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SURVEY/EXPOSITORY PAPER

CLASSIFYING THE COMPUTATIONAL COMPLEXITY OF PROBLEMS

LARRY STOCKMEYER

§1. Introduction. One of the more significant achievements of twentieth century mathematics, especially from the viewpoints of logic and computer science, was the work of Church, Gödel and Turing in the 1930's which provided a precise and robust definition of what it means for a problem to be computationally solvable, or decidable, and which showed that there are undecidable problems which arise naturally in logic and computer science. Indeed, when one is faced with a new computational problem, one of the first questions to be answered is whether the problem is decidable or undecidable. A problem is usually defined to be decidable if and only if it can be solved by some Turing machine, and the class of decidable problems defined in this way remains unchanged if "Turing machine" is replaced by any of a variety of other formal models of computation. The division of all problems into two classes, decidable or undecidable, is very coarse, and refinements have been made on both sides of the boundary. On the undecidable side, work in recursive function theory, using tools such as effective reducibility, has exposed much additional structure such as degrees of unsolvability. The main purpose of this survey article is to describe a branch of computational complexity theory which attempts to expose more structure within the decidable side of the boundary.

Motivated in part by practical considerations, the additional structure is obtained by placing upper bounds on the amounts of computational resources which are needed to solve the problem. Two common measures of the computational resources used by an algorithm are *time*, the number of steps executed by the algorithm, and *space*, the amount of memory used by the algorithm. Given a specific decidable problem, one typically obtains an upper bound on the required time and space by exhibiting a particular algorithm which solves the problem and bounding its resources. However, in judging the optimality of algorithms it is necessary also to have corresponding lower bounds on the computational complexity of the problem; that is, one must show that a certain amount of time or space is used by any of the (in general, infinitely many) algorithms which solve the problem. One method, based on diagonalization, has been developed for proving lower bounds, and many applications of this method have been made to problems in areas including logic,

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combinatorial games, and algebra. However, for many interesting and important problems this method does not appear to be applicable, and proofs of nontrivial lower bounds are not known. Even if close explicit upper and lower bounds on the complexity of a problem are not known, it may still be possible to implicitly classify the problem by relating its complexity to that of any problem in some large class of problems. Both types of classification, explicit and implicit, are surveyed here. Before getting into technical details in later sections, the basic ideas are outlined informally in this Introduction.

We first consider an explicit classification. Historically, the first explicit exponential lower bounds on the complexities of natural decision problems were proved by Meyer and Stockmeyer [MeS] for a certain problem in formal language theory and by Meyer [Me1] for the weak monadic second-order theory of one successor; the method introduced in these papers was used in subsequent papers to prove lower bounds. By “natural problem” we mean a problem with a reasonable practical or mathematical motivation, not a problem which is constructed specifically to be complex. As our first example we choose another logical decision problem, the first-order theory of the real numbers with addition, since this problem is probably more familiar to many readers than the problems considered in [MeS] and [Me1]. Consider formulas written in first-order predicate calculus with equality using the binary function symbol $+$ and the binary relation symbol $<$, together with the usual logical connectives such as *and*, *or* and *implies*, quantifiers \exists and \forall , variables, and parentheses. A *sentence* is a formula in which every variable is bound by a quantifier. When variables are interpreted as ranging over the real numbers, $+$ is interpreted as addition of real numbers, and $<$ is interpreted as the order relation on real numbers, every sentence is either true or false. Denote the set of true sentences by $\text{Th}(\mathbf{R}, +)$. Decidability of $\text{Th}(\mathbf{R}, +)$ follows from the result of Tarski [Tars] that $\text{Th}(\mathbf{R}, +, \cdot)$, the first-order theory of the reals with both addition and multiplication, is decidable. We say that a Turing machine *accepts* $\text{Th}(\mathbf{R}, +)$ if, when started with (an encoding of) a sentence s on its tape, the machine always halts and it halts in a distinguished accepting state iff s is true. The time and space used by a Turing machine depend, in general, on the particular input. One simplification which is commonly made is to measure the consumption of these resources as a function of the *length* of the input. Let us take the length of a sentence s , denoted $|s|$, to be the number of occurrences of variable symbols and other symbols, \exists , $+$, \cdot , etc., in s . The following theorem, due to Fischer and Rabin [FiR], is an example of an explicit lower bound on the computational complexity of a problem.

THEOREM 1.1. *There is a rational constant $c > 1$, such that if M is a Turing machine which accepts $\text{Th}(\mathbf{R}, +)$, then M runs for at least $c^{|s|}$ steps when started on input s , for infinitely many sentences s .*

Of course, the same lower bound holds for the decision problem $\text{Th}(\mathbf{R}, +, \cdot)$ originally considered by Tarski. The fact that any Turing machine requires exponentially growing time implies the same (with possibly a different constant c) for more realistic models of computers such as random-access register machines (see [CoR] and [AHU]); this is true because there are sufficiently efficient simulations of random-access machines by Turing machines.

Regarding upper bounds, Ferrante and Rackoff [FeR1] have shown that there is a constant d and a Turing machine M which accepts $\text{Th}(\mathbf{R}, +)$ and which uses space

(i.e., amount of tape) at most $d^{|s|}$ when deciding the truth of sentence s . The time used by this procedure grows double-exponentially in $|s|$. Ben-Or, Kozen and Reif [BeKR] establish the upper bound $d^{|s|^2}$ on the space complexity of $\text{Th}(\mathbf{R}, +, \cdot)$, where d is a constant. (Collins [Col] and Monk [Mo] had earlier given decision procedures for $\text{Th}(\mathbf{R}, +, \cdot)$ where the time and space are both doubly exponential in $|s|$. The time and space used by Tarski's original decision procedure cannot be bounded above by the composition of any fixed number of exponential functions.) Thus the computational complexities of deciding $\text{Th}(\mathbf{R}, +)$ and $\text{Th}(\mathbf{R}, +, \cdot)$ have been roughly classified as lying between exponential time and exponential space.

One consequence of results such as Theorem 1.1 has been to blur the classical distinction between decidable and undecidable problems. The fact that $\text{Th}(\mathbf{R}, +)$ and $\text{Th}(\mathbf{R}, +, \cdot)$ are decidable is of little use in designing practical decision algorithms. The exponential growth of the time required to accept $\text{Th}(\mathbf{R}, +)$ suggests that any decision procedure for this problem will use hopelessly large amounts of time on relatively short sentences, and therefore that $\text{Th}(\mathbf{R}, +)$ is "practically undecidable" even though it is technically decidable. Even though the value of c and the density of sentences for which the theorem applies have not yet been determined well enough to draw solid conclusions, the term practical undecidability seems apt, since classical undecidability results are prone to similar objections. At the very least, an exponential lower bound on the time complexity of a problem serves as a warning not to seek a uniformly efficient decision algorithm but either to settle for an algorithm which does not work in all cases or to simplify the problem so that it becomes tractable. The implications of lower bounds such as Theorem 1.1 are discussed in more depth by Rabin [Rab4].

To demonstrate that it is possible to prove an astronomical lower bound on the complexity of a decidable theory, even when the length of sentences is restricted, one example has been studied in detail. This example is the weak monadic second-order theory of one successor (WS1S) restricted to sentences of length 616 or less. Decidability of WS1S in general is proved by Büchi [Bu] and Elgot [Elg]. For a particular model of computation, the *logical network* model, which is appropriate for measuring the computational complexity of finite decision problems, Meyer and Stockmeyer [Sto1] show that if a logical network decides truth or falsity of sentences of length 616 or less in WS1S, then the size of the network must exceed the size of the known universe. This result, together with more discussion of the logical network model, is the subject of §7.4. A paper of Ehrenfeucht [Ehr] (originally written in 1967) must also be mentioned as an early influence in this context. It is shown there that if the first-order theory of the integers with addition and multiplication is made decidable by requiring that all quantifiers be bounded by constants defined using iterated exponential notation (e.g., 2^{7^3}), then the sizes of logical networks which decide truth of sentences of length n must grow faster than any polynomial in n .

Beginning with papers of Cobham [Cob] and Edmonds [Edm], the class of "practically decidable" problems has been identified with the class P of problems which can be solved in polynomial time, that is, in time cn^k for some constants c and k , where n is the length of the input. Of course, this identification must be taken with several grains of salt, since an exponential time algorithm may be preferable in practice to an algorithm with running time n^{100} , at least for small enough n .

However, as a mathematical concept, the class P has proven to be a useful one. One reason is that P , like the class of decidable problems, is invariant under a variety of reasonable choices for the model of computation, e.g., Turing machines or random-access machines. After a problem has been found to be decidable, a reasonable next question to resolve is whether the problem belongs to P . If so, one can then seek more precise information about the time required to solve the problem, e.g., whether time proportional to n , or $n \log n$, or n^2 , etc., is sufficient. The search for efficient algorithms for problems in P , both general techniques and algorithms for specific problems, is an active and interesting branch of theoretical computer science which lies outside the scope of this paper; see, for example, [AHU], [PaS], and [Tarj].

Unfortunately, there are an embarrassingly large number of important problems whose membership in P is unresolved. Work initiated by Cook [Co1] has decreased the embarrassment somewhat by showing that many of these problems can be grouped into classes such that either all of the problems in a class belong to P or none of them do. Again, we use an example. Let SAT denote the set of formulas $F(y_1, \dots, y_m)$ written in propositional calculus which are satisfiable, i.e., for which there is an assignment of truth values to the propositional variables y_1, \dots, y_m such that F becomes true. An obvious algorithm is to try all 2^m assignments; since m will, in general, increase as the length of F increases, this is not a polynomial time algorithm. No polynomial time algorithm for SAT is known, but there is no proof that one does not exist. However, SAT can be solved in "polynomial time" by a nondeterministic Turing machine. The class NP of problems solvable in polynomial time by nondeterministic Turing machines is defined in §2. For now, we can define NP to be the class of decision problems (formally, sets of words) A which can be specified by

$$(1.1) \quad x \in A \quad \text{iff} \quad (\exists y)[|y| \leq p(|x|) \text{ and } R(x, y)]$$

for some polynomial p and some binary relation R on words which is computable by an ordinary (deterministic) Turing machine in polynomial time. It is not hard to see that $\text{SAT} \in \text{NP}$: x is the formula F being tested for satisfiability, the word y specifies an assignment of truth values to the variables in x , and $R(x, y)$ is true iff the formula x is true under the assignment y . Another example of a problem in NP which is not known to be in P is HC, the set of all undirected graphs which have a Hamiltonian cycle, i.e., a cycle which visits every vertex of the graph exactly once. In this case, the word y would specify a cyclic permutation of the vertices of the graph x , and $R(x, y)$ would check that y specifies a Hamiltonian cycle in x . In general, NP is the class of sets A such that $x \in A$ iff there is a short "proof" y of membership of x in A , where "short" means that $|y| \leq p(|x|)$ for some polynomial p , and such that the validity of the proof can be checked by a relation R computable in polynomial time. Even though a given proof can be checked in polynomial time, there are $2^{p(|x|)}$ potential proofs to be checked, so the algorithm which checks all potential proofs does not run in polynomial time. Of course, this does not rule out the possibility that there is some more clever way of determining whether $x \in A$ in time polynomial in $|x|$, and the question of whether or not $P = \text{NP}$ is one of the central open questions in complexity theory.

