

Formal Languages and Automata Theory

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<https://www.cse.cuhk.edu.hk/~siuon/csci3130>

Tentative syllabus and schedule

Reference book

Introduction to the Theory of Computation, Michael Sipser

Please sign up on [piazza.com](https://www.piazza.com) and ask questions

Or come to our office hours

Computers can chat with you

<https://lacker.io/ai/2020/07/06/giving-gpt-3-a-turing-test.html>

Human: What is your favorite animal?

AI: My favorite animal is a dog.

Human: Why?

AI: Because dogs are loyal and friendly.

Human: What are two reasons that a dog might be in a bad mood?

AI: Two reasons that a dog might be in a bad mood are if it is hungry or if it is hot.

Human: How many eyes does a giraffe have?

AI: A giraffe has two eyes.

Human: How many legs does a frog have?

AI: A frog has four legs.

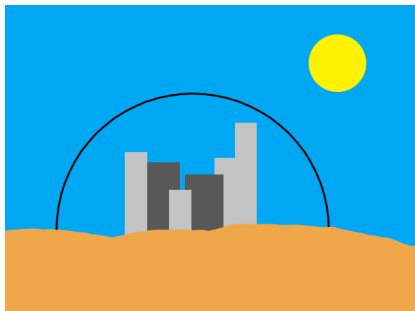
Human: Are there any animals with three legs?

AI: No, there are no animals with three legs.

Human: Why don't animals have three legs?

AI: Animals don't have three legs because they would fall over.

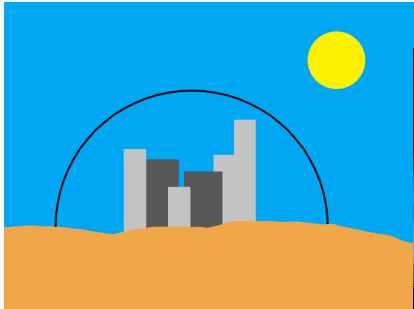
AI generated image (Stable diffusion)



A distant futuristic city full of tall buildings inside a huge transparent glass dome, In the middle of a barren desert full of large dunes, Sun rays, Artstation, Dark sky full of stars with a shiny sun, Massive scale, Fog, Highly detailed, Cinematic, Colorful

Source: https://www.reddit.com/r/StableDiffusion/comments/wzlnty/its_some_kind_of_black_magic_i_swear/

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Is there anything that a computer **cannot** do?

Impossibilities

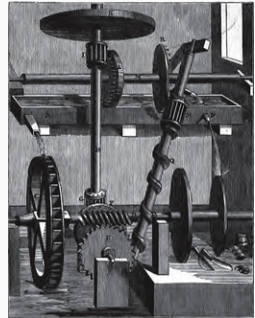
Why care about the **impossible**?

Example from Physics:

Since the Middle Ages, people tried to design machines that use no energy

Later physical discoveries forbid creating energy out of nothing

Perpetual motion is **impossible**



“water screw” perpetual
motion machine

Understanding the **impossible** helps us to focus on the **possible**

Laws of computation

Just like [laws of physics](#) tell us what are (im)possible in nature...

$$\Delta U = Q + W \qquad dS = \frac{\delta Q}{T} \qquad S - S_0 = k_B \ln \Omega$$

[Laws of computation](#) tell us what are (im)possible to do with computers

Part of computer [science](#)

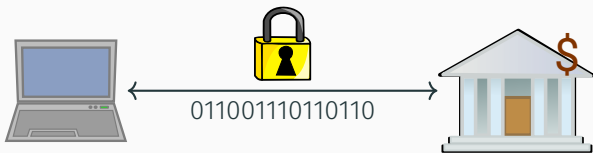
To some extent, laws of computation are studied in [automata theory](#)

