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Polynomial Time Inductive Inference of Ordered Term Trees with Contractible Variables from Positive Data

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1 Introduction

Due to the rapid growth of Internet usage, tree structured data such as Web documents have been rapidly increasing. In order to analyze such tree structured data, efficient learning from tree structured data becomes more and more important. Tree structured data such as HTML/XML files are represented by rooted trees with ordered children and edge labels [1]. In order to represent a tree structured pattern common to such tree structured data, we proposed an *ordered term tree*, which is a rooted tree with ordered children and structured variables [7]. A variable can be substituted by an arbitrary tree. An ordered term tree t is said to be *regular* if all variable labels in t are mutually distinct. Many tree structured data such as HTML/XML files have no rigid structure and have essential information in subtrees containing leaves. In order to deal with such tree structured data, we introduce a new type of variable, called a *contractible variable*, which is regarded as an anonymous subtree in an ordered term tree and matches any subtree including a singleton vertex. A usual variable, called an *uncontractible variable*, in a term tree does not match a singleton vertex.

The *language* of a regular ordered term tree t is the set of all ordered trees which are obtained from t by substituting ordered trees for variables in t . The language of a regular ordered term tree t shows the representing power of t . A *least generalized* regular ordered term tree t explaining given tree structured data S is a term tree t whose language contains S and is minimal. Consider the examples in Fig. 1. The term tree t_2 is a least generalized regular ordered term tree for T_1 , T_2 and T_3 . The ordered term tree t_1 also explains the three trees. But t_1 explains any tree with 2 or more vertices. So t_1 is overgeneralized and meaningless.

Let A be a set of edge labels used in tree structured data. OTT_A^c denotes the set of all regular ordered term trees all of whose contractible variables are adjacent to leaves. First we give an efficient polynomial time algorithm for deciding whether or not a given regular ordered term tree in OTT_A^c matches a tree, where $|A| \geq 1$. Second when $|A| \geq 2$, we give a polynomial time algorithm for finding a least generalized regular ordered term tree in OTT_A^c which explains all given data. These results imply that the class OTT_A^c with $|A| \geq 2$ is polynomial time inductively inferable from positive data.

An ordered term tree is different from other representations of ordered tree structured patterns such as in [2, 4, 13] in that an ordered term tree has structured variables which can be substituted by arbitrary ordered trees. We showed that some classes of regular *unordered* term tree languages are polynomial time inductively inferable from positive data [5, 8, 9]. In [10, 12], we showed that some fundamental classes of regular ordered term tree languages without any contractible variable are polynomial time inductively inferable from positive data. In [6], we showed that some classes of regular ordered term tree languages without any contractible variable are exactly learnable in polynomial time using queries. In [7], we gave a data mining method from semistructured data using ordered term trees.

