2$ :

$$E \rightarrow E + T|T$$

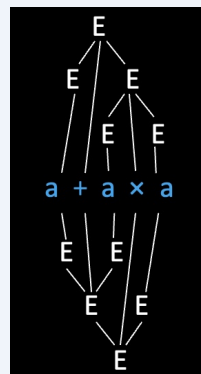
$$T \rightarrow T \times F|F$$

$$F \rightarrow (E)|_a$$

 $G_3$ 

$$E \rightarrow E + E|E \times E|(E)|a$$

Both of them recognize the same language,  $L(G_2) = L(G_3)$ , however  $G_2$  is an unambiguous CFG and  $G_3$  is ambiguous.



This tree shows the ambiguity of  $G_3$ :

## 4.2 Pushdown Automata (PDA)

The **Pushdown Automaton** operates like an NFA except can write-add(push) or read-remove(pop) symbols from the top of stack.

**Example (PDA).** PDA for  $D = \{0^k 1^k | k \geq 0\}$

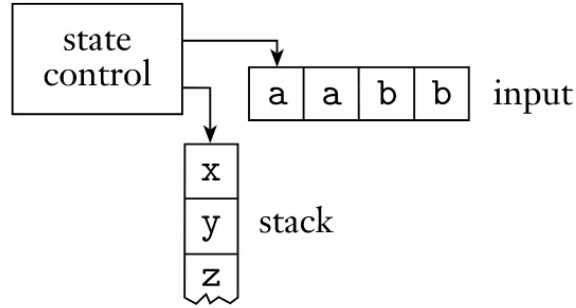


Figure 4.1: Schematic of a pushdown automaton

1. Read 0s from input, push onto stack until read 1.
2. Read 1s from input, while popping 0s from stack
3. Enter accept state if stack is empty (acceptance only at end of input)

**Definition 4.2.1 (PDA).** A **pushdown automaton** is a 6-tuple  $(Q, \Sigma, \Gamma, \delta, q_0, F)$ , where  $Q, \Sigma, \Gamma, F$  are all finite sets:

1.  $\Sigma$  input alphabet
2.  $\Gamma$  stack alphabet
3.  $\delta: Q \times \Sigma_\epsilon \times \Gamma_\epsilon \rightarrow P(Q \times \Gamma_\epsilon)$  ( $\Sigma_\epsilon = \Sigma \cup \{\epsilon\}$  and  $\Gamma_\epsilon = \Gamma \cup \{\epsilon\}$ , we allow nondeterminism here)  
Left side is the domain (the set of possible inputs to a function) of the transition function; The current state, and the reading (popping) from the top of the stack and reading from the input (can read  $\epsilon$ ) decide the input of the transition function  
Right side is the writing, the combination of the state and the writing to the top of the stack (can write  $\epsilon$ ) decide the output of the transition
4.  $q_0$ : the start state
5.  $F$ : the accept states

For a transition function like  $\delta(q, a, c) = \{(r_1, d), (r_2, e)\}$ , the current state is  $q$ , and reading an input  $a$  and popping from the stack  $c$ , then we might end up going to:

- state  $r_1$  and writing  $d$  to the top of stack
- state  $r_2$  and writing  $e$  to the top of the stack

One interesting thing about this definition is that we have no primitive to decide whether the stack is empty at the end.

The reason for that is **we don't need to!** Because we can write special symbol to the bottom of the stack at the beginning when the machine starts.

**Remark.** Should do some example here to understand deeper into the PDA.

**Theorem 4.2.1 (Equal of CFL and PDA).** A language is context free if and only if some pushdown automaton recognize it.

**Proof.** We need to prove it in 2 directions:

**Lemma 4.2.1 (CFL to PDA).** If a language is context free, then some pushdown automaton recognize it.

and:

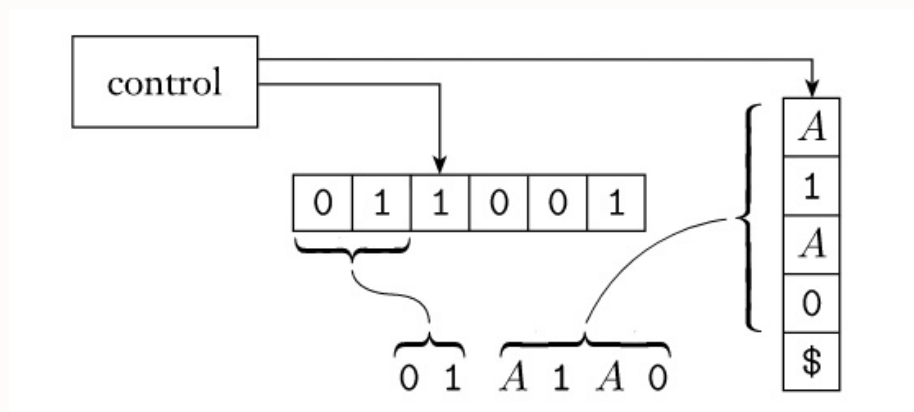
**Lemma 4.2.2 (PDA to CFL).** If a pushdown automaton recognize some language, then it is context free.

