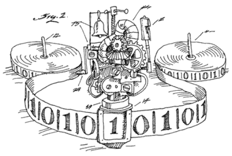
EECS 376: Foundations of Computer Science

Lecture 08 – Introduction to Computability



Introduction to Computability: Deterministic Finite Automata

Techniques and Paradigms in this Course

- Divide-and-conquer, greed, dynamic programming, the power of randomness — Problems that are **easy** for a computer
- Computability — Problems that are **impossible** for a computer
- NP-completeness and approximation algorithms — Problems that are **"probably hard"** for a computer
- Cryptography — Using "probably hard" problems for our benefit (hiding secrets)

What is a computer?

Plan in 5 lectures

Two models of computations (types of "hardware")

Finite Automaton = a person (system whose space **cannot** grow according input size)
- **Q:** What type of problems can a person solve?
- **A:** Very limited!

Turing Machine = a person + papers (as much as they want)
- **Q:** What type of problems can a person with papers solve?
- **A:** Every solvable problem! (Church-Turing thesis)
  - Ignoring efficiency: Nothing is more powerful than Turing Machine

Is every problem solvable? No. Why not?

Problems and Decision Problems

Def

An algorithm solves a problem if it gives the correct solution on every instance.

We'll define last 3 terms now.

What is a computational **problem**?

We'll start with an example.

Example problem:

MULTIPLICATION

Instance (also known as ***input***)	***Solution***
3, 7	21
610, 25	15250
50, 610	30500
15251, 252	3843252
12345679, 9	111111111

Example problem:

PALINDROME

Instance (also known as ***input***)	***Solution***
`a`	`Yes`
`10101`	`Yes`
`selfless`	`No`
`huh`	`Yes`
`376`	`No`
`emus sail i assume`	`Yes`

Def ①

A problem is a collection of instances and the solution to each instance.

Def

Decision problem:

Problems where the solution is **Yes / No**.

(Also known as **True / False, 1 / 0, accept / reject.**)

Languages

String notation

① **Alphabet: A nonempty finite set Σ of symbols.**

e.g. $\Sigma = \{0,1\}$ or Σ = ASCII characters

ex: $\{0,1\}^3$ = {all binary strings of length 3}

② **String: A finite sequence of 0 or more symbols.**
(or "word")

The empty string is denoted ε.

Σ^k 是finite的

For any $a \in \Sigma$:

string — a^k means k a's

language — a^* means ≥0 a's

a^+ means ≥1 a's

Σ^k means all strings over Σ of length k.

Σ^* means **all** (finite) strings over Σ.

Σ^+ means all nonempty (finite) strings over Σ

$\Sigma^+ = \Sigma^* \cup \varepsilon$

For any $a,b \in \Sigma$: $a|b$ means a OR b

③ **Language: A (possibly infinite) set of strings.**

i.e. any subset $L \subseteq \Sigma^*$.

但是 Σ^* 本身是infinite (就像R).

The empty language is denoted Ø.

Examples of Languages

L = a* = {ε, a, aa, aaa, … }

L = 01* = all strings of one 0 followed by zero or more 1's

{0, 01, 011, 0111, …}

L = $\{x^k y^k : k \geq 0\}$ = all strings consisting of some number of x's followed by the same number of y's {ε, xy, xxyy, ..}

Question: L = {ε}. Is L = Ø?

Answer: No. L has 1 element, Ø has 0 elements

Question: How is a*|b* different from (a|b)*

all possible combinations of all possible numbers of a|b

= {ε, a, b, ab, ba, bab, …}

note: a*, b*是language

即: {ε, a, aa, …} ∪ {ε, b, bb, …}

Decision Problems ≡ Languages

Representing instances of a problems

The instances of a problem can be:

- numbers
- strings
- pairs of numbers
- lists of strings
- graphs
- images
- …

These can all be conveniently encoded by **strings.**

For an input G, $\langle G \rangle$ denotes its encoding as a string

Representing problems

We can encode instances and solutions as strings.

Thus, we can think of a **problem** as a **function**

$f : \Sigma^* \to \Sigma^*$

mapping instances (string) to solutions (string).