The importance of the P vs. NP question is due to results of the following type which were first proved independently by Cook [Co1] and Levin [Lev]. The

following result, for example, shows that the complexities of SAT and HC are closely related and implicitly classifies them as being among the most complex problems in NP.

THEOREM 1.2 (COOK [Co1], KARP [Ka1]). $\text{SAT} \in \text{P} \text{ iff } \text{HC} \in \text{P} \text{ iff } \text{P} = \text{NP}$.

There are now known to be a few hundred natural decision problems A with the property that $A \in \text{P}$ iff $\text{P} = \text{NP}$ [GaJ].

We now describe informally the concepts which are used in the proofs of Theorems 1.1 and 1.2 and related results. These are described more formally in later sections of the paper. One concept, borrowed from recursive function theory [Rog], is reducibility. A set A is many-one reducible to a set B if there is a computable function f such that $x \in A$ iff $f(x) \in B$. Then, for example, the undecidability of A implies the undecidability of B . In 1971, Cook [Co1] made a key observation concerning reducibility: if one also has an upper bound on the resources used in computing f , then one can relate the complexity of accepting the set B to the complexity of accepting A . Informally,

$$(1.2) \quad \text{"complexity of } A" \leq \text{"complexity of } B" + \text{"complexity of } f",$$

since from any algorithm M_B which accepts B we can obtain an algorithm M_A which accepts A : given an input x , the algorithm M_A first computes $f(x)$ and then applies M_B to $f(x)$. In applications of efficient reducibility, the resources used in computing f are negligible compared to what we are trying to establish about the complexities of A and B . Let us informally write $A \leq_{\text{eff}} B$ to indicate that A is reducible to B via a function f which is so efficiently computable that its complexity can be ignored. For example, Theorem 1.2 is proved by first observing that SAT and HC belong to NP, and then showing that if A is any decision problem in NP then $A \leq_{\text{eff}} \text{SAT}$ (Cook [Co1]) and $A \leq_{\text{eff}} \text{HC}$ (Karp [Ka1]), where in this case $A \leq_{\text{eff}} B$ means that A is reducible to B via a function f which is computable in polynomial time.

Although Cook and Karp did not use efficient reducibility to prove explicit lower bounds, it was not long before others, beginning with Meyer and Stockmeyer [MeS], noticed that (1.2) could be used in this way. If we somehow knew that a set A were complex, then we could show other sets B to be complex by efficiently reducing A to B . The existence of complex sets goes back to the early years (1960's) of complexity theory and the important papers of Rabin [Rab1] and Hartmanis and Stearns [HarS] which show that the complexity of decision problems can be as large as any recursive function. In particular, Hartmanis and Stearns [HarS] show that there is a set of words A_{exp} such that any Turing machine which accepts A_{exp} requires time $d^{|x|}$ for infinitely many inputs x , where $d > 1$ is a constant; moreover, A_{exp} is accepted by a Turing machine which uses time at most 2^n on any input x of length n . This is proved by showing that a Turing machine M running in time 2^n can diagonalize and differ from all Turing machines which run within time d^n for a suitably small constant $d > 1$. Then A_{exp} is the set of words accepted by M . (See [AHU, Chapter 11] or [HoU, Chapter 12] for details.)

To prove Theorem 1.1, Fischer and Rabin show that $A_{\text{exp}} \leq_{\text{eff}} \text{Th}(\mathbf{R}, +)$, where again \leq_{eff} is polynomial time reducibility. Actually, they show that any member of a large class of sets is efficiently reducible to $\text{Th}(\mathbf{R}, +)$. In proofs of this type, one usually chooses the class to be a *complexity class*, i.e., the class of all sets accepted by Turing machines running within some prescribed time or space bound. In Fischer

and Rabin's case, this class is the class of all sets which can be accepted within time 2^n . They show that for any set A in this class and for any input word x , there is a sentence $s_{A,x}$ in the language of $\text{Th}(\mathbf{R}, +)$ such that $x \in A$ iff $s_{A,x} \in \text{Th}(\mathbf{R}, +)$. Moreover, $s_{A,x}$ is computable from x in time polynomial in $|x|$, and there is a constant b_A depending only on A such that $|s_{A,x}| \leq b_A \cdot |x|$ for all x . In particular, $A_{\text{exp}} \leq_{\text{eff}} \text{Th}(\mathbf{R}, +)$ and Theorem 1.1 follows as outlined above; i.e., if there were a fast algorithm for $\text{Th}(\mathbf{R}, +)$ then there would be a fast algorithm for A_{exp} , contradicting the fact that A_{exp} requires time d^n for infinitely many inputs. The constant c in Theorem 1.1 depends on the dilation constant b_A in the reduction and on the constant d such that A_{exp} requires time d^n . The reduction is reminiscent of the "arithmetizations" of Turing machines used in the early undecidability proofs of Church and Turing (see [Dav]), although the requirement that the reducibility be efficiently computable introduces some new complications. Details can be found in [FiR] or [HoU, §13.6].

A general scenario for classifying problems goes as follows. Suppose that one has a specific decision problem (i.e., for each instance of the problem there is a yes/no answer) which is viewed as a recognition problem for a set B of words. The goal is to find complexity classes $\mathcal{C}_{\text{lower}}$ and $\mathcal{C}_{\text{upper}}$ such that

- (1) $\mathcal{C}_{\text{lower}} \leq_{\text{eff}} B$ (i.e., every set A in $\mathcal{C}_{\text{lower}}$ is efficiently reducible to B), and
- (2) B belongs to $\mathcal{C}_{\text{upper}}$.

Of course, it is desirable to make the two classes $\mathcal{C}_{\text{lower}}$ and $\mathcal{C}_{\text{upper}}$ as close as possible. Ideally, if $\mathcal{C}_{\text{lower}} = \mathcal{C}_{\text{upper}} = \mathcal{C}$, then we say that B is \mathcal{C} -complete. If $\mathcal{C}_{\text{lower}}$ is known to contain complex sets (say, by invoking the theorem of Hartmanis and Stearns), then one can infer a lower bound on the complexity of accepting B , as outlined above for the example $\text{Th}(\mathbf{R}, +)$.

Sometimes one shows that B is \mathcal{C} -complete where the class \mathcal{C} is not presently known to contain complex sets. Even in this case there is a sense in which such a result classifies B . Several open questions in automata-based complexity theory ask, for certain complexity classes \mathcal{D} and \mathcal{C} , whether or not $\mathcal{D} = \mathcal{C}$. Quite often, inclusion is known in one direction, say, that $\mathcal{D} \subseteq \mathcal{C}$. If B is \mathcal{C} -complete and \mathcal{D} satisfies certain technical conditions related to the particular efficient reducibility being used, then $B \in \mathcal{D}$ iff $\mathcal{D} = \mathcal{C}$. To answer the general question, "Does every set in \mathcal{C} also belong to \mathcal{D} ?" it is sufficient to focus on a single complete set B and answer the question "Does B belong to \mathcal{D} ?". Theorem 1.2 is an example of such a classification where $\mathcal{D} = \text{P}$, $\mathcal{C} = \text{NP}$, and SAT and HC are both NP-complete. Following the work of Cook and Karp, complete problems have been found for other interesting complexity classes such as P, polynomial space, and exponential time.

We now outline the remainder of the paper. §2 contains basic definitions, including those of Turing machines, efficient reducibilities, and complete problems. In §3 we state some general consequences of a problem being complete in a complexity class. §4 gives examples of complete problems in four important complexity classes. §5 touches on some other interesting complexity classes, such as classes defined by probabilistic Turing machines and by parallel models of computation. In §6 we survey a number of results giving upper and lower bounds on the complexities of decision problems from logic, game theory, formal language theory, and algebra. §7 discusses some related issues. §8 contains a few closing

remarks. Most of the paper is carried out at a level of formality sufficient to state results precisely. Space does not permit the inclusion of full proofs, although a few proofs are sketched to give the flavor of how results of the form $\mathcal{C} \leq_{\text{eff}} B$ are proved. Readers who would prefer a less formal introduction to computational complexity theory should see the Turing Award papers of Cook [Co6] and Karp [Ka2]. No attempt has been made to give an exhaustive list of known lower bounds and complete problems. Rather, the goal has been to mention early seminal papers as well as representative later papers in various subareas. Historically, the period covered by this article begins with Cook's 1971 paper [Co1] which gave the first example of an NP-complete problem, although much foundational work occurred earlier. Hartmanis [Har] gives a subjective account of this earlier period.

§2. Definitions.

2.1. Decision problems and encodings. Most of the computational problems considered here are viewed as problems of recognizing particular sets of words. If Σ is a finite alphabet, Σ^* denotes the set of finite words, i.e., finite strings of symbols, over Σ . A *decision problem*, or simply *problem*, is a subset of Σ^* for some finite Σ . In the literature, a set of words is also often called a *language*. In reality, a decision problem is usually defined as the problem of recognizing some specific set of mathematical objects such as true logical formulas, graphs having a certain property, etc. This requires encoding each object as a string of symbols over some finite alphabet. In the case of $\text{Th}(\mathbf{R}, +)$, for example, each well-formed sentence is already a string of symbols over a finite alphabet containing $+$, \wedge , \rightarrow , \exists , etc., except that as the length of sentences grows, the number of variables need not remain fixed. This is handled by tagging each distinct variable symbol with a different string over $\{0, 1\}$, that is, distinct variables are $v_0, v_1, v_{10}, v_{11}, v_{100}, \dots$. We prefer not to get bogged down in the details of encodings in this paper since in each case there is an obvious and natural encoding, and the results are invariant under minor differences in the encoding used.

The length of a word x is denoted $|x|$. If $A \subseteq \Sigma^*$ is a problem, $\bar{A} = \Sigma^* - A$ denotes the *complement* of A . If \mathcal{C} is a class of problems, $\text{co-}\mathcal{C} = \{\bar{A} \mid A \in \mathcal{C}\}$. \mathbf{N} denotes the nonnegative integers and \mathbf{R} denotes the real numbers.

