POTT'S PARTITION FUNCTION AND ISOMORPHISMS OF TREES

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Abstract. We explore the well-known Stanley conjecture stating that the symmetric chromatic polynomial distinguishes non-isomorphic trees. The graph isomorphism problem has been extensively studied for decades. There are strong algorithmic advances, but our research concentrates on the following question: is there a natural function on graphs that decides graph isomorphism? Curiously, in mathematics and in physics the concepts of a "natural" graph function bear strong similarities: it essentially means that the function comes from the Tutte polynomial, which in physics is called the Potts partition function. Somewhat surprisingly, after decades of study, this bold project is still not infirmed. The aim of our research is to present a result that supports the project: we prove that the Stanley isomorphism conjecture holds for every good class of vertex-weighted trees. Good classes are rich: letting $C$ be the class of all vertex-weighted trees, one can obtain for each weighted tree $(T, w)$ a weighted tree $(T', w')$ in polynomial time, so that $C' := \{ (T', w') : (T, w) \in C \}$ is good and two elements $(A, b)$ and $(X, y)$ of $C$ are isomorphic if and only if $(A', b')$ and $(X', y')$ are.

1. Introduction

We are interested in the classical question about the existence of a natural function on graphs that decides graph isomorphism. We start by introducing Stanley’s conjecture along with related graph polynomials.

Stanley’s conjecture. A $k$-colouring of a graph $G = (V, E)$ is a mapping $s : V \to \mathbb{N}$. The colouring $s$ is a $k$-colouring if $f(V) = \{0, \ldots, k - 1\}$, and it is proper if $s(u) \neq s(v)$ whenever $uv \in E$. We let $\text{Col}(G; k)$ be the set of proper $k$-colourings of $G$ and $\text{Col}(G)$ be the set of all proper colourings of $G$, that is, $\text{Col}(G) := \bigcup_{k \in \mathbb{N}} \text{Col}(G; k)$.

The symmetric function generalisation of the chromatic polynomial is defined by

$$X_G(x_0, x_1, \ldots) := \sum_{s \in \text{Col}(G)} \prod_{v \in V} x_{s(v)}.$$

Further, the symmetric function generalisation of the bad colouring polynomial is defined by

$$XB_G(t, x_0, x_1, \ldots) := \sum_{s : V \to \mathbb{N}} (1 + t)^{b(s)} \prod_{v \in V} x_{s(v)},$$

where $b(s) := |\{ uv \in E : s(u) = s(v) \}|$ is the number of monochromatic edges of $f$ (note that the sum ranges over all (not necessarily proper) colourings of $G$).

The Stanley isomorphism conjecture proposes that $X_G$ distinguishes non-isomorphic trees. As far as we know, the only result towards the Stanley’s conjecture has been recently verified for the class of proper caterpillars. (A caterpillar is a tree where the edges not-incident to a leaf...
form a path, and a caterpillar is proper if each vertex is a leaf or adjacent to a leaf.) Let us also mention that Conti, Contucci and Falcone [3] defined a polynomial $P_T$ for each tree $T$ so that $P_T = P'_T$ only if the trees $T$ and $T'$ are isomorphic. However, the polynomial $P_T$ is not related to the Tutte polynomial.

Noble and Welsh’s conjecture. Noble and Welsh [4] defined the $U$-polynomial and showed that it is equivalent to $XB_G$. Sarmiento [2] proved that the polychromatic defined by Brylawski [2] is also equivalent to the $U$-polynomial. Hence the $U$-polynomial serves as ‘the’ mighty polynomial graph invariant. It is defined as follows. Given a partition $\tau = (C_1, \ldots, C_\ell)$ of a set, we define $x(\tau)$ to be $x_{|C_1|} \ldots x_{|C_\ell|}$:

$$U_G(z, x_1, x_2 \ldots) := \sum_{A \subseteq E(G)} x(\tau_A)(z - 1)^{|A| - |V| + c(A)},$$

where $\tau_A = (C_1, \ldots, C_\ell)$ is the partition of $|V|$ given by the components of the spanning subgraph $(V, A)$ of $G$.

Noble and Welsh conjectured that $U_G$ distinguishes non-isomorphic trees. As observed by Thatte [9], it turns out that Stanley’s and Noble and Welsh’s conjectures are equivalent.