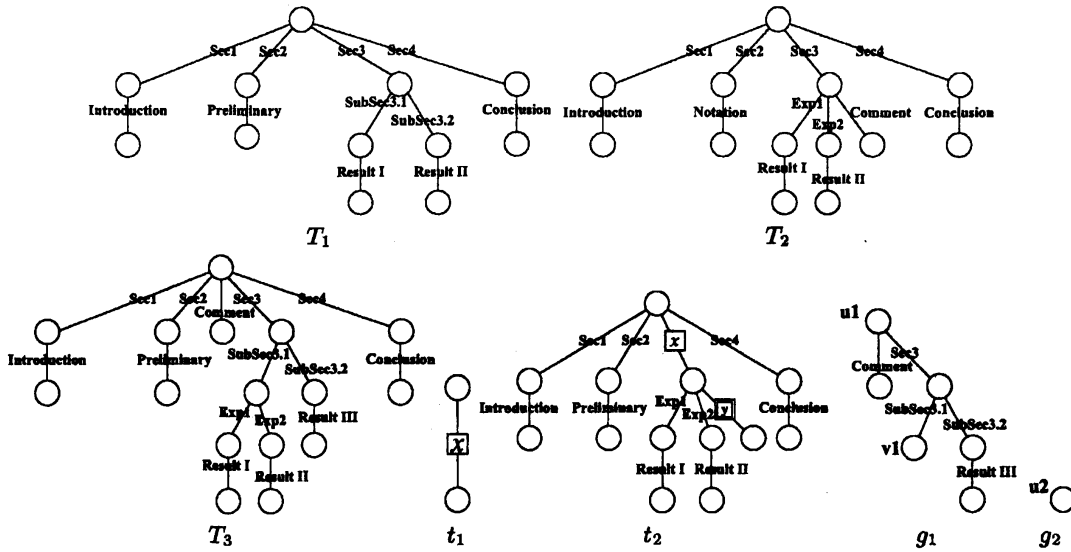


Fig. 1. Term trees t_1 , t_2 and trees T_1 , T_2 and T_3 . An uncontractible (resp. contractible) variable is represented by a single (resp. double) lined box with lines to its elements. The label inside a box is the variable label of the variable.

2 Ordered Term Trees with Contractible Variables

Let $T = (V_T, E_T)$ be a rooted tree with ordered children (or simply a *tree*) which has a set V_T of vertices and a set E_T of edges. Let E_g and H_g be a partition of E_T , i.e., $E_g \cup H_g = E_T$ and $E_g \cap H_g = \emptyset$. And let $V_g = V_T$. A triplet $g = (V_g, E_g, H_g)$ is called a *term tree*, and elements in V_g , E_g and H_g are called a *vertex*, an *edge* and a *variable*, respectively. We assume that every edge and variable of a term tree is labeled with some words from specified languages. A label of a variable is called a *variable label*. Λ and X denote a set of edge labels and a set of variable labels, respectively, where $\Lambda \cap X = \emptyset$. For a term tree g and its vertices v_1 and v_i , a *path* from v_1 to v_i is a sequence v_1, v_2, \dots, v_i of distinct vertices of g such that for any j with $1 \leq j < i$, there exists an edge or a variable which consists of v_j and v_{j+1} . If there is an edge or a variable which consists of v and v' such that v lies on the path from the root to v' , then v is said to be the *parent* of v' and v' is a *child* of v . We use a notation $[v, v']$ to represent a variable $\{v, v'\} \in H_g$ such that v is the parent of v' . Then we call v the *parent port* of $[v, v']$ and v' the *child port* of $[v, v']$.

Definition 1. Let X^c be a distinguished subset of X . We call variable labels in X^c *contractible variable labels*. A contractible variable label can be attached to a variable whose child port is a leaf. We call a variable with a contractible variable label a **contractible variable**, which is allowed to substitute a tree with a singleton vertex, as stated later. We call a variable which is not a contractible variable an **uncontractible variable**. For a variable $[v, v']$, when we pay attention to the kind of the variable, we denote by $[v, v']^c$ and $[v, v']^u$ a contractible variable and an uncontractible variable, respectively.

A term tree g is called *ordered* if every internal vertex u in g has a total ordering on all children of u . The ordering on the children of u is denoted by $\langle \cdot \rangle_u^g$. An ordered term tree g is called *regular* if all variables in H_g have mutually distinct variable labels in X . For a set S , the number of elements in S is denoted by $|S|$.

Definition 2. An ordered term tree with no variable is called a **ground ordered term tree**, which is a standard ordered tree. \mathcal{OT}_Λ denotes the set of all ground ordered term trees whose edge labels are in Λ . \mathcal{OTT}_Λ^c denotes the set of all ordered term trees with contractible or uncontractible variables whose edge labels are in Λ . In this paper, we treat only regular ordered term trees with contractible variables. Therefore we call it a **term tree** simply.

Let $f = (V_f, E_f, H_f)$ and $g = (V_g, E_g, H_g)$ be term trees. We say that f and g are *isomorphic*, denoted by $f \equiv g$, if there is a bijection φ from V_f to V_g such that (i) the root of f is mapped to the root of g by φ , (ii) $\{u, v\} \in E_f$ if and only if $\{\varphi(u), \varphi(v)\} \in E_g$ and the two edges have the same edge label, (iii) $[u, v] \in H_f$ if and only if $[\varphi(u), \varphi(v)] \in H_g$, in particular, $[u, v]^c \in H_f$ if and only if $[\varphi(u), \varphi(v)]^c \in H_g$, and (iv) for any internal vertex u in f which has more than one child, and for any two children u' and u'' of u , $u' <_u^f u''$ if and only if $\varphi(u') <_{\varphi(u)}^g \varphi(u'')$.

