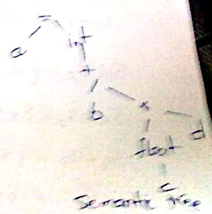
Phases of Compiler:-

1. Lexical phase (source code input → c file; tokens output)
2. Syntax phase (syntax tree, Grammar)
3. Semantic phase
4. Intermediate code generation
5. code optimization
6. Final code generation
7. error handling

Output .asm file

$a = b + c * d$ → actual $a = (int)(b + (float) c * d)$

Syntax tree



Semantic tree

Automata - machine (which says whether input is recognized or not i.e Yes/No as output)

→ Finite automata → no memory
→ Pushdown automata → one stack (memory)
→ Turing Machine → magnetic tape

} Deterministic or non-deterministic

Ⓔ Sets

Ⓔ Graphs

Ⓔ Relations

$E = \{2x : x \in N\}$

Operations

Union

Intersection

Difference

Complement

$S_1 \cup S_2 = \{x : x \in S_1 \text{ or } x \in S_2\}$

$S_1 \cap S_2 = \{x : x \in S_1 \text{ and } x \in S_2\}$

$S_1 - S_2 = \{x : x \in S_1 \text{ and } x \notin S_2\}$

$\overline{S_1} = \{x : x \notin S_1 \text{ and } x \in U\}$

Show that $S_n = \sum_{i=0}^{n} = \frac{n(n+1)}{2}$

let P(n) be statement

For P(1)

LHS $= S_1 = 1+1$ $= 1$ RHS $= \frac{1(1+1)}{2}$ $= 1$

LHS = RHS

P(1) is true

Let P(k) be true

$\sum_{i=0}^{k} = \frac{k(k+1)}{2}$

Adding k+1 on both sides

$\sum^{k} + (k+1) = \frac{k(k+1)}{2} + (k+1)$

$\sum_{i=0} = \frac{\quad}{2}$

$= \frac{(k+1)((k+1)+1)}{2}$

$\therefore$ P(k+1) is true

$\therefore$ P(n) is true $\forall n \in N$

Three Basic Concepts

Languages → Collection of strings/sentences
↓
collection of characters

Grammar

Automata

Operation on Strings

1. Reverse
2. Substring
3. Prefix
4. Suffix
5. Proper prefix
6. Proper suffix
7. Proper substring
8. Length

Let S = {computer}

rev → retupmoc

len → 8

Prefix → ϕ, co, com, comp, compu, comput, compute, computer

proper prefix → c, co, com, comp, compu, comput, compute
(except ϕ & computer(s))

Suffix → ϕ, r, er, ter, uter, puter, mputer, omputer, computer

r, er, ter, uter, puter, mputer, omputer

Operations on languages:-

→ union
→ Intersection
→ concatenation
→ star closure (kleene closure)
→ positive closure } only on language
→ reverse
→ complement

$L_1 = \{ab, c\}$ $L_2 = \{1, 23\}$

find all operations on languages

$L_1 \cup L_2 = \{ab, c, 1, 23\}$

$L_1 \cap L_2 = \phi$

$L_1 . L_2 = \{ab1, ab23, c1, c23\}$

$L_1^R = \{ba, c\}$

$\overline{L_1} = \Sigma^* - L_1$

Star closure = 0 or more occurence of L

$L_1^* = L_1^0 \cup L_1^1 \cup L_1^2 \cup L_1^3$ $\{\phi, ab, c, ...\}$

$L_1^0 = \phi$

$L_1^1 = \{ab, c\}$

$L^2 = L_1 . L_1 = \{abab, abc, cab, cc\}$

positive closure

$L_1^+ = L_1^* - \phi$

Find the language generated by $G = \{\{S\}, \{a, b\}, S, \{S \to aSb, S \to \lambda\}\}$

$S \to aSb$, $S \to \lambda$

$L = \{\lambda, ab, aabb, aaabbb, \ldots\}$

$L = \{a^n b^n : n \geq 0\}$

Derivation: the process of starting from the start symbol arriving at string of the language is called derivation.

Find the grammar for the language

$L = \{a^n b^{n+1} : n \geq 0\}$

$S \to b \mid aSb$

$G = \{\{S\}, \{a, b\}, S, \{S \to aSb \mid b\}\}$

(3) $L = \{a^n b^{2n} : n \geq 0\}$

$S \to aSbb$

$S \to \lambda$

(4) $L = \{a^{n+3} b^n\}$

(5) $G = \{\{S\}, \{a, b\}, S, \{S \to aSbb, S \to \lambda\}\}$

(4) $G = \{\{S\}, \{a, b\}, S, \{S \to aSb, S \to aaab\}\}$

$L = \{a^n b^m : n > m\}$ $L = \{a^n b^{n-3} : n \geq 0\}$

$S \to aSb \mid A$

$A \to aA \mid a$

$S \to aaA \mid aSb$

$S \to aSb \mid A$

$A \to aaa$

Generate the grammar on

$\Sigma = \{a, b\}$

(i) strings with exactly one a

(ii) string with atleast one a

(iii) no more than three a's.

(iv) atleast three a's

(1) $S \to BaB$

$B \to bB \mid \lambda$

(2) $A \to aA \mid \lambda$

$S \to ABaBA$

$B \to bB \mid \lambda$

$S \to BaBaBaB \mid BaB \mid BaBaB$

$B \to bB \mid \lambda$

$S \to$
$L = \{ w : |w| \bmod 3 = 0$ on $\Sigma = \{a\}\}$

$S \to aaaS / \lambda$

$L = \{ w : |w| \bmod 3 > 0$ on $\Sigma = \{a\}\}$

$S \to aA / \cancel{aaA}$

$A \to aaaA / \lambda$

$S \to aaaS / aa / a$

$L = \{ ww^R : w \in \{a, b\}^* \}$

$S \to aSa / bSb / \lambda$

$L = \{ w : n_a(w) = n_b(w) \}$

no of a's on w — no of b's on w

$S \to aSb / bSa / abS / baS / Sab$

or

$S \to aSb / bSa / SS / \lambda$

asb
absab

Check Derive aabb

$\Rightarrow aSb$ aabb
$\Rightarrow aSb$ ab
λ

Find the language generated by grammar

1) $S \to aA$

$A \to bS$

$S \to \lambda$

$L = \{(ab)^n \; n \geq 0\}$

2) $S \to Aa$

$A \to B$

$B \to Aa$

Undefined

(i) $S \to aSb \mid ab \mid \lambda$

(ii) $S \to aAb \mid ab$

$A \to aAb \mid \lambda$

$\Sigma = \{a, b\}$ and

$L = \{a^n b^n : n \geq 0\}$

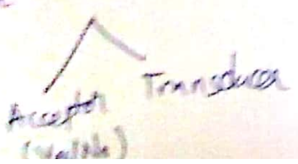
Find L^R L^2

$L^R = \{b^n a^n : n \geq 0\}$

$L^2 = \{a^n b^n a^m b^m : m, n \geq 0\}$

~~Automata~~:-

Finite Automata:



	0	1
$\rightarrow q_0$	q_0	q_1
$\circledcirc q_1$	q_0	q_2
q_2	q_2	q_1

Check if the strings

(i) 011010

$q_0 \xrightarrow{0} q_0 \xrightarrow{1} q_1 \xrightarrow{1} q_2 \xrightarrow{0} q_2 \xrightarrow{1} q_1 \xrightarrow{0} q_0$

Reject

(ii) 10011

$q_0 \xrightarrow{1} q_1 \xrightarrow{0} q_0 \xrightarrow{0} q_0 \xrightarrow{1} q_1 \xrightarrow{1} q_2$

Reject

extended transition - The default transition is

$$\delta^*(Q,\lambda) = Q$$

(i) $\delta^*(q_0, 011010) = \delta(\delta^*(q_0, 01101), 0)$

$= \delta(\delta(\delta^*(q_0, 0110), 1), 0)$

$= \delta(\delta(\delta(\delta^*(q_0, 011), 0), 1), 0)$

$= \delta(\delta(\delta(\delta(\delta^*(q_0, 01), 1), 0), 1), 0)$

$= \delta(\delta(\delta(\delta(\delta(\delta^*(q_0, 0), 1), 1), 0), 1), 0)$

$= \delta(\delta(\delta(\delta(\delta(\delta(\delta^*(q_0, \lambda), 0), 1), 1), 0), 1), 0)$

1001

(Accept)

$q_0 \xrightarrow{1} q_1 \xrightarrow{0} q_0 \xrightarrow{0} q_0 \xrightarrow{1} q_1$

1001

$\delta^*(q_0, 1001)$

$\delta(\delta^*(q_0, 100), 1)$

$\delta(\delta(\delta^*(q_0, 10), 0), 1)$

$\delta(\delta(\delta(\delta^*(q_0, 1), 0), 0), 1)$

$\delta(\delta(\delta(\delta(\delta^*(q_0, \lambda), 1), 0), 0), 1)$

$\delta(\delta(\delta(\delta(q_0, 1), 0), 0), 1)$

$\delta(\delta(\delta(q_1, 0), 0), 1)$

$\delta(\delta(q_0, 0), 1)$

$\delta(q_0, 1)$

$= q_1 \in F$

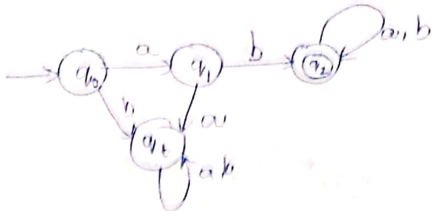
(Accepted)

The language accepted by DFA M is defined as

$$L(M) = \{ w \in \Sigma^* : \delta^*(q_0, w) \in F \}$$

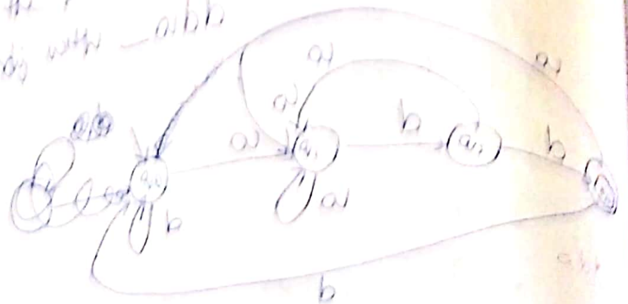
$$\overline{L(M)} = \{ w \in \Sigma^* : \delta^*(q_0, w) \notin F \}$$

Find the DFA for set of all strings of $\Sigma = \{a, b\}$ that starts with prefix ab.



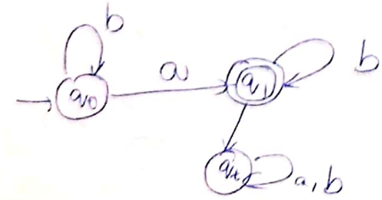
$\rightarrow q_0$	q_1	q_2
q_1	q_t	q_2
◎q_2	q_2	q_t
q_t	q_t	

Find the DFA for all the string on $\Sigma = a,b$ ending with abb

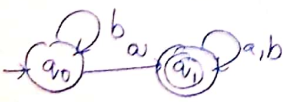


DFA on $\Sigma = \{a,b\}$ for (i) exactly one a
(ii) atleast one a
(iii) no more than three a
(iv) atleast three a

(i)



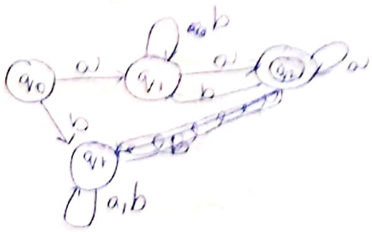
(ii)



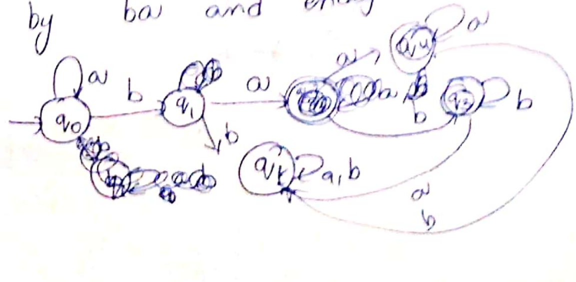
A language L is said to be regular if and only if there exist a valid DFA

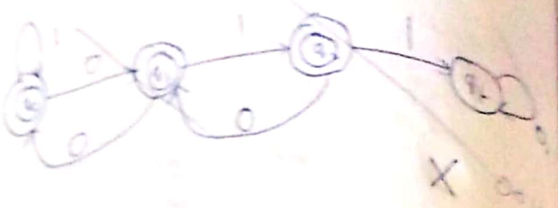
Show that

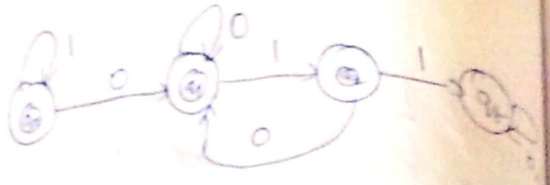
$L = \{awa,\ w \in \{a,b\}^*\}$



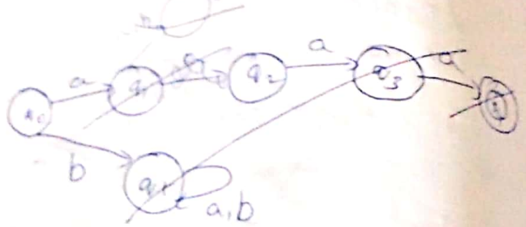
Find the DFA which accept any number of a followed by ba and ending with a or b

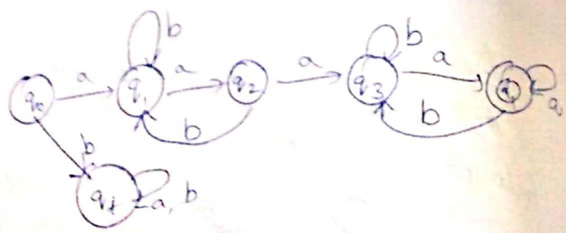






$a \; w_1 \, a \, a \, w_2 \, a$ $\quad w_1 w_2$



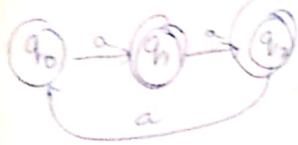


aba

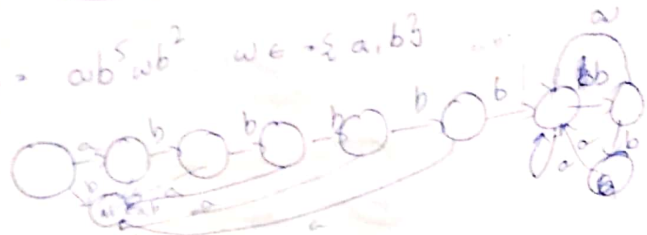
ababaa

$L = \{ |w| \bmod 2 = 0$

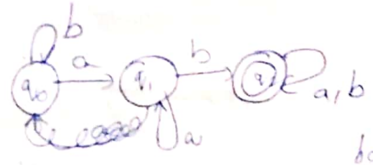
$L = \{ |w| \bmod 3 \neq 0$ on $\Sigma = \{a, b\}$