Loebl’s conjectures. Let $k \in \mathbb{N}$. The $q$-chromatic function [5] of a graph $G = (V, E)$ is

$$M_G(k, q) := \sum_{x \in \text{Col}(G, k)} q^{\sum_{v \in V} s(v)}.$$  

It is known [5] that

$$M_G(k, q) = \sum_{A \subseteq E} (-1)^{|A|} \prod_{W \in C(A)} (k)_q^{|W|},$$

where $C(A)$ is the set of components of the spanning subgraph $(V, A)$ and $|C|$ is the number of vertices in the component $C$. Moreover the $q$-dichromate is defined as

$$B_G(x, y, q) := \sum_{A \subseteq E} x^{|A|} \prod_{W \in C(A)} (y)_q^{|W|}$$

and it is known that $B_G(x, y, q)$ is equal to the partition function of Potts model with certain magnetic field contribution.

Loebl conjectures that the $q$-dichromate is equivalent to the $U$-polynomial, and that $q$-dichromate distinguishes non-isomorphic chordal graphs. There is a close link between these strong conjectures and Stanley’s conjecture, since chordal graphs have a very distinguished tree structure — in graph theory, they are often referred to as ‘blown-up trees’. On the other hand, the isomorphism problem for general graphs is equivalent to the isomorphism problem restricted to chordal graphs: given a graph $G = (V, E)$, consider the chordal graph $G' = (V', E')$ so that $V' := V \cup E$ and $E' = \left(\binom{V}{2}\right) \cup \{\{u, e\}, \{v, e\} : \{u, v\} = e \in E\}$. It clearly holds that $G$ and $H$ are isomorphic if and only if $G'$ and $H'$ are isomorphic.

Recently a variant of the $q$-dichromate, $B_{r, G}(x, k, q)$, was proposed [4]:

$$B_{r, G}(x, k, q) := \sum_{A \subseteq E(G)} x^{|A|} \prod_{C \in C(A)} \sum_{i=0}^{k-1} r^{|C|} q^i.$$  

It is proved that if $(k, r) \in \mathbb{N}^2$ with $r > 1$ and $x := e^{\beta J} - 1$, then

$$B_{r, G}(x, k, q) = \sum_{\sigma : V \rightarrow \{1, \ldots, k\}} e^{\beta \sum_{uv \in E(G)} J(\sigma(u), \sigma(v))} \prod_{v \in V} q^{s(v)}.$$  

Hence $B_{r,G}(x, k, q)$ is the Potts partition function with variable $(k)$ number of states and with magnetic field contribution $r \sum_{v \in V} q^r(v)$. Moreover, it is proved that $B_{r,G}$ is equivalent to $U_G$.

**Summarising**, establishing the conjecture that $U_G$ distinguishes non-isomorphic chordal graphs would successfully finish the isomorphism project since $U_G$ is equivalent to the Potts partition function with variable number of states and with magnetic field contribution, and the isomorphism problem for general graphs is equivalent to the isomorphism problem of the chordal graphs. Moreover the Stanley’s conjecture is equivalent to the assertion that $U_G$ distinguishes non-isomorphic trees.

The purpose of this work is to prove that the U-polynomial distinguishes non-isomorphic **weighted trees** in any good family. Good families are rich: we provide examples of good families $F$ so that the isomorphism problem for general weighted trees is equivalent to the isomorphism problem in $F$. We hope that eventually it will be possible to introduce an analogous notion restricted to chordal graphs, relying on the extensively studied tree-decomposition theory.

### 1.1. Main Results.

A weighted tree is a pair $(T, w)$ where $T$ is a tree and $w : V(T) \to \mathbb{N}^+$ is a positive integer vertex-weight function on $T$. Two weighted trees are isomorphic if there is an isomorphism of the trees that preserves the vertex weights. If $(T, w)$ is a weighted tree then naturally

$$U(T, w)(z, x_1, x_2 \ldots) = \sum_{A \subset E(G)} x(\alpha_A)((z - 1)^{|A| - \sum_e w(e) + c(A)},$$

where $\alpha_A = (V_1, \ldots, V_\ell)$ is the partition of $V$ determined by the components of the spanning subgraph $(V, A)$ of $G$.

Let $(T, w)$ be a weighted tree. If $e \in E(T)$, then $T - e$ is the disjoint union of two trees, which we consider to be weighted and rooted at the endvertex of $e$ that they contain. A rooted weighted tree $(S, w_S)$ is a shape of $(T, w)$ if $2 \leq |V(S)| \leq |V(T)| - 2$ and there exists an edge $e \in E(T)$ such that $S$ is one of the two components of $T - e$; moreover $w_S$ is the restriction of $w$ to the vertices of $S$. We consider $S$ rooted at the end-vertex of $e$. We usually shorten the notation and write $S$ for the shape $(S, w_S)$. In a tree, a vertex of degree one is called a leaf.