Let $\sigma = [u, u']$ be a list of two vertices in g where u is the root of g and u' is a leaf of g . The form $x := [g, \sigma]$ is called a *binding* for x . If x is a contractible variable label in X^c , g may be a tree with a singleton vertex u and thus $\sigma = [u, u]$. It is the only case that a tree with a singleton vertex is allowed for a binding. A new term tree $f\{x := [g, \sigma]\}$ is obtained by applying the binding $x := [g, \sigma]$ to f in the following way. Let $e = [v, v']$ be a variable in f with the variable label x . Let g' be one copy of g and w, w' the vertices of g' corresponding to u, u' of g , respectively. For the variable $e = [v, v']$, we attach g' to f by removing the variable e from H_f and by identifying the vertices v, v' with the vertices w, w' of g' , respectively. If g is a tree with a singleton vertex, i.e., $u = u'$, then v becomes identical to v' after the binding. A *substitution* θ is a finite collection of bindings $\{x_1 := [g_1, \sigma_1], \dots, x_n := [g_n, \sigma_n]\}$, where x_i 's are mutually distinct variable labels in X . The term tree $f\theta$, called the *instance* of f by θ , is obtained by applying the all bindings $x_i := [g_i, \sigma_i]$ on f simultaneously. Further we define a new total ordering $<_v^{f\theta}$ on every vertex v of $f\theta$ in a natural way. In this paper, we omit the exact definition of the ordering after applying a binding to a term tree. The readers can refer it to [10] or [12].

For example, let t_2 be a term tree described in Fig. 1 and $\theta = \{x := [g_1, [u_1, v_1]], y := [g_2, [u_2, u_2]]\}$ be a substitution, where g_1 and g_2 are trees in Fig. 1. Then the instance $t_2\theta$ of the term tree t_2 by θ is the tree T_3 in Fig. 1.

3 An Efficient Matching Algorithm for Term Trees

A matching algorithm for term trees is an algorithm which decides whether or not a term tree t matches a tree T . We gave matching algorithms for term trees with no contractible variable in [10] and for term trees with variables having more than two child ports in [11]. In this section, we give a matching algorithm for \mathcal{OTT}_A^c by extending the matching algorithm in [10].

Let $t = (V_t, E_t, H_t)$ and $T = (V_T, E_T)$ be a term tree in \mathcal{OTT}_A^c and a tree in \mathcal{OT}_A , respectively. We assume that all vertices of a term tree t are associated with mutually distinct numbers, called *vertex identifiers*. We denote by $I(u')$ the vertex identifier of $u' \in V_t$. A *correspondence-set* (C-set for short) is a set of vertex identifiers, which are with or without parentheses, of vertices of t . A vertex identifier with parentheses shows that the vertex is a child port of a variable.

Our matching algorithm proceeds by constructing C-sets for each vertex of a given tree T in the bottom-up manner, that is, from the leaves to the root of T . At first, we construct the *C-set-attaching rule* of a vertex u' of t as follows. Let c'_1, \dots, c'_m be all ordered children of u' . The C-set-attaching rule of u' is of the form $I(u') \leftarrow J(c'_1), \dots, J(c'_m)$, where $J(c'_i) = I(c'_i)$ if $\{u', c'_i\}$ is an edge, $J(c'_i) = I(\emptyset)$ if $[u', c'_i]$ is a contractible variable, $J(c'_i) = (I(c'_i))$ otherwise. $I(\emptyset)$ is a special symbol which shows c'_i is the child port of a contractible variable. The C-set-attaching rule of t , denoted by $Rule(t)$, is defined as follows.

