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On the Ancestral Compatibility of Two Phylogenetic Trees with Nested Taxa

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Abstract Compatibility of phylogenetic trees is the most important concept underlying widely-used methods for assessing the agreement of different phylogenetic trees with overlapping taxa and combining them into common supertrees to reveal the tree of life. The notion of ancestral compatibility of phylogenetic trees with nested taxa was introduced in [3, 10]. In this paper we analyze in detail the meaning of this compatibility from the points of view of the local structure of the trees, of the existence of embeddings into a common supertree, and of the joint properties of their cluster representations. Our analysis leads to a very simple polynomial-time algorithm for testing this compatibility, which we have implemented and is freely available for download from the BioPerl collection of Perl modules for computational biology.

Keywords Phylogenetic tree · Compatibility · Topological embedding

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1 Introduction

A rooted phylogenetic tree can be seen as a static description of the evolutive history of a family of contemporary species: these species are located at the leaves of the tree, and their common ancestors are organized as the inner nodes of the tree. These interior nodes represent taxa at a higher level of aggregation or nesting than that of their descendents, ranging for instance from families over genera to species. Phylogenetic trees with nested taxa have thus all leaves as well as some interior nodes labeled, and they need not be fully-resolved trees and may have unresolved polytomies, that is, they need not be binary trees.

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Often one has to deal with two or more phylogenetic trees with overlapping taxa, probably obtained through different techniques by the same or different researchers. The problem of combining these trees into a single supertree containing the evolutive information of all the given trees has recently received much attention, and it has been identified as a promising approach to the reconstruction of the tree of life [2]. This information corresponds to evolutive precedence, and hence it is kept when every arc in each of the trees becomes a path in the supertree.

It is well known that it is not always possible to combine phylogenetic trees into a single supertree: there are *incompatible* phylogenetic trees that do not admit their simultaneous inclusion into a common supertree. Compatibility for leaf-labeled phylogenetic trees was first studied in [15]. Incompatible phylogenetic trees can still be partially combined into a maximum agreement subtree [14]. Compatible phylogenetic trees, on the other hand, can be combined into a common supertree, two of the most widely used methods being matrix representation with parsimony [1,8] and mincut [5,12] and it is clear that, because of Occam's razor, one is interested in obtaining not only a common supertree of the given phylogenetic trees, but the smallest possible one. The relationship between the largest common subtree and the smallest common supertree of two leaf-labeled phylogenetic trees was established in [9] by means of simple constructions, which allow one to obtain the largest common subtree from the smallest common supertree, and vice versa.

The study of the compatibility of phylogenetic trees with nested taxa, also known as *semi-labeled trees*, was asked for in [6]. Polynomial-time algorithms were proposed in [3,10] for testing a weak form of compatibility, called *ancestral compatibility*, and a stronger form called *perfect compatibility*. Roughly, two or more semi-labeled trees are ancestrally compatible if they can be refined into a common supertree, and they are perfectly compatible if there exists a common supertree whose topological restriction to the taxa in each tree is isomorphic to that tree.

In this paper, we are concerned with the notion of ancestral compatibility of semi-labeled trees. In particular, we establish the equivalence between this notion and the absence of certain 'incompatible' pairs and triples of labels in the trees under comparison. We also prove the equivalence between ancestral compatibility and a certain property of the cluster representations of the trees. These equivalences lead to a new polynomial-time algorithm for testing ancestral compatibility of semi-labeled trees, which we have implemented and is freely available for download from the BioPerl collection of Perl modules for computational biology [13].

The rest of the paper is organized as follows. Basic notions and notation are recalled in Section 2. A notion of local compatibility as the absence of incompatible pairs and triples of labels is introduced in Section 3, together with some basic results about a relaxed notion of semi-labeled trees. Weak topological embeddings, and the notion of ancestral compatibility that derives from them, are studied in Section 4. In Section 5, the equivalence between local compatibility in the sense of Section 3 and ancestral compatibility in the sense of Section 4 is established, as well as a characterization in terms of cluster representations. The BioPerl implementation of the algorithm for testing compatibility of two semi-labeled trees is described in Section 6. Finally, some conclusions and further work are outlined in Section 7.

2 Preliminaries

Throughout this paper, by a *tree* we mean a *rooted tree*, that is, a directed finite graph $T = (V,E)$ with V either empty or containing a distinguished node $r \in V$, called the *root*, such that for every other node $v \in V$ there exists one, and only one, path from the root r to v. Recall that every node in a tree has in-degree 1, except the root, which has in-degree 0.

Henceforth, and unless otherwise stated, given a tree T we shall denote its set of nodes by $V(T)$ and its set of arcs by $E(T)$. The *children* of a node v in a tree T are those nodes w such that $(v,w) \in E(T)$. The nodes without children are the *leaves* of the tree, and we shall call *elementary* the nodes with only one child.

Given a path $(v_0, v_1, \ldots, v_k)$ in a tree T, its *origin* is v_0, its *end* is v_k, and its *intermediate nodes* are $v_1, \ldots, v_{k-1}$. Such a path is *non-trivial* when $k \geqslant 1$. We shall represent a path *from v to w*, that is, a path with origin v and end w, by $v \rightsquigarrow w$. When there exists a path $v \rightsquigarrow w$, we say that w is a *descendant* of v and also that v is an *ancestor* of w. Every node is both an ancestor and a descendant of itself, through a trivial path.

Two non-trivial paths $(a, v_1, \ldots, v_k)$ and $(a, w_1, \ldots, w_\ell)$ in a tree T are said to *diverge* when the only node they have in common is their origin a. Notice that, by the uniqueness of paths in trees, it is equivalent to the condition $v_1 \neq w_1$. For every two nodes v, w of a tree that are not connected by a path, there exists one, and only one, common ancestor a of v and w such that there exist divergent paths from a to v and to w. We shall call it the *most recent common ancestor* of v and w. When there is a path $v \rightsquigarrow w$, we say that v is the *most recent common ancestor* of v and w.

3 $\mathscr{A}$-trees

Let $\mathscr{A}$ be throughout this paper a fixed set of labels. In practice, we shall use the first capital letters, $A, B, C \ldots$, as labels.

Definition 1 A *semi-labeled tree over $\mathscr{A}$* is a tree with some of its nodes, including all its leaves and all its elementary nodes, injectively labeled in the set $\mathscr{A}$.

To simplify several proofs, we shall usually allow the existence of unlabeled elementary nodes. This motivates the following definition.

Definition 2 An *$\mathscr{A}$-tree* is a tree with some of its nodes, including all its leaves, injectively labeled in the set $\mathscr{A}$.

We shall always use the same name to denote an $\mathscr{A}$-tree and the (unlabeled) tree that *supports* it. Furthermore, for every $\mathscr{A}$-tree T, we shall use henceforth the following notations:

- $\mathscr{L}(T)$ and $\mathscr{A}(T)$ will denote, respectively, the set of the labels of its leaves and the set of the labels of all its nodes.

– For every $v \in V(T)$, we shall denote by $\mathscr{A}_T(v)$ the set of the labels of all its descendants, including itself, and we shall call it, following [11], the *cluster* of v in T; if T is irrelevant or clearly determined by the context, we shall usually write $\mathscr{A}(v)$ instead of $\mathscr{A}_T(v)$. Notice that if there exists a path $w \rightsquigarrow v$, then $\mathscr{A}(v) \subseteq \mathscr{A}(w)$.
– We shall set
$$\mathscr{C}_{\mathscr{A}}(T) = \{\mathscr{A}_T(v) \mid v \in V(T)\}.$$
Notice that $\emptyset \notin \mathscr{C}_{\mathscr{A}}(T)$ unless T is empty. If T is a semi-labeled tree over $\mathscr{A}$, then $\mathscr{C}_{\mathscr{A}}(T)$ coincides with the cluster representation [11] of T, up to the trivial cluster for the root of T. Consequently, even for $\mathscr{A}$-trees, we shall call $\mathscr{C}_{\mathscr{A}}(T)$ the *cluster representation* of T.
– For every $X \subseteq \mathscr{A}(T)$, we shall denote by $v_{T,X}$ the most recent common ancestor of the nodes of T with labels in X; when T is irrelevant or clearly determined by the context, we shall usually write v_X instead of $v_{T,X}$. Moreover, when X is given by the list of its members between brackets, we shall usually omit these brackets in the subscript. So, in particular, for every $A \in \mathscr{A}(T)$, we shall denote the node of T labeled A by $v_{T,A}$ or simply v_A.
Notice that $\mathscr{A}(v_{T,X}) = X$ if and only if $X \in \mathscr{C}_{\mathscr{A}}(T)$.

We shall often use the following easy results, usually without any further mention.

Lemma 1 *Let T be an $\mathscr{A}$-tree, and let $x, y \in V(T)$. If $\mathscr{A}(x) \cap \mathscr{A}(y) \neq \emptyset$, then x is a descendant of y or y is a descendant of x.*

Proof Let $A \in \mathscr{A}(x) \cap \mathscr{A}(y)$, so that there exist paths $x \rightsquigarrow v_A$ and $y \rightsquigarrow v_A$, and let r be the root of T. Then, both x and y appear in the path $r \rightsquigarrow v_A$. This entails that either x appears in the path $y \rightsquigarrow v_A$ or y appears in the path $x \rightsquigarrow v_A$, meaning that there is either a path from y to x or from x to y. □

Corollary 1 *Let T be an $\mathscr{A}$-tree, and let $x, y \in V(T)$. If $\mathscr{A}(x) \subsetneq \mathscr{A}(y)$, then there is a non-trivial path $y \rightsquigarrow x$.*

Proof By the previous lemma, if $\mathscr{A}(x) \subsetneq \mathscr{A}(y)$, then either x is a descendant of y or y is a descendant of x. But, being the inclusion strict, y cannot be a descendant of x. □

Corollary 2 *Let T be an $\mathscr{A}$-tree, and let $x, y \in V(T)$ be two different nodes. If $\mathscr{A}(x) = \mathscr{A}(y)$, then there is a path $x \rightsquigarrow y$ or a path $y \rightsquigarrow x$, such that its origin and all its intermediate nodes are unlabeled and elementary.*

Proof By Lemma 1, if $\mathscr{A}(x) = \mathscr{A}(y)$, there is either a path $x \rightsquigarrow y$ or a path $y \rightsquigarrow x$. If the origin or some intermediate node in this path is labeled or if any one of these nodes has more children that those appearing in this path, then the set of labels will decrease from this node to its child in the path, and *a fortiori* from the origin to the end of the path. □

In particular, in a semi-labeled tree over $\mathscr{A}$, which does not contain any unlabeled elementary node, $\mathscr{A}(x) = \mathscr{A}(y)$ if and only if $x = y$, and $\mathscr{A}(x) \subsetneq \mathscr{A}(y)$ if and only if there exists a non-trivial path $y \rightsquigarrow x$. This entails that the cluster representation $\mathscr{C}_{\mathscr{A}}(T)$ of a semi-labeled tree T over $\mathscr{A}$ determines T up to isomorphism [11, Theorem 3.5.2].