Exploiting impossibilities

Certain tasks are believed impossible to solve quickly on current computers

Given $n = pq$ that is the product of two unknown primes, find p and q

Building block of **cryptosystems**



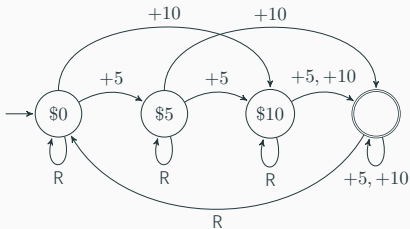
Candy machine



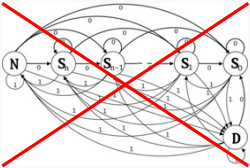
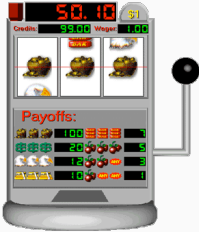
Machine takes \$5 and \$10 coins

A gumball costs \$15

Actions: +5, +10, Release

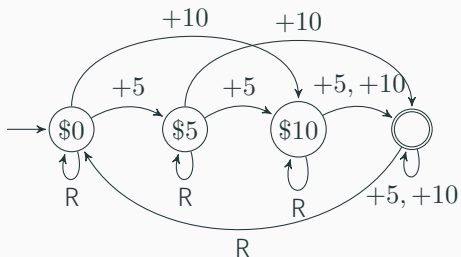


Slot machine



Why?

Different kinds of machines



Only one example of a machine

We will look at different kinds of machines and ask

- what kind of **problems** can this kind of machines **solve**?
- What are **impossible** for this kind of machines?
- Is **machine A** more powerful than **machine B**?

Machines with different resources in this course

finite automata	Devices with a small amount of memory These are very simple machines
push-down automata	Devices with unbounded memory that can be accessed in a restricted way Used to parse grammars
Turing machines	Devices with unbounded memory These are actual computers
time-bounded Turing Machines	Devices with unbounded memory but bounded running time These are computers that run fast

- Finite automata

Closely related to [pattern searching in text](#)

Find $(ab)^*(ab)$ in abracadabra

- Grammars

- Describe the meaning of sentences in English, and the meaning of programs in Java (or any language)
- Useful for natural language processing and compilers

Turing machines

- General model of computers, capturing anything we could ever hope to compute
- Still, computers cannot do many things

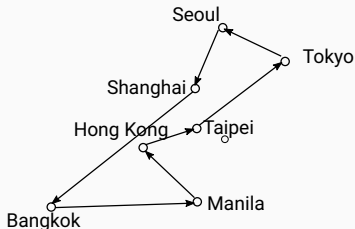
Given a program, tell if it prints the string “3130”

```
#include <stdio.h>
main(t,_,a)char *a;{return!0<t?t<3?main(-79,-13,a+main(-87,1-_,
main(-86,0,a+1)*a)):1,t<_?main(t+1,_,a):3,main(-94,-27*t,a)66t++?<13?
main(2,_,+1,"%s %d %d\n"):9:16:t<0?t<-72?main(,t,
"@n'*,#/'*{}w+/wcdnr/*,{}r/*de}*,/*{**,/w{**,/w#q#n*,#{l,*,/n{n+,*#n+,#\
;q#n+,*k#;*,/'r : 'd*3,}{w*K w'K:'}e#';dq#'l \
q#*d'K#!/*k#;q#*r}eKK#w'r}eKK{nl}'/#;q#n'})}{nl}'/*#n';d}rw' i;# \
){nl}!/n{n#'; r{w'r nc{nl}'/#{l,*'K {rw' iK;[nl]'/w#q#n'wk nw' \
iwk{KK{nl]!/w{#l#w#w' i; :{nl}'/*{q#l'd;r'}{nlwb}'/de}'c \
;;{nl}'-}{rw}'/*,}##'*)#nc,'#nw}'/*kd'+e};#rdq#w! nr/' ')}{rl#n' ')}# \
};*}##(1/"
:t<-50?_==a?putchar(31[a]):main(-65,_,a+1):main((*a=='/')+t,_,a+1)
:0<t?main(2,2,"%s"):a=='/'||main(0,main(-61,a,
"iek;dc iqbk'(q)-[w]*%n+r3#l,{}:n\w\loca-0;m .vpbks,fxntdCeghiry"),a+1);}
```

Formal verification of software must fail on corner cases

Time-bounded Turing machines

- Many problems can be solved on a computer **in principle**, but it takes too much time in practice
- **Traveling salesperson**: Given a list of cities, find the shortest way to visit them all and return home



- For 100 cities, takes **100+ years** to solve even on the fastest computer!