$L = ab^5 w b^2 \quad w \in \{a, b\}^*$



$L = w_1 a b w_2$



baaab

b

ab

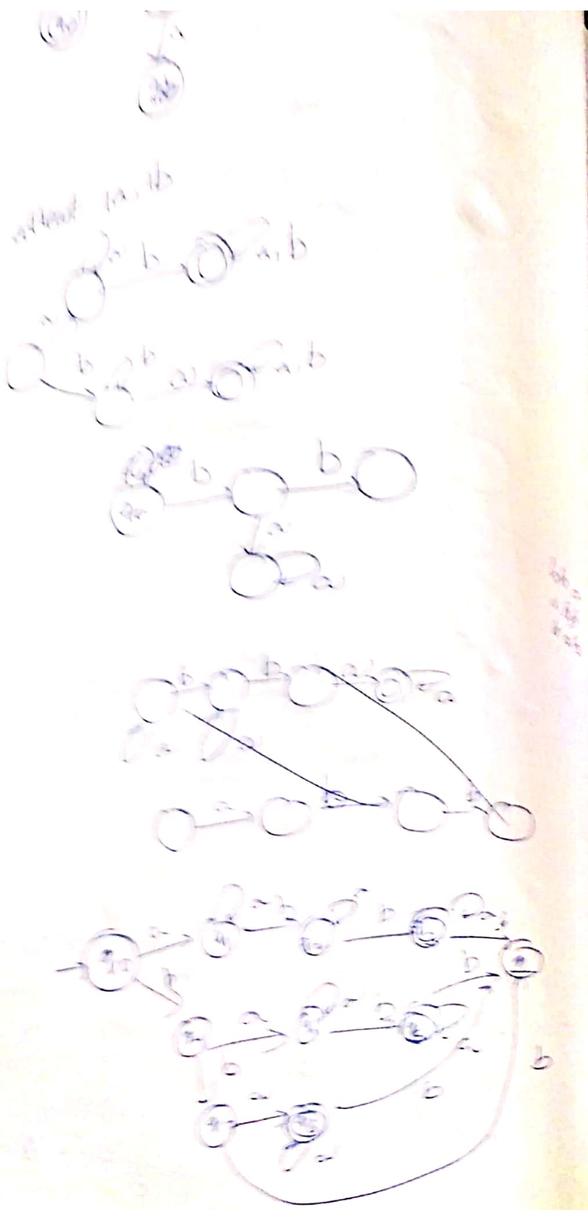
DFA for $\Sigma = \{a, b\}$ with

(i) atleast one b

(ii) with atmost a

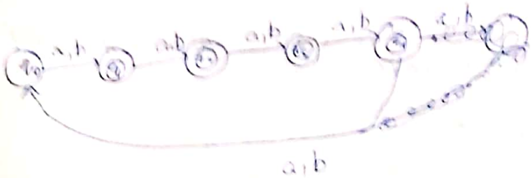
(iii) atleast one a, b

(v) atleast one a exactly two b's



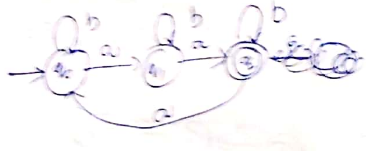
DFA for all the strings with exactly two a's and more than two b's

$L = \{w$ where $|w| \bmod 5 \neq 0$ $\{a,b\}$



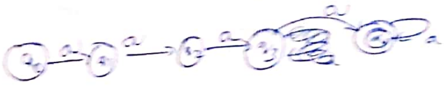
	a	b
$\rightarrow q_0$	q_1	q_1
q_1	q_2	q_2
q_2	q_3	q_3
q_3	q_4	q_4
q_4	q_1	q_1

$L = \{w$ $n_a(w) \bmod 3 > 1$ $w \in \{a,b\}$

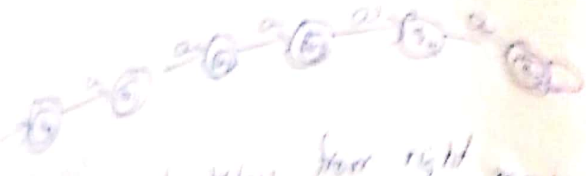


Show that

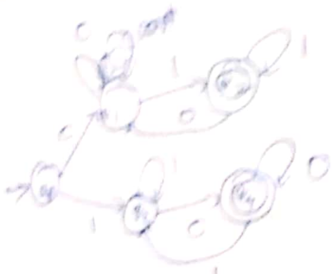
$L = \{a^n : n \geq 4\}$ on $\Sigma\{a\}$



L = 2a



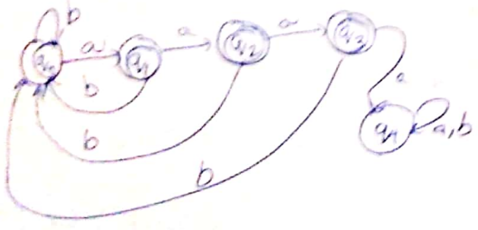
left most symbol differs from right most symbol on $\Sigma = \{0,1\}$



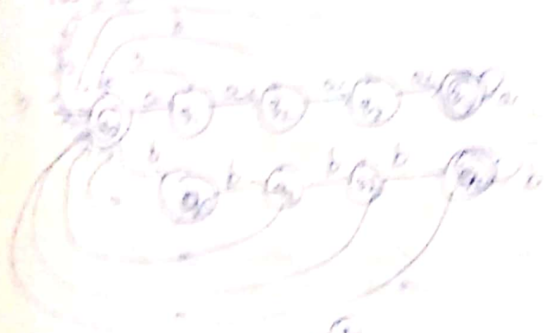
run - A run in a string is a substring of length atleast two as long as possible and consisting entirely of same symbol.

Find DFA for

$L = \{w :$ every run of a's has length either 2 or 3 on $\Sigma = \{a,b\}\}$



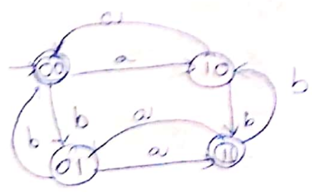
$L = \{w \mid w$ contains no runs of length less than 4 on $\Sigma = \{a,b\}\}$

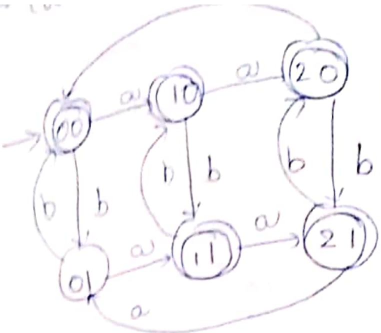


All string contains 00 but not 000 on $\Sigma = \{0,1\}$

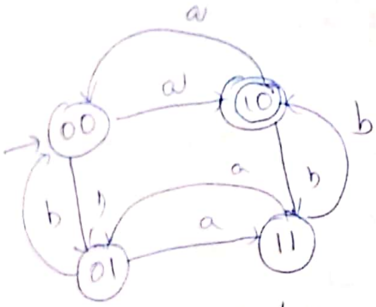
$L = \{ n_a(w) \bmod 2 = n_b(w) \bmod 2 \}$ $\Sigma = \{a,b\}$

modulo logic -

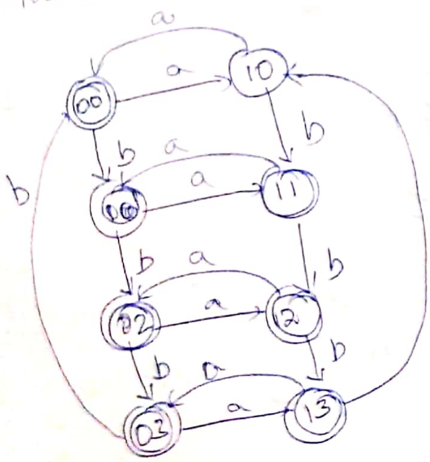




$n_b(w)$ mod odd a's even



$n_a(w) \% 2 \leq n_b(w) \% 4$



Draw DFA to accept the binary strings divisible by 5.

101
1010
1111

1010
− 101
101

Division by k

$j = ((r*i)+d) \% k$

r → radix, i → states, d → digits

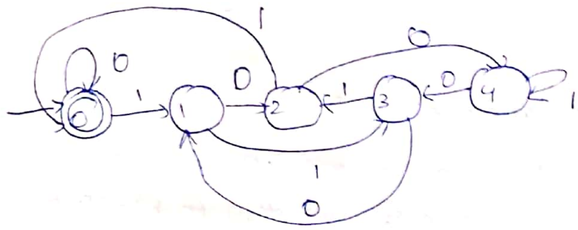
$k = 5$

$i = 0,1,2,3,4$

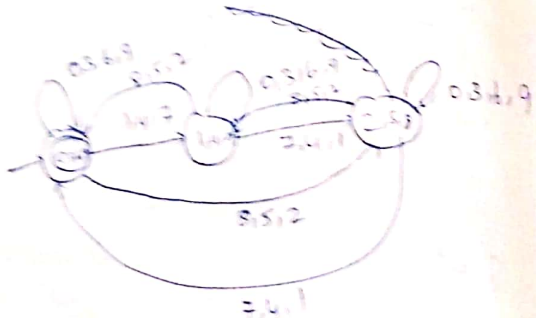
d

i	d	j
0	0	0
	1	1
1	0	2
	1	3
2	0	4
	1	0
3	0	1
	1	2
4	0	3
	1	4

$\delta = (q_i, d) = q_j$



DFA to accept the decimal digits divisible by 3



Regular expression (RE):-

- $*$ → zero or more occurrences a^*
- $\cdot$ → concatenation $(a.b)$ → a followed by b
- $+$ → or $(a+b)$ → a or b

1. ϕ, λ, a are primitive regular expressions.
2. $r_1^*, r_1+r_2, r_1.r_2, (r_1)$ are also regular expressions if r_1 is a regular expressions

Find the language generated by regular expression

$L(a+bc) = L(a) + L(b.c)$

$= \{a\} + \{bc\}$

$L(r_1^*) = (L(r_1))^*$

$L(a^*(c+b)c^*)$

$L(a^*) . L(c+b) . L(c^*)$

$\{L(a)\}^* . L(c)+L(b) . \{L(c)\}^*$

$a^* . c+b . c^*$

$\{\lambda, a, aa\}$ $\{c, b\}$ $\{c, cc, \ldots\}$

$(ab)^* \neq a^*b^*$

$L((ab)^*)$

$\{L(ab)\}^*$

$\{L(a).L(b)\}^*$

$(ab)^*$

$\{\lambda, ab, abab, \ldots\}$

$L(a^*).L(b^*)$

$\{L(a)\}^* \{L(b)\}^*$

$a^* . b^*$

$\{a, aa, \ldots\} . \{\lambda, b, bb, \ldots\}$

length

$l = (a+b)^*$

$(a+b)^* = (a^*.b^*)^*$

Set of strings a and b ending

$(a+b)^*.abb$

{a,b} starts with ba

$ba.(a+b)^*$

$\Sigma = \{a,b\}$ having aa

$(a+b)^* aa (a+b)^*$

any numbers of a, any number of b, followed by c

$a^*b^*c^*$

atleast one a followed by atleast b follo..

$\cancel{(a+b+c)^* a (a+b+c)^* b (a+b+c)^* c}$

$aa^*bb^*cc^*$ (or) $a^+b^+c^+$

String a, b either a or bb

$(a+b)^*.(a+bb)$

even no of a's followed by odd no of b's

$aa+b$

$(aa)^*((bb)^*b+b)$ or $(aa)^* b (bb)^*$

1 or 0 followed by any number of 1's

$(1+0).1^*$

$\Sigma = \{0,1\}$ without any consecutive 1's

$1+10$

$(10+0)^*(1+\lambda)$

all strings with even zeroes on $\Sigma\{0,1\}$

$(1^*01^*01^*)^* + 1^*$

$\Sigma = \{a,b\}$ of length 2

$aa+bb+ab+ba$

(or)

$(a+b)(a+b)$

even length

$((a+b)(a+b))^*$

$(\cancel{(a+b)(a+b)(a+b)}^* + (a+b))$

odd length

$((a+b)(a+b))^* (a+b)$

String a's and b's with alternate

$(ab)^* + (ba)^*$

+00

(or)

$(+ \ldots + \lambda)\ (0-9)^+$

Set of floating point

$(+|-|\lambda)\ .\ (0-9)^*\ .\ (.)\ (0-9)^+$

$? \to 0$ or 1 occurrence of previous symbol
or preceeding

All strings with exactly on exactly a on $\Sigma = a, b, c$

$(b+c)^* a\ (b+c)^*$

All strings with no more than 3 a's on $\Sigma\, a, b, c$

$(b+c)^*\ a?\ (b+c)^* a?\ (b+c)^* a?\ (b+c)^*$

$L = \{w : |w| \bmod 3 = 0\}$

$((a+b)(a+b)(a+b))^*$

$L = \{w : n_a(w)\ \%\ 3 = 0)$

$(b^*ab^*ab^*ab^*)^* + b^*$

$L = \{a^n b^m : n, m \geq 1\ \ nm \geq 3\}$

$a^+bbb^+ + aab\,b^+ + aaa^+b^+$

$L = \{ab^n w$ where $n \geq 3$ $w \in a, b^*$

$abbb(a+b)^*$ ✓

$abbb^+(a+b)^*$

$L = \{a^n b^m : n < 4, m \leq 3\}$

$a?a?a?\,b?b?b?$

$L = \{a^n b^m : n \geq 4\ m \leq 3\}$

$aaaa^+\,b?b?b?$

$L = \{a^n b^m$ $m+m$ is even$\}$

$(aa)^*(bb^*) + a(aa)^*.\,b(bb)^*$

$L = \{w : n_a(w)\ \%\ 3\ != 0\}$

$\Sigma = \{a, b\}$

$b^*ab^*a?\,b^*)$

~~b^*ab+a~~

$b^*ab^*ab^*a$ $*$

$(a+b)\ (\cancel{(a+b)(a+b)(a+b)})$

$+ (a+b)(a+b)\ ((a+b)(a+b)(a+b))^*$

~~$(b^*ab^*)(b^*ab)?$~~

$b^*ab^*a?b^*$

Strings of zeroes & ones with at most one pair of consecutive zeroes.