2.2. Turing machines and complexity classes. The formal model of computation used here is the Turing machine. In the literature, this choice is made in part for historical reasons, but mainly because the simplicity of the definition of Turing machines makes them convenient to work with. The results obtained in terms of Turing machines usually carry over to more realistic models of computation; we discuss this further below. For completeness we review the definition of Turing machines, although we assume that the reader is already somewhat familiar with this model. More information, if needed, can be found in [AHU] and [HoU]. We first define *nondeterministic Turing machines* (NTM's) with a finite number of read/write work-tapes and a 2-way read-only input-tape. "Nondeterministic" means that there may be several ways for the computation to proceed. A particular NTM M is specified by finite sets Q (the states), Σ (the input alphabet), Γ (the work-tape alphabet), designated states q_0 (the initial state) and q_a (the accepting state), an endmarker $\$ \notin \Sigma$, an integer $k \geq 1$ (the number of work-tapes), and a transition

function δ ,

$$\delta: Q \times (\Sigma \cup \{\$, \#\}) \times \Gamma^k \rightarrow \text{powerset}(Q \times \Gamma^k \times \{\text{left, right, stationary}\}^{k+1}),$$

where $\text{powerset}(S)$ denotes the set of subsets of S . If the machine is in state q scanning σ on the input-tape and scanning γ_i on the i th work-tape for $1 \leq i \leq k$, and if

$$(q', \gamma'_1, \dots, \gamma'_k, m_1, \dots, m_{k+1}) \text{ belongs to } \delta(q, \sigma, \gamma_1, \dots, \gamma_k),$$

then M can in one step change its state to q' , print γ'_i on the i th work-tape and move the head in direction m_i , and move the input head in direction m_{k+1} . A *configuration* of M is specified by giving the nonblank contents of all tapes, the positions of all heads, and the state. Write $C \vdash_M C'$ if configuration C can reach C' in one step of M . The machine is given input $x \in \Sigma^*$ by writing $\$x\$$ on the input-tape with the head scanning the first symbol of x ; the state is q_0 and all work-tapes are blank. Let Init_x denote this initial configuration on input x . An *accepting computation* of M on input

J adner Lynch and Sclman [LS] Logspace reducibility was introduced inde-

pndently by Cook [Co3], Jones [Jon], and Meyer and Stockmeyer [StoM]. Since

logspace \subseteq polytime (cf. (2.3c)), $A \leq_{\log} B$ implies $A \leq_p B$. Since polytime is clearly closed under functional composition and since Jones [Jon] and Meyer [StoM] show that logspace is closed under composition, \leq_{\log} , $\leq_{\log\text{-lin}}$, \leq_p and $\leq_{p\text{-lin}}$ are all

general phenomenon, as pointed out by Book [Bo] using the following definition. A class \mathcal{D} of problems is *closed under* \leq_{eff} provided that if $B \in \mathcal{D}$ and $A \leq_{\text{eff}} B$ then $A \in \mathcal{D}$. For example, P is closed under \leq_p . The proof of the following is immediate from definitions.

PROPOSITION 3.1. *Let \mathcal{D} and \mathcal{C} be classes of problems such that $\mathcal{D} \subseteq \mathcal{C}$ and \mathcal{D} is closed under \leq_{eff} , and say that B is \mathcal{C} -complete with respect to \leq_{eff} . Then $B \in \mathcal{D}$ if and only if $\mathcal{D} = \mathcal{C}$.*

3.2. Lower bounds on computational complexity. As outlined in the Introduction, if $\mathcal{C} \leq_{\text{eff}} B$ and if \mathcal{C} is known to contain sufficiently complex problems, then one can infer an explicit lower bound on the computational complexity of B . In order to make this formal, we need two lemmas.

When $A \leq_{\text{eff}} B$ the first lemma provides an upper bound on the complexity of A in terms of an upper bound on the complexity of B . Two relevant parameters of \leq_{eff} are the resources used in computing the reducibility function f and the extent to which f increases the length of its argument.

LEMMA 3.1. *Let A and B be problems and let S and T be nondecreasing functions from reals to reals.*

- (1) *If $A \leq_{\text{eff}} B$ via f , and $L: \mathbb{N} \rightarrow \mathbb{R}$ is such that $|f(x)| \leq L(|x|)$ for all x , then*

$$B \in \text{DTIME}(T(n)) \text{ implies } A \in \text{DTIME}(T(L(n)) + p(n))$$

for some polynomial $p(n)$.

- (2) *If $A \leq_{\log} B$ via f , and L is as above, then*

$$B \in \text{DSpace}(S(n)) \text{ implies } A \in \text{DSpace}(S(L(n)) + \log n).$$

Moreover, (1) is true with NTIME in place of DTIME, and (2) is true with NSPACE in place of DSPACE.

PROOF (sketch). (1) Say that M is a DTM which accepts B within time $T(n)$. A DTM M' accepts A as follows: given input x , first compute $f(x)$ (this takes time polynomial in $|x|$ and produces a word $f(x)$ of length $\leq L(|x|)$) and then apply M to $f(x)$ (this takes time at most $T(L(|x|))$ by assumption). The proof for NTIME is identical.

(2) The obvious approach of part (1) does not work here because writing $f(x)$ on a work-tape might exceed the desired space bound $S(L(n)) + \log n$. However, it is possible to simulate the computation of M on $f(x)$ by simply keeping track of the position of M 's input head on the input $f(x)$ (which can be done using an integer with at most $\log n$ digits) and then recomputing the symbols of $f(x)$ whenever they are needed in this simulation. This technique is due to Jones and Meyer [Jon], [StoM]. \square

The second lemma concerns "hierarchy" theorems for time and space complexity which state that for small increases in the growth rate of the resource bounding function $S(n)$ or $T(n)$, more problems can be accepted.

We use the following terminology: For a problem A and a function $G(n)$, the phrase " A requires nondeterministic time $G(n)$ i.o." means that if A is accepted by an NTM within time $T(n)$ then $T(n) \geq G(n)$ for infinitely many n (i.o. stands for "infinitely often"). Similar terminology is obtained by replacing nondeterministic by deterministic and/or replacing time by space.

The following lemma, which concerns hierarchies for NTM's, is due to Seiferas, Fischer and Meyer [Se], [SeFM] and refines earlier results of Ibarra [Ib] and Cook [Co2].

LEMMA 3.2. (1) Let $T_1(n)$ and $T_2(n)$ be functions such that

$$\lim_{n \rightarrow \infty} T_1(n+1)/T_2(n) = 0.$$

There is a problem $A \in \text{NTIME}(T_2(n))$ such that A requires nondeterministic time $T_1(n)$ i.o.

(2) Let $S_1(n)$ and $S_2(n)$ be functions such that

$$\lim_{n \rightarrow \infty} S_1(n+1)/S_2(n) = 0.$$

There is a problem $A \in \text{NSPACE}(S_2(n))$ such that A requires nondeterministic space $S_1(n)$ i.o.

Similar hierarchies are known for DTM's [HarS], [StHL] (see also [HoU, Chapter 12]) although the known time hierarchy is slightly coarser in the deterministic case.

To illustrate the use of Lemmas 3.1 and 3.2, we restate and outline the proof of Theorem 1.1.

THEOREM 3.1. There is a constant $c > 1$ such that $\text{Th}(\mathbf{R}, +)$ requires nondeterministic time c^n i.o.

PROOF (sketch). The key fact, proved by Fischer and Rabin [FiR], is that

$$(3.1) \quad \text{NTIME}(2^n) \leq_{\text{p-lin}} \text{Th}(\mathbf{R}, +).$$

The proof of (3.1) is quite involved and we do not attempt to reproduce it here. Our goal is only to show how (3.1) is used to prove a lower bound on $\text{Th}(\mathbf{R}, +)$.

Using Lemma 3.2(1), let A be a problem in $\text{NTIME}(2^n)$ such that A requires nondeterministic time $2^{n/2}$ i.o. From (3.1), $A \leq_{\text{p-lin}} \text{Th}(\mathbf{R}, +)$ via a function f such that $|f(x)| \leq b|x|$ for some constant b . Choose c such that $0 < c < 2^{1/2b}$, and assume for contradiction that $\text{Th}(\mathbf{R}, +) \in \text{NTIME}(c^n)$. Using Lemma 3.1(1) it follows that $A \in \text{NTIME}(c^{bn} + p(n))$, where $p(n)$ is a polynomial. But $c^{bn} + p(n) < 2^{n/2}$ for all but finitely many n , contradicting the fact that A requires nondeterministic time $2^{n/2}$ i.o. \square

The reader should have no trouble generalizing this proof to other situations. For example, if B is a problem such that $\text{DSpace}(2^n) \leq_{\log} B$, and moreover for each $A \in \text{DSpace}(2^n)$ there is a function f and a constant b such that $A \leq_{\log} B$ via f and $|f(x)| \leq b|x|^2$, then one concludes that there is a constant $c > 1$ such that B requires deterministic space $c^{n^{1/2}}$ i.o.

We should point out that it is not strictly necessary to use the hierarchy theorems in proving lower bounds. Once one has shown that $\mathcal{C} \leq_{\text{eff}} B$ for a sufficiently rich class \mathcal{C} , then it should be possible to carry out a direct diagonalization (in the spirit of classical undecidability results, cf. [Dav]) to establish a lower bound. In fact, this is how Fischer and Rabin proceed in their proof of Theorem 3.1. We prefer to make explicit use of the hierarchy theorems.

A lower bound on the computational complexity of a problem sometimes implies a lower bound on some other measure of the complexity of the problem. For a logical decision problem another measure is the length of proofs required to prove

the true statements. Suppose that AX is a system of axioms for $\text{Th}(\mathbf{R}, +)$ such that (i) a sentence s is provable from AX iff s is true, and (ii) AX , when viewed as a set of words, belongs to P . Then there is a constant $c > 1$ and an infinite set $S \subseteq \text{Th}(\mathbf{R}, +)$ of true sentences such that, for all $s \in S$, the shortest proof of s from AX has length at least $c^{|s|}$. Briefly, this is true because if proofs were always “short” then there would be a “fast” NTM which accepts $\text{Th}(\mathbf{R}, +)$: given an input s , such an NTM would nondeterministically guess a “short” string ρ and then verify that ρ is a valid proof of s from AX . Fischer and Rabin [FiR] discuss this further.

3.3. Speed-up. Given a sufficiently complex problem A and given an algorithm M which accepts A , one can sometimes find a more clever algorithm M' which runs much faster than M on infinitely many inputs. Blum in [Blu1] and [Blu2] shows that there exist problems with this speed-up property for *any* given M . To simplify the discussion, let us restrict attention to DTM's which halt on all inputs, and let $\text{Time}_M(x)$ denote the number of steps in the computation of DTM M on input x . Let us say that a problem $A \subseteq \Sigma^*$ has *$T(n)$ -to-polynomial effective i.o. speed-up* if there is a polynomial $p(n)$ such that from any DTM M which accepts A we can effectively produce a DTM M' which accepts A and an infinite recursive set $U \subseteq \Sigma^*$ such that

$$\text{Time}_M(x) \geq T(|x|) \quad \text{for all } x \in U,$$

and

$$\text{Time}_{M'}(x) \leq p(|x|) \quad \text{for all } x \in U.$$

Blum's work is carried out for a general axiomatic complexity measure. However, the proof of Theorem 3 in [Blu2] can be carried out for the particular measure of DTM time, and the proof yields the following result (this was pointed out to me by A. Meyer).

THEOREM 3.2. *For any constructible $T(n)$, there is a problem A in $\text{DTIME}(O(T(n)^2))$ which has $T(n)$ -to-polynomial effective i.o. speed-up.*

However, the problem A in this theorem is constructed specifically to have the speed-up property; it is not a natural problem. Stockmeyer [Sto1], following a suggestion of Meyer, has shown that if $A \leq_{\text{eff}} B$ via f , if f satisfies the mild conditions of being one-to-one and efficiently invertible (all of the known reductions satisfy these conditions), and if A has i.o. speed-up then so does B . (Although the details are carried out in [Sto1] only for the space measure, the details for the time measure are analogous.) Combining this with Theorem 3.2 and results such as (3.1), it follows that natural problems such as $\text{Th}(\mathbf{R}, +)$ have i.o. speed-up. In particular, the following can be shown.

