

Course Notes

COMP130023.01 Theory of Computation

Spring 2024

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What do we study?

- What is computation, i.e., computation model
- Finite automaton, context-free grammar
- Turing machine (= algorithm)
- Computability
- Complexity class (P, NP, PSPACE, EXP, L, NL, ...)
- NP completeness, reduction

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1 Lesson 1

1.1 Big-O Notation

def 1.1. Let $f, g : \mathbb{N} \rightarrow \mathbb{R}$

- Write $f = O(g)$ if $(\exists c > 0)(\exists N)(\forall n \geq N)(|f(n)| \leq cg(n))$.
- Write $f = \Omega(g)$ if $(\exists c > 0)(\exists N)(\forall n \geq N)(|f(n)| \geq cg(n))$.
- Write $f = \Theta(g)$ if $(\exists c_1, c_2 > 0)(\exists N)(\forall n \geq N)(c_1g(n) \leq |f(n)| \leq c_2g(n))$.
- Write $f = o(g)$ if $(\forall \epsilon > 0)(\exists N)(\forall n \geq N)(|f(n)| \leq \epsilon g(n))$.

Big-O Notation is the most commonly used one among the four.

e.g. 1.1. $f(n) = 6n^4 - 3n^3 + 5 \Rightarrow f(n) = O(n^4)$

Proof. $|6n^4 - 3n^3 + 5| \leq 6n^4 + 3n^4 + 5n^4 = 13n^4$ □

e.g. 1.2. $\sum_{i=1}^n i^2 = \frac{n(n+1)(2n+1)}{6} = O(n^3)$

exercises 1.1. Write in big-O notation:

1. $5 + 0.001n^3 + 0.25n$
2. $500n + 100n^{1.5} + 50n \log_{10} n$
3. $n^2 \log_2 n + n(\log_2 n)^2$
4. $3 \log_8 n + \log_2(\log_2 n)$

solution $O(n^3); O(n^{1.5}); O(n^2 \log n); O(\log n)$ □

prop 1.1.

- $f_1 = O(g_1), f_2 = O(g_2) \Rightarrow f_1 f_2 = O(g_1 g_2)$
- $f(O(g)) = O(fg)$
- $f_1 = O(g_1), f_2 = O(g_2) \Rightarrow f_1 + f_2 = O(\max(g_1, g_2))$
- $f_1 = O(g), f_2 = O(g) \Rightarrow f_1 + f_2 = O(g)$
- $f = O(g) \Rightarrow kf = O(g)$

often encountered:

- *constant*: $O(1)$
 - $\sum_{k=1}^n \frac{1}{k} = \ln n + O(1)$
 - $\sum_{k=1}^n \frac{1}{k^2} = O(1)$
 - $\sum_{k=1}^n \frac{1}{k \ln k} = \ln \ln n + O(1)$
- *double logarithmic*: $O(\log \log n)$
- *logarithmic*: $O(\log n)$
- *polylogarithmic*: $O((\log n)^c), c > 0$
- *linear*: $O(n)$
- *quasilinear*: $O(n \log^c n), O(n \log^{O(1)} n)$
- *quadratic*: $O(n^2)$

def 1.2. $\omega(g), \theta(g)$

- $f = \omega(g)$ if $(\forall c > 0)(\exists N)(\forall n \geq N)(f(n) \geq cg(n))$
- $g = \theta(g)$ (or equivalently $f \sim g$) if $(\forall \epsilon > 0)(\exists N)(\forall n \geq N)(|f(n) - g(n)| < \epsilon g(n))$

1.2 Alphabets and Languages

def 1.3. (*alphabet*) An alphabet is a set of symbols

- *Roman alphabet* : a, b, c, d, \dots, z
- *binary alphabet* : $0, 1$

def 1.4. (*string and its length*)

A **string** (over an alphabet) is a finite sequence of symbols from the alphabet.

Empty string is string of no symbols, denoted by ε .

The set of all string is denoted by Σ^* . Denote by Σ^n the set of all **string of length** n .

So, $\Sigma^* = \cup_{n \geq 0} \Sigma^n$.

Denote the length of a string w by $|w|$

e.g. 1.3. $\{0, 1\}^* = \{\varepsilon, 0, 1, 00, 01, \dots\}, |\varepsilon| = 0, |0110| = 4$

def 1.5. (*concatenation*) Two strings over the same alphabet can be combined by the operation of **concatenation**. The concatenation of x and y is denoted by xy .

def 1.6. (*substring, suffix, prefix*)

A string v is a substring of w if \exists strings x and y such that $w = xvy$.

If $w = xv$ for some x , then v is a **suffix** of w .

