

## Lecture Notes 3

### 7 Reductions and $\mathcal{NP}$ -completeness

Let  $L, L'$  be languages. We say  $L$  is *polynomial-time reducible* to  $L'$  and write  $L \leq_p L'$  if there exists a polynomial-time computable function  $f$  such that

$$x \in L \text{ iff } f(x) \in L'.$$

If we think of  $L$  and  $L'$  as “problems”, then  $f$  maps a problem in  $L$  to an equivalent problem in  $L'$ , in the sense that the new problem has a “solution” iff the original one does. This is interesting computationally since if we have an algorithm  $A'$  to solve  $L'$ , then we can build an algorithm  $A$  for  $L$  as follows:

- Given input  $x$ :
1. Compute  $y = f(x)$ .
  2. Compute  $r = A'(y)$  and return  $r$ .

The time for  $A$  is the time for  $f(x)$  plus the time for  $A'(y)$  (plus a little bit of overhead). This will be polynomial in  $|x|$  if  $A'$  is also polynomial-time computable, but the polynomials will not be the same. In particular,  $y$  can be longer than  $x$ , so we must argue that  $A(|y|)$  is polynomially bounded in  $|x|$ . This is true since  $f$  is polynomial-time computable, and the output of a computation cannot be longer than the length of the input plus the running time. Thus, if  $f$  runs in time  $p(\cdot)$  and  $A$  runs in time  $q(\cdot)$  for polynomials  $p$  and  $q$ , then  $A$  runs in time approximately  $p(n) + q(p(n))$ , which is itself a polynomial in  $n$ .

A language  $L'$  is said to be  *$\mathcal{NP}$ -complete* if  $L' \in \mathcal{NP}$  and for every  $L \in \mathcal{NP}$ ,  $L \leq_p L'$ . If any  $\mathcal{NP}$ -complete language  $L'$  is decidable in polynomial time, then all languages in  $\mathcal{NP}$  can be decided in polynomial time by the above algorithm. This gives us the fundamental theorem of  $\mathcal{NP}$ -completeness.

**Theorem 1** *If any  $\mathcal{NP}$ -complete language  $L'$  is in  $\mathcal{P}$ , then  $\mathcal{P} = \mathcal{NP}$ .*

The contrapositive is also of interest, namely, if  $\mathcal{P} \neq \mathcal{NP}$  (as is widely believed to be the case), then the membership problem for every  $\mathcal{NP}$ -complete language is infeasible.

We remark that hundreds of  $\mathcal{NP}$ -complete languages are known. One of the first to be shown  $\mathcal{NP}$ -complete is the *satisfiability problem* SAT. This is the set of Boolean formulas which evaluate to true under some assignment of truth values to the variables appearing in the formula.

Once one problem is known to be  $\mathcal{NP}$ -complete, then others can easily be shown to be  $\mathcal{NP}$ -complete using reductions.

**Theorem 2** *Let  $L_0$  be  $\mathcal{NP}$ -complete. Suppose  $L_1 \in \mathcal{NP}$  and  $L_0 \leq_p L_1$ . Then  $L_1$  is also  $\mathcal{NP}$ -complete.*

**Proof:** We must show for every language  $L \in \mathcal{NP}$  that  $L \leq_p L_1$ . This easily follows from the transitivity of  $\leq_p$  since we have  $L \leq_p L_0$  (by the assumed  $\mathcal{NP}$ -completeness of  $L_0$ ), and we’re given that  $L_0 \leq_p L_1$ . ■

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**Robert R. Redfield**



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