

# COMP11212 - Fundamentals of Computation

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## Introduction

The building of real-life computing systems, e.g. mobile phone, tv/video remote control, internet shopping, air-traffic control, internet banking, etc., is always a complex task. Mistakes can be very annoying, costly and sometimes life threatening. Methods and techniques to support the building and understanding of such systems are essential. This course unit provides an introduction to the basic computer science ideas underlying such methods. It is also a part of, and an introduction to, the Modelling and Rigorous Development theme.

# Aims

This course unit provides a first approach to answering the following questions. What methods are there that can help understanding complicated systems or programs? How can we make sure that a program does what we intend it to do? How do computers go about recognizing pieces of text? If there are two ways of solving the same problem, how can we compare them? How do we measure that one of them gives the solution faster? How can we understand what computers can do in principle, and are there problems that are not solvable by a computer?

## Additional reading

None.

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# 1 Terminology

In order to talk about Strings in any meaningful way, we must first define terminology that we can use to describe exactly what we mean. What follows is a list of the terminology used throughout the course:

- A **symbol** is basically a letter. They are the basic component of all the data we use in the course. Examples include:  $a$ ,  $A$ ,  $($ ,  $\$$ ,  $\gamma$ .
- An **alphabet** is a collection of symbols that we can think of as a set. Example alphabets may include binary  $(0, 1)$ , Latin letters  $(a, \dots, z, A, \dots, Z)$  etc.
- A **String** is a collection of symbols from an alphabet grouped together, sometimes called a word. Examples include *ababa* and *100101*.
- The *empty word* is a String consisting of no symbols. It is denoted by the letter  $\epsilon$ .
- **Concentration** an operation that takes two Strings and combines them to create one longer String. For example concentrating *t* and *he* would create *the*. We can use the power notation to concentrate a String with itself any number of times. For example,  $ho^3$  would give us *hohoho*.
- A **language** is a collection of Strings that can be thought of as a set. Examples of languages could be  $\{\emptyset\}$ ,  $\{\epsilon\}$ ,  $\{hot, hotter, hottest\}$  or  $\{a^n | n \in \mathbb{N}\}$ .

We also have notation for describing generic instances of such entities:

Entity	Generic notation
Symbol	$x, y, z$
Alphabet	$\Sigma$
String	$s, t, u$
Language	$\mathcal{L}$

**Languages as sets** Since languages are thought of as sets, we can perform all the usual set operations on them (see my COMP11120 notes for more information on these operations). Languages can be concentrated as described above.

Sometimes, we may want to define any finite number of concatenations of a language, and this is known as the **Kleene star**. The notation is  $(\mathcal{L})^*$ .

An interesting case of this is when a languages is subject to concatenation zero times  $(\mathcal{L}^0)$ , since this would return the empty word  $\epsilon$ .

Note:

*Kleene* is pronounced like *genie*.

## 2 Describing languages

### 2.1 Describing languages through patterns

A pattern describes a generic form that a set of Strings can take. If any String from the set is compared with the pattern then it will match the pattern. Any String from outside the set will not match the pattern.

For example, the pattern  $(ab)^*$  would match Strings such as  $\epsilon$ ,  $ab$ ,  $abab$ ,  $abab \dots ab$ .

Note:

$\epsilon$  is matched here since it satisfies the pattern  $(ab)^0$ . This comes about because, the Kleene star matches all concatenations of a String.

## 2.2 Regular expressions

The terms *pattern* and *regular expression* are pretty much synonymous. The operators allowed in a regular expression are:

<b>Empty pattern</b>	The character $\emptyset$ is a pattern.
<b>Empty word</b>	The character $\epsilon$ is a pattern.
<b>Letters</b>	Every letter in $\Sigma$ is a pattern.
<b>Concatenation</b>	If $x$ and $y$ are patterns, then so is $(xy)$ .
<b>Alternative</b>	If $x$ and $y$ are patterns, then so is $(x y)$ .
<b>Kleene Star</b>	If $x$ is a pattern, then so is $(x^*)$ .

