



COMP4141 Slides Week 2

Brendan Mabbett

UNSW

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Tutorial Solutions

- They will be posted once all the tutes have been held for the week

Quizes

(20% in total)

- They start **today!**
- They will be 20 minutes; you will write your answers and I will collect at the end. This will be similar to exam conditions; laptop and phones away. No talking to your fellow students during the quiz.
- Please write down your name, student ID, and the tutorial session on top of the first page.
- Please use a black pen

ϵ -NFAs

ϵ -Nondeterministic Finite Automata

Definition

An ϵ -NFA is an NFA that allows state changes that do not consume input symbols. The only difference in the formal definition is the transition relation:

$$\delta : Q \times (\Sigma \cup \{\epsilon\}) \rightarrow 2^Q.$$

ϵ -Closure

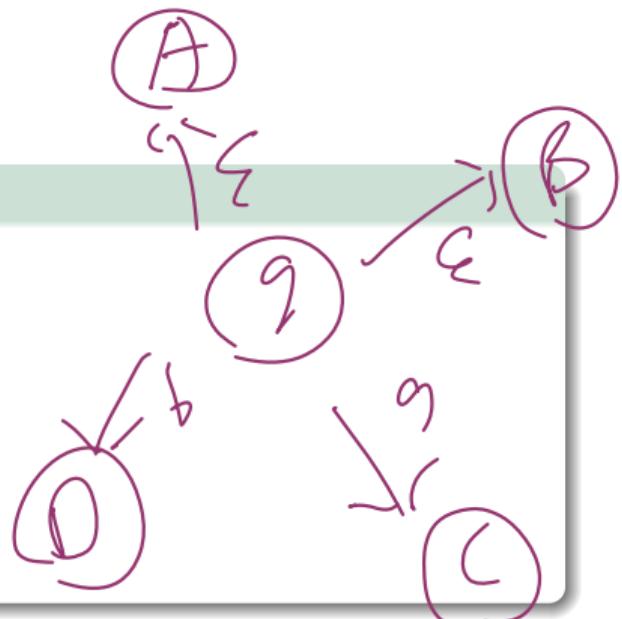
Definition

For $q \in Q$, define $E(q)$ to be the least set satisfying:

- $q \in E(q)$,
- if $s \in E(q)$ and $t \in \delta(s, \epsilon)$, then $t \in E(q)$.

For a set $S \subseteq Q$, define

$$E(S) = \bigcup_{q \in S} E(q).$$



$$E(q) = \{q, A, B\}$$

Proof Constructions

Lemma

Let $L \subseteq \Sigma^*$ be a regular language. Then $\Sigma^* \setminus L$ is also a regular language.

Proof idea: Replace F with $Q \setminus F$.

Lemma

Let $L_1, L_2 \subseteq \Sigma^*$ be regular languages. Then $L_1 \cap L_2$ is regular.

Proof idea: Construct a product automaton with $Q = Q_1 \times Q_2$,

$$\delta((q, q'), a) = (\delta_1(q, a), \delta_2(q', a)), \quad F = F_1 \times F_2 = \{(q, q') : q \in F_1 \text{ and } q' \in F_2\}.$$

Regular Languages

Regular Languages

Regular Expressions (Inductive Definition)

The set of regular expressions over an alphabet Σ is defined inductively:

- If $a \in \Sigma$, then a is a regular expression.
- \emptyset is a regular expression.
- ϵ is a regular expression.
- If R_1 and R_2 are regular expressions, then:
 - $R_1 \cup R_2$ is a regular expression,
 - $R_1 \cdot R_2$ is a regular expression,
 - R_1^* is a regular expression.

Match R_1 or R_2

$$R_1 \cdot R_2 = \{ w_1 w_2 : w_1 \in R_1, w_2 \in R_2 \}$$

$$\mathbb{R}^{\mathbb{P}} = \bigcup_{n=0}^{\infty} \mathbb{R}^n$$

$(L') have exactly 4 0's$

$$\mathbb{R}^n = \sum w_1 w_2 \dots w_n : w_i \in \mathbb{R} \wedge i \in \mathbb{N}$$

$$\mathbb{R}^0 = \emptyset$$

Equivalence with Automata

Kleene's Theorem

Let $L \subseteq \Sigma^*$ be a language. The following are equivalent:

- L is accepted by a DFA,
- L is accepted by an NFA,
- L is accepted by a GNFA,
- $L = L(R)$ for some regular expression R .

From Regular Expressions to Finite Automata (Union)

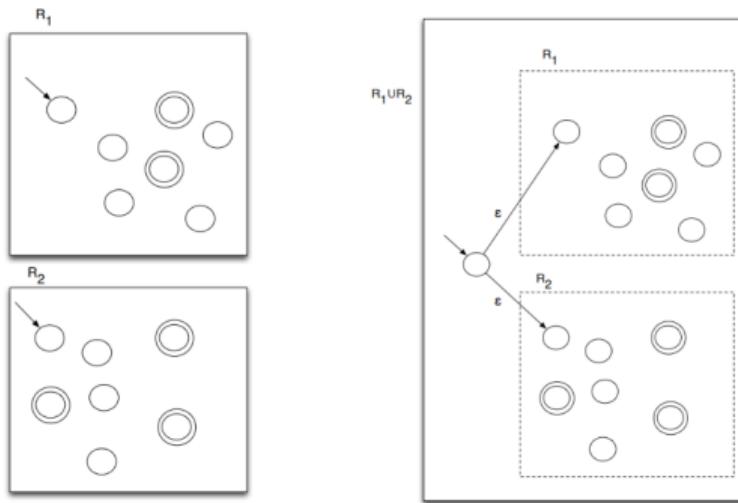


Figure: Proof By Picture (Union)

From Regular Expressions to Finite Automata (Concatenation)