$$\begin{aligned} Rule(t) = & \{I(u') \leftarrow J(c'_1), \dots, J(c'_m) \mid \text{the C-set-attaching rule of all inner vertices}\} \\ & \cup \{(I(u')) \leftarrow (I(u')) \mid u' \text{ is the child port of an uncontractible variable}\} \\ & \cup \{I(u') \leftarrow I(u') \mid u' \text{ has just one child and connects to} \\ & \qquad \qquad \qquad \text{the child with a contractible variable}\}. \end{aligned}$$

The algorithm (Fig. 2) runs for $|A| = 1$. A matching algorithm for $|A| \geq 2$ can be easily constructed from this algorithm. The only work we have to do is to check whether or not edge labels of a tree is the same as corresponding edge labels of a term tree at the first foreach-loop of C-SET-ATTACHING. Then we can prove this theorem in a similar way to the proof of the correctness of the matching algorithm for a term tree [10].

Theorem 1. *Let t be a term tree with n vertices in \mathcal{OTT}_A^c and T a tree with N vertices in \mathcal{OT}_A . The problem for deciding whether or not t matches T is solvable in $O(nN)$ time.*

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Procedure MATCHING( $t, T$ );
input  $t$ : a term tree in  $\mathcal{OTT}_A^c$  with root  $r$ ,  $T$ : a tree in  $\mathcal{OT}_A$  with root  $R$ ;
begin
  Construct  $Rule(t)$ ;
  foreach leaf  $\ell$  of  $T$  do
     $CS(\ell) := \{I(\ell') \mid \ell' \text{ is a leaf of } t \text{ that is not a child port of a contractible variable,}$ 
       $\text{or } \ell' \text{ has just one child and connects to it with a contractible variable}\}$ ;
    while there is a vertex  $v$  of  $T$  s.t.  $v$  has no C-set and all children of  $v$  have C-sets
      do C-Set-Attaching( $v, Rule(t)$ );
    if  $I(r) \in CS(R)$  then  $t$  matches  $T$  else  $t$  does not match  $T$ 
  end.

