Counting unlabelled subtrees of a tree is #P-complete*

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Abstract

The problem of counting unlabelled subtrees of a tree (i.e., subtrees that are distinct up to isomorphism) is #P-complete, and hence equivalent in computational difficulty to evaluating the permanent of a 0,1-matrix.

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1 Introduction

Valiant's complexity class #P [10] stands in relation to counting problems as NP does to decision problems. A function $f : \Sigma^* \to \mathbb{N}$ is in #P if there is a nondeterministic polynomial-time Turing machine M such that the number of accepting computations of M on input x is $f(x)$, for all $x \in \Sigma^*$. A counting problem, i.e., a function $f : \Sigma^* \to \mathbb{N}$, is said to be #P-*hard* if every function in #P is polynomial-time Turing reducible to f; it is *complete for* #P if, in addition, $f \in$ #P. A #P-complete problem is equivalent in computational difficulty to such problems as counting the number of satisfying assignments to a Boolean formula, or evaluating the permanent of a 0,1-matrix, which are widely believed to be intractable. For background information on #P and its completeness class, refer to one of the standard texts, e.g., [3, 8].

The main result of the paper—advertised in the abstract, and stated more formally below—is interesting on two counts. First, it provides a rare example of a natural question about trees which is unlikely to be polynomial-time solvable. (Two other examples are determining a vertex ordering of minimum bandwidth [1, 4], or determining the "harmonious chromatic number" [2].) Second, it is, as far as we are aware, the first intractability result concerning the counting of unlabelled structures.

Some definitions. By *rooted tree* (T, r) we simply mean a tree T with a distinguished vertex r, the *root*. An *embedding* of a tree T' in a tree T is a injective map ι from the vertex set of T' to the vertex set of T such that $(\iota(u), \iota(v))$ is an edge of T whenever (u, v) is a edge of T'. Sometimes T' and T will be rooted, in which case we may insist that ι maps the root r' of T' to the root $r = \iota(r')$ of T. We now define a sequence of problems leading to one of interest; we do not claim that both the intermediate problems are particularly natural.

Name. #BipartiteMatchings.

Instance. A bipartite graph G.

Output. The number of matchings of all sizes in G.

Name. #CommonRootedSubtrees.

Instance. Two rooted trees, (T_1, r_1) and (T_2, r_2).

Output. The number of distinct (up to isomorphism) rooted trees (T, r) such that (T, r) embeds in (T_1, r_1) and (T_2, r_2) with r mapped to r_1 and r_2, respectively.

Name. #RootedSubtrees.

Instance. A rooted tree, (T, r).

Output. The number of distinct (up to isomorphism) rooted trees (T', r') such that (T', r') embeds in (T, r) with r' mapped to r.

Name. #SUBTREES.

Instance. A tree T.

Output. The number of distinct (up to isomorphism) subtrees of T.

We will use each of the problem names in an obvious way to denote a function from instances to outputs: thus #ROOTEDSUBTREES(T, r) denotes the number of distinct rooted subtrees of the rooted tree (T, r). Our main result is the following.

Theorem 1 *#SUBTREES is #P-complete.*

Proof. #BIPARTITEMATCHINGS is the sixth problem on Valiant's original list of #P-complete problems [10]. So #P-hardness of #SUBTREES follows from Lemmas 2–4 and from the transitivity of polynomial-time Turing reducibility. We will now show that #SUBTREES is in #P. Suppose that T is a tree with vertex set $V_n = \{v_0, \ldots, v_{n-1}\}$. We will order the vertices in V_n so that $v_i < v_j$ iff $i < j$. For every (labelled) subtree T' of T, let $V(T')$ denote the vertex set of T'. We will say that subtree T'' is *larger* than subtree T' if and only if there is a vertex $v_i \in V_n$ such that $v_i \in V(T'')$, $v_i \notin V(T')$ and

$$V(T') \cap \{v_{i+1}, \ldots, v_n\} = V(T'') \cap \{v_{i+1}, \ldots, v_n\}.$$

Let T'' be a subtree of T. Either T'' is the smallest subtree of T in its isomorphism class or there is a vertex $v_\ell \in V(T'')$ such that the sub-forest F_ℓ of T induced by vertex set

$$\{v_i \in V_n \mid v_i < v_\ell\} \cup \{v_i \in V(T'') \mid v_i > v_\ell\}$$

contains a tree isomorphic to T''. Thus, one can determine whether T'' is the smallest subtree of T in its isomorphism class by solving *subgraph isomorphism* with inputs F_ℓ and T'' for all $v_\ell \in V(T'')$. Since F_ℓ is a forest and T'' is a tree, this can be done in polynomial time [3] using the method of Edmonds and Matula. It is now simple to describe the #P computation: With input T, each branch picks a subtree T'' of T and rejects unless T'' is the smallest subtree of T in its isomorphism class.

