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Then  $G = S : h$  where  $S \in DSPACE((\log n)^l)$  and  $|h(x)| \leq k \log_2 |x|$ , for some  $k$ . Then  $x \in G \Leftrightarrow \exists w \forall w' \text{Win}(w, w', x)$ , where  $w$  and  $w'$  range over all strings of length  $\leq k \log_2 |x|$ . Clearly space  $O((\log n)^l)$  suffices to deterministically enumerate all pairs  $(w, w')$  and, for each, to play out  $\text{Strat}(w)$  against  $\text{Strat}(w')$  from position  $x$ , with the help of repeated calls on a deterministic space  $(\log n)^l$  recognizer for  $S$ . It follows that

$$G \in DSPACE((\log n)^l).$$

## 5. THE SELF-REDUCIBILITY METHOD

The “hardest” problems in complexity classes defined by bounds on nondeterministic time or space often possess a structural property called *self-reducibility*. Various formal definitions of self-reducibility can be found in the literature ([12, 18, 20]). Here is one version of the idea. Let  $K$  be a subset of  $\{0, 1\}^*$ . A *self-reducibility structure* for  $K$  is specified by a partial ordering  $<$  of  $\{0, 1\}^*$  such that

(i)  $A$ , the set of minimal elements in  $<$ , is recursive and

(ii)  $A \cap K$  is recursive

together with a pair of computable functions  $G_0$  and  $G_1$  mapping  $\{0, 1\}^* - A$  into  $\{0, 1\}^*$ , such that, for all  $x \in \{0, 1\}^* - A$ ,

(iii)  $G_0(x) < x$ ,  $G_1(x) < x$ ,  $|G_0(x)| = |G_1(x)| = |x|$   
and  $x \in K \Leftrightarrow G_0(x) \in K \text{ or } G_1(x) \in K$ .

If  $K$  has a self-reducibility structure, then  $K$  is called *self-reducible*.

To illustrate the concept, we give self-reducibility structures for two important examples. The first example is the satisfiability problem for propositional formulas, encoded so that the following property holds: Let  $F(t_1, t_2, \dots, t_n)$  be a formula in which the variables  $t_1, t_1, \dots, t_n$  appear, and let  $F(a, t_2, \dots, t_n)$  be the same formula with the Boolean constant  $a$  substituted for  $t_1$ . Let  $\langle F(t_1, t_2, \dots, t_n) \rangle$  and  $\langle F(a, t_2, \dots, t_n) \rangle$  denote the encodings of these two formulas as strings. Then

$$|\langle F(t_1, t_2, \dots, t_n) \rangle| = |\langle F(a, t_2, \dots, t_n) \rangle|.$$

Let SAT denote this version of the satisfiability problem. The set SAT has a self-reducibility structure in which  $A$  is the set of propositional formulas containing no variables,

$$G_0(<F(t_1, t_2, \dots, t_n)>) = <F(0, t_2, \dots, t_n)> \text{ and} \\ G_1(<F(t_1, t_2, \dots, t_n)>) = <F(1, t_2, \dots, t_n)> .$$

As a second example, let DAG denote the set of encodings of triples  $(\Psi, s, t)$  such that

- (i)  $\Psi$  is a directed acyclic graph in which the out-degree of each vertex is either 0 or 2; if  $v$  has out-degree 2 then its successor vertices are denoted  $\sigma_0(v)$  and  $\sigma_1(v)$ ;
- (ii)  $s$  is a vertex and  $t$  is a vertex of out-degree 0;
- (iii) there exists a directed path from  $s$  to  $t$ .

Assume that, for any directed acyclic graph  $G$ , any vertex  $t$  of out-degree 0, and any two vertices  $v$  and  $w$ , the encodings of  $(\Psi, v, t)$  and  $(\Psi, w, t)$  are of the same length. Then DAG is clearly self-reducible. Let  $A$  be the set of triples  $(\Psi, s, t)$  such that  $s$  is of out-degree 0, and let  $G_0((\Psi, s, t)) = (\Psi, \sigma_0(s), t)$  and  $G_1((\Psi, s, t)) = (\Psi, \sigma_1(s), t)$ .

It is possible to relate the uniform complexity of a self-reducible set  $K$  to its nonuniform complexity. Suppose  $K$  has a self-reducibility structure  $(<, A, G_0, G_1)$  and  $K = S : h$ . For each  $w \in \{0, 1\}^*$  define  $reduct_w$ , a total function over  $\{0, 1\}^*$ , by the following recursive definition:

$$reduct_w(x) = \text{if } x \in A \text{ then } x \text{ else} \\ \text{if } w \cdot G_0(x) \in S \text{ then } reduct_w(G_0(x)) \text{ else} \\ reduct_w(G_1(x)).$$

Then, for all  $w$ ,  $reduct_w(x) \in A$ . Also,  $reduct_w(x) \in K \Rightarrow x \in K$  and  $x \in K \Leftrightarrow reduct_{h(|x|)}(x) \in K$ . These observations imply the following lemma.