A **decision problem** can be thought of as

$f : \Sigma^* \to \{\text{No}, \text{Yes}\}$

Representing decision problems

A **decision problem** can be thought of as

$f : \Sigma^* \to \{\text{No}, \text{Yes}\}$

or equivalently as a **language**

$L \subseteq \Sigma^*$

$L = \{x \in \Sigma^* : f(x) = \text{Yes}\}$ $\quad f(x) = \begin{cases} \text{Yes if } x \in L \\ \text{No if } x \notin L \end{cases}$

E.g.: $L_{\text{PALINDROME}} = \{x \in \Sigma^* : x \text{ is a palindrome}\}$

all strings

Let us practice this notations

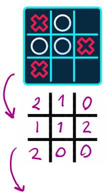
What is a language corresponding to this problem?

Q: Is an input number x even?

- $\langle x \rangle$ = binary string encoding a number x.
- $L_1 = \{\langle x \rangle \in \{0,1\}^* \mid x \bmod 2 = 0\}$

Q: Given a tic-tac-toe board B, can "x" always win?

- $\langle B \rangle$ = encoding of a current board B
- $L_2 = \{\langle B \rangle \in \{0,1,2\}^9 \mid \text{"x" can win in } B\}$



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Upshot

Languages and decision problems are two ways to think of the same things

First Model of Computation: Deterministic Finite Automata

capturing any system whose space **cannot** grow according input size

This lecture:

A computational model: 只对decisive problem有用

Deterministic Finite Automata (DFA)

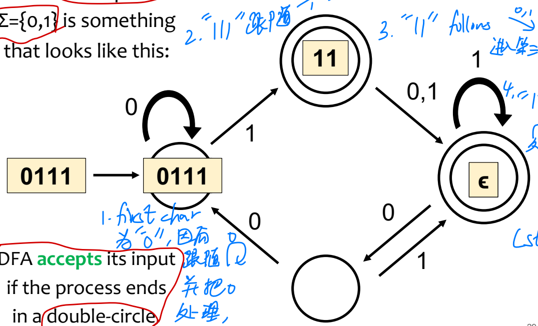
Weak model of computation

Capture a very weak type of algorithms

Good warmup before we study Turing Machine (most powerful model of computation)...

Deterministic Finite Automata (DFAs)

A DFA over alphabet $\Sigma=\{0,1\}$ is something that looks like this:



1. first char 为"0"，因而跟随自己并把0处理，变为111

2. "111"跟随1处理掉首个1并进入第二个states

3. "11" follows 0,1 进入第三个state

4. "1"跟随1被处理掉 ⇓ ε (stop)

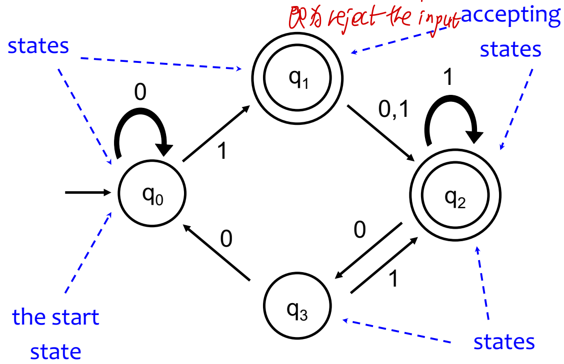
DFA **accepts** its input if the process ends in a double-circle

⇓

即 accepting states

如果DFA最后停在accepting states，即为accept the input；停在别的地方即为reject the input

Anatomy of a DFA



transition rules: the labeled arrows

Computing with DFAs

Let M be a DFA, using alphabet Σ.

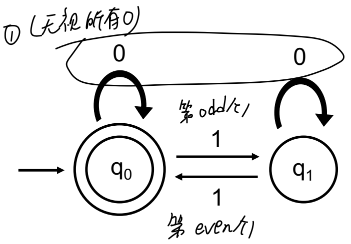
M accepts some strings in Σ^* and rejects the rest.

Definition: $L(M) = \{x \in \Sigma^* : M \text{ accepts } x\}$ 注意: problem size 可以 infly large

Called the “language decided by M”.

If L is a language,

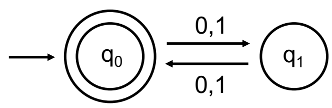
we say M decides L if $L(M) = L$.



What language does this DFA decide?

binary string with even 个 1

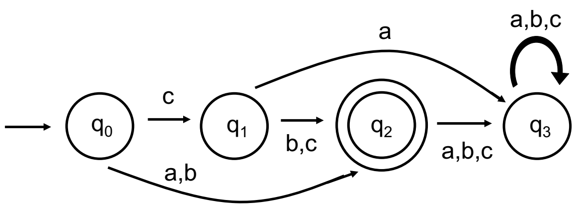
$(aa)^*$



What language does this DFA decide?