Procedure C-SET-ATTACHING( $v, Rule(t)$ );
input  $v$ : a vertex of  $T$ ,  $Rule(t)$ : the C-set-attaching rule of  $t$ ;
begin
   $CS(v) := \emptyset$ ; Let  $c_1, \dots, c_m$  be all ordered children of  $v$  in  $T$ ;
  foreach  $I(u') \leftarrow J(c'_1), \dots, J(c'_{m'})$  in  $Rule(t)$  do
    if there is a sequence  $0 = j_0 \leq j_1 \leq \dots \leq j_i \leq \dots \leq j_{m'-1} \leq j_{m'} = m$  s.t.
      1. if  $J(c'_i) = I(c'_i)$  then  $j_i - j_{i-1} = 1$  and  $I(c'_i) \in CS(c_{j_i})$ ,
      2. if  $J(c'_i) = (I(c'_i))$  then  $CS(c_{j_i})$  has  $I(c'_i)$  or  $(I(c'_i))$  for some  $k_i$  ( $j_{i-1} < k_i \leq j_i$ )
      for all  $i = 1, \dots, m'$  // we have no condition on  $j_i$  when  $J(c'_i) = I(\emptyset)$ .
    then  $CS(v) := CS(v) \cup \{(I(u'))\}$ ;
  foreach  $(I(u')) \leftarrow (I(u'))$  in  $Rule(t)$  do
    if there is a set in  $CS(c_1), \dots, CS(c_m)$  which has  $I(u')$  or  $(I(u'))$  then  $CS(v) := CS(v) \cup \{(I(u'))\}$ ;
  foreach  $I(u') \leftarrow I(u')$  in  $Rule(t)$  do  $CS(v) := CS(v) \cup \{I(u')\}$ 
end.

```

Fig. 2. An algorithm for deciding whether or not a term tree $t \in \mathcal{OTT}_A^c$ matches a tree $T \in \mathcal{OT}_A$, where $|A| = 1$.

4 Algorithms for Finding a Least Generalized Term Tree

In this section, we present polynomial time algorithm for finding a least generalized term tree where $|A| \geq 2$, explaining given semistructured data. We can consider the language $L_A(t)$ to be the descriptive power of a term tree t . A *least generalized term tree* explaining a given set of trees $S \subseteq \mathcal{OT}_A$ is a term tree t such that $S \subseteq L_A(t)$ and there is no term tree t' satisfying that $S \subseteq L_A(t') \subsetneq L_A(t)$. The problem for finding a least generalized term tree for a given set of trees is discussed as the minimal language problem (MINL for short) in computational learning theory. The main algorithm is described in Fig. 4.

Lemma 1. Let g and t be term trees in \mathcal{OTT}_A^c for any A which are described in one of Cases 1-3 of Fig. 3. Then $L_A(g) = L_A(t)$.

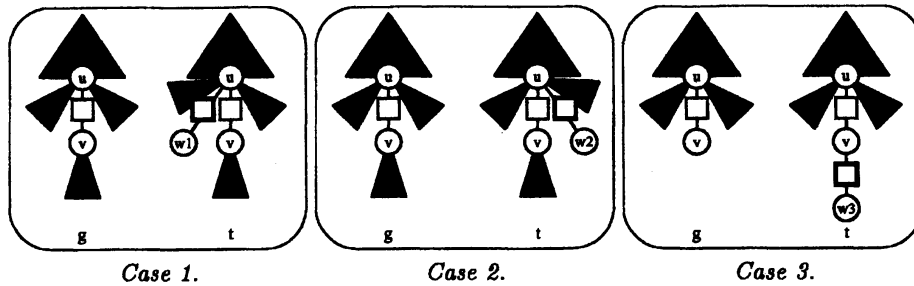


Fig. 3. Cases 1-3: $g \neq t$ and $L_A(g) = L_A(t)$ for $|A| \geq 2$. The parts A, B, C, D of g are the same as the corresponding parts A, B, C, D of t .

Algorithm MINL(S);
input $S = \{T_1, \dots, T_m\} \subseteq \mathcal{OT}_A$: a set of trees;
output t : a least generalized term tree for S ;
begin
 Let Λ_S be the set of all edge labels which appear in S ;
 $t := (\{u, v\}, \emptyset, \{\{u, v\}\})$; Let q be a list initialized to be $\{\{u, v\}\}$;
 VARIABLE-EXTENSION(t, S, q);
 Let r_t be the root of t ;
 EDGE-REPLACING(t, S, r_t);
 output t
end.

Procedure VARIABLE-EXTENSION(t_{input}, S, q);
input t_{input} : a term tree, S : a set of trees, q : a queue of variables;
begin
 $t := t_{input}$;
 while q is not empty **do begin**
 $[u, v] := q[1]$; Let w_1, w_2 , and w_3 be new vertices;
 // w_1 becomes a vertex between u and v .
 $t' := (V_t \cup \{w_1\}, E_t, H_t \cup \{\{u, w_1\}, \{w_1, v\}\} - \{\{u, v\}\})$;
 if $S \subseteq L_A(t')$ **then begin** $t := t'$; $q := q \& \{[w_1, v]\}$; **continue end else** $q := q[2..]$;
 // w_2 and w_3 become the previous and next siblings of v , respectively.
 $t' := (V_t \cup \{w_2\}, E_t, H_t \cup \{\{u, w_2\}\})$;
 if $S \subseteq L_A(t')$ **then begin** $t := t'$; $q := q \& \{[u, w_2]\}$ **end**;
 $t' := (V_t \cup \{w_3\}, E_t, H_t \cup \{\{u, w_3\}\})$;
