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The complexity of Shortest Common Supersequence for inputs with no identical consecutive letters

A. Lagoutte*  S. Tavenas*

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Abstract

The Shortest Common Supersequence problem (SCS for short) consists in finding a shortest common supersequence of a finite set of words on a fixed alphabet Σ. It is well-known that its decision version denoted [SR8] in [4] is NP-complete. Many variants have been studied in the literature. In this paper we settle the complexity of two such variants of SCS where inputs do not contain identical consecutive letters. We prove that those variants denoted ϕSCS and MSCS both have a decision version which remains NP-complete when |Σ| ≥ 3. Note that it was known for MSCS when |Σ| ≥ 4 [3].

1 Introduction

Given two words u and v over an alphabet Σ, u is a supersequence of v if one can find in u a sequence of non-necessarily successive letters that spells v. The shortest supersequence of u is obviously u, but the problem becomes more difficult if the input is a set of words and one wants to find a common supersequence for these words as short as possible. The decision version of this problem, called SCS for Shortest Common Supersequence has been proven NP-complete in 1981 by Räihä and Ukkonen [8], even if the alphabet has size only 2. It is even NP-complete for some very restricted input, such as in the result of Middendorf [7] on which our work deeply relies: the alphabet is Σ2 = {0, 1}, and all the input words have the same length and each contains exactly two non-consecutive 1. However, another variant of SCS, which we will call Modified SCS (MSCS for short), appears very naturally in the study of combinatorial flood-filling games such as Flood-It and HONEY-BEE (studied for example in [1, 3, 5, 6]). In particular in [5], the authors show the NP-completeness of Flood-It, using a reduction to MSCS with an alphabet of size 3. This variant is stated as follows:

Modified Shortest Common Supersequence :

MSCS - decision version

Input: A set L = {w1, . . . , wn} of words on an alphabet Σ = {a1, a2, . . . , ad} such that no word wi contains two consecutive identical letters and no word wi starts with letter a1, and an integer k.

Output: Does there exist a supersequence of L of size less than k?

At first sight, it can seem easy to reduce SCS with Σ2 = {0, 1} to MSCS with Σ3 = {0, 1, 2} by replacing every occurrence of 0 by 02 in every word of the input set L, and doing the reverse

*LIP, Université de Lyon, ENS Lyon, CNRS UMR5668, INRIA, UCB Lyon 1, France
operation on the solution to \( \text{MSCS} \) to get the shortest common supersequence of \( L \). Unfortunately, this very natural idea does not work in general as shown on the following counter-example. Let \( L = \{00111, 11100\} \) be a input for \( \text{SCS} \) (in the minimization version), then the corresponding input for \( \text{MSCS} \) is \( L' = \{0202111, 1110202\} \). The shortest solution for \( \text{MSCS} \) is 111020111 of length 10, and its corresponding candidate solution for \( \text{SCS} \) is 11100111 of length 8. However, the shortest solution for \( L \) has size 7: 0011100. The problem here is that the operation transforms 0 into a double-counting letter and looses the symmetry between the two letters.

The second idea that occurs to mind is then to transform every occurrence of 0 by 02, and also every occurrence of 1 by 12. Then one can hope solving the newly created instance of \( \text{MSCS} \), and delete every 2 from the solution of \( \text{MSCS} \) to get the shortest solution to \( \text{SCS} \). This does not work either: consider the instance of \( \text{SCS} \) (in its minimization version) with \( L = (\Sigma_2)^3 \setminus \{111\} \), that is to say that \( L \) contains every word of length 3 on \( \Sigma_2 = \{0, 1\} \) except 111. The shortest supersequence for \( L \) is 01010 and is unique. Let \( L' \) be the set of words obtained from \( L \) by replacing every occurrence of 0 by 02 and every occurrence of 1 by 12. There is no supersequence for \( L' \) of length 9 obtained from 01010 by inserting some 2’s (there is one of length 10: 0212021202). However there does exist a shortest supersequence for \( L' \) of length 9, namely 012012012. Consequently, the very natural ideas do not work for reducing \( \text{SCS} \) to \( \text{MSCS} \).