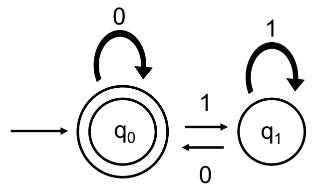
even length binary string

M is the following DFA,
with alphabet $\Sigma=\{a,b,c\}$:



$L(M) = \{a, b, cb, cc\}$

M:



$L(M) = \{\varepsilon\} \cup \{\text{strings ending with } 0\}$

易证: swap 普通state 和 acc state 即可.

Fact: If there is a DFA that decides a language L, then there is also a DFA that decides the **complement of L**. Why?

E.g. L = {strings containing “01”}
complement of L = {strings NOT containing “01”}

Formal definition of DFAs

A deterministic finite automaton is a 5-tuple:

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

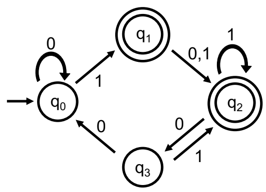
① Q is a nonempty finite set of states,
② Σ is an alphabet,
③ $\delta : Q \times \Sigma \to Q$ is the state-transition function,
④ $q_0 \in Q$ is the start state,
⑤ $F \subseteq Q$ is the set of accepting states.

即: graph 的 abstraction. 有几个 states, 哪个 start, 哪些 acc, 使用什么 alphabet, states 间怎么 transit.

Formal definition of DFAs

A deterministic finite automaton is a 5-tuple:

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



$Q = \{q_0, q_1, q_2, q_3\}$

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

δ we’ll come back to

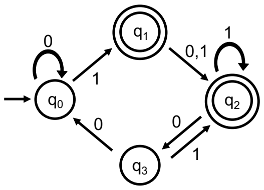
q_0 is the start state

$F = \{q_1, q_2\}$

Formal definition of DFAs

A deterministic finite automaton is a 5-tuple:

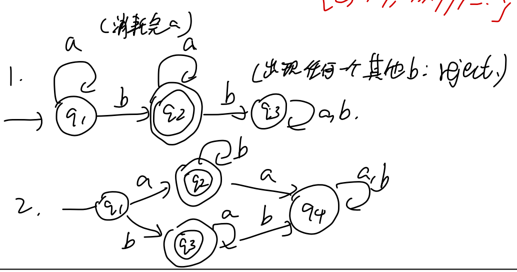
$M = (Q, \Sigma, \delta, q_0, F)$



$\delta : Q \times \{0,1\} \rightarrow Q$ is...

δ	0	1
q_0	q_0	q_1
q_1	q_2	q_2
q_2	q_3	q_2
q_3	q_0	q_2

- For Σ = {a,b}, consider the language of strings with exactly one b
  1. Write using string notation a^*ba^*
  2. Draw a DFA
- Draw a DFA for ab*|ba* $\{a, ab, abb, \ldots, b, ba, baa, \ldots\}$
- Draw a DFA for $L = \{x^ky^k : k \geq 0\}$ $\{\varepsilon, xy, xxyy, \ldots\}$ $\cup\ \varepsilon$



Limitation and Characterization of DFAs

Thm: No DFA can decide $\{x^ky^k : k \geq 0\}$

Suppose for contradiction there's a DFA **M** that decides $\{x^ky^k : k \geq 0\}$

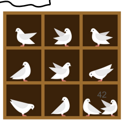
Let **s** = #states of **M**. 这是核心问题: memory是有限的!

Consider the input string $x^{s+1}y^{s+1}$.

There are **s states** (pigeonholes) and **s+1 x's** (pigeons), so there must be two values **i , j** ≤ s+1 such that **state**(x^i) = **state**(x^j).

Claim. The two inputs x^iy^i and x^jy^i have the same final state. Why?

But **M** is supposed to accept x^iy^i and reject x^jy^i.
Contradiction!



Intuitive reason why DFAs cannot decide many languages:

Finite memory!