**Definition 1.1.** A set $\mathcal{T}$ of weighted trees $(T, w)$ is good if it satisfies the following properties:

1. If a vertex of $T$ is adjacent to a leaf, then all its neighbours but one are leaves.
2. If $v$ is a leaf or has a neighbour that is a leaf, then $w(v) = 1$.
3. Let $(T, w), (T', w') \in \mathcal{T}$ and let $S$ be a shape of $T$ such that $w(S) \leq w(T)/2$. Let $S'$ be a shape of $T'$ such that the multi-set of the vertex weights with multiplicities of $S$ is equal to the multi-set of the vertex weights with multiplicities of $S'$. Then $S$ is isomorphic to $S'$.

**Definition 1.2.** A set $S$ of weighted trees is relevant if there is an efficient algorithm that computes, for each weighted tree $(T, w)$, a weighted tree $(T', w') \in S$ so that whenever $(T_1, w_1)$ and $(T_2, w_2)$ are weighted trees, $(T_1, w_1)$ is isomorphic to $(T_2, w_2)$ if and only if $(T'_1, w'_1)$ is isomorphic to $(T'_2, w'_2)$.

An example of a good relevant set of weighted trees is that composed of all weighted single vertices. Indeed, the classical isomorphism test for trees can easily be extended to the weighted trees; it amounts to coding $n$-vertex-weighted trees by $0$-$1$ vectors of length polynomial in $n$. This can be seen as assigning a non-negative integer weight to a single vertex. Such weighted single vertices are of course distinguished by the U-polynomial.

Our purpose is to provide a wide generalisation of this fact, by proving the next statement.

**Theorem 1.** The U-polynomial distinguishes non-isomorphic weighted trees in any good set.
Our proof of Theorem 2 is not constructive in the sense that we are not able to reconstruct the weighted tree \( T \) from \( \mathcal{U}_T \).

We illustrate the richness of good sets of weighted trees by our next theorem. Let \( \mathcal{C} \) be the class of all vertex-weighted trees \((T, w)\) with \( \max \{ w(v) : v \in V(T) \} \leq 2^{|V(T)|} \), where we assume for convenience that each weight is given as a binary number with exactly \(|V(T)|\) bits. For each tree \( T \) we define \( T' \) to be the tree obtained from \( T \) by identifying each leaf \( h \) with the root of one new star \( S_h \) with three vertices.

**Theorem 2.** For each \((T, w) \in \mathcal{C}\), one can construct a weight function \( w' \) for the vertices of \( T' \) such that two elements \((T_1, w_1)\) and \((T_2, w_2)\) of \( \mathcal{C} \) are isomorphic if and only if the corresponding elements \((T'_1, w'_1)\) and \((T'_2, w'_2)\) are isomorphic. Furthermore, the set \( \mathcal{C}' := \{(T', w') : (T, w) \in \mathcal{C}\} \) is good.

**Proof.** Let \((T, w) \in \mathcal{C}\). We start by showing how to construct a weight function \( w' \) for \( T' \). First, we let the weight of each leaf of \( T' \), that is, each vertex of \( T' \setminus T \), be 1. Next we perform, to \((T, w) \subset (T', w)\), a variant of the coding for the classical isomorphism test for weighted trees mentioned above. The coding gradually assigns a binary vector \( w''(v) \) to each vertex \( v \), starting with the neighbours of the leaves of \( T' \), i.e., the leaves of \( T \), which are all assigned \((01)\) in the first step. We assume binary vectors to be ordered according to the positive integer they code.

In each further step \( t > 1 \), we let \( S_t \) be the set of the vertices \( v \) with exactly one neighbour that has not been assigned its \( w'' \)-code before step \( t \). For each \( v \in S_t \), we define \( c(v) \) to be obtained from \( w(v) \) and from the constructed \( w''\)-codes \( z_1 \geq z_2 \geq \ldots \geq z_m \) of all but one of the neighbours of \( v \), as follows:

\[
c(v) := (0z_1 \ldots z_m1w(v)).
\]

We choose one vertex \( x \in S_t \) such that \( c(x) = \min \{ c(v) : v \in S_t \} \) and we set \( w''(x) := c(x) \).

This finishes step \( t \).

We observe that the following hold after each step \( t \).

(i) If a vertex \( x \) is assigned its code \( w''(x) \) in step \( t \) and its neighbour \( y \) is assigned its code \( w''(y) \) in an earlier step, then \( w''(x) > w''(y) \).

(ii) If a vertex \( x \) is assigned its code \( w''(x) \) in step \( t \), then there is exactly one shape \( S(x) \) rooted at \( x \) such that each vertex \( v \in S(x) \setminus x \) has been assigned its \( w'' \)-code before step \( t \).

The coding terminates if there is a vertex \( r \) such that all of its neighbours have been assigned a \( w'' \)-code. We observe that when the coding terminates, each vertex but \( r \) has been assigned its \( w'' \)-code.

