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# Improved worst-case complexity for the MIN 3-SET COVERING problem\*

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## Abstract

We consider MIN SET COVERING when the subsets are constrained to have maximum cardinality three. We propose an exact algorithm whose worst case complexity is bounded above by  $O^*(1.3957^n)$ . This is an improvement, based on a refined analysis, of a former result ( $O^*(1.4492^n)$ ) by F. Della Croce and V. Th. Paschos, *Computing optimal solutions for the MIN 3-SET COVERING problem*, Proc. ISAAC'05, LNCS 3827, pp. 685–692.

**Keywords:** Worst-case complexity, Exact algorithm, MIN SET COVERING

In MIN SET COVERING, we are given a universe  $U$  of elements and a collection  $\mathcal{S}$  of (non-empty) subsets of  $U$ . The aim is to determine a minimum cardinality sub-collection  $\mathcal{S}' \subseteq \mathcal{S}$  which covers  $U$ , i.e.,  $\cup_{S \in \mathcal{S}'} S = U$  (we assume that  $\mathcal{S}$  covers  $U$ ). The frequency  $f_i$  of  $u_i \in U$  is the number of subsets  $S_j \in \mathcal{S}$  in which  $u_i$  is contained. The cardinality  $d_j$  of  $S_j \in \mathcal{S}$  is the number of elements  $u_i \in U$  that  $S_j$  contains. We say that  $S_j$  *hits*  $S_k$  if both  $S_j$  and  $S_k$  contain an element  $u_i$  and that  $S_j$  *double-hits*  $S_k$  if both  $S_j$  and  $S_k$  contain at least two elements  $u_i, u_l$ . Finally, we denote by  $n$  the size (cardinality) of  $\mathcal{S}$  and by  $m$  the size of  $U$ . In what follows, we restrict ourselves to MIN SET COVERING-instances such that:

1. no element  $u_i \in U$  has frequency  $f_i = 1$ ;
2. no set  $S_i \in \mathcal{S}$  is a subset of another set  $S_j \in \mathcal{S}$ .
3. no pair of elements  $u_i, u_j$  exists such that every subset  $S_i \in \mathcal{S}$  containing  $u_i$  contains also  $u_j$ .

Indeed, if item 1 is not verified, then the set containing  $u_i$  belongs to any feasible cover of  $U$ . On the other hand, if item 2 is not verified, then  $S_i$  can be replaced by  $S_j$  in any solution containing  $S_i$  and the resulting cover will not be worse than the one containing  $S_i$ . Finally, if item 3 is not verified, then element  $u_j$  can be ignored as any sub-collection  $\mathcal{S}'$  covering  $u_i$  will necessarily cover also  $u_j$ . So, for any instance of MIN SET COVERING, a preprocessing of data, obviously performed in polynomial time, leads to instances where all items 1, 2 and 3 are verified.

Let  $T(\cdot)$  be a super-polynomial and  $p(\cdot)$  be a polynomial, both on integers. In what follows, using notations in [9], for an integer  $n$ , we express running-time bounds of the form  $p(n).T(n)$  as  $O^*(T(n))$ , the asterisk meaning that we ignore polynomial factors. We denote by  $T(n)$  the

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worst case time required to exactly solve the MIN SET COVERING problem with  $n$  subsets. We recall (see, for instance, [5]) that, if it is possible to bound above  $T(n)$  by a recurrence expression of the type  $T(n) \leq \sum T(n-r_i) + O(p(n))$ , we have  $T(n) = O^*(\alpha(r_1, r_2, \dots)^n)$  where  $\alpha(r_1, r_2, \dots)$  is the largest zero of the function  $f(x) = 1 - \sum x^{-r_i}$ .