**CFL to PDA.** The idea is to use the stack to do partial substitution, and if the top of the stack matches the input string, we pop it out.

The reason that why we can always do the correct substitution is because of the nondeterminism nature of PDA, so actually we fork a lot of branches and there'll be the correct substitution in it.

Here's the informal description of the PDA P:

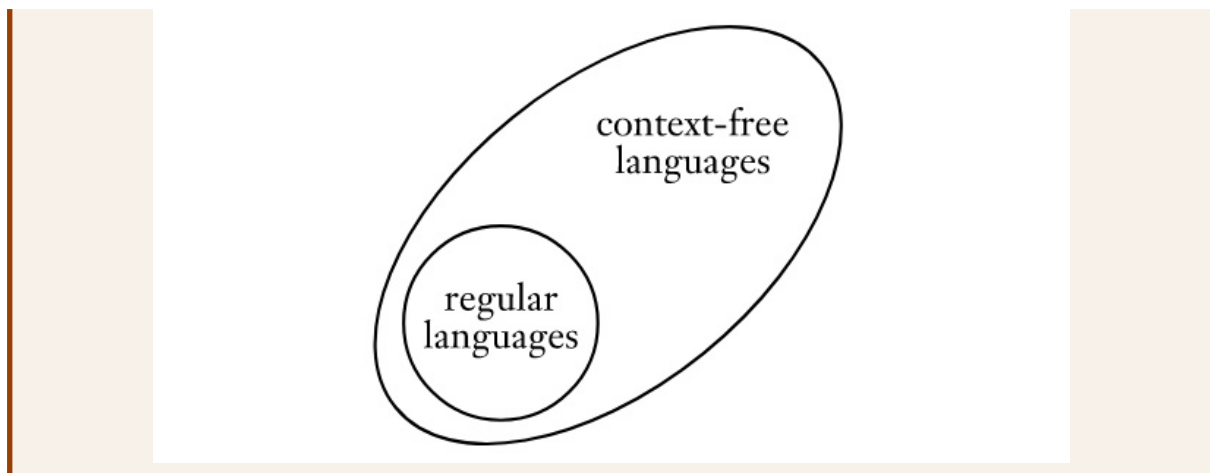
1. Place the marker symbol \$ and the start variable on the stack.
2. Repeat the following steps forever:
  - (a) If the top of the stack is a variable A, nondeterministically select one of the rules for A and substitute A by the string on the right-hand side of the rule.
  - (b) If the top of stack is a terminal symbol  $a$ , read the next symbol from the input and compare it to  $a$ . If match, repeat; if not, reject on this branch of the nondeterminism.
  - (c) If the top of stack is the symbol \$, enter the accept state. Doing so accepts the input if it has all been read.



**PDA to CFL.** I will omit this proof as it's too complicated and not included in the course. But there's a proof for that in the book for LEMMA 2.27.

Because every finite automaton is automatically a pushdown automaton that simply ignores its stack, we have:

**Corollary 4.2.1.** Every regular language is context free.



#### 4.2.1 Recap

	Recognizer	Generator
Regular language	DFA or NFA	Regular expression
Context Free language	PDA	Context Free Grammar

A Venn diagram on a black background with white outlines. It shows a large ellipse labeled "Context Free languages". Inside this ellipse, towards the bottom-left, is a smaller circle labeled "Regular languages".

Figure 4.2: Recap until now

## Chapter 5

# The CF Pumping Lemma, Turing Machines

### 5.1 Non-context-free languages

Based on [the equivalence of CFGs and PDAs](#), there are some more corollaries we can see or easy to prove:

#### Corollary 5.1.1.

Need to notice that the class of CFLs is not closed under  $\cap$  which is different from regular languages. To prove a language is not context free, we need another tool:

**Example.** Let  $B = \{0^k 1^k 2^k | k \geq 0\}$ , we will show that B is not a CFL.

The tool we'll use is **Pumping Lemma for CFLs**:

**Lemma 5.1.1** (Pumping Lemma for CFLs).

**Proof.** ■

Let's go back to the [\(example\)](#):

**Example.**

Another example:

**Example.** Let  $F = \{ww | w \in \Sigma^*\}$ .  $\Sigma = \{0, 1\}$ .

Show: F is not a CFL.

### 5.2 Turing Machines(TMs)

**Example.**

**Definition 5.2.1** (Turing Machine).

TM recognizers and deciders: