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Linear High-Order Deterministic Tree transducers with Regular look-ahead

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Abstract
We introduce the notion of high-order deterministic top-down tree transducers (HODT) whose outputs correspond to simply-typed lambda-calculus formulas. These transducers are natural generalizations of known models of top-tree transducers such as: Deterministic Top-Down Tree Transducers, Macro Tree Transducers, Streaming Tree Transducers... We focus on the linear restriction of high order tree transducers with look-ahead (HODTR\textsubscript{\text{lin}}), and prove this corresponds to tree to tree functional transformations defined by Monadic Second Order (MSO) logic. We give a specialized procedure for the composition of those transducers that uses a flow analysis based on coherence spaces and allows us to preserve the linearity of transducers. This procedure has a better complexity than classical algorithms for composition of other equivalent tree transducers, but raises the order of transducers. However, we also indicate that the order of a HODTR\textsubscript{\text{lin}} can always be bounded by 3, and give a procedure that reduces the order of a HODTR\textsubscript{\text{lin}} to 3. As those resulting HODTR\textsubscript{\text{lin}} can then be transformed into other equivalent models, this gives an important insight on composition algorithm for other classes of transducers. Finally, we prove that those results partially translate to the case of almost linear HODTR: the class corresponds to the class of tree transformations performed by MSO with unfolding (not closed by composition), and provide a mechanism to reduce the order to 3 in this case.

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1 Introduction

Tree Transducers formalize transformations of structured data such as Abstract Syntax Trees, XML, JSON, or even file systems. They are based on various mechanisms that traverse tree structures while computing an output: Top-Down and Bottom-Up tree transducers [17, 4] which are direct generalizations of deterministic word transducers [8, 7, 3], but also more complex models such as macro tree transducers [11] (MTT) or streaming tree transducers [1] (STT) to cite a few.

Logic offers another, more descriptive, view on tree transformations. In particular, Monadic Second Order (MSO) logic defines a class of tree transformations (MSOT) [5, 6] which is expressive and is closed under composition. It coincides with the class of transformations definable with MTT enhanced with a regular look-ahead and restricted to finite copying [9, 10], and also with the class of STT [1].

We argue here that simply typed $\lambda$-calculus gives a uniform generalisation of all these different models. Indeed, they can all be considered as classes of programs that read input tree structures, and, at each step, compose tree operations which in the end produce the final output. Each of these tree operations can be represented using simply typed $\lambda$-terms.

In this paper, we define top-down tree transducers that follow the usual definitions of such machines, except that rules can produce $\lambda$-terms of arbitrary types. We call these machines, High-Order Top-down tree transducers, or High-Order Deterministic Tree Transducers (HODT) in the deterministic case. This class of transducers naturally contains top-down tree transducers, as they are HODT of order 0 (the output of rules are trees), but also MTT, which are HODT of order 1 (outputs are tree contexts). They also contain STT, which can be translated directly into HODT of order 3 with some restricted continuations. Also, STT traverse their input tree represented as a string in a leftmost traversal (a stream). This constraint could easily be adapted to our model but would yield technical complications that are not the focus of this paper. Finally, our model generalizes High Level Tree Transducers defined in [12], which also produce $\lambda$-term, but restricted to the safe $\lambda$-calculus case.

In this paper we focus on the linear and almost linear restrictions of HODT. In terms of expressiveness, linear HODTR (HODTR$_{\text{lin}}$) corresponds to the class of MSOT. This links our formalism to other equivalent classes of transducers, such as finite-copying macro-tree transducers [9, 10], with an important difference: the linearity restriction is a simple syntactic restriction, whereas finite-copying or the equivalent single-use-restricted condition are both global conditions that are harder to enforce. For STT, the linearity condition corresponds to the copyless condition described in [1] and where the authors prove that any STT can be made copyless.

The relationship of HODTR$_{\text{lin}}$ to MSOT is made via a transformation that reduces the order of transducers. We indeed prove that for any HODTR$_{\text{lin}}$, there exists an equivalent HODTR$_{\text{lin}}$ whose order is at most 3. This transformation allows us to prove then that HODTR$_{\text{lin}}$ are equivalent to Attribute Tree Transducers with the single use restriction (ATT$_{\text{sur}}$). In turn, this shows that HODTR$_{\text{lin}}$ are equivalent to MSOT [2].