There exist to our knowledge few results on worst-case complexity of exact algorithms for MIN SET COVERING or for cardinality-constrained versions of it. Let us note that an exhaustive algorithm computes any solution for MIN SET COVERING in  $O(2^n)$ . For MIN SET COVERING the most recent non-trivial result is the one of [6] (that has improved the result of [8]) deriving a bound (requiring exponential space) of  $O^*(1.2301^{(m+n)})$ . We consider here, the most notorious cardinality-constrained version of MIN SET COVERING, the MIN 3-SET COVERING, namely, MIN SET COVERING where  $d_j \leq 3$  for all  $S_j \in \mathcal{S}$  (notice that the bound of [6], for the case where  $f_i = 2$ ,  $u_i \in U$ , and  $d_j = 3$ , for any  $S_j \in \mathcal{S}$  corresponds to  $O^*(1.2301^{(5n/2)}) \approx O^*(1.6782^n)$ ). It is well known that MIN 3-SET COVERING is **NP**-hard, while MIN 2-SET COVERING (where any set has cardinality at most 2) is polynomially solvable by matching techniques ([2, 7]).

Our purpose is to devise an exact (optimal) algorithm with provably improved worst-case complexity for MIN 3-SET COVERING. We propose a search tree-based algorithm with running time  $O^*(1.3957^n)$ . This result, largely inspired by the one of [4], further improves it by reducing the complexity of the tree-based algorithm from  $O^*(1.4492^n)$  down to  $O^*(1.3957^n)$ . This outcome is due to a different complexity analysis of the algorithm by the introduction of a kind of weights on the fixed sets. This technique seems to be quite close to the one very recently introduced in [6].

The following straightforward lemma holds, inducing some useful domination conditions for the solutions of MIN SET COVERING.

**Lemma 1.** *There exists at least one optimal solution of MIN SET COVERING where:*

1. *for any subset  $S_j$  with  $d_j = 2$  containing elements  $u_i, u_p$ , if  $S_j$  is included in  $\mathcal{S}'$ , then all subsets  $S_k$  hitting  $S_j$  are excluded from  $\mathcal{S}'$ ;*
2. *for any subset  $S_j$  with  $d_j = 3$  containing elements  $u_i, u_p, u_q$ , where  $S_j$  double-hits another subset  $S_k$  with  $d_k = 3$  on  $u_i$  and  $u_p$ , if  $S_j$  is included in  $\mathcal{S}'$  then  $S_k$  must be excluded from  $\mathcal{S}'$  and viceversa;*
3. *for any subset  $S_j$  with  $d_j = 3$  containing elements  $u_i, u_p, u_q$ , if  $S_j$  is included in  $\mathcal{S}'$ , then either all subsets  $S_k$  hitting  $S_j$  on element  $u_i$  are excluded from  $\mathcal{S}'$ , or all subsets  $S_k$  hitting  $S_j$  on elements  $u_p$  and  $u_q$  are excluded from  $\mathcal{S}'$ .*

**Proof.** We only prove item 1, items 2 and 3 being proved by the same kind of analysis. Assume, without loss of generality, that  $S_j$  hits  $S_k$  on  $u_i$  and  $S_l$  on  $u_p$ . Suppose by contradiction that the optimal solution  $\mathcal{S}'$  includes  $S_j$  and  $S_k$ . Then, it cannot include no more  $S_l$ , or else, it would not be optimal as a better cover would be obtained by excluding  $S_j$  from  $\mathcal{S}'$ . On the other hand, suppose that  $\mathcal{S}'$  includes  $S_j, S_k$  but does not include  $S_l$ . Then, an equivalent optimal solution can be derived by swapping  $S_j$  with  $S_l$ . ■

In what follows, we consider the following counting. When we fix the status of a set of size 3, then our benefit is 1. When we do not fix a set of size 3 but cover one element of this set (hence this set will have size 2 is the remaining instance), we consider that our benefit is  $\alpha \leq 1$ . Obviously, when a set of size 2 is fixed, we can only consider that (in the worst case) our benefit is  $1 - \alpha$ . Hence, in some cases, the benefit is increasing with  $\alpha$  while, in other cases, it is decreasing. An optimal value for  $\alpha$ , following our analysis, is  $\alpha = 0.297$ .

The rest of the paper is devoted to the proof of the following result.

**Theorem 1.** *MIN 3-SET COVERING can be optimally solved within time  $O^*(1.396^n)$ .*

The algorithm either reduces the MIN 3-SET COVERING instance according to assumptions 1, 2 and 3 on the form of the instance (by detecting a subset  $S_j$  to be immediately included in (excluded from)  $\mathcal{S}'$  or an element  $u_i$  to be ignored (correspondingly reducing the size of several subsets)), or applies a branching on subset  $S_j$ , where the following exhaustive relevant branching cases may occur.