Definition 3 The *restriction* $T|\mathscr{X}$ of an $\mathscr{A}$-tree T to a set $\mathscr{X} \subseteq \mathscr{A}$ of labels is the subtree of T supported on the set of nodes

$$\begin{aligned} V(T|\mathscr{X}) &= \{v \in V(T) \mid \text{there exists a path } v \rightsquigarrow v_A \text{ for some } A \in \mathscr{X}\} \\ &= \{v \in V(T) \mid \mathscr{A}(v) \cap \mathscr{X} \neq \emptyset\}, \end{aligned}$$

and where a node is labeled when it is labeled in T and this label belongs to $\mathscr{X}$, in which case its label in $T|\mathscr{X}$ is the same as in T.

If $\mathscr{X} \cap \mathscr{A}(T) = \emptyset$, then $T|\mathscr{X}$ is the empty $\mathscr{A}$-tree, while if $\mathscr{X} \cap \mathscr{A}(T) \neq \emptyset$, then $T|\mathscr{X}$ has the same root as T and leaves the nodes of T with labels in $\mathscr{X}$ that do not have any descendant with label in $\mathscr{X}$.

Now we introduce the notion of *locally compatible $\mathscr{A}$-trees* as the absence of *incompatible pairs and triples* of labels.

Definition 4 Two $\mathscr{A}$-trees T_1 and T_2 are *locally compatible* when they satisfy the following two conditions:

(C1) For every two labels $A, B \in \mathscr{A}(T_1) \cap \mathscr{A}(T_2)$, there is a path $v_A \rightsquigarrow v_B$ in T_1 if and only if there is a path $v_A \rightsquigarrow v_B$ in T_2.
(C2) For every three labels $A, B, C \in \mathscr{A}(T_1) \cap \mathscr{A}(T_2)$, if there exists a non-trivial path $v_{B,C} \rightsquigarrow v_{A,B}$ in T_1, then there does not exist any non-trivial path $v_{A,B} \rightsquigarrow v_{B,C}$ in T_2.

Any pair of labels A, B violating condition (C1) and any triple of labels A, B, C violating condition (C2) in a pair of trees T_1 and T_2 are said to be *incompatible*.

Two $\mathscr{A}$-trees T_1 and T_2 are *locally incompatible* when they are not locally compatible, that is, when they contain an incompatible pair or triple of labels.

So, if T_1 and T_2 represent phylogenetic trees with nested taxa, an incompatible pair of labels in T_1 and T_2 corresponds to a pair of taxa whose evolutive precedence is different in both trees, while an incompatible triple of labels in T_1 and T_2 corresponds to three taxa whose evolutive divergence is different in both trees.

Example 1 Let T_1, T_2 be two locally compatible $\mathscr{A}$-trees, and let $A, B, C \in \mathscr{A}(T_1) \cap \mathscr{A}(T_2)$. If T_1 contains a structure above v_A, v_B, v_C as the one shown in the left-hand side of Fig. 1,[1] then T_2 contains either the same structure above v_A, v_B, v_C as T_1 or the one shown in the right-hand side of the same figure.

Fig. 1 T_1 and T_2 are locally compatible

[1] In this figure, as well as in Figs. 2 to 4, edges may represent actually non-trivial paths.

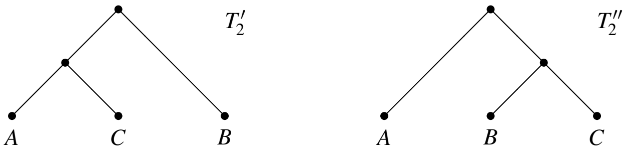

Fig. 2 T_2' and T_2'' are locally incompatible with T_1 in Fig. 1

Indeed, since no two among v_A, v_B, v_C are connected in T_1 by a path, condition (C1) implies that no two among the nodes in T_2 labeled A,B,C are connected by a path, either. Beside the structures shown in Fig. 1, only the structures T_2' and T_2'' shown in Fig. 2 satisfy this property. Now, T_1 contains a non-trivial path $v_{A,C} \rightsquigarrow v_{A,B}$, while T_2' contains a non-trivial path $v_{A,B} \rightsquigarrow v_{A,C}$; and T_1 contains a non-trivial path $v_{B,C} \rightsquigarrow v_{A,B}$, while T_2'' contains a non-trivial path $v_{A,B} \rightsquigarrow v_{B,C}$. So, in both cases we find incompatible triples of labels. On the other hand, in the $\mathscr{A}$-tree T_2 shown in Fig. 1, $v_{A,B} = v_{A,C} = v_{B,C}$, and therefore this $\mathscr{A}$-tree clearly satisfies condition (C2) with T_1 as far as the labels A,B,C go.

Example 2 Let T_1, T_2 be two locally compatible $\mathscr{A}$-trees, and let $A,B,C \in \mathscr{A}(T_1) \cap \mathscr{A}(T_2)$. If T_1 contains a structure above v_A, v_B, v_C as the one shown in the left-hand side of Fig. 3, then T_2 contains either the same structure above v_A, v_B, v_C as T_1 or the one shown in the right-hand side of the same figure.

Fig. 3 T_1 and T_2 are locally compatible

Indeed, in order to satisfy condition (C1), the existence in T_1 of paths $v_C \rightsquigarrow v_A$, $v_C \rightsquigarrow v_B$ and the fact that v_A and v_B are not connected by a path in this $\mathscr{A}$-tree, entail that T_2 also contains paths $v_C \rightsquigarrow v_A$, $v_C \rightsquigarrow v_B$ and that v_A and v_B are not connected by a path either. Therefore, T_2 must either contain the same structure above v_A, v_B, v_C as T_1, or non-trivial paths $v_C \rightsquigarrow v_{A,B}$, $v_{A,B} \rightsquigarrow v_A$, $v_{A,B} \rightsquigarrow v_B$. And since, in T_1, $v_{A,B} = v_{A,C} = v_{B,C}$, it is clear that in the last case the labels A,B,C do not form an incompatible triple in T_1 and T_2.

Example 3 Let T_1, T_2 be two locally compatible $\mathscr{A}$-trees, and let $A,B,C \in \mathscr{A}(T_1) \cap \mathscr{A}(T_2)$. If T_1 contains above v_A, v_B, v_C one of the structures shown in Fig. 4, then T_2 must contain the same structure above v_A, v_B, v_C.

Indeed, it is a simple consequence of the application of condition (C1). In the left-hand side structure, T_1 contains a path $v_B \rightsquigarrow v_A$, and v_B and v_C are not connected by a path in it, and therefore the same must happen in T_2 and this leads to the same structure. And in the right-hand side structure, T_1 contains paths $v_C \rightsquigarrow v_B \rightsquigarrow v_A$, and then the same must happen in T_2, entailing again the same structure in this tree.

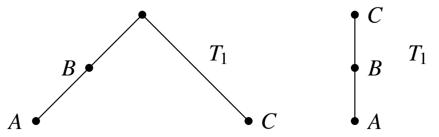

Fig. 4 These two $\mathscr{A}$-trees are only locally compatible with themselves

The following construction will be used henceforth several times.

Definition 5 For every pair of $\mathscr{A}$-trees T_1 and T_2, let

$$\bar{T}_1 = T_1|\mathscr{A}(T_1)\cap\mathscr{A}(T_2), \quad \text{and} \quad \bar{T}_2 = T_2|\mathscr{A}(T_1)\cap\mathscr{A}(T_2).$$

Notice that, by construction, every leaf of each $\bar{T}_i$ is labeled, and therefore $\bar{T}_1$ and $\bar{T}_2$ are $\mathscr{A}$-trees. Notice also that if $\mathscr{A}(T_1) = \mathscr{A}(T_2)$, then $\bar{T}_1 = T_1$ and $\bar{T}_2 = T_2$. In general,

$$\mathscr{A}(\bar{T}_1) = \mathscr{A}(\bar{T}_2) = \mathscr{A}(T_1)\cap\mathscr{A}(T_2).$$

Since local compatibility of two $\mathscr{A}$-trees refers to labels appearing in both $\mathscr{A}$-trees, we clearly have the following result.

Lemma 2 *Two $\mathscr{A}$-trees T_1 and T_2 are locally compatible if and only if $\bar{T}_1$ and $\bar{T}_2$ are so.* □

4 Weak topological embeddings

Compatibility of phylogenetic trees is usually stated in terms of the existence of simultaneous embeddings of some kind into a common supertree. In this section we introduce the embeddings that will correspond to local compatibility.

First, recall from [10] the definition of ancestral displaying, which we already present translated into our notations.

Definition 6 An $\mathscr{A}$-tree T *ancestrally displays* an $\mathscr{A}$-tree S if the following properties hold:

- $\mathscr{A}(S) \subseteq \mathscr{A}(T)$.
- For every $A,B \in \mathscr{A}(S)$, there is a path $v_A \rightsquigarrow v_B$ in S if and only if there is a path $v_A \rightsquigarrow v_B$ in T.
- S is *refined* by $T|\mathscr{A}(S)$, that is, $\mathscr{C}_{\mathscr{A}}(S) \subseteq \mathscr{C}_{\mathscr{A}}(T|\mathscr{A}(S))$.

We introduce now the following, more algebraic in flavour, definition of embedding that will turn out to be equivalent to ancestral displaying, up to the removal of elementary unlabeled nodes: cf. Proposition 1 below.

Definition 7 A *weak topological embedding* of trees $f : S \to T$ is a mapping $f : V(S) \to V(T)$ satisfying the following conditions:

- It is *injective*.
- It *preserves labels*: for every $A \in \mathscr{A}(S)$, $f(v_A) = v_A$.
- It *preserves and reflects paths*: for every $a,b \in V(S)$, there is a path from a to b in S if and only if there is a path from $f(a)$ to $f(b)$ in T.

When a weak topological embedding of $\mathscr{A}$-trees $f : S \to T$ exists, we say that S is a *weak $\mathscr{A}$-subtree* of T and that T is a *weak $\mathscr{A}$-supertree* of S.

Example 4 Let S and T be the $\mathscr{A}$-trees described in Fig. 5, and let $f : V(S) \to V(T)$ be the mapping defined by $f(r) = r'$, $f(v_{S,A}) = v_{T,A}$ and $f(v_{S,B}) = v_{T,B}$. This mapping is injective, preserves labels and preserves paths, but it does not reflect paths: there is a path $v_{T,A} \rightsquigarrow v_{T,B}$ is T, but no path from $v_{S,A}$ to $v_{S,B}$ in S. Therefore, it does not define a weak topological embedding $f : S \to T$.

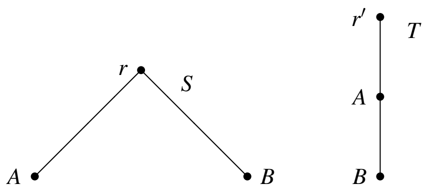

Fig. 5 The $\mathscr{A}$-trees in Example 4

Example 5 Let S and T the $\mathscr{A}$-trees described in Fig. 6. Let $f : V(S) \to V(T)$ be the mapping that sends the root r of S to the root r' of T, and every leaf of S to the leaf of T with the same label. This mapping is injective, preserves labels, and preserves and reflects paths. Therefore, it is a weak topological embedding $f : S \to T$.

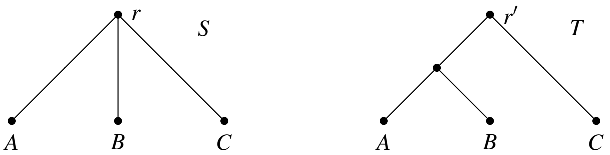

Fig. 6 The $\mathscr{A}$-trees in Example 5

Example 6 For every $\mathscr{A}$-tree T and for every $\mathscr{X} \subseteq \mathscr{A}(T)$, the inclusion of the restriction $T|\mathscr{X}$ into T is a weak topological embedding.

Remark 1 It is straightforward to prove that a mapping $f : V(S) \to V(T)$ preserves paths if and only if it *transforms arcs into paths*, that is, for every $a, b \in V(S)$, if $(a, b) \in E(S)$, then there exists a path $f(a) \rightsquigarrow f(b)$ in T. We shall sometimes use this alternative formulation without any further mention.

The following lemmas will be used several times in the sequel.

Lemma 3 *Let $f : S \to T$ be a weak topological embedding. Then, for every $v \in V(S)$, $\mathscr{A}(v) = \mathscr{A}(f(v)) \cap \mathscr{A}(S)$.*

Proof The inclusion $\mathscr{A}(v) \subseteq \mathscr{A}(f(v)) \cap \mathscr{A}(S)$ is a direct consequence of the fact that f preserves labels and paths, while the converse inclusion is a direct consequence of the fact that f preserves labels and reflects paths. □

Lemma 4 *Let $f : S \to T$ be a weak topological embedding of $\mathscr{A}$-trees. Then:*

(i) $\mathscr{L}(S) = \mathscr{L}(T|\mathscr{A}(S))$.
(ii) *f induces a weak topological embedding $f : S \to T|\mathscr{A}(S)$.*

Proof Notice first of all that $\mathscr{A}(S) \subseteq \mathscr{A}(T)$, because f preserves labels, and therefore it makes sense to define the restriction $T|\mathscr{A}(S)$; actually, the nodes of T with labels in $\mathscr{A}(S)$ are exactly the images of the labeled nodes of S. To simplify the notations, we shall denote in the rest of this proof $T|\mathscr{A}(S)$ by T'.

To prove (i), it is enough to check that the leaves of T' are exactly the images of leaves of S under f. And recall that $w \in V(T')$ is a leaf of T' if and only if $w = f(v_{S,A})$ for some $A \in \mathscr{A}(S)$ and $\mathscr{A}_T(w) \cap \mathscr{A}(S) = \{A\}$. Since, by the previous lemma, $\mathscr{A}(f(v_{S,A})) \cap \mathscr{A}(S) = \mathscr{A}(v_{S,A})$, we deduce that $w \in V(T')$ is a leaf of T' if and only if $w = f(v_{S,A})$ for some $A \in \mathscr{A}(S)$ such that $\mathscr{A}(v_{S,A}) = \{A\}$, that is, if and only if $w = f(v_{S,A})$ for some leaf $v_{S,A}$ of S, as we wanted to prove.

As far as (ii) goes, let us prove first that $f(V(S)) \subseteq V(T')$. Let $v \in V(S)$. If it is a leaf of S, then, as we have just seen, $f(v) \in V(T')$. If v is not a leaf of S, then there is a path in S from v to some leaf v'. Since f preserves paths, there is a path in T from $f(v)$ to $f(v')$, and $f(v')$ is labeled in $\mathscr{A}(S)$. Therefore, by the definition of restriction of an $\mathscr{A}$-tree, $f(v) \in V(T')$, too.

This proves that $f(V(S)) \subseteq V(T')$. And then it is straightforward to deduce that $f : S \to T'$ is injective, preserves labels, and that it preserves and reflects paths, from the corresponding properties for $f : S \to T$. □

Now we can prove that, as we announced, weak topological embeddings capture ancestral displaying.

Proposition 1 *Let S and T be two $\mathscr{A}$-trees, and let S' be the semi-labeled tree obtained from S by removing the elementary unlabeled nodes in it and replacing by arcs the maximal paths with all their intermediate nodes elementary and unlabeled.*

Then, T ancestrally displays S if and only if there exists a weak topological embedding $f : S' \to T$.

Proof Assume that T ancestrally displays S, and in particular that $\mathscr{A}(S) \subseteq \mathscr{A}(T)$ and $\mathscr{C}_{\mathscr{A}}(S) \subseteq \mathscr{C}_{\mathscr{A}}(T|\mathscr{A}(S))$; to simplify the notations, we shall denote $T|\mathscr{A}(S)$ by T''. Since elementary unlabeled nodes do not contribute any new member to the cluster representation, $\mathscr{C}_{\mathscr{A}}(S) = \mathscr{C}_{\mathscr{A}}(S')$. Therefore, $\mathscr{C}_{\mathscr{A}}(S') \subseteq \mathscr{C}_{\mathscr{A}}(T'')$.

We define the mapping

$$\begin{aligned} f : V(S') &\to V(T'') \\ v &\mapsto v_{T'',\mathscr{A}(v)} \end{aligned}$$

Let us check that this mapping defines a weak topological embedding $f : S' \to T''$.

- *It is injective*. Let v, w be two different nodes of S'. Since every node in S' is the most recent common ancestor of its labeled descendants, that is, $x = v_{S',\mathscr{A}(x)}$ for every $x \in V(S')$, we have that $\mathscr{A}(v) \neq \mathscr{A}(w)$. And then, since $\mathscr{C}_{\mathscr{A}}(S') \subseteq \mathscr{C}_{\mathscr{A}}(T'')$, it turns out that $\mathscr{A}(v), \mathscr{A}(w)$ are two different members of $\mathscr{C}_{\mathscr{A}}(T'')$, and hence $\mathscr{A}(v_{T'',\mathscr{A}(v)}) = \mathscr{A}(v) \neq \mathscr{A}(w) = \mathscr{A}(v_{T'',\mathscr{A}(w)})$, which clearly implies that $v_{T'',\mathscr{A}(v)} \neq v_{T'',\mathscr{A}(w)}$.
- *It preserves labels*. Let $A \in \mathscr{A}(S')$ and $v = v_{S',A}$. Then, $f(v) = v_{T'',\mathscr{A}(v_{S',A})}$ is labeled A because, by the second property of ancestral displaying, the labeled nodes in S' that are descendants of v are exactly the labeled nodes in T'' that are descendants of $v_{T'',A}$, and therefore $v_{T'',A}$ is the least common ancestor of the nodes with labels in $\mathscr{A}(v_{S',A})$, that is, $v_{T'',A} = v_{T'',\mathscr{A}(v_{S',A})} = f(v)$, as we claimed.
- *It preserves and reflects paths*. Since $\mathscr{A}(v) = \mathscr{A}(f(v))$ for every $v \in V(S')$, we have the following sequence of equivalences: for every $v, w \in V(S')$,

$$
\begin{aligned}
&\text{there exists a non-trivial path } v \rightsquigarrow w \\
&\qquad \iff \mathscr{A}(w) \subsetneq \mathscr{A}(v) \\
&\qquad \iff \mathscr{A}(f(w)) \subsetneq \mathscr{A}(f(v)) \\
&\qquad \iff \text{there exists a non-trivial path } f(v) \rightsquigarrow f(w).
\end{aligned}
$$

  The implications $\Leftarrow$ in the first equivalence and $\Rightarrow$ in the last equivalence are given by Corollary 1, while the converse implication in both cases is entailed by the fact that $v, w, f(v), f(w)$ are most recent common ancestors of sets of labeled nodes, and then non-trivial paths between them imply strict inclusions of sets of labels of descendants.

So, we have a weak topological embedding $f : S' \to T''$, and since T'' is a weak $\mathscr{A}$-subtree of T, it induces a weak topological embedding $f : S' \to T$, as we wanted to prove.

Conversely, assume that we have a weak topological embedding $f : S' \to T$. Then:

- $\mathscr{A}(S) = \mathscr{A}(S') \subseteq \mathscr{A}(T)$ because f preserves labels.
- For every $A, B \in \mathscr{A}(S)$, by construction, $v_{S,A} = v_{S',A}$ and $v_{S,B} = v_{S',B}$, and there exists a path $v_{S,A} \rightsquigarrow v_{S,B}$ in S if and only if there exists a path $v_{S',A} \rightsquigarrow v_{S',B}$ in S'. Moreover, since f preserves labels and preserves and reflects paths, there exists a path $v_{S',A} \rightsquigarrow v_{S',B}$ in S' if and only if there exists a path $v_{T,A} = f(v_{S',A}) \rightsquigarrow f(v_{S',B}) = v_{T,B}$ in T. Combining these equivalences, we obtain that, for every $A, B \in \mathscr{A}(S)$, there exists a path $v_{S,A} \rightsquigarrow v_{S,B}$ in S if and only if there exists a path $v_{T,A} \rightsquigarrow v_{T,B}$ in T.
- Let $X \in \mathscr{C}_{\mathscr{A}}(S)$ and let $v = v_{S,X} = v_{S',X}$. It turns out that $\mathscr{A}_{T|\mathscr{A}(S)}(f(v)) = X$. Indeed, by Lemma 4, $f : S' \to T$ induces a weak topological embedding $f : S' \to T|\mathscr{A}(S') = T|\mathscr{A}(S)$ and then, by Lemma 3, $\mathscr{A}_{T|\mathscr{A}(S)}(f(v)) = \mathscr{A}_{S'}(v) = \mathscr{A}_S(v) = X$.
  Therefore, $X \in \mathscr{C}(T|\mathscr{A}(S))$, and, being X arbitrary, we conclude that $\mathscr{C}_{\mathscr{A}}(S) \subseteq \mathscr{C}(T|\mathscr{A}(S))$.

This proves that T ancestrally displays S. □

Now, recall from [10] the notion of ancestral compatibility.