Note:

If we were to analyse a pattern in a recursive fashion, then in order to end our analysis, we would eventually have to find one of a selection of *base cases*. The highlighted rows here represent *step cases* (that is to say that at least another level of recursion is needed to finish our analysis), while the un-highlighted lines are base cases.

### 2.2.1 Discarding brackets

Just like in high-school mathematics, brackets can be discarded when unnecessary. For example, the pattern  $((0|1)^*0)$  is equivalent to  $(0|1)^*0$ , and  $(2|(1|0))$  is the same as  $(2|1|0)$ .

### 2.2.2 Matching a regular expression

As was implied above, we can define a regular expression by recursively applying more operators to a ‘base case’ until we have the desired pattern.

The following patterns match the following words:

<b>Empty word</b>	The empty word only matches the pattern $\epsilon$ .
<b>Base case</b>	A pattern $x$ will match a character $x$ where $x$ is a member of $\Sigma$
<b>Concatenation</b>	If $p_1$ is a pattern and $p_2$ is a pattern, then $p_1p_2$ will match any word matched by $p_1$ prepended to and word matched by $p_2$
<b>Alternative</b>	$(p_1 p_2)$ will match a word from either $p_1$ or $p_2$ .
<b>Kleene star</b>	The pattern $(p^*)$ will match any number of words that are matched by $p$ concatenated with each other. It also matches the empty word.

## 2.3 Languages described by regular expressions

A language  $\mathcal{L}$  described by a regular expression  $p$  is one made up of every word  $s$  that is matched by  $p$ :

$$\mathcal{L}(p) = \{s \in \Sigma^* \mid s \text{ matches } p\}$$

Obviously, we can describe the same language using different patterns, for example:

$$\mathcal{L}((1|1)(0|0)) = \mathcal{L}(10)$$

We can find out the exact language defined by a pattern in the following manner:

$$\begin{aligned}\mathcal{L}((0|1)(1)^*) &= \mathcal{L}(0|1) \cdot \mathcal{L}(1^*) \\ &= \mathcal{L}(0) \cup \mathcal{L}(1) \cdot \mathcal{L}(1^*) \\ &= \mathcal{L}(0) \cup \mathcal{L}(1) \cdot \mathcal{L}(1)^* \\ &= \{0\} \cup \{1\} \cdot \mathcal{L}(1)^* \\ &= \{0\} \cup \{1\} \cdot \{1\}^*\end{aligned}$$

### 2.3.1 Regular languages

We say that a language is regular if we can describe the language by defining a regular expression.



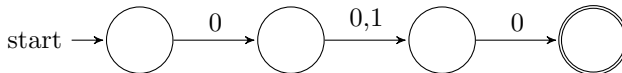
# 3 Finite State Automata

It is often useful to be able to describe languages using pictures. These are called finite state automata (FSA's). Every FSA must have the following things:

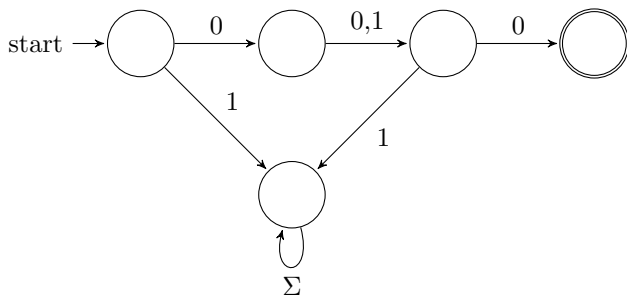
- One or more states.
- Arrows between states with labels directing the required conditions to traverse the arrow.
- A start state (indicated by an arrow with it's tail free).
- One or more accepting states. If we end up here after traversing the automation, then it will match our word.

## 3.1 Example automata

Here is an automata that will match the pattern  $0(0|1)0$ :



If we wanted to, we could include all the *dump states* in the automata. Dump states are states that once entered into, it is impossible to reach an accepting state. The same automata with a dump state in would look like:



## 3.2 Formalising the automata

If we wanted to, we could define the set  $Q$  as the set of states in an automata, and the set  $F$  as the set of the accepting states, where  $F \subset Q$ . The transitions in the automata could be represented as a function  $\delta$ , which takes an input state  $s_{in} \in Q$ , and a character  $c \in \Sigma$ , and returns another state  $s_{out} \in Q$ .

$$\delta : \{(s_{in}, c) | s_{in} \in Q, c \in \Sigma\} \rightarrow Q$$

Note:

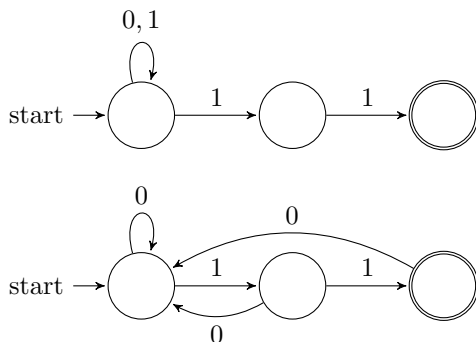
When an automata is defined like this, it can be seen as a *finite state machine*

## 3.3 Deterministic and non-deterministic automata

An automata is said to be deterministic if there is only one path through it for every word in  $\mathcal{L}$ , however, if there are

multiple possible routes through an automata (i.e. there is no unique path for one or more words), then we say that the automata is non-deterministic.

Here is an example of a deterministic and a non-deterministic automata that will accept the language of words defined by the pattern  $(0|1)^*(11)$ :

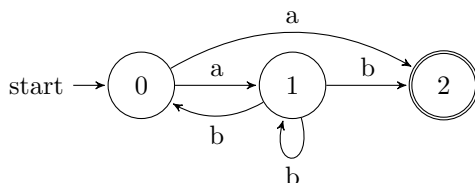


## 4 Algorithm one

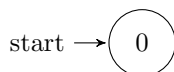
Algorithm one is a method for converting an NFA to a DFA. In order to do this, algorithm one walks through an NFA, in a recursive manner, finding all the possible collections of states that can be reached from each state. Unfortunately, this behaviour is hard to describe in a general and abstract manner, so it's probably easiest to just do an example.

### 4.1 Algorithm one example

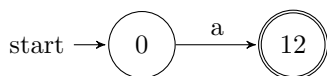
We'll do Exercise 19 in Andrea's notes, which is to convert the following NFA into a DFA:



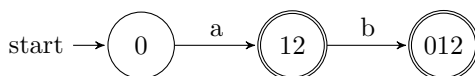
In order to apply algorithm one to this automata, we first need to write down the start state:



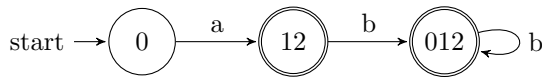
From the state 0, we can go to the state 1 or the state 2 with an  $a$  transition, therefore algorithm one dictates that we have to create a new state in our DFA called 12 that is linked to the state 0 with an  $a$  transition. Since 2 is an accepting state in the NFA, then our new state must also be an accepting state.



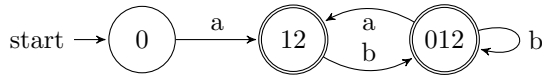
Now, we've dealt with the 0 state, we must concern us with where we can go from the state 12. Since this represents both the state 1 and the state 2 in the NFA, we must consider the transitions we can do from either of them. From state 1 in the NFA, we can go to either state 0, 1 or 2 with a  $b$  transition. Consequently, we should make a new state in our DFA for this:



From the state 0, 1 and 2, we can go anywhere with a  $b$ , so we should make a transition in our DFA for that:



From the states 0, 1 or 2 in the NFA, we can go to the states 1 or 2 with an  $a$  transition:



### Note:

If you want a formal definition of algorithm one, take a look at page 33 of Andrea's notes. although it's well explained, I don't think it's worth including here, since the formal definition won't be very useful in the exam.

## 5 Algorithm two

Algorithm two takes a DFA and converts it into a regular expression. If you want to convert an NFA into a regular expression, then you must first convert it into a DFA using algorithm one.