$1^*\ (01^*)^* 1^* (00+\lambda)\ 1^* (10)^*\ 1^*$

$(1+01)^*\ (\lambda+0+00)\ (1+10)^*$

Scanned by CamScanner

$(1+0)^* \, 000 \, (1+0)^*$

a^*bc DFA

$(ab)^* b$

$(a+b)^* ba$

$(a^*b^*)^*$

$b(a+b)^*$

NFA

Nondeterministic finite acceptor

$M = (Q, \Sigma, \delta, q_0, F)$ is defined as

Q = represent of finite set of internal states

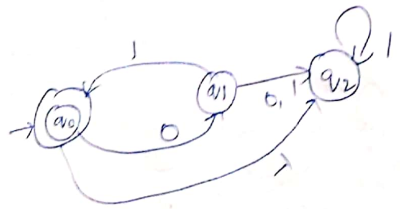
Σ = finite set of input symbols

δ = It is a transition function denoted as

$Q \times \{\Sigma \cup \lambda\} \rightarrow 2^Q$

$q_0 \in Q$ denoting starting state

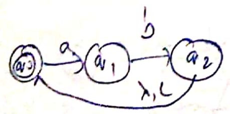
$F \rightarrow$ it is a subset of Q denoting final states



	0	1
q_0	q_1	ϕ
q_1	q_2	q_0, q_2
q_2	ϕ	q_2

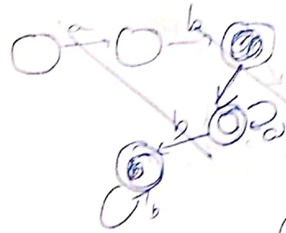
Write NFA with three states that accepts

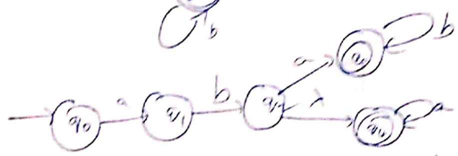
$\{ab, abc\}^*$



NFA with no more than five states to accept

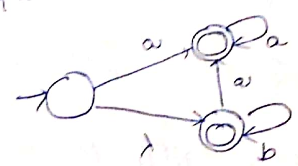
$\{abab^n \; n \geq 0\}$ $\{aba^n \; n \geq 0\}$





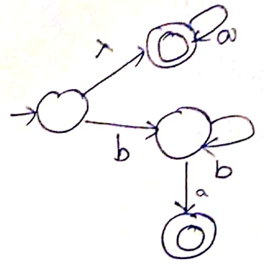
NFA with three states with three states

$L = \{a^n : n \geq 1\} \cup \{b^m a^k \; m \geq 0, k \geq 0\}$

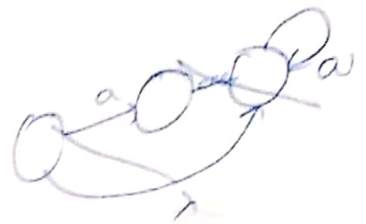


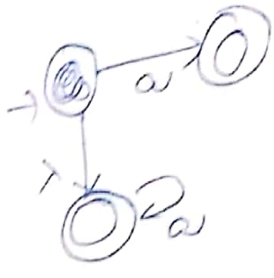
NFA with four states for the language

$L = \{a^n : n \geq 0\} \cup \{b^n a \; n \geq 1\}$

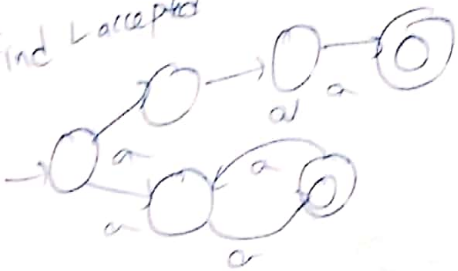


Draw NFA that accept a ... removed that resulting only a





Find L accepted



$a^3 \cup$

$a^2 a^3$

$a^3 \cup a^{2n}$

$L = \{ a^3 \cup a^{2n} : n \geq 1 \}$

The language accepted by NFA 'M' is defined as

$L(M) = \{ w \in \Sigma^* : \delta^*(q_0, w) \cap F \neq \phi \}$

Regular expression to NFA :-

RE $\to$ Thompson's Algorithm

$\downarrow$

NFA $\to$ subset construction

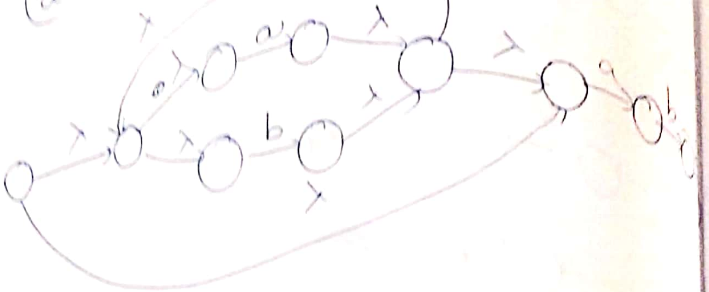
$\downarrow$

DFA $\to$ Tabulation

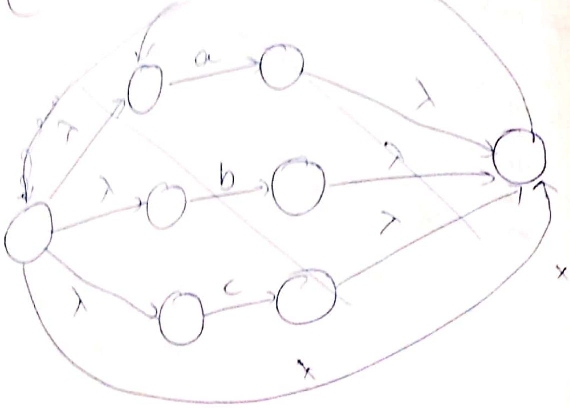
$\downarrow$

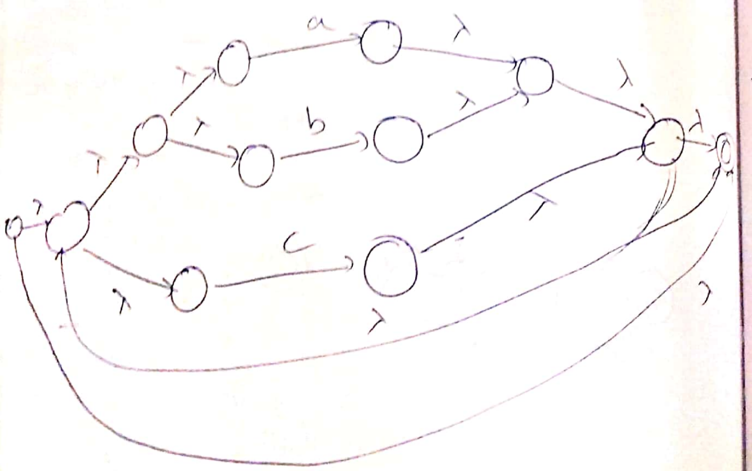
minimized DFA

$(a+b)^* abb$

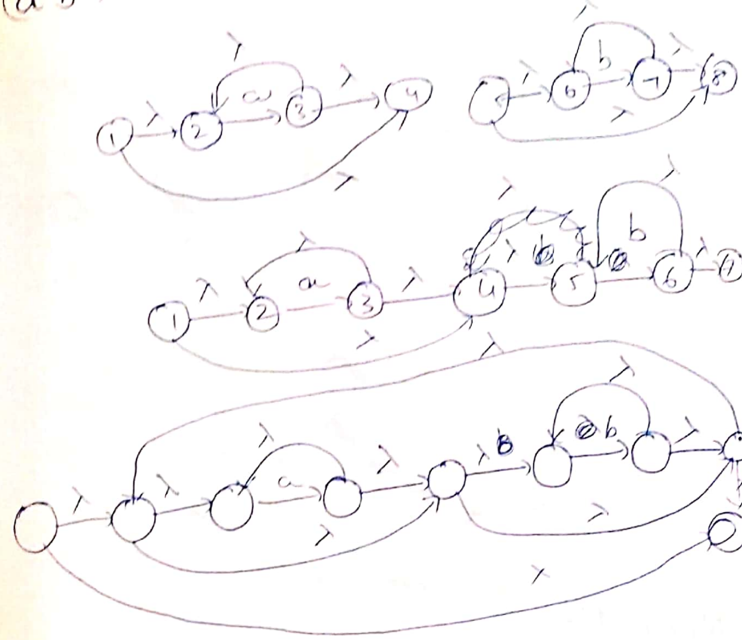


$(a+b+c)^*$

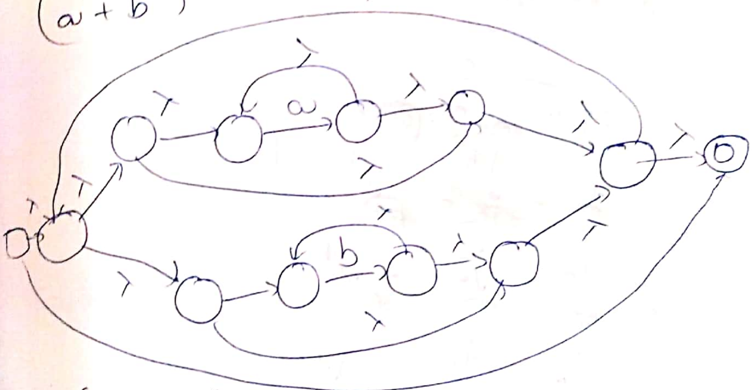




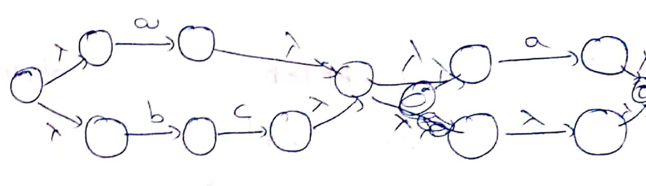
$(a^* b^*)^*$



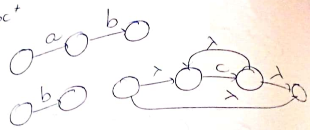
$(a^* + b^*)^*$

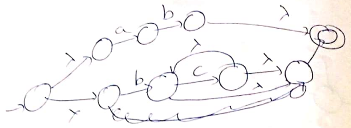


$(a+bc)(a+\lambda)$



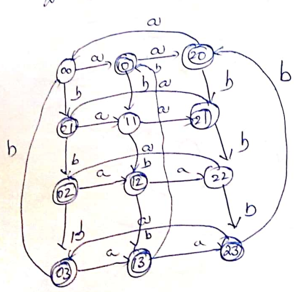
$ab + bc^*$





② Obtain a DFA

$L = \{w : n_a \bmod 3 \neq n_b(w) \bmod 4\}$



③ $S \to aAb \mid ab$

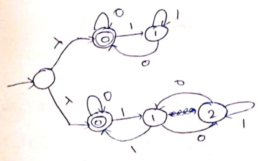
$A \to aAb \mid \lambda$

$L = \{a^n b^n : n \geq 1\}$

ab, aabb

aAb
aaAbb

Write DFA (NFA) that only binary which are divisible by 2 or 3.



$j = (r * i) + d \bmod k$

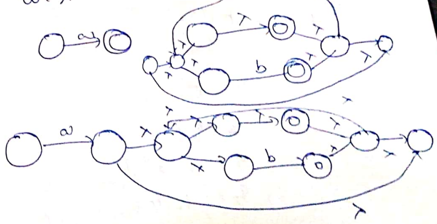
0	0	0
1	1	1
2	0	2
	1	0
	0	1
	1	2

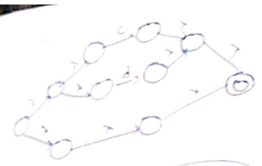
$L = \{a^{2n} b^{2m+1} \quad n, m \geq 0\}$

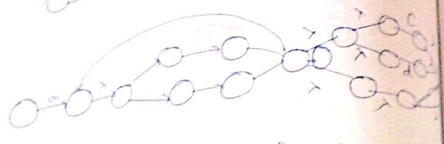
$(aa)^*(bb)^* b$

Construct NFA for

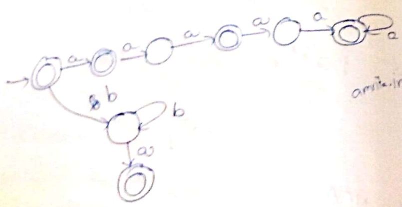
$a(\lambda + b)^* (c + d + \lambda)$





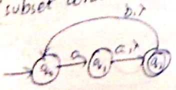


$L = \{a^n : n \neq 2 \text{ and } n \neq 4\} \cup \{b^n a : n \geq 1\}$

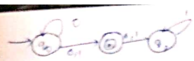


omite input

NFA to DFA:-
(subset construction)



λ-closure q_0 $\{q_0\}$
$q_1 = \{q_1, q_2, q_0\}$
$q_2 = \{q_2, q_0\}$



λ-closure on $q_0 = \{q_0\}$
$q_1 = \{q_1\}$
$q_2 = \{q_2\}$

λ-closure $(\delta(q_0, 0))$
λ-closure $(\delta(q_0, 1)\}$
λclosure $(q_0, q_1) = \{q_0, q_1\}$ ✓
λclosure $\{q_1\} = \{q_1\}$ ✓

λclosure $(\delta(\{q_0 q_1\}, 0)) = \{q_0, q_1, q_2\}$ ✓
λclosure $(\delta(\{q_0 q_1\}, 1)\} = \lambda_c\{q_1, q_2\} = \{q_1, q_2\}$

$\lambda_{c1}(\delta(q_1, 0)) = \lambda_{c1}\{q_2\} = \{q_2\}$
$\lambda_{c1}(\delta(q_1, 1)\} = \lambda_{c1}(q_2\} = \{q_2\}$

$\lambda(\delta(q_0 q_1 q_2, 0)\} = \lambda_{c1}(\{q_0, q_1\}, q_2\}$
$= \{q_0, q_1, q_2\}$

