

Complexity Theory

Easter 2015

Suggested Exercises 1

1. In the lecture, a proof was sketched showing a $\Omega(n \log n)$ lower bound on the complexity of the sorting problem. It was also stated that a similar analysis could be used to establish the same bound for the Travelling Salesman Problem. Give a detailed sketch of such an argument. Can you think of a way to improve the lower bound?
2. Say we are given a set $V = \{v_1, \dots, v_n\}$ of vertices and a cost matrix $c : V \times V \rightarrow \mathbb{N}$. For a set $S \subseteq V$, let $t_{S,i}$ denote the cost of the shortest path that starts at v_1 , visits all vertices in S and ends at v_i . Describe a *dynamic programming* algorithm that computes $t_{S,i}$ for all sets S and all i . Show that your algorithm can be used to solve the Travelling Salesman Problem in $O(n^2 2^n)$.
3. Consider the language **Unary-Prime** in the one letter alphabet $\{a\}$ defined by

$$\text{Unary - Prime} = \{a^n \mid n \text{ is prime}\}.$$

Show that this language is in P.

4. We say that a propositional formula ϕ is in 2CNF if it is a conjunction of clauses, each of which contains exactly 2 literals. The point of this problem is to show that the satisfiability problem for formulas in 2CNF can be solved by a polynomial time algorithm.

First note that any clause with 2 literals can be written as an implication in exactly two ways. For instance $(p \vee \neg q)$ is equivalent to $(q \rightarrow p)$ and $(\neg p \rightarrow \neg q)$, and $(p \vee q)$ is equivalent to $(\neg p \rightarrow q)$ and $(\neg q \rightarrow p)$.

For any formula ϕ , define the directed graph G_ϕ to be the graph whose set of vertices is the set of all literals that occur in ϕ , and in which there is an edge from literal x to literal y if, and only if, the implication $(x \rightarrow y)$ is equivalent to one of the clauses in ϕ .

- (a) If ϕ has n variables and m clauses, give an upper bound on the number of vertices and edges in G_ϕ .
- (b) Show that ϕ is *unsatisfiable* if, and only if, there is a literal x such that there is a path in G_ϕ from x to $\neg x$ and a path from $\neg x$ to x .
- (c) Give an algorithm for verifying that a graph G_ϕ satisfies the property stated in (b) above. What is the complexity of your algorithm?

- (d) From (c) deduce that there is a polynomial time algorithm for testing whether or not a 2CNF propositional formula is satisfiable.
- (e) Why does this idea not work if we have 3 literals per clause?
5. A clause (i.e. a disjunction of literals) is called a *Horn* clause, if it contains *at most one* positive literal. Such a clause can be written as an implication: $(x \vee (\neg y) \vee (\neg w) \vee (\neg z))$ is equivalent to $((y \wedge w \wedge z) \rightarrow x)$. **HORNSAT** is the problem of deciding whether a given Boolean expression that is a conjunction of Horn clauses is satisfiable.
- (a) Show that there is a polynomial time algorithm for solving **HORNSAT**. (Hint: if a variable is the only literal in a clause, it must be set to **true**; if all the negative variables in a clause have been set to **true**, then the positive one must also be set to **true**. Continue this procedure until a contradiction is reached or a satisfying truth assignment is found).
- (b) In the proof of the **NP**-completeness of **SAT** it was shown how to construct, for every nondeterministic machine M , integer k and string x a Boolean expression ϕ which is satisfiable if, and only if, M accepts x within n^k steps. Show that, if M is deterministic, then ϕ can be chosen to be a conjunction of Horn clauses.
- (c) Conclude from (b) that the problem **HORNSAT** is **P**-complete under **L**-reductions.
6. In general k -colourability is the problem of deciding, given a graph $G = (V, E)$, whether there is a colouring $\chi : V \rightarrow \{1, \dots, k\}$ of the vertices such that if $(u, v) \in E$, then $\chi(u) \neq \chi(v)$. That is, adjacent vertices do not have the same colour.
- (a) Show that there is a polynomial time algorithm for solving 2-colourability.
- (b) Show that, for each k , k -colourability is reducible to $k + 1$ -colourability. What can you conclude from this about the complexity of 4-colourability?