### 5.1 Numbering states

Algorithm two relies on us having named all the states in the DFA before we attempt to apply the algorithm. Although in theory, the algorithm will work with any state numbering, it is easiest to apply when the states are ordered in *reverse order of complexity*. That is to say that the states with the fewest connections will have the lowest number.

### Note:

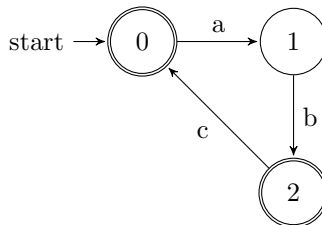
The numbering of the states isn't vital. If you get one or two the wrong way round, then it probably won't make the algorithm too complicated. Also, whether the algorithm is an acceptance state has no bearing on its number.

## 5.2 Applying algorithm two

First of all, we must determine which states a word from the language  $\mathcal{L}$  accepted by the automation must start and end in. In order to do this, we must find the start states and all of the possible end states:

$$\mathcal{L} = \mathcal{L}_{start \rightarrow accepting_0} \cup \mathcal{L}_{start \rightarrow accepting_1} \cup \dots \cup \mathcal{L}_{start \rightarrow accepting_n}$$

If the automation we were looking at was something like this:



Then the language described by the automation would be:

$$\mathcal{L} = \mathcal{L}_{0 \rightarrow 0} \cup \mathcal{L}_{0 \rightarrow 2}$$

We must now break down this expression into its component parts,  $\mathcal{L}_{0 \rightarrow 0}$  and  $\mathcal{L}_{0 \rightarrow 2}$  and evaluate them individually.

$$\mathcal{L}_{0 \rightarrow 0}^{\leq 2} = \mathcal{L}_{0 \rightarrow 0}^{\leq 1} \cup \left( \mathcal{L}_{0 \rightarrow 2}^{\leq 1} \cdot \mathcal{L}_{2 \rightarrow 2}^{\leq 1 *} \cdot \mathcal{L}_{2 \rightarrow 0}^{\leq 1} \right)$$

$$\mathcal{L}_{0 \rightarrow 0}^{\leq 1} = \epsilon$$

$$\begin{aligned} \mathcal{L}_{0 \rightarrow 2}^{\leq 1} &= \mathcal{L}_{0 \rightarrow 2}^{\leq 0} \cup \left( \mathcal{L}_{0 \rightarrow 1}^{\leq 0} \cdot \mathcal{L}_{1 \rightarrow 1}^{\leq 0 *} \cdot \mathcal{L}_{1 \rightarrow 2}^{\leq 0} \right) \\ &= \emptyset \cup (a \cdot \epsilon^* \cdot b) \\ &= ab \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{2 \rightarrow 2}^{\leq 1} &= \mathcal{L}_{2 \rightarrow 2}^{\leq 0} \cup \left( \mathcal{L}_{2 \rightarrow 1}^{\leq 0} \cdot \mathcal{L}_{1 \rightarrow 1}^{\leq 0 *} \cdot \mathcal{L}_{1 \rightarrow 2}^{\leq 0} \right)^* \\ &= \epsilon \cup (ca \cdot \epsilon^* \cdot b)^* \\ &= \epsilon | (cab)^* \end{aligned}$$

$$\mathcal{L}_{2 \rightarrow 0}^{\leq 1} = c$$

$$\mathcal{L}_{0 \rightarrow 0}^{\leq 2} = \epsilon | ab(cab)^* c$$

$$\begin{aligned} \mathcal{L}_{0 \rightarrow 2}^{\leq 2} &= \mathcal{L}_{0 \rightarrow 2}^{\leq 1} \cdot \mathcal{L}_{2 \rightarrow 2}^{\leq 1 *} \\ &= \{ab\} \cdot \{(cab)^*\} \\ &= ab(cab)^* \end{aligned}$$

We can now just concatenate the two languages we found and simplify the resulting regular expression:

$$\begin{aligned} \mathcal{L} &= \epsilon | ab(cab)^* c \cup ab(cab)^* \\ &= \epsilon | ab(cab)^* (c | \epsilon) \end{aligned}$$

## 6 Algorithm three

The role of algorithm three is to construct a non-deterministic finite automata from a regular expression.