□

2 The reductions

Denote by $\leq_{\mathrm{T}}$ the relation "is polynomial-time Turing reducible to."

Lemma 2

$$\#\text{BIPARTITEMATCHINGS} \leq_{\mathrm{T}} \#\text{COMMONROOTEDSUBTREES}.$$

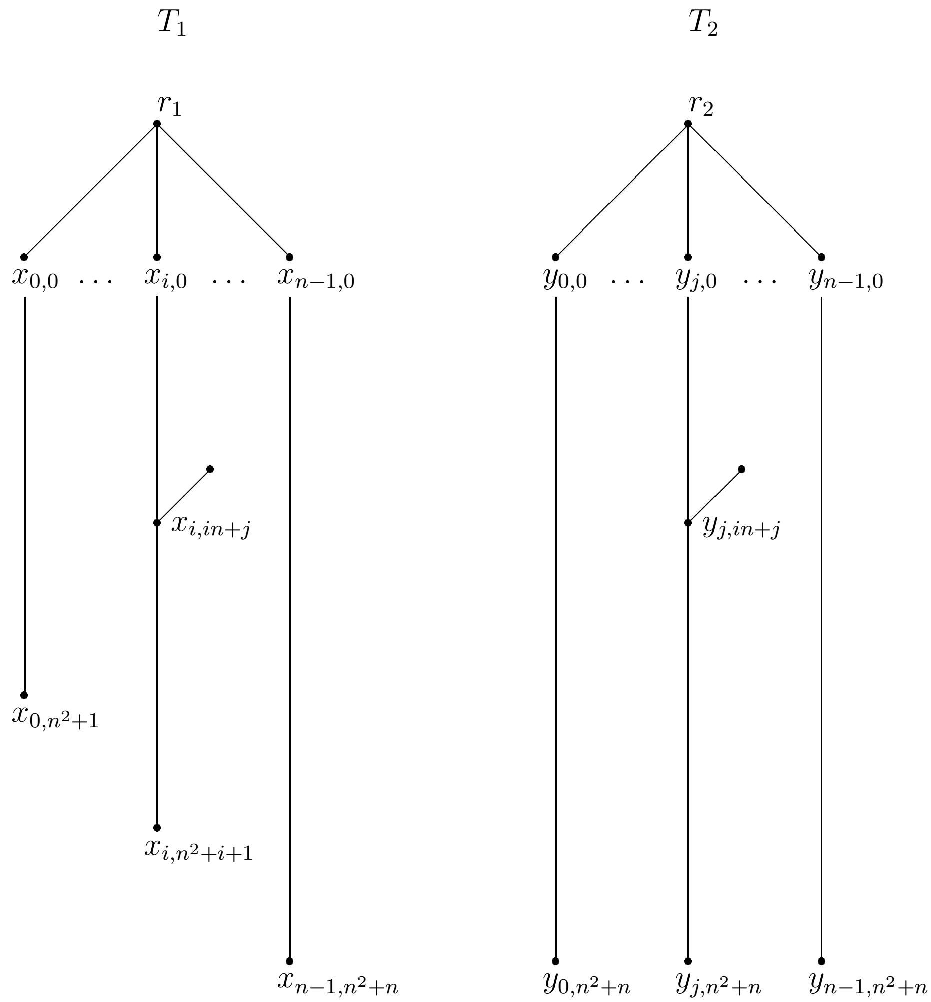

Figure 1: The skeleton of trees T_1 and T_2, illustrating the presence of edge (u_i, v_j) in G.

Proof. Let G be an instance of #BIPARTITEMATCHINGS with vertex sets $\{u_0, \ldots, u_{n-1}\}$ and $\{v_0, \ldots, v_{n-1}\}$. From G, we construct two rooted trees, (T_1, r_1) and (T_2, r_2), each based on a fixed skeleton. The skeleton of T_1 has vertex set

$$\{x_{i,j} : 0 \le i \le n-1 \text{ and } 0 \le j \le n^2 + i + 1\} \cup \{r_1\},$$

and edge set

$$\{(x_{i,j}, x_{i,j+1}) : 0 \le i \le n-1 \text{ and } 0 \le j \le n^2 + i\} \cup \{(r_1, x_{i,0}) : 0 \le i \le n-1\}.$$

Informally, the skeleton of T_1 consists of n paths of different lengths emanating from the root r_1, as illustrated in Figure 1. These n paths correspond to the n vertices $\{u_i\}$ of G.