THEOREM 3.3. *There is a constant $c > 1$ such that $\text{Th}(\mathbf{R}, +)$ has c^n -to-polynomial effective i.o. speed-up.*

Berman [Ber1] has shown that if a problem is $\text{DTIME}(T(n))$ -complete where $T(n)$ grows faster than polynomially in n , then the problem has the i.o. speed-up property even without imposing an efficient invertibility condition on the reducibility function.

§4. Complete problems in four important complexity classes. The purpose of this section is to give examples of complete problems in four important complexity classes, attempt to give the reader some feeling for how such results are proved, and

examine the consequences of complete problems to open questions in complexity theory. From the inclusions (2.1), (2.2), and (2.3) it is known that

$$(4.1) \quad \text{DLOG} \subseteq \text{NLOG} \subseteq \text{P} \subseteq \text{NP} \subseteq \text{PSPACE}.$$

It is presently an open question whether any of these containments are proper. (However it is known that $\text{NLOG} \neq \text{PSPACE}$, which follows from (2.2b) and Lemma 3.2(2).) Since it is not known that $\text{P} \neq \text{PSPACE}$, we cannot use the method of §3.2 to show that problems complete in these classes require more than polynomial time. However, using the method of §3.1 it is easy to relate the complexities of complete problems to questions of proper inclusion in (4.1). It is an easy consequence of Lemma 3.1 that all five of the classes in (4.1) are closed under \leq_{\log} and that the last three are closed under \leq_p . Let \mathcal{C}_i denote the i th class from the left in (4.1) for $1 \leq i \leq 5$. By Proposition 3.1, if B is \mathcal{C}_i -complete then $B \in \mathcal{C}_{i-1}$ iff $\mathcal{C}_{i-1} = \mathcal{C}_i$.

In each of the following four subsections we choose as our main example a problem which has been useful as a starting point for proving other problems to be complete. Note that since \leq_{\log} and \leq_p are transitive, once a particular problem A has been proved \mathcal{C} -hard, one can show other problems B to be \mathcal{C} -hard by showing that $A \leq_{\text{eff}} B$ for the appropriate \leq_{eff} . This is sometimes easier than showing $\mathcal{C} \leq_{\text{eff}} B$ directly.

Since several of our examples involve propositional variables and formulas, we first introduce some terminology for this. Let $\{X_0, X_1, X_2, \dots\}$ be a set of propositional variables where variables are encoded as described in §2.1 by writing subscripts in binary notation, $X_0, X_1, X_{10}, X_{11}, X_{100}$, etc. A *propositional formula* either is a propositional variable or is of the form $(\neg F)$, $(F \rightarrow G)$, $(F \wedge G)$, or $(F \vee G)$ where F and G are propositional formulas. An assignment of truth values to the propositional variables in a formula determines a truth value for the formula in the obvious way. A propositional formula is *satisfiable* if the formula is true for some

4.1 PSPACE-complete problems PSPACE-completeness is in a certain tech-

polynomial function of n . One more trick allows us to write F_k in terms of one copy of F_{k-1} so that the length of F_k grows only polynomially in k :

$$F_k(V, V') \\ = (\exists W)(\forall Y)(\forall Z)[((Y = V \wedge Z = W) \vee (Y = W \wedge Z = V')) \rightarrow F_{k-1}(Y, Z)].$$

Let $q(n)$ be a polynomial such that M accepts within time $2^{q(n)}$. We can use $F_{q(n)}$ to express the fact that the initial configuration of M on input x can reach an accepting configuration within $2^{q(n)}$ steps. \square

QBF remains PSPACE-complete even when restricted to formulas in conjunctive or disjunctive normal form with at most three literals per conjunct or disjunct [Sto2]. By noting that the reduction of PSPACE to QBF described above can be computed in logarithmic space and that the reduction maps an input x of length n to a formula of length $O(n^2 \log n)$ in the case that M is an NTM with a linear space bound (i.e., $p(n) = n$), the method of §3.2 can be used to show that QBF requires nondeterministic space n^δ i.o. for any fixed $\delta < \frac{1}{2}$. Theorem 4.4 can be used to show PSPACE-hardness of *any* first-order theory which has the ability to emulate QBF. One example from [Sto2] is the first-order theory of equality which is, in fact, PSPACE-complete. We shall see other examples of PSPACE-complete problems in §6.

§5. Other classes.

5.1. Alternation and the polynomial-time hierarchy. Alternating Turing machines (ATM's) were defined by Chandra, Kozen and Stockmeyer [ChKS]. One of the motivations for the definition was to generalize the concept of a nondeterministic computation. Another way to think of the definition of acceptance for NTM's is that a configuration C of an NTM M leads to acceptance iff there exists a configuration C' , with $C \vdash_M C'$, such that C' leads to acceptance. The definition of alternation generalizes this to alternating quantifiers. A particular ATM is specified like an NTM as described in §2.2, but in addition a particular subset U of the states Q is specified. The states in U are called *universal states* and the states in $Q - U$ are called *existential states*. Configurations are called universal or existential according to the state of the configuration. Informally, a universal configuration C leads to acceptance if C' leads to acceptance for all C' such that $C \vdash_M C'$. More formally, an *accepting computation* of an ATM M on an input x is a rooted tree whose nodes are labelled by configurations of M such that the root is labelled by Init_x , all leaves are labelled by accepting configurations, if an internal (i.e., nonleaf) node is labelled by an existential configuration C then the node has one son which is labelled by some C' with $C \vdash_M C'$, and if an internal node is labelled by a universal configuration C and if C_1, \dots, C_d are the configurations reachable from C in one step of M then the node has d sons labelled C_1, \dots, C_d . The *time* of a computation is the maximum length of a path from the root to some leaf. The *space* of a computation is the maximum number of work-tape squares visited in each of the configurations labelling nodes of the configuration. A particular root-to-leaf path has k *alternations* if the number of times the machine switches from an existential to a universal configuration, or vice versa, on the path is $k - 1$. The *alternations* of a computation is the maximum, over all root-to-leaf paths, of the alternations of the path. In complete analogy to the

definitions of §2.2 for NTM's and DTM's, we can define the set of words $L(M)$ accepted by the ATM M , the notion of M accepting in time $T(n)$, space $S(n)$, or alternations $A(n)$, and the alternating complexity classes $\text{ATIME}(T(n))$ and $\text{ASPACE}(S(n))$ defined by ATM's which accept within time $T(n)$ or space $S(n)$, respectively. Alternating complexity classes are related to deterministic complexity classes by the following result from [ChKS] which shows that alternating time (space) corresponds to deterministic space (time).

THEOREM 5.1. (a) $\text{ATIME}(\text{poly}(T(n))) = \text{DSPACE}(\text{poly}(T(n)))$.

(b) $\text{ASPACE}(S(n)) = \text{DTIME}(2^{\text{O}(S(n))})$.

These relationships have been useful in classifying the complexities of certain problems in logic and game theory, two areas where alternating quantifiers arise naturally. We shall see some examples in §6.

Of special interest are classes defined by ATM's which accept within polynomial time and within a constant number of alternations. Such classes give a polynomial time bounded analogue of Kleene's arithmetical hierarchy [Rog, Chapter 14], where P is the analogue of the recursive sets and NP is the analogue of the r.e. sets. (To help see the analogy, note that the definition of NP given by (1.1) defines the r.e. sets if the polynomial bound on the length of y is omitted.) The classes of the *polynomial-time hierarchy* are Σ_k^P and Π_k^P for $k \geq 0$. $\Sigma_0^P = \Pi_0^P = P$. For $k > 0$, Σ_k^P (resp., Π_k^P) is the class of problems accepted by ATM's whose initial state is existential (resp., universal) and which accept simultaneously within time $\text{poly}(n)$ and within k alternations. The original definition of the polynomial-time hierarchy, given by Meyer and Stockmeyer [MeS], more closely mimics the definition of the arithmetical hierarchy. Specifically, Σ_k^P can be defined equivalently as the class of problems accepted in polynomial time by nondeterministic oracle Turing machines with oracles in Σ_{k-1}^P . (An oracle machine can write words on a special oracle tape, and in one step find out whether or not the word written on the oracle tape belongs to the oracle set.) The definition in terms of oracle machines also allows us to define Δ_k^P to be the class of problems accepted in polynomial time by deterministic oracle machines with oracles in Σ_{k-1}^P . Trivial relationships are

$$\begin{aligned}\Sigma_1^P &= NP, & \Pi_k^P &= \text{co-}\Sigma_k^P, \\ \Sigma_k^P \cup \Pi_k^P &\subseteq \Delta_{k+1}^P \subseteq \Sigma_{k+1}^P \cap \Pi_{k+1}^P, \\ \Sigma_k^P &\subseteq \text{PSPACE}\end{aligned}$$

for all $k \geq 0$, although none of these inclusions are known to be proper. It is easy to show that if $\Sigma_k^P = \Sigma_{k+1}^P$ for some $k \geq 0$, then $\Sigma_k^P = \Sigma_j^P$ for all $j \geq k$ [Sto2]. In particular, if $P \neq \Sigma_k^P$ for any $k \geq 1$, then $P \neq NP$.

One of the original hopes in defining the polynomial-time hierarchy was that it would be useful in classifying certain recursive problems, just as the arithmetical hierarchy has been useful in classifying certain nonrecursive problems. This hope has not been completely borne out, although a few results are known. Sagiv and Yannakakis [SaY] show that a certain problem in relational database theory is Σ_2^P -complete. Huynh [Huy] shows that the equivalence problem for context-free grammars with a one-letter terminal alphabet is Π_2^P -complete. Papadimitriou

[Pa1] shows that, given a graph with an integer distance assigned to each edge, determining uniqueness of the optimal traveling salesman tour is Δ_2^P -complete. Jeroslow [Je] shows that a certain linear programming game is complete in various levels of the hierarchy, the level depending on the number of players. Other, more artificial, problems complete in various levels of the hierarchy are given in [Sto2] and [Wr].

5.2. Probabilistic classes. There are certain problems which are not known to be solvable in deterministic polynomial time but which can be solved in polynomial time by algorithms which can utilize random numbers in their computations and which may make errors with small probability. A simple example of this, as noted by Schwartz [Schw], is the problem of checking whether a polynomial expression is identically zero. Let x_1, x_2, \dots be a sequence of indeterminates. An indeterminate is a polynomial expression of degree 1. An integer is a polynomial expression of degree 0. If F and G are polynomial expressions then $(F + G)$ and $(F - G)$ are polynomial expressions of degree $\max(\deg(F), \deg(G))$, and (FG) is a polynomial expression of degree $\deg(F) + \deg(G)$. Let ZERO be the set of polynomial expressions which are identically zero. For example, $(x_1 + x_2)(x_1 - x_2) - x_1x_1 + x_2x_2$ is in ZERO. An obvious approach for solving this problem is to expand the given expression into a sum of monomials. This is not a polynomial time algorithm since the expansion could cause an exponential blow-up in the length of the expression. However, it is not hard to prove that if a polynomial expression $F(x_1, \dots, x_m)$ is not identically zero and if $N \geq c \cdot \deg(F)$, then F has at most $c^{-1}N^m$ integral roots in $[1, N]^m$ [Schw]. Thus, another approach would be to independently choose m random integers from the interval $[1, N]$ for $N = 2 \cdot \deg(F)$, evaluate F on the chosen random integers, and accept iff F evaluates to 0. For inputs F with $F \in \text{ZERO}$, this procedure is always correct. For inputs with $F \notin \text{ZERO}$, this procedure makes an error with probability at most $1/2$. By repeating this procedure t times, using a new random assignment at each trial, the error probability decreases to at most 2^{-t} .

