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A Third Strike Against Perfect Phylogeny

LEO VAN IERSEL¹, MARK JONES^{1,*}, AND STEVEN KELK²

¹Delft Institute of Applied Mathematics, Delft University of Technology, Van Mourik Broekmanweg 6, 2628 XE, Delft, The Netherlands; ²Department of Data Science and Knowledge Engineering (DKE), Maastricht University, Bouillonstraat 8-10 6211 LH, Maastricht, The Netherlands

*Correspondence to be sent to: Delft Institute of Applied Mathematics, Delft University of Technology, Van Mourik Broekmanweg 6, 2628 XE, Delft, The Netherlands;

E-mail: M.E.L.Jones@tudelft.nl.

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Abstract.—Perfect phylogenies are fundamental in the study of evolutionary trees because they capture the situation when each evolutionary trait emerges only once in history; if such events are believed to be rare, then by Occam's Razor such parsimonious trees are preferable as a hypothesis of evolution. A classical result states that 2-state characters permit a perfect phylogeny precisely if each subset of 2 characters permits one. More recently, it was shown that for 3-state characters the same property holds but for size-3 subsets. A long-standing open problem asked whether such a constant exists for each number of states. More precisely, it has been conjectured that for any fixed number of states r there exists a constant $f(r)$ such that a set of r -state characters C has a perfect phylogeny if and only if every subset of at most $f(r)$ characters has a perfect phylogeny. Informally, the conjecture states that checking fixed-size subsets of characters is enough to correctly determine whether input data permits a perfect phylogeny, irrespective of the number of characters in the input. In this article, we show that this conjecture is false. In particular, we show that for any constant t , there exists a set C of 8-state characters such that C has no perfect phylogeny, but there exists a perfect phylogeny for every subset of at most t characters. Moreover, there already exists a perfect phylogeny when ignoring just one of the characters, independent of which character you ignore. This negative result complements the two negative results ("strikes") of Bodlaender et al. (1992, 2000). We reflect on the consequences of this third strike, pointing out that while it does close off some routes for efficient algorithm development, many others remain open. [Four gamete condition; local obstructions conjecture; maximum parsimony; perfect phylogeny; phylogenetic tree.]

The traditional model for capturing the evolution of a set X of contemporary species or taxa is the *phylogenetic tree*. In such trees, internal nodes represent hypothetical (common) ancestors. The central goal in phylogenetics is to infer phylogenetic trees given only data obtained from (or observed at) X for example DNA sequences, amino acid sequences, or morphological features (Felsenstein 2004). The data observed at a taxon x in X is typically represented as an ordered length- m vector of discrete states, where the states are elements of some size- r alphabet. For example, if we have a length-200 sequence of aligned DNA data for each of the X taxa, where X denotes the number of taxa in X , this can be summarized as a matrix M on X rows and 200 columns, where each entry of the matrix is an element from $\{A, G, C, T\}$, so $r=4$. Each of the 200 columns is then known as a *character*.

Given such data, how do we quantify the "goodness of fit" of the data on a given tree T ? A classical optimality criterion for T is the *parsimony score* of T . Informally, this is the minimum number of state-changes that would necessarily be incurred along the branches of T if the data observed at X had evolved following the topology of the tree. If, for each character, each state is introduced at most once along the branches of the tree, we say that T is a *perfect phylogeny* for the data (Semple and Steel 2003). If such a tree T exists, we say that the data permit a perfect phylogeny. The parsimony score of each character is then equal to the number of observed states (i.e., number of distinct states in the corresponding column) minus one. Perfect phylogeny

is thus the best case for phylogenetic trees constructed under the popular *maximum parsimony* optimality criterion, where (motivated by Occam's Razor) trees are preferred that explain the observed data with as few evolutionary changes as possible (Felsenstein 2004). We refer to Figure 1 for clarifying examples of perfect phylogenies.

Determining whether the input data permits a perfect phylogeny is a fundamental combinatorial problem in phylogenetics, with a long history [see Lam et al. (2011) and Shutters et al. (2013) for excellent overviews], and it has also attracted substantial attention from the discrete optimization community (Bodlaender et al. 1992; Fernández-Baca 2001; Gramm et al. 2008; Lam et al. 2011; Misra et al. 2011). The latter is due to links with the literature on (variously) graph triangulations, parameterized complexity, and Steiner Trees. For binary data ($r=2$) a classical result from Buneman from 1971 states that the data permit a perfect phylogeny if and only if every pair of characters (i.e., every pair of columns) permits a perfect phylogeny (Buneman 1971). A consequence of this is that, for binary data, looking only "locally" at the data is sufficient to determine the presence or absence of perfect phylogeny. Is testing pairs of characters also sufficient for $r \geq 3$? In 1975, Fitch refuted this claim by showing data which does not permit a perfect phylogeny, but where every pair of characters does (Fig. 1) (Fitch 1975, 1977). However, later it was shown that for $r=3$ the data permit a perfect phylogeny if and only if all size-3 subsets of the characters do (Lam et al. 2011).

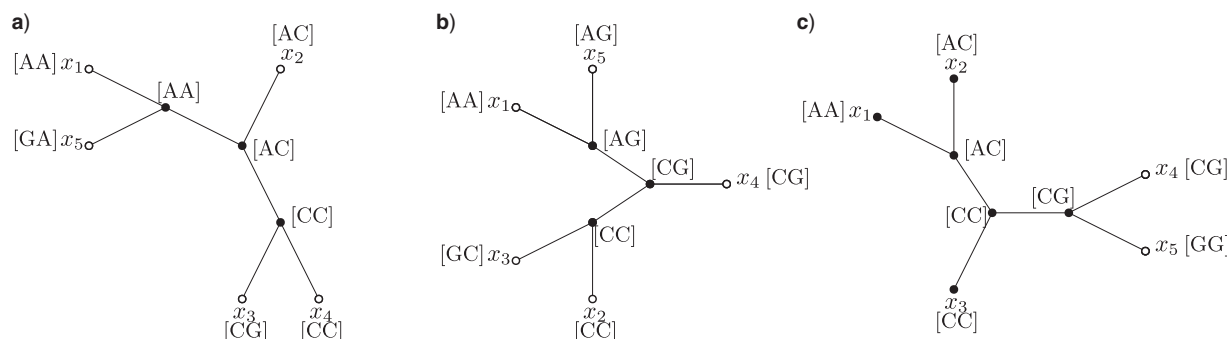


FIGURE 1. The example of Fitch (1975, 1977), showing that $f(3) > 2$. The five leaves $x_1, \dots, x_5$ have sequences AAA, ACC, CGC, CCG, and GAG, respectively. In our notation, the character set is $C = \{\chi_1, \chi_2, \chi_3\}$, where $\chi_1 = x_1x_2|x_3x_4|x_5$, $\chi_2 = x_1x_5|x_2x_3|x_4$, and $\chi_3 = x_1|x_2x_3|x_4x_5$. For example, $\chi_1 = x_1x_2|x_3x_4|x_5$ indicates that, at the first position, x_1 and x_2 have the same state, x_3 and x_4 have the same state, and x_5 has a third state. The figure shows a perfect phylogeny for each pair of characters. However, no perfect phylogeny exists for the full character set (this can easily be observed by checking that each of the three perfect phylogenies is the unique solution for its respective pair of characters). a) $\{\chi_1, \chi_2\}$. b) $\{\chi_2, \chi_3\}$. c) $\{\chi_1, \chi_3\}$.

The intriguing question thus arises: is it true that, for every number of states $r \geq 2$, there exists a number $f(r)$ such that r -state data permits a perfect phylogeny if and only every size- $f(r)$ subset of the characters does? To make this more concrete: could it be true that r -state data, irrespective of the number of characters in the input, permits a perfect phylogeny if and only if every subset of characters of size at most, say, r^2 permits a perfect phylogeny? How about 2^r instead of r^2 ? Or 2^{2^r} ? Or is it the case that, however large we choose this function $f(r)$, at some point a sufficiently large input will be encountered whereby focusing only on size $f(r)$ subsets will deceive us into thinking that the input permits a perfect phylogeny—when in fact it does not? A conjecture, which has thus been circulating in various forms for approximately 50 years [see Habib and To (2011) for a recent treatment], states that such a constant $f(r)$ does indeed exist for each $r \geq 2$. This would mean that, provided $f(r)$ is chosen to grow quickly enough, there is no danger that we will be deceived: we can always determine perfect phylogeny by restricting our attention to subsets of characters of size at most $f(r)$. Here, we refer to this as the *local obstructions conjecture for perfect phylogeny*. Note that $f(r)$ should depend only on r and no other parameters (such as X or the number of characters in the input). We know that $f(2) = 2$ and $f(3) = 3$, but what about larger r ? If the local obstructions conjecture is true, how fast does $f(r)$ grow?

In the absence of positive progress—it is still unknown whether $f(4)$ exists—various authors have described lower bounds on $f(r)$, if it exists. It is known that $f(4) \geq 5$ (if it exists) (Habib and To 2011) and the currently strongest general lower bound is given in Shutters et al. (2013), where it is shown that for $r \geq 2$, $f(r) \geq \lfloor \frac{r}{2} \rfloor \lceil \frac{r}{2} \rceil + 1$ (if it exists). Such results do not, however, disprove the local obstructions conjecture, since $f(r)$ might still exist but grow at least quadratically.

Here we show emphatically that the local obstructions conjecture is *false*, forming a third strike against perfect phylogeny. [The first is the NP-hardness of the problem

(Bodlaender et al. 1992), and the second excludes the existence of certain parameterized algorithms (Bodlaender et al. 1992; Bodlaender et al. 2000)]. Specifically, we show that for every even $n \geq 4$ there exists an 8-state input with $2n$ taxa and $2n - 4$ characters with the following property: the input does *not* permit a perfect phylogeny, but all proper subsets *do* permit a perfect phylogeny. This shows that, to decide whether there exists a perfect phylogeny for character data with at least 8 states, it is not enough to check all groups of a certain number of characters. It is necessary to consider all characters simultaneously. In particular, this shows that the constant $f(8)$ cannot exist (and consequently also $f(9), f(10), \dots$ do not exist). We emphasize that our construction can be extended to any number of taxa, odd or even, as long as it is at least 8. It is not a transient phenomenon that disappears as the number of taxa increases.

One implication of this result is the following. For $r = 2$ the fact that $f(r)$ exists forms the basis of an efficient, fixed parameter tractable algorithm for the *near-perfect phylogeny* problem (Sridhar et al. 2007). [See Cygan et al. (2015) for an introduction to parameterized complexity]. Essentially, this problem asks: “does there exist a tree that has a parsimony score of at most k with respect to the input data?” The algorithm leverages the insight that state-changes which occur above the perfect phylogeny lower bound must occur inside small $f(2)$ -size subsets of the input. Given that $f(2)$ is a constant, there are not too many size- $f(2)$ subsets and inside such a subset there are not too many places where the state change could occur. However, our result shows that such an approach is doomed to fail for $r \geq 8$. In a similar vein, the line of attack posed in Shutters et al. (2013) to establish the fixed parameter tractability of the *character removal* problem (i.e., deleting a minimum number of characters to obtain a perfect phylogeny), will also fail for $r \geq 8$. This is unfortunate, since data sets certainly do arise in practice with a large number of states: for amino acids $r = 20$, and nonmolecular character data such as that which arises in linguistics can easily have 8 or more

states. Another negative consequence of our result is the following. If we allow gaps/indels in the input, we can reduce the number of states in our construction from 8 to 4. This shows that the conjecture also fails for the practical case of aligned DNA data (without relying on any complexity assumption).

On the positive side, $f(r)$ might still exist for $r \in \{4, 5, 6, 7\}$ (which includes the case of DNA data without gaps, i.e., $r = 4$). Also, although our result is negative for algorithmic approaches that look only at small subsets of the input *in isolation*, this is certainly *not* a case of *three strikes and out!* In particular, it does not exclude algorithmic approaches that analyze the input data in a more sophisticated way. For example, the question “does the input permit a perfect phylogeny,” although NP-hard in general (Bodlaender et al. 1992), can be answered in time $O(2^{2r} m^2 |X|)$ using dynamic programming (Kannan and Warnow 1997), which for fixed r becomes $O(m^2 |X|)$. Similarly, it is still possible that fixed parameter tractable algorithms exist to solve the near-perfect phylogeny problem, but more advanced algorithmic approaches will be required. Despite the refutation of the local obstructions conjecture, perfect phylogeny will continue to play a central role in both applied and theoretical phylogenetics.

The structure of the article is as follows. We start by giving an informal description of an example of the construction for 8 taxa. After that, we give formal mathematical definitions. In “Main Results,” we first describe the most important parts of the construction of the general counter example and explain the main ideas behind the construction. We then provide the full construction, and finally prove that this gives a counterexample to the local obstructions conjecture for perfect phylogeny.

Example for Eight Taxa

In this section, we describe our counter example for the case of 8 taxa, the smallest number of taxa for which the construction works. We describe four (6-state) characters that are incompatible, that is, they do not permit a perfect phylogeny, while any three of the four characters do permit a perfect phylogeny. Note that this example is not a new result in itself, because it was already known that, for 6-state characters, we would need to consider at least $\lfloor \frac{6}{2} \rfloor \lceil \frac{6}{2} \rceil + 1 = 10$ characters simultaneously (Shutters et al. 2013). Nevertheless, the example is of interest because it can be generalized to higher numbers of taxa and characters, as we will show in the remaining sections, thus proving that the local obstructions conjecture is false.

Consider eight taxa named $a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4$ and the following four characters:

$$\Omega_A = a_1 b_1 b_2 | a_2 a_3 b_3 a_4 b_4$$

$$\chi_2 = a_1 | b_1 | a_2 a_3 | b_2 b_3 | a_4 | b_4$$

$$\phi_3 = a_1 a_2 | b_1 | b_2 | a_3 | a_4 | b_3 b_4$$

$$\Omega_B = a_1 b_1 a_2 b_2 b_3 | a_3 a_4 b_4.$$

The names of the characters might seem odd, but they correspond to the names used in the general counter example, where they will make more sense. Also note that it actually does not matter for the problem which states taxa have. The only thing that matters is which taxa have the same state, this is indicated in the characters by separating blocks of taxa with the same state by |. For example, in the first character Ω_A , taxa a_1, b_1 , and b_2 all have the same state while a_2, a_3, b_3, a_4 , and b_4 have a different state. In χ_2 , we have six states: a_2 and a_3 have one state, b_3 and b_4 have a second state, and the remaining four taxa all have their own unique state. The fact that we have only 6 character states is due to the small number of taxa. The general example will have 8 character states.

Figure 2 shows that any combination of three of the four characters does permit a perfect phylogeny.

We now argue that the combination of all four characters is incompatible, which is a bit more work. First we look at the characters Ω_A and Ω_B . In character Ω_A , taxa a_1, b_1 , and b_2 all have the same state, while all other taxa have a different state. Hence, in any perfect phylogeny, there must be a branch with the taxa a_1, b_1 , and b_2 on one side and the remaining taxa on the other side. Similarly, character Ω_B says that there must be a branch with the taxa a_3, a_4 , and b_4 on one side and the remaining taxa on the other side. What the parts of the tree containing a_1, b_1, b_2 and a_3, a_4, b_4 look like is not important. What is important is what happens in the middle part of the tree, which contains the remaining taxa a_2 and b_3 .

Basically, characters χ_2 and ϕ_3 give us contradictory information about the order of taxa a_2 and b_3 , see Figure 3. First look at character ϕ_3 . Because taxa a_1 and a_2 have the same state, and taxa b_3 and b_4 have another state, we know that the path connecting a_1 and a_2 may not overlap with the path connecting b_3 and b_4 . Hence a_2 must be on the side of a_1 and b_3 on the side of b_4 , as indicated in Figure 3a. In a similar way, character χ_2 tells us exactly the opposite, that is, that b_3 is on the side of b_2 (and a_1) and a_2 is on the side of a_3 (and b_4), as indicated in Figure 3b. Hence, a perfect phylogeny would need to simultaneously look like Figure 3a and like Figure 3b, which is impossible. We can therefore conclude that no perfect phylogeny exists.

In the remaining sections, we show how to generalize this example to more taxa, thereby also increasing the number of characters. We note that the proofs for the general case will be more involved.

Mathematical Definitions

Let X be a set of labels. For any positive integer r , an r -state character on X is a partition $\chi = S_1 | S_2 | \dots | S_{r'}$, where X is the union of $S_1, \dots, S_{r'}$ and $r' \leq r$. We refer to the sets $S_1, \dots, S_{r'}$ as *states*. For the sake of brevity, in this context we will sometimes write $x_1 \dots x_t$ as shorthand for a set

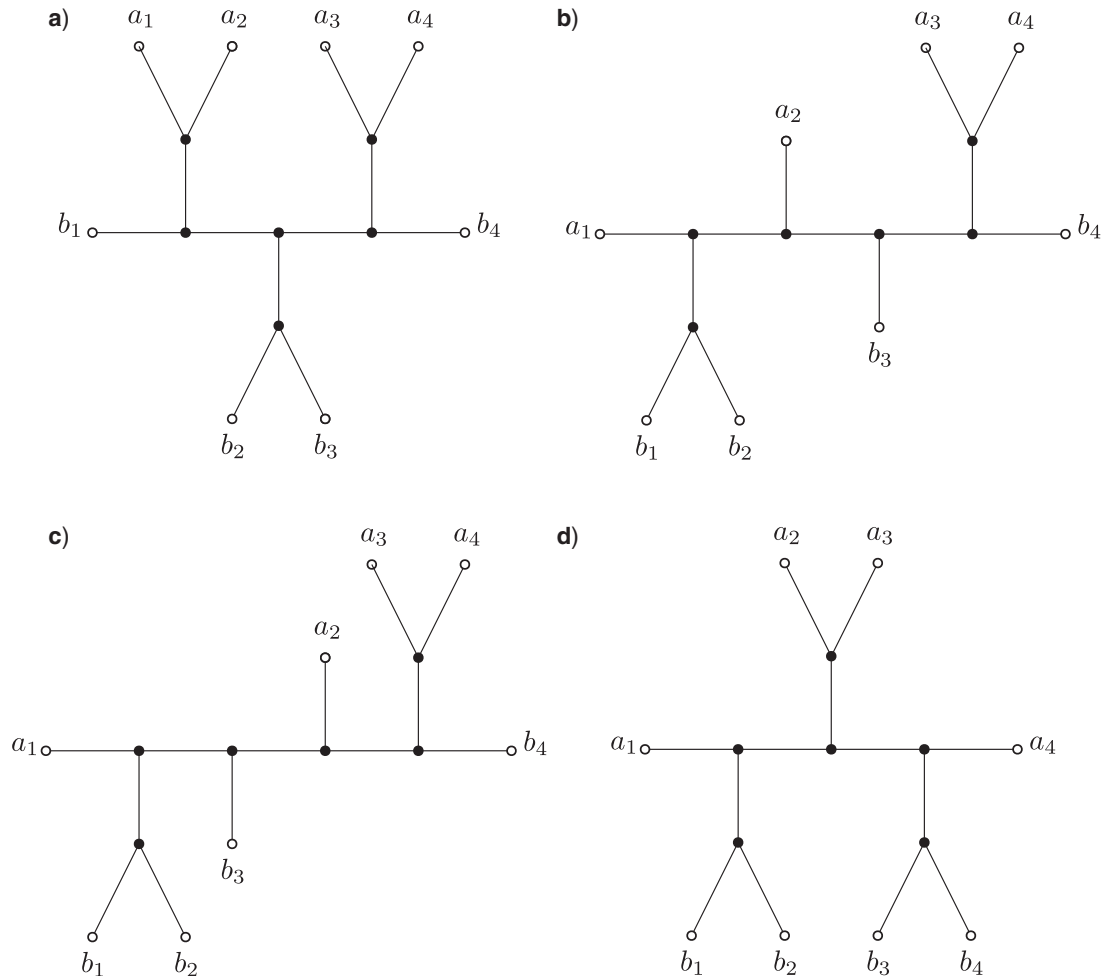


FIGURE 2. Four trees showing that, for eight taxa, ignoring one character of Ω_A , χ_2 , ϕ_3 , and Ω_B makes the remaining three characters compatible. a) Tree T_1 displaying χ_2 , ϕ_3 , and Ω_B . b) Tree T_2 displaying Ω_A , ϕ_3 , and Ω_B . c) Tree T_3 displaying Ω_A , χ_2 , and Ω_B . d) Tree T_4 displaying Ω_A , χ_2 , and ϕ_3 .

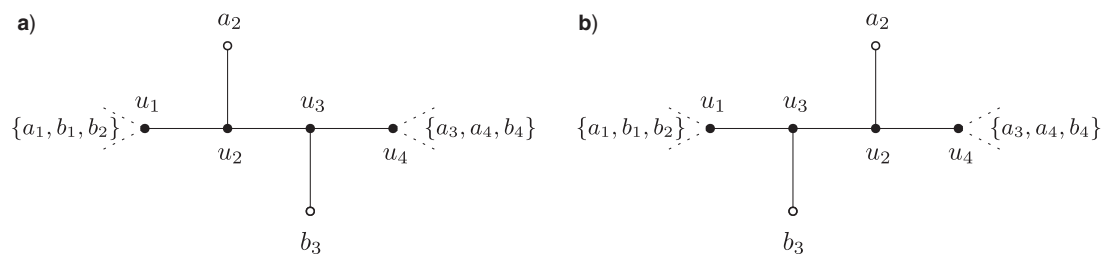


FIGURE 3. Illustration of the proof that, for eight taxa, characters Ω_A , χ_2 , ϕ_3 , and Ω_B are incompatible. a) Structure of a perfect phylogeny implied by Ω_A , ϕ_3 , and Ω_B . b) Structure of a perfect phylogeny implied by Ω_A , χ_2 , and Ω_B .

$\{x_1, \dots, x_t\}$. Thus for example, if $X = \{x_1, \dots, x_n\}$ then $\chi = x_1|x_2|x_3x_4|\{x_i : i \geq 5\}$ is a character on X . (Note that some states may be empty; in such cases we may treat these states as nonexistent. Thus for example if $S_i = \emptyset$ then $S_1|S_2|\dots|S_{r'}$ is equivalent to $S_1|S_2|\dots|S_{i-1}|S_{i+1}|\dots|S_{r'}$.)

A tree T on X is an unrooted tree with leaves bijectively labelled with the elements of X . Given a subset $S \subset X$, let $T[S]$ denote the minimal subtree of T whose vertices contain S . We note that degree-2 vertices are usually not

allowed in phylogenetic trees; however our definition of $T[S]$ allows for degree-2 vertices, as this makes certain proofs simpler and does not affect the results.

For any positive integer n , $[n]$ denotes the set $\{1, \dots, n\}$. We say T displays a character $\chi = S_1|\dots|S_{r'}$ on X if there exists a partition $V_1|\dots|V_{r'}$ of the vertices of T , such that the subtree of T induced by V_i is connected and $V_i \cap X = S_i$ for each $i \in [r']$. Equivalently, T displays χ if the subtrees $T[S_i]$ and $T[S_j]$ are vertex-disjoint for $i \neq j$.

We say T is *compatible* with a set C of characters (or equivalently, C is *compatible* with T) if T displays χ for each $\chi \in C$. If this is the case, we also say that T is a *perfect phylogeny* for C . We say a set C of characters is *compatible* if there exists a perfect phylogeny for C .

In this article, we show that the following conjecture is false:

Conjecture 1.1. *For each positive integer r , there exists an integer $f(r)$ such that for any finite set X and any set C of r -state characters on X , C is compatible if and only if every subset of at most $f(r)$ characters in C is compatible.*

MAIN RESULTS

Counterexample: Main Concepts

In this section, we outline the main concepts and ideas used in the construction of our counterexample to Conjecture 1.1. We also define the label set X and two trees on X that will be used to show that most subsets of characters are compatible.

In what follows, let n be any positive even integer.

Definition 2.1. *Given a positive even integer n , let $X = \{a_1, \dots, a_n, b_1, \dots, b_n\}$. For any $i \in [n]$, let $X_{\leq i} = \{a_j, b_j : 1 \leq j \leq i\}$, and $X_{\geq i} = \{a_j, b_j : m \geq j \geq i\}$.*

We now define two trees A and B on X . These trees appear quite similar on a large scale—they are both lobsters (trees in which every vertex is of distance at most 2 from a central path), with leaves of smaller index closer to one end of the central path than leaves of larger index. However, on a local scale they appear quite different—for example, each $x \in X$ has a different sibling in A than in B .

Informally, A consists of a number of cherries that are attached as pendant subtrees to a central path. The endpoints of the path are a_1 and a_n . Starting at a_1 and walking along the path, the first cherry attached is (b_1, b_2) , then (a_2, a_3) , then (b_3, b_4) , and so on. The definition of tree B is similar to A , but with the roles of the a and b leaves reversed. (Fig. 4.)

We give a more formal definition below.

Definition 2.2. *The tree A on X is defined as follows: A has leaves $a_1, \dots, a_n, b_1, \dots, b_n$, and internal nodes $u_1, \dots, u_{n-1}, v_1, \dots, v_{n-1}$. A contains a central path $a_1, u_1, u_2, \dots, u_{n-1}, a_n$. For each $i \in [n-1]$, there is an edge $u_i v_i$. For odd $i \in [n-1]$, the vertex v_i is adjacent to leaves b_i and b_{i+1} . For even $i \in [n-2]$, the vertex v_i is adjacent to leaves a_i and a_{i+1} .*

The tree B on X is defined as follows: B has leaves $a_1, \dots, a_n, b_1, \dots, b_n$ and internal nodes $u_1, \dots, u_{n-1}, v_1, \dots, v_{n-1}$. B contains a central path $b_1, u_1, u_2, \dots, u_{n-1}, b_n$. For each $i \in [n-1]$, there is an edge $u_i v_i$. For odd $i \in [n-1]$, the vertex v_i

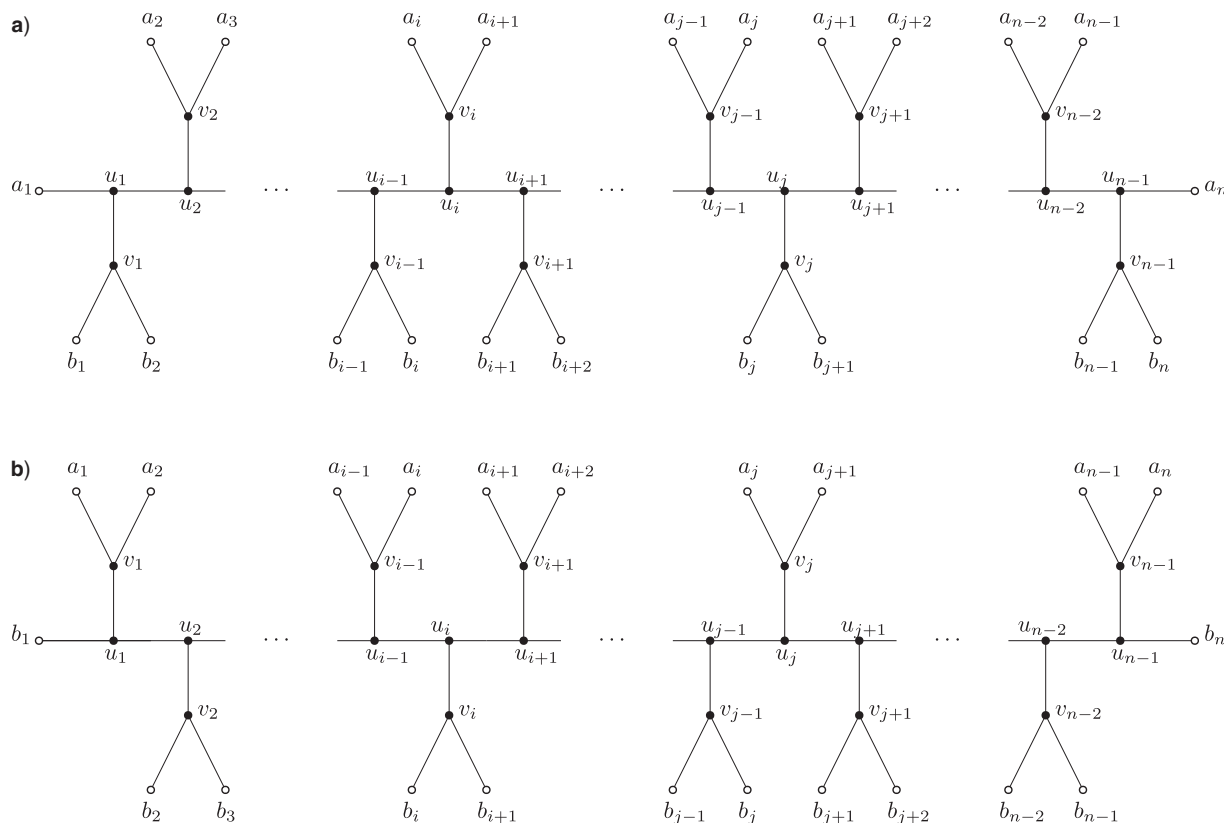


FIGURE 4. The lobsters A and B . The middle part of each figure shows some of the vertices near u_i , for i even, and near u_j , for $j > i$ and j odd. a) Lobster A . b) Lobster B .

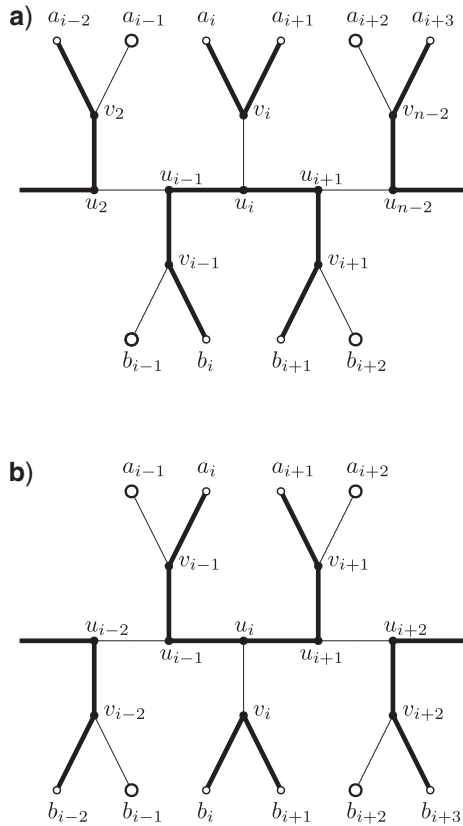


FIGURE 5. How A and B each display the character χ_i , for i even. a) Lobster A . b) Lobster B .

is adjacent to leaves a_i and a_{i+1} . For even $i \in [n-2]$, the vertex v_i is adjacent to leaves b_i and b_{i+1} .

We next describe a set of characters χ_i for each i such that $2 \leq i \leq n-2$ (we note that this is not the full set of characters that will be used in the complete example). Informally, each character χ_i can be thought of as caring about a small local part of the tree. It roughly enforces that if one segment of the tree looks like A , then so does the next segment along.

For each $2 \leq i \leq n-2$, define

$$\chi_i = X_{\leq i-2} | a_{i-1} | b_{i-1} | a_i a_{i+1} | b_i b_{i+1} | a_{i+2} | b_{i+2} | X_{\geq i+3}.$$

(Note that for $i=2$ the set $X_{\leq i-2}$ is empty; thus χ_2 could be equivalently written as $a_1 | b_1 | a_2 a_3 | b_2 b_3 | a_4 | b_4 | X_{\geq 5}$. Similarly, for $i=n-2$ the set $X_{\geq i+3}$ is empty and so χ_{n-2} can be written as $X_{\leq n-4} | a_{n-3} | b_{n-3} | a_{n-2} a_{n-1} | b_{n-2} b_{n-1} | a_n | b_n$.)

Observe that both A and B display χ_i for each $2 \leq i \leq n-2$, but the structure of the subtrees involved is quite different between the two. In particular, assuming i is even, in A the path from a_i to a_{i+1} has length 2, whereas in B the same path has length 6, and similarly in A the path from b_i to b_{i+1} has length 6, whereas in B it has length 2. (See Figure 5 for an example when i is even.)

With the addition of further characters (to be described in the next section), we will be able to enforce that A and B are in fact the only trees compatible with all those characters. In order to make the full set of characters incompatible, we will add two more characters Ω_A and

Ω_B , defined as follows:

$$\Omega_A = a_1 b_1 b_2 | \{a_2\} \cup X_{\geq 3}$$

$$\Omega_B = X_{\leq n-2} \cup \{b_{n-1}\} | a_{n-1} a_n b_n.$$

Observe that Ω_A is displayed by A but not by B , while Ω_B is displayed by B but not by A .

We will claim that every strict subset of this set of characters is compatible. In order to show this, we will prove that for each integer i between 2 and $n-2$, there is a tree displaying all characters except χ_i . The intuition here is as follows: χ_i enforces something about the local structure of a perfect phylogeny; in particular it is the only character in the constructed set requiring that the path from a_i to a_{i+1} and the path from b_i to b_{i+1} are vertex-disjoint. Removing χ_i allows us to consider X as being made of two parts: $X_{\leq i}$ and $X_{\geq i+1}$. We can construct a tree which is isomorphic to A when restricted to $X_{\leq i}$, and isomorphic to B when restricted to $X_{\geq i+1}$. Such a tree is denoted $A_i B$, and is defined below (Fig. 6).

Definition 2.3. For $2 \leq i \leq n-2$, the tree $A_i B$ on X is defined as follows: $A_i B$ has leaves $a_1, \dots, a_n, b_1, \dots, b_n$ and internal nodes $u_1, \dots, u_{i-1}, u_{i+1}, \dots, u_{n-1}, v_1, \dots, v_{i-1}, v_{i+1}, \dots, v_{n-1}, u_A, u_B$ (note that $A_i B$ does not have vertices u_i or v_i but instead has u_A and u_B). $A_i B$ contains a central path $a_1, u_1, u_2, \dots, u_{i-1}, u_A, u_B, u_{i+1}, \dots, u_{n-1}, b_n$. For each $j \in [n-1] \setminus \{i\}$, there is an edge $u_j v_j$. If i is even then u_A is adjacent to a_i and u_B is adjacent to b_{i+1} . On the other hand, if i is odd then u_A is adjacent to b_i and u_B is adjacent to a_{i+1} . For $j < i$, the vertex v_j is adjacent to b_j and b_{j+1} if j is odd, and adjacent to a_j and a_{j+1} if j is even. For $j > i$, v_j is adjacent to a_j and a_{j+1} if j is odd, and adjacent to b_j and b_{j+1} if j is even.

Observe that $A_i B$ does not display χ_i , but it does display Ω_A and χ_j for each $j < i$ (by a similar argument to how A displays those characters), and it does display Ω_B and χ_j for each $j > i$ (by a similar argument to how B displays those characters).

It follows that any strict subset of characters in the set is compatible (since any subset missing Ω_A is compatible with B , any subset missing Ω_B is compatible with A , and any subset missing χ_i for some $2 \leq i \leq n-2$ is compatible with $A_i B$).

In the next section, we make the concepts described above more formal. The main work will be to define additional characters (used to enforce that any tree compatible with all characters except Ω_B must have a similar structure to A), and then to prove formally that the observations outlined above (that the full set of characters is incompatible, and that it becomes compatible if any character is removed) hold when the new characters are considered.

Full Counterexample

We now describe the full set C of 8-state characters on X . C will be a set that is incompatible, but such that every strict subset of C is compatible. In what follows we assume that n is a positive even integer, and that $n \geq 6$

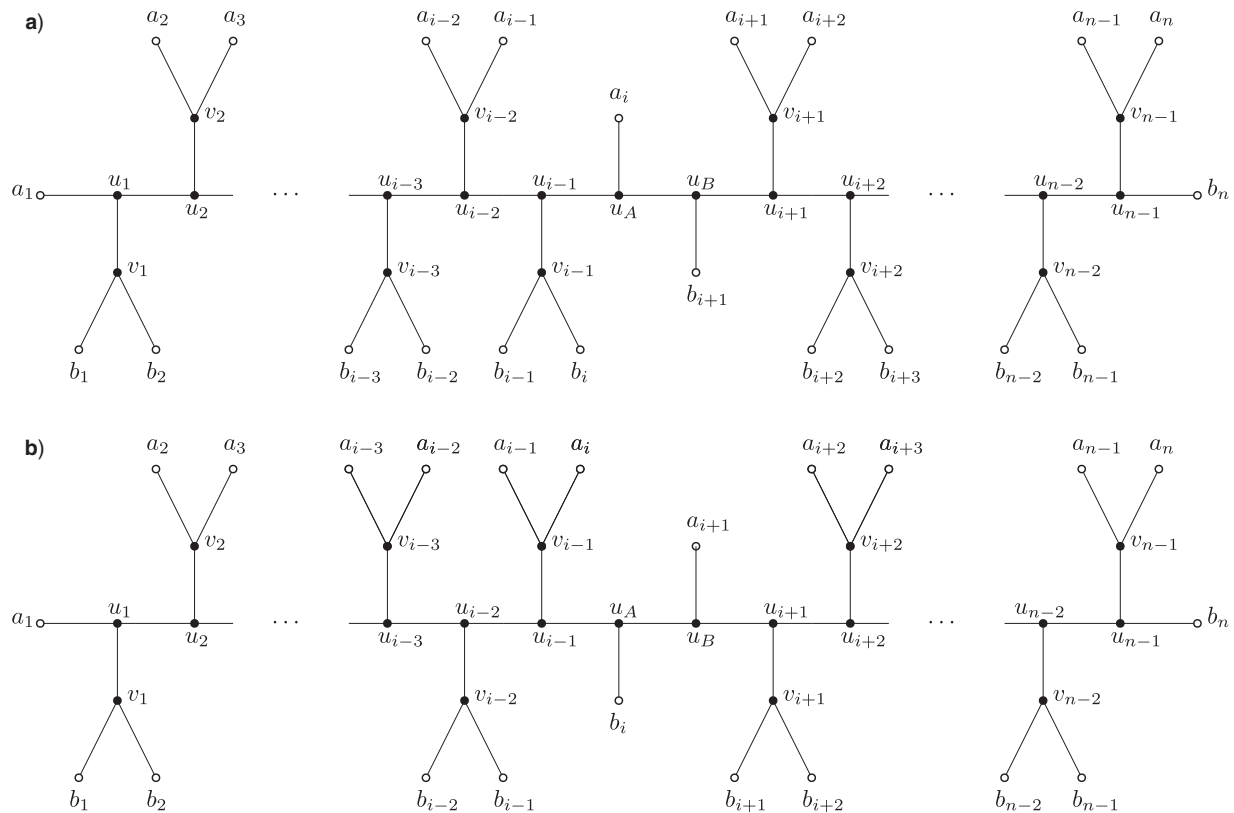


FIGURE 6. The lobster $A_i B$, for the cases when i is even and i is odd. a) Lobster $A_i B$ for i even. b) Lobster $A_i B$ for i odd.

(as we already gave a counterexample with $n=4$ in the Introduction).

(In order to avoid tedious repetition of definitions, for some values of j the characters below may be described as containing elements a_h or b_h for $h \notin [n]$. Such elements should be treated as nonexistent, as they are not in X . Note that certain states of some characters will be empty as a result.)

Definition 2.4. For each $2 \leq j \leq n-2$, define the following character on X :

$$\chi_j = X_{\leq j-2} | a_{j-1} | b_{j-1} | a_j a_{j+1} | b_j b_{j+1} | a_{j+2} | b_{j+2} | X_{\geq j+3}.$$

For $3 \leq j \leq n-1$, define the following characters:

$$\phi_j = \begin{cases} X_{\leq j-3} \cup b_{j-2} b_{j-1} | a_{j-2} | a_{j-1} | b_j | b_{j+1} | a_j a_{j+1} \\ \quad \cup X_{\geq j+2} \text{ if } j \text{ is even} \\ X_{\leq j-3} \cup a_{j-2} a_{j-1} | b_{j-2} | b_{j-1} | a_j | a_{j+1} | b_j b_{j+1} \\ \quad \cup X_{\geq j+2} \text{ if } j \text{ is odd.} \end{cases}$$

Finally define the two characters:

$$\Omega_A = a_1 b_1 b_2 | \{a_2\} \cup X_{\geq 3}$$

$$\Omega_B = X_{\leq n-2} \cup \{b_{n-1}\} | a_{n-1} a_n b_n.$$

Let C be the set of all $2n-4$ characters described above.

Observe that the construction of C is the same as in the section “Counterexample: Main Concepts” with the addition of characters ϕ_j for $3 \leq j \leq n-1$. We give a full

proof that C is incompatible and that every strict subset of C is compatible in the Appendix.

DISCUSSION

First note that we have only described a counterexample for the case that there are $2n$ taxa with $n \geq 4$ even. However, we can easily create examples for any number of taxa, that is at least 8, by “copying” taxa. More precisely, we can replace, say, a_1 by any number of taxa that all have the same state as a_1 in any characters.

Secondly, we describe how our counterexample can be seen as a counterexample with four different states and gaps. Considering Definition 2.4, observe that each of the characters has at most four states that contain more than one taxon. The remaining states contain just one taxon and can therefore be replaced by gaps (indicating that we do not know which state the taxon has in that character). This gives a counterexample with four different states and gaps. One can argue that the local obstruction conjecture is anyway unlikely to be true even for binary characters with gaps, because if it were true we would then be able to solve the quartet compatibility problem [see, e.g., Semple and Steel (2003)] in polynomial time, which would in turn imply that the complexity classes P and NP would coincide. However, one appealing feature of our counterexample is that it does not rely on any assumptions on complexity classes.

We conclude the paper by reiterating that, if we do not allow gaps, the local obstructions conjecture restricted to characters with 4, 5, 6, or 7 states is still open.

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APPENDIX

COUNTEREXAMPLE PROOF

In this section, we show that every strict subset of C is compatible and that C itself is incompatible. We begin

by proving formally that the lobster A displays every character in C except for Ω_B .

Compatibility of $C \setminus \{\Omega_B\}$.— Before continuing, we note that if a state S of some character χ consists of a single element of X , then for any tree T on X , the subtree $T[S]$ is automatically vertex-disjoint from $T[S']$ for any other state S' of χ . This is because $T[S]$ consists only of a single leaf in T , and as S and S' are disjoint, $T[S']$ does not contain that leaf. Therefore, when showing that a tree displays a particular character, we may focus on the states of size at least 2 in that character.

Lemma A.5. *Lobster A displays Ω_A .*

Proof. Observe that cutting the edge u_1u_2 separates A into two trees, one with leaves a_1, b_1, b_2 and one with leaf set $\{a_2\} \cup X_{\geq 3}$. It follows that the subtrees of AB spanning these two sets are vertex-disjoint, and so A displays Ω_A . ■

Lemma A.6. *For each $2 \leq j \leq n-2$, lobster A displays χ_j .*

Proof. The nonsingleton states of χ_j are $X_{\leq j-2}$, $\{a_j, a_{j+1}\}$, $\{b_j, b_{j+1}\}$, and $X_{\geq j+3}$. Cutting the edge $u_{j-2}u_{j-1}$ separates $X_{\leq j-2}$ from the other nonsingleton states. Similarly, cutting the edge $u_{j+1}u_{j+2}$ separates $X_{\geq j+3}$ from the other nonsingleton states. It remains to show that the trees $A[\{a_j, a_{j+1}\}]$, $A[\{b_j, b_{j+1}\}]$ are vertex disjoint. This can be seen by cutting the edge u_jv_j (as v_j is adjacent either to the leaves a_j and a_{j+1} , or to the leaves b_j and b_{j+1} , depending on whether j is even or odd). ■

Lemma A.7. *For each $3 \leq j \leq n-1$, lobster A displays ϕ_j .*

Proof. The character ϕ_j has two nonsingleton states. If j is even, then the nonsingleton states are $X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ and $\{a_j, a_{j+1}\} \cup X_{\geq j+2}$. Note that in this case b_{j-2} is adjacent to v_{j-3} , b_{j-1} is adjacent to v_{j-1} , and a_j and a_{j+1} are both adjacent to v_j . It follows that cutting the edge $u_{j-1}u_j$ (which separates v_j from v_{j-1} and v_{j-3}) will separate the two nonsingleton states from each other.

If j is odd, then the nonsingleton states are $X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ and $\{b_j, b_{j+1}\} \cup X_{\geq j+2}$. In this case, a_{j-2} is adjacent to v_{j-3} (unless $j=3$, in which case $a_{j-2}=a_1$ is adjacent to $u_1=u_{j-2}$), a_{j-1} is adjacent to v_{j-1} , and b_j and b_{j+1} are adjacent to v_j . Thus, we again have that cutting the edge $u_{j-1}u_j$ will separate the two nonsingleton states from each other. ■

The next lemma follows from Lemmas A.5, A.6, and A.7.

Lemma A.8. *Lobster A is compatible with $C \setminus \{\Omega_B\}$.*

Compatibility of $C \setminus \{\Omega_A\}$.—We next prove formally that the lobster B displays every character in C except for Ω_A . The proofs here are very similar to those for A .

Lemma A.9. *Lobster B displays Ω_B .*

Proof. Observe that cutting the edge $u_{n-2}u_{n-1}$ separates B into two trees, one with leaves a_{n-1}, a_n, b_n and one with leaf set $X_{\leq n-2} \cup \{b_{n-1}\}$. It follows that the subtrees of B spanning these two sets are vertex-disjoint, and so B displays Ω_B . ■

Lemma A.10. For each $2 \leq j \leq n-2$, lobster B displays χ_j .

Proof. The nonsingleton states of χ_j are $X_{\leq j-2}$, $\{a_j, a_{j+1}\}$, $\{b_j, b_{j+1}\}$, and $X_{\geq j+3}$. Cutting the edge $u_{j-2}u_{j-1}$ separates $X_{\leq j-2}$ from the other nonsingleton states. Similarly, cutting the edge $u_{j+1}u_{j+2}$ separates $X_{\geq j+3}$ from the other nonsingleton states. It remains to show that the trees $B[\{a_j, a_{j+1}\}]$, $B[\{b_j, b_{j+1}\}]$ are vertex disjoint. This can be seen by cutting the edge $u_j v_j$ (as v_j is adjacent either to the leaves a_j and a_{j+1} , or to the leaves b_j and b_{j+1} , depending on whether j is even or odd). ■

Lemma A.11. For each $3 \leq j \leq n-1$, lobster B displays ϕ_j .

Proof. The character ϕ_j has two nonsingleton states. If j is even, then the nonsingleton states are $X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ and $\{a_j, a_{j+1}\} \cup X_{\geq j+2}$. Note that in this case b_{j-2} and b_{j-1} are adjacent to v_{j-2} , a_j is adjacent to v_{j-1} , and a_{j+1} is adjacent to v_{j+1} . It follows that cutting the edge $u_{j-2}u_{j-1}$ (which separates v_{j-2} from v_{j-1} and v_{j+1}) will separate the two nonsingleton states from each other.

If j is odd, then the non-singleton states are $X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ and $\{b_j, b_{j+1}\} \cup X_{\geq j+2}$. In this case, a_{j-2} and a_{j-1} are adjacent to v_{j-2} , b_j is adjacent to v_{j-1} , and b_{j+1} is adjacent to v_{j+1} (unless $j = n-1$, in which case $b_{j+1} = b_n$ is adjacent to $u_{n-1} = u_j$). Thus, we again have that cutting the edge $u_{j-2}u_{j-1}$ will separate the two non-singleton states from each other. ■

The next lemma follows from Lemmas A.9, A.10, and A.11.

Lemma A.12. Lobster B is compatible with $C \setminus \{\Omega_A\}$.

Compatibility of $C \setminus \{\chi_i\}$ for each $2 \leq i \leq n-2$.—We now show that for any $2 \leq i \leq n-2$, the set $C \setminus \{\chi_i\}$ is compatible. Recall the definition of Lobster $A_i B$ (Definition 2.3 and Fig. 6). We will show that $A_i B$ displays every character in C except for χ_i .

Recall that $A_i B$ restricted to $X_{\leq i}$ is isomorphic to $A[X_{\leq i}]$, while $A_i B$ restricted to $X_{\geq i+1}$ is isomorphic to $B[X_{\geq i+1}]$.

Lemma A.13. For any $2 \leq i \leq n-2$, lobster $A_i B$ displays Ω_A and Ω_B .

Proof. To see that $A_i B$ displays Ω_A , observe that cutting the edge $u_1 u_2$ (or $u_1 u_A$ if $i = 2$) separates $A_i B$ into two trees, one with leaves a_1, b_1, b_2 and one with leaf set $\{a_2\} \cup X_{\geq 3}$. It follows that the subtrees of $A_i B$ spanning these two sets are vertex-disjoint, and so $A_i B$ displays Ω_A . Similarly, to see that $A_i B$ displays Ω_B , observe

that cutting the edge $u_{n-2}u_{n-1}$ (or $u_B u_{n-1}$ if $i = n-2$) separates $A_i B$ into two trees, with leaf sets $X_{\leq n-2} \cup \{b_{n-1}\}$ and $\{a_{n-1} a_n b_n\}$, respectively. ■

Lemma A.14. For any $2 \leq i, j \leq n-2$ such that $i \neq j$, lobster $A_i B$ displays χ_j .

Proof. The nonsingleton states of χ_j are $X_{\leq j-2}$, $\{a_j, a_{j+1}\}$, $\{b_j, b_{j+1}\}$, and $X_{\geq j+3}$. Cutting the edge $u_{j-2}u_{j-1}$ ($u_{j-2}u_A$ if $j = i+1$, $u_B u_{j-1}$ if $j = i+2$) separates $X_{\leq j-2}$ from the other nonsingleton states. Similarly, cutting the edge $u_{j+1}u_{j+2}$ ($u_{j+1}u_A$ if $j = i-2$, $u_B u_{j+2}$ if $j = i-1$) separates $X_{\geq j+3}$ from the other nonsingleton states. It remains to show that the trees $A_i B[\{a_j, a_{j+1}\}]$, $A_i B[\{b_j, b_{j+1}\}]$ are vertex disjoint. This can be seen by cutting the edge $u_i v_j$ (as v_j is adjacent either to the leaves a_i and a_{i+1} , or to the leaves b_i and b_{i+1}). ■

Lemma A.15. For any $2 \leq i \leq n-2$ and for each $3 \leq j \leq n-1$, lobster $A_i B$ displays ϕ_j .

Proof. The character ϕ_j has two nonsingleton states; these are either $X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ and $\{a_j, a_{j+1}\} \cup X_{\geq j+2}$ (if j is even) or $X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ and $\{b_j, b_{j+1}\} \cup X_{\geq j+2}$ (if j is odd).

We first consider the case when $j \notin \{i, i+1, i+2\}$. In this case, there are four possibilities to consider:

- If j is even and $j < i$, then cutting the edge $u_{j-1}u_j$ separates $X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ from $\{a_j, a_{j+1}\} \cup X_{\geq j+2}$.
- If j is even and $j > i+2$, then cutting the edge $u_{j-2}u_{j-1}$ separates $X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ from $\{a_j, a_{j+1}\} \cup X_{\geq j+2}$.
- If j is odd and $j < i$, then cutting the edge $u_{j-1}u_j$ separates $X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ from $\{b_j, b_{j+1}\} \cup X_{\geq j+2}$.
- If j is odd and $j > i+2$, then cutting the edge $u_{j-2}u_{j-1}$ separates $X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ from $\{b_j, b_{j+1}\} \cup X_{\geq j+2}$.

We now consider the case when $j \in \{i, i+1, i+2\}$, and suppose first that i is even.

- If $j = i$, then cutting $u_{i-1}u_A$ separates $X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ from $\{a_j, a_{j+1}\} \cup X_{\geq j+2}$.
- If $j = i+1$, then cutting the edge $u_A u_B$ separates $X_{\leq i-2} \cup \{a_{i-1}, a_i\} = X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ from $\{b_{i+1}, b_{i+2}\} \cup X_{\geq i+3} = \{b_j, b_{j+1}\} \cup X_{\geq j+2}$.
- If $j = i+2$, then cutting $u_B u_{i+1}$ separates $X_{\leq i-1} \cup \{b_i, b_{i+1}\} = X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ from $\{a_{i+2}, a_{i+3}\} \cup X_{\geq i+4} = \{a_j, a_{j+1}\} \cup X_{\geq j+2}$.

Finally, consider the case when $j \in \{i, i+1, i+2\}$, and i is odd.

- If $j=i$, then $u_{i-1}u_A$ separates $X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ from $\{b_j, b_{j+1}\} \cup X_{\geq j+2}$.
- If $j=i+1$, then cutting the edge $u_A u_B$ separates $X_{\leq i-2} \cup \{b_{i-1}, b_i\} = X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ from $\{a_{i+1}, a_{i+2}\} \cup X_{\geq j+3} = \{a_j, a_{j+1}\} \cup X_{\geq j+2}$.
- If $j=i+2$, then cutting the edge $u_B u_{i+1}$ separates $X_{\leq i-1} \cup \{a_i, a_{i+1}\} = X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ from $\{b_{i+2}, b_{i+3}\} \cup X_{\geq i+4} = \{b_j, b_{j+1}\} \cup X_{\geq j+2}$.