If $w = vy$ for some y , then v is a **prefix** of w .

def 1.7. ("power") The string w^i is defined: $w^0 = \varepsilon, w^{i+1} = w^i w, i \in \mathbb{N}$

e.g. 1.4. $01^0 = \varepsilon, 01^1 = 01, 01^2 = 0101$

def 1.8. (*reversal*) The reversal of a string w , denoted by w^R , is the string "spelled backwards"

A formal definition can be given by induction on length:

1. If $w = \varepsilon, w^R = w = \varepsilon$
2. If $|w| = n + 1$, where $w = ua, a \in \Sigma$, then $w^R = au^R$

def 1.9. (*language*) **Language** is a set of strings over an alphabet, That is, $L \subseteq \Sigma^*$.

For example, $\emptyset, \Sigma^*, \Sigma$ are all languages

- $\sigma = \{0, 1\}$
- $Even = \{0, 10, 100, 110, \dots\}$
- $Odd = \{1, 11, 101, \dots\}$
- $Prime = \{10, 11, 101, 111, \dots\}$
- $Palindrome = \{w | w^R = w\} = \{\varepsilon, 0, 1, 00, 11, \dots\}$

def 1.10. (*complement, binary language operations*)

Let L be a language. The **complement** of L , denoted by \bar{L} , is $\Sigma^* - L$. So $\overline{\bar{L}} = L$.

Note that since L is a set, we can define **union**(\cup), **intersection**(\cap) and difference.

The **concatenation** of L_1 and L_2 is defined by $L_1 L_2 = \{w \in \Sigma^*, w = xy, \exists x \in L_1, y \in L_2\}$

1.3 Encoding of Problems

1.3.1 Examples

1. (**Integer multiplication**) Given two non-negative integers x, y , compute xy .
2. (**Primality testing**) Given $n \in \mathbb{N}$, decide if n is a prime.
3. (**Hamiltonian cycle**) Given an undirected graph G , test if G has a Hamiltonian cycle.

1.3.2 Analysis

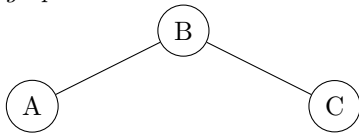
- *Decision problem: 2,3*
- *Computation problem: 1*

1.3.3 Conclusion

- By **encoding**, decision problem is language. Any computation problem is a function from Σ^* to Σ^* . Our course only concerns decision problem, namely language.
- By **preprocessing**, one can switch between encodings.

e.g. 1.5.

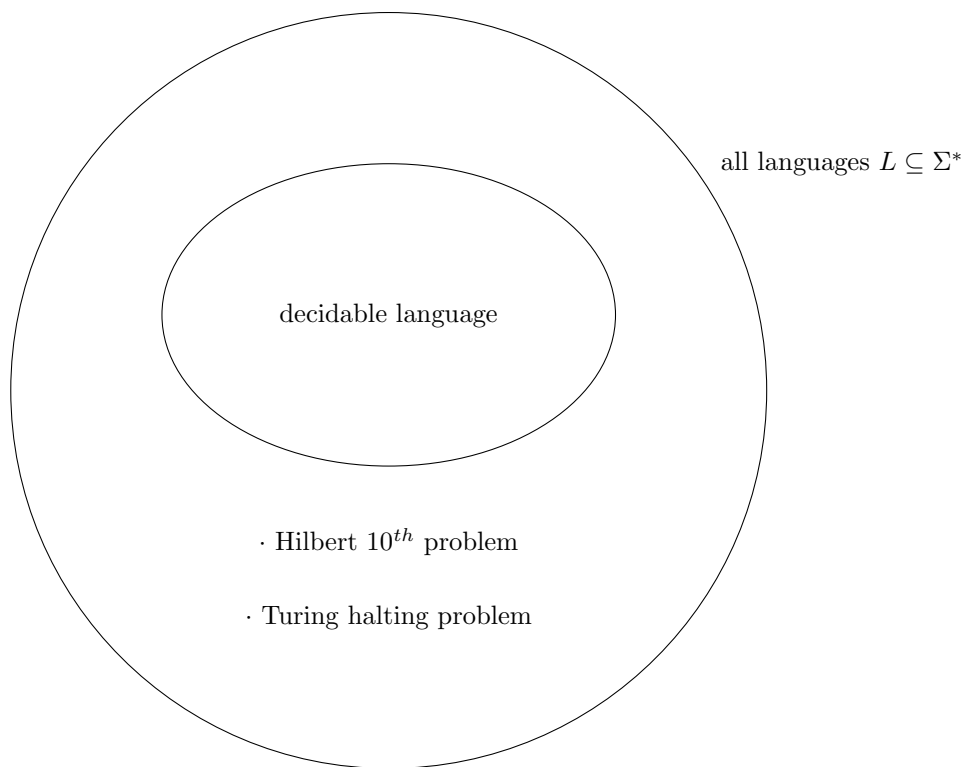
- *graph*



- *adjacency matrix*

$$\begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix}$$

- *adjacency list*
 $(1,2), (1,3), \dots$



2 Lesson 2