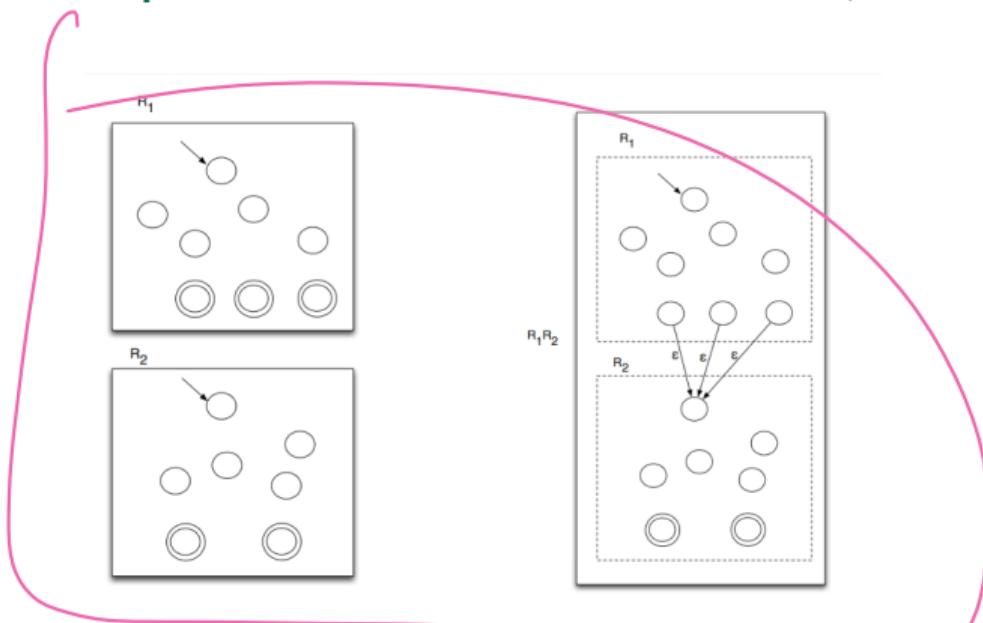


Figure: Proof By Picture (Concatenation)

From Regular Expressions to Finite Automata (Kleene Star)

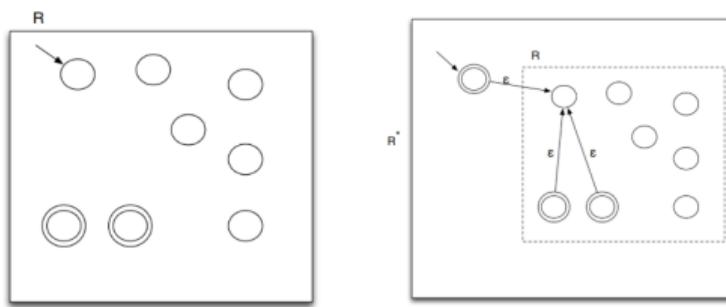


Figure: Proof By Picture (Kleene Star)

Generalised NFAs (GNFAs)

Definition

A **generalised nondeterministic finite automaton (GNFA)** is a 5-tuple $(Q, \Sigma, \delta, q_0, q_F)$ where:

- Q is a finite set of states,
- Σ is the input alphabet,
- $\delta : (Q \setminus \{q_F\}) \times (Q \setminus \{q_0\}) \rightarrow \text{RE}_\Sigma$ is the transition function,
- $q_0 \in Q$ is the start state,
- $q_F \in Q$ is the accept state.

Pumping Lemma

Pumping Lemma

If $L \subseteq \Sigma^*$ is regular, then there exists $p \in \mathbb{N}$ (the *pumping length*) such that for every $w \in L$ with $|w| \geq p$, we can write $w = xyz$ satisfying:

1. $|xy| \leq p$,
2. $|y| > 0$,
3. $xy^i z \in L$ for all $i \in \mathbb{N}$.

Myhill–Nerode Theorem

Distinguishability

Let $L \subseteq \Sigma^*$.

We say x and y are *distinguishable by L* if there exists $z \in \Sigma^*$ such that:

$$xz \in L \quad \text{and} \quad yz \notin L$$

(or vice versa).

We write $x \equiv_L y$ if x and y are not distinguishable by L .

The *index* of L is the number of \equiv_L -equivalence classes.

Myhill–Nerode Theorem

A language $L \subseteq \Sigma^*$ is regular if and only if the index of L is finite.

Moreover, this index equals the minimum number of states of any DFA that accepts L .

Using Myhill–Nerode

Myhill–Nerode proof format

Find an infinite sequence of words (not necessarily in L), u_1, u_2, u_3, \dots , and a doubly indexed sequence of words $w_{i,j}$ for $i < j \in \mathbb{N}_0$ such that

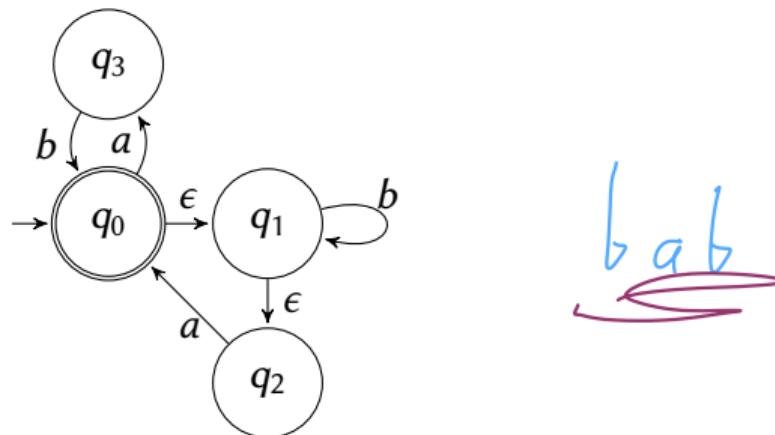
$$u_i w_{i,j} \in L \quad \text{and} \quad u_j w_{i,j} \notin L$$

(or vice versa).