~~$\lambda\{\delta(q_1 q_2, 1)\} = \lambda_{c1}\{q_2\}$~~

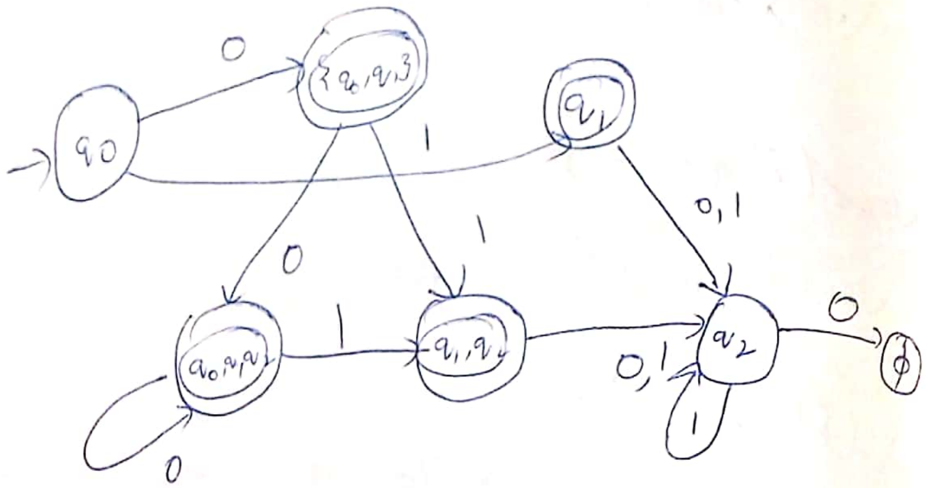
$\lambda(\delta(q_0 q_1, q_2, 1) = \lambda_{c1}\{q_1, q_2\}$
$= \{q_1, q_2\}$

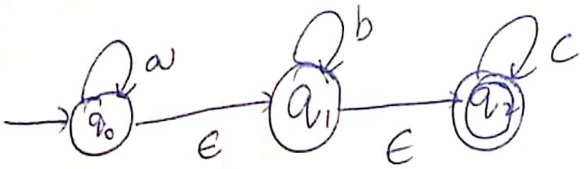
$\lambda_{c1}(\delta(q_1, q_2), 0) = \lambda_{c1}(q_2) = \{q_2\}$
$\lambda_{c1}(\delta(q_1, q_2), 1) = \lambda_{c1}(q_2) = \{q_2\}$

$\lambda_1 \delta(q_2, 0)$ -

$\lambda_1(\delta(q_2, 1) = \{q_2\}$

	0	1
q_0	$\{q_0, q_1\}$	$\{q_1\}$
$\{q_0, q_1\}$	$\{q_0, q_1, q_2\}$	$\{q_1, q_2\}$
q_1	$\{q_2\}$	$\{q_2\}$
q_0, q_1, q_2	q_0, q_1, q_2	$\{q_1, q_2\}$
q_1, q_2	q_2	q_2
q_2	ϕ	$\{q_2\}$





$\lambda_{c1}\{q_0\} = \{q_0, q_1, q_2\} \rightarrow A$

$\lambda_{c1}\{q_1\} = \{q_1, q_2\}$

$\lambda_{c1}\{q_2\} = \{q_2\}$

~~$\lambda_{c1}(\delta(q_0, q_1, q_2), a) = \lambda_{c1}\{q_0, q_1, q_2\}$~~

$\lambda_{c1}(A, a) \rightarrow \{q_0, q_1, q_2\}$

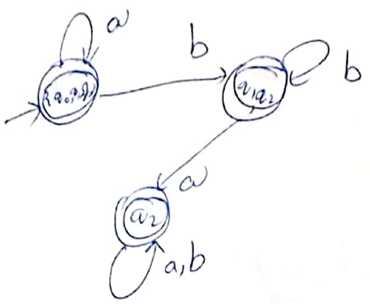
$\lambda_{c1}(A, b) \rightarrow \lambda_{c1}\{q_1\} = \{q_1, q_2\}$

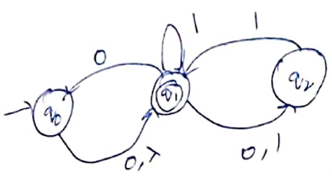
$\lambda_{c1}(A, c) \rightarrow \lambda_{c1}\{q_2\} = \{q_2\}$

$\{q_1, q_2\}, a)$ -

$\{q_1, q_2\}, b = \lambda_1(q_1, q_2\}$

$= \{q_1, q_2\}$





$\lambda_{c1}(q_0) = \{q_0, q_1\}$

$\lambda_{c1}(q_1) = \{q_1\}$

$\lambda_{c1}(q_2) = \{q_2\}$

$\lambda_{c1}((q_0, q_1), 0) = \lambda_c\{q_1, q_2\}$

$= \{q_1, q_2\}$

	0	1
$\{q_0, q_1\}$	$\{q_1, q_2\}$	$\{q_1$
$\{q_0, q_1, q_2\}$	$\{q_0, q_1, q_2\}$	$\{q$
$\{q_1, q_2\}$	$\{q_0, q_1, q_2\}$	$\{q$

$\lambda_{c1}((q_0, q_1), 1) = \lambda_{c1}\{q_1, q_2\}$

$= \{q_1, q_2\}$

$\lambda_{c1}(q_0, q_1, q_2, 0) = \{q$

$= \{q$

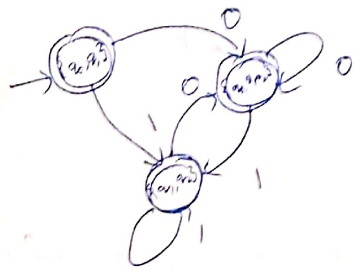
$\cancel{\lambda_{c1}\{(q_1, q_2), 0) = \{q_2\}}$

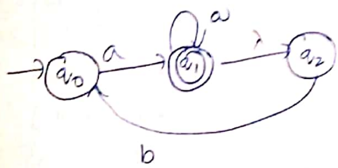
$\cancel{\lambda_{c1}((q_1, q_2), 1\} = \lambda_c\{q_1, q_2}$

$\lambda_{c1}\{(q_0, q_1, q_2), 1)$

$\lambda_{c1}(\{q_1, q_2\}, 0) = \{q$

$\lambda_{c1}\{(q_0, q_1), 0) = \{q_1\}$





$\lambda_{c1}\{q_0\} = \{q_0\}$

$\lambda_{c1}\{q_1\} = \{q_1\}$

$\lambda_{c1}\{q_2\} = \{q_2\}$

	a	b
$\{q_0\}$	$\{q_1, q_2\}$	ϕ
$\{q_1, q_2\}$	$\{q_1, q_2\}$	q_0

$\lambda_{c1}\{q_0, a) = \lambda_c\{q_1\}$

$= \{q_1, q_2\}$

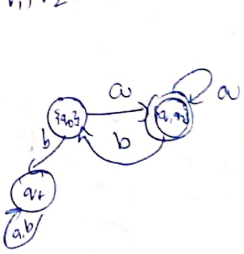
$\lambda_c\{q_0, b) = \phi$

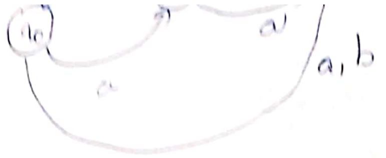
$\lambda_{c1}\{\{q_1, q_2\}, a\} = \{q_1\} = \{q_1, q_2\}$

$\lambda_{c1}\{q_1, q_2, b\} = \lambda_c\{q_0\} = q_0$

a — b —

b —





$\lambda_{c}\{q_0\} = \{q_0\}$

$\lambda_{c}\{q_1\} = \{q_1\}$

$\lambda_{c}\{q_2\} = \{q_2\}$

$\lambda_{c}\{q_0, a\} = \{q_1, q_2\}$

$\lambda_{c}\{q_0, q_1\} = \{q_2\}$

$\lambda_{c}\{(q_1, q_2), a\} = \{q_1, q_2\}$

$\lambda_{c}\{(q_1, q_2), b\} = \{q_0, q_1\}$

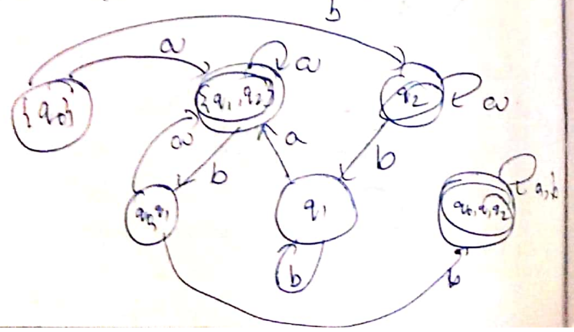
$\{q_2, a\} = \{q_2\}$

$\{q_2, b\} = \{q_2\}$

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

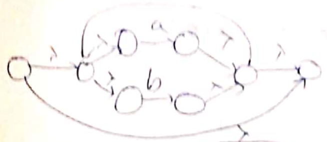
$\{(q_0, q_1), b\} = \{q_2, q_0, q_1\}$

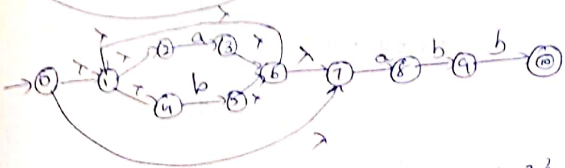
		a	b
A	$\{q_0\}$	$\{q_1, q_2\}$	$\{q_2\}$
B	$\{q_1, q_2\}$	$\{q_1, q_2\}$	$\{q_0, q_1\}$
C	$\{q_2\}$	$\{q_2\}$	$\{q_2\}$
	$\{q_0, q_1\}$	$\{q_1, q_2\}$	$\{q_0, q_1, q_2\}$
	$\{q_1\}$	$\{q_1, q_2\}$	[illegible]
	$\{q_0, q_1, q_2\}$	$\{q_0, q_1, q_2\}$	[illegible]



Convert the regular expression

$(a+b)^* abb$





$\lambda_{c}(0) = \{0, 1, 7, 2, 4\} = \{0, 1, 2, 4, 7\} \rightarrow A$

$\lambda_{c}(1) = \{1, 2, 4\}$

$\lambda_{c}(2) = \{2\}$

$\lambda_{c}(3) = \{3, 6, 1, 2, 4, 7\} = \{1, 2, 3, 4, 6, 7\}$

$\lambda_{c}(4) = \{4\}$

$\lambda_{c}(5) = \{5, 6, 1, 7, 2, 4\} = \{1, 2, 4, 5, 6, 7\}$

$\lambda_{c}\{6\} = \{6, 7, 1, 2, 4\} = \{1, 2, 4, 6, 7\}$

$\lambda_{c}\{7\} = \{7\}$

$\lambda_{c}\{8\} = \{8\}$

$\lambda_{c}(9) = \{9\}$

$\lambda_{c}(10) = \{10\}$

$\lambda_{c}(0, 1, 2, 4, 7, a) = \lambda_{c}\{3, 8\}$
$= \{1, 2, 3, 4, 6, 7, 8\} \rightarrow B$

$\lambda_{c}(0, 1, 2, 4, 7, b) = \lambda_{c}\{5\}$
$= \{1, 2, 4, 5, 6, 7\} \rightarrow C$

→B D	B	D
E	B	C
	B	C

$\lambda_{cl}\{1,2,3,4,6,7,8,b\} = \lambda_{cl}\{5,9\}$

$= \{1,2,4,5,6,7,9\}$

$\to D$

$\lambda_{cl}(1,2,4,5,6,7,a\} = \lambda_{cl}\{3,8\}$

$= B$

$\lambda_{cl}(1,2,4,5,6,7,b\} = \lambda_{cl}\{5\}$

$= \{$

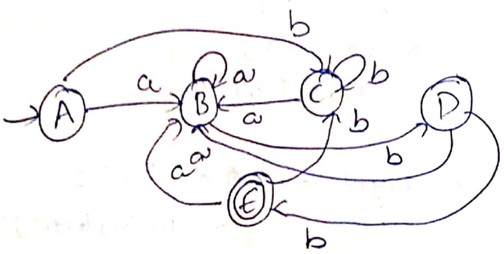
$\lambda_{cl}(1,2,4,5,6,7,9,a\} = \lambda\{3,8\}$

$\lambda_{cl}(1,2,4,5,6,7,9,b\} = \lambda_{cl}\{5,10\}$

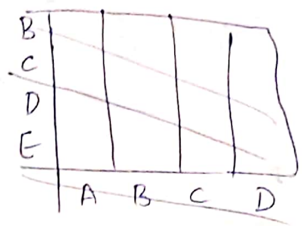
$= \{1,2,4,5,6,7,10\}$

$\lambda_{cl}\{1,2,4,5,6,7,10,a\} = B$

$\lambda_{cl}\{1,2,4,5,6,7,10,b\} = \{5\}$



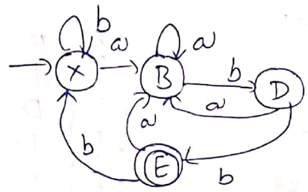
Mark & Reduce or Tabulation method -



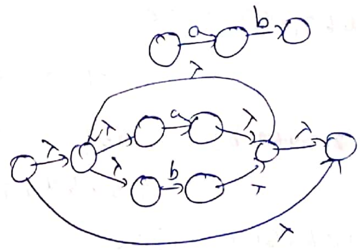
B	X			
C		X		
D	X	X	X	
E	X	X	X	X
	A	B	C	D