One of the main interests of HODTR$_{\text{lin}}$ is that $\lambda$-calculus also offers a simple composition algorithm. This approach gives an efficient procedure for composing two HODTR$_{\text{lin}}$. In general, this procedure raises the order of the produced transducer. In comparison, composition in other equivalent classes are either complex or indirect (through MSOT). In any case, our procedure has a better complexity. Indeed, it benefits from higher-order which permits a larger number of implementations for a given transduction. The complexity of the construction is also lowered by the use of a notion of determinism slightly more liberal than
usual that we call weak determinism.

The last two results allow us to obtain a composition algorithm for other equivalent classes of tree transducer, such as MTT or STT: compile into HODTR\textsubscript{lin}, compose, reduce the order, and compile back into the original model. The advantage of this approach over the existing ones is that the complex composition procedure is decomposed into two simpler steps (the back and forth translations between the formalisms are unsurprising technical procedures). We believe in fact that existing approaches [12, 1] combine in one step the two elements, which is what makes them more complex.

The property of order reduction also applies to a wider class of HODT, almost linear HODT (HODTR\textsubscript{al}). Again here, this transformation allows us to prove that this class of tree transformations is equivalent to that of Attribute Tree Transducers which is known to be equivalent to MSO tree transformations with unfolding [2], i.e. MSO tree transduction that produce Directed Acyclic Graphs (i.e. trees with shared sub-trees) that are unfolded to produce a resulting tree. We call these transductions Monadic Second Order Transductions with Sharing (MSOTS). Note however that HODTR\textsubscript{al} are not closed under composition.

Section 2 presents the technical definitions used throughout the paper. In particular, it gives the definitions of the various notions of transducers studied in the paper and also the notion of weak determinism. Section 3 studies the expressivity of linear and almost linear higher-order transducer by relating them to MSOT and MSOTS. It focuses more specifically on the order reduction procedure that is at the core of the technical work. Section 4 presents the composition algorithm for linear higher-order transducers. This algorithm is based on Girard’s coherence spaces and can be interpreted as a form of partial evaluation for linear higher-order programs. Finally we conclude.

2 Definitions

This section presents the main formalisms we are going to use throughout the paper, namely simply typed λ-calculus, finite state automata and high-order transducers.

2.1 λ-calculus

Fix a finite set of atomic types \( \mathcal{A} \), we then define the set of types over \( \mathcal{A} \), \( \text{types}(\mathcal{A}) \), as the types that are either an atomic type, i.e. an element of \( \mathcal{A} \), or a functional type \( (A \to B) \), with \( A \) and \( B \) being in \( \text{types}(\mathcal{A}) \). The operator \( \to \) is right-associative and \( A_1 \to \cdots \to A_n \to B \) denotes the type \( (A_1 \to (\cdots \to (A_n \to B) \cdots)) \). The order of a type \( A \) is inductively defined by \( \text{order}(A) = 0 \) when \( A \in \mathcal{A} \), and \( \text{order}(A \to B) = \max(\text{order}(A) + 1, \text{order}(B)) \).

A signature \( \Sigma \) is a triple \( (C, \mathcal{A}, \tau) \) with \( C \) being a finite set of constants, \( \mathcal{A} \) a finite set of atomic types, and \( \tau \) a mapping from \( C \) to \( \text{types}(\mathcal{A}) \), the typing function.

We allow ourselves to write \( \text{types}(\Sigma) \) to refer to the set \( \text{types}(\mathcal{A}) \). The order of a signature is the maximal order of a type assigned to a constant (i.e. \( \max\{\text{order}(\tau(c)) \mid c \in C\} \)). In this work, we mostly deal with tree signatures which are of order 1 and whose set of atomic types is a singleton. In such a signature with atomic type \( o \), the types of constants are of the form \( o \to o \to o \to o \). We write \( o^n \to o \) for an order-1 type which uses \( n + 1 \) occurrences of \( o \), for example, \( o^2 \to o \) denotes \( o \to o \to o \). When \( c \) is a constant of type \( A \), we may write \( c^A \) to make explicit that \( c \) has type \( A \). Two signatures \( \Sigma_1 = (C_1, \mathcal{A}_1, \tau_1) \) and \( \Sigma_2 = (C_2, \mathcal{A}_2, \tau_2) \) so that for every \( c \) in \( C_1 \cap C_2 \) we have \( \tau_1(c) = \tau_2(c) \) can be summed, and we write \( \Sigma_1 + \Sigma_2 \) for the signature \( (C_1 \cup C_2, \mathcal{A}_1 \cup \mathcal{A}_2, \tau) \) so that if \( c \) is in \( C_1 \), \( \tau(c) = \tau_1(c) \) and if \( c \) is in \( C_2 \), \( \tau(c) = \tau_2(c) \). The sum operation over signatures being associative and commutative, we write \( \Sigma_1 + \cdots + \Sigma_n \) to denote the sum of several signatures.
We assume that for every type $A$, there is an infinite countable set of variables of type $A$. When two types are different the set of variables of those types are of course disjoint. As with constants, we may write $x^A$ to make it clear that $x$ is a variable of type $A$.