Finally, if \( v \neq r \), then \( w'(v) \) is the positive integer coded by \( w''(v) \) and we set \( w'(r) := w(r) + \sum_{v \neq r} w'(v) \). The vertex \( r \) is the root of \((T', w')\). This finishes the construction of \((T', w')\).

Let us observe that \((T, w)\) can be reconstructed from \((T', w')\): first, notice that \( T \) is obtained from \( T' \) by deleting all the leaves. In particular, we thus know \(|V(T)|\). Next, the vertex \( r \) is the unique vertex of \( T' \) with the largest weight. Moreover, \( w(r) = w'(r) - \sum_{v \in V(T') \setminus \{r\}} w'(v) \).

In addition, for each vertex \( v \neq r \) the weight \( w(v) \) can be deduced from \( w'(v) \) as follows: the binary representation of \( w(v) \) is equal to the last \(|V(T)|\) digits of the binary representation of \( w'(v) \). This proves the first part of the statement of Theorem 2.

It remains to show that \( \mathcal{C}' \) is a good class of weighted trees. Clearly, Properties [1] and [2] of Definition [3] hold and so it remains to show that so does [4]. Let \((A', b')\) be an element of \( \mathcal{C}' \) and let \( S \) be a shape of \( A' \) such that \( b'(S) \leq b'(A)/2 \). Then the root of \((A', b')\) does not belong to \( S \). Hence, letting \( s \) be the root of \( S \) we infer that \( S = S(s) \) thanks to Property [5]. It follows that \( s \) is the unique vertex of \( S \) with maximum \( b' \)-weight and \( S \) can be uniquely reconstructed from \( b'(s) \). This shows the second part of the statement of Theorem 2 thereby ending the proof. □
2. The Structure of the Proof of Theorem 1

We fix a good set of weighted trees and, from now on, we say that a weighted tree is *good* if it belongs to this set. We write down a procedure and with its help prove Theorem 1. The rest of the paper then describes our realisation of the procedure.

A *j-Shape* is an isomorphism class of rooted weighted trees with total weight $j$. We note that a shape is a weighted rooted subtree, while a *j-Shape* is an isomorphism class. We start with an observation.

**Observation 2.1.** Let $(T, w)$ be a weighted tree. Assume that for each $j$-Shape $S$ and each $j \leq w(T)/2$, we know the number of shapes of $(T, w)$ that are isomorphic to $S$. Then we know $T$.

*Proof.* We use an easy but important observation that two shapes of $T$ are either disjoint or one is contained in the other. Let us order the shapes of $(T, w)$ of weight at most $w(T)/2$ decreasingly according to their weight. Let $m$ be the maximum weight of a shape of $T$ and let $S_1, \ldots, S_n$ be the shapes with weight $m$. Clearly, either the shapes $S_1, \ldots, S_n$ are joined in $T$ to the same vertex, or $a = 2$ and $m = w(T)/2$. In the latter case, $T$ is determined. In the former case, let $r$ be the vertex of $T$ to which each of $S_1, \ldots, S_k$ is joined. The shapes of $T$ of weight equal to $m - 1$, if any, are either shapes of $S_1, \ldots, S_n$, which we know, or joined by an edge to $r$. Continuing in this way with weights $m - 2, m - 3, \ldots$, we gradually increase the tree containing $r$ until we reach weight $w(T)$. The resulting tree is $T$. \hfill $\square$

### 2.1. Isomorphism of good weighted trees is U-recognisable

Let $(T, w)$ be a good weighted tree. Let $\alpha(T) = (\alpha_1, \ldots, \alpha_n)$ be the weights of the shapes of $T$, with $\alpha_1 < \ldots < \alpha_n$. The definition of a shape implies that $\alpha_1 \geq 2$. We shall consider both partitions of the integer $w(T)$ and partitions of the tree $T$. To distinguish between them clearly, partitions of an integer are referred to as *expressions*. For each partition $P$ of $T$, the weights of the parts of $T$ form an expression $E$ of $w(T)$, which we call the *characteristic* of $P$.

- A *j-expression* of an integer $W$ is a partition of $W$ in which one of the part has size $W - j$.
- A *j-partition* of $T$ is a partition of $T$ whose characteristic is a *j-expression* of $w(T)$.
- A *j-partition* $(T_0, \ldots, T_k)$ of $T$ with $w(T_0) = w(T) - j$ is *shaped* if there exists an edge $e$ of $T$ such that $T_0$ is one of the components of $T - e$.

For an expression $E$ of a positive integer, we let $U(T, w, E)$ be the number of partitions of $(T, w)$ with characteristic $E$. Note that this number is 0 if $E$ is not an expression of $w(T)$. We notice that, for each expression $E$, the polynomial $U(T, w, E)$ determines $U(T, w, E)$.

We note that among the partitions of $T$ corresponding to an expression, some are shaped and others are not. The proof of Theorem 1 relies on the following procedure.

**Procedure 1.**

**Input:** The polynomial $U(T, w)$, an integer $j \in \{\alpha_1 + 1, \ldots, w(T)/2\}$, a *j-expression* $E$ and, for each $j' < j$ and each $j'$-Shape $S$, the number of shapes of $T$ that are isomorphic to $S$.

**Output:** The number of shaped *j-partitions* of $T$ with characteristic $E$.

Let us see how this procedure allows us to establish Theorem 1.

*Proof of Theorem 1.* Let $(T, w)$ and $(T', w')$ be good weighted trees with $U(T, w) = U(T', w')$. The vector $\alpha(T) = (\alpha_1, \ldots, \alpha_n)$ can be computed from the $U$-polynomial, since its coordinates correspond to the partitions of $T$ into two subtrees, each of weight at least 2. (The same applies for $T'$.)

Recall that $\alpha_1 \geq 2$. Furthermore, a shape $S$ of $T$ or $T'$ is isomorphic to an $\alpha_1$-Shape if and only if $S$ is the star $S^1$ on $\alpha_1$ vertices rooted at its centre. This is because the leaves and...
For any given \( j \)-Shape \( S \), the numbers of shapes of \( T \) and of \( T' \) isomorphic to \( S \) are the same.

This can be argued as follows. A \( j \)-expression \( E \) is valid if there is a shaped \( j \)-partition of \( T \) with characteristic \( E \). If \( E \) is a \( j \)-expression, then we let \( W(E) \) be the multi-set consisting of all the parts of \( E \). We define \( S(E) \) to be the \( j \)-Shape isomorphic to a shape of \( T \) whose vertex weights are given by \( W(E) \), which can be done thanks to (3) of Definition 1.1 since \( T \) is good. It is possible that \( S(E) \) does not exist in which case \( E \) is redefined as invalid. (Indeed, \( S(E) \) does not exist when the following holds: if \( S \) is a shape of \( T \) with shaped partition \( W \), then at least one part of \( W \) does not correspond to a single vertex of \( S \).)

A valid \( j \)-expression \( E \) is minimal if no proper refinement of \( E \) is valid. If \( E \) is minimal, then the number of shaped \( j \)-partitions of \( T \) with characteristic \( E \) is equal to the number of shapes of \( T \) isomorphic to \( S(E) \). We note that we do not know \( S(E) \), but we do know that \( T \) and \( T' \) have the same number of shapes isomorphic to \( S(E) \).

Finally, consider a valid \( j \)-expression \( E \) such that for each valid refinement \( E' \) of \( E \), we know that \( T \) and \( T' \) have the same number \( n(E') \) of shapes isomorphic to \( S(E') \). Now, the number of shapes of \( T \) (and of \( T' \)) isomorphic to \( S(E) \) is equal to the number of shaped \( j \)-partition of \( T \) with characteristic \( E \) minus a non-negative integer linear combination of \( n(E') \), where \( E' \) is a valid refinement of \( E \). Again we note that we do not know the coefficients \( n(E') \), since we do not know the Shapes \( S(E') \). But we do know that these coefficients are the same in \( T' \) as well, and so we can conclude that the numbers of shapes of \( T \) and of \( T' \) isomorphic to \( S(E) \) are the same.

\[ \Box \]

### 3. Designing Procedure \( \mathcal{E} \)

An \( \alpha_j \)-situation \( \sigma \) is a tuple \( (\{\sigma_1, w_1\}, \ldots, (\sigma_t(\sigma), w_t(\sigma))) \) of disjoint weighted rooted trees with \( t(\sigma) \geq 2 \) such that \( w_1(\sigma_1) \leq \ldots \leq w_t(\sigma)(\sigma_t(\sigma)) \) and \( \sum_{i=1}^{t(\sigma)} w_i(\sigma_i) = \alpha_j \). An \( \alpha_j \)-situation \( \sigma \) is said to occur in a tree \( T \) if there exists a subtree \( T' \) of \( T \) and \( t(\sigma) \) distinct edges \( e_1, \ldots, e_t(\sigma) \) with exactly one end in \( V(T') \) such that, for each \( i \in \{1, \ldots, t(\sigma)\} \), there is an isomorphism preserving the root and the weights between \( \sigma_i \) and the component of \( T - e_i \) different from \( T' \). Note that if \( \sigma \) occurs in \( T \), then for each \( i \in \{1, \ldots, t(\sigma)\} \) the tree \( T \) has a shape isomorphic to \( \sigma_i \).

We proceed in steps, the first one being an exhaustive listing that depends only on \( \alpha_j \).