1.  $d_j = 2$ : then no double-hitting occurs to  $S_j$  or else, due to the preprocessing step of the algorithm,  $S_j$  can be excluded from  $\mathcal{S}'$  without branching. The following subcases occur.

(a)  $S_j$  contains elements  $u_i, u_k$  with  $f_i = f_k = 2$  where  $S_j$  hits  $S_l$  on  $u_i$  and  $S_m$  on  $u_k$ . Due to Lemma 1, if  $S_j$  is included in  $\mathcal{S}'$ , then both  $S_l$  and  $S_m$  must be excluded from  $\mathcal{S}'$ ; alternatively,  $S_j$  is excluded from  $\mathcal{S}'$  and, correspondingly, both  $S_l$  and  $S_m$  must be included in  $\mathcal{S}'$  to cover elements  $u_i, u_k$ . For the analysis, consider the two following cases.

- i.  $d_l = 3$ , or  $d_m = 3$ , say  $d_l = 3$ . Then, in both cases (including or excluding  $S_j$ ) we fix  $3 - 2\alpha$  (1 for  $S_l$ , (at least)  $1 - \alpha$  for  $S_j$  and  $S_m$ ).
- ii.  $d_l = d_m = 2$ ,  $S_l$  contains  $u_i$  and  $u_l$  and  $S_m$  contains  $u_k$  and  $u_m$ , (with  $u_l \neq u_m$ , otherwise no need to branch). By including  $S_j$  we fix  $3(1 - \alpha)$ . Otherwise,  $u_l$  is contained in  $S_p$  and  $u_m$  in  $S_q$ . If  $S_p \neq S_q$ , then we fix at least  $3(1 - \alpha) + 2\alpha = 3 - \alpha$ . Indeed, we fix  $1 - \alpha$  for any of the sets  $S_j, S_l, S_m$ ; by covering  $u_m$ , we fix  $\alpha$  (resp.,  $1 - \alpha \geq \alpha$ ) if  $d_p = 3$  (resp., if  $d_p = 2$ , since we can exclude  $S_p$ ), and the same holds for covering  $u_k$ . Note that this is still valid if  $S_p = S_q$ , since in this case we can exclude this set, which gives at least  $1 - \alpha \geq 2\alpha$ .

In case 1(a)i, we have  $T(n) \leq 2T(n - 3 + 2\alpha) + O(p(n))$ . This results in a time-complexity of  $O^*(1.334^n)$ . In case 1(a)ii, we have  $T(n) \leq T(n - 3 + 3\alpha) + T(n - 3 + \alpha) + O(p(n))$ . This results in a time-complexity of  $O^*(1.336^n)$ .

(b)  $S_j$  contains elements  $u_i, u_k$  with  $f_i = 2$  and  $f_k \geq 3$ , where  $S_j$  hits  $S_l$  on  $u_i$  and  $S_m, S_p$  on  $u_k$ . Due to Lemma 1, if  $S_j$  is included in  $\mathcal{S}'$ , then  $S_l, S_m, S_p$  must be excluded from  $\mathcal{S}'$ ; alternatively,  $S_j$  is excluded from  $\mathcal{S}'$  and, correspondingly,  $S_l$  must be included in  $\mathcal{S}'$  to cover element  $u_i$ . For the analysis, consider the two following cases.

- i.  $d_l = 2$ , i.e.,  $S_l$  contains  $u_i, u_l$ ; then,  $f_l \geq 3$  (or else we are in case 1a). Then, by including  $S_j$ , we fix  $4(1 - \alpha)$  ( $(1 - \alpha)$  for any of the sets  $S_j, S_l, S_m, S_p$ ); by excluding  $S_j$ , we fix  $2(1 - \alpha) + 2\alpha = 2$  ( $(1 - \alpha)$  for any of the sets  $S_j, S_l$ , and (at least)  $\alpha$  for each set containing  $u_l$ ).
- ii. If  $d_l \geq 3$ , i.e.,  $S_l$  contains at least  $u_i, u_l, u_m$ , then by including  $S_j$ , we fix  $3(1 - \alpha) + 1$  (since now fixing  $S_l$  gives benefit 1); by excluding  $S_j$ , we fix  $(1 - \alpha) + 1 + 2\alpha = 2 + \alpha$  ( $\alpha$  from covering  $u_l$ , and  $\alpha$  from covering  $u_m$ , with the same reasoning as in case 1(a)ii).