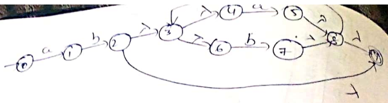
$x = \{A, C\}$

x	a	b
→X	B	X
B	B	D
D	B	E
E	B	X



$ab(a+b)^*$





$\lambda_{cl}\{0\} = \{0\} \to A$

$\lambda_{cl}(1) = \{1\}$

$\lambda_{cl}(2) = (2, 3, 4, 6, 9\}$

$\lambda_{cl}(3) = \{3, 4, 6\}$

$\lambda_{cl}(4) = \{4\}$

$\lambda_{cl}(5) = \{5, 8, 3, 4, 6, 9\} = \{3, 4, 5, 6, 8, 9\}$

$\lambda_{cl}(6) = \{6\}$

$\lambda_{cl}(7) = \{7, 8, 3, 4, 6, 9\} \to \{3, 4, 6, 7, 8, 9\}$

$\lambda_{cl}(8) = \{8, 9, 3, 4, 6\} \to \{3, 4, 6, 8, 9\}$

$\lambda_{cl}(9) = \{9\}$

$\lambda_{cl}(0, a) = \{1\} \to B$

$\lambda_{cl}(0, b) = \phi$

$\lambda_{cl}(1, a) = \phi$

$\lambda_{cl}(1, b) = \lambda\{2\}$

$= \{2, 3, 4, 6, 9\} \to C$

	a	b
→ A	B	ϕ
B	ϕ	C
• C	D	E
• D	D	E
• E	D	E

$\lambda_{cl}\{2, 3, 4, 6, 9, a\} = \lambda_{cl}\{5\}$

$= \{3, 4, 5, 6, 8, 9\} \to D$

$\lambda_{cl}\{2, 3, 4, 6, 9, b\} = \lambda_{cl}\{7\}$

$= \{3, 4, 6, 7, 8, 9\}$

$\lambda_{cl}\{3, 4, 5, 6, 8, 9\} = \lambda_{cl}\{5\}$

$\lambda_{cl}\{3, 4, 5, 6, 8, 9\} \to \lambda_{cl}\{7\}$

$\lambda_{cl}\{3, 4, 6, 7, 8, 9, a\} = \lambda_{cl}\{5\}$

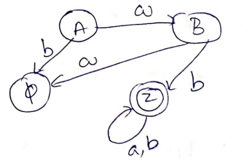
B				
C				
D				
E				
	A	B	C	D

B	X			
C	X	X		
D	X	X		
E	X	X		
	A	B	C	D

	a	b
A	B	ϕ
B	ϕ	Z
Z	Z	Z

$\lambda_2(, t$

DE = D,*



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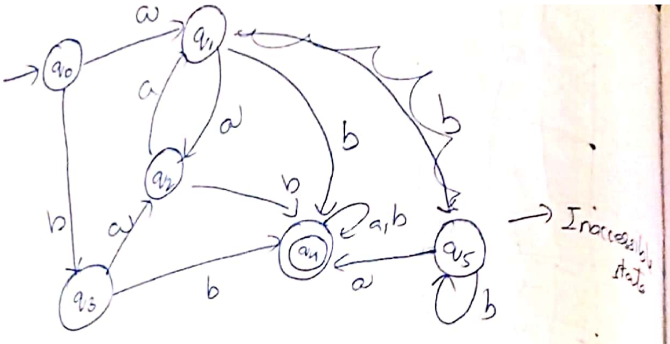
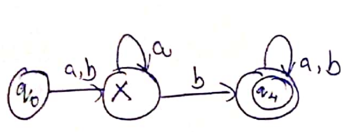


	a	b
→ q0	q1	q3
q1	q2	q4
q2	q1	q4
q3	q2	q4
⊙ q4	q4	q4
~~q5~~	q4	q5

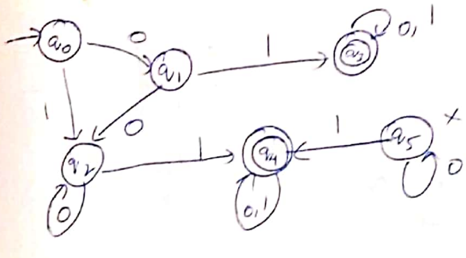
q1	X			
q2	X			
q3	X			
q4	X	X	X	X
	q0	q1	q2	q3

X→q1, q2, q3   q2, q3

q4→



	a	b
q0	X	X
X	X	q4
q4	q4	q4

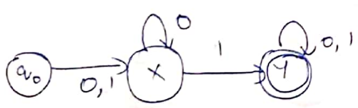


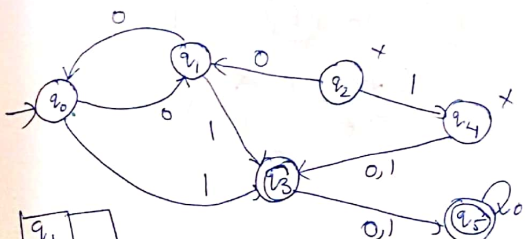
	0	1
→ q0	q1	q2
q1	q2	q3
q2	q2	q4
⊙ q3	q3	q3
⊙ q4	q4	q4

q1	X			
q2	X			
q3	X	X	X	
q4	X	X	X	
	q0	q1	q2	q3

X → q1, q2   Y → q3, q4

	0	1
q0	X	X
X	X	Y
Y	Y	Y





q1			
q3	X	X	
q5	X	X	
	q0	q1	q3

X → {q0, q1}

Y → {q3, q5}

	0	1
→ q0	q1	q3
q1	q0	q3
⊙ q3	q5	q5
⊙ q5	q5	q5

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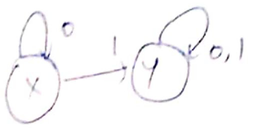
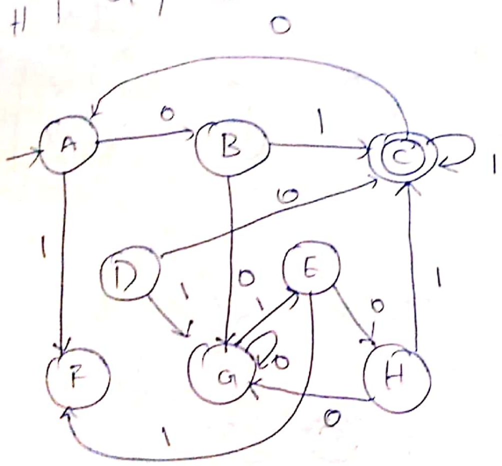


X	X	
Y	Y	Y
		Y

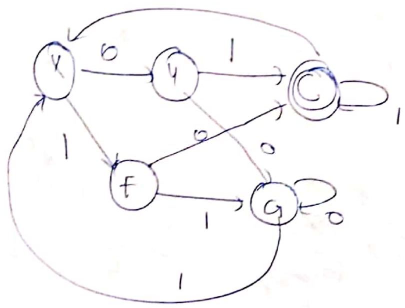
	0	1
→ A	B	F
B	G	C
C	A	C
~~D~~	~~C~~	~~G~~
E	H	F
F	C	G
G	G	E
H	G	C



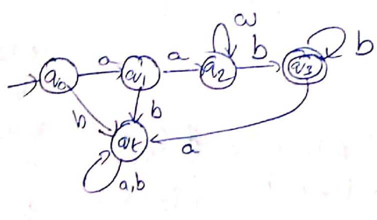
B	X					
C	X	X				
E		X	X			
F	X	X	X	X		
G	X	X	X	X	X	
H	X		X	X	X	X
	A	B	C	E	F	G

X → A, E
Y → B, H

	0	1
X	Y	F
Y	G	C
C	X	C
F	C	G
G	G	X



L: $\{a^n b^m : n \geq 2, m \geq 1\}$

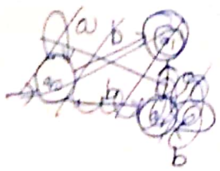


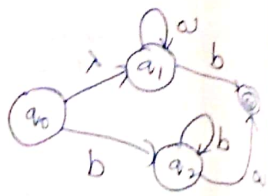
	a	b
q_0		ϕ
$\rightarrow q_0$	q_1	ϕ
q_1	q_2	q_3
q_2	q_2	q_3
$\circledcirc q_3$	ϕ	q_3

q_1	X		
q_2	X	X	
q_3	X	X	X
	q_0	q_1	q_2

Find minimal DFA

$L = \{a^n b \quad n \geq 0\} \cup \{b^m a \quad m \geq 1\}$





$\lambda_{cl}\{q_0\} = \{q_0, q_1\}$

$\lambda_{cl}\{q_1\} = \{q_1\}$

$\lambda_{cl}\{q_2\} = \{q_2\}$

$\lambda_{cl}\{q_3\} = \{q_3\}$

$\lambda_{cl}(\{q_0, q_1\}, a) = \{q_1\}$

$\lambda_{c}(\{q_0, q_1\}, b) = \{q_2, q_3\}$

	a	b
$\{q_0, q_1\}$	q_1	$\{q_2, q_3\}$
q_1	q_1	q_3
$\{q_2, q_3\}$	q_3	q_2
q_3	ϕ	ϕ
q_2	q_3	q_2

Indistinguishable -

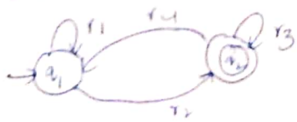
Two states p and q of a DFA are indistinguishable if $\delta^*(p, \omega) \in F$ and $\delta^*(q, \omega) \in F$ (or)

$\delta^*(p, \omega) \notin F$ and $\delta^*(p, \omega) \notin F \quad \forall \omega \in \Sigma^*$

Two states p and q of a DFA are distinguishable if $\delta^*(p, \omega) \in F$ and $\delta^*(q, \omega) \notin F$ or

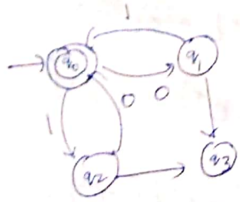
$\delta^*(p, \omega) \notin F$ and $\delta^*(p, \omega) \in F \quad \forall \omega \in \Sigma^*$

Finite Automata to Regular expression

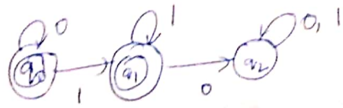


~~$((r_1^* r_2 r_4)^* + r_3^*)^*$~~

$r_1^* r_2 [r_3 + r_4 r_1^* r_2]^*$

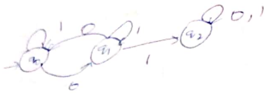


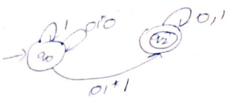
$((01)^* + (10)^*)^*$



$0^* 1 ? 1^*$

$0^* + (0^* 1 1^*)$





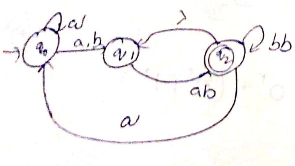
$(1+01^*0)^*01^*1(0^*+1)^*$

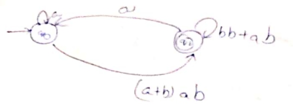
a b c d e b

$ae^*b + (ce^*b)^*$

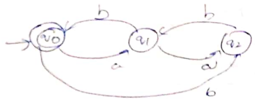
$\cancel{(ae^*d)^*(ae^*b+(ce^*b)^*)}$

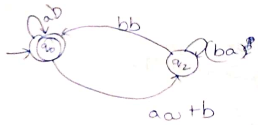
$(ae^*d)^*ae^*b[ce^*b+ce^*d(ae^*d)^*$





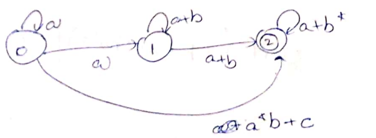
$a^*(a+b)ab[(bb+ab)+aa^*(a+b)ab]^*$





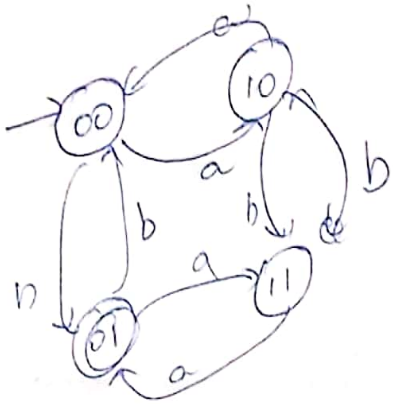
$(ab)^*(aa+b)(ba)^*.bb)^*$

$(a(ab)^*b)^*$



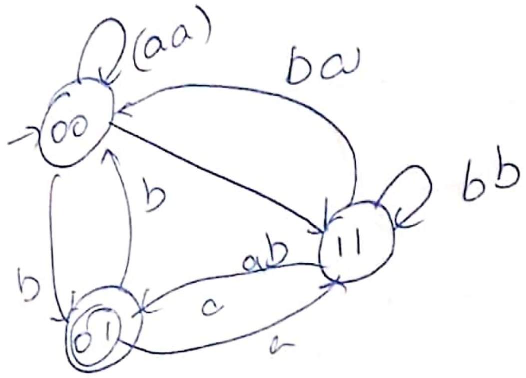
$(a^*b+c)+(a.(a+b)^*(a+b)^*)$

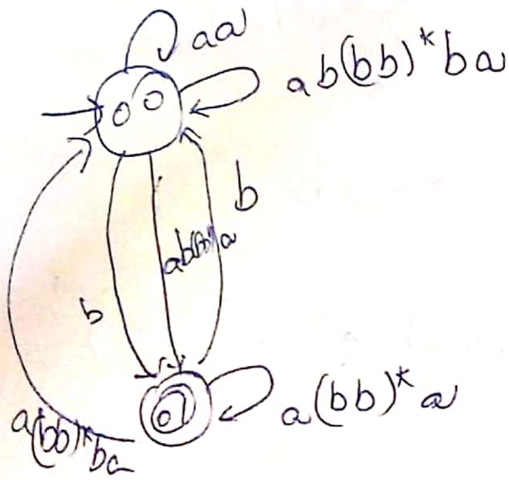
$a^*((a^*b+c)+(a.(a+b)^*(a+b)))$



$1,2 = 0$

$(aa)^* b(bb)^*$





$$(aa+ab(bb)^*ba)^*(b+ab(bb)^*a)\left[a(bb)^*a+(b+a(bb)^*ba)\left((aa+ab(bb)^*\right.\right.$$

$(b+ab(bb)^*$

Regular Grammar :-

Right linear Grammar

Left linear Grammar

$S \to aA \mid ab$

$A \to aA\,bB \mid \lambda$

Context free Grammar

Right & Left Linear Grammar for

$L((ab)^* a)$

$S \to abS \mid a$ → Right Linear

$S \to Sba \mid a$ → Left Linear

abab a

ababa ba

(2) $aa^*(ab+a)^*$

$S \to aX_1 \mid a$

$X_1 \to aX_1 \mid \lambda \mid X_2$

$X_2 \to abX_2 \mid aX_2 \mid \lambda$

$S \to X_1 \mid X_2 \mid a$

$X_1 \to X_1 ab \mid X_1 a \mid X_2 \mid \lambda$

$X_2 \to X_2 a \mid \lambda$

$L = \{a^n b^m,\ n \geq 2\ \ m \geq 3\}$ $aaa^* bbbb^*$

$S \to aaA$

$A \to aA \mid B$

$B \to bB \mid bbb$

$S \to Sb \mid Abbb$

$A \to Aa \mid aa$

$L((aab^*ab)^k)$

$S \to \lambda \mid A$

$A \to aaB$

$B \to bB \mid abS$

$S \to \lambda \mid Aab$

$A \to bA \mid Saa$

$S \rightarrow Sab \mid Sb \mid B$

$B \rightarrow Bb \mid A$

$A \rightarrow a$

Find the langg generated by given gramms

$S \rightarrow S_1 ab$

$S_1 \rightarrow S_1 ab \mid S_2$

$S_2 \rightarrow a$

$L(a(ab)^* ab)$

$L = \{ a(ab)^n : n \geq 1 \}$

Find the - langge

$S \rightarrow abA$

$A \rightarrow baB$

$B \rightarrow aA \mid bb$

abbabb

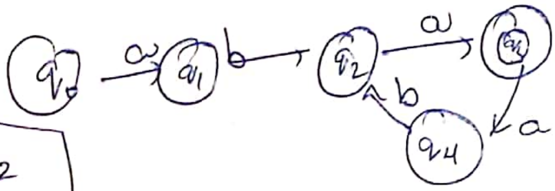
abbaababb

$abba(aba)^*bb$

$L(abba(aba)^*bb)$

$S \rightarrow S_1 bb$

$S_1 \rightarrow S_1 aba \mid abba$



$\boxed{\begin{array}{l} q_0 \rightarrow abq_2 \\ q_2 \rightarrow aq_3 \\ q_3 \rightarrow abq_2 \mid \lambda \end{array}}$

~~abaa~~

$S \rightarrow abaS \mid aba$

$\overline{aba(ab)^*a}$

$(aba)^+$

$aba(aba)^*$

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Closure Properties of regular grammar

1. If L_1 & L_2 are regular languages then $L_1 \cup L_2$, $L_1 \cap L_2$, $L_1 . L_2$, $\overline{L_1}$, L_1^* are also regular. i.e family of regular languages is closed under union, intersection, concatenation, complement, star closure.