 if $S \subseteq L_A(t')$ **then begin** $t := t'$; $q := q \& \{[u, w_3]\}$ **end**;
 end;
 return t
end;

Procedure EDGE-REPLACING(t_{input}, S, u);
input t_{input} : a term tree, S : a set of trees, u : a vertex;
begin
 if u is a leaf **then return**;
 $t := t_{input}$; Let v_1, \dots, v_k be the children of u ;
 for $i := 1$ **to** k **do** LABELED-EDGE-REPLACING(t, S, v_i);
 for $i := 1$ **to** k **do**
 foreach edge label $\lambda \in \Lambda_S$ **do**
 // Let $\{u, v_i\}$ be an edge with label λ and w_1, w_2 , and w_3 new vertices. w_1 and w_2 become
 // the previous and next siblings of v_i , respectively, and if v_i is a leaf, w_3 becomes a child of v_i ;
 if v_i is a leaf **then begin**
 $t' := (V_t \cup \{w_1, w_2, w_3\}, E_t \cup \{\{u, v_i\}\}, H_t \cup \{\{u, w_1\}^c, \{u, w_2\}^c, \{v_i, w_3\}^c\} - \{\{u, v_i\}\})$;
 if $S \subseteq L_A(t')$ **then begin**
 $t_1 := (V_{t'} - \{w_1\}, E_{t'}, H_{t'} - \{\{u, w_1\}^c\})$; **if** $S \subseteq L_A(t_1)$ **then** $t' := t_1$;
 $t_2 := (V_{t'} - \{w_2\}, E_{t'}, H_{t'} - \{\{u, w_2\}^c\})$; **if** $S \subseteq L_A(t_2)$ **then** $t' := t_2$;
 $t_3 := (V_{t'} - \{w_3\}, E_{t'}, H_{t'} - \{\{v_i, w_3\}^c\})$; **if** $S \subseteq L_A(t_3)$ **then** $t' := t_3$;
 $t := t'$; **continue**
 end
 end else begin
 $t' := (V_t \cup \{w_1, w_2\}, E_t \cup \{\{u, v_i\}\}, H_t \cup \{\{u, w_1\}^c, \{u, w_2\}^c\} - \{\{u, v_i\}\})$;
 if $S \subseteq L_A(t')$ **then begin**
 $t_1 := (V_{t'} - \{w_1\}, E_{t'}, H_{t'} - \{\{u, w_1\}^c\})$; **if** $S \subseteq L_A(t_1)$ **then** $t' := t_1$;
 $t_2 := (V_{t'} - \{w_2\}, E_{t'}, H_{t'} - \{\{u, w_2\}^c\})$; **if** $S \subseteq L_A(t_2)$ **then** $t' := t_2$;
 $t := t'$; **continue**
 end
 end;
 end;
 return t
end;

Fig. 4. Algorithm MINL

Definition 3. Let t be a term tree in OTT_A^c for $|A| > 2$. The term tree t is said to be a *canonical term tree* if t has no combination of variables and edges of the right term trees t described in *Cases 1-3*. For an arbitrary term tree t , we can transform t into the canonical term tree g such that $L_A(g) = L_A(t)$ by transforming the right trees in *Cases 1-3* into the left trees.

Lemma 2. Let g and t be canonical term trees in OTT_A^c for any A . If $L_A(g) \subseteq L_A(t)$ then there exists a substitution θ such that $g \equiv t\theta$.

The procedure VARIABLE-EXTENSION extends a term tree by adding uncontractible variables as much as possible. A term tree outputted by VARIABLE-EXTENSION is a least generalized term tree for S consisting of only uncontractible variables. Then the procedure EDGE-REPLACING tries to replace variables with labeled edges from leaves to the root. Since the output term tree is not larger than the largest tree in S , we have the following lemma.

Lemma 3. Let t be the output of the algorithm MINL for an input S . Let t' be a term tree satisfying that $S \subseteq L_A(t') \subseteq L_A(t)$. Let g and g' be the canonical term trees such that $L_A(g) = L_A(t)$ and $L_A(g') = L_A(t')$, respectively. Then $g \equiv g'$.

Theorem 2. Let A be a set of edge labels where $|A| \geq 2$. The algorithm MINL finds a least generalized term tree in OTT_A^c for a given set of trees in OT_A in polynomial time.

In this paper, we have presented polynomial time algorithms for solving the membership and MINL problems for the class of labeled term trees. From these algorithms and Angluin's theorem [3], we can show that the class is polynomial time inductively inferable from positive data.

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