The concept of a resource bounded Turing machine which can make random choices was formalized by Gill [Gi]. The definition of a *probabilistic Turing machine* is actually identical to the definition of an NTM. The difference arises in the definition of acceptance. When a probabilistic Turing machine M is in a configuration C and there are d configurations C' such that $C \vdash_M C'$, we imagine that M generates a random integer between 1 and d to choose which of the d successors of C to enter next. For simplicity, let us restrict attention to Turing machines with the property that all computations, accepting or not, halt within $p(n)$ steps for some polynomial p . For each input x , there is a well-defined probability $\rho_M(x)$ that M accepts x .

A problem A is in the class R , called *random polynomial time*, if there is a probabilistic Turing machine M which always halts in polynomial time and a constant $\varepsilon > 0$ such that $\rho_M(x) \geq \varepsilon$ for all $x \in A$ and $\rho_M(x) = 0$ for all $x \notin A$. Note that M , when viewed as an NTM, accepts A and has the additional property that, for each accepted input, at least the fraction ε of the possible computations are accepting. It follows that

$$P \subseteq R \subseteq NP.$$

We have noted above that the complement of ZERO belongs to R . Some

generalizations of this result are given by Ibarra and Moran [IbM]. An interesting example of a problem which is known to belong to R, but whose membership in P is unresolved, is the set of binary representations of composite integers. The proof that the set of composite integers belongs to R is due to Solovay and Strassen [SoS] and independently to Rabin [Rab5], who bases the algorithm on a method of Miller [Mi]. Berlekamp [Ber1] and Rabin [Rab6] give probabilistic algorithms for other number-theoretic problems, such as factoring polynomials over finite fields, which are faster than the known deterministic algorithms.

Gill also defines the probabilistic complexity class BPP which allows errors on both accepted and rejected inputs. Precisely, A is in BPP if there is a polynomially time bounded probabilistic Turing machine M and a constant $\delta > 1/2$ such that $\rho_M(x) \geq \delta$ for all $x \in A$ and $\rho_M(x) \leq 1 - \delta$ for all $x \notin A$. It is known that

$$R \subseteq BPP \subseteq \Sigma_2^P \cap \Pi_2^P.$$

The second inclusion is due to Sipser and Gács [Sip3] and is not obvious; a simpler proof is given by Lautemann [Lau]. From a practical point of view, showing a problem to be in R or BPP is almost as good as showing the problem to be in P, since by repeating the probabilistic algorithm t times, the error probability decreases exponentially in t . There are no problems known to be R-complete or BPP-complete. Gill [Gi] also defines probabilistic classes by requiring only $\rho_M(x) > \frac{1}{2}$ for $x \in A$ and $\rho_M(x) \leq \frac{1}{2}$ for $x \notin A$, so that the probabilities of accepting and rejecting need not remain bounded away from one another; such classes are more of mathematical than practical interest. Space bounded probabilistic classes are also considered in [Gi]. Further discussion of probabilistic complexity classes and related issues can be found in [Joh3].

5.3. Parallel computation. As the price of computer hardware continues to decrease, it becomes quite attractive to speed up the solution to problems by having many processors work on the problem in parallel. For this to succeed, it must be possible to partition the computation among the processors so that the various parts can be carried out more or less independently. This raises the theoretical question of determining which problems can be solved much faster in parallel than sequentially.

A very simple example of a problem which can be solved much faster in parallel than sequentially is the problem of recognizing the set of words x such that $x = uu$ for some $u \in \{0, 1\}^*$. Given an input x of even length n , and assuming that we have $n/2$ processors, the i th processor can compare the i th symbol of x with the $(n/2 + i)$ th symbol of x for $1 \leq i \leq n/2$. All of these comparisons are done in one parallel step. In the next parallel step, the i th processor communicates the outcome of its comparison to the $(i - n/2)$ th processor for $n/2 + 1 \leq i \leq n$. Then the i th processor communicates to the $(i - n/4)$ th processor for $n/4 + 1 \leq i \leq n/2$, and so on. After $\log n$ of these communication steps, the information of whether or not all the comparisons resulted in equality has been fanned into the first processor. Thus, a problem which requires time n to be solved sequentially can be solved in time $O(\log n)$ in parallel. For some problems in P, it is not known whether they can be solved in parallel time $O(\log n)$, although we can do almost as well by showing that $\text{poly}(\log n)$ parallel time suffices. One example is the problem GAP discussed in §4.1

which can be solved in parallel time $O((\log n)^2)$ using $O(n^{3/2})$ processors (see, for example, Borodin [Boro]). For certain other problems in P, such as the problem CVP defined in §4.2, it is not known whether parallel time $\text{poly}(\log n)$ suffices. In the case of CVP, since a variable X_i depends on other variables X_j for $j < i$, there is apparently no way to partition the computation into many independent pieces. The following question is open.

(5.1) *Can every problem in P be solved in parallel time $\text{poly}(\log n)$?*

Of course, before we can begin to answer this question, a precise definition of “parallel time” is needed. Several parallel computational models have been proposed. We do not attempt to reproduce a detailed definition of one of these models, but we will attempt to give the idea. Probably the most popular theoretical model is a parallel version of the random access machine described in §2.3. The PRAM, defined by Fortune and Wyllie [FoW], consists of a sequence of deterministic RAM processors, $R_1, R_2, \dots, R_{P(n)}$, operating in parallel. The number $P(n)$ of processors can be a function of the length n of the input. In order for the RAM’s to communicate among one another, we assume that there is a *common memory* consisting of registers c_1, c_2, c_3, \dots , and there are instructions in the programs of the individual RAM’s for writing into and reading from the common memory. Each RAM has the same program. However, initially i is written in one of the local memory registers of R_i , so that different RAM’s can operate differently. Initially, the symbols of the input are written in the first n registers of common memory. The computation of a PRAM proceeds synchronously, that is, at each parallel step all RAM’s execute the next step of their program in parallel. We assume that the program is such that two different RAM’s never attempt to write into the same common memory register at the same parallel step. The PRAM accepts if R_1 accepts. For function computation, the output is in common memory when the computation halts. Two resource bounds of interest are the parallel time $T(n)$, that is, the number of parallel steps in a computation, and the number of processors $P(n)$. In this subsection, we permit parallel time bounds $T(n)$ to be as small as $\log n$. Another feature of the definition of the PRAM is that initially there is only one “active” processor, R_1 , but a processor can activate another at any step. Thus, after t parallel steps, 2^t processors could be active but no more.

Investigation of a variety of parallel models has shown that if no explicit upper bound is placed on the number of processors, then the class of problems accepted by parallel machines in time $\text{poly}(T(n))$ is precisely the class of problems accepted by DTM’s in space $\text{poly}(T(n))$. This was first proved by Pratt and Stockmeyer [PrS] for a parallel model called the vector machine. Fortune and Wyllie [FoW] prove this equivalence for PRAM’s. If we view ATM’s (see §5.1) as a parallel model, then Theorem 5.1(a) is another example of the equivalence. This has led to the formulation of a “parallel computation thesis” by Chandra and Stockmeyer [ChS] and Goldschlager [Go2] that parallel time is equivalent to Turing machine space, at least to within composition with a polynomial. Adopting this thesis, the question (5.1) is equivalent to a question we have seen before in §4.2, namely,

(5.2) *Is $P \subseteq \text{DSPACE}(\text{poly}(\log n))$?*

As a result, proving a problem to be P-complete is viewed as evidence that the problem cannot be solved in $\text{poly}(\log n)$ parallel time. We should point out that the

parallel models for which the parallel computation thesis has been verified all have the property that if a parallel computation has t parallel steps then at most $2^{O(t)}$ processors can take part in the computation; thus, there is the implicit bound that $P(n)$ is $2^{O(T(n))}$. Blum [Blu3] points out that the parallel computation thesis can fail if many more than $2^{O(T(n))}$ processors can be employed.

Parallel time classes can be refined by also placing an upper bound on the number of processors, and such upper bounds are necessary if parallel algorithms are to have any practical significance. For example, it was shown in [PrS] that any context-free language can be accepted in $\text{poly}(\log n)$ parallel time, but the number of processors was not bounded above by a polynomial in n . Pippenger [Pi] suggested that an interesting complexity class to study would be the class of problems solvable by parallel machines in $\text{poly}(\log n)$ time using $\text{poly}(n)$ processors; this class has come to be known as NC (for “Nick’s class”). Pippenger also provided a characterization of NC in terms of Turing machines: NC is the class of problems solvable by DTM’s which accept in polynomial time and whose work-tape heads make at most $\text{poly}(\log n)$ reversals. Another characterization of NC, by Ruzzo [Ruz], is that NC is the class of problems accepted by ATM’s which accept simultaneously within space $O(\log n)$ and within time $\text{poly}(\log n)$. Ruzzo [Ruz] also shows that any context-free language is in NC. One of the first problems shown to be in NC (even before the class was formally defined) was the problem of inverting and computing the determinant of a matrix (Csanky [Cs]). Placing problems in NC, including problems which are not obviously amenable to significant parallelization, is currently a very active area. The reader interested in finding out more about the theory of parallel computation would do well to start with two survey articles of Cook, [Co4] and [Co5].

5.4. #P. Valiant [Va1] has introduced the class #P to capture the complexity of various counting problems. #P is a class of functions rather than decision problems. A function $g: \Sigma^* \rightarrow \mathbb{N}$ is in #P if there is an NTM M which always halts in polynomial time such that, for all $x \in \Sigma^*$, M has $g(x)$ accepting computations on input x . For example, the function which maps a propositional formula $F(X_1, \dots, X_m)$ to the number of satisfying truth assignments of F is easily seen to be in #P. Polynomial time Turing reducibility is the appropriate reducibility to use in defining #P-completeness. A function g is #P-complete if $g \in \text{\#P}$ and, for all $h \in \text{\#P}$, h can be computed in polynomial time by a deterministic oracle Turing machine with an oracle for g ; the oracle machine can write words on a special oracle tape and in one step obtain the binary representation of $g(w)$, where w is written on the oracle tape.

It is clear that any function in #P can be computed in polynomial space, but the relation between #P and the polynomial-time hierarchy is not known. #P-completeness is also evidence of computational intractability, since if any #P-complete function can be computed in polynomial time then the number of accepting computations of an arbitrary polynomially time bounded NTM can be computed in deterministic polynomial time; of course, this implies that $P = NP$.

Not surprisingly, #P-complete problems include counting versions of many NP-complete problems, such as counting the number of satisfying assignments to a given propositional formula and counting the number of Hamiltonian cycles in a given graph. A more surprising result, due to Valiant [Va1], is that the problem of

computing the permanent of a matrix with integer entries is $\#P$ -complete, and the problem remains $\#P$ -complete even for zero-one entries. The permanent of an $m \times m$ matrix $\{a_{i,j}\}_{i,j=1}^m$ is the sum, over all permutations $\pi: \{1, \dots, m\} \rightarrow \{1, \dots, m\}$, of the product

$$t_\pi = a_{1,\pi(1)}a_{2,\pi(2)} \cdots a_{m,\pi(m)}.$$

The $\#P$ -completeness of the permanent is interesting because the existential version of the problem (Does there exist a permutation π such that $t_\pi \neq 0$?) can be solved in deterministic polynomial time by a simple reduction to the problem of checking whether a bipartite graph has a perfect matching, which can be decided in polynomial time [PaS]. Other $\#P$ -complete problems in [Va2] include the problem of computing the probability that a graph is connected when each edge of the graph is present with a given probability.

