Complexity of k-SAT

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Abstract

The problem of k-SAT is to determine if the given k-CNF has a satisfying solution. It is a celebrated open question as to whether it requires exponential time to solve k-SAT for $k \geq 3$. Define s_k (for $k \geq 3$) to be the infimum of $\{\delta$: there exists an $O(2^{\delta n})$ algorithm for solving k-SAT$\}$. Define **ETH** *(Exponential-Time Hypothesis) for k-SAT as follows: for $k \geq 3$, $s_k > 0$. In other words, for $k \geq 3$, k-SAT does not have a subexponential-time algorithm. In this paper, we show that s_k is an increasing sequence assuming* **ETH** *for k-SAT. Let s_∞ be the limit of s_k. We will in fact show that $s_k \leq (1 - d/k)s_\infty$ for some constant $d > 0$.*

Although all **NP**-complete problems are equivalent as far as the existence of polynomial-time algorithms is concerned, there is wide variation in the worst-case complexity of known algorithms for these problems. For example, there have been several algorithms for maximum independent set [7, 12, 17, 18], and the best of these takes time 1.2108^n in the worst-case [12]. Recently, a 3-coloring algorithms with 1.3446^n worst-case time complexity is presented [2] and it is known that k-coloring can be solved in 2.442^n time [4]. However, it is not known what if any relationships exist among the worst-case complexities of various problems. In this paper, we examine the complexity of k-SAT, and derive a relationship that governs the complexity of k-SAT for various k under the assumption that k-SAT does not have subexponential algorithms for $k \geq 3$.

When we consider algorithms for k-SAT, we find detailed information on the variation in the worst-case complexity: Experimental evidence suggests that variants of classical Davis-Putnam heuristic scales as $2^{n/17}$ for the hardest instances of 3-SAT [3]. Furthermore, it has been observed [16] that the Davis-Putnam heuristic scales much worse due to reduced number of unit clauses and the noneffectiveness of shortest clause heuristic. Also, all the recent results that show improved exponential-time algorithms for k-SAT [9, 8, 5, 13, 14, 10, 11, 15] exhibit increasing complexity as k increases. In particular, the best of these results [11] exhibits a randomized algorithm for solving k-SAT with time complexity $O(2^{(1-\frac{\mu_k}{k-1})n})$ where $\mu_k > 1$ is an increasing function of k and approaches $\pi^2/6 \approx 1.644$. The algorithm is a variant of Davis-Putnam procedure and its analysis relies on accounting for the number of variables *forced* due to unit clauses. The key idea of the analysis [10] is that the k-SAT either has a sufficiently isolated solution and thus a solution which has several *critical clauses* for many variables or has a large number of satisfying solutions. If a variable has l critical clauses at a satisfying solution, it is argued that the probability that the variable is forced is at least l/k. On the other hand, if the k-SAT has sufficiently many solutions, then it is easier to randomly find one. In either case, it is shown that the probability of finding a satisfying solution is $2^{-n(1-1/k)}$ which implies a time bound of poly$(n)2^{n(1-1/k)}$. A more intricate analysis of critical clauses [11] yields the better lower bounds mentioned earlier. More recently, using a very simple analysis, Schöning [15] also obtained upper bounds of the form $2^{(1-\frac{\gamma_k}{k})n}$ although the constant γ_k is smaller than the constant μ_k in [11].

Despite the accumulated evidence regarding the complexity of k-SAT, we do not have any results that rigorously support the claim that the complexity of k-SAT increases with increasing k. Define s_k (for $k \geq 3$) to be the infimum of $\{\delta$: there exists an $O(2^{\delta n})$ algorithm for solving k-SAT$\}$. Define **ETH** (Exponential-Time Hypothesis) for k-SAT as follows: for $k \geq 3$, $s_k > 0$. In other words, for $k \geq 3$, k-SAT does not have a subexponential-time algorithm. In this paper, we show that s_k is an increasing sequence assuming **ETH** for k-SAT. Although many non-trivial algorithms for k-SAT exist, all are strictly exponential, $2^{\Omega(n)}$, in the worst-case, and it is an important open question whether subponential algorithms exist. The plausibility of such a subexponential time algorithm for k-SAT was investigated in [6], using subexponential time reductions. It is shown there that linear size 3-SAT is complete for the class **SNP** with respect to such reductions, where **SNP** is the class of properties expressible by a series of

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second order existential quantifiers, followed by a series of first order universal quantifiers, followed by a basic formula (a boolean combination of input and quantified relations applied to the quantified element variables.) This result implies that the **ETH** mentioned earlier can be equivalently stated as "For some $k \geq 3$, $s_k > 0$" or "$\mathbf{SNP} \not\subseteq \mathbf{SUBEXP}$", or "Satisfiability of linear-sized circuits can be solved in sub-exponential time". We feel that this provides at least intuitive evidence that such an algorithm is unlikely to exist.