W1 P7 & P8

Problems 7 & 8 (ϵ -Nondeterministic Finite Automata; Week 1)

Assume the alphabet $\Sigma = \{a, b\}$. Consider the following ϵ -NFA.



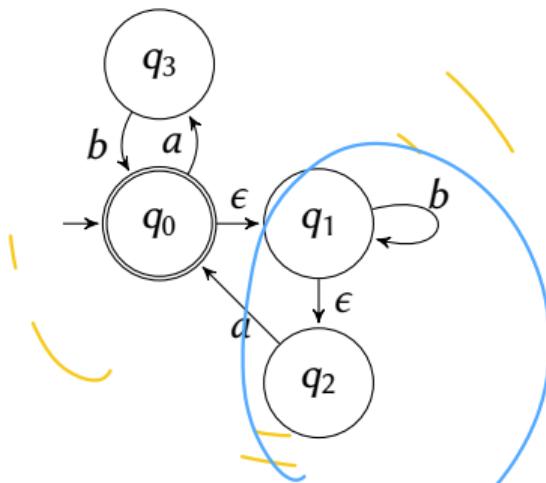
7. List all strings of length ≤ 3 that this automaton accepts.

| | | |
|----|---|---|
| | q | ✓ |
| | a | ✓ |
| | b | ✗ |
| ab | | ✓ |
| ba | | ✗ |
| aa | | ✓ |

| | |
|-----|---|
| qqq | ✓ |
| qqb | ✓ |
| qbq | ✓ |
| bbb | ✗ |
| bqb | ✓ |
| bqb | ✗ |
| bab | ✓ |
| bab | ✓ |
| bab | ✗ |

Problems 7 & 8 (ϵ -Nondeterministic Finite Automata; Week 1)

Assume the alphabet $\Sigma = \{a, b\}$. Consider the following ϵ -NFA.

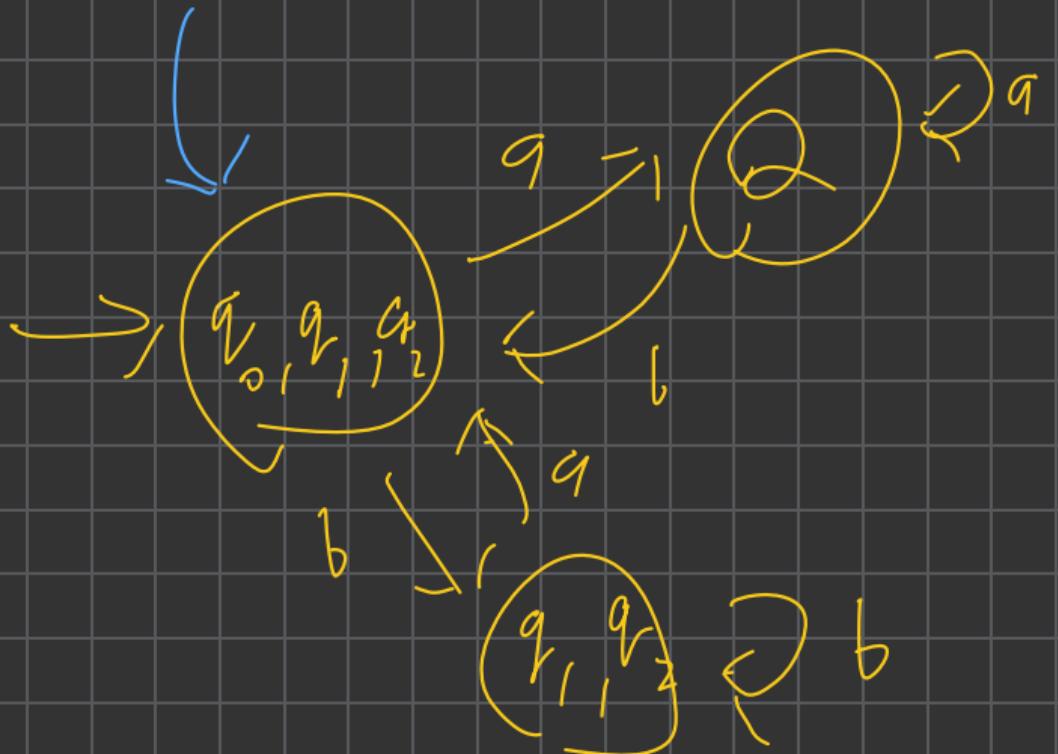


8. Using the subset construction, build a DFA that accepts the same language. Give the graphical representation of this DFA, clearly indicating the set of NFA states associated to each DFA state. Show only the reachable states.

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

$$E(q_0, q_3) = \emptyset$$

$$E(q_1) = \{q_1, q_2\}$$



W2 P1

Problem 1 (Week 2)

Give regular expressions for each of the following subsets of $\{a, b\}^*$.

(a) $\{x : x \text{ contains an even number of } a's\}$

L

$L' := \{x : x \text{ contains 2 } a's\}$

$\overbrace{\quad\quad\quad}^a$
 $\overbrace{\quad\quad\quad}^a$
 $\overbrace{\quad\quad\quad}^a$
 b's b's b's

Regular expression
 for L'
 $b^* a b^* a b^*$

try for L

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

(counterexamples

are

b

$b b$

$,$

$:$

Correct is

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

Another way is

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

Problem 1 (Week 2)

Give regular expressions for each of the following subsets of $\{a, b\}^*$.

- (b) $\{x : x \text{ contains an odd number of } b's\}$

Problem 1 (Week 2)

Give regular expressions for each of the following subsets of $\{a, b\}^*$.