Thus in each case, we have that $A_i B$ displays ϕ_j . ■

The next lemma follows from Lemmas A.13, A.14, and A.15.

Lemma A.16. *For any $i \in [n-1]$, lobster $A_i B$ is compatible with $C \setminus \{\chi_i\}$.*

Compatibility of $C \setminus \{\phi_i\}$ for each $3 \leq i \leq n-1$.— We now show that for any $3 \leq i \leq n-1$, the set $C \setminus \{\phi_i\}$ is compatible. To this end, we need to define a new type of tree $A^i B$, which we will show is compatible with $C \setminus \{\phi_i\}$. This tree will be isomorphic to A when restricted to $X_{\leq i-1}$, and isomorphic to B when restricted to $X_{\geq i}$. This property is also true of $A_{i-1} B$, but the structure of $A^i B$ is slightly different (Fig. A.1).

Definition A.17. *For $2 \leq i \leq n-2$, the tree $A^i B$ on X is defined as follows: $A^i B$ has leaves $a_1, \dots, a_n, b_1, \dots, b_n$ and internal nodes $u_1, \dots, u_{i-2}, u_i, \dots, u_{n-1}, v_1, \dots, v_{i-2}, v_i, \dots, v_{n-1}, u_A, u_B$ (note that $A_i B$ does not have vertices u_{i-1} or v_{i-1} but instead has u_A and u_B). $A^i B$ contains a central path $a_1, u_1, u_2, \dots, u_{i-2}, u_A, u_B, u_i, \dots, u_{n-1}, b_n$. For each $j \in [n-1] \setminus \{i-1\}$, there is an edge $u_j v_j$. If i is even then u_A is adjacent to a_i and u_B is adjacent to b_{i-1} . On the other hand, if i is odd then u_A is adjacent to b_i and u_B is adjacent to a_{i-1} . For $j < i-1$, the vertex v_j is adjacent to b_j and b_{j+1} if j is odd, and adjacent to a_j and a_{j+1} if j is even. For $j > i-1$, v_j is adjacent to a_j and a_{j+1} if j is odd, and adjacent to b_j and b_{j+1} if j is even.*

Observe that for i even, $A^i B$ is equivalent to $A_{i-1} B$ with the leaves a_i and b_{i-1} swapped; for i odd, $A^i B$ is equivalent to $A_{i-1} B$ with the leaves a_{i-1} and b_i swapped. We are now ready to show that $A^i B$ displays every character in C except for ϕ_i .

Lemma A.18. *For any $3 \leq i \leq n-1$, lobster $A^i B$ displays Ω_A and Ω_B .*

Proof. To see that $A^i B$ displays Ω_A , observe that cutting the edge $u_1 u_2$ (or $u_1 u_A$ if $i=3$) separates $A_i B$ into two trees, one with leaves a_1, b_1, b_2 and one with leaf set $\{a_2\} \cup X_{\geq 3}$. It follows that the subtrees of $A^i B$ spanning these two sets are vertex-disjoint, and so $A^i B$ displays Ω_A . Similarly, to see that $A^i B$ displays Ω_B , observe that cutting the edge $u_{n-2} u_{n-1}$ (or $u_B u_{n-1}$ if $i=n-1$) separates $A^i B$ into two trees, with leaf sets $X_{\leq n-2} \cup \{b_{n-1}\}$ and $\{a_{n-1} a_n b_n\}$, respectively. ■

Lemma A.19. *For any $3 \leq i \leq n-1$ and for each $2 \leq j \leq n-2$, lobster $A^i B$ displays χ_j .*

Proof. The nonsingleton states of χ_j are $X_{\leq j-2}, \{a_j, a_{j+1}\}, \{b_j, b_{j+1}\}$ and $X_{\geq j+3}$. Cutting the edge $u_{j-2} u_{j-1}$ ($u_{j-2} u_A$ if $j=i$, $u_B u_{j-1}$ if $j=i+1$) separates $X_{\leq j-2}$ from the other nonsingleton states. Similarly, cutting the edge $u_{j+1} u_{j+2}$ ($u_{j+1} u_A$ if $j=i-3$, $u_B u_{j+2}$ if $j=i-2$) separates $X_{\geq j+3}$ from the other nonsingleton states.

It remains to show that the trees $A^i B[\{a_j a_{j+1}\}]$, $A^i B[\{b_j b_{j+1}\}]$ are vertex disjoint. For $j \neq i-1$, this can be seen by cutting the edge $u_j v_j$ (as v_j is adjacent either to the leaves a_i and a_{i+1} , or to the leaves b_i and b_{i+1}). For $j=i-1$, this can be seen by cutting the edge $u_A u_B$. ■

Lemma A.20. *For any $3 \leq i \leq n-1$ and for each $3 \leq j \leq n-1$ with $j \neq i$, lobster $A^i B$ displays ϕ_j .*

Proof. The character ϕ_j has two nonsingleton states; these are either $X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ and $\{a_j, a_{j+1}\} \cup X_{\geq j+2}$ (if j is even) or $X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ and $\{b_j, b_{j+1}\} \cup X_{\geq j+2}$ (if j is odd).

We first consider the case when $j \notin \{i-1, i, i+1\}$. In this case, there are four possibilities to consider:

- If j is even and $j < i-1$, then cutting the edge $u_{j-1} u_j$ separates $X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ from $\{a_j, a_{j+1}\} \cup X_{\geq j+2}$.
- If j is even and $j > i+1$, then cutting the edge $u_{j-2} u_{j-1}$ separates $X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ from $\{a_j, a_{j+1}\} \cup X_{\geq j+2}$.
- If j is odd and $j < i-1$, then cutting the edge $u_{j-1} u_j$ separates $X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ from $\{b_j, b_{j+1}\} \cup X_{\geq j+2}$.
- If j is odd and $j > i+1$, then cutting the edge $u_{j-2} u_{j-1}$ separates $X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ from $\{b_j, b_{j+1}\} \cup X_{\geq j+2}$.

We now consider the case when $j \in \{i-1, i+1\}$, and suppose first that i is even (and thus j is odd).

- If $j=i-1$, then cutting the edge $u_A u_B$ separates $X_{\leq i-4} \cup \{a_{i-3}, a_{i-2}\} = X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ from $\{b_{i-1}, b_i\} \cup X_{\geq j+1} = \{b_j, b_{j+1}\} \cup X_{\geq j+2}$.
- If $j=i+1$, then again cutting the edge $u_A u_B$ separates $X_{\leq i-2} \cup \{a_{i-1}, a_i\} = X_{\leq j-3} \cup \{a_{j-2}, a_{j-1}\}$ from $\{b_{i+1}, b_{i+2}\} \cup X_{\geq j+3} = \{b_j, b_{j+1}\} \cup X_{\geq j+2}$.

Finally, consider the case when $j \in \{i-1, i+1\}$, and i is odd (and thus j is even).

- If $j=i-1$, then cutting the edge $u_A u_B$ separates $X_{\leq i-4} \cup \{b_{i-3}, b_{i-2}\} = X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ from $\{a_{i-1}, a_i\} \cup X_{\geq j+1} = \{a_j, a_{j+1}\} \cup X_{\geq j+2}$.

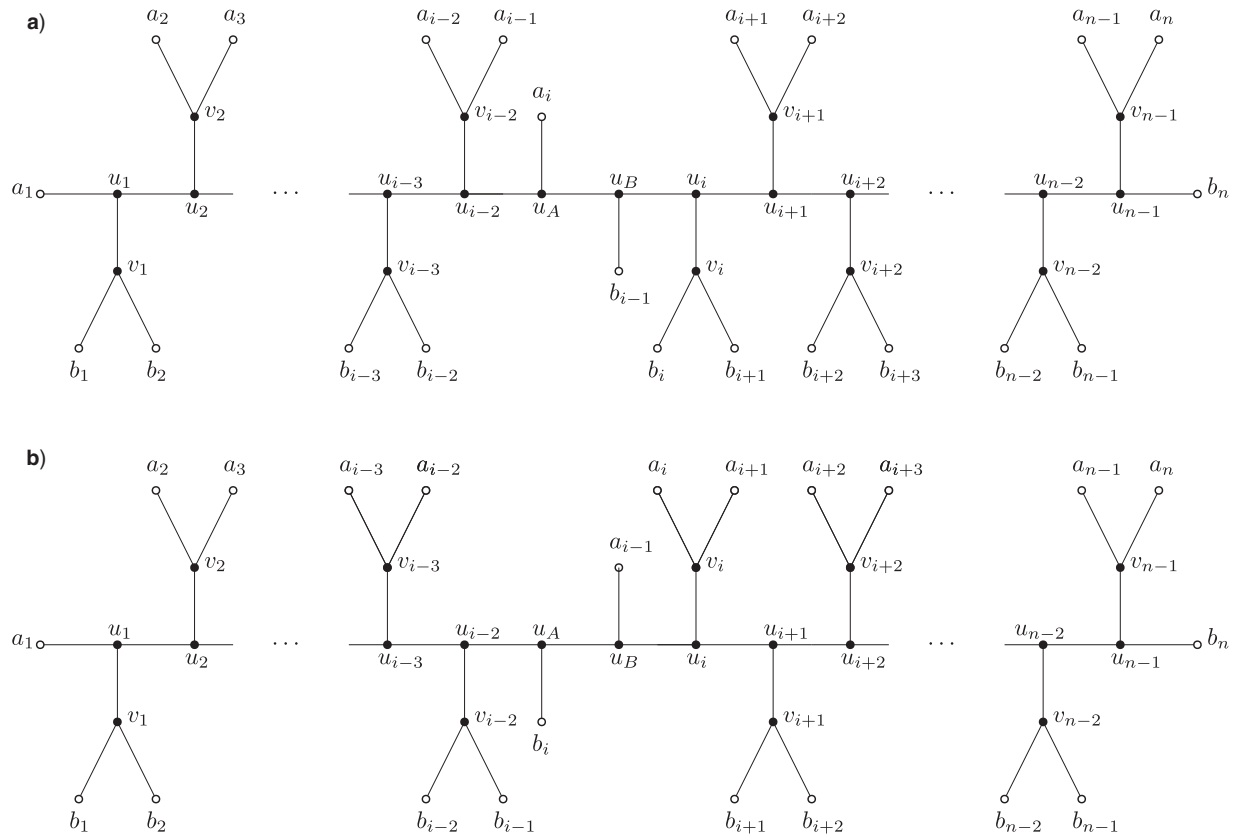


FIGURE A.1. The lobster $A^i B$, for the cases when i is even and i is odd. a) Lobster $A^i B$ for i even. b) Lobster $A^i B$ for i odd.