Note that Fleischer and Woeginger designed in [3] a reduction proving that \( \text{MSCS} \) is NP-complete when \( \lvert \Sigma \rvert \geq 4 \) (the conference version of the paper states the result for \( \lvert \Sigma \rvert \geq 3 \), but the very simple proof turned out to be false; the correct statement appears in the later-published journal version). One should also mention Darte’s work [2] which does not focus directly on \( \text{MSCS} \), but states a result about typed fusions for typed directed graphs in a compilation context. However, as he explains at the beginning of Section 3.5, when the directed graphs are disjoint union of chains, his problem is equivalent to \( \text{SCS} \). Moreover the conditions over its typed fusions and digraphs implies that the \( \text{SCS} \) inputs equivalent to his digraph inputs, are words with no identical consecutive letters. Thus Proposition 3 in [2] can be interpreted as the fact that \( \text{SCS} \) for inputs with no identical consecutive letters is NP-complete. His reduction from Vertex Cover uses the alphabet \( \Sigma = \{0, 1, \bar{a}\} \) and a careful look shows that he generates \( \text{SCS} \) inputs where no word starts with \( \bar{a} \). Consequently one could state that the \( \text{NP-completeness of } \text{MSCS} \) for three letters is shown there. His reduction is derived from a paper of Räihä and Ukkonen [8] as well as its proof. Unfortunately it is 10 pages long and hard to check.

The main purpose of our work is to provide a new NP-completeness reduction for \( \text{MSCS} \) when \( \lvert \Sigma \rvert \geq 3 \), with a shorter proof, so that the result becomes undisputed. To this end, we introduce yet another variant of \( \text{SCS} \), called \( \varphi \text{SCS} \). We first define the alphabets \( \Sigma_2 = \{0, 1\} \) and \( \Sigma_3 = \{0, 1, 2\} \), and the word morphism \( \varphi : \Sigma^*_2 \to \Sigma^*_3 \) by \( \varphi(0) = 0202 \) and \( \varphi(1) = 1 \).

**Shortest Common Supersequence for some inputs generated by \( \varphi : \varphi \text{SCS} \) - decision version**

**Input:** A set \( L = \{w_1, \ldots, w_n\} \) of words on the alphabet \( \Sigma_3 \) such that \( L \subseteq \varphi(\Sigma^*) \), each \( w_i \) contains exactly two ones, which moreover are non consecutive, and an integer \( k \).

**Output:** Does there exist a supersequence of \( L \) of size less than \( k \)?

A careful look at those two problems shows that \( \varphi \text{SCS} \) is a particular case of \( \text{MSCS} \) if \( \lvert \Sigma \rvert \geq 3 \). The input words for \( \varphi \text{SCS} \) are a concatenation of patterns 0202 and 1 with no consecutive ones, thus they do not contain consecutive identical letters. Moreover none of those input words starts with letter 2. Up to relabelling the letters, one may consider that \( a_1 = 2 \). Consequently, we will
show that ϕ_{SCS} is NP-complete, which implies that MSCS is also NP-complete if |Σ| ≥ 3. One may wonder why we use the block 0202 instead of the more natural block 02 (that is to say, why ϕ(0) = 0202 and not 02). The key reason appears in the third item of Lemma 2: the elementary technique we use to prove it does not work for the case of blocks 02.

Besides, observe that the threshold on |Σ| which involves NP-hardness is tight: when |Σ| = 2, MSCS is trivially polynomial. Finally, let us notice that our proof is a very close adaptation of the proof of Middendorf’s result [7, Theorem 4.2] mentioned in the first paragraph.

Notation

Given two words over an alphabet Σ, u = u_1 . . . u_p (u_i ∈ Σ) and v = v_1 . . . v_q (v_i ∈ Σ), an embedding of u into v is an injection f from {1, . . . , p} into {1, . . . , q} such that u_i = v_{f(i)}. It tells that v is a supersequence of u and we also say that f maps letters of u onto letters of v. We will also use equivalently the terms pattern, block or factor to designate a sequence of consecutive letters in a word. A supersequence for a set of words is a word which is a supersequence for each of those words.

2 Result

The NP-completeness reduction will start from Vertex Cover, but we will need the next two lemmas.

Lemma 2.1. Let L be a set of words over Σ_3, such that L ⊆ ϕ(Σ^*), and S = s_1 . . . s_l be a supersequence of L. Then there exists a supersequence S' of L of size ≤ |S| such that S' ⊆ ϕ(Σ^*).

Proof. • First step: Let S' be a supersequence of L and let S'' be the string obtained from S' after applying one of the following operations:

1. If S' ends by 0, delete it.
2. If S' starts by 2, delete it.
3. If S' contains 00, replace it by 0.
4. If S' contains 22, replace it by 2.
5. If S' contains 01, replace it by 10.
6. If S' contains 12, replace it by 21.