The skeleton of T_2 is similar to the skeleton of T_1, except the paths now have equal length. It has vertex set

$$\{y_{i,j} : 0 \le i \le n-1 \text{ and } 0 \le j \le n^2+n\} \cup \{r_2\},$$

and edge set

$$\{(y_{ij}, y_{i,j+1}) : 0 \le i \le n-1 \text{ and } 0 \le j \le n^2+n-1\} \cup \{(r_2, y_{i,0}) : 0 \le i \le n-1\}.$$

The n paths emanating from r_2 correspond to the to the n vertices $\{v_i\}$ of G.

The trees T_1 and T_2 themselves are built by adding to the respective skeletons certain edges encoding the graph G. Specifically, for each edge (u_i, v_j) of G, we add an edge from a new vertex to vertex $x_{i,in+j}$ of T_1 and add an edge from a new vertex to vertex $y_{j,in+j}$ of T_2.

Let $\mathcal{T}^*$ denote the set of all finite (unlabelled) rooted trees (T, r) that have leaves at all distances in the range $[n^2+2, n^2+n+1]$ from the root r. For any rooted tree (T, r), let $\mathcal{T}(T, r)$ denote the set of all (unlabelled) rooted subtrees of (T, r). Thus, the quantity #RootedSubtrees(T, r) is just the size of $\mathcal{T}(T, r)$. We first observe that there is a bijection between the set of matchings (of all sizes) in G and the set $\mathcal{T}(T_1, r_1) \cap \mathcal{T}(T_2, r_2) \cap \mathcal{T}^*$, and then conclude the proof by showing how to compute the size of $\mathcal{T}(T_1, r_1) \cap \mathcal{T}(T_2, r_2) \cap \mathcal{T}^*$ using an oracle for #CommonRootedSubtrees.

Consider some tree $(T, r) \in \mathcal{T}(T_1, r_1) \cap \mathcal{T}(T_2, r_2) \cap \mathcal{T}^*$. From the definition of $\mathcal{T}^*$ we see that T must contain the entire skeleton of T_1. In addition, T may contain up to n additional pendant edges. Any pendant edge must be attached to the skeleton at a vertex at distance $in+j+1$ from the root r, where $(u_i, v_j) \in E(G)$. Furthermore, if there are pendant edges at distances $in+j+1$ and $i'n+j'+1$ from the root then $i \ne i'$ and $j \ne j'$. Thus, every such rooted tree (T, r) may be interpreted as a matching in G, and vice versa. This is the sought for bijection between the set of matchings in G and the set $\mathcal{T}(T_1, r_1) \cap \mathcal{T}(T_2, r_2) \cap \mathcal{T}^*$. To conclude, we just need to show how compute the size of the latter set using an oracle for #CommonRootedSubtrees.

Let L be the set of all *leaves* in (T_1, r_1) whose distances from the root r_1 are in the range $[n^2+2, n^2+n+1]$. Let U be the set of *all* vertices in (T_2, r_2) whose distances from r_2 are in the range $[n^2+2, n^2+n+1]$. For each $j \in \{0, \dots, n\}$, let T_1^j be the tree formed from (T_1, r_1) by adorning every vertex in L with a tuft of $n+j$ edges and let T_2^j be the tree formed from (T_2, r_2) by adorning every vertex in U with a tuft of $n+j$ edges. By the phrase "adorning a vertex v with a tuft of t edges" we mean the following: create t new vertices and add an edge from each of these new vertices to v." For $k \in \{0, \dots, n\}$, let a_k be the number of rooted trees in $\mathcal{T}(T_1^0, r_1) \cap \mathcal{T}(T_2^0, r_2)$ that have k vertices of degree $n+1$. Clearly,

$$a_n = |\, \mathcal{T}(T_1, r_1) \cap \mathcal{T}(T_2, r_2) \cap \mathcal{T}^* \,|.$$

So we want to show how to compute a_n using an oracle for #CommonRootedSubtrees.