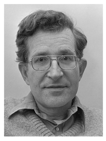
note: 何为decide?
Decide的意思是: 对于无论多大的input, 都能弄出结果
xy^*, 实际上只需要两个state, 可以在有限memory的DFA中完成;
而 x^ky^k, k可以想多大就多大, 因而finite memory无法完成

THE TRAGEDY OF A THREE SECOND MEMORY

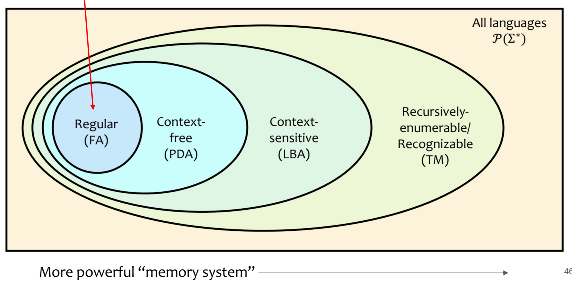
Which language can be decided by DFAs?

- There is an exact characterization!
- **Regular Expression**
  - A regular expression = finite expression using the string notations
    - Start from finite alphabet.
    - Compose them using **concantenation, alternation "|", or Kleen star "*"**
  - Examples:
    - $L(\epsilon) = \{\epsilon\}$
    - $L(ab*|ba*) = \{a, ab, abb, \ldots\} \cup \{b, ba, baa, \ldots\}$
- **Theorem** (RegExp = DFA):
  - L is defined by regular expression ⟺ L is decided by a DFA
- These languages are called **regular languages.**

The Chomsky Hierarchy (1956)



"Regular Language": Language decidable by some DFA



Noam Chomsky

- Noam Chomsky is an American professor and public intellectual known for his work in linguistics, political activism, and social criticism.
- Sometimes called "the father of modern linguistics", Chomsky is also a major figure in analytic philosophy and one of the founders of the field of cognitive science.
- He is a laureate professor of linguistics at the University of Arizona and an institute professor emeritus at the Massachusetts Institute of Technology (MIT).

DFAs/regularity are widely used in practice

- Simple household devices (switches, garage doors, …)
- Software for designing and checking the behavior of digital circuits
- "Lexers," the first stage of compilers
- Flexible string search in text files (logs, latex, …)
  - **Warning:** "Regular exprs" in practice often ***aren't* regular!**
- and much more…

(Bonus) Exercises

Regular Expression Exercises

- All strings over $\{a, b\}$ with an ***even*** number of as.
  - $b^*(b^*ab^*ab^*)^*$
- All strings over $\{a, b\}$ without 2 consecutive as.
  - $(b^*ab)^*\big(b^*(a|\epsilon)\big)$
- All strings over $\{0,1\}$ that begin and end with the same symbol.
  - $(0(0|1)^*0)|(1(0|1)^*1)$
- $N = (0|1|2|\cdots|9)$ $\quad$ $L = (A|B|\cdots|Z)$
  - Dates: $NN - LLL - NN(NN|\epsilon)$ (E.g., 16-Feb-2023 or 16-Feb-23)
  - Michigan License Plates: $LLL\ NNNN$

DFA Exercises

- Design a DFA to decide $\{x \in \{0,1\}^* \mid (unsigned\ int)\ x\ is\ divisible\ by\ 5\}$
- Design a DFA to decide $\{x \in \{0,1\}^* \mid (unsigned\ int)\ x^R\ is\ divisible\ by\ 5\}$
  - x^R is the *reversal* of x, i.e., least significant digits comes first.

- You need to keep track of the score in a tennis game between A and B. The sequence of points scored is represented by a string $x \in \{A, B\}^*$.
  - The first player to get ≥4 points AND be ahead by 2 wins.
  - For weird historical reasons, 0 pts is "love", 1 is "15", 2 is "30", 3 is "40".
- Design a DFA to decide $\left\{\begin{matrix} x \in \{A, B\}^* \mid A \text{ has already won after seeing} \\ x \text{ points recorded.} \end{matrix}\right\}$

DFA Impossibility Exercises

- Prove $\mathrm{L}_{\mathrm{Palindrome}} = \{x \in \{0,1\}^* \mid x \text{ is a palindrome}\}$ cannot be decided by a DFA.
  - Let s = #states
  - Hint: consider $0^{s+1}110^{s+1}$

- Prove $\mathrm{L}_{\mathrm{Prime}} = \{x \in \{0,1\}^* \mid x = 1^p \text{ and } p \text{ is prime}\}$ cannot be decided by a DFA.