Then S'' is still a supersequence of L: indeed, item (i) and (ii) are obvious since no word of L starts by 2 nor ends by 0. For item (iii), observe that no embedding can map two 0 onto two consecutive 0, since no word contains two consecutive 0. Thus if S'' contains 00 at index i, and f is an embedding of w ∈ L so that f maps a zero of w onto s_{i+1}, we can modify f to map this zero onto s_i. Then s_{i+1} is useless and we can delete it. The same argument applies for item (iv). For item (v), observe that no embedding can map a 0 and a 1 onto two consecutive 0 and 1 because this pattern does not appear in any word of L. Thus if S'' contains 01 at index i, and f is an embedding of w ∈ L so that f maps a zero of w onto s_i (resp. a one of w onto s_{i+1}), we can swap the 0 and the 1 in S and modify f to map the zero of w onto s_{i+1} (resp. the one of w onto s_i). The same argument applies for item (vi).

Consequently, starting from S, we can iterately “push” the zeros from left to right by deletion (transformation 00 into 0) or switching (01 into 10), and delete the last letter if it is a zero, until getting a supersequence S_1 where each 0 is followed by a 2. In the same manner, starting
Lemma 2.2. Let \( n \) be a positive even integer, \( L = \{S_0, \ldots, S_{n^2}\} \) be a set of strings with \( S_i = (0202)^i1(0202)^{n^2-i} \) for \( i \in [0 : n^2] \). Then let \( S \) be a supersequence of \( L \) such that \( S \in \varphi(\Sigma^*) \):

- If \( S \) contains exactly \( k \) ones, then \( S \) contains at least \( \lceil (n^2 + 1)/k \rceil - 1 + n^2 \) blocks of 0202.
- If \( S \) contains exactly \( n^2 - 1 + k \) blocks of 0202, then \( S \) contains at least \( \lceil (n^2 + 1)/k \rceil \) ones.

The string \( S_{\text{min}} = 1((02)^n1)^{2n}((02)^{n-2} \) is a shortest supersequence of \( L \). It has length \( 4n^2 + 4n - 3 \).

Proof. Let \( S \) containing \( k \) ones. There must be a subset \( L' \) of \( L \) which contains at least \( \lceil (n^2 + 1)/k \rceil \) strings such that the strings in \( L' \) can be embedded in \( S \) in such a way that the ones in these strings are mapped onto the same one of \( S \). Let \( i_{\text{max}} = \max\{|i|S_i \in L'\} \) and \( i_{\text{min}} = \min\{|i|S_i \in L'\} \). Since \( S_{\text{min}} \) and \( S_{\text{max}} \) are mapped onto the same one, \( S \) must contain at least \( i_{\text{max}} + n^2 - i_{\text{min}} \) zeros. Moreover, \( i_{\text{max}} \geq i_{\text{min}} + \lceil (n^2 + 1)/k \rceil - 1 \), so \( S \) contains at least \( \lceil (n^2 + 1)/k \rceil - 1 + n^2 \) blocks of 0202.

Let \( S \) containing \( n^2 - 1 + k \) blocks of 0202. Consider a one in \( S \) and let \( L' \) be the subset of \( L \) such that the one in the strings of \( L' \) is mapped onto this one. Let \( j \) be the number of blocks of 0202 before this one in \( S \). Then \( S_i \in L' \) only if \( i \leq j \) and \( n^2 - i \leq n^2 - 1 + k - j \), i.e. only if \( j + 1 - k \geq i \geq j \). Let \( i_{\text{max}} = \max\{|i|S_i \in L'\} \) and \( i_{\text{min}} = \min\{|i|S_i \in L'\} \). Then \( |L'| \leq i_{\text{max}} - i_{\text{min}} + 1 \leq j - j - 1 + k + 1 \leq k \). At most \( k \) strings are mapped onto the same one, thus there are at least \( \lceil (n^2 + 1)/k \rceil \) ones.
• $S_{\text{min}}$ is indeed a supersequence of $L$: first, it is a supersequence of $S_0$. Secondly, if $i \neq 0$, there exists $j \in [1 : 2n]$ such that $(j - 1)n/2 + 1 \leq i \leq jn/2$. Then the one in $S_i$ can be mapped to the $(j + 1)$th one, and there is $jn/2 \geq i$ blocks of 0202 before the one, and $(2n - j)n/2 + n/2 - 1$ blocks of 0202 after the one, which is enough to map the suffix $(0202)^{n^2 - i}$ because $(2n - j)n/2 + n/2 - 1 \geq n^2 - (j - 1)n/2 + 1 \geq n^2 - i$. So $S_{\text{min}}$ is indeed a supersequence of $L$.