- (c) $\{x : x \text{ contains an even number of } a\text{'s or an odd number of } b\text{'s}\}$

W2 P2

Problem 2 (Week 2)

Convert the following regular expressions into DFAs:

(a) $(0 \cup 1) \cdot (0 \cup 1) \cdot (0 \cup 1)$



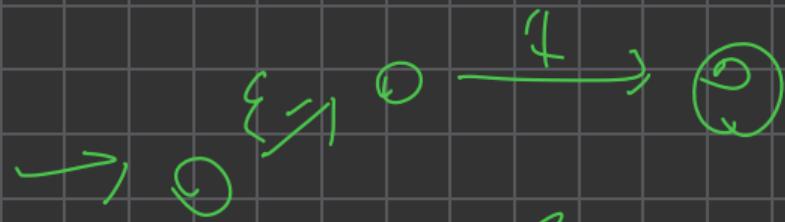
$$R = (0 \cup 1)$$

union of ϵ -NFA for 0:



with the ϵ -NFA for 1

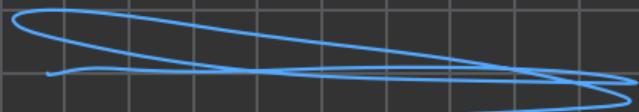




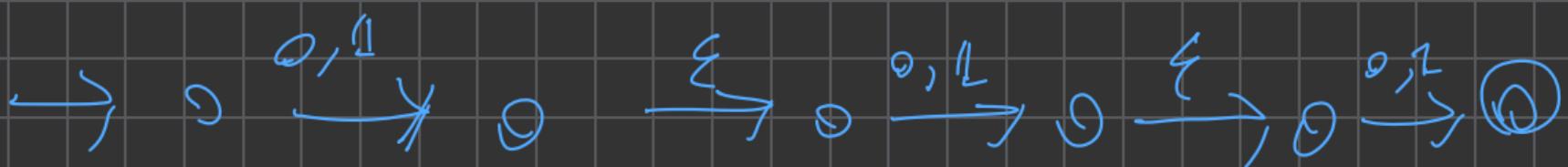
For $\neg q \vee \neg q$ is $\neg q$



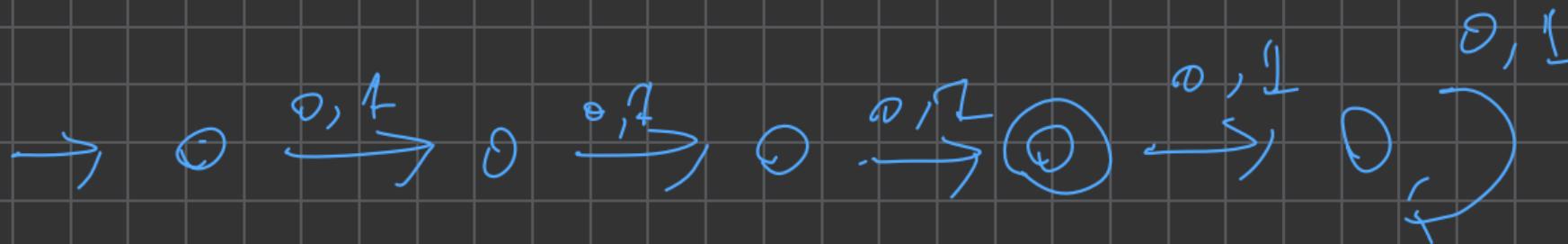
(For $(0 \vee 1)$)



To get $(0 \vee 1) \cdot (0 \vee 1) \cdot (0 \vee 1)$



To get DFA:



Problem 2 (Week 2)

Convert the following regular expressions into DFAs:

(b) $0^* \cdot 1^*$

Problem 2 (Week 2)

Convert the following regular expressions into DFAs:

(c) $(0 \cup 1^*) \cdot (0^* \cup 1)$

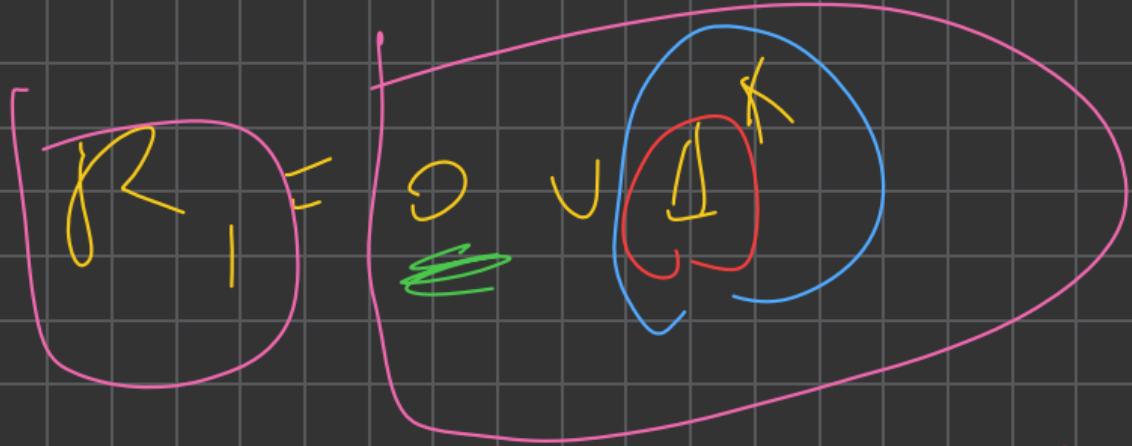
$$(\mathbb{O} \cup \mathbb{L}^*) \circ (\mathbb{L} \cup \mathbb{O}^*)$$