Definition 8 Two $\mathscr{A}$-trees T_1, T_2 are *ancestrally compatible* when there exists an $\mathscr{A}$-tree that ancestrally displays both of them. If two $\mathscr{A}$-trees are not ancestrally compatible, we say that they are *ancestrally incompatible*.

Weak topological embeddings have been defined as they have so ancestral compatibility turns out to be exactly the same as 'compatibility for weak topological embeddings.'

Proposition 2 *Two $\mathscr{A}$-trees T_1, T_2 are ancestrally compatible if and only if they have a common weak $\mathscr{A}$-supertree, that is, if and only if they admit a weak topological embedding into a same $\mathscr{A}$-tree.*

Proof For every $\ell = 1,2$, let T'_ℓ be the semi-labeled tree obtained by removing the elementary unlabeled nodes in T_ℓ and replacing by arcs the maximal paths with all their intermediate nodes elementary and unlabeled.

Assume that there exist weak topological embeddings $f_1 : T_1 \to T$ and $f_2 : T_2 \to T$ of T_1 and T_2 into a same $\mathscr{A}$-tree T. Since each T'_ℓ is a weak $\mathscr{A}$-subtree of the corresponding T_ℓ, each one of these weak topological embeddings induces a weak topological embedding $f'_\ell : T'_\ell \to T$, showing that T ancestrally displays T_1 and T_2.

Conversely, assume that there exist weak topological embeddings $g_1 : T'_1 \to T$ and $g_2 : T'_2 \to T$ of T'_1 and T'_2 into a same $\mathscr{A}$-tree T. Let $\tilde{T}$ be the $\mathscr{A}$-tree obtained from T in the following way. For every arc $(v,w) \in E(T)$, if there exists an arc (v_ℓ, w_ℓ) in one T_ℓ such that $g_\ell(v_\ell) = v$ and $g_\ell(w_\ell) = w$, we split the arc (v,w) in T into a path $v \rightsquigarrow w$, with all its intermediate nodes elementary and unlabeled, of length equal to the length of the path $v_\ell \rightsquigarrow w_\ell$; if there are arcs $(v_1, w_1) \in E(T_1)$ and $(v_2, w_2) \in E(T_2)$ such that $g_1(v_1) = g_2(v_2) = v$ and $g_1(w_1) = g_2(w_2) = w$, then we split the arc (v,w) in T into a path $v \rightsquigarrow w$ as before, but now of length the maximum of the lengths of the paths $v_1 \rightsquigarrow w_1$ and $v_2 \rightsquigarrow w_2$. It is clear then that each $g_T : T \to T_0$ can be extended to a weak topological embedding $\tilde{g}_T : T \to \tilde{T}$. $\square$

From now on, we shall use this characterization of ancestral compatibility as the working definition of it.

The main result of this paper will establish that ancestral compatibility is equivalent to local compatibility. To prove it, we shall need a preliminary result, Proposition 3, which establishes that ancestral compatibility of two $\mathscr{A}$-trees can be checked at the level of $\bar{T}_1$ and $\bar{T}_2$, as it was also the case for local compatibility.

Lemma 5 *Let T_1 and T_2 be two $\mathscr{A}$-trees and let $\bar{T}_1$ and $\bar{T}_2$ be their $\mathscr{A}$-subtrees described in Definition 5. If T_1 and T_2 are ancestrally compatible, then $\mathscr{L}(\bar{T}_1) = \mathscr{L}(\bar{T}_2)$.*

Proof Assume that T_1 and T_2 are ancestrally compatible. Then, since $\bar{T}_1$ and $\bar{T}_2$ are weak $\mathscr{A}$-subtrees of T_1 and T_2, respectively, it is clear that they are also ancestrally compatible; let $f_1 : \bar{T}_1 \to T$ and $f_2 : \bar{T}_2 \to T$ be weak topological embeddings. Recall that $\mathscr{A}(\bar{T}_1) = \mathscr{A}(\bar{T}_2)$.

If $A \in \mathscr{L}(\bar{T}_1)$, then $\mathscr{A}_{\bar{T}_1}(v_{\bar{T}_1,A}) = \{A\}$ and hence

$$\begin{aligned}\mathscr{A}_{\bar{T}_2}(v_{\bar{T}_2,A}) &= \mathscr{A}_T(f_2(v_{\bar{T}_2,A})) \cap \mathscr{A}(\bar{T}_2) = \mathscr{A}_T(v_{T,A}) \cap \mathscr{A}(\bar{T}_2) \\ &= \mathscr{A}_T(f_1(v_{\bar{T}_1,A})) \cap \mathscr{A}(\bar{T}_1) = \mathscr{A}_{\bar{T}_1}(v_{\bar{T}_1,A}) = \{A\},\end{aligned}$$

which says that $v_{\bar{T}_2,A}$ is a leaf of $\bar{T}_2$ and thus $A \in \mathscr{L}(\bar{T}_2)$.

This proves that $\mathscr{L}(\bar{T}_1) \subseteq \mathscr{L}(\bar{T}_2)$ and, by symmetry, the equality between these two sets. □

Proposition 3 *Let T_1 and T_2 be $\mathscr{A}$-trees and let $\bar{T}_1$ and $\bar{T}_2$ be their $\mathscr{A}$-subtrees described in Definition 5. Then, T_1 and T_2 are ancestrally compatible if and only if $\bar{T}_1$ and $\bar{T}_2$ are ancestrally compatible.*

Proof As we have seen in the proof of the last lemma, if T_1 and T_2 are ancestrally compatible, then $\bar{T}_1$ and $\bar{T}_2$ are also so. Conversely, let $f_1 : \bar{T}_1 \to T$ and $f_2 : \bar{T}_2 \to T$ be two weak topological embeddings. By the last lemma, we know that $\mathscr{L}(\bar{T}_1) = \mathscr{L}(\bar{T}_2)$. Recall, moreover, that $\mathscr{A}(\bar{T}_1) = \mathscr{A}(\bar{T}_2) = \mathscr{A}(T_1) \cap \mathscr{A}(T_2)$.

By Lemma 4, f_1 and f_2 induce weak topological embeddings into the restriction of T to $\mathscr{A}(\bar{T}_1) = \mathscr{A}(\bar{T}_2)$. Therefore, by replacing T by this $\mathscr{A}$-subtree if necessary, we shall assume without any loss of generality that $\mathscr{L}(T) = \mathscr{L}(\bar{T}_1) = \mathscr{L}(\bar{T}_2)$. We shall also assume, again without any loss of generality, that $\mathscr{A}(T) = \mathscr{A}(\bar{T}_1) = \mathscr{A}(\bar{T}_2)$: we simply remove from T the labels that do not belong to this set.

Finally, we shall assume that there does not exist any pair of different labels A_1, A_2 such that $v_{T_1,A_1} \in V(\bar{T}_1)$ and $v_{T_2,A_2} \in V(\bar{T}_2)$ and $f_1(v_{T_1,A_1}) = f_2(v_{T_2,A_2})$. Indeed, assume that such a pair of labels exists. Then, to begin with, $A_1, A_2 \notin \mathscr{A}(T_1) \cap \mathscr{A}(T_2)$: if, say, $A_2 \in \mathscr{A}(T_1) \cap \mathscr{A}(T_2)$ then, since f_1 and f_2 preserve labels, it happens that $f_2(v_{T_2,A_2}) = f_1(v_{T_1,A_2})$ and then $v_{T_1,A_2} = v_{T_1,A_1}$, that is, $A_2 = A_1$. Therefore, v_{T_1,A_1} and v_{T_2,A_2} do not keep their labels in $\bar{T}_1$ and $\bar{T}_2$. Now, given the node $w = f_1(v_{T_1,A_1}) = f_2(v_{T_2,A_2})$ (which, by what we have just discussed, will be unlabeled, either), we 'blow out' it by adding a new node w', splitting the arc going from w's parent w_0 to w into two arcs $(w_0, w'), (w', w)$ —if w was the root of T, we simply add a new arc (w', w)— and redefining f_1 by sending v_{T_1,A_1} to w' while we do not change f_2 (alternatively, we could have redefined f_2, by sending v_{T_2,A_2} to w', and left f_1 unchanged). It is straightforward to check that the new mapping f_1 obtained in this way and the 'old' f_2 are still weak topological embeddings from T_1 and T_2 to the new $\mathscr{A}$-tree. After repeating this process as many times as necessary, and still calling T the target $\mathscr{A}$-tree obtained at the end, we obtain weak topological embeddings $f_1 : \bar{T}_1 \to T$ and $f_2 : \bar{T}_2 \to T$ as we assumed at the beginning of this paragraph.

We shall expand this common weak $\mathscr{A}$-supertree T of $\bar{T}_1$ and $\bar{T}_2$ to a common weak $\mathscr{A}$-supertree of T_1 and T_2. To begin with, we expand T to an $\mathscr{A}$-labeled graph T' by "adding $T_1 - \bar{T}_1$" to it. More specifically, to obtain T', we add to T all nodes in $V(T_1) - V(\bar{T}_1)$, and arcs of two types: on the one hand, those between these nodes in T_1, and on the other hand, for every arc $(a,b) \in E(T_1)$ with $a \in V(\bar{T}_1)$ and $b \in V(T_1) - V(\bar{T}_1)$, an arc between $f_1(a)$ and b in T'. As far as the labels go, on the one hand the nodes of T' belonging to $V(T_1) - V(\bar{T}_1)$ inherit their labels, and on the other hand the nodes in T' that are images of nodes in $\bar{T}_1$ labeled in $\mathscr{A}(T_1) - \mathscr{A}(\bar{T}_1)$, are labeled with this label. None of the labels we add in this way could be present in T, because otherwise they would have belonged to $\mathscr{A}(\bar{T}_1)$, which is impossible, and no already labeled node in T receives a second label, because the nodes labeled in T received their labels from $\bar{T}_1$.

This T' is clearly an $\mathscr{A}$-tree, and has T as a weak $\mathscr{A}$-subtree: actually, $T = T'|\mathscr{L}(T)$. Therefore, it is a weak $\mathscr{A}$-supertree of $\bar{T}_2$. And it is also a weak $\mathscr{A}$-

supertree of T_1. Indeed, consider the mapping $f_1' : V(T_1) \to V(T')$ that is defined on $V(\bar{T}_1)$ as the original embedding $f_1 : V(\bar{T}_1) \to V(T)$ and on $V(T_1) - V(\bar{T}_1)$ as the identity. It is clearly injective and preserves labels. Moreover, it preserves paths, because f_1 sends arcs in $\bar{T}_1$ to paths in T, and arcs outside $\bar{T}_1$ become arcs in T'; and it reflects paths, because it reflects paths in T and the arcs that have been added come from arcs in T_1.

So, T' is a common weak $\mathscr{A}$-supertree of T_1 and $\bar{T}_2$. Now, we expand T' to a new $\mathscr{A}$-tree T'' by means of a similar process, but now "adding $T_2 - \bar{T}_2$" to it. We add to T' all nodes in $V(T_2) - V(\bar{T}_2)$, all arcs between these nodes in T_2, an arc $(f_2(a), b)$ for every arc $(a,b) \in E(T_2)$ with $a \in V(\bar{T}_2)$ and $b \in V(T_2) - V(\bar{T}_2)$. The new nodes, coming from $V(T_2) - V(\bar{T}_2)$, are labeled as they were in T_2, while the old ones receive their labels from T_2, if any and necessary. No new label added in this way could be already present in T'. And no already labeled node receives a second label, because the images of $f_1' : T_1 \to T'$ and $f_2 : \bar{T}_2 \to T'$ are still disjoint except for the nodes with labels in $\mathscr{A}(T_1) \cap \mathscr{A}(T_2)$.

The $\mathscr{A}$-labeled graph T'' obtained in this way is again an $\mathscr{A}$-tree, and now it is a weak $\mathscr{A}$-supertree of T_1 and of T_2: the proof is similar to the previous one in the case of T'. Therefore, T_1 and T_2 are ancestrally compatible, as we wanted to prove. □

Example 7 Consider the semi-labeled trees T_1 and T_2 described in Fig. 7. The corresponding $\mathscr{A}$-trees $\bar{T}_1$ and $\bar{T}_2$, which are no longer semi-labeled trees, are described in Fig. 8; notice that the nodes c, h and i are no longer labeled in these trees.

The $\mathscr{A}$-trees $\bar{T}_1$ and $\bar{T}_2$ are ancestrally compatible. A weak common $\mathscr{A}$-supertree of them is given by the $\mathscr{A}$-tree T described in Fig. 9, together with the weak topological embeddings $f_1 : \bar{T}_1 \to T$ and $f_2 : \bar{T}_2 \to T$ that are indicated by assigning in the picture to each non-labeled node in T its preimages under f_1 and f_2. Notice that $\mathscr{A}(T) = \mathscr{A}(\bar{T}_1) = \mathscr{A}(\bar{T}_2)$, but $f_1(v_{T_1,C}) = f_2(v_{T_2,H})$. To avoid it, we blow up this node into an arc and we separate these two images: the corresponding new weak $\mathscr{A}$-supertree T is described in Fig. 10. Now, the new weak topological embeddings f_1 and f_2 satisfy the assumptions in the proof of the last proposition.

The $\mathscr{A}$-trees T' and T'' that are successively obtained by first 'adding $T_1 - \bar{T}_1$ to T' and then 'adding $T_2 - \bar{T}_2$ to T'' are described in Figs. 11 and 12, respectively. At the end, T'' is a weak common $\mathscr{A}$-supertree of T_1 and T_2 under the embeddings indicated as before.

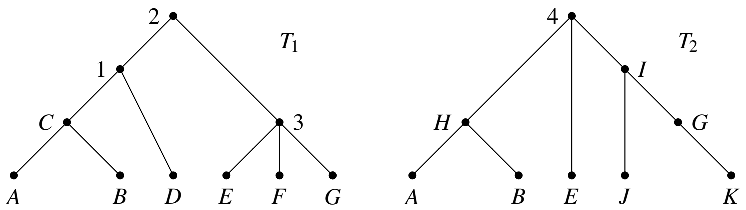

Fig. 7 The semi-labeled trees T_1, T_2 in Example 7

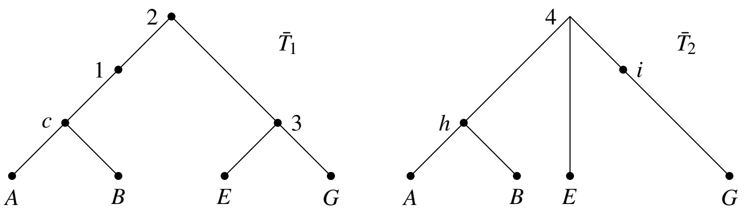

Fig. 8 The $\mathscr{A}$-trees $\bar{T}_1, \bar{T}_2$ corresponding to the semi-labeled trees T_1, T_2 in Fig. 7

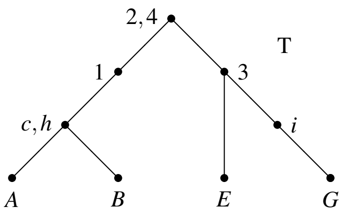

Fig. 9 A weak common $\mathscr{A}$-supertree of $\bar{T}_1$ and $\bar{T}_2$

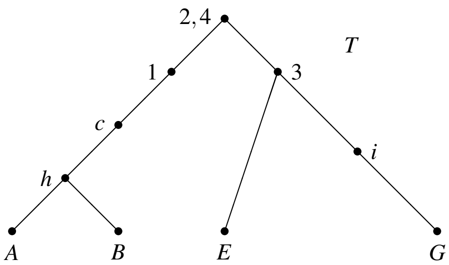

Fig. 10 The new $\mathscr{A}$-tree T obtained after blowing out the node c,h in the $\mathscr{A}$-tree T in Fig. 9

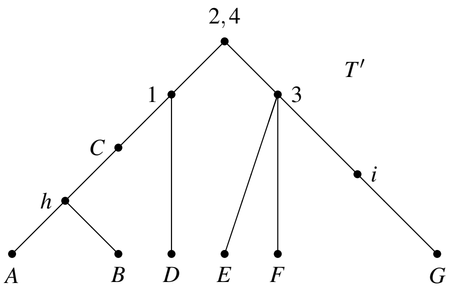

Fig. 11 The $\mathscr{A}$-tree T' obtained by 'adding $T_1 - \bar{T}_1$' to T

5 Main results

In this section we establish that local compatibility is the same as ancestral compatibility. We also provide a characterization of the ancestral, or local, compatibility of a family of $\mathscr{A}$-trees in terms of joint properties of their cluster representations.

Definition 9 Let T_1 and T_2 be two $\mathscr{A}$-trees.

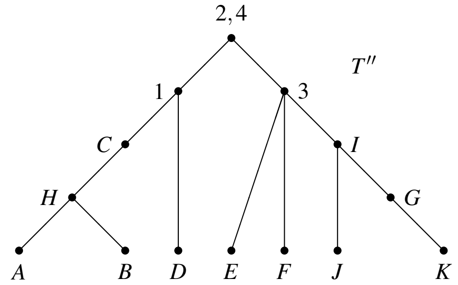

Fig. 12 The weak common $\mathscr{A}$-supertree T'' of T_1 and T_2 obtained by 'adding $T_2 - \bar{T}_2$' to T'

(a) Assume that $\mathscr{A}(T_1) = \mathscr{A}(T_2)$. In this case, the *join* of T_1 and T_2 is the $\mathscr{A}$-labeled graph $T_{1,2}$ defined as follows.
For every $\ell = 1,2$ and for every $Y \in \mathscr{C}_{\mathscr{A}}(T_\ell)$, let

$$m_{\ell,Y} = \#\{v \in V(T_\ell) \mid \mathscr{A}_{T_\ell}(v) = Y\}.$$

Set $\mathscr{C} = \mathscr{C}_{\mathscr{A}}(T_1) \cup \mathscr{C}_{\mathscr{A}}(T_2)$. Then:

- Its nodes are

$$w_{Y,j} \quad \text{with } Y \in \mathscr{C} \text{ and } j = 1,\dots,n_Y,$$

where $n_Y = \max\{m_{1,Y}, m_{2,Y}\}$.

- Its arcs are:

$$\begin{array}{ll} (w_{Y,j}, w_{Y,j-1}) & j = 2,\dots,n_Y \\ (w_{Y,1}, w_{Z,n_Z}) & \text{if } Z \subsetneq Y \text{ and there is no } Z' \in \mathscr{C} \text{ such that } Z \subsetneq Z' \subsetneq Y. \end{array}$$

- If there exists some $Y \in \mathscr{C}$ such that

$$Y = \left(\bigcup\{Z \in \mathscr{C} \mid Z \subsetneq Y\}\right) \sqcup \{A\}$$

for some label $A \in \mathscr{A}$, then the node $w_{Y,1}$ is labeled with this A. In particular, the nodes $w_{A,1}$, with $\{A\}$ any singleton in $\mathscr{C}$, are labeled with the corresponding label A.

Now, for every $\ell = 1,2$, we define a mapping $f_\ell : V(T_\ell) \to V(T_{1,2})$ as follows.
For every $Y \in \mathscr{C}_{\mathscr{A}}(T_\ell)$, let $\{x^{(\ell)}_{Y,1}, \dots, x^{(\ell)}_{Y,m_{\ell,Y}}\} \in V(T_\ell)$ be the set of nodes of T_ℓ with cluster Y, ordered as follows: $x^{(\ell)}_{Y,1} = v_{T_\ell,Y}$, and $(x^{(\ell)}_{Y,i+1}, x^{(\ell)}_{Y,i}) \in E(T_\ell)$ for every $i = 1,\dots,m_{\ell,Y} - 1$.
With these notations, $f_\ell : V(T_\ell) \to V(T)$ is defined by

$$f_\ell(x^{(\ell)}_{Y,i}) = w_{Y,i} \text{ for every } Y \in \mathscr{C}_{\mathscr{A}}(T_\ell) \text{ and } i = 1,\dots,m_Y.$$

Since $\mathscr{C}_{\mathscr{A}}(T_\ell) \subseteq \mathscr{C}$ and, for every $Y \in \mathscr{C}_{\mathscr{A}}(T_\ell)$, $m_{\ell,Y} \leqslant n_Y$, it is clear that f_ℓ is well defined and injective.

(b) If $\mathscr{A}(T_1) \neq \mathscr{A}(T_2)$, let $\bar{T}_1$ and $\bar{T}_2$ be the $\mathscr{A}$-subtrees of T_1 and T_2 described in Definition 5. Then, the *join* $T_{1,2}$ of T_1 and T_2 is the result of applying the construction in the proof of Proposition 3 to the join $\bar{T}_{1,2}$ of $\bar{T}_1$ and $\bar{T}_2$ (that is, first blowing out into arcs the nodes that are images of pairs of nodes labeled with different labels, next 'adding $T_1 - \bar{T}_1$' to this $\mathscr{A}$-tree, and finally 'adding $T_2 - \bar{T}_2$' to the result), and the mappings $f_\ell : V(T_\ell) \to V(T_{1,2})$, $\ell = 1,2$, are obtained by extending the mappings $f_\ell : V(\bar{T}_\ell) \to V(\bar{T}_{1,2})$ also in the way described in that proof.

Notice that, by construction, the mappings $f_l : V(T_l) \to V(T_{1,2})$, $l = 1,2$, are *jointly surjective*, that is, every node of $T_{1,2}$ belongs to the image of one or the other.

Theorem 1 *Let T_1 and T_2 be two $\mathscr{A}$-trees with $\mathscr{A}(T_1) = \mathscr{A}(T_2)$. Then, the following assertions are equivalent:*

(i) T_1 and T_2 are ancestrally compatible.
(ii) T_1 and T_2 are locally compatible.
(iii) $\mathscr{C}_{\mathscr{A}}(T_1)$ and $\mathscr{C}_{\mathscr{A}}(T_2)$ satisfy jointly the following two conditions:
- *For every $A \in \mathscr{A}(T_1) = \mathscr{A}(T_2)$, the smallest member of $\mathscr{C}_{\mathscr{A}}(T_1)$ containing A is equal to the smallest member of $\mathscr{C}_{\mathscr{A}}(T_2)$ containing this label.*
- *For every $X \in \mathscr{C}_{\mathscr{A}}(T_1)$ and $Y \in \mathscr{C}_{\mathscr{A}}(T_2)$, if $X \cap Y \neq \emptyset$, then $X \subseteq Y$ or $Y \subseteq X$.*

(iv) The join $T_{1,2}$ of T_1 and T_2 is an $\mathscr{A}$-tree and the mappings $f_1 : V(T_1) \to V(T_{1,2})$ and $f_2 : V(T_2) \to V(T_{1,2})$ are weak topological embeddings.

Proof (i)$\Longrightarrow$(ii) Assume that T_1 and T_2 are ancestrally compatible, and let $f_1 : T_1 \to T$ and $f_2 : T_2 \to T$ be two weak topological embeddings. To prove that they are locally compatible, we shall show that they satisfy conditions (C1) and (C2).

(C1) Assume that T_1 contains a path $v_A \rightsquigarrow v_B$. Since f_1 preserves this path, there exists a path $v_A \rightsquigarrow v_B$ in T, and then this path must be reflected by f_2, yielding a path $v_A \rightsquigarrow v_B$ in T_2.

(C2) Let $A,B,C \in \mathscr{A}(T_1) = \mathscr{A}(T_2)$. Let

$$y = v_{T_1,A,B} \quad \text{and} \quad z = v_{T_1,B,C},$$

and assume that there is a non-trivial path $z \rightsquigarrow y$; see Fig. 13. In particular, y cannot be an ancestor of v_C: otherwise, it would be a common ancestor of v_B and v_C, which would entail a path from y to z that cannot exist.

Moreover,

$$z = v_{T_1,A,C}.$$

Indeed, there are paths $z \rightsquigarrow v_A$, through y, and $z \rightsquigarrow v_C$, and therefore z is a common ancestor of v_A and v_C. Then, $v_{T_1,A,C}$ must be a node in the path $z \rightsquigarrow v_A$. Assume that it is an intermediate node of this path. If it is an intermediate node of the path $z \rightsquigarrow y$, then it will be a common ancestor of v_B, through y, and v_C, and therefore z cannot be the most recent common ancestor of these two nodes. And if $v_{T_1,A,C}$ is a node of the path $y \rightsquigarrow v_A$, then y will be an ancestor of v_C, something that, as we have seen above, cannot happen.

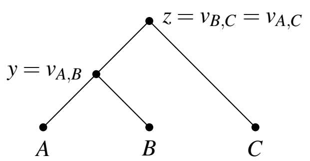

Fig. 13 The structure of T_1 above v_A, v_B, v_C. The edges represent paths; any one of them can be trivial, except the path $z \rightsquigarrow y$, which is non-trivial by assumption

Let us move now to T. Since f_1 preserves paths, $f_1(y)$ is a common ancestor of v_A and v_B and $f_1(z)$ is a common ancestor of v_B and v_C, and there is a non-trivial path from $f_1(z)$ to $f_1(y)$. Let

$$y' = v_{T,A,B} \quad \text{and} \quad z' = v_{T,B,C}.$$

Then, T contains paths $f_1(y) \rightsquigarrow y'$ and $f_1(z) \rightsquigarrow z'$, and it turns out that there is a non-trivial path $z' \rightsquigarrow f_1(y)$. Indeed, there are paths from z' and from $f_1(y)$ to v_B, and therefore there must exist either a non-trivial path $z' \rightsquigarrow f_1(y)$ or a path $f_1(y) \rightsquigarrow z'$; but the latter cannot exist, because if it existed, then composing it with $z' \rightsquigarrow v_C$ we would obtain a path $f_1(y) \rightsquigarrow v_C$ that, when reflected by f_1, would entail a path $y \rightsquigarrow v_C$ in T_1 that does not exist.

In particular, there is a non-trivial path $z' \rightsquigarrow y'$ in T. Arguing as in T_1, this implies that z' is also the most recent common ancestor of v_A and v_C in T. See Fig. 14 for a representation of the structure of T between $f_1(z)$ and v_A, v_B, v_C.

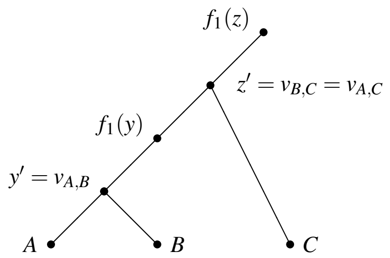

Fig. 14 The structure of T above v_A, v_B, v_C. The edges represent paths; any one of them can be trivial, except the path $z' \rightsquigarrow f_1(y)$, which is non-trivial

Consider finally the $\mathscr{A}$-tree T_2, and set $x = v_{T_2,B,C}$. Then, $f_2(x)$ will be a common ancestor of v_B and v_C in T and therefore there will be a path $f_2(x) \rightsquigarrow z'$. Composing this path with $z' \rightsquigarrow v_A$ we obtain a path $f_2(x) \rightsquigarrow v_A$ which entails, since f_2 reflects paths, the existence of a path $x \rightsquigarrow v_A$. Therefore, x is also an ancestor of v_A, and thus there exists a path $x \rightsquigarrow v_{T_2,A,B}$. But then, there cannot exist a non-trivial path $v_{T_2,A,B} \rightsquigarrow x$.

This finishes the proof that T_1 and T_2 satisfy condition (C2).

(ii)$\Longrightarrow$(iii) Assume that T_1 and T_2 satisfy conditions (C1) and (C2).

Let $A \in \mathscr{A}(T_1) = \mathscr{A}(T_2)$. The smallest members of $\mathscr{C}_{\mathscr{A}}(T_1)$ and $\mathscr{C}_{\mathscr{A}}(T_2)$ containing A are, of course, $\mathscr{A}(v_{T_1,A})$ and $\mathscr{A}(v_{T_2,A})$, respectively. Now, the inequality $\mathscr{A}(v_{T_1,A}) \neq \mathscr{A}(v_{T_2,A})$ violates property (C1): if, say, there exists a label $B \in \mathscr{A}(v_{T_1,A}) - \mathscr{A}(v_{T_2,A})$, then T_1 contains a path $v_A \rightsquigarrow v_B$ but T_2 does not contain the corresponding path $v_A \rightsquigarrow v_B$. This proves the first condition in point (iii).

Let now $X = \mathscr{A}_{T_1}(x) \in \mathscr{C}_{\mathscr{A}}(T_1)$ and $Y = \mathscr{A}_{T_2}(y) \in \mathscr{C}_{\mathscr{A}}(T_2)$ be such that $X \cap Y \neq \emptyset$, say $B \in X \cap Y$. If none of them is included into the other one, then there exist labels $A \in X - Y$ and $C \in Y - X$. Then, $C \notin \mathscr{A}(v_{T_1,A,B})$, because, since x is a common ancestor of v_A and v_B, there is a path $x \rightsquigarrow v_{T_1,A,B}$ that entails the inclusion $\mathscr{A}(v_{T_1,A,B}) \subseteq \mathscr{A}(x)$, and by assumption $C \notin \mathscr{A}(x)$. Therefore, $v_{T_1,B,C}$ is "above" $v_{T_1,A,B}$, that is, there exists a non-trivial path from $v_{B,C}$ to $v_{T_1,A,B}$: since

$B \in \mathscr{A}(v_{T_1,A,B}) \cap \mathscr{A}(v_{T_1,B,C}$, if this path does not exist, then there must exist a path $v_{T_1,A,B} \rightsquigarrow v_{T_1,B,C}$ that will entail that $C \in \mathscr{A}(v_{T_1,A,B})$.

In a similar way, we have that $A \notin \mathscr{A}(v_{T_2,B,C})$ and this entails a path $v_{T_2,A,B} \rightsquigarrow v_{T_2,B,C}$ in T_2.

In all, if there exist $X \in \mathscr{C}_{\mathscr{A}}(T_1)$ and $Y \in \mathscr{C}_{\mathscr{A}}(T_2)$ such that $X \cap Y \neq \emptyset$, but $X \not\subseteq Y$ and $Y \not\subseteq X$, then there exist three labels $A,B,C \in \mathscr{A}(T_1) \cap \mathscr{A}(T_2)$ and non-trivial paths $v_{T_1,B,C} \rightsquigarrow v_{T_1,A,B}$ in T_1 and $v_{T_2,A,B} \rightsquigarrow v_{T_2,B,C}$ in T_2, which would contradict the assumption that T_1 and T_2 satisfy condition (C2).

(iii)$\Longrightarrow$(iv) Assume that T_1 and T_2 satisfy the conditions stated in point (iii). Notice that the first condition in (iii) entails that $\mathscr{L}(T_1) = \mathscr{L}(T_2)$, because labels of leaves in an $\mathscr{A}$-tree are characterized by the fact that the smallest member of the cluster representation containing the label is a singleton.