Can machine A solve problem B ?

- Examples of problems we will consider
 - Given a **word** s , does it contain “to” as a subword?
 - Given a **number** n , is it divisible by 7?
 - Given **two words** s and t , are they the same?
- All of these have “yes/no” answers (**decision** problems)
- There are other types of problems, like “**Find this**” or “**How many of that**” but we won’t look at them

Alphabets and Strings

- **Strings** are a common way to talk about words, numbers, pairs of numbers

Which symbols can appear in a string? As specified by an alphabet

An **alphabet** is a finite set of symbols

- Examples
 - $\Sigma_1 = \{a, b, c, d, \dots, z\}$: the set of English letters
 - $\Sigma_2 = \{0, 1, 2, \dots, 9\}$: the set of digits (base 10)
 - $\Sigma_3 = \{a, b, c, \dots, z, \#\}$: the set of letters plus special symbol #

Strings

An input to a problem can be represented as a string

A string over alphabet Σ is a finite sequence of symbols in Σ

axyzzy is a string over $\Sigma_1 = \{a, b, c, \dots, z\}$

3130 is a string over $\Sigma_2 = \{0, 1, \dots, 9\}$

ab#bc is a string over $\Sigma_3 = \{a, b, \dots, z, \#\}$

- The **empty string** will be denoted by ε
(What you get using "" in C, Java, Python)
- Σ^* denotes the set of **all strings** over Σ
All possible inputs using symbols from Σ only

A language is a set of strings (over the same alphabet)

Languages describe problems with “yes/no” answers:

$L_1 =$ All strings containing the substring “to” $\Sigma_1 = \{a, \dots, z\}$

stop, to, toe are in L_1

ϵ , oyster are not in L_1

$$L_1 = \{x \in \Sigma_1^* \mid x \text{ contains the substring “to”}\}$$

Examples of languages

$$L_2 = \{x \in \Sigma_2^* \mid x \text{ is divisible by } 7\} \qquad \Sigma_2 = \{0, 1, \dots, 9\}$$

L_2 contains 0, 7, 14, 21, ...

Examples of languages

$$L_2 = \{x \in \Sigma_2^* \mid x \text{ is divisible by } 7\} \qquad \Sigma_2 = \{0, 1, \dots, 9\}$$

L_2 contains 0, 7, 14, 21, ...

$$L_3 = \{s\#s \mid s \in \{a, \dots, z\}^*\} \qquad \Sigma_3 = \{a, b, \dots, z, \#\}$$

Which of the following are in L_3 ?

ab#ab

ab#ba

a##a#

Examples of languages

$$L_2 = \{x \in \Sigma_2^* \mid x \text{ is divisible by } 7\} \qquad \Sigma_2 = \{0, 1, \dots, 9\}$$

L_2 contains 0, 7, 14, 21, ...

$$L_3 = \{s\#s \mid s \in \{a, \dots, z\}^*\} \qquad \Sigma_3 = \{a, b, \dots, z, \#\}$$

Which of the following are in L_3 ?

ab#ab

Yes

ab#ba

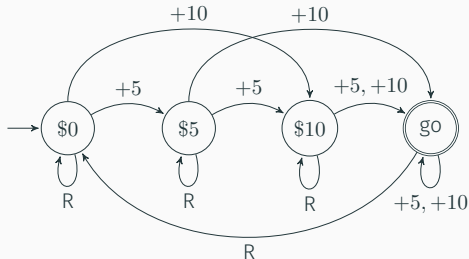
No

a##a#

No

Finite Automata

Example of a finite automaton



- There are **states** \$0, \$5, \$10, go
- The **start state** is \$0
- Takes **inputs** from {+5, +10, R}
- The state go is an **accepting state**
- There are **transitions** specifying where to go to for every state and every input symbol

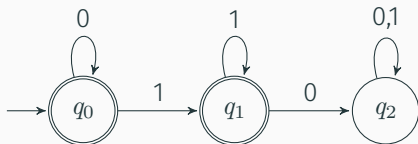
Deterministic finite automaton

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

- Q is a finite set of **states**
- Σ is an **alphabet**
- $\delta : Q \times \Sigma \rightarrow Q$ is a **transition function**
- $q_0 \in Q$ is the **initial state**
- $F \subset Q$ is the set of **accepting states** (or **final states**)

In diagrams, the accepting states will be denoted by **double circles**

Example



alphabet $\Sigma = \{0, 1\}$

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

initial state q_0

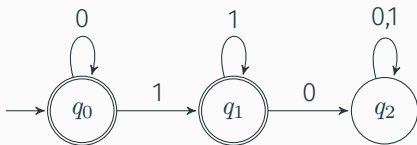
accepting states $F = \{q_0, q_1\}$

table of transition
function δ

		inputs	
		0	1
states	q_0	q_0	q_1
	q_1	q_2	q_1
	q_2	q_2	q_2

Language of a DFA

A DFA accepts a string x if starting from the initial state and following the transitions as x is read from left to right, the DFA ends at an accepting state

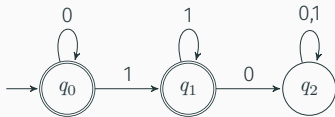
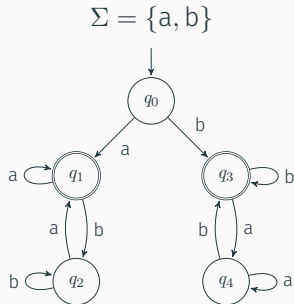
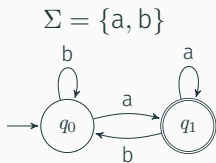


The DFA accepts 0 and 011 but not 10 and 0101

The language of a DFA is the set of all strings x accepted by the DFA

0 and 011 are in the language 10 and 0101 are not

The languages of these DFAs?

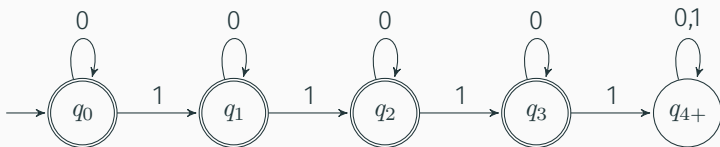


$\Sigma = \{0, 1\}$

Draw a DFA over $\{0, 1\}$ that accepts all strings with at most three 1s

Examples

Draw a DFA over $\{0, 1\}$ that accepts all strings with at most three 1s



Examples

Draw a DFA over $\{0, 1\}$ that accepts all strings ending in 01

Examples

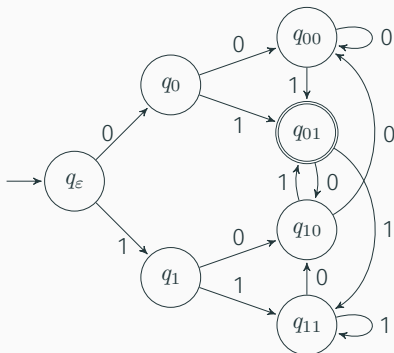
Draw a DFA over $\{0, 1\}$ that accepts all strings ending in 01

Hint: The DFA should “remember” the last 2 bits of the input string

Examples

Draw a DFA over $\{0, 1\}$ that accepts all strings **ending in 01**

Hint: The DFA should “remember” the last 2 bits of the input string



We will see a much simpler DFA in the next lecture

Examples

Draw a DFA over $\{0, 1\}$ that accepts all strings ending in 101