$$R_1 = \mathbb{O} \cup \mathbb{L}^*$$

$$R_2 = \mathbb{L} \cup \mathbb{O}^*$$

~~Want $R_1 \cdot R_2$~~

Want $R_1 \cdot R_2$

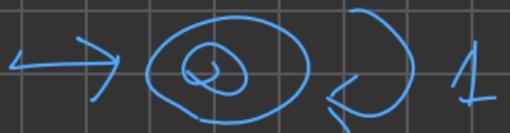


$\rightarrow Q$

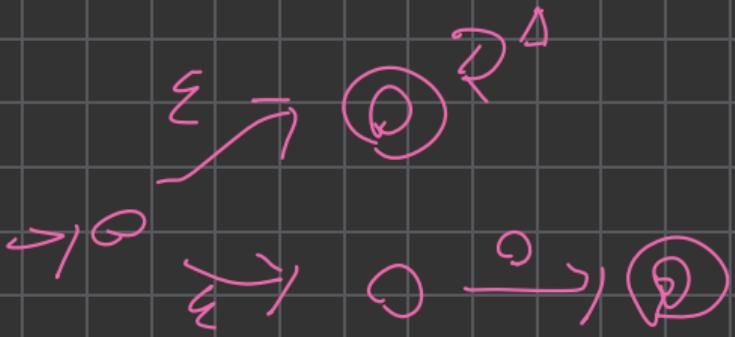
$\rightarrow Q$

$\rightarrow Q$ $\rightarrow Q$ $\rightarrow Q$

For A^* , simplify to



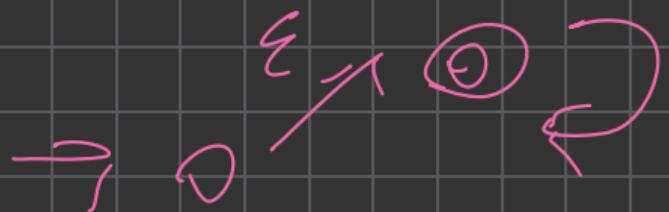
Combine with $O \left(\rightarrow O \xrightarrow{O} O \right)$