We claim (and shall justify presently) that

$$|\mathcal{T}(T_1^j, r_1) \cap \mathcal{T}(T_2^j, r_2)| = \sum_{k=0}^{n} a_k (j+1)^k. \quad (1)$$

Thus, we can use an oracle for #CommonRootedSubtrees to evaluate the left-hand side of 1 at $j = 0, \ldots n$; then we can compute a_n by Lagrange interpolation.[1]

It remains to prove equation (1). We define a projection function

$$\pi : \mathcal{T}(T_1^j, r_1) \cap \mathcal{T}(T_2^j, r_2) \to \mathcal{T}(T_1^0, r_1) \cap \mathcal{T}(T_2^0, r_2)$$

as follows. For any rooted tree (T, r) in the domain, $(T', r) = \pi(T, r)$ is the maximum r-rooted subtree of (T, r) that has no vertex of degree greater than $n+1$. To see that T' is uniquely defined, consider an embedding of (T, r) into (T_1^j, r_1). The only vertices of degree greater than $n+1$ are those which are mapped to tufts. Thus, (T', r) is obtained from (T, r) by pruning tufts with more than n pendant edges down to exactly n pendant edges. Note also that the resulting tree (T', r) can be embedded in both (T_1^0, r_1) and (T_2^0, r_2), so π is indeed well defined.

How large is $\pi^{-1}(T', r)$? To every tuft with exactly n pendant edges we may add any number of pendant edges, from 0 to j. All the tufts are distinguishable, because they are all at distinct distances from the root r. Thus all these possible augmentations lead to distinct trees, and $\pi^{-1}(T', r) = (j+1)^k$, where k is the number of vertices in (T', r) of degree $n+1$. Thus, each of the a_k rooted trees in $\mathcal{T}(T_1^0, r_1) \cap \mathcal{T}(T_2^0, r_2)$ with k vertices of degree $n+1$ are mapped by π^{-1} to $(j+1)^k$ trees in $\mathcal{T}(T_1^j, r_1) \cap \mathcal{T}(T_2^j, r_2)$. The lemma follows. □

Lemma 3

$$\#\textsc{CommonRootedSubtrees} \leq_{\mathrm{T}} \#\textsc{RootedSubtrees}.$$

Proof. Suppose that (T_1, r_1) and (T_2, r_2) constitute an instance of #CommonRootedSubtrees. Let (T, r) be the rooted tree formed by taking T_1 and T_2 and adding a new root, r, and edges (r, r_1) and (r, r_2). For notational convenience, introduce the following quantities:

$$\begin{aligned} N_1 &= \#\textsc{RootedSubtrees}(T_1, r_1), \\ N_2 &= \#\textsc{RootedSubtrees}(T_2, r_2), \\ N &= \#\textsc{RootedSubtrees}(T, r), \text{ and} \end{aligned}$$

[1] See Valiant [10] for details of this process, particularly the claim that interpolation is a polynomial-time operation.

$$C = \#\textsc{CommonRootedSubtrees}((T_1, r_1), (T_2, r_2)).$$

We start by observing that

$$N = 1 + N_1 + N_2 - C + N_1 N_2 - \binom{C}{2}.$$

To see this, note that (T, r) has

- one distinct subtree in which the degree of r is 0, and
- $N_1 + N_2 - C$ distinct subtrees in which the degree of r is 1, and
- $N_1 N_2 - \binom{C}{2}$ distinct subtrees in which the degree of r is 2.

Thus, $C(C+1) = 2Z$, where Z denotes

$$1 + N_1 + N_2 + N_1 N_2 - N.$$

To compute C, first calculate Z using an oracle for #RootedSubtrees. Then, observe that

$$C^2 < 2Z < (C+1)^2,$$

so C is the *integer square root* of $2Z$, which can be computed in $\Theta(\log Z)$ time. Note that $\log Z$ is polynomial in the size of the input, since, for example, $N_1 \leq 2^{n_1}$, where n_1 is the number of vertices in T_1. □

Lemma 4

$$\#\textsc{RootedSubtrees} \leq_{\mathrm{T}} \#\textsc{Subtrees}.$$

Proof. For any i, an "i-star" is a tree consisting of one (centre) vertex with degree i and i (outer) vertices, each of which has degree 1.

Suppose that (T, r) is an instance of #RootedSubtrees. Let Δ denote the maximum degree of a vertex in T. Let T' be the tree formed from T by taking a new $(\Delta + 3)$-star, and identifying one of the outer vertices with r. Let T'' be the tree formed from T by taking a new $(\Delta + 2)$-star, and identifying one of the outer vertices with r. Let N' denote #Subtrees(T') and let N'' denote #Subtrees(T''). Then #RootedSubtrees(T, r) is equal to $N' - N''$, so it can be computed using an oracle for #Subtrees. □

3 Some consequences

Following Valiant [10], we say that a function $f : \Sigma^* \to \mathbb{N}$ is in FP if it can be computed by a deterministic polynomial-time Turing machine. We say that it is in FP^g for a problem g if it can be computed by a deterministic polynomial-time Turing machine which is equipped with an oracle for g. Finally, we say that it is in FP^A for a complexity class A if there is some $g \in A$ such that $f \in \mathrm{FP}^g$.