5.5. D^P . Papadimitriou and Yannakakis [PaY] consider the class D^P defined as

$$D^P = \{A \cap B \mid A \in NP \text{ and } B \in co-NP\}.$$

Obviously,

$$NP \cup co-NP \subseteq D^P \subseteq A_2^P.$$

D^P has been useful for classifying various extremal graph problems such as recognizing the set of undirected graphs G such that G does not have a Hamiltonian cycle but adding any new edge to G produces a graph with a Hamiltonian cycle, and recognizing the set of pairs (G, k) such that G is an undirected graph, k is an integer, and the largest complete subgraph of G has exactly k vertices. Both of these problems are D^P -complete (see [PaY] and [PaW]). (In contrast, the set of (G, k) such that G has a complete subgraph with *at least* k vertices is NP-complete.) One of the original motivations for D^P was to classify the problem of recognizing the set of linear inequalities which describe facets of the traveling salesman polytope. This problem has now been shown D^P -complete by Papadimitriou and Wolfe [PaW]. Valiant and Vazirani [VaV] show that the *unique satisfiability problem* (given a propositional formula F , does it have exactly one satisfying assignment?) is D^P -complete with respect to *randomizing* polynomial-time reducibility (i.e., the reducibility function is computed by a probabilistic Turing machine which can make errors with small probability). Further discussion of D^P and the complexity of problems having unique solutions can be found in [Joh4].

§6. Complexities of some specific problems. In this section we survey several classification results. The problems are grouped by the area (logic, games, algebra, and formal languages) from which they are drawn. In each subsection it is assumed that the reader is already somewhat familiar with the area being discussed. This section is by no means an exhaustive list of known results. In particular, [GaJ] lists many other NP-complete problems as well as a few PSPACE-complete ones.

6.1. *Logic.* The complexities of nearly all the classical decidable theories have been classified in terms of time or space requirements, although gaps between known upper and lower bounds remain in a few cases. Since many of the relevant time and space bounds involve iterated exponentiation, we define notation for this.

Define the function $g(k, n)$ for $n, k \in \mathbb{N}$ by $g(0, n) = n$ and $g(k + 1, n) = 2^{g(k, n)}$ for $k \geq 0$.

We first consider decision problems which cannot be accepted within space $g(k, n)$ for any fixed k ; such problems are termed *nonelementary*. The first example of a decidable but nonelementary logical decision problem, the weak monadic second-order theory of one successor, was due to Meyer [Me1]. In this theory, formulas involve individual variables, set variables, primitive relations “ $y = x + 1$ ” and “ $x \in S$ ” where x and y denote individual variables and S denotes a set variable, quantifiers \exists and \forall for both individual variables and set variables, and the usual logical connectives. Let WS1S denote the set of sentences (i.e., closed formulas) which are true when individual variables range over \mathbb{N} and set variables range over finite subsets of \mathbb{N} .

THEOREM (MEYER [Me1]). *There is a constant $c > 0$ such that*

$$\text{DSPACE}(g(\lceil c \cdot \log n \rceil, 1)) \leq_p \text{WS1S},$$

and WS1S requires space $g(\lceil c \cdot \log n \rceil, 1)$ i.o.

M. Rabin has observed that “ $\log n$ ” can be replaced by “ n ” in this theorem. This improved lower bound of $g(\lceil cn \rceil, 1)$ is closer to the known upper bound of space $g(n, 1)$ which is implicit in the decision procedures of Büchi [Bu] and Elgot [Elg]. Meyer and Stockmeyer [Sto1] and Robertson [Ro] have shown that if “ $x < y$ ” is also included as a primitive relation, then just one set quantifier suffices to make the decision problem nonelementary. Meyer’s theorem implies that the more powerful theory SnS, proved decidable by Rabin [Rab3], is also nonelementary. Thus, the popular method of proving decidability by reduction to SnS, although a powerful method for proving decidability, might give a poor upper bound on computational complexity.

Provably nonelementary first-order theories include the theory of linear order (Meyer [Me2], [Sto1]) and the theory of any nonempty family of pairing functions (Rackoff [Rac1], [FeR2]). Other examples are given in the survey article by Meyer [Me2].

We now turn to elementary theories, i.e., those which can be decided in space $g(k_0, n)$ for some fixed constant k_0 . Table 1 summarizes known upper and lower bounds for several first-order theories. In each row, $\mathcal{C}_{\text{lower}}$ is reducible to the decision problem for the theory via the indicated reducibility, and the decision problem belongs to $\mathcal{C}_{\text{upper}}$. In each case it is straightforward to obtain an explicit lower bound using the method of §3.2. Row 1 is due to Stockmeyer [Sto2], row 2 is due to Ferrante [Fe], [FeR2], the lower bounds in rows 3–7 are by Fischer and Rabin [FiR], the upper bounds in rows 3 and 5 are by Ferrante and Rackoff [FeR1], the upper bound in row 4 is by Rackoff [Rac1], [Rac3], [FeR2], the upper bound in row 6 is due to Ben-Or, Kozen and Reif [BeKR], and the upper bound in row 7 is by Lo [Lo] who also gives upper bounds for other decision problems concerning abelian groups.

Berman [Ber2] has given a more precise classification for $\text{Th}(\mathbb{R}, +)$ by showing that it is complete in the class of problems accepted by ATM’s (see §5.1) which accept simultaneously within time $2^{O(n)}$ and within $O(n)$ alternations. In a technical sense, this class lies between $\text{NTIME}(2^{O(n)})$ and $\text{DSPACE}(2^{O(n)})$, since if we fix the time

bound at $2^{O(n)}$, then $\text{NTIME}(2^{O(n)})$ corresponds to 1 alternation and $\text{DSpace}(2^{O(n)})$ corresponds to $2^{O(n)}$ alternations (cf. Theorem 5.1(a)). (However it is not known whether the class lies properly between; it is not even known that $\text{NTIME}(2^{O(n)}) \neq \text{DSpace}(2^{O(n)})$.) Similar classifications using ATM's which are both time and alternation bounded are known for $\text{Th}(\mathbf{N}, +)$ (Berman [Ber2]) and the theory of Boolean algebras (Kozen [Ko2]). Further evidence that $\text{Th}(\mathbf{R}, +)$ does not fit neatly into a time or space class is given by Bruss and Meyer [BrM], who show that there is a constant $c > 0$ such that $\text{Th}(\mathbf{R}, +)$ either requires nondeterministic space 2^{cn} i.o. or requires nondeterministic time 2^{cn^2} i.o. It is an interesting open question to give a more precise classification of $\text{Th}(\mathbf{R}, +, \cdot)$ than the one given in row 6 of Table 1.

Theory	$\mathcal{C}_{\text{lower}}$	$\mathcal{C}_{\text{upper}}$	reducibility
1. equality	$\text{NSPACE}(\sqrt{n})$	$\text{DSpace}(n \log n)$	$\leq \log\text{-lin}$
2. \mathbf{N} with successor	$\text{NSPACE}(n)$	$\text{DSpace}(n^2)$	$\leq \log\text{-lin}$
3. \mathbf{N} with addition	$\text{NTIME}(g(2, n))$	$\text{DSpace}(g(2, O(n)))$	$\leq p\text{-lin}$
4. \mathbf{N} with multiplication	$\text{NTIME}(g(3, n))$	$\text{DSpace}(g(3, O(n)))$	$\leq p\text{-lin}$
5. \mathbf{R} with addition	$\text{NTIME}(g(1, n))$	$\text{DSpace}(g(1, O(n)))$	$\leq p\text{-lin}$
6. \mathbf{R} with addition and multiplication	$\text{NTIME}(g(1, n))$	$\text{DSpace}(g(1, O(n^2)))$	$\leq p\text{-lin}$
7. finite abelian groups	$\text{NTIME}(g(2, n))$	$\text{DSpace}(g(2, O(n)))$	$\leq p\text{-lin}$

TABLE 1. Complexities of some first-order theories

Many of the lower bounds on the complexities of logical decision problems (including all those in Table 1) rely on the ability to write formulas with many alternations of quantifiers. The effect of the number of alternations on the complexity of $\text{Th}(\mathbf{N}, +)$ is studied by Reddy and Loveland [ReL] (upper bounds) and Fürer [Fu2] (lower bounds). Sistla, Vardi and Wolper [SiVW] show that for sentences of WS1S in prenex normal form, each additional alternation of second-order quantifiers causes an exponential increase in the space complexity of the decision problem; moreover, the same result holds for the (full) monadic theory S1S, allowing quantification over infinite sets. This improves a previous result of Robertson [Ro].

Meyer and Rackoff [Rac2] show that the satisfiability problem for the monadic predicate calculus requires nondeterministic time $c^{n/\log n}$ for some constant $c > 1$, and Lewis [Lew] gives a similar upper bound of $\text{NTIME}(d^{n/\log n})$ for some constant d . Lewis [Lew] also gives upper and lower bounds for other decidable subcases of the predicate calculus obtained by restricting the form of the quantifier prefix. For formulas in Schönfinkel-Bernays form, Plaisted [Pl] considers the effect of also restricting the form of the matrix, for example, to a conjunction of Horn clauses.

Compton and Henson [CoH] describe a method for proving lower bounds on the computational complexity of decidable theories, which is analogous to known machinery for proving undecidability of logical theories (see [Rab2]). In particular, the method gives new proofs of the nonelementary complexity of the first-order theory of one unary function and the first-order theory of a linear order.

There has also been much work on the complexity of modal logics. Ladner [Lad3] shows that the satisfiability problems for the classical modal logics T and S4 are PSPACE-complete and that S5 is NP-complete in the case of one modality, i.e.,

one “knower”. For the case of many modalities, Halpern and Moses [HalM] show that T and S4 remain PSPACE-complete and that S5 becomes PSPACE-complete. Halpern and Moses [HalM] also consider the effect of adding an operator for “common knowledge” to these logics, and find that all three become $\text{DTIME}(2^{O(n)})$ -complete in the case of m knowers for any $m \geq 2$. This line of work has been continued by Halpern and Vardi [HalV], who classify the complexities of various logics for reasoning about knowledge and time together. Propositional modal logics are of considerable current interest in computer science as languages for expressing the behavior of programs. Pnueli [Pn] has suggested this role for linear temporal logic. Sistla and Clarke [SisC] and Halpern and Reif [HalR] show that linear temporal logic is PSPACE-complete. Several new modal logics have also been defined for this purpose. One of the more important is *propositional dynamic logic* (PDL) which was defined by Fischer and Ladner [FiL] as a propositional version of a first-order modal logic proposed earlier by Pratt [Pr1]. Formulas in PDL have primitive symbols α , β , etc. which stand for programs. Semantics is in terms of Kripke structures, and each primitive program is interpreted as a binary relation on Kripke states (in general, a nonsymmetric nontransitive relation). New programs can be formed using combining operators such as $\alpha; \beta$ (run program α , then run program β), $\alpha \cup \beta$ (nondeterministically run either α or β), and α^* (run α zero or more times); the interpretation of the new program is obtained by relational composition, union, and transitive closure, respectively. There are modal operators $[\gamma]$ and $\langle \gamma \rangle$ for each program γ . For example, $[\gamma]\phi$ is true in state s iff ϕ is true in all states t such that (s, t) is in the relation γ . Fischer and Ladner [FiL] show that PDL is $\text{DTIME}(2^{O(n)})$ -hard and Pratt [Pr2] shows that PDL is in $\text{DTIME}(2^{O(n)})$. Various extensions of PDL have been defined to capture the ongoing behavior of programs by adding temporal operators which can, for example, express the fact that a formula holds infinitely often during every infinite execution of a program. A recent paper of Vardi and Stockmeyer [VarS] gives results on the complexities of some of these temporal logics and contains references to earlier work.