To simplify the notations, we shall denote the join of T_1 and T_2 by simply T. In this case, since $\mathscr{A}(T_1) = \mathscr{A}(T_2)$, this join T is obtained using the construction given in Definition 9.(a). Let us check that it is an $\mathscr{A}$-tree:

- It is clear that its leaves are the nodes of the form $w_{A,1}$, and they are labeled.
- The nodes of T are injectively labeled: it is impossible the existence of two different sets of labels $Y_1, Y_2 \in \mathscr{C}$ such that

$$Y_1 = (\bigcup\{Z \in \mathscr{C} \mid Z \subsetneq Y_1\}) \sqcup \{A\}, \quad Y_2 = (\bigcup\{Z \in \mathscr{C} \mid Z \subsetneq Y_2\}) \sqcup \{A\},$$

  because in this case $Y_1 \cap Y_2 \neq \emptyset$ and therefore $Y_1 \subsetneq Y_2$ or $Y_2 \subsetneq Y_1$, which would entail that one of them contains a member of $\mathscr{C}$ that already contains A.
  As we shall see below, $\mathscr{A}(T) = \mathscr{A}(T_1) = \mathscr{A}(T_2)$.
- It is a tree. To prove it, assume first that a node $w_{Z,j}$ has two parents. Then, by construction, it must happen that $j = n_Z$ and then the parents are nodes $w_{Y_1,1}$ and $w_{Y_2,1}$ with $Y_1, Y_2 \in \mathscr{C}$, $Y_1 \neq Y_2$, such that $Z \subsetneq Y_1$, $Z \subsetneq Y_2$ and in both cases such that no other member of $\mathscr{C}$ lies strictly between Z and the corresponding Y_i. But then $Y_1 \cap Y_2 \neq \emptyset$ and therefore $Y_1 \subseteq Y_2$ or $Y_2 \subseteq Y_1$: if $Y_1, Y_2 \in \mathscr{C}_{\mathscr{A}}(T_1)$ or $Y_1, Y_2 \in \mathscr{C}_{\mathscr{A}}(T_2)$, by Lemma 1, and if each one of them belongs to a different cluster representation, by assumption. This forbids that both Y_1 and Y_2 are minimal over Z. Therefore, each $w_{Z,j}$ can have only one parent.
  Now, if $X,Y \in \mathscr{C}$ and $Y \subseteq X$, there is a unique path $w_{X,i} \rightsquigarrow w_{Y,j}$ for every $i = 1,\dots,n_X$ and $j = 1,\dots,n_Y$ (if $X = Y$, then this happens for every $1 \leqslant j \leqslant i \leqslant n_X$). If $X = Y$, it is obvious by construction, and when $Y \subsetneq X$, if

$$Y \subsetneq Z_1 \subsetneq Z_2 \subsetneq \cdots \subsetneq Z_k \subsetneq X$$

  is a maximal chain of sets of labels between Y and X with $Z_1,\dots,Z_k \in \mathscr{C}$, then this path is obtained as the composition of paths

$$w_{X,i} \rightsquigarrow w_{X,1} \rightsquigarrow w_{Z_k,n_{Z_k}} \rightsquigarrow w_{Z_k,1} \rightsquigarrow w_{Z_{k-1},n_{Z_{k-1}}} \rightsquigarrow \cdots \rightsquigarrow w_{Z_1,1} \rightsquigarrow w_{Y,n_Y} \rightsquigarrow w_{Y,j}.$$

  And this path is unique because every node has at most one parent.
  Then, since $\mathscr{A}(T_1) = \mathscr{A}(T_2) \in \mathscr{C}$, because it is the cluster of the roots of both trees, every node $w_{Y,j}$ is a descendant of $w_{\mathscr{A}(T_1),1}$, that is, $w_{\mathscr{A}(T_1),1}$ is the root of T.

This $\mathscr{A}$-tree T satisfies the following properties that we shall use below:

- $\mathscr{A}(w_{Y,j}) = Y$, for every node $w_{Y,j}$.
  This is easily proved by algebraic induction over the structure of T. If $Y = \{A\}$ and $j = 1$, then $w_{Y,1}$ is a leaf of T labeled A, while if $Y = \{A\}$ and $j > 1$, then the only labeled descendant of $w_{Y,j}$ in T is the leaf $w_{Y,1}$. Thus, $\mathscr{A}(w_{A,j}) = \{A\}$ for every $A \in \mathscr{L}(A_1) = \mathscr{L}(A_2)$ and $j = 1,\dots,n_A$.
  Now assume that $\mathscr{A}(w_{Z,j}) = Z$ for every $Z \subsetneq Y$ and $j = 1,\dots,n_Z$, and let us prove it for Y and every $j = 1,\dots,n_Y$. If $j = 1$, then the children of $w_{Y,1}$ are the nodes w_{Z,n_Z} with $Z \subsetneq Y$ and maximal with this property. And then, if $w_{Y,1}$ is not labeled,
  $$\begin{aligned}\mathscr{A}(w_{Y,1}) &= \bigcup\{\mathscr{A}(w_{Z,n_Z}) \mid Z \subsetneq Y \text{ and maximal with this property}\}\\ &= \bigcup\{\mathscr{A}(w_{Z,n_Z}) \mid Z \subsetneq Y\} = \bigcup\{Z \mid Z \subsetneq Y\} = Y\end{aligned}$$
  (in the second equality we use that if $Z \subsetneq Y$, then there exists some maximal $Z_0 \subsetneq Y$ such that $Z \subseteq Z_0$, and then there exists a path $w_{Z_0,1} \rightsquigarrow w_{Z,1}$ that entails that $\mathscr{A}(w_{Z,1}) \subseteq \mathscr{A}(w_{Z_0,1})$), while, if $w_{Y,1}$ is labeled, say with label A, then
  $$\begin{aligned}\mathscr{A}(w_{Y,1}) &= (\bigcup\{\mathscr{A}(w_{Z,n_Z}) \mid Z \subsetneq Y \text{ and maximal with this property}\}) \sqcup \{A\}\\ &= (\{\mathscr{A}(w_{Z,n_Z}) \mid Z \subsetneq Y\}) \sqcup \{A\} = (\bigcup\{Z \mid Z \subsetneq Y\}) \sqcup \{A\} = Y.\end{aligned}$$
  Finally, if $j > 1$, then there is a path $w_{Y,j} \rightsquigarrow w_{Y,1}$ with the origin and all its intermediate nodes elementary and unlabeled, and therefore $\mathscr{A}(w_{Y,j}) = \mathscr{A}(w_{Y,1}) = Y$.
- In particular, $w_{Y,1} = v_{T,Y}$, for every $Y \in \mathscr{C}$, because, as we have just proved, $\mathscr{A}(w_{Y,1}) = Y$, and all children w_{Z,n_Z} of $w_{Y,1}$ are such that $\mathscr{A}(w_{Z,n_Z}) = Z \subsetneq Y$.

Let us prove now that $f_1 : V(T_1) \to V(T)$ is a weak topological embedding $f_1 : T_1 \to T$; by symmetry, it will be true also for T_2.

Let us check that f_1 preserves labels. Let $A \in \mathscr{A}(T_1)$ and $Y = \mathscr{A}(v_{T_1,A})$. Then, in particular, and using the notations of Definition 9, $v_{T_1,A} = v_{T_1,Y} = x^{(1)}_{Y,1}$, and hence $f_1(v_{T_1,A}) = w_{Y,1}$. We must check that this node has label A, that is, that
$$Y = (\bigcup\{Z \in \mathscr{C} \mid Z \subsetneq Y\}) \sqcup \{A\},$$
because in this case, and only in this case, $w_{Y,1}$ is labeled A.

So, assume that there exists some $Z \in \mathscr{C}$ such that $Z \subsetneq Y$ and $A \in Z$. Such a Z cannot belong to $\mathscr{C}_{\mathscr{A}}(T_1)$, and therefore there exists some $z \in V(T_2)$ such that $\mathscr{A}(z) = Z$. Since $A \in \mathscr{A}(z)$, there exists a path $z \rightsquigarrow v_{T_2,A}$ in T_2 and therefore $\mathscr{A}(v_{T_2,A}) \subseteq \mathscr{A}(z)$. But, by the first condition in (iii), $\mathscr{A}(v_A) = Y$ and therefore this inequality says $Y \subseteq Z$, which is impossible. Therefore, $A \notin Z$ for every $Z \subsetneq Y$, as we wanted to have.

Finally, let us prove that f_1 preserves and reflects paths. Let $u \rightsquigarrow v$ be a non-trivial path in T_1, so that $\mathscr{A}(v) \subseteq \mathscr{A}(u)$. If $\mathscr{A}(v) = \mathscr{A}(u)$, then $u = x^{(1)}_{\mathscr{A}(v),i}$ and $v = x^{(1)}_{\mathscr{A}(v),j}$ with $i > j$, and then by construction T contains a path from $f_1(u) = w_{\mathscr{A}(v),i}$ to $f_1(v) = w_{\mathscr{A}(v),j}$. If, on the contrary, $\mathscr{A}(v) \subsetneq \mathscr{A}(u)$, then $f_1(u) = w_{\mathscr{A}(u),i}$ and $f_1(v) = w_{\mathscr{A}(v),j}$ for some i, j, and, as we saw when we proved that T is an $\mathscr{A}$-tree, T contains a path $w_{\mathscr{A}(u),i} \rightsquigarrow w_{\mathscr{A}(v),j}$.

Conversely, let $f_1(u) \rightsquigarrow f_1(v)$ be a path in T, and assume that $f_1(u) = w_{\mathscr{A}(u),i}$ and $f_1(v) = w_{\mathscr{A}(v),j}$. Then, the existence of this path entails that

$$\mathscr{A}(v) = \mathscr{A}(w_{\mathscr{A}(v),j}) \subseteq \mathscr{A}(w_{\mathscr{A}(u),i}) = \mathscr{A}(u).$$

If this inclusion is strict, then Corollary 1 implies the existence of a path $u \rightsquigarrow v$ in T_1. On the other hand, if $\mathscr{A}(v) = \mathscr{A}(u)$, then $u = x^{(1)}_{\mathscr{A}(u),i}$ and $v = x^{(1)}_{\mathscr{A}(u),j}$ for some $1 \leqslant i, j \leqslant m_{1,\mathscr{A}(u)}$, and then the definition of f_1 implies that if T contains a path $f_1(u) \rightsquigarrow f_1(v)$, then $i > j$ and therefore there is a path $u \rightsquigarrow v$ in T_1.

This finishes the proof that $f_1 : T_1 \to T$ is a weak topological embedding.

(iv)$\Longrightarrow$(i) This implication is obvious. □

Corollary 3 *Let T_1 and T_2 be $\mathscr{A}$-trees. Then, the following assertions are equivalent:*

(i) T_1 and T_2 are ancestrally compatible.
(ii) T_1 and T_2 are locally compatible.
(iii) Their $\mathscr{A}$-subtrees $\bar{T}_1$ and $\bar{T}_2$ described in Definition 5 satisfy condition (iii) in Theorem 1.
(iv) The join $T_{1,2}$ of T_1 and T_2 is an $\mathscr{A}$-tree and the mappings $f_1 : V(T_1) \to V(T_{1,2})$ and $f_2 : V(T_2) \to V(T_{1,2})$ are weak topological embeddings.