When $\Sigma$ is a signature, we define the family of simply typed $\lambda$-terms over $\Sigma$, denoted $\Lambda(\Sigma) = (\Lambda^A(\Sigma))_{A \in \text{Types}(\Sigma)}$, as the smallest family indexed by types$(\Sigma)$ so that:

- if $c^A$ is in $\Sigma$, then $c^A$ is in $\Lambda^A(\Sigma)$,
- $x^A$ is in $\Lambda^A(\Sigma)$,
- if $A = B \rightarrow C$ and $M$ is in $\Lambda^C(\Sigma)$, then $(\lambda x^B.M)$ is in $\Lambda^A(\Sigma)$,
- if $M$ is in $\Lambda^{B \rightarrow A}(\Sigma)$ and $N$ is in $\Lambda^B(\Sigma)$, then $(M N)$ is in $\Lambda^A(\Sigma)$.

The term $M$ is a pure $\lambda$-term if it does not contain any constant $c^A$ from $\Sigma$. When the type is irrelevant we write $M \in \Lambda(\Sigma)$ instead of $M \in \Lambda^A(\Sigma)$. We drop parentheses when it does not bring ambiguity. In particular, we write $\lambda x_1 \ldots x_n.M$ for $(\lambda x_1(\ldots(\lambda x_n.M)\ldots))$, and $M_0 \ldots M_n$ for $((\ldots(M_0 M_1)\ldots)M_n)$.

The set $\text{fv}(M)$ of free variables of a term $M$ is inductively defined on the structure of $M$:

- $\text{fv}(c) = \emptyset$,
- $\text{fv}(x) = \{x\}$,
- $\text{fv}(M N) = \text{fv}(M) \cup \text{fv}(N)$,
- $\text{fv}(x. M) = \text{fv}(M) - \{x\}$.

Terms which have no free variables are called closed. We write $M[x_1, \ldots, x_k]$ to emphasize that $\text{fv}(M)$ is included in $\{x_1, \ldots, x_k\}$. When doing so, we write $M[N_1, \ldots, N_k]$ for the capture avoiding substitution of variables $x_1, \ldots, x_k$ by the terms $N_1, \ldots, N_k$. In other contexts, we simply use the usual notation $M[N_1/x_1, \ldots, N_k/x_k]$. Moreover given a substitution $\theta$, we write $M.\theta$ for the result of applying this (capture avoiding) substitution and we write $\theta[N_1/x_1, \ldots, N_k/x_k]$ for the substitution that maps the variables $x_i$ to the terms $N_i$ but is otherwise equal to $\theta$. Of course, we authorize such substitutions only when the $\lambda$-term $N_i$ has the same type as the variable $x_i$.

We take for granted the notions of $\beta$-contraction, noted $\rightarrow_\beta$, $\beta$-reduction, noted $\rightarrow_\beta$, $\beta$-conversion, noted $=_\beta$, and $\beta$-normal form for terms.

Consider closed terms of type $o$ that are in $\beta$-normal form and that are built on a tree signature, they can only be of the form $a t_1 \ldots t_n$ where $a$ is a constant of type $o^o \rightarrow o$ and $t_1, \ldots, t_n$ are closed terms of type $o$ in $\beta$-normal form. This is just another notation for ranked trees. So when the type $o$ is meant to represent trees, types of order 1 which have the form $o \rightarrow \cdots \rightarrow o \rightarrow o$ represent functions from trees to trees, or more precisely tree contexts. Types of order 2 are types of trees parametrized by contexts. The notion of order captures the complexity of the operations that terms of a certain type describe.

A term $M$ is said linear if each variable (either bound or free) in $M$ occurs exactly once in $M$. A term $M$ is said syntactically almost linear when each variable in $M$ of non-atomic type occurs exactly once in $M$. Note that, through $\beta$-reduction, linearity is preserved but not syntactic almost linearity.