The worst case is 1(b)i where we get  $T(n) \leq T(n - 2) + T(n - 4 + 4\alpha) + O(p(n))$ , resulting in a time-complexity of  $O^*(1.338^n)$ .

(c)  $S_j$  contains elements  $u_i, u_k$  with  $f_i = 3$  and  $f_k \geq 3$  where  $S_j$  hits  $S_l, S_m$  on  $u_i$  and (at least)  $S_p, S_q$  on  $u_k$ . Note that we can suppose that  $S_j$  hits at least one set of size 3. Due to Lemma 1, if  $S_j$  is included in  $\mathcal{S}'$ , then  $S_l, S_m, S_p, S_q$  must be excluded from  $\mathcal{S}'$ ; alternatively,  $S_j$  is excluded from  $\mathcal{S}'$ . For the analysis, consider the three following cases.

- i. If  $d_l = d_m = d_p = d_q = 3$ , then we fix either  $5 - \alpha$ , or  $1 - \alpha$ .

- ii. If  $d_l = 2$  or  $d_m = 2$ , say  $d_l = 2$ , then we fix either  $5 - 4\alpha$ , or  $1 - \alpha$ . But in the case where we exclude  $S_j$  from  $\mathcal{S}'$ , then  $S_l$  has size 2 and contains  $u_i$ , whose frequency is now 2. Hence, we are either in case 1a or in case 1b. In the worst case, the branching gives (with case 1(b)i)  $5 - 4\alpha$ ,  $5(1 - \alpha)$  and  $3 - \alpha$ .
- iii. Finally, if  $d_l = d_m = 3$ , then we can suppose that  $f_k \geq 4$  (otherwise we are either in case 1(c)i or in case 1(c)ii). In this case, by including  $S_j$  we fix  $2 + 4(1 - \alpha)$  and by excluding  $S_j$  we fix  $1 - \alpha$ .

In case 1(c)i, we get  $T(n) \leq T(n - 1 + \alpha) + T(n - 5 + \alpha) + O(p(n))$ , i.e., a time-complexity of  $O^*(1.3953^n)$ . In case 1(c)ii, we get  $T(n) \leq T(n - 3 + \alpha) + T(n - 5 + 5\alpha) + T(n - 5 + 4\alpha) + O(p(n))$ . This results in a time-complexity of  $O^*(1.3942^n)$ . In case 1(c)iii, we get  $T(n) \leq T(n - 6 + 4\alpha) + T(n - 1 + \alpha) + O(p(n))$ , i.e., a time-complexity of  $O^*(1.389^n)$ .