Simplify to $\rightarrow O \xrightarrow{A^*} O$



$$R_2 = \perp \vee \textcircled{e}^*$$

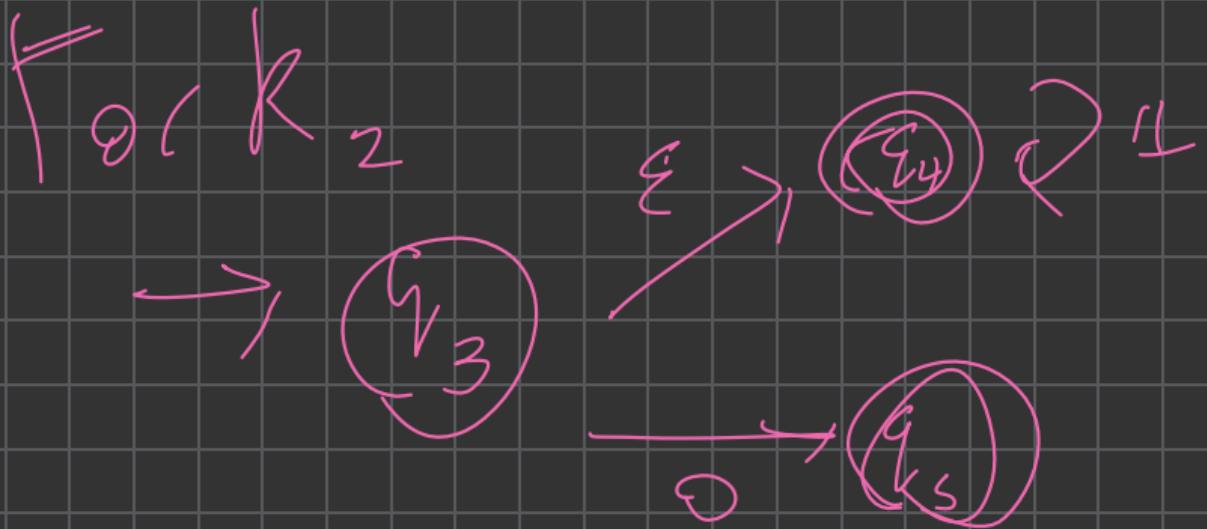


Simplify to



F_{oil} $R,$





1



$\epsilon \nearrow q_1$

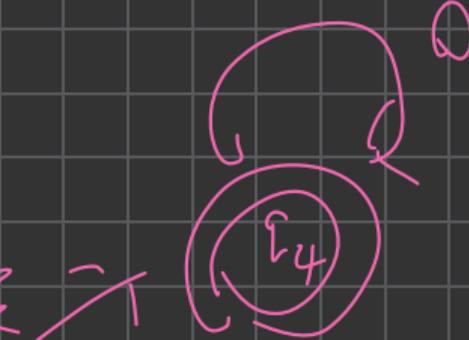
$\rightarrow q_0$

\downarrow