- If $j=i+1$, then again cutting the edge $u_A u_B$ separates $X_{\leq i-2} \cup \{b_{i-1}, b_i\} = X_{\leq j-3} \cup \{b_{j-2}, b_{j-1}\}$ from $\{a_{i+1}, a_{i+2}\} \cup X_{\geq j+3} = \{a_j, a_{j+1}\} \cup X_{\geq j+2}$.

Thus in each case, we have that $A^i B$ displays ϕ_j . ■

The next lemma follows from Lemmas A.18, A.19, and A.20.

Lemma A.21. For any $3 \leq i \leq n-1$, lobster $A^i B$ is compatible with $C \setminus \{\phi_i\}$.

Combining Lemmas A.8, A.12, A.16, and A.21, we have the following lemma.

Lemma A.22. For any $C' \subseteq C$ with $C' \neq C$, C' is compatible.

Incompatibility of C .— Let $S_1|S_2|S_3|S_4$ be a partition of $X' \subseteq X$. We say a tree T on X displays the quartet $S_1|S_2 \parallel S_3|S_4$ if there exist internal vertices u and v , such that deleting any edge on the path from u to v separates $S_1 \cup S_2$ from $S_3 \cup S_4$, and in addition deleting u separates S_1 from S_2 , and deleting v separates S_3 from S_4 (Fig. A.2). Note that this notion is a generalization of the usual notion of displaying a quartet, in which each of the sets $S_1, \dots, S_4$ consists of a single leaf.

Definition A.23. Given a tree T on X and a leaf $x \notin X' \subseteq X$, we say that x meets $T[X']$ at a vertex v if v is a vertex in $T[X']$

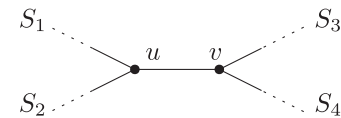


FIGURE A.2. A tree displaying the quartet $S_1|S_2 \parallel S_3|S_4$.

and there is a path from v to x in T that is edge-disjoint from $T[X']$. We say x meets $T[X']$ between u and v if u, v are two vertices in $T[X']$ and x meets $T[X']$ at v' for some vertex v' on the path from u to v .

To prove that C is incompatible, we will prove that any tree compatible with $C \setminus \{\Omega_B\}$ must display certain quartets. In particular, it must display a quartet that cannot be displayed by a tree displaying Ω_B . This implies that there is no tree compatible with C . The next lemma gives the base case, and the following two lemmas give the inductive step of this proof.

Lemma A.24. If T is a tree on X that displays Ω_A , χ_2 , ϕ_3 , χ_3 , and χ_4 , then T displays $X_{\leq 2} \cup \{a_3\} | a_4 \parallel b_3 | b_4$.

Proof. Let u_1 be the vertex in T at which a_2 joins the subtree $T[\{a_1, b_1, b_2\}]$. Let u_2 be the vertex at which b_3 joins $T[\{a_1, b_1, a_2, b_2\}]$. Observe that since T displays Ω_A , u_2 must be between u_1 and a_2 . Indeed, if this is not the case then the path from a_2 to b_3 must pass through u_1 , which is also part of the subtree $T[\{a_1, b_1, b_2\}]$,

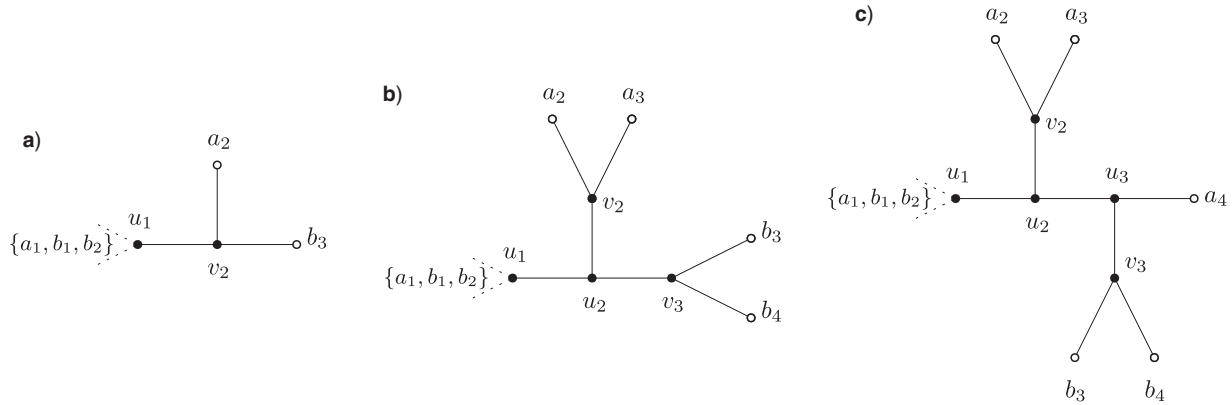


FIGURE A.3. Illustration of the Proof of Lemma A.24. Trees are drawn with their degree-2 vertices suppressed. a) $T[\{a_1, b_1, a_2, b_2, b_3\}]$. b) $T[X_{\leq 3} \cup \{b_4\}]$. c) $T[X_{\leq 4}]$.

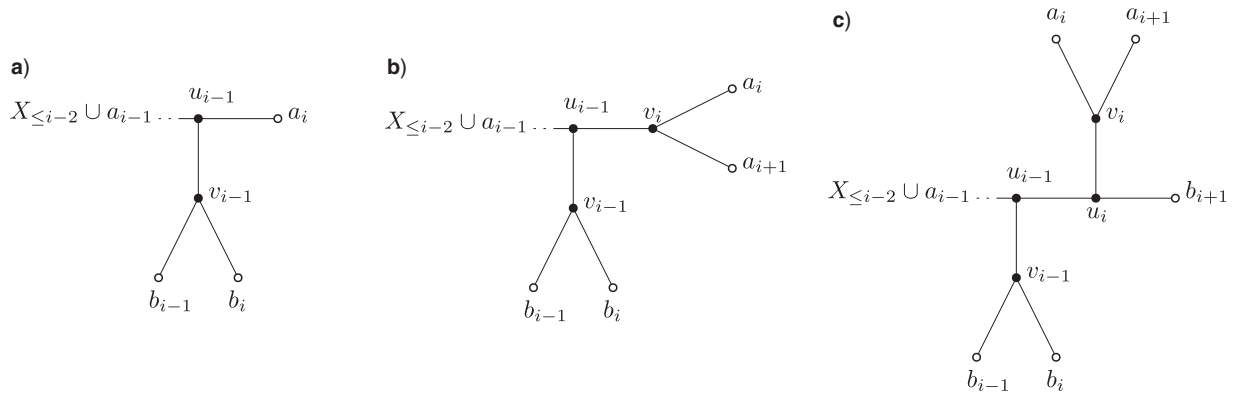


FIGURE A.4. Illustration of the Proof of Lemma A.25. Trees are drawn with their degree-2 vertices suppressed. a) $T[X_{\leq i}]$. b) $T[X_{\leq i} \cup \{a_{i+1}\}]$. c) $T[X_{\leq i+1}]$.

contradicting the fact that $T[\{a_1, b_1, b_2\}]$ and $T[\{a_2\} \cup X_{\geq 3}]$ are vertex-disjoint (Fig. A.3a).

Now let v_2 be the vertex at which a_3 joins $T[\{a_1, b_1, a_2, b_2, b_3\}]$. As T displays χ_2 , v_2 must be between u_2 and a_2 , since otherwise the subtrees $T[\{a_2, a_3\}]$ and $T[\{b_2, b_3\}]$ both contain u_2 . Next let v_3 be the vertex at which b_4 joins $T[X_{\leq 3}]$. As T displays ϕ_3 , v_3 must be between u_2 and b_3 , since otherwise the subtrees $T[\{a_1, a_2\}]$ and $T[\{b_3, b_4\} \cup X_{\geq 5}]$ both contain u_2 (Fig. A.3b).

Now in order to show that T displays $X_{\leq 2} \cup \{a_3\} | a_4 \parallel b_3 | b_4$, it remains to determine the relative position of a_4 . In order to do this, we need to consider a_5 , although we will not determine the position of a_5 itself. As T displays ϕ_3 , the subtrees $T[\{a_1, a_2\}]$ and $T[\{b_3, b_4\} \cup X_{\geq 5}]$ are vertex-disjoint, and in particular the path from b_4 to a_5 must not contain u_2 . Also as T displays χ_4 (and thus $T[X_{\leq 2}]$ and $T[\{a_4, a_5\}]$ are vertex-disjoint), the path from a_4 to a_5 does not contain u_2 . As neither of the paths $T[\{b_4, a_5\}]$ and $T[\{a_4, a_5\}]$ contain u_2 , it follows that the path $T[\{a_4, b_4\}]$ does not contain u_2 either (note that the path $T[\{a_4, b_4\}]$ is a subgraph of the union of $T[\{b_4, a_5\}]$ and $T[\{a_4, a_5\}]$). This implies that a_4 meets $T[X_{\leq 3} \cup \{b_4\}]$ in one of three places: either between v_3 and b_4 , between v_3 and b_3 , or

between u_2 and v_3 . However, as T displays χ_3 (and thus $T[\{a_3, a_4\}]$ and $T[\{b_3, b_4\}]$ are vertex-disjoint), the path $T[\{a_3, a_4\}]$ cannot contain v_3 . This implies that a_4 must meet $T[X_{\leq 3} \cup \{b_4\}]$ between u_2 and v_3 . Let u_3 be the vertex at which a_4 meets $T[X_{\leq 3} \cup \{b_4\}]$ (Fig. A.3c).

Now observe that deleting the edge $u_3 v_3$ separates $X_{\leq 2} \cup \{a_3, a_4\}$ from $\{b_3, b_4\}$, that deleting u_3 separates $X_{\leq 2} \cup \{a_3\}$ from a_4 , and that deleting v_3 separates b_3 from b_4 . Thus, T displays $X_{\leq 2} \cup \{a_3\} | a_4 \parallel b_3 | b_4$. ■

Lemma A.25. Let $i \in [n-2]$ such that $i \geq 4$ and i is even. If T is a tree on X such that T displays $X_{\leq i-2} \cup \{a_{i-1}\} | a_i \parallel b_{i-1} | b_i$ and T displays χ_{i-2}, χ_i and ϕ_i , then T displays $X_{\leq i-1} \cup \{b_i\} | b_{i+1} \parallel a_i | a_{i+1}$.