Let $S'$ be the shortest supersequence of $L$. By Lemma 1, $S' \in \varphi(\Sigma^*)$, so we can apply (i): if $k$ is the number of ones of $S'$, then $|S'| \geq k + 4\lceil(n^2 + 1)/k\rceil - 4 + 4n^2 \geq f(k)$ where $f$ is the function defined on $\mathbb{N}$ by $f(x) = x + 4(n^2 + 1)/x - 4 + 4n^2$. However, $f$ admits a minimum on $\mathbb{N}$ which is $f(2\sqrt{n^2 + 1}) = 4\sqrt{n^2 + 1} + 4n^2 - 4 > 4n + 4n^2 - 4$. Consequently, $|S'| \geq f(k) > 4n + 4n^2 - 4$. Since $|S'|$ is an integer, $|S'| \geq 4n + 4n^2 - 3 = |S|$.

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**Theorem 2.3.** $\varphi_{\text{SCS}}$ is NP-complete.

**Proof.** Obviously, $\varphi_{\text{SCS}}$ is in NP. We reduce the Vertex Cover problem to it. Let $G = (V, E)$ be a graph with vertices $V = \{v_1, \ldots, v_n\}$ and edge set $E = \{e_1, \ldots, e_m\}$ and an integer $k$ be an instance of Vertex Cover. Recall that the Vertex Cover problem asks whether $G$ has a vertex cover of size $\leq k$, i.e., a subset $V' \subseteq V$ with $|V'| \leq k$ such that for each edge $v_i v_j \in E$, at least one of $v_i$ and $v_j$ is in $V'$. Let us now construct our instance of $\varphi_{\text{SCS}}$:

For all $i \in [1 : n], j \in [0 : 36n^2]$, let

$A_i = (0202)^{6n(l-1)+3n}1(0202)^{6n(n+1-i)}$, 

$B_j = (0202)^{j}1(0202)^{36n^2-j}$, 

$X_i^j = A_i B_j$.

For each edge $e_t = v_i v_j \in E$, $i < j$, let

$T_t = (0202)^{6n(l-1)}1(0202)^{6n(l-j-1)+3n}1(0202)^{6n(n+2-j)}(0202)^{36n^2-1}$. 

Now let $L = \{X_i^j | i \in [1 : n], j \in [0 : 36n^2]\} \cup \{T_t | t \in [1 : m]\}$. Clearly, $L$ can be constructed in polynomial time, each string in $L$ is in $\varphi(\Sigma^*)$ and has exactly two ones, which are non-consecutive. We will now show that $L$ has a supersequence of length $\leq 168n^2 + 37n - 3 + k$ if and only if $G$ has a vertex cover $V'$ of size $\leq k$.

Suppose $V' = \{v_{i_1}, \ldots, v_{i_k}\}$ is a vertex cover of $G$. Define

$S' = ((0202)^{6n}1(0202)^{6n})^{i_1-1}((0202)^{6n}1(0202)^{6n})^{i_2-2}1 \ldots ((0202)^{6n}1(0202)^{6n})^{i_k-1}1((0202)^{6n}1(0202)^{6n})^{n+1-i_k}(0202)^{6n}$, 

$S'' = 1((0202)^{6n}1(0202)^{6n})^{i_1-1}((0202)^{6n}1(0202)^{6n})^{i_2-2}1 \ldots ((0202)^{6n}1(0202)^{6n})^{i_k-1}1((0202)^{6n}1(0202)^{6n})^{n+1-i_k}(0202)^{6n}$, 

$S = S' S''$, then $|S| = 168n^2 + 37n - 3 + k$.

By Lemma 2, $S''$ is a supersequence of $\{B_j | j \in [0 : 36n^2]\}$. Moreover, $((0202)^{6n}1(0202)^{6n})^{n}(0202)^{6n}$ is a supersequence of $\{A_i | i \in [1 : n]\}$ thus $S'$ also is. From this we deduce that $S$ is a supersequence of $\{X_i^j | i \in [1 : n], j \in [0 : 36n^2]\}$.