Proof By Lemma 2, T_1 and T_2 are locally compatible if and only if $\bar{T}_1$ and $\bar{T}_2$ are so, and by Proposition 3, T_1 and T_2 are ancestrally compatible if and only if $\bar{T}_1$ and $\bar{T}_2$ are so. These facts, together with the last theorem, prove the implications (i)⇒(ii) and (ii)⇒(iii). As far as (iii)⇒(iv) goes, it is a direct consequence of the corresponding implication in the last theorem together with the proof of Proposition 3. □

Corollary 4 *Let T_1 and T_2 be semi-labeled trees over $\mathscr{A}$. Then, the following assertions are equivalent:*

(i) T_1 and T_2 admit simultaneous weak topological embeddings into a same semi-labeled tree over $\mathscr{A}$.
(ii) T_1 and T_2 are ancestrally compatible.
(iii) T_1 and T_2 are locally compatible.
(iv) Their $\mathscr{A}$-subtrees $\bar{T}_1$ and $\bar{T}_2$ described in Definition 5 satisfy condition (iii) in Theorem 1.
(v) The join $T_{1,2}$ of T_1 and T_2 is a semi-labeled tree and the mappings $f_1 : V(T_1) \to V(T_{1,2})$ and $f_2 : V(T_2) \to V(T_{1,2})$ are weak topological embeddings.

Proof It only remains to prove (iv)$\Longrightarrow$(v). And to do that, it is enough to notice that if T_1 and T_2 are semi-labeled trees over $\mathscr{A}$ such that $\bar{T}_1$ and $\bar{T}_2$ satisfy condition (iii) in Theorem 1, then their join $T_{1,2}$ is not only an $\mathscr{A}$-tree, but a semi-labeled tree, because, since $f_1 : T_1 \to T_{1,2}$ and $f_2 : T_2 \to T_{1,2}$ are jointly surjective, no elementary node in it remains unlabeled. □

6 Algorithmic Details

The equivalence between ancestral compatibility and the properties of the cluster representations of the trees established in Theorem 1, leads to a very simple polynomial-time algorithm for testing ancestral compatibility of two semi-labeled trees. The detailed pseudo-code of the algorithm is shown in Fig. 15.

```
compatible(T1, T2)
𝒜 := 𝒜(T1) ∩ 𝒜(T2)
T̄1 := T1|𝒜
T̄2 := T2|𝒜
foreach label A ∈ 𝒜 do
    let X1 be the smallest member of 𝒞𝒜(T̄1) containing A
    let X2 be the smallest member of 𝒞𝒜(T̄2) containing A
    if X1 ≠ X2 then
        return X1 and X2 are incompatible
foreach cluster X1 ∈ 𝒞𝒜(T̄1) do
    foreach cluster X2 ∈ 𝒞𝒜(T̄2) do
        if X1 ∩ X2 ≠ ∅ and X1 ⊈ X2 and X2 ⊈ X1 then
            return X1 and X2 are incompatible
return T1 and T2 are compatible
```

Fig. 15 Algorithm for testing ancestral compatibility of two semi-labeled trees T_1 and T_2

We have implemented in Perl this compatibility test, and the implementation is freely available for download from the BioPerl collection of Perl modules for computational biology [13]. Given two semi-labeled trees T_1 and T_2 with common labels $\mathscr{A} = \mathscr{A}(T_1) \cap \mathscr{A}(T_2)$, if the trees are incompatible, the actual implementation collects and returns all labels $A \in \mathscr{A}$ such that be the smallest member of $\mathscr{C}_{\mathscr{A}}(T_1|\mathscr{A})$ containing A does not coincide with be the smallest member of $\mathscr{C}_{\mathscr{A}}(T_2|\mathscr{A})$ containing A, as well as all pairs of clusters $X_1 \in \mathscr{C}_{\mathscr{A}}(T_1|\mathscr{A})$ and $X_2 \in \mathscr{C}_{\mathscr{A}}(T_2|\mathscr{A})$ such that $X_1 \cap X_2 \neq \emptyset$, $X_1 \not\subseteq X_2$, and $X_2 \not\subseteq X_1$. This additional information constitutes a *certificate of incompatibility*, which can be useful for checking the underlying phylogenetic studies that have lead to incompatible clusters.

The following Perl code illustrates the use of the `Bio::Tree::Compatible` module for testing compatibility of two semi-labeled trees and listing all pairs of incompatible clusters in the trees.

```
use Bio::Tree::Compatible;
use Bio::TreeIO;

my $filename = $ARGV[0];
my $input = new Bio::TreeIO('-format' => 'newick',
                            '-file' => $filename);
my $t1 = $input->next_tree;
my $t2 = $input->next_tree;

my ($incompat, $ilabels, $inodes) =
  $t1->Bio::Tree::Compatible::is_compatible($t2);
```

```
if ($incompat) {
  print "the␣trees␣are␣incompatible\n";

  my %cluster1 = %{
    $t1->Bio::Tree::Compatible::cluster_representation };
  my %cluster2 = %{
    $t2->Bio::Tree::Compatible::cluster_representation };

  if (scalar(@$ilabels)) {
    foreach my $label (@$ilabels) {
      my $node1 = $t1->find_node(-id => $label);
      my $node2 = $t2->find_node(-id => $label);
      my @c1 = sort @{ $cluster1{$node1} };
      my @c2 = sort @{ $cluster2{$node2} };
      print "label␣$label";
      print "␣cluster"; map { print "␣",$_ } @c1;
      print "␣cluster"; map { print "␣",$_ } @c2;
      print "\n";
    }
  }

  if (scalar(@$inodes)) {
    while (@$inodes) {
      my $node1 = shift @$inodes;
      my $node2 = shift @$inodes;
      my @c1 = sort @{ $cluster1{$node1} };
      my @c2 = sort @{ $cluster2{$node2} };
      print "cluster"; map { print "␣",$_ } @c1;
      print "␣properly␣intersects␣cluster";
      map { print "␣",$_ } @c2; print "\n";
    }
  }
} else {
  print "the␣trees␣are␣compatible\n";
}
```

An application of `Bio::Tree::Compatible` is shown in Fig. 16. The input consists of two phylogenetic trees describing the evolution of angiosperms (plants that flower and form fruits with seeds), obtained from study S11x5x95c19c35c30 in the TreeBASE [4] phylogenetic database.

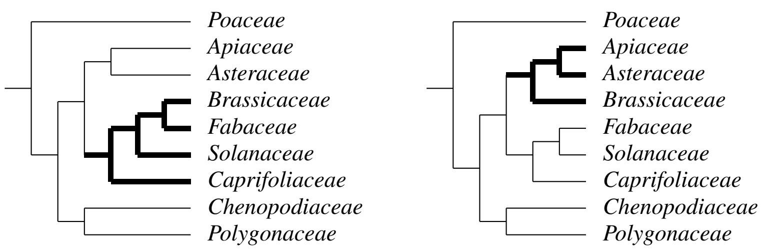

Fig. 16 Two incompatible phylogenetic trees, obtained from study S11x5x95c19c35c30 in TreeBASE. The clusters shown with thick lines are incompatible.

Another application of `Bio::Tree::Compatible` is shown in Fig. 17. The input consists of two semi-labeled trees describing the evolution of Skinnera (a group of four Fuchsia species that grows spontaneously out of the American continent, in New Zealand and on Tahiti), obtained from study S11x4x95c21c16c44 in TreeBASE.

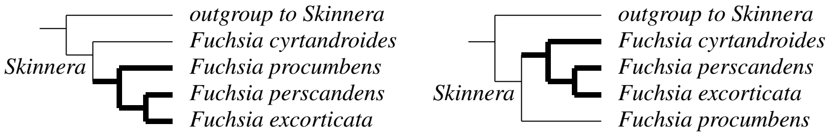

Fig. 17 Two incompatible semi-labeled trees, obtained from study S11x4x95c21c16c44 in TreeBASE. The clusters shown with thick lines are incompatible.

A third application of `Bio::Tree::Compatible` is shown in Fig. 18. The input consists of two semi-labeled trees describing the evolution of net-veined Lilliaflorae, obtained from study S2x4x96c17c14c22 in TreeBASE.

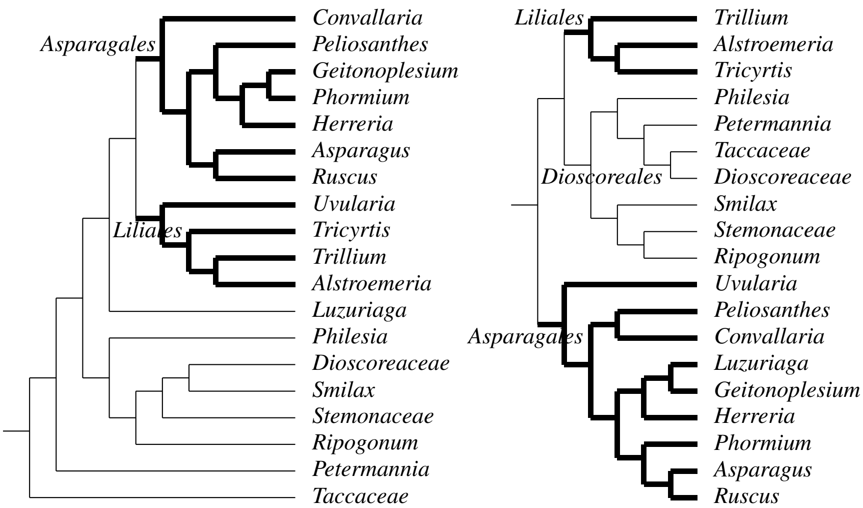

Fig. 18 Two incompatible semi-labeled trees, obtained from study S2x4x96c17c14c22 in TreeBASE. The clusters shown with thick lines are incompatible.

Using the `Bio::Tree::Compatible` module, we have performed a systematic study of tree compatibility on TreeBASE, which currently contains 2,592 phylogenies with over 36,000 taxa among them. In this study, we have found 2,527 pairs of incompatible trees (like those shown in Figs. 16 to 18) from a total of 3,357,936 pairs of trees. The resulting ratio of 0.075% shows the high internal consistency among the phylogenies, and it complements previous large-scale analyses of TreeBASE [7].

7 Conclusions

Phylogenetic tree compatibility is the most important concept underlying widely-used methods for assessing the agreement of different phylogenetic trees with overlapping taxa and combining them into common supertrees to reveal the tree of life. The study of the compatibility of phylogenetic trees with nested taxa, also known as semi-labeled trees, was asked for in [6], and the notion of ancestral compatibility was introduced in [3, 10].

We have analyzed in detail the meaning of the ancestral compatibility of semi-labeled trees from the points of view of the local structure of the trees, of the existence of embeddings into a common supertree, and of the joint properties of their cluster representations. We have established the equivalence between ancestral compatibility and the absence of certain incompatible pairs and triples of labels in the trees under comparison, and have also proved the equivalence between ancestral compatibility and a certain property of the cluster representations of the trees.

Our analysis has lead to a very simple polynomial-time algorithm for testing ancestral compatibility, which we have implemented and is freely available for download from the BioPerl collection of Perl modules for computational biology. Future work includes extending the `Bio::Tree::Compatible` implementation into a `Bio::Tree::Supertree` module for building a common supertree of two compatible semi-labeled trees.

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