**Step 1.** Explicitly list all \( \alpha_j \)-situations for \( \alpha_j \leq w(T)/2 \).

**Step 2.** For each \( \alpha_j \leq w(T)/2 \) and each \( \alpha_j \)-situation \( \sigma \) from Step 1, compute the number \( mT(\sigma) \) of times \( \sigma \) occurs in \( T \).

Before designing Step 2, we show how Steps 1 and 2 accomplish Procedure \( \mathcal{E} \). Suppose that the two steps are completed. Let \( E = \{E_1, \ldots, E_k\} \) be an \( \alpha_j \)-expression of \( w(T) \).
For each α_j-situation σ = ((σ_1, w_1), . . . , (σ_t(σ), w_t(σ))), let \( \Psi_σ \) be the collection of all surjections from the expression \( \{ E_1, \ldots, E_b \} \) to \( \{ σ_1, \ldots, σ_t(σ) \} \). We observe that the number \( X \) of non-shaped \( j \)-partitions of \( T \) with characteristic \( E \) is

\[
\sum_{α_j\text{-situation } σ} m_T(σ) \sum_{f ∈ \Psi_σ} \sum_{i=1}^{t(σ)} U(σ, f^{-1}(σ_i)),
\]

where \( f^{-1}(σ_i) \) is naturally interpreted as an expression. Notice that this formula allows us to compute \( X \): for each \( i ∈ \{1, \ldots, t(σ)\} \), the tree \( σ_i \) is given by \( σ \), hence the \( U \)-polynomial of \( σ_i \) can be computed. Consequently, we can compute the number of shaped \( α_j \)-partitions of \( T \) with characteristic \( E \), which is

\[
U(T, w, E) - X.
\]

This accomplishes Procedure \[1\].

It remains to design Step 2. Fix a situation \( σ = ((σ_1, w_1), . . . , (σ_t, w_t)) \).

**Observation 3.1.** For every pair \((i, j) ∈ \{1, \ldots, t\}^2 \), if \( T_i \) and \( T_j \) are two shapes of a tree \( T \) that are isomorphic to \( σ_i \) and \( σ_j \), respectively, then either \( T_i ⊆ T_j \) or \( T_j ⊆ T_i \), or \( T_i \cap T_j = ø \).

To see this, let \( e_k \) be the edge of \( T \) such that \( T_j \) is a component of \( T - e_k \) for \( k ∈ \{i, j\} \). Then, either \( e_j ∈ E(T_i) \) or \( e_j ∈ E(T - T_i) \). If \( e_j ∈ E(T - T_i) \), then either \( T_j ⊆ T_i \) or \( T_j ⊆ T - T_i \), in which case \( T_i \cap T_j = ø \). If \( e_j ∈ E(T_i) \), then \( T_j ⊆ T_i \); otherwise, \( T_j \cap T_i ≠ ø \) and \( T - T_i ⊆ T_j \), so that \( w(T_i) + w(T_j) > w(T) \). This would contradict the hypothesis that \( \sum_{i=1}^{t(σ)} w_k(σ_k) = α_j \), since \( α_j ≤ w(T)/2 \). This concludes the proof of Observation \[3.1\].

Define \( Λ \) to be the set of all \( t \)-tuples \((T_1, . . . , T_t)\) such that for each \( i ∈ \{1, . . . , t\} \),

- \( T_i \) is a shape of \( T \) that is isomorphic to \( (σ_i, w_i) \), and
- if \( j ∈ \{1, . . . , t\} \setminus \{i\} \), then \( T_i \) is not a subtree of \( T_j \).

**Observation 3.2.** The number of times that \( σ \) occurs in \( T \) is equal to \(|Λ|\).

**Proof.** We prove that the elements of \( Λ \) are exactly occurrences of \( σ \) in \( T \). By the definition, each occurrence of \( σ \) gives rise to an element of \( Λ \).

Conversely, let \((T_1, . . . , T_t)\) be an element of \( Λ \). Observation \[3.1\] implies that the shapes \( T_i \) are mutually disjoint. For each \( k ∈ \{1, . . . , t\} \), let \( e_k \) be the edge of \( T \) associated to the shape \( T_k \) and let \( v_k \) be the endvertex of \( e_k \) that does not belong to \( T_k \). Note that \( v_k ≠ \cup_{j=1}^{t} T_j \) since no tree \( T_i \) is a subtree of another tree \( T_j \) and \( α_j ≤ w(T)/2 \). Set \( T'_k := T_{k-1} - T_k \), where \( T'_0 := T \).