Algorithm three recursively analyses the regular expression into small chunks of NFA and then makes use of *epsilon transitions* to link these parts together.

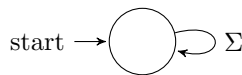
### Note:

An epsilon transition is a transition between states in the NFA that does not require a letter from the word to be traversed. This allows you to join NFA's together.

There are a number of general cases in algorithm three, where a regular expression of a particular form will create an NFA with a certain structure:

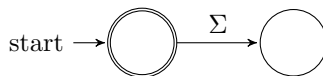
### The empty pattern $\emptyset$ :

A regular expression that accepts no words will produce an NFA like this:



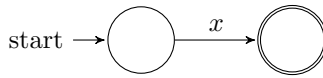
### The $\epsilon$ pattern:

A regular expression that the empty word will produce an NFA like this:



### A pattern accepting a word $x, x \in \Sigma$ :



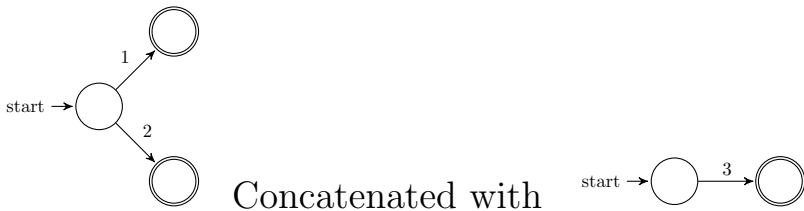


In order to produce a meaningful NFA, we must also handle cases where regular expressions implement concatenation, alternatives and the kleene star:

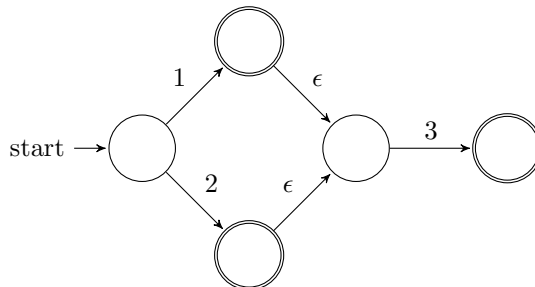
### Concatenation:

In order to create an NFA that will recognise the same language as a pattern that uses concatenation (e.g.  $xy$ ), we must first create two NFA's to accept each half of the concatenation, lets call these  $X$  and  $Y$ . In order to connect them, we must change all the accepting states in  $X$  to non-accepting states and make an  $\epsilon$  transition from them to the start state of  $Y$ .

For example:



Goes to:

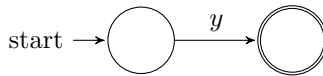
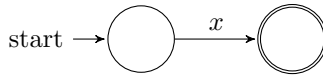


### Alternative:

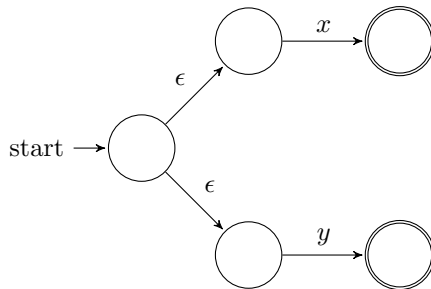
To create an NFA that implements an alternative such

as  $x|y$ , then we must make a new NFA that has a start state that connects to the other NFA's that will accept  $x$  and  $y$  with  $\epsilon$  transitions:

For example:



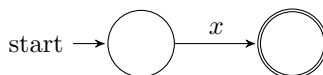
Combine to make:



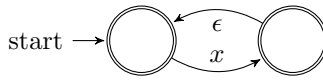
## Kleene star:

To implement a Kleene star with an NFA, you simply create an epsilon transition from each accepting state in the NFA to the start state, and make sure that the start state is an accepting state.