If k-SAT does not have a subexponential time algorithm (**ETH** for k-SAT), it is interesting to have a more precise idea regarding the constant s_k in the exponent. For instance, even under **ETH** for k-SAT, it still probably is a very challenging question to prove any lower bounds on s_∞. Can we at least show that s_k is an increasing sequence? How are s_k related? Uncovering the relationships among s_k will enable us to bound s_k in terms of s_∞ and k thus giving some evidence as to the optimality or nonoptimality (under the assumption **ETH** for k-SAT) of the recent exponential-time algorithm for k-SAT.

In this paper, we will show that $s_k \leq (1 - d/k)s_\infty$ where the constant $d \approx s_\infty/(2e\log(2/s_\infty))$. More precisely, given any integer $k \geq 3$ and any $\epsilon > 0$, we find a k' so that the following type of reduction is possible: Let F be a k-CNF in the variables $\{x_1, \ldots, x_n\}$. For some $m \leq 2^{\epsilon n}$, we will construct k'-CNF's $F_1, \ldots, F_m$ in at most $n(1 - d/k)$ variables in time poly$(n)2^{\epsilon n}$ such that F is satisfiable iff $\bigvee_{i=1}^{m} F_i$ is satisfiable. Then we bound s_k as follows: By solving each F_i using an algorithm running in $2^{(s_{k'}+\epsilon)(1-d/k)n}$ time, we can determine whether F is satisfiable in time poly$(n)2^{s_{k'}(1-d/k)n+2\epsilon n} \leq 2^{s_\infty(1-d/k)n+2\epsilon n}$. Thus $s_k \leq s_\infty(1 - d/k) + 2\epsilon$. Since ϵ is arbitrarily small, we get the desired bound for s_k.

Our proof relies on earlier ideas regarding critical clauses [10, 11] and the *decomposition* of an arbitrary k-CNF into linear size k-CNFs [6]. The new key idea in the paper is a reduction by which we can decrease the number of variables by increasing the width of the clauses. In the following we develop the ideas we need to prove our result.

Let F be a k-CNF. We say that a satisfying solution $\vec{x} = (x_1, \ldots, x_n)$ of F is *isolated* with respect to a variable x if $\vec{x}$ is no longer a satisfying solution when the bit x is flipped. The crucial observation [10] is that if a satisfying solution $\vec{x}$ is isolated with respect to variable x (a *critical variable* for $\vec{x}$), there must exist a clause C (a *critical clause* for x at $\vec{x}$) in F such that the only true literal in C at the assignment $\vec{x}$ is the one corresponding to the variable x. One of our key ideas is to use critical clauses to express the critical variables in terms of other variables. In order to efficiently identify the critical clauses, at the outset we express an arbitrary k-CNF as a subexponential disjunction of linear size k-CNFs. Such an expression is possible from the *Sparsification Lemma* [6]: For all $\epsilon > 0$, k-CNF F can be written as the disjunction of at most $2^{\epsilon n}$ k-CNF F_i such that F_i contains each variable in at most $c(k, \epsilon)$ clauses. Moreover, this reduction takes at most $O(\text{poly}(n)2^{\epsilon n})$ time.

Hence, it is sufficient to deal with k-CNF F where each variable occurs at most c times for some $c > 0$. To prove our result, we first consider the case of k-CNF containing exactly one solution. Since the unique solution is isolated in all directions, the k-CNF must contain at least one critical clause for each variable. We then argue that if a general k-CNF has a satisfying solution with at most δn (for an appropriately chosen $\delta > 0$) 1's, then such a solution can be found in time $2^{h(\delta)n}$ using exhaustive search where $h(\delta)$ is the binary entropy function. In the other case, we are guaranteed that if the k-CNF is satisfiable, then it has a solution that is critical with respect to at least δn variables. We then extend the proof for the unique solution (n critical clauses) case to the case where we have a solution which is sufficiently isolated (δn critical clauses).

Unique k-SAT

Let F be a k-CNF with at most one satisfying solution with each variable appearing in at most c clauses. If F is uniquely satisfiable, then there is at least one critical clause for each variable at the unique solution. If we apply the standard Davis-Putnam procedure with a random ordering of the variables, then we expect that at least n/k of the variables to appear as unit clauses and thus are forced if all the other nonforced variables are set according to the unique solution. We will make the dependencies among the variables explicit by trading up the clause width for a reduced number of variables.