Observe that each of \( T_{k+1}, . . . , T_t \) is a shape of \( T'_k \). Hence, \( T'_k \) is connected and contains all vertices \( v_1, . . . , v_t \). Therefore, setting \( T' := T'_t \) shows that \((T_1, . . . , T_t)\) occurs in \( T \). \( \square \)

Our goal is to compute \(|Λ|\). For a tree \( T' \), define \( Λ_0(T') \) to be the set of all \( t \)-tuples \((T_1, . . . , T_t)\) such that \( T_i \) is a shape of \( T' \) that is isomorphic to \((σ_i, w_i)\) for each \( i ∈ \{1, . . . , t\} \). Set \( Λ_0 := Λ_0(T, w) \). In this notation, the weight shall be omitted when there is no risk of confusion. The advantage of \( Λ_0 \) is that its size can be computed. Indeed,

\[
|Λ_0| = \prod_{i=1}^{t} P((σ_i, w_i) \rightarrow T),
\]

where \( P((σ_i, w_i) \rightarrow T) \) is the number of shapes of \( T \) that are isomorphic to \((σ_i, w_i)\). This number is given in the input of Procedure \[1\] since \( w_i(σ_i) < α_j \).

Next, we compute \(|Λ|\) using the principle of inclusion and exclusion. Setting \( I := \{1, . . . , t\}^2 \setminus \{(i, i) : 1 ≤ i ≤ t\} \), we have

\[
|Λ| = |Λ_0| - \bigg| \bigcup_{(i,j)∈I} Λ_{(i,j)} \bigg|,
\]
where \( \Lambda_{(i,j)} \) is the subset of \( \Lambda_0 \) composed of the elements \((T_1, \ldots, T_t)\) with \( T_i \subseteq T_j \).

By the principle of inclusion-exclusion, we deduce that the output of Step 2 is equal to

\[
|\Lambda_0| - \sum_{\emptyset \neq F \subseteq I} (-1)^{|F|-1} \left| \bigcap_{(i,j) \in F} \Lambda_{(i,j)} \right|.
\]

It remains to compute \( \bigcap_{(i,j) \in F} \Lambda_{(i,j)} \) for each non-empty subset \( F \) of \( I \). We start with an observation, which characterises the sets \( F \) for which the considered intersection is not empty.

**Observation 3.3.** Let \( F \subseteq I \). Then, \( \bigcap_{(i,j) \in F} \Lambda_{(i,j)} \neq \emptyset \) if and only if for every \((i,j) \in F\), either \( \sigma_i \) is isomorphic to \( \sigma_j \), or \( \sigma_j \) has a shape that is isomorphic to \( \sigma_i \).

From now on, we consider only contributing sets \( F \). We construct four directed graphs \( W_0, W_1, W_2 \) and \( W_3 \) that depend on \( F \). Each vertex \( x \) of \( W_k \) is labeled by a subset \( \ell(x) \) of \( \{(\sigma_1, w_1), \ldots, (\sigma_t, w_t)\} \). These labels will have the following properties.

1. \( \ell(x) \) is a partition of \( \{(\sigma_i, w_i)\} \).
2. For each vertex \( x \) of \( W_k \), all weighted trees in \( \ell(x) \) are isomorphic.
3. \( |\bigcap_{(i,j) \in F} \Lambda_{(i,j)}| \) is equal to the number of elements \( \{T_1, \ldots, T_t\} \) of \( \Lambda_0 \) such that
   - for each vertex \( x \) of \( W_k \), if \( \ell(\sigma_i, w_i) \in \ell(x) \) then \( T_i = T_j \); and
   - for every arc \((x, y)\) of \( W_k \), if \((\sigma_i, w_i), (\sigma_j, w_j) \in \ell(x) \times \ell(y)\), then \( T_i \subseteq T_j \).

The directed graph \( W_0 \) is obtained as follows. We start from the vertex set \( \{z_1, \ldots, z_t\} \). For each \( i \in \{1, \ldots, t\} \), the label \( \ell(z_i) \) of \( z_i \) is set to be \( \{(\sigma_i, w_i)\} \). For each \((i,j) \in F\), we add an arc from \( z_i \) to \( z_j \). Thus \( W_0 \) satisfies properties (1)--(3). Note that \( W_0 \) may contain directed cycles, but by Observation 3.3, if \( C \) is a directed cycle then all elements in \( \cup_{x \in V(C)} \ell(x) \) are isomorphic.

Now, \( W_1 \) is obtained by the following recursive operation. Let \((x, y, z)\) be a triple of vertices such that \((x, y)\) and \((x, z)\) are arcs, but neither \((y, z)\) nor \((z, y)\) are arcs. Let \((\sigma_y, w_y) \in \ell(y)\) and \((\sigma_z, w_z) \in \ell(z)\). We add the arc \((y, z)\) if \( |V(\sigma_y)| \leq |V(\sigma_z)| \), and the arc \((z, y)\) if \( |V(\sigma_z)| |V(\sigma_y)| \). (In particular, if \( |V(\sigma_y)| = |V(\sigma_z)| \), then both arcs are added.)