For example:

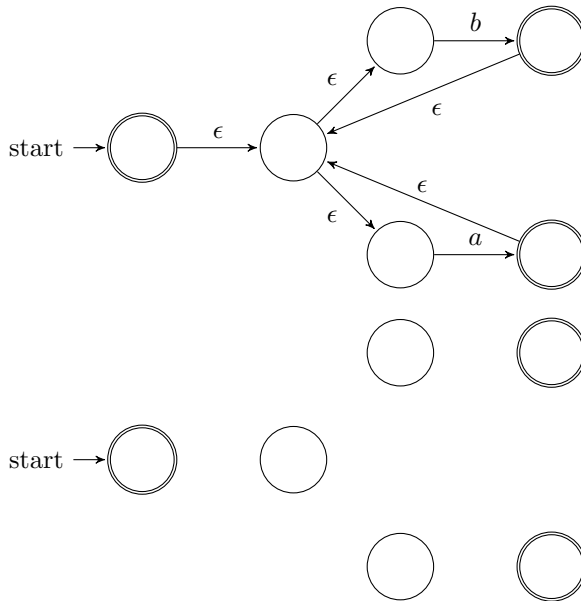


Goes to:

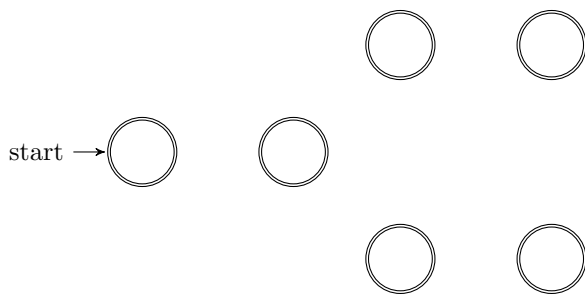


## 7 Algorithm four

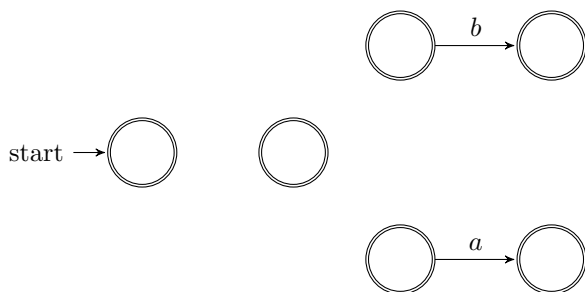
The purpose of algorithm four is to convert an NFA into a DFA. In order to do this, you start with an NFA and then create a new automation with the same states as the NFA, but with no transitions:



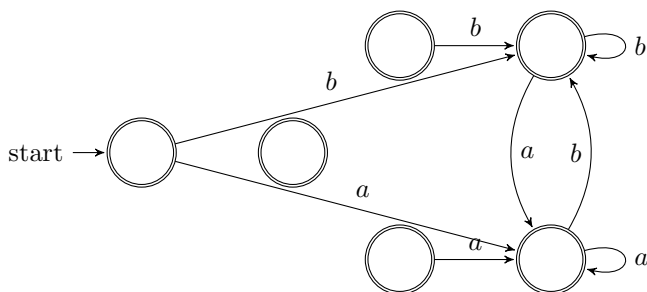
We then look at each non-accepting state, and if we can reach it using *only* epsilon transitions from an accepting state, then we convert that non- accepting state to an accepting state.



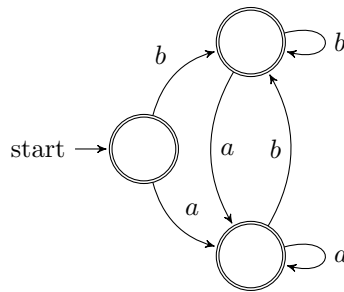
Then we copy all of the transitions with a letter (not  $\epsilon$ ) to the new automaton.



Then we look at all the transitions where an actual letter is involved, and see if there are epsilon transitions leading to the start state for that transition, in which case we can link the state where the epsilon transition started to the end state of the letter transition.



Then we can take out the states that have no input transitions:



### Note:

You can see that this automata accepts all the words matching the pattern  $(a|b)^*$ , which obviously could be represented by a different, more concise DFA. However, the goal of algorithm four isn't to produce efficient an efficient DFA, only to get rid of the epsilon transitions while still maintaining the same set of accepted words.