Although the implicit dependencies among the variables do not seem obvious, we show that we need only search a relatively smaller search space to uncover these dependencies. We first show that by a simple random selection we can concentrate the forced variables. Let the variables be partitioned into sets A and B. We say that the variable x is *forced* by an assignment α to the variables in A if $x \in B$ and F contains a clause containing x or its complement such that all the other literals in the clause are from A and are set to False by the assignment α.

Lemma 1 *Let F be a uniquely satisfiable k-CNF. Let A and B be random sets of variables created by the process: variable $x \in B$ with probability $1/k$, otherwise $x \in A$. Then B contains at least $n/(ek)$ forced variables on average with respect to the assignment α_A, which assigns values to variables in A according to the unique satisfying assignment.*

Proof: Let x be a variable and C_x be a critical clause for it at the unique solution. Since the unique satisfying assignment makes all the other literals in the clause False, the probability x is forced by α_A is the same as the probability $x \in B$ and all other variables in C_x are in A, which is at least $\frac{1}{k}(1-1/k)^{k-1} \geq 1/(ek)$. Hence B contains at least $n/(ek)$ forced variables on average with respect to α_A.

■

In fact, we can eliminate the randomness by using a k-wise independent distribution. We can construct k-wise random space of size $O(n^{3k})$ in polynomial time [1]. We will try all possible selections of A and B from such a space.

In the rest of the discussion, we will assume A and B are a partition for which the conclusion of the lemma is true and we assign the variables in A accroding to the unique satisfying assignment of F.

For each variable $x \in B$, the proposition "x is forced by the assignment" can be expressed by the formula G_x where G_x is a DNF with at most c terms and with each term containing at most $(k-1)$ literals. Each term corresponds to a clause in F containing x or its negation such that all the other variables in the clause are in A and it is precisely the product of the negations of all the other literals in the clause. Similarly, we define G'_x as the disjunction of such terms where x appears positively, expressing "x is forced to be true". If the clause were a critical clause for x at a solution, then all the other literals in the clause will assume the value False at the solution. Observe that G_x and $G' - X$ depend only on at most $c(k-1)$ variables in A.

Let l be an integer (to be chosen later). To identify the forced variables in B further, we partition B into sets $B_1, \ldots, B_p$ of size l. For each B_i, we nondeterministically select the number $f_i \in \{0, 1, \ldots, l\}$ of forced variables in B_i such that $\sum_i f_i \geq n/(ek)$. We will eliminate the nondeterminism by trying out at most $2^{n \log(l+1)/l}$ such choices.

Let Φ_i be the f_i-th slice function in the variables G_x for $x \in B_i$. Φ_i depends only on the variables in A and furthermore only on at most $cl(k-1)$ of them.

Having sufficiently identified the forced variables, we will express each variable in B_i in terms of a fewer number, $l - f_i$, of variables. Let $Y_i = \{y_{i_1}, \ldots, y_{i_{l-f_i}}\}$. Let $B_i = \{x_1, \ldots, x_l\}$ without loss of generality. For $x_j \in B_i$, observe that the following proposition is satisfiable: F **and** [x_j is true iff either x_j is forced to be true or if x_j is not forced, then x_j is the j'-th unforced variable $y_{i_{j'}}$ in Y_i and $y_{i_{j'}}$ is true]. To figure out which new variable $y_{j'}$ is to be assigned to x_j in case x_j is not forced, we consider all the variables $x_1, x_2, \ldots, x_{j-1}$ in B_i that occur before x_j and check how many of them are forced. Let $\beta_j = \beta_j(G_{x_1}, \ldots, G_{x_{j-1}}, y_{i_1}, \ldots, y_{i_j})$ be a Boolean expression that evaluates to y_{i_q} if and only if $q-1$ of the G are true. Let Ψ_{i,x_j} be the condition $G'_{x_j} \vee (\bar{G}_{x_j} \wedge \beta_j)$. Ψ_{i,x_j} expresses the proposition "x_j is true iff either x_j is forced to be true or if x_j is not forced, then x_j is the j'-th unforced variable $y_{i_{j'}}$ in Y_i and $y_{i_{j'}}$ is true". Ψ_{i,x_j} only depends on at most $lc(k-1)$ variables in A and on the variables in Y_i and thus on a total of lck variables.

Substitute Ψ_{i,x_j} for x_j in F. After the substitution, each clause in F depends on at most lck^2 variables from $Y = A \cup \bigcup_{i=1}^{p} Y_i$. Call the new formula F'. Define $\Gamma_{\vec{f}} = F' \wedge \bigwedge_{i=1}^{p} \Phi_i$. Define $k' = clk^2$. Thus $\Gamma_{\vec{f}}$ is k'-CNF in the variables in Y. Intuitively, $\Gamma_{\vec{f}}$ expresses that for a satisfying assignment α of F, f_i variables are forced by α_A in B_i and the remaining variables in B are renamed as y_{i_j}'s.