We observe that \( W_1 \) satisfies (1)--(3). Since neither the vertices nor the labels were changed, the only thing that we need to show is that if the arc \((y, z)\) was added, then for all tuples \((T_1, \ldots, T_t) \in \bigcap_{(i,j) \in F} \Lambda_{(i,j)} \) and all \((\sigma_i, w_i), (\sigma_j, w_j) \in \ell(y) \times \ell(z)\), it holds that \( T_i \subseteq T_j \). This follows from Observation 3.3 since \((y, z)\) was added, there exists \( s \in \{1, \ldots, t\} \) such that \( T_s \) is contained in both \( T_i \) and \( T_j \).

The directed graph \( W_2 \) is obtained by recursively contracting all directed cycles of \( W_1 \). Specifically, for each directed cycle \( C \), all the vertices of \( C \) are contracted into a vertex \( z_C \) (parallel arcs are removed, but not directed cycles of length 2), and \( \ell(z_C) := \cup_{x \in V(C)} \ell(x) \). We again observe that \( W_2 \) satisfies properties (1)--(3).

Finally, \( W_3 \) is obtained from \( W_2 \) by recursively deleting transitivity arcs, that is, the arc \((y, z)\) is removed if there exists a directed path of length greater than 1 from \( y \) to \( z \). Note that \( W_2 \) and \( W_3 \) have the same vertex-set, and every arc of \( W_3 \) is also an arc in \( W_2 \). Again, \( W_3 \) readily satisfies properties (1)--(3).

Now, let us prove that each component of \( W_3 \) is an arborescence, that is a directed acyclic graph with each out-degree at most one. We only need to show that every vertex of \( W_3 \) has outdegree at most 1.

Assume that \((x, y)\) and \((x, z)\) are two arcs of \( W_3 \). First, note that, in \( W_2 \), there is no directed path from \( y \) to \( z \) or from \( z \) to \( y \), for otherwise the arc \((x, y)\) or the arc \((x, z)\) would not belong to \( W_2 \), respectively. Therefore, regardless whether \( y \) and \( z \) arose from contractions of directed cycles in \( W_1 \), there exist three vertices \( x', y' \) and \( z' \) in \( W_1 \) such that both \((x', y')\) and \((x', z')\) are arcs but neither \((y', z')\) nor \((z', y')\) is an arc. This contradicts the definition of \( W_1 \). Consequently, every vertex of \( W_3 \) has outdegree at most 1, as wanted.
Set \( \tau(T) := \{ z((\sigma_i, w_i) \mapsto H) : H \in \{(T, w), (\sigma_1, w_1), \ldots, (\sigma_t, w_t)\} \text{ and } 1 \leq i \leq t \} \). We recall that \( \tau(T) \) is known from the assumptions of Procedure 1. Step 2 is completed by the following procedure.

**Procedure 2.**

**input:** A labeled directed forest \( W \) of arborescences and the set \( \tau(T) \).

**output:** For each \( H \in \{(T, w), (\sigma_1, w_1), \ldots, (\sigma_t, w_t)\} \), the number \( P_3(H, W, \tau(T)) \) of elements \((T_1, \ldots, T_t)\) of \( \Lambda_0(H) \) such that

- for each vertex \( x \) of \( W \), if \((\sigma_i, w_i), (\sigma_j, w_j) \in \ell(x)\) then \( T_i = T_j \); and
- for every arc \((x, y)\) of \( W \), if \(((\sigma_i, w_i), (\sigma_j, w_j)) \in \ell(x) \times \ell(y)\), then \( T_i \subseteq T_j \).

The output of Procedure 2 can be recursively computed as follows. Let \( W_{\text{max}} \) be the set of vertices of \( W \) with outdegree 0. For each vertex \( x \) of \( W \), let \((\sigma^x, w^x)\) be a representative of \( \ell(x) \).

\[
P_3(H, W, \tau(T)) = \prod_{x \in W_{\text{max}}} (z((\sigma^x, w^x) \mapsto H)) \cdot P_3((\sigma^w, w^x), \tilde{W}(w), \tau(T)),
\]

where \( \tilde{W}(w) \) is obtained from the component of \( W \) that contains \( x \) by removing \( x \), and \( z((\sigma^x, w^x) \mapsto H) \) is known thanks to the set \( \tau(T) \).

By property (3) of the labels, the output \( P_3(T, W_3, \tau(T)) \) is equal to \( |\cap_{(i,j) \in F}\Lambda(i,j)| \). This concludes the design of Procedure 1.

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