2. Family of regular languages is closed under difference ($L_1 - L_2 = L_1 \cap \overline{L_2}$)

3. Family of regular languages is closed under reversal L_1^R

4. If L_1 & L_2 are regular languages then L_1 / L_2 called as right quotient is also regular.

L_1 / L_2 $\{ x : xy \in L_1$ for some $y \in L_2 \}$

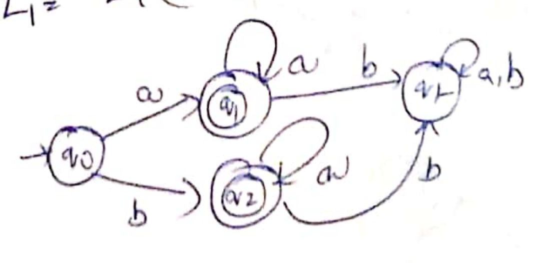
5. Family of regular language is closed under homomorphism.

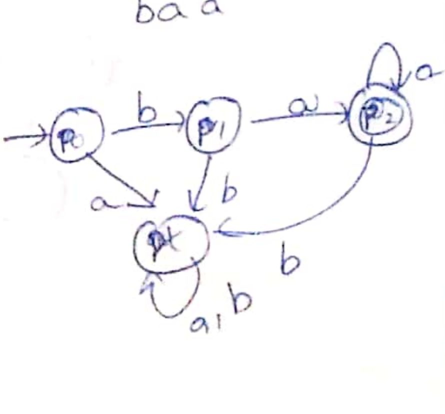
Every regular grammar is linear but vice-versa is not true.

Show that union of two languages L_1 & L_2 is regular

$L_1 = L((a+b)a^*)$ $L_2 = L(baa^*)$

baa^*

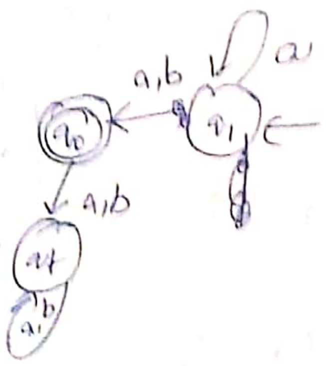




ii) L_1 L_2

(v) $\overline{L_1}$

(vi) L_1^R



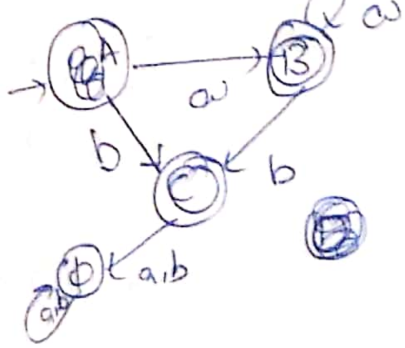
$\lambda(q_1) = q_1$

(q_1, a)

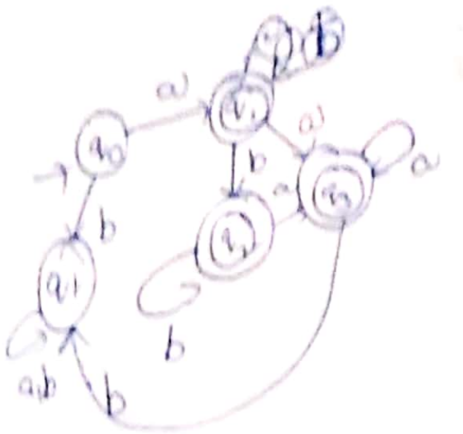
$((q_1, q_0), a =$

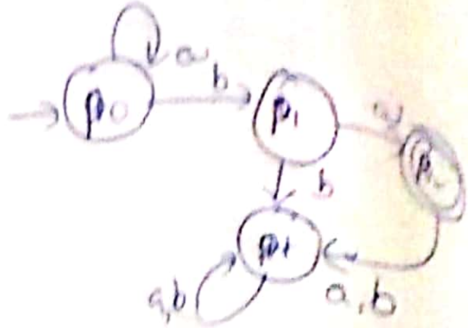
$((q_1, q_0), b) = q_0$

		a	b
A	q_1	q_1, q_0	q_0
B	q_1, q_0	q_1, q_0	q_0
C	q_0	ϕ	ϕ



$L_1 = L(aba^*)$





$((q_0, p_0), a) = (q_1, p_0)$

$((q_0, p_0), b) = (q_t, p_1)$

$((q_1, p_0), a) = (q_3, p_0)$

$((q_1, p_0), b) = (q_2, p_1)$

$((q_t, p_1), a) = (q_t, p_2)$

$((q_t, p_1), b) = (q_t, p_t)$

$((q_3, p_0), a) = (q_3, p_0)$

$((q_3, p_0), b) = (q_t, p_1)$

$((q_2, p_1), a) = (q_3, p_2)$

$((q_2, p_1), b) = (q_2, p_t)$

$((q_t, p_2), a) = (q_t, p_t)$

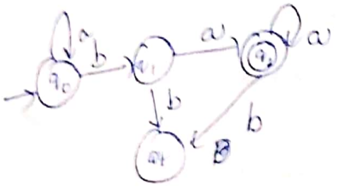
$((q_t, p_2), b) = (q_t, p_t)$

$((q_3, p_2), a) = (q_3, p_t)$

$((q_3, p_2), b) = (q_t, p_t)$

A	$\rightarrow q_0, p_0$	q_1, p_0	[illegible]
B	q_1, p_0	(q_3, p_0)	[illegible]
C	q_t, p_1	(q_t, p_2)	[illegible]
D	q_3, p_0	(q_3, p_0)	[illegible]
E	q_2, p_1	(q_3, p_2)	[illegible]
F	q_t, p_2	(q_t, p_t)	[illegible]
G	q_3, p_2	(q_3, p_t)	[illegible]
H	q_2, p_t	(q_3, p_t)	[illegible]
I	q_3, p_t	q_3, p_t	[illegible]

pf L_1/L_2 is regular

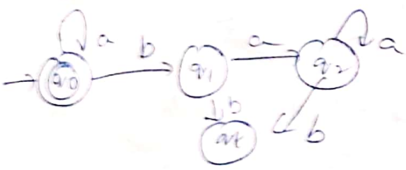


$L(q_0) \cap L_2 = \{aba^*\} \neq \phi$

$L(q_1) \cap L_2 = \phi$

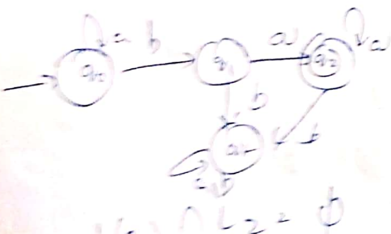
$L(q_2) \cap L_2 = \phi$

$L(q_t) \cap L_2 = \phi$



$L_1 = L(a^*baa^*)$

$L_2 = L(ab^*)$

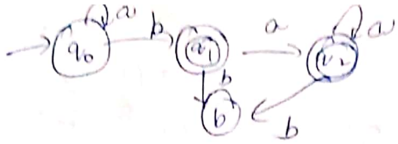


$L(q_0) \cap L_2 = \phi$

$L(q_1) \cap L_2 = \{a\}$

$L(q_2) \cap L_2 = \{a\}$

$L(q_t) \cap L_2 = \phi$

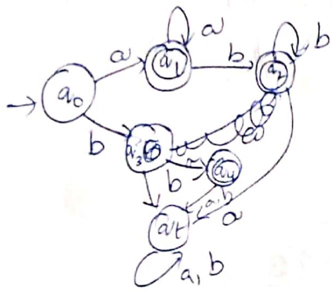


a^*ba^*

$L_1 = \{a^n b^m : n \geq 1, m \geq 0\} \cup \{ba\}$

$L_2 = \{b^m : m \geq 1\}$

L_1 / L_2



$L(q_0) \cap L_2 = \phi$

$L(q_1) \cap L_2 \rightarrow \{b\}$

$L(q_2) \cap L_2 = \{b\}$

$L(q_3) \cap L_2 = \phi$

$L(q_t) \cap L_2 = \phi$

$L(q_4) \cap L_2 = \phi$

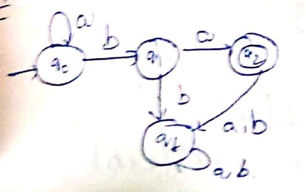
$L_1 = L(a^*ba)$

$L_2 = L(a^*)$

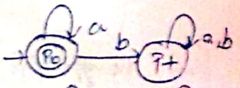
$L_1 - L_2$

$L_1 \cap \overline{L_2}$

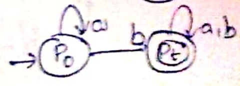
L_1



L_2



$\overline{L_2}$



$((q_0,P_0),a) \rightarrow (q_0,P_0)$

$((q_0,P_0),b) \rightarrow (q_1,P_t)$

$((q_1,P_t),a) \rightarrow (q_2,P_t)$

$((q_1,P_t),b) \rightarrow (q_t,P_t)$

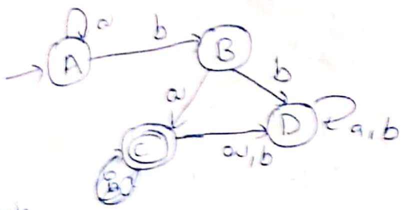
$((q_2,P_t),a) \rightarrow (q_t,P_t)$

$((q_2,P_t),b) \rightarrow (q_t,P_t)$

(q_1,P_t) (q_0,P_0) (q_2,P_t)

(q_2,P_t) (q_t,P_t)

(q_0,P_0)



Homomorphism

$\boxed{h : \Sigma \rightarrow \Gamma^*}$

$\Sigma = \{a, b\}$

$\Gamma = \{a, b, c\}$

Suppose Σ and Γ are alphabets then

$h : \Sigma \rightarrow \Gamma^*$ is called homomorphism

$\Sigma = \{a, b\}$ $\Gamma = \{1, 2, 3\}$

and $h(a) = \{12\}$

$h(b) = \{23\}$

Find homomorphic image

$h(L(r = ab)) = L(121223)$

$h(r)$ $r = a + b^*(a+b)$

$h(r)$ $12 + (23)^*$ $(12 + 23)$

does $h(r)$ accept 1223 ×

Show that family of regular languages is closed under nor operation

$nor(L_1, L_2)$ $\{w : w \notin L_1$ and $w \notin L_2\}$

$\cancel{\bar{L_1} \cap \bar{L_2} \cup}$

$\cancel{\bar{L_1} \cap L_2}$

$\overline{x+y}$

$\bar{x} \cdot \bar{y}$

$nor(L_1, L_2) \subseteq \bar{L_1} \cap \bar{L_2}$

$con(L_1, L_2) = \{w \in \bar{L_1}$ or $w \in \bar{L_2}\}$

$\bar{L_1} \cup \bar{L_2}$

$S_1 \ominus S_2 = \{x : x \in S_1$ or $x \in S_2$ but $x \notin S_1$ and S_2 both

$L_1 \cup L_2 - (L_1 \cap L_2)$

$L = \{a^n b^n : n \geq 1\}$

aa^*bb^* ↓ not regular language

Pumping Lemma :-

Let L be an infinite regular language then there exist some positive integer n such that any $w \in L$ with $|w| \geq n$ can be decomposed as $w = xyz$ with length of $x, y \leq n$ and length of $y \geq 1$ such that

$|xy| \leq n$ and $|y| \geq 1$

$xy^iz \in L$ $\forall i = 0, 1 \ldots$

$L = \{a^n b^n : n \geq 1\}$

Assume L is regular

$n = 5$

$w = \underset{x}{aa}\underset{y}{a}bbb \in L$

$|w| = 6 \geq 5$

$|xy| = 3 \leq 5 \quad |y| \geq 1$

$aa(a)^i\, bbb$

if $i=0$ $aabbb \notin L$

Hence our assumption is wrong

Hence L is not regular.

$L = \{ww^R : w \in \{a,b\}^+\}$

Let L be regular

$n = 5$

$\underset{x}{a}\underset{y}{bb}bba$

$|xy| = 3 \leq 5 \quad |y| \geq 1$

$x y^i z \qquad i=0$

$abbba \notin L$

Our assumption is wrong.

So L is not regular

$\underset{x}{ba}\underset{y}{bb}ab$

babbabab

$L = \{a^n b^l : n \neq l\}$

Let L be regular

Let $n = 3$

$l = 4$

$w \in \underset{x}{aaa}\,\underset{y}{b}\,\underset{z}{bbb}$

$|xy| \leq 5 \quad |y| \geq 1$

$x(y^0)^i z$ for $i=0$

$aaa\,bbb \notin L$

So L is not regular

$L = \{a^{n!} : n \geq 0\}$

$n = 5$

$w \in \underset{x}{aa}\underset{y}{a}aaa$

$|xy| \leq 5 \quad |y| \geq 1$

$x(y^0)^i z$ for $i=0$

$aaaaa \notin L$

so L is not regular.

$L = \{a^n b^m c^{m+n} : n,m \geq 0\}$

Assume L is Regular

homomorphism

$h(a)=a \quad h(b)=a \quad h(c)=c$

$L = \{a^n a^m c^{m+n}\}$

$= \{a^{m+n} c^{m+n}\} \qquad a^x c^x$

$L = \{ a^n : n \geq 2 \text{ \& } n \text{ is prime} \}$

Identify the following languages are regular.