Let #ConnectedSubgraphs be the problem of counting unlabelled connected subgraphs of a graph. Formally, let it be defined as follows.

Name. #ConnectedSubgraphs

Instance. A graph G.

Output. The number of distinct (up to isomorphism) connected subgraphs of G.

Corollary 5 #ConnectedSubgraphs *is complete for* $\mathrm{FP}^{\#\mathrm{P}}$.

Proof. #ConnectedSubgraphs is $\mathrm{FP}^{\#\mathrm{P}}$-hard by Theorem 1. We will show that #ConnectedSubgraphs is in the class $\mathrm{FP}^{\text{span-P}}$, which will be defined shortly. The result will then follow by Toda's theorem [9].

We start by defining the relevant complexity classes. A function $f : \Sigma^* \to \mathbb{N}$ is in the class span-P [7] if there is a polynomial-time nondeterministic Turing machine M (with an output device) such that the number of *different* accepting outputs of M on input x is $f(x)$, for all $x \in \Sigma^*$.

A function $f : \Sigma^* \to \mathbb{N}$ is in #NP if there is a polynomial-time nondeterministic Turing machine M and an an oracle $A \in \mathrm{NP}$ such that the number of accepting computations of M^A on input x is $f(x)$, for all $x \in \Sigma^*$.

The classes #P, span-P, and #NP are related [7] by

$$\#\mathrm{P} \subseteq \text{span-P} \subseteq \#\mathrm{NP}.$$

Thus,

$$\mathrm{FP}^{\#\mathrm{P}} \subseteq \mathrm{FP}^{\text{span-P}} \subseteq \mathrm{FP}^{\#\mathrm{NP}}.$$

As Welsh notes [11, eq. (1.8.6)], the identity

$$\mathrm{FP}^{\#\mathrm{P}} = \mathrm{FP}^{\#\mathrm{NP}}. \tag{2}$$

follows from Toda's theorem [9]. Thus,

$$\mathrm{FP}^{\#\mathrm{P}} = \mathrm{FP}^{\text{span-P}}.$$

(To verify (2) independently, start with Toda's Theorem 4.10, concerning the complexity classes PH and PP. Then the required inclusion $\mathrm{FP}^{\#\mathrm{NP}} \subseteq \mathrm{FP}^{\#\mathrm{P}}$ follows via a little manipulation involving the elementary relationships $\mathrm{NP} \subseteq \mathrm{PH}$ and $\mathrm{FP}^{\mathrm{PP}} = \mathrm{FP}^{\#\mathrm{P}}$.)

We now complete the proof by showing that #ConnectedSubgraphs is in $\mathrm{FP}^{\text{span-P}}$. Let $N(G, k)$ denote $k!$ times the number of distinct (up to isomorphism) connected size-k subgraphs of G. Since

$$\#\textsc{ConnectedSubgraphs}(G) = \sum_{k=1}^{n} \frac{1}{k!} N(G, k),$$

where n is the number of vertices of G, it suffices to show that computing $N(G, k)$ is in span-P. Each branch of the computation tree for $N(G, k)$ chooses

- a size-k connected subgraph H of G,
- a bijection σ from the vertices of H to the set $\{v_1, \ldots, v_k\}$, and
- a permutation π of $v_1, \ldots, v_k$.

Let H' be the graph formed from H by relabelling each vertex v of H with the label $\sigma(v)$. If π is an automorphism of H' then (H', π) is output. Otherwise, the branch rejects. The result now follows from Burnside's Lemma, which implies that for any given isomorphism class of k-vertex graphs, the number of graphs in the isomorphism class times the number of automorphisms of any member of the class is equal to $k!$. (For example, see [5].) □

Let #GraphSubtrees be the problem of counting unlabelled subtrees of a graph. Formally, let it be defined as follows.

Name. #GraphSubtrees

Instance. A graph G.

Output. The number of distinct (up to isomorphism) subtrees of G.

Corollary 6 #GraphSubtrees *is complete for* $\mathrm{FP}^{\#\mathrm{P}}$.

Proof. This is the same as the proof of Corollary 5, except that the span-P computation rejects any subgraph H which is not a tree. A more direct proof could be obtained by using a polynomial-time canonical labelling algorithm for trees such as the one by Hopcroft and Tarjan [6]. □

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