- (d)  $S_j$  contains elements  $u_i, u_k$  with  $f_i \geq 4$  and  $f_k \geq 4$  where  $S_j$  hits  $S_l, S_m, S_p$  on  $u_i$  and  $S_q, S_r, S_s$  on  $u_k$ . Note that we can suppose that  $S_j$  hits at least one set of size 3. Due to Lemma 1, if  $S_j$  is included in  $\mathcal{S}'$ , then  $S_l, S_m, S_p, S_q, S_r, S_s$  must be excluded from  $\mathcal{S}'$ ; alternatively,  $S_j$  is excluded from  $\mathcal{S}'$ . Then, we fix either  $7 - 6\alpha$  or  $1 - \alpha$  getting  $T(n) \leq T(n - 1 + \alpha) + T(n - 7 + 6\alpha) + O(p(n))$ , resulting so in a time-complexity of  $O^*(1.366^n)$ .
2.  $d_j = 3$  (that is, there does not exist  $S_k \in \mathcal{S}$  such that  $d_k = 2$ ) and there is at least one element  $u_i$  with  $f_i = 2$ . Then,  $S_j$  contains  $u_i, u_j, u_k$ , and  $S_k$  contains  $u_i, u_l, u_m$  (notice that no double crossing can occur between  $S_j$  and  $S_k$  due to the preprocessing step of the algorithm). Then, either we include  $S_j$ , and we fix  $1 + 3\alpha$  new sets, or we exclude  $S_j$ , and we have to include  $S_k$  fixing so  $2 + 2\alpha$  new sets. In this case, we get  $T(n) \leq T(n - 1 - 3\alpha) + T(n - 2 - 2\alpha) + O(p(n))$ . This results in a time-complexity of  $O^*(1.366^n)$ .
  3.  $d_j = 3$ , all elements have a frequency at least 3, with  $S_j$  double-hitting one or more subsets. The following exhaustive subcases may occur.
    - (a)  $S_j$  double-hits at least three subsets  $S_k, S_l, S_m$ . Due to Lemma 1, if  $S_j$  is included in  $\mathcal{S}'$  then  $S_k, S_l, S_m$  must be excluded from  $\mathcal{S}'$ ; alternatively,  $S_j$  is excluded from  $\mathcal{S}'$ . This can be seen as a binary branching where either one subset ( $S_j$ ) is fixed, or four subsets ( $S_j, S_k, S_l, S_m$ ) are fixed and hence,  $T(n) \leq T(n - 1) + T(n - 4) + O(p(n))$ . This results in a time-complexity of  $O^*(1.3803^n)$ .
    - (b)  $S_j$  double-hits two subsets  $S_k, S_l$ . Note that the double-hit elements must be contained by another set. Note also that (at least) one element, say  $u_i$ , is in  $S_j, S_k$  and  $S_l$ . Consider the two following cases.
      - i. If  $f_i \geq 4$ , then either we include  $S_j$  and then, by Lemma 1, we can exclude  $S_k$  and  $S_l$ , or we exclude  $S_j$ . Then, either we fix  $3 + 3\alpha$  (3 for  $S_j, S_k, S_l$ , and  $3\alpha$  since  $u_i, u_j$  and  $u_k$  belong to at least one other set) or 1.
      - ii. If  $f_i = 3$ , then we must include at least one set among  $S_j, S_k, S_l$ , but we can suppose that we do not include two such sets. In other words, we have a branching on the three following choices:
        - taking  $S_j$  (and not  $S_k, S_l$ ),
        - taking  $S_k$  (and not  $S_j, S_l$ ),
        - taking  $S_l$  (and not  $S_j, S_k$ ).

In any case, we fix  $3 + 2\alpha$  ( $2\alpha$  since each element has a frequency at least 3)

In the first case,  $T(n) \leq T(n-1) + T(n-3-3\alpha) + O(p(n))$ . This results in a time-complexity of  $O^*(1.388^n)$ . In the second case,  $T(n) \leq 3T(n-3-2\alpha) + O(p(n))$ , and this results in a time-complexity of  $O^*(1.358^n)$ .

(c)  $S_j$  contains elements  $u_i, u_k, u_l$  and double-hits one subset  $S_k$  on elements  $u_i, u_k$ . The following exhaustive subcases must be considered.

- i.  $f_i = 3, f_k \geq 3, f_l \geq 3$ , with  $u_i$  contained by  $S_j, S_k, S_m$ ,  $u_k$  contained at least by  $S_j, S_k, S_p$  and  $u_l$  contained at least by  $S_j, S_q, S_r$ . A composite branching can be devised.
  - Suppose that  $S_j$  is included in  $\mathcal{S}'$  and then  $S_k$  is excluded from  $\mathcal{S}'$ . In this case, we fix  $2 + 4\alpha$  ( $\alpha$  from reduction of the sizes of  $S_m, S_p, S_q, S_r$ ).
  - Suppose that  $S_j$  is excluded from  $\mathcal{S}'$  and  $S_k$  is included in  $\mathcal{S}'$ . In this case, we fix  $2 + 4\alpha$  (since no other double hit occurs on  $S_k$ ).
  - Suppose finally that  $S_j$  and  $S_k$  are excluded from  $\mathcal{S}'$ . In this case, we have to include  $S_m$  in  $\mathcal{S}'$ . Since  $d_m = 3$ , all elements have frequency at least 3, and at most one double crossing occurs on  $S_m$ ; we can see that  $S_m$  hits at least three new sets. Hence, we fix  $3 + 3\alpha$ .
- ii.  $f_i \geq 4, f_k \geq 4, f_l \geq 3$ , with  $u_i$  contained at least by  $S_j, S_k, S_m, S_p$ ,  $u_k$  contained at least by  $S_j, S_k, S_q, S_r$  and  $u_l$  contained at least by  $S_j, S_u, S_v$ . Either we include  $S_j$  in  $\mathcal{S}'$ , and then we can exclude  $S_k$  from  $\mathcal{S}'$  and fix  $2 + 6\alpha$ , or we exclude  $S_j$  and fix 1.