① $L = \{ a^m b^l a^k : m + l + k > 5 \}$ R

② $L = \{ a^n b^l a^k : n > 5, l > 3, k \geq 0 \}$ R

③ $L = \{ a^n b^l a^k : n \geq 5, l > 3, k \leq l \}$ NR

④ $L = \{ u w w^R v : \forall\ u, v, w \in \{a, b\}^+ \}$ R

⑤ $L = \{ u w w^R v : \forall\ u, v, w \in \{a, b\}^+ \text{ \& } |u| = |v| \}$ NR

babba
x y z
baba

Content Free Grammar (CFG) :-

A Grammar G is (V, T, S, P) is said to be context free grammar if all the products are of the form

$A \to \alpha$

where $A \in V$
$\alpha \in (V \cup T)^*$

$S \to aSb \mid \lambda$

Generate a context free grammar

$L = \{ a^n b^m c^{n+m} : n, m \geq 0 \}$

$S \to aSc \mid B$
$B \to bBc \mid \lambda$

Generate a context free grammar for the language

$L = \{ a^n b^m c^k : n = m \text{ or } m \leq k$
$n, m, k \geq 0 \}$

~~$S \to aSb$~~

$S \to S_1 \mid S_2$

$S_1 \to AB$

$A \to aAb \mid \lambda$

$B \to cB \mid \lambda$

$S_2 \to aS_2 \mid E$

$E \to bEc \mid Z$

$Z \to cZ \mid \lambda$

$L = \{ a^n b^m c^k$ where $k = |n - m|$
$k, n, m \geq 0 \}$

$k = n - m$ or
$k = m - n$
$k + m = n$ $\quad k + n = m$

$S \to S_1 \mid S_2$

$S_1 \to aS_1c \mid A$

$A \to aAb \mid \lambda$

$S_2 \to XY$

$X \to aXb \mid \lambda$

$Y \to bYc \mid \lambda$

$L = \{a^n b \ldots$

$S \to aSc \mid B$

$B \to bBc \mid \lambda$

$L = \{a^n w w^R b^n \quad n \geq 0 \quad w \in \{a,b\}^*\}$

$S \to \cancel{aSb} \quad aSb \mid W$

$W \to aWa \mid bWb \mid \lambda$

Show L^2 is context free

$L = a^n b^n \quad n \geq 0$

$L \cdot L \qquad a^n b^n a^m b^m$

$S \to AA$

$A \to aAb \mid \lambda$

Show L^k is context free for $k \geq 1$

$S \to \lambda$

$S \to AS \mid A$

$A \to aAb \mid \lambda$

$L = \{w : w \in \{a,b\}^+, \ n_a(w) = n_b(w) + 1\}$

$S \to aSb \mid bSa \mid Sab \mid abS \mid baS \mid Sba \mid a$

$L \ \{u v w^R v^R, \quad u,v,w \in \{a,b\}^+, \ |u| = |w| = 2\}$

$$\boxed{\begin{aligned} S &\to aaV \mid abV \mid baV \mid bbV \\ V &\to aVa \mid bVb \mid aa \mid bb \mid ba \mid ab \end{aligned}}$$

$S \to TTV$

$T \to a \mid b$

$V \to aVa \mid bVb \mid TT$

$L = \{a^n b^m c^k \quad n + 2m = k \quad n, m, k \geq 0\}$

$S \to aSc \mid B$

$B \to bBcc \mid \lambda$

Context free grammar to generate valid

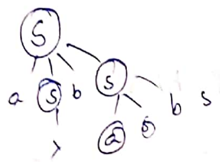
$S \to (S) \mid [S] \mid \{S\} \mid \lambda$

Scanned by CamScanner

Check whether ... Ambiguous/left :- If a Grammar has two different parse tree/ two left most derivation / right most derivation

$S \to aSbS \mid bSaS \mid \lambda$

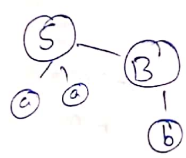
abab

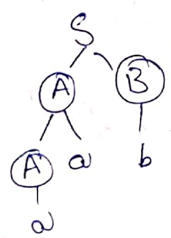


$S \to AB \mid aaB$

$A \to a \mid Aa$

$B \to b$



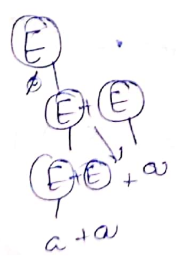


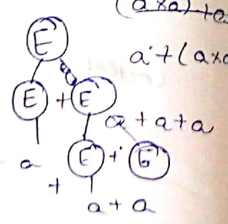
$E \to E+E \mid E\times E \mid a$

~~(id+id)~~ id

~~(a×a)+a~~

a+(a×a)





$E \Rightarrow E+E$

$\Rightarrow E+E+a$

$\Rightarrow a+a+a$

$E \Rightarrow E+E$

$\Rightarrow a+E+E$

$\Rightarrow a+a+a$

Unambiguous grammar

$E \to E+T \mid T$

$T \to T*F \mid F$

$F \to id$

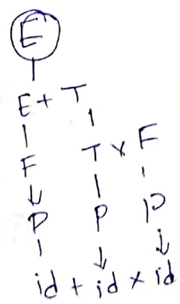
$E \to E+T \mid E-T \mid T$

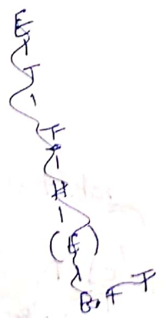
$T \to T*F \mid T/F \mid F$

$F \to H\wedge F \mid H$

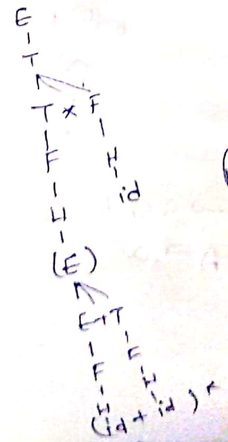
$H \to id \mid (E) \mid -E$

(id+id) *id





(id+id)*id



Find the grammar and derive two string from gram

$S \to aaSSb \mid \lambda \mid a$

aab

aabb

S

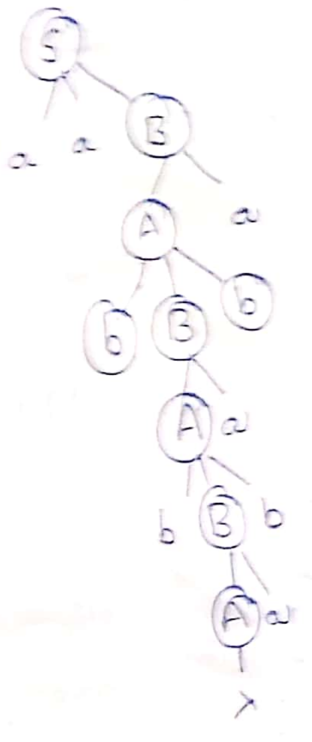
$S \to aaB$

$A \to bBb \mid \lambda$

$B \to Aa$

Derive

aabbababa



$S \Rightarrow aaB$

$\Rightarrow aaAa$ [B→Aa

$\Rightarrow aabBba$ [A→bB

$\Rightarrow aabAaba$ [B→

$\Rightarrow aabbBbba$ [A→

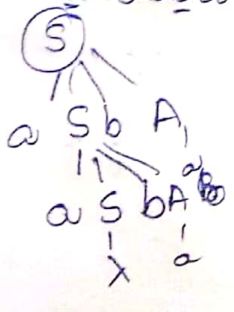
$\Rightarrow aabbAabba$ [B→

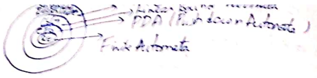
$\Rightarrow aabbabba$ [A

$S \to aSbA \mid \lambda$

$A \to a$

aababa





Simplification of CFG's:-

- → Substitution rule/method
- → Elimination of left recursion
- → Elimination of λ production
- → Elimination of unit production
- → Elimination of useless production.

Simplify the grammar

$S \to aS / A$
$A \to a / ba$

After substitution
$S \to aS / a / ba$
$A \to a / bA$

$S \to aS/bA/Ab$
$A \to a/bA$

no minimization possible

Elimination of left recursion:-

$A \to A\alpha / \beta$

$S \to Sab/a/b/Sba$

$S \to aS' / bS'$
$S' \to abS' / baS' / \lambda$

$S \to aSa / bSb / aA$
$A \to Aa / Ab / Bab / a$
$B \to aB / b$

$S \to aSa / bSb / aA$
$A \to BabA' / aA'$
$A' \to aA' / bA' / \lambda$
$B \to aB / b$

$S \to Aa / b$
$A \to Sa / b$

$S \to Saa / ba / b$
$S \to baS' / bS'$
$S' \to aaS' / \lambda$

$S \to Ab / a$
$A \to Ab / Sa / b$

$S \to Ab / a$
$A \to SaA' / bA'$
$A' \to bA' / \lambda$
↓
$S \to SaA'b / bA'b / a$
$A \to SaA' / bA'$
$A' \to bA' / \lambda$

→
$S \to bA'bA''/ aA''$
$A'' \to aA'bA'' / \lambda$
$A' \to baA' / bA'$
$A' \to bA' / \lambda$

A → Ab | Sa

Sub ⑤ in ④

S → Abb | Sa~~b~~ | bb | a } Both are left recursive
A → Ab | Sa | b

Sub ① in ②
S → Ab | a
A → Ab | Aba | aa | b

S → Ab | a
A → aaA' | bA'
A' → bA' | baA' | λ

E → E+T | T
T → id
F → id

E → E+T | id
T → id
F → id

E → id E'
E' → +TE' | λ
T → id
F → id

Nullable variables
E'

S → ABaC
A → BC
B → b | λ
C → D | λ
D → d
E → d

A, B, C are nullable
eliminate λ
~~S → ABaC | BaC | AaC~~

S → ABac | Bac | Aac | ABa | ac | Aa | Ba | a
A → BC | B | C
B → b
C → D
D → d
E → d

eliminate unit productions.

S → ABac | Bac | Aac | ABa | ac | Aa | Ba | a

Precedence Graph
A → B
A → C → D

A → BC | b | d

B → b
C → d
D → d
E → d

Elimination of useless productions

S → ABac | Bac | Aac | ABa | ac | Aa | Ba | a

B → b
C → d

$S \to aA \mid a \mid Bb \mid ac$

$A \to aB$

$B \to a \mid Aa$

$C \to e\,CD$

$D \to ddd$

(I) $S \to a \mid Bb \mid aA$

$B \to a \mid Aa$

$D \to ddd$

$A \to aB$

(II) $S \to a$

$S \to Bb$

$S \to aA$

$B \to a \mid Aa$

$A \to aB$

⇓

$S \to a \mid Bb \mid aA$

$A \to aB$

$B \to a \mid Aa$

$S \to BAAB$

$A \to 0A2 \mid 2A0 \mid \lambda$

$B \to AB \mid 1B \mid \lambda$

when start derives λ you cannot eliminate it

No left recursion

S, A, B

After λ-production

$S \to BAAB \mid AAB \mid BAB \mid A \mid B \mid BB \mid AA \mid AB \mid BA$

$A \to 0A2 \mid 2A0 \mid 02 \mid 20$

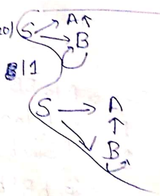
$B \to AB \mid 1B \mid A \mid B \mid 1$

After unit production

$S \to BAAB \mid AAB \mid BAB \mid 0A2 \mid 2A0 \mid 02 \mid 20 \mid AB \mid 1B \mid 0A2 \mid 2A0 \mid \lambda$

$B \to AB \mid 1B \mid 0A2 \mid 2A0 \mid 02 \mid 20 \mid B \mid 1$

$A \to 0A2 \mid 2A0 \mid 02 \mid 20$



No useless productions

$S \to aA \mid aBB$

$A \to aaA \mid \lambda$

$B \to bB \mid bbc$

$C \to B$

$E \to E + T \mid T$

$T \to id$

$F \to num$

$S \to aA \mid aBB$

$A \to aaA \mid \lambda$

$B \to bB \mid bbC$

$C \to B$

No left recursion

Nullable variables

A

$S \to aA \mid aBB \mid a$

$A \to aaA \mid aa$

$B \to bB \mid bbC$

$C \to B$

precedence graph

$C \to B$

$S \to aA \mid aBB \mid a$

$A \to aaA \mid aa$

$B \to bB \mid bbC$

$C \to \cancel{B}\ bB \mid bbC$

$S \to a \mid aA$

$A \to aa$

$S \to abSb \mid aa$

$\Downarrow$

$S \to abSb$

$S \to aa$

$S \to A_1 B$

$A_1 \to a$

$S \to A_1 A_1$

$B \to B_1 B_2$

$B_1 \to b$

$B_2 \to SB_1$

CNF

$S \to AB \mid aB$

$A \to aab \mid \lambda$

$B \to bbA$

$\Rightarrow$

~~$S \to AB \mid A$~~

$S \to AB \mid aB \mid B$

$A \to aab$

$B \to bbA \mid bb \mid bbaab$

$S \to AB \mid aB \mid bbA \mid bb \mid bbaab$

$A \to aab$

$B \to bbA \mid bb \mid$ ~~bbaab~~

$S \to AB \mid A_1 B \mid B_1 B_2 \mid B_1 B_1 \mid B_1 C_1$

$A_1 \to a$

$B_1 \to b$

$A \to A_1 C_3$

$B_2 \to B_1 A$

$C_1 \to B_1 C_2$

$C_2 \to A_1 C_3$

$C_3 \to A_1 B_1$

$B \to B_1 D_1 \mid B_1 B_1$

$D_1 \to B_1 A$

Scanned by CamScanner

(3)

$S \to aSB \mid bSA \mid a \mid b$

$A \to a$

$B \to b$

(4) $S \to ab \mid aS \mid aaS$

$S \to aB \mid aS \mid aAS$

$B \to b$

$A \to a$

(5) $E \to E+T \mid T$

$T \to T*F \mid F$

$F \to a$

$E \to TE'$

$E' \to +TE' \mid \lambda$ $\qquad E', T'$

$T \to FT'$

$T' \to *FT' \mid \lambda$

$F \to a$

$E \to TE' \mid T$ $\qquad E \to T \to f$

$E' \to +TE' \mid +T$

$T \to FT' \mid F$

$T' \to *FT' \mid *F$ $\qquad F \to a$

~~$E \to FE' \mid F$~~

~~$E' \to +FE' \mid +F$~~

~~$T \to FT' \mid a$~~

~~$T' \to *FT' \mid *F$~~

~~$F \to a$~~

$E \to TE' \mid FT' \mid a$

$E' \to +TE' \mid +T$

$T \to FT' \mid a$

$T' \to *FT' \mid *F$

$F \to a$

CNF

$E \to TE' \mid FT' \mid a$

$E' \to XY \mid XT$

$X \to +$

$Y \to TE'$

$T \to FT' \mid a$

$T' \to ZA \mid ZF$

$Z \to *$

$A \to FT'$

$F \to a$

GNF

$E \to aT' \mid aE' \mid aT' \mid a$

$E' \to +TE' \mid +T$

$T \to aT' \mid a$

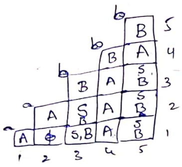
$T' \to *FT' \mid *F$

$F \to a$

CYK algo

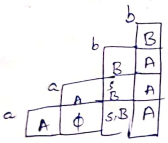
$S \to AB$
$A \to BB / a$
$B \to AB / b$