6.2. Games. In this section we consider decision problems of the following form: Given a position in some two-player game, decide whether the player moving first has a “forced win”, that is, a strategy which leads to victory no matter which strategy the second player employs. For many common games, including chess and go and their generalization to boards of arbitrary size, this question is clearly decidable simply by examining the full game tree rooted at the given starting position. But since the size of the game tree could grow exponentially in the size of the initial position, this is not a polynomial time algorithm.

We have seen one example of a game already in the problem QBF defined in §4.4. To view QBF as a game, imagine that the first (second) player controls the odd (even) numbered variables, and the players alternately fix the truth values of these variables in order X_1, X_2, \dots, X_m . After all the variables have been set, the first player wins iff $F(X_1, \dots, X_m)$ is true. Obviously, $F \in \text{QBF}$ iff the first player has a winning strategy, so this is an example of a PSPACE-complete game. Variations of this game are proved PSPACE-complete by Schaefer [Scha]. Reisch [Reis] shows that the game of hex is PSPACE-complete when generalized to boards of arbitrary size and to arbitrary starting positions. The games which have been proved PSPACE-complete all have the property that when the game is played starting from a position

of size n , the game is certain to end after at most $\text{poly}(n)$ moves. It is not hard to see that the acceptance condition for an ATM M (§5.1) can be defined as a game between two players, the existential player and the universal player, in such a way that M accepts x iff the existential player has a winning strategy starting from the initial configuration on input x . Since alternating polynomial time equals PSPACE (Theorem 5.1(a)), it should not be surprising that polynomially time bounded games are PSPACE-complete.

However, some games such as chess and go are not polynomially time bounded when generalized to large boards, since the game could conceivably cycle through most of the exponentially many positions before ending. But since the board does not grow in size as the game is played, these games are $O(n)$ space bounded. The equivalence $\text{ASPACE}(O(n)) = \text{DTIME}(2^{O(n)})$ (Theorem 5.1(b)) suggests that these games are $\text{DTIME}(2^{O(n)})$ -complete. Stockmeyer and Chandra [StoC] first proved games to be $\text{DTIME}(2^{O(n)})$ -complete. These were artificial games played on propositional formulas. These artificial games were later used to show that generalizations of natural games are exponential-time-complete. Fraenkel and Lichtenstein [FrL] show that chess is $\text{DTIME}(2^{O(n)})$ -complete. Robson [Rob1], [Rob2] shows that go and checkers are $\text{DTIME}(2^{O(n)})$ -complete. In all three cases, the games are generalized to large boards in a natural way. For example, in the case of chess, an input is an m -by- m chessboard for some m together with a placement of pieces on some squares of the board (the placement need not correspond to the usual starting position of a game of chess). Each player has only one king, but the other pieces can occur any number of times.

Papadimitriou [Pa2] and Babai [Ba] study the complexity of games where one of the players chooses his moves randomly. Papadimitriou calls these “games against nature”; the decision problem here is whether the nonrandom player has a strategy which leads to victory with probability greater than $1/2$. In Babai’s case, the probabilities of winning or losing must remain bounded away from one another, say, greater than $2/3$ or less than $1/3$, respectively.

The games discussed above are all games of perfect information; both players have complete knowledge of the position of the game at all times. Reif [Reif] has considered games of imperfect information where some or all of the position is hidden from one of the players. He defines new types of ATM’s to model games of imperfect information and characterizes their complexity classes in terms of deterministic complexity classes. Ladner and Norman [LaN] define automata to model solitaire games where one player (the “dealer”) makes a number of moves at the beginning of the game, but after the other player enters the game the dealer must respond deterministically; solitaire games of both perfect and imperfect information are considered. A recent direction is to consider the effect of partial information on the random games of Papadimitriou and Babai (see, for example, Condon and Ladner [CoL], Goldwasser and Sipser [GoSi]).

Other results on the complexity of games are summarized in [Joh1].

6.3. Algebraic word problems. Let Θ be a finite alphabet of symbols. A *semi-Thue system* over Θ is a finite set \mathcal{P} of productions of the form $l \rightarrow r$, where $l, r \in \Theta^*$. The word α *derives* the word β in one step, written $\alpha \rightarrow \beta$, if $\alpha = \mu l \nu$ and $\beta = \mu r \nu$ for some $l \rightarrow r$ in \mathcal{P} . Let $\xrightarrow{*}$ denote the transitive closure of \rightarrow . The *reachability set* $R(\alpha, \mathcal{P})$ is the set of words β such that $\alpha \xrightarrow{*} \beta$. A semi-Thue system \mathcal{P} is *commutative* if $ab \rightarrow ba$

is in \mathcal{P} for all $a, b \in \Theta$ (when it is clear that a semi-Thue system is commutative, these productions do not appear explicitly in \mathcal{P}). A *Thue system* is a semi-Thue system such that, for all l and r , $(l \rightarrow r) \in \mathcal{P}$ iff $(r \rightarrow l) \in \mathcal{P}$. The *uniform word problem for commutative semigroups* (CSG) is the set of all $(\alpha, \beta, \mathcal{P})$ such that \mathcal{P} is a commutative Thue system and $\beta \in R(\alpha, \mathcal{P})$. Mayr and Meyer [MaM2] show that CSG is $\text{DSPACE}(2^{O(n)})$ -complete. They also show that CSG is efficiently reducible to the *polynomial ideal word problem* (PI) defined as the set of all tuples of polynomials $(p_0, p_1, \dots, p_m) \in \mathbf{Q}[X]^{m+1}$, where X is a finite set of indeterminates, such that p_0 is in the ideal of $\mathbf{Q}[X]$ generated by p_1, \dots, p_m . Therefore, PI is $\text{DSPACE}(2^{O(n)})$ -hard. It is also noted in [MaM2] that work of G. Hermann implies that PI is elementary recursive.

Another result should be mentioned here since it holds the current record for the size of a lower bound established for a “natural” decidable problem. Notational variants of commutative semi-Thue systems, called *vector replacement systems* and *Petri nets*, have been used in computer science to model the behavior of asynchronous systems. Consider the *finite equality problem* (FEP) defined as the set of $(\alpha, \mathcal{P}, \alpha', \mathcal{P}')$ such that \mathcal{P} and \mathcal{P}' are commutative semi-Thue systems, $R(\alpha, \mathcal{P})$ and $R(\alpha', \mathcal{P}')$ are finite, and $R(\alpha, \mathcal{P}) = R(\alpha', \mathcal{P}')$. Decidability of FEP follows from an algorithm of Karp and Miller [KaM] which checks whether a reachability set is finite and generates it if it is finite. Mayr and Meyer [MaM1] show that FEP is not primitive recursive. (Without the finiteness condition on the reachability sets, the equality problem for commutative semi-Thue systems is undecidable, as shown by Rabin and Hack [Hac].)

Kozen [Ko1] shows that the uniform word problem for finitely presented nonassociative algebras is P-complete.

6.4. Formal language theory. Many of the early classification results concerned problems in formal language theory. We have noted in §4.4 that the first problem proved PSPACE-complete was the equivalence problem for Kleene regular expressions containing only the operations of union, concatenation and Kleene star [MeS]. Other results have been obtained for other combinations of operations. For example, Stockmeyer [Sto1] shows that the equivalence problem for *star-free expressions*, which contain only union, concatenation and complementation, is nonelementary. Fürer [Fu1] improves the lower bound of [Sto1] by showing that the equivalence problem for star-free expressions requires space $g(\lceil cn/(\log^* n)^2 \rceil, 1)$ i.o., where $\log^* n$ is defined as the smallest j such that $g(j, 1) \geq n$. Hunt and Rosenkrantz [HuR1], [HuR2] give various complexity-theoretic analogues of Rice’s theorem [Rog, §2.1], which show that other decision problems concerning regular expressions are at least as hard as the equivalence problem. Although the equivalence problem for context-free grammars is undecidable, it is decidable in special cases such as for grammars generating finite languages; Hunt, Rosenkrantz and Szymanski [HuRS] show that this special case requires nondeterministic exponential time i.o.

§7. Related issues

7.1. Relativization. For a complexity class \mathcal{C} and a set A of words, let \mathcal{C}^A denote the same complexity class defined in terms of oracle Turing machines with oracle A rather than in terms of ordinary Turing machines. For example, NP^A is the class of

problems accepted in polynomial time by nondeterministic oracle machines with oracle A . Baker, Gill and Solovay [BaGS] show that there are recursive sets A and B such that $P^A = NP^A$ and $P^B \neq NP^B$. One conclusion to be drawn from this result is that any proof of either $P = NP$ or $P \neq NP$ cannot generalize to an arbitrary oracle, so in trying to settle the P vs. NP question we can rule out proof methods which relativize. The construction of an oracle B such that $P^B \neq NP^B$ was shown independently by Dekhtiar [Dek]. There are many other results showing that various complexity classes can be made equal or unequal relative to an oracle. Recently Yao [Ya], using a line of attack suggested by Furst, Saxe and Sipser [FuSS] and Sipser [Sip2], has shown that there is an oracle relative to which all classes of the polynomial-time hierarchy (§5.1) are distinct, thus settling a question which had remained open for over ten years. Yao's proof has been simplified by Hastad [Has]. Rackoff [Rac4] exhibits oracles D and E for which $P^D \neq R^D$ and $P^E = R^E$, where R is random polynomial time (§5.2). Bennett and Gill [BeG] show that for a *random* oracle A , $P^A \neq NP^A$ with probability 1 and $P^A = R^A$ with probability 1. Other open questions, besides questions about equality of complexity classes, have been studied in the relativized case. For example, Sipser [Sip1] shows that there are oracles A and B such that R^A and $NP^B \cap \text{co-}NP^B$ do not have complete problems with respect to \leq_p .

7.2. Structural issues. There has been a considerable amount of work on the structure of complete problems. We mention a few examples.

Define $A \equiv_p B$ if $A \leq_p B$ and $B \leq_p A$. Each equivalence class under \equiv_p is called a *p-degree*. For example, the class of NP-complete problems is a p-degree. Ladner [Lad1] shows that if $P \neq NP$ then the ordering of the p-degrees within NP is dense. In particular, there is a problem in $NP - P$ which is not NP-complete. This is significant since there are natural problems in NP which are neither known to be in P nor known to be NP-complete; one interesting example is the problem of checking whether two given undirected graphs are isomorphic. A recent paper of Ambos-Spies [Amb] gives results on the structure of p-degrees and references to other work on this subject.