In case 3(c)i, we get  $T(n) \leq 2T(n-2-4\alpha) + T(n-3-3\alpha) + O(p(n))$ . This results in a time-complexity of  $O^*(1.381^n)$ . In case 3(c)ii, we get  $T(n) \leq T(n-1) + T(n-2-6\alpha) + O(p(n))$ . This results in a time-complexity of  $O^*(1.3957^n)$ .

4.  $d_j = 3$  and no double-hitting occurs to  $S_j$  (nor to any other subset) that contains elements  $u_i, u_k, u_l$ . The following subcases occur.

- (a)  $f_i = 3, f_k \geq 3, f_l \geq 3$  with  $u_i$  contained by  $S_j, S_k, S_l$ ,  $u_k$  contained by  $S_j, S_m, S_p$  and  $u_l$  contained at least by  $S_j, S_q, S_r$ . A composite branching can be devised:
  - if  $S_j$  is included in  $\mathcal{S}'$ , then we fix  $1 + 6\alpha$  new sets;
  - if  $S_j$  is excluded from  $\mathcal{S}'$  and  $S_k$  is included in  $\mathcal{S}'$ , then there exist at least five other subsets hitting  $S_k$  and hence we fix  $2 + 5\alpha$ ;
  - finally, if  $S_j, S_k$  are excluded from  $\mathcal{S}'$ , then we have to include  $S_l$  in  $\mathcal{S}'$  (in order to cover  $u_i$ ); there exist at least four other subsets hitting  $S_l$  and hence we fix  $3 + 4\alpha$ .

Thus,  $T(n) \leq T(n-1-6\alpha) + T(n-2-5\alpha) + T(n-3-4\alpha) + O(p(n))$ , resulting in a time-complexity of  $O^*(1.378^n)$ .

- (b)  $f_i \geq 4, f_k \geq 4, f_l \geq 4$ ,  $u_i$  is contained by  $S_j, S_k, S_l, S_m$ ,  $u_k$  is contained by  $S_j, S_p, S_q, S_r$  and  $u_l$  is contained at least by  $S_j, S_t, S_u, S_v$ . A composite branching on  $S_j$  can be devised:
  - if  $S_j$  is excluded from  $\mathcal{S}'$ , then we fix 1;
  - if  $S_j$  is included in  $\mathcal{S}'$ , then  $S_k, S_l, S_m$  are excluded from  $\mathcal{S}'$ ; in this case we fix  $4 + 6\alpha$ ;
  - finally, if  $S_j$  is included in  $\mathcal{S}'$ , then  $S_p, S_q, S_r, S_t, S_u, S_v$  are excluded from  $\mathcal{S}'$ ; in this case we fix  $7 + 3\alpha$ .

Hence,  $T(n) \leq T(n-1) + T(n-4-6\alpha) + T(n-7-3\alpha) + O(p(n))$ . This results in a time-complexity of  $O^*(1.355^n)$ .

Putting things together, the global worst case complexity is  $O^*(1.3957^n)$  and the proof of the theorem is complete.

As a last word, let us note that a straightforward (improvable) analysis along the lines of Theorem 1, leads to an  $O^*(1.1679^n)$  time bound for minimum vertex covering in graphs of maximum size 3. Such a bound is the best-known dealing with search tree-based algorithms and is only dominated by the bounds in [1, 3], ( $O^*(1.1252^n)$  and  $O^*(1.152^n)$ , respectively) that are not based upon such algorithms. Note also, dealing with minimum dominating set in graphs of maximum size 3, analysis along the same lines reaches  $O^*(1.344^n)$ , which is always the best-known search-tree complexity.

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