Check if the string aabbb



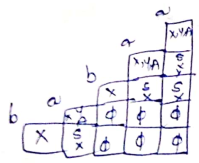
aabb

aabb

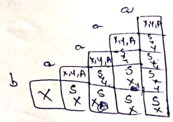


$S \to XY$
$X \to XA / a / b$
$Y \to AY / a$
$A \to a$

babaa



baaaa



Push Down Automata :- (PDA)

A PDA is defined as

$P = (Q, \Sigma, \Gamma, \delta, q_0, Z, F)$

where

Q = finite set of internal states
Σ = finite set of input symbols
Γ = finite set of stack symbols
δ = It is a transition function
$Q \times (\Sigma \cup \lambda) \times \Gamma \to Q \times \Gamma^*$
$q_0 \in Q$ is a initial state
$Z \in \Gamma$ stack initial top symbol
$F \subseteq Q$ is a set of final state

$L = \{a^n b^n : n \geq 1\}$

$\delta(q_0, a, Z) = (q_0, aZ)$
$\delta(q_0, a, a) = (q_0, aa)$
$\delta(q_0, b, a) = (q_1, \lambda)$
$\delta(q_1, b, a) = (q_1, \lambda)$
$\delta(q_1, \lambda, Z) = (q_2, Z) \to$ Accept

s.t. aabb

Instantaneous description (ID)

$\delta^*(q_0, w, z)$

$\delta^*(q_0, aabb, z) \vdash \delta(q_0, abb, az)$

$\vdash \delta(q_0, bb, aaz) \vdash \delta(q_0, b, az)$

$\vdash \delta(q_0, \lambda, z) \vdash (q_2, z)$ accept

aaba

$\delta(q_0, aaba, z) \vdash \delta(q_0, aba, az)$

$\vdash \delta(q_0, ba, aaz) \vdash \delta(q_0, a, az)$

No such transition
so string is rejected
or $w \notin L$

PDA acceptance

- acceptance by final state
- acceptance by empty state

~~abbcabb~~

$\cancel{(q_0, abbcabb, z) \vdash (q_0, bbcabb, az)}$

$\cancel{\vdash (q_0, bcabb, baz) \vdash (q_0, cabb, bbaz)}$

$\cancel{\vdash (q_0, abb}$

abcba

$(q_0, abcba, z) \vdash (q_0, bcba, az)$

$\vdash (q_0, cba, baz) \vdash (q_1, ba, baz)$

$\vdash (q_1, a, az) \vdash (q_1, \lambda, z) \vdash \underline{(q_2, z)}$

For $ww^R \longrightarrow$ no DPDA

NPDA

$(q_0, \lambda, a) \rightarrow (q_1, a)$

$(q_0, \lambda, b) \rightarrow (q_1, b)$

$L = \{a^m b^m c^{n+m} : n, m \geq 0\}$

$\delta(q_0, a, z) = \delta(q_0, az)$

$\delta(q_0, a, a) = \delta(q_0, aa)$

$\delta(q_0, c, a) = (q_2, \lambda)$

$\delta(q_0, b, z) = \delta(q_1, bz)$

$\delta(q_0, b, a) = (q_1, ba)$

$\delta(q_1, b, b) = (q_1, bb)$

$\delta(q_1, c, b) = (q_2, \lambda)$

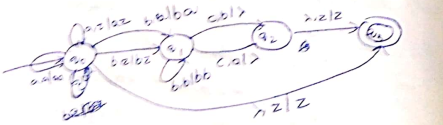
$\delta(q_1, c, a) = (q_2, \lambda)$

$\delta(q_2, c, b) = (q_2, \lambda)$

$\delta(q_2, c, a) = (q_2, \lambda)$

$\delta(q_2, \lambda, z) = (q_3, z)$ //accept

$\delta(q_0, \lambda, z) = (q_3, z)$ //accept



$\delta(q_0, (, z) = (q_0, (z)$

$\delta(q_0, [, z) = (q_0, [z)$

$\delta(q_0, (, [) = (q_0, ([)$

$\delta(q_0, (, () = (q_0, (()$

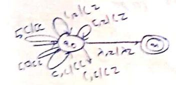
$\delta(q_0, [, () = (q_0, [()$

$\delta(q_0, [, [) = (q_0, [[)$

$\delta(q_0,], [) = (q_0, \lambda)$

$\delta(q_0,), () = (q_0, \lambda)$

$(q_0, \lambda, z) = (q_1, z)$ //accept



RE: aab^*aba^*

$\delta(q_0, a, z) = (q_1, z)$

$\delta(q_1, a, z) = (q_2, z)$

$\delta(q_2, b, z) = (q_2, bz)$

$(q_2, a, z) = (q_3, z)$

$(q_3, b, z) = (q_4, z)$ //accept

$(q_4, a, z) = (q_4, z)$ //accept

Language accepted by PDA

$L(P) = \{w : w \in \Sigma^* \text{ and } \delta(q_0, w, z) \vdash_P^* (q_f, F)\}$

$q_f \in F$

$n_a(w) = n_b(w)$

$\delta(q_0, a, z) = (q_1, az)$

$\delta(q_0, b, z) = (q_2, bz)$

$\delta(q_1, a, a) = (q_1, aa)$

$\delta(q_1, b, b) = (q_1, bb)$

$\delta(q_0, a, z) = (q_0, az)$

$\delta(q_0, b, z) = (q_0, bz)$

$\delta(q_0, a, a) = (q_0, aa)$

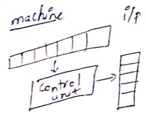
$\delta(q_0, b, b) = (q_0, bb)$

$\delta(q_0, a, b) = (q_0, \lambda)$

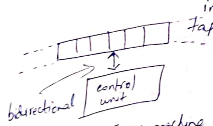
$\delta(q_0, b, a) = (q_0, \lambda)$

accept // $\delta(q_0, \lambda, z) = (q_1, z)$

Turing machine   i/p buffer/tape



PDA



Turing machine

A turing machine is represented as
$M(Q, \Sigma, \Gamma, \delta, q_0, \boxed{B}, F)$ where
Blank

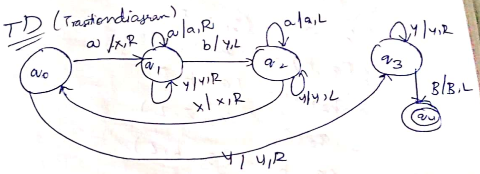
Q = finite set of internal states
Σ = set of input symbols
Γ = finite set of tape symbols
$\delta : Q \times (\Sigma \cup \square) \rightarrow Q \times \Gamma \times \{L, R\}$
$q_0 \in Q$ initial state
$\square \in \Gamma$ represents symbol on tape
$F \subseteq Q$ which denote set of final states

It is also called as ~~non~~deterministic touring machine

$L = \{a^n b^n : n \geq 1\}$

$(q_0, a) = (q_1, X, R)$
$(q_1, a) = (q_1, a, R)$
$(q_1, b) = (q_2, Y, L)$
$(q_2, a) = (q_2, a, L)$
$(q_2, X) = (q_0, X, R)$
$(q_1, Y) = (q_1, Y, R)$
$(q_2, Y) = (q_2, Y, L)$
$(q_0, Y) = (q_3, Y, R)$
$(q_3, Y) = (q_3, Y, R)$
$(q_3, B) = (q_4, B, L)$ //accept

TD (Transition diagram)



Transition table -

	a	b	X	Y	B
q_0	q_1,X,R			q_3,Y,R	
q_1	q_1,a,R	q_2,Y,L		q_1,Y,R	
q_2	q_2,a,L		q_0,X,R	q_2,Y,L	
q_3				q_3,Y,R	q_4,B,L
q_4					

$q_0aabb \vdash xq_1abb \vdash xaq_1bb \vdash xq_2ayb$

$\vdash q_2xayb \vdash xq_0ayb \vdash xxq_1yb$

$\vdash xxyq_1b \vdash xxq_2yy \vdash xq_2xyy$

$\vdash xxq_0yy \vdash xxyq_3y \vdash xxyyq_3$

$\vdash xxyq_4y$

$\downarrow$

Accept

$a^n b^n c^n \quad n \geq 1$

$\delta(q_0, a) = (q_1, x, R)$

$\delta(q_1, a) = (q_1, a, R)$

$\delta(q_1, b) = (q_2, y, R)$

$\delta(q_2, b) = (q_2, b, R)$

$\delta(q_2, c) = (q_3, z, L)$

$\delta(q_3, b) = (q_3, b, L)$

$\delta(q_3, y) = (q_3, y, L)$

$\delta(q_3, a) = (q_3, a, L)$

$\delta(q_3, x) = (q_0, x, R)$

$\delta(q_1, y) = (q_1, y, R)$

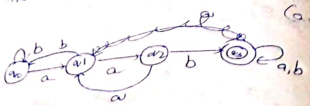
$\delta(q_2, z) = (q_2, z, R)$

$\delta(q_3, z) = (q_3, z, L)$

$\delta(q_0, y) = (q_4, y, R)$

Obtain turing machine containing the substring 'aab'

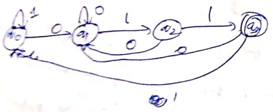
$(a+b)^*$ aab...



	a	b	B
q_0	(q_1, a, R)	(q_0, b, R)	~~(q_0, q, R)~~
q_1	(q_2, a, R)	(q_0, b, R)	
q_2	(q_3, b, R)	(q_2, b, R)	
q_3	(q_3, a, R)	(q_3, b, R)	(q_4, B, L)

Generate turing machine all the strings on 0, 1 ending with 011

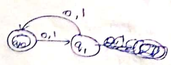
$(0+1)^* 011$



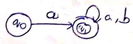
	0	1	B
q_0	$(q_1, 0, R)$	$(q_0, 1, R)$	
q_1	$(q_1, 0, R)$	$(q_2, 1, R)$	
q_2	$(q_1, 0, R)$	$(q_3, 1, R)$	
q_3	$(q_1, 0, R)$	$(q_0, 1, R)$	(q_4, B, L)

$L = w$ where $|w|$ is even or $\Sigma = 0, 1$

$((0+1)(0+1))^*$



	0	1	B
q_0	$(q_1, 0, R)$	$(q_1, 0, R)$	(q_2, B, L)
q_1	$(q_0, 0, R)$	$(q_0, 1, R)$	



	a	b	B
q_0	(q_1, a, R)		
q_1	(q_1, a, R)	(q_1, b, R)	(q_2, B, L)

$L = \{ww^R : w \in \{a,b\}^*\}$

abbbba

$\delta(q_0, a) = (q_1, B, R)$

$\delta(q_1, a) = (q_1, a, R)$

$\delta(q_1, b) = (q_1, b, R)$

$\delta(q_1, B) = (q_2, B, L)$

$\delta(q_2, a) = (q_3, B, L)$

$\delta(q_3, a) = (q_3, a, L)$

$\delta(q_3, b) = (q_3, b, L)$

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$\delta(q_3, B) = (q_0, B, R)$

$\delta(q_0, b) = (q_4, B, R)$

$\delta(q_4, a) = (q_4, a, R)$

$\delta(q_4, b) = (q_4, b, R)$

$\delta(q_4, B) = (q_5, B, L)$

$\delta(q_5, b) = \delta(q_6, B, L)$

$\delta(q_6, a) = (q_6, a, L)$

$\delta(q_6, b) = (q_6, L)$

$\delta(q_6, B) = (q_0, B, R)$

$\delta(q_0, B) = (q_7, B, L)$ //Accept

abba

$(q_0, abba)$

$q_0abba \vdash Bq_1bba \vdash Bbq_1ba \vdash Bbbq_1a$

$\vdash Bbbaq_1 \vdash Bbbq_2a \vdash Bbbq_3BB \vdash Bq_3bbB$

$\vdash q_3BbbB \vdash Bq_0bbB \vdash BBq_4bB$

$\vdash BBbq_4B \vdash BBq_5bB \vdash BBq_6BBB$

$\vdash q_6BBBB \vdash Bq_0BBB \vdash q_7BBBB$

$n_a(w) = n_b(w)$

Types of TM

① Standard Turing Machine ($\delta : Q \times \{\Sigma \cup \lambda\} \to Q \times \Gamma \times \{L, R\}$)

② Non-Deterministic TM ($\delta : Q \times \{\Sigma \cup \lambda\} \to 2^{Q \times \Gamma \times \{L, R\}}$)

③ Turing Machine with stay option

($\delta : Q \times \{\Sigma \cup \lambda\} \to Q \times \Gamma \times \{L, R, S\}$)

④ multi-track turing machine

($\delta : Q \times \{\Sigma \cup \lambda\}^n \to Q \times \Gamma^n \times \{L, R\}$)

n - no. of tracks

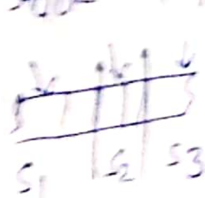
⑤ Multi Dimensional TM

($\delta : Q \times \{\Sigma \cup \lambda\} \to Q \times \Gamma \times \{L, R, U, D\}$)

⑥ Multi Tape TM

($\delta : Q \times \{\Sigma \cup \lambda\}^n \to Q \times \Gamma^n \times \{L, R, S\}$)

⑦ Multi stack TM



($\delta : Q \times \{\Sigma \cup \lambda\}^n \to Q \times \Gamma^n \times \{L, R, S\}$)

A multi stack TM is similar to multi-Tape but the tape works like a stack and has a limit in accessing

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Recursively enumerable & Recursive

Recursive (decidable):-

There exists a TM that accepts every string in the language and rejects every string not in the language then the language is recursive, i.e. TM halts

Recursively enumerable (acceptable):-

There exists a TM that accepts/rejects or may go to infinite loop then the language is recursively enumerable.

Every recursive is recursively enumerable but not the vice versa

Type	Grammar	Syntax	Language	Machine	Storing unit	Parsing complexity
Type 0	Unrestricted	$\alpha \to \beta$ $\alpha \in (V \cup T)^+$ $\beta \in (V \cup T)^*$	Recursive Enumerable	Turing Machine	Infinite tape	undecidable
Type 1	Context sensitive	$\alpha \to \beta$ $\alpha, \beta \in (V \cup T)^*$ $\lvert\beta\rvert \geq \lvert\alpha\rvert$ α contains a variable	Context sensitive	Linear Bound Automation	Restricted tape	NP complete
Type 2	Context free	$\alpha \to \beta$ $\alpha \in V$ $\beta \in (V \cup T)^*$	Context free	Push down Automata	Stack	$O(n^3)$
Type 3	Regular	$\alpha \to aB \mid a$ or $\alpha \to Ba \mid a$ $\alpha, \beta \in V$ $a \in T^*$	Regular	Finite Automata	None	$O(n)$