Proof. Let u_{i-1}, v_{i-1} be internal vertices in T such that deleting any edge on the path from u_{i-1} to v_{i-1} separates $X_{\leq i-2} \cup \{a_{i-1}, a_i\}$ from $\{b_{i-1}, b_i\}$, deleting u_{i-1} separates $X_{\leq i-2} \cup \{a_{i-1}\}$ from $\{a_i\}$, and deleting v_{i-1} separates b_{i-1} from b_i (Fig. A.4a).

As T displays ϕ_i , it must be that a_{i+1} meets $T[X_{\leq i}]$ between u_{i-1} and a_i , as otherwise the subtrees $T[X_{\leq i-3} \cup \{b_{i-2}, b_{i-1}\}]$ and $T[\{a_i, a_{i+1}\} \cup X_{i \geq 2}]$ are not vertex-disjoint (in particular, the paths $T[\{b_{i-2}, b_{i-1}\}]$ and $T[\{a_i, a_{i+1}\}]$

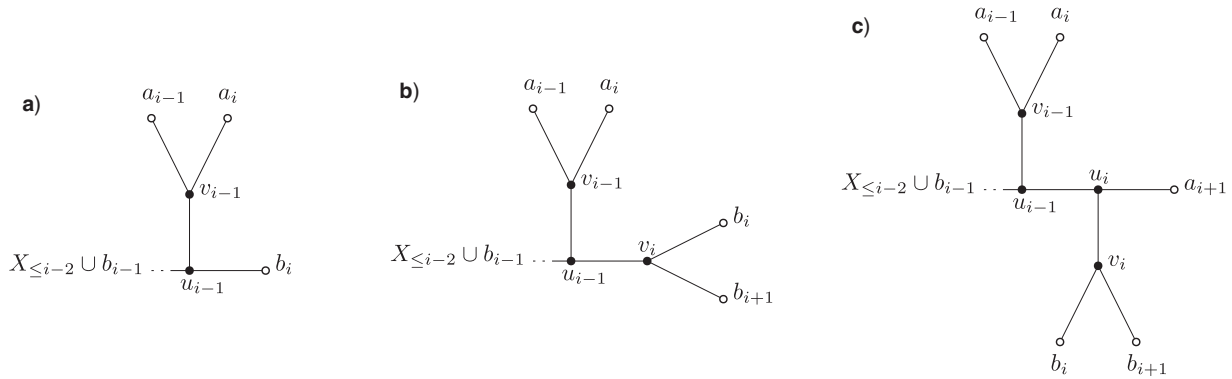


FIGURE A.5. Illustration of the Proof of Lemma A.26. Trees are drawn with their degree-2 vertices suppressed. a) $T[X_{\leq i}]$. b) $T[X_{\leq i} \cup \{b_{i+1}\}]$. c) $T[X_{\leq i+1}]$.

both contain u_{i-1}). Let v_i be the vertex at which a_{i+1} meets $T[X_{\leq i}]$ (Fig. A.4b).

Now consider b_{i+1} . As T displays χ_{i-2} , the paths $T[\{b_{i-2}, b_{i-1}\}]$ and $T[\{a_{i+1}, b_{i+1}\}]$ are vertex-disjoint. It follows that $T[\{a_{i+1}, b_{i+1}\}]$ cannot contain u_{i-1} , and so b_{i+1} joins $T[X_{\leq i} \cup \{a_{i+1}\}]$ at one of three places: either between v_i and a_{i+1} , between v_i and a_i , or between u_{i-1} and v_i . Furthermore as T displays χ_i , the paths $T[\{a_i, a_{i+1}\}]$ and $T[\{b_i, b_{i+1}\}]$ are vertex disjoint, and in particular $T[\{b_i, b_{i+1}\}]$ cannot contain v_i . It follows that b_{i+1} joins $T[X_{\leq i} \cup \{a_{i+1}\}]$ between u_{i-1} and v_i . Let u_i be the vertex at which b_{i+1} joins $T[X_{\leq i} \cup \{a_{i+1}\}]$ (Fig. A.4c).

Now observe that deleting $u_i v_i$ separates $X_{\leq i-1} \cup \{b_i, b_{i+1}\}$ from $\{a_i, a_{i+1}\}$, that deleting u_i separates $X_{\leq i-1} \cup \{b_i\}$ from b_{i+1} , and that deleting v_i separates a_i from a_{i+1} . Thus, T displays $X_{\leq i-1} \cup \{b_i\} | b_{i+1} \parallel a_i | a_{i+1}$. ■

Lemma A.26. Let $i \in [n-2]$ such that $i > 4$ and i is odd. If T is a tree on X such that T displays $X_{\leq i-2} \cup \{b_{i-1}\} | b_i \parallel a_{i-1} | a_i$ and T displays χ_{i-2} , χ_i and ϕ_i , then T displays $X_{\leq i-1} \cup \{a_i\} | a_{i+1} \parallel b_i | b_{i+1}$.

Proof. The proof is symmetric to that of Lemma A.25. Let u_{i-1}, v_{i-1} be internal vertices in T such that deleting any edge on the path from u_{i-1} to v_{i-1} separates $X_{\leq i-2} \cup \{b_{i-1}, b_i\}$ from $\{a_{i-1}, a_i\}$, deleting u_{i-1} separates $X_{\leq i-2} \cup \{b_{i-1}\}$ from $\{b_i\}$, and deleting v_{i-1} separates a_{i-1} from a_i (Fig. A.5a).

As T displays ϕ_i , it must be that b_{i+1} meets $T[X_{\leq i}]$ between u_{i-1} and b_i , as otherwise the subtrees $T[X_{\leq i-3} \cup \{a_{i-2}, a_{i-1}\}]$ and $T[\{b_i, b_{i+1}\} \cup X_{i \geq 2}]$ are not edge-disjoint (in particular, the paths $T[\{a_{i-2}, a_{i-1}\}]$ and $T[\{b_i, b_{i+1}\}]$ both contain u_{i-1}). Let v_i be the vertex at which b_{i+1} meets $T[X_{\leq i}]$ (Fig. A.5b).

Now consider a_{i+1} . As T displays χ_{i-2} , the paths $T[\{a_{i-2}, a_{i-1}\}]$ and $T[\{a_{i+1}, b_{i+1}\}]$ are vertex-disjoint. It follows that a_{i+1} joins $T[X_{\leq i} \cup \{b_{i+1}\}]$ at one of three places: either between v_i and b_{i+1} , between v_i and b_i , or between u_{i-1} and v_i . Furthermore as T displays χ_i , the paths $T[\{b_i, b_{i+1}\}]$ and $T[\{a_i, a_{i+1}\}]$ are vertex disjoint, and in particular $T[\{a_i, a_{i+1}\}]$ cannot contain v_i . It follows that

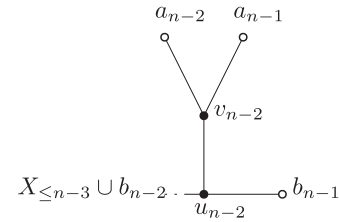


FIGURE A.6. Illustration of the Proof of Lemma A.28.

a_{i+1} joins $T[X_{\leq i} \cup \{b_{i+1}\}]$ between u_{i-1} and v_i . Let u_i be the vertex at which a_{i+1} joins $T[X_{\leq i} \cup \{b_{i+1}\}]$ (Fig. A.5c).

Now observe that deleting $u_i v_i$ separates $X_{\leq i-1} \cup \{a_i, a_{i+1}\}$ from $\{b_i, b_{i+1}\}$, that deleting u_i separates $X_{\leq i-1} \cup \{a_i\}$ from a_{i+1} , and that deleting v_i separates b_i from b_{i+1} . Thus T displays $X_{\leq i-1} \cup \{a_i\} | a_{i+1} \parallel b_i | b_{i+1}$. ■

Lemma A.27. For any $3 \leq i \leq n-2$, if a tree T is compatible with Ω_A and with χ_j for all $2 \leq j \leq i$ and ϕ_j for all $3 \leq j \leq i$, then T displays $X_{\leq i-1} \cup \{b_i\} | b_{i+1} \parallel a_i | a_{i+1}$ if i is even, and T displays $X_{\leq i-1} \cup \{a_i\} | a_{i+1} \parallel b_i | b_{i+1}$ if i is odd. In particular, if T is compatible with $C \setminus \{\phi_{n-1}, \Omega_B\}$ then T displays $X_{\leq n-3} \cup \{b_{n-2}\} | b_{n-1} \parallel a_{n-2} | a_{n-1}$.

Proof. The claim follows by induction on i . For $i=3$, the claim follows from Lemma A.24. For larger values of i , if i is even then the claim follows from Lemma A.25 and the fact that the claim holds for $i-1$. If i is odd, the claim follows from Lemma A.26 and the fact that the claim holds for $i-1$. ■

Lemma A.28. If T is a tree on X such that T displays $X_{\leq n-3} \cup \{b_{n-2}\} | b_{n-1} \parallel a_{n-2} | a_{n-1}$, then either T does not display ϕ_{n-1} or T does not display Ω_B .

Proof. Let u_{n-2}, v_{n-2} be internal vertices in T such that deleting any edge on the path from u_{n-2} to v_{n-2} separates $X_{\leq n-3} \cup \{b_{n-2}, b_{n-1}\}$ from $\{a_{n-2}, a_{n-1}\}$, deleting u_{n-2} separates $X_{\leq n-3} \cup \{b_{n-2}\}$ from $\{b_{n-1}\}$, and deleting v_{n-2} separates a_{n-2} from a_{n-1} (Fig. A.6).

If T displays ϕ_{n-1} , then the subtrees $T[X_{\leq n-4} \cup \{a_{n-3}, a_{n-2}\}]$ and $T[\{b_{n-1}, b_n\}]$ are vertex-disjoint, and in particular $T[\{a_{n-1}, a_n, b_n\}]$ are the path $T[\{b_{n-1}, b_n\}]$ does not contain u_{n-2} . It follows that b_n joins $T[X_{\leq n-1}]$ between u_{n-2} and b_{n-1} . On the other hand, if T displays Ω_B , then the subtrees $T[X_{\leq n-2} \cup \{b_{n-1}\}]$ and vertex-disjoint, and in particular the path $T[\{a_{n-1}, b_n\}]$ does not contain v_{n-2} . It follows that b_n joins $T[X_{\leq n-1}]$ between v_{n-2} and a_{n-1} . As b_n cannot join $T[X_{\leq n-1}]$ in two different locations, T either does not display ϕ_{n-1} or does not display Ω_B . ■

Lemma A.29. *C is not compatible.*

Proof. This follows immediately from Lemmas A.27 and A.28. ■

By choosing n such that $2n-4 > t$, Lemmas A.22 and A.29 give us the following theorem, which shows that Conjecture 1.1 is false.

Theorem A.30. *For any integer t , there exists a set C of 8-state characters such that C is incompatible but every subset of at most t characters in C is compatible.*