Finally, let us prove that $S$ is a supersequence of $T_t$ for $t \in [1 : m]$. Let $e_t = v_i v_j$, $i < j$, and consider the two following cases:

• **Case 1:** $v_i \in V'$, i.e., there exists $t \in [1 : k]$ such that $i = i_t$. The suffix $(0202)^{36n^2-1}$ of $T_t$ can be embedded in $S''$. The goal is to prove that the prefix $P_t = (0202)^{6n(i-1)}1(0202)^{6n(j-i-1)+3n}1(0202)^{6n(n+2-j)}$ can be embedded in $S'$. Observe that one can obtain the following subsequence $S_i'$ of $S'$ by deleting a few ones:

$S_i' = ((0202)^{6n}1(0202)^{6n})^{i-1}1((0202)^{6n}1(0202)^{6n})^{n+1-i_t}(0202)^{6n}$. Now $S_i'$ can be rewritten
Since each $S$ that has a supersequence $P_i$ again, implies $i < j$ be mapped onto $S$. Assume for contradiction that the claim does not hold for an $S'$. Let us state the following two claims:

Claim 2.4. For each $i \in [1 : n]$, $S'$ must contain a one between the $(6n(i - 1) + 3n)$th block of $0202$ and the $(6n(i) + 3n)$th block of $0202$. Consequently, $S'$ contains at least $n$ ones.

Proof. Assume for contradiction that the claim does not hold for an $i \in [1 : n]$. Then the one in $A_i$ is mapped on a one in $S$ which is after at least $6n$ blocks of $0202$. Since $S'$ contains exactly $6n^2 + 3n$ blocks of $0202$, the suffix $(0202)^3n$ of $A_i = (0202)^{6n(i - 1) + 3n}1(0202)^{6n^2 + 3n}0$ must be mapped onto $S''$. Consequently, $S''$ is a supersequence of $(0202)^{3n}B_{j+1} j \in [0 : 36n^2]$, thus by Lemma 2, $|S''| \geq 4 \cdot 3 \cdot 6n$ and $|S''| \geq 4 \cdot 3 \cdot 6n < 3$. Since $|S''| \geq 4(6n^2 + 3n)$, we have $|S''| \geq 4(6n^2 + 3n)$. Consequently, $S''$ contains at least $6n^2 + 3n$ blocks of $0202$, the last zero $f$ is mapped onto $S''$. Assume $S''$ contains $36n^2 + p$ blocks of $0202$ with $p \geq 6n - 1$. By Lemma 2, $|S''| \geq 4(36n^2 + 3n) = 4(6n^2 + 6n - 1) + (36n^2 + 3n)/3n > 144n^2 + 24n - 4 + 6n$. Thus $|S''| \geq 144n^2 + 30n - 3$. Consequently, $|S''| \geq 36n^2 + 3n$. Since $S''$ contains exactly $6n^2 + 3n$ blocks of $0202$, the last zero of $P_i$ is mapped onto $S''$.

Finally, $S$ is a supersequence of $L$ of size $168n^2 + 37n - 3 + k$.

Suppose now that $L$ has a supersequence of length $\leq 168n^2 + 37n - 3 + k$. By Lemma 1, $L$ has a supersequence $S'$ of size $\leq 168n^2 + 37n - 3 + k$ such that $S' \in \varphi(S')$. Define $S'$ and $S''$ such that $S = S' \cdot S''$, where $S''$ contains $6n^2 + 3n$ blocks of $0202$. Since each $A_i$ contains $6n^2 + 3n$ blocks of $0202$, like $S'$, and $S$ is a supersequence of $X_i$. Thus $S$ is the shorthand of $S'$ and checking that the number of blocks of $0202$ is enough.
Conclusion By Lemma 2, $|S''| \geq 144n^2 + 24n - 3$. By definition, $S'$ contains $6n^2 + 3n$ blocks of 0202. Since $|S| \leq 168n^2 + 37n - 3 + k$, $S'$ can contain at most $168n^2 + 37n - 3 + k - (144n^2 + 24n - 3) - 4(6n^2 + 3n) = n + k$ ones. By Claim 4, there is a one between the $(6n(i - 1) + 3n)$th zero and the $6in$th zero of $S'$ for each $i \in [1:n]$, which makes $n$ ones. This implies that there can be at most $k$ indices $i \in [1:n]$ such that there is a one between the $6n(i - 1)$th zero and the $(6n(i - 1) + 3n)$th zero of $S'$. Let $i_1, \ldots, i_p$ be these indices, $p \leq k$. Thanks to Claim 5, we see that $\{v_{i_1}, \ldots, v_{i_k}\}$ is a vertex cover of $G$ of size $p \leq k$.

As explained in the presentation of the two variants, inputs for $\varphi \text{SCS}$ have no identical consecutive letters and do not start with 2, thus we immediately gain the following corollary.

Corollary 2.6. $\text{MSCS}$ is NP-complete when $|\Sigma| \geq 3$.

References