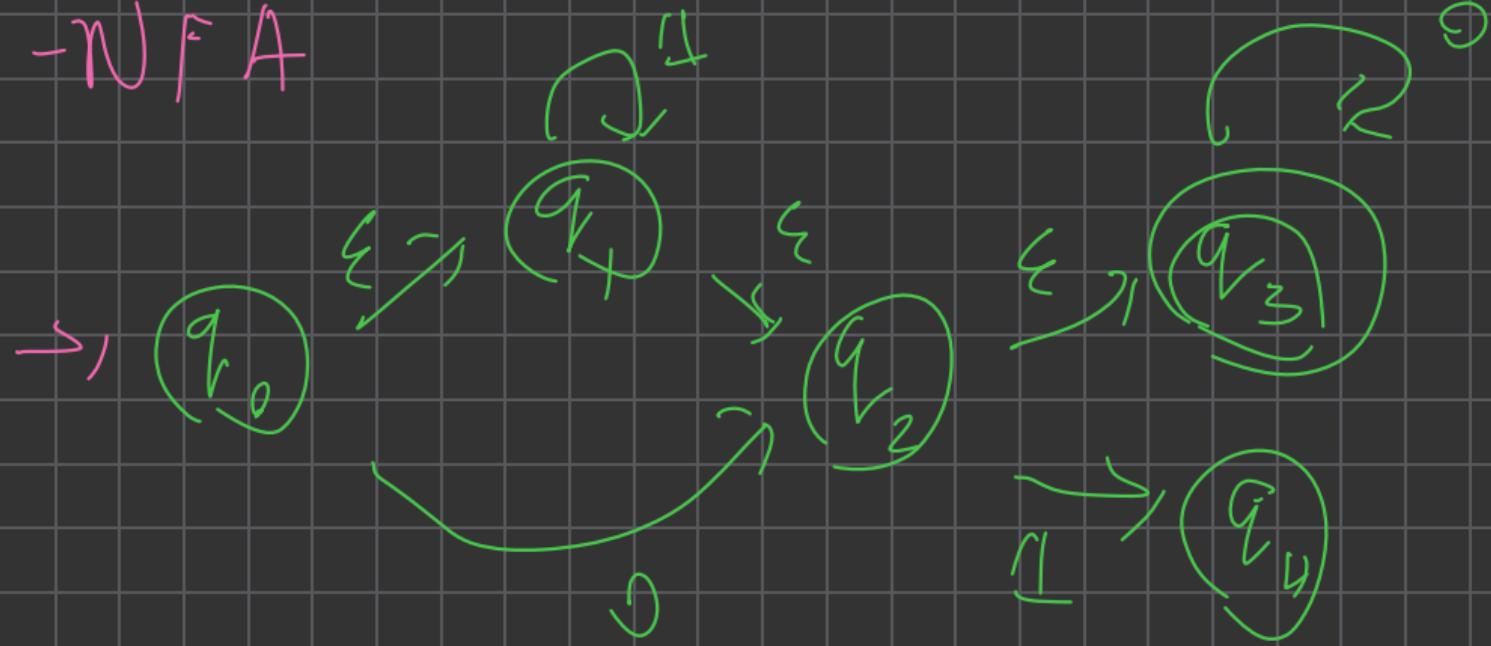
q_3

$\epsilon \nearrow$

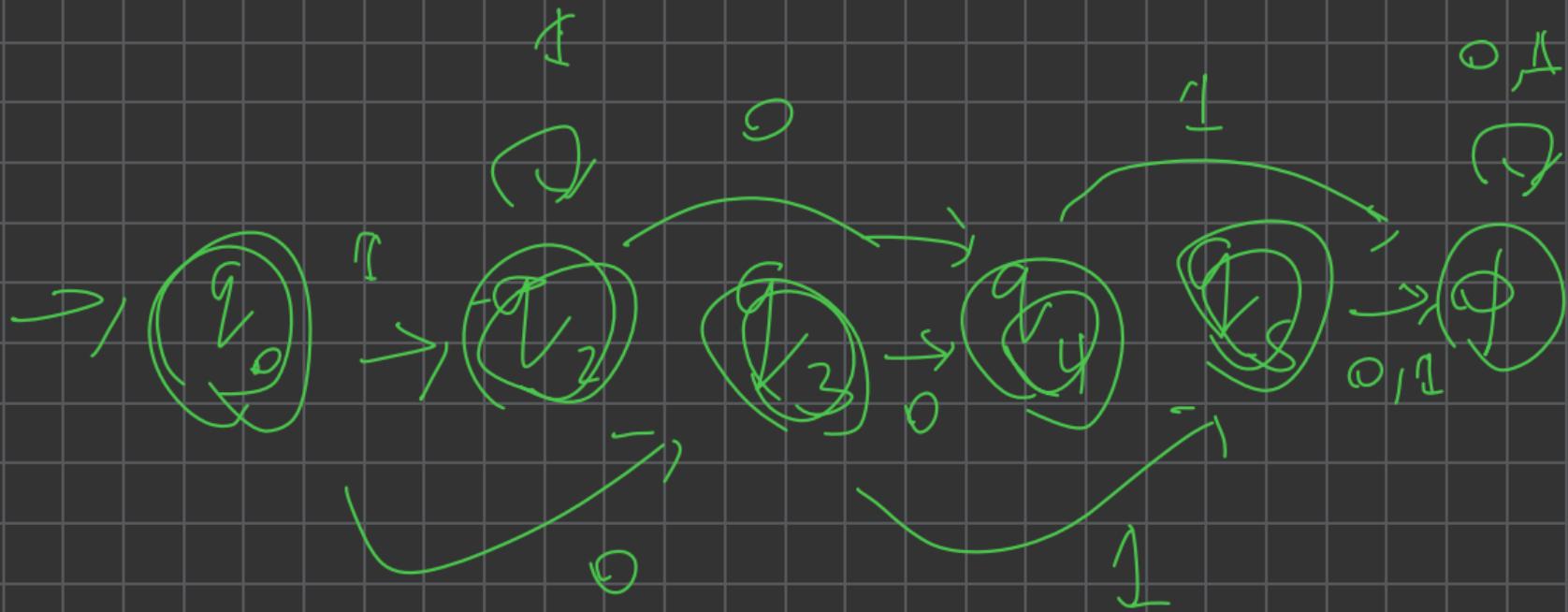


1

ϵ -NFA



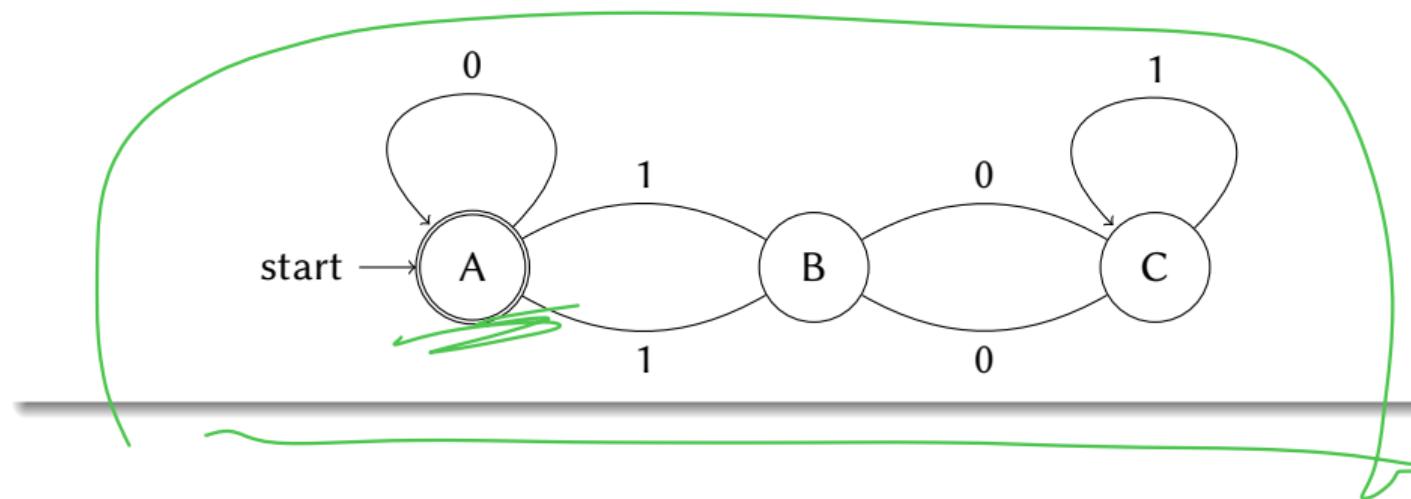
After Wock: $\emptyset \models A$



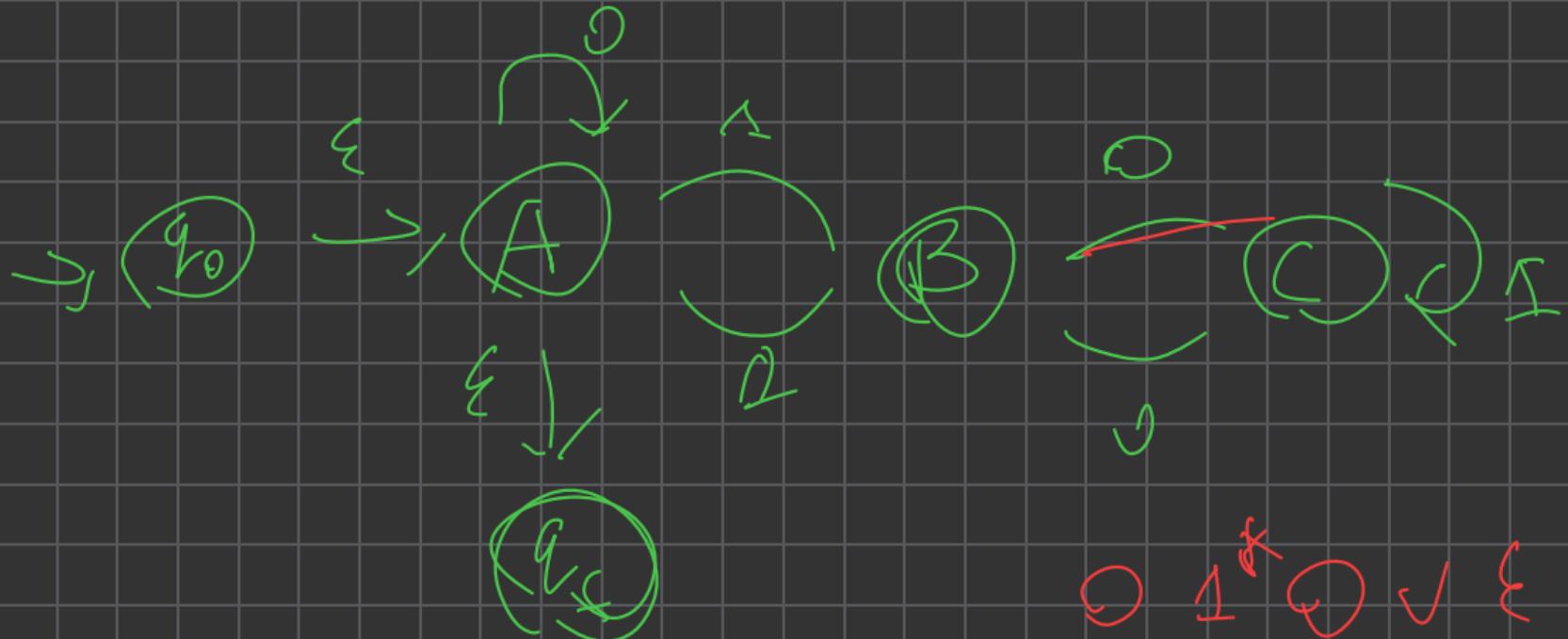
W2 P3

Problem 3 (Week 2)