In recursive function theory it is known that all r.e.-complete sets under many-one reducibility are recursively isomorphic. In analogy, Berman and Hartmanis [BerH] conjecture that all NP-complete problems are p-isomorphic. Sets $A \subseteq \Sigma^*$ and $B \subseteq \Delta^*$ are *p-isomorphic* if there is a bijection $f: \Sigma^* \rightarrow \Delta^*$ such that f and f^{-1} are computable in polynomial time, $A \leq_p B$ via f and $B \leq_p A$ via f^{-1} . This conjecture implies $P \neq NP$, since if $P = NP$ then the finite sets $\{0\}$ and $\{0, 1\}$ are NP-complete but they are obviously not p-isomorphic. Nevertheless, machinery is developed in [BerH] which can be applied to show that many of the known NP-complete problems are p-isomorphic. Mahaney [Mah1] shows that, within the class of NP-complete problems, the number of p-isomorphism classes is either one or infinite.

A question raised in [BerH] is whether there are any sparse NP-complete problems. A set A of words is *sparse* if there is a polynomial $p(n)$ such that, for all n , A contains at most $p(n)$ words of length n . The existence of a sparse NP-complete problem would provide a counterexample to the conjecture of Berman and Hartmanis, since a nonsparse NP-complete problem such as SAT cannot be p-isomorphic to a sparse problem. The question remained open a few years but was

finally settled by Mahaney [Mah2], who showed that if $P \neq NP$ then there are no sparse NP-complete problems. The history of the solution is described by Hartmanis and Mahaney [HarM].

Lynch [Ly] shows that for every problem A which is not in P there is an infinite recursive set X such that, given any DTM M which accepts A and any polynomial $p(n)$, there is an integer n_0 such that M runs for more than $p(|x|)$ steps on input x for all $x \in X$ with $|x| \geq n_0$. We can think of X as a “hard-core” for A , since it is a set of inputs which are hard for all acceptors of A . General hard-core theorems for other complexity classes are proved by Even, Selman and Yacobi [EvSY].

7.3. Languages which capture complexity classes. So far, logic has entered the discussion mainly as a source of decision problems whose complexities have been successfully classified. Logic can also be used to give alternate definitions of complexity classes, and in some cases questions about computational complexity can be rephrased as questions about logic. One of the first examples of this was work of Jones and Selman [JoS] and Fagin [Fa] on spectra. Given a first-order sentence ϕ with equality, the *spectrum* of ϕ is the set of cardinalities of finite models of ϕ . Spectra were first considered by Scholz [Scho], who raised the question of characterizing spectra. Jones and Selman [JoS] show that a set S of nonnegative integers is a spectrum of some first-order sentence iff the set of binary representations of integers in S belongs to $NTIME(2^{O(m)})$. Similarly, S is a spectrum iff the set of unary representations of integers in S belongs to NP (the unary representation of the nonnegative integer z is the word $111 \cdots 1$ (z times))). It follows that the following two questions are equivalent:

- (1) Is the complement of every spectrum also a spectrum?
- (2) Does $NP = co-NP$ when both classes are restricted to subsets of $\{1\}^*$?

Question (1) was posed by Asser [As]. In particular, if Asser's question has a negative answer then $NP \neq co-NP$, which in turn implies that $P \neq NP$.

Fagin [Fa] characterizes NP in terms of generalized second-order spectra. Consider a second-order formula $\phi(R_1, \dots, R_m)$ where some predicates R_1, \dots, R_m occur free in ϕ and where all second-order quantifiers are existential. The *generalized spectrum* of ϕ is the set of finite models of ϕ . Fagin shows that a set of finite models, suitably encoded as a set of words, is a generalized spectrum of some ϕ iff it belongs to NP . For example, consider the set of undirected 3-colorable graphs (an NP -complete problem). A graph can be represented by its edge relation E . It is straightforward to write a formula containing three existentially quantified unary predicates R, B and G (the three colors) and the free binary predicate E which states that each vertex is colored with exactly one color (i.e., $\forall u$ exactly one of $R(u), B(u)$ or $G(u)$ is true) and that if $E(u, v)$ then u and v are colored differently. Given Fagin's characterization of NP , it is easy to see that the classes of the polynomial-time hierarchy can be similarly characterized by allowing a bounded number of alternations of second-order quantifiers in ϕ . Börger [Borg] gives a historical discussion of the connection between complexity theory and spectra.

Immerman [Im1] and Vardi [Var] characterize P in terms of fixed point logic over linearly ordered finite domains. Sentences in this logic are written using $<$, first-order quantifiers, and the least fixed point operator (LFP). The least fixed point operator has been extensively studied in mathematical logic (see [Mos]), although

Chandra and Harel [ChH] initiated the study of its expressive power in the context of finite structures. It is defined as follows. Given two k -ary relations R and R' defined on some domain U , write $R \subseteq R'$ if $R(u_1, \dots, u_k) \rightarrow R'(u_1, \dots, u_k)$ for all $u_1, \dots, u_k \in U$. Let $\phi(u_1, \dots, u_k, R)$ be a first-order formula, where R is a k -ary relation symbol and where u_1, \dots, u_k and R occur free in ϕ . For each interpretation of R , ϕ defines a k -ary relation which we denote $\phi(R)$. We say that ϕ is *monotone* if $R \subseteq R'$ implies $\phi(R) \subseteq \phi(R')$. For a monotone ϕ define

$$\text{LFP}(\phi) = \min\{R \mid \phi(R) = R\}.$$

(For a monotone ϕ , it is known that $\text{LFP}(\phi)$ exists and can be computed in deterministic time polynomial in the cardinality of the domain.) Unaware of the results concerning LFP, Livchak [Liv] independently defined another extension of first-order logic which, together with order, captures P. It is an open question whether there is a natural extension of first-order logic which captures P without the use of order (without order, first-order logic with LFP cannot express “the cardinality of the domain is even” [ChH]). Immerman [Im2] characterizes other complexity classes in terms of logical languages and also summarizes previous work. Two articles of Gurevich, [Gu2] and [Gu3], contain more discussion about the subject of capturing P and the connections between logic and theoretical computer science in general.

Gurevich [Gu1] shows that if primitive recursive definitions are interpreted over finite domains instead of over \mathbb{N} , then the class of functions which can be defined is precisely the class of functions computable in deterministic space $\log n$. For recursive definitions over finite domains, precisely the class of polynomial time computable functions can be defined.

7.4. Complexity of finite problems. An objection both to undecidability results and to lower bounds such as Theorem 1.1 is that in the real world one is not interested in solving all instances of a problem but only a finite collection of them. In the case of $\text{Th}(\mathbf{R}, +)$, for example, one might be uninterested in all sentences of length greater than 1000. Thus, the value of c in the lower bound c^n and the minimum length of sentences for which the lower bound takes effect become germane. Estimates of these values are implicit in the proofs of lower bounds obtained as in §3.2. However, in the literature on lower bounds these values are usually not estimated, since this would be tedious and the estimates would not be very useful in practice. However, one example of a finite decision problem has been studied in detail. Consider sentences of WS1S (see §6.1) where order relations such as “ $x < y$ ” and “ $x \geq y$ ” are allowed as primitives, and integer constants can be written in decimal notation. Let \mathcal{P} denote the set of sentences of length 616 or less. It turns out that the alphabet used in writing sentences has 63 symbols, so each symbol can be uniquely encoded as a binary word of length 6. In this way, each sentence in \mathcal{P} is encoded as a binary word of length $6 \cdot 616 = 3696$. Turing machine time is not sufficient to measure the complexity of finite decision problems, since any finite problem can be decided in linear time by building a table of all the answers into the finite state control of the Turing machine. Thus, for assessing the complexity of finite problems, account must be taken of the size of the device performing an algorithm as well as the time required by the algorithm. One quite general way to do

this is to measure the number of logical operations or “gates”, *and*, *or*, *exclusive-or*, etc., in an acyclic logical network which is capable of solving the finite decision problem. In the case of deciding WS1S on sentences of length 616 or less, the network would have 3696 input lines and a single output line which should carry the value 1 iff the values on the input lines are the code of a true sentence of length at most 616. Formally, the network can be defined as a sequence of equations as in §4.2, except that the 3696 variables corresponding to input lines do not appear as the left side of any equation, and X_m is the output line. The number of gates is the number of equations of the form $X_i = X_j @ X_k$.

THEOREM (MEYER AND STOCKMEYER [Sto1]). *Any network which decides truth of sentences of length 616 in WS1S contains at least 10^{123} gates.*

Even if gates were the size of a proton and were connected by infinitely thin wires, the network would densely fill the known universe.

Having brought up the subject of logical networks, we should mention that interest in the complexity of problems as measured by the size of logical networks is much wider than the example above. For each (infinite) problem A , one can define the function $C_A(n)$, called the *combinational complexity* of A , which maps n to the minimum number of gates in a network which decides membership in A restricted to words of length n . It is easy to see that if $A \in \text{DTIME}(T(n))$ then $C_A(n)$ is at most polynomial in $T(n)$; Pippenger and Fischer [PiF] sharpen this to $C_A(n) = O(T(n) \log T(n))$. There is no relationship in the other direction since the network model is *nonuniform*, i.e., we can choose a different network for each input length n . In particular, it is easy to see that $C_A(n)$ is $2^{O(n)}$ for any A (even nonrecursive A). However, if Turing machines are made nonuniform by giving them access to arbitrary oracle sets $D \subseteq \{1\}^*$ or if the network model is made uniform by requiring that the networks be efficiently constructable, then deterministic Turing machine time complexity and combinational complexity are polynomially related; see, for example, Schnorr [Schn]. Other relationships between Turing machine complexity and network complexity are proved by Borodin [Boro].

As mentioned in the Introduction, Ehrenfeucht [Ehr] has shown that the combinational complexity of the first-order theory of \mathbf{N} with addition and multiplication grows faster than any polynomial in n , even if the theory is made decidable by bounding all quantifiers. A. Meyer has observed that a similar proof can be done for any problem which is hard for the class of problems accepted by ATM's which accept simultaneously within time $2^{O(n)}$ and within $O(1)$ alternations. For example, if A is $\text{Th}(\mathbf{R}, +)$ or $\text{Th}(\mathbf{N}, +)$, then $C_A(n) > c^n$ for some constant $c > 1$ and infinitely many n .

§8. Conclusion. The main message of this paper is that after a problem has been proved decidable, there is still the opportunity to obtain much more precise information about the problem's computational complexity. Precise classifications are often challenging mathematical questions. In addition, for problems with practical applications such information can be useful. If a problem requires exponential time i.o. or even if it is NP-complete, it suggests that one should not waste time looking for an algorithm which is always fast and always correct. A more reasonable approach for such problems might be to apply heuristic methods which

are sometimes slow or sometimes incorrect (for example, see [GaJ, Chapter 6] for a discussion of “approximation” algorithms for certain NP-complete optimization problems) or to abandon the worst-case notion of complexity and seek algorithms which do well on the average (for example, see [Joh2] for a survey).

Efficient reducibility, completeness, and explicit lower bounds are now tools of the trade in the theoretical computer science community. These methods should be useful in other areas of mathematics where decision problems arise.

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