We will now define $\Gamma = \bigvee_{\vec{f}} \Gamma_{\vec{f}}$ where $\vec{f}$ ranges over all vectors $(f_1, \ldots, f_p)$ such that $\sum_{i=1} f_i \geq n/(ke)$.

Since $|B| \leq n$, it then follows that the number of vectors $\vec{f}$ under consideration is at most $(l+1)^{n/l}$. By selecting l such that l satisfies $\log(l+1)/l \leq \epsilon$, we have Γ as the disjunction of at most $2^{\epsilon n}$ k'-CNF on at most $n(1-1/(ek))$ variables where $k' = clk^2$.

It is clear that if F is uniquely satisfiable then there is exactly one $\vec{f}$ such that $\Gamma_{\vec{f}}$ is uniquely satisfiable and all other $\Gamma_{\vec{f}}$ are unsatisfiable. Moreover if F is not satisfiable, then Γ is also not satisfiable.

To eliminate the randomness in the selection of the partition A and B, we try all the partitions (A, B) from an appropriate pesudorandom space and construct Γ_{AB} as above. Define $\Gamma = \vee \Gamma_{AB}$ where the disjunction ranges over all partitions from the pseudorandom space of size $n^{O(k)}$.

So far we assumed that F contains at most c clauses for each variable. If this is not true, we first use the Sparsification Lemma to write $F = \bigvee_i F_i$ where each F_i contains at most $c(k, \epsilon)$ occurrences of each variable and there are at most $2^{\epsilon n}$ formulas F_i. Then for each F_i, we construct Γ_i as above and $\Gamma = \bigvee_i \Gamma_i$. Since each Γ_i is a disjunction of at most $2^{\epsilon n}$ k'-CNF, Γ is a disjunction of at most $2^{2\epsilon n}$ k'-CNF.

Thus we obtain the following theorem.

Theorem 1 *For any $\epsilon > 0$, there is a k' such that the following holds: If F is a k-CNF with at most one satisfying assignment, then the satisfiability of F is equivalent to the satisfiability of $\hat{F}$ where $\hat{F}$ is a disjunction of at most $2^{2\epsilon n}$ k'-CNF on at most $n(1-1/(ek))$ variables. Moreover, $\hat{F}$ can be computed from F in time $O(poly(n)2^{2\epsilon n})$.*

Let $\sigma_k = \inf\{\sigma |$ Unique k-SAT is solvable in time $2^{\sigma n}\}$. Let $\sigma_\infty = \lim_{k \to \infty} \sigma_k$. Then we have

Corollary 1 $\sigma_k \leq (1-1/(ek))\sigma_\infty$

General k-SAT

Once again, consider a satisfiable k-CNF where each variable appears at most c times. Let $\delta > 0$ (to be selected later). We will consider all inputs $\vec{x} = (x_1, \ldots, x_n)$ with at most δn 1's. If one such $\vec{x}$ is a satisfying solution, we can find a satisfying solution in time poly$(n)2^{h(\delta)n}$ where $h(\delta)$ is the binary entropy function. In the other case, we are guaranteed that there exists a satisfying solution of F which is isolated with respect to at least δn variables. Since we have a sufficiently isolated solution, we will do a similar analysis as in the unique k-SAT case to conclude

Theorem 2 *Let F be a k-CNF. Assume that it has no solution with fewer than δn 1's. For any $\epsilon > 0$, there exists a k' such that the following holds: The satisfiability of F is equivalent to the satisfiability of $\hat{F}$ where $\hat{F}$ is a disjunction of at most $2^{2\epsilon n}$ k'-CNF on at most $n(1 - \delta/(ek))$ variables. Moreover, $\hat{F}$ can be computed from F in time $O(poly(n)2^{2\epsilon n})$.*

Sketch of the Proof: Assume that F has a saitsfying solution. By hypothesis, any such solution must have δn 1's. We fix one one such solution α and for any parition A and B of variables, we define our notion of 'forcing' with respect to the assignment α_A. A random partition A and B guarantees that B contains at least $\delta n/(ek)$ forced variables on average with respect to α_A. The rest of the proof follows a very similar line to that of the unique satisfiability case.

By selecting δ so that $h(\delta) \leq s_\infty/2$, we get the following corollary (assuming **ETH**).

Corollary 1 *$s_k \leq s_\infty(1 - d/k)$ where $d \approx s_\infty/(2e\log(2/s_\infty))$.*

Open Problems

Efficiently reduce k-CNF to k'-CNF so that the clause width is reduced ($k' < k$) by increasing the number of variables.

Assuming **ETH** for k-SAT, obtain evidence for the hypothesis $s_\infty = 1$.

Obtain a relationship for the worst-case complexity for various k-colorability problems.

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