LEMMA 5.1. Let  $w$  range over some set which includes  $h(|x|)$ . Then

$$x \in K \Leftrightarrow \exists w [reduct_w(x) \in K] .$$

Lemma 5.1 suggests a uniform way of testing membership in  $K$ : for each  $w$  in a suitable set, compute  $reduct_w(x)$  and test whether

$$reduct_w(x) \in A \cap K .$$

The complexity of this algorithm will depend on the time and space needed to test membership in  $A$ , and in  $A \cap K$ , on the lengths of chains in the

partial ordering  $<$ , and on the number of strings  $w$  that need to be considered.

Now we are ready to give some applications of self-reducibility.

**THEOREM 5.2.**  $P = NP \Leftrightarrow NP \subseteq P/\log$ .

*Proof.* The implication  $P = NP \Rightarrow NP \subseteq P/\log$  is immediate. Since SAT is NP-complete, the reverse implication will follow once we prove that

$$\text{SAT} \in P/\log \Rightarrow \text{SAT} \in P.$$

Assume that  $\text{SAT} \in P/\log$ . Then  $\text{SAT} = S : h$ , where  $S \in P$  and, for some  $k$ ,  $|h(n)| \leq k \log_2 n$ .

Using the self-reducibility structure for SAT given above, coupled with the method of lemma 5.1, we can test whether string  $x$  is in SAT. It is necessary to compute  $\text{reduct}_w(x)$  for each of the polynomially-many strings  $w$  of length  $\leq k \log_2 n$  and, for each, to test whether

$$\text{reduct}_w(x) \in A \cap K.$$

Each such computation can be done in polynomial time. Hence we conclude that  $\text{SAT} \in P$ . ■

By similar methods we can relate the nonuniform and uniform complexities of other self-reducible problems. For example, we can state the following result.

**THEOREM 5.3.** Let *Factor* denote the set of triples of integers  $\langle x, y, z \rangle$  such that  $x$  has a factor between  $y$  and  $z$ . Then

$$\text{Factor} \in P/\log \Leftrightarrow \text{Factor} \in P.$$

As another application of the self-reducibility method, we give the following theorem.

**THEOREM 5.4.**

$$\begin{aligned} \text{NSPACE}(\log n)/\log &\subseteq \text{DSPACE}(\log n)/\log \\ &\Leftrightarrow \text{NSPACE}(\log n) = \text{DSPACE}(\log n). \end{aligned}$$

*Proof.* It is sufficient to prove

$$\begin{aligned} \text{NSPACE}(\log n)/\log &\subseteq \text{DSPACE}(\log n)/\log \\ &\Rightarrow \text{NSPACE}(\log n) = \text{DSPACE}(\log n). \end{aligned}$$

Since DAG is logspace complete in  $NSPACE(\log n)$ , it suffices to show that

$$\text{DAG} \in DSPACE(\log n)/\log \Rightarrow \text{DAG} \in DSPACE(\log n).$$

Suppose that  $\text{DAG} = S : h$ , where  $S \in DSPACE(\log n)$  and

$$|h(n)| \leq k \log_2 n.$$

Then, guided by the self-reducibility of DAG, we can test whether  $(\Psi, s, t) \in \text{DAG}$  by performing the following computation for each string  $w$  of length  $\leq k \log_2 n$ :

$v := s$ ;

while  $v$  has out-degree 2 do

$v :=$  if  $w \cdot (\Psi, v_0, t) \in S$  then  $v_0$  else  $v_1$ .

If  $v$  is ever set equal to  $t$  then accept  $(\Psi, s, t)$ ; otherwise, reject it. It is clear that this method recognizes DAG deterministically within space  $O(\log n)$ . ■

## 6. THE METHOD OF RECURSIVE DEFINITION

Let  $K$  be a subset of  $\{0, 1\}^*$ , and let  $C_K : \{0, 1\}^* \rightarrow \{0, 1\}$  be the characteristic function of  $K$ . By a recursive definition of  $C_K$  we mean a rule that specifies  $C_K$  on a "basis set"  $A \subseteq \{0, 1\}^*$ , and uniquely determines  $C_K$  on the rest of  $\{0, 1\}^*$  by a recurrence formula of the form

$$C_K(x) = F(x, C_K(f_1(x)), C_K(f_2(x)), \dots, C_K(f_t(x))), \\ x \in \{0, 1\}^* - A.$$

*Example 1.* Let  $G$  be a game, as defined in Section 4, and let  $G$  be the set of positions from which the player to move can force a win. Then  $G$  is uniquely determined by

- (i) if  $x \in W$  then  $x \in G$
- (ii) if  $x \in \{0, 1\}^* - W$  then  $x \in G \Leftrightarrow F_0(x) \notin G$  or  $F_1(x) \notin G$ .

*Example 2.* Let  $(<, A, G_0, G_1)$  be a self-reducibility structure for the set  $K \subseteq \{0, 1\}^*$ . Then  $K$  is determined uniquely by its intersection with  $A$ , together with the recurrence

$$\text{for } x \notin A, x \in K \Leftrightarrow G_0(x) \in K \cup G_1(x) \in K.$$