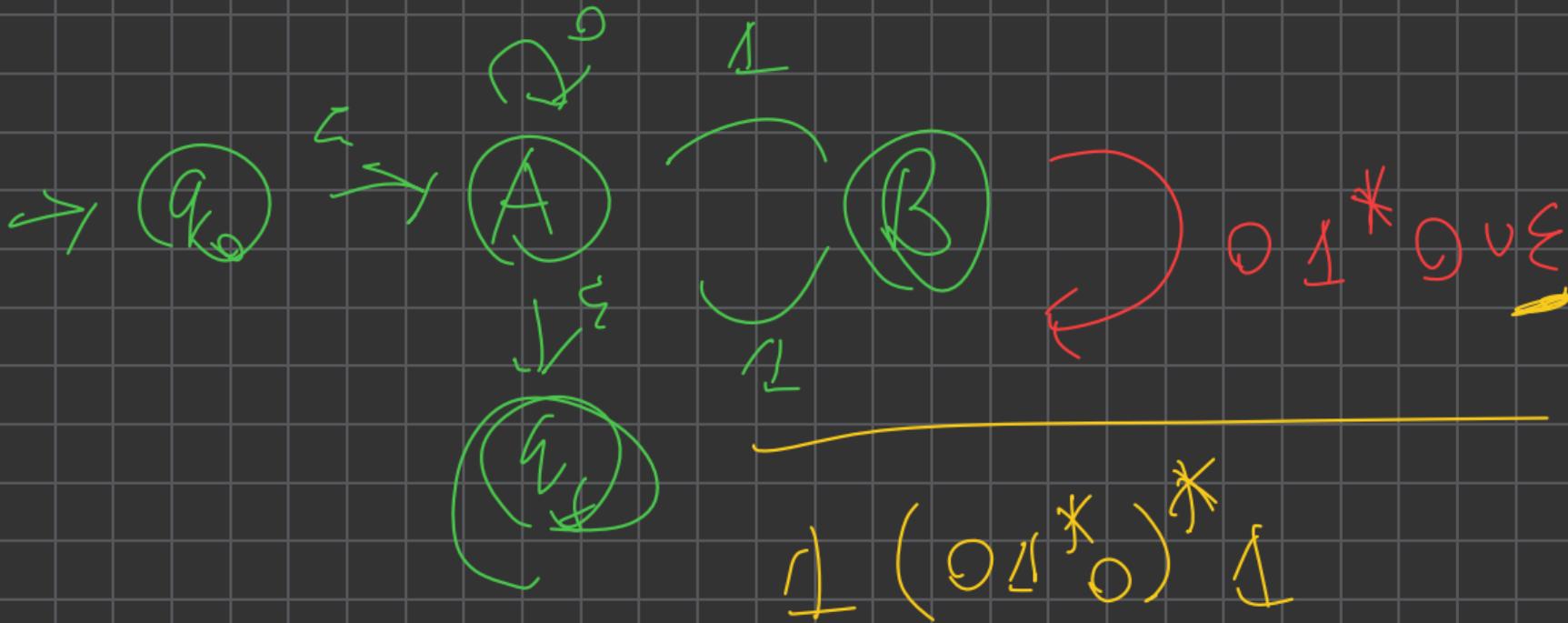
Give a regular expression that matches the language of the following DFA:

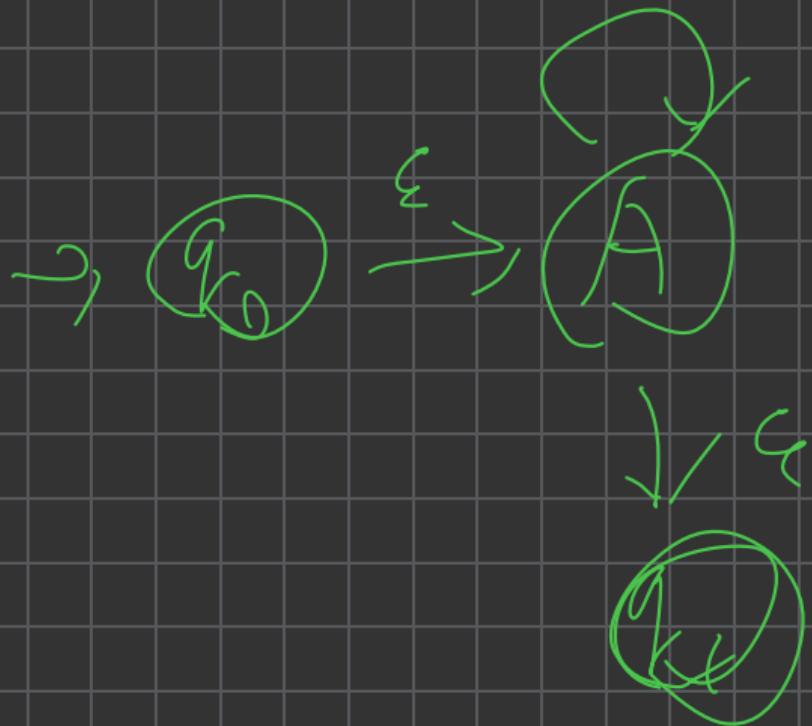


Build GNFA



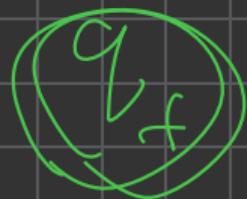
Get rid of C



$$0 \vee \perp (0 \perp *_0) * \perp$$




$\left[\epsilon \cup (0 \cup 1 (01^*)^* 1)^* \right] \times$



$\left[\epsilon \cup (0 \cup 1 (01^*)^* 1)^* \right]$

Regular
expression

W2 P4

Problem 4 (Week 2)

Show that the following languages are not regular:

- (a) $\{0^i 1^j : 0 \leq i \leq j\}$

Problem 4 (Week 2)

Show that the following languages are not regular:

- (b) $\{w \in \{0, 1\}^*: \text{the number of } 0\text{'s in } w \text{ is equal to the number of } 1\text{'s in } w\}$

Problem 4 (Week 2)

Show that the following languages are not regular:

- (c) $\{ww : w \in \{0, 1\}^*\}$



Bonus

Discussion

- (a) Given an NFA A , how can you determine if $L(A) = \emptyset$?
- (b) Using the above process, outline an algorithm that takes two regular expressions E_1 and E_2 and determines if $L(E_1) \subseteq L(E_2)$.
- (c) If $|E_1| = n$ and $|E_2| = m$, what is an upper bound (using big-O notation) for the number of states in the DFA that is used in the previous algorithm.