For example, given a tree signature $\Sigma_1$ with one atomic type $o$ and two constants $f$ of type $o^o \rightarrow o$ and $a$ of type $o$, the term $M = (\lambda y_1 y_2.f y_1(f a y_2)) a(f x a)$ with free variable $x$ of type $o$ is linear because each variable $(y_1, y_2$ and $x)$ occurs exactly once in $M$. The term $M$ contains a $\beta$-redex so: $(\lambda y_1 y_2.f y_1(f a y_2)) a(f x a) \rightarrow_\beta (\lambda y_2.f a(f a y_2)) (f x a) \rightarrow_\beta f a(f x a))$. The term $f a(f x a))$ has no $\beta$-redex so it is the $\beta$-normal form of $M$.

Another example: the term $M_2 = (\lambda y.f y)(x a)$ with free variable $x$ of type $o \rightarrow o$ is syntactically almost linear because the variable $y$ which occurs twice in the term is of the atomic type $o$. It $\beta$-reduces to the term $M_2' = f(x a)(x a)$ which is not syntactically almost linear, so $\beta$-reduction does not preserve syntactical almost linearity.
We call a term *almost linear* when it is $\beta$-convertible to a syntactically almost linear term. Almost linear terms are characterized also by typing properties (see [15]).

### 2.2 Tree Automata

We present here the classical definition of deterministic bottom-up tree automaton (BOT) adapted to our formalism. A BOT $A$ is a tuple $(\Sigma_P, \Sigma, R)$ where:

- $\Sigma = (C, \{o\}, \tau)$ is a first-order tree signature, the *input signature*,
- $\Sigma_P = (P, \{o\}, \tau_P)$ is the *state signature*, and is such that for every $p \in P$, $\tau_P(p) = o$.
- Constants of $P$ are called *states*,
- $R$ is a finite set of rules of the form $a p_1 \ldots p_n \rightarrow p$ where:
  - $a$ is a constant of $\Sigma$ with type $o^o \rightarrow o$.
- An automaton is said *deterministic* when there is at most one rule in $R$ for each possible left-hand side. It is *non-deterministic* otherwise.

Apart from the notation, our definition differs from the classical one by the fact there are no final states, and hence, the automaton does not describe a language. This is due to the fact that BOT will be used here purely for look-ahead purposes.

### 2.3 High-Order Deterministic top-down tree Transducers

From now on we assume that $\Sigma_i$ is a tree signature for every number $i$ and that its atomic type is $o_i$.

A Linear High-Order Deterministic top-down Transducer with Regular look-ahead (HODTRlin) $T$ is a tuple $(\Sigma_Q, \Sigma_1, \Sigma_2, q_0, R, A)$ where:

- $\Sigma_1 = (C_1, \{o_1\}, \tau_1)$ is a first-order tree signature, the *input signature*,
- $\Sigma_2 = (C_2, \{o_2\}, \tau_2)$ is a first-order tree signature, the *output signature*,
- $\Sigma_Q = (Q, \{o_1, o_2\}, \tau_s)$ is the *state signature*, and is such that for every $q \in Q$, $\tau_s(q)$ is of the form $o_1 \rightarrow A_q$ where $A_q$ is in types($\Sigma_2$). Constants of $Q$ are called *states*,
- $q_0 \in Q$ is the *initial state*,
- $A$ is a BOT over the tree signature $\Sigma_1$, the *look-ahead* automaton, with set of states $P$,
- $R$ is a finite set of rules of the form
  $$q(a \bar{x})(\bar{p}) \rightarrow M(q_1 x_1) \ldots (q_n x_n)$$
  where:
  - $q, q_1, \ldots, q_n \in Q$ are states of $\Sigma_Q$,
  - $a$ is a constant of $\Sigma_1$ with type $o_i^o \rightarrow o_1$,
  - $\bar{x} = x_1, \ldots, x_n$ are variables of type $o_1$, they are the child trees of the root labeled $a$,
  - $\bar{p} = p_1, \ldots, p_n$ are in $P$ (the set of states of the look-ahead $A$),
  - $M$ is a linear term of type $A_{q_1} \rightarrow \cdots \rightarrow A_{q_n} \rightarrow A_q$ built on signature $\Sigma_2 + \Sigma_Q$.
- there is one rule per possible left-hand side (determinism).

Notice that we have given states a type of the form $o_1 \rightarrow A$ where $A \in \text{types}(o_2)$. The reason why we do this is to have a uniform notation. Indeed, a state $q$ is meant to transform, thanks to the rules in $R$, a tree built in $\Sigma_1$ into a $\lambda$-term built on $\Sigma_2$ with type $A_q$. So we simply write $q M N_1 \ldots N_n$ when we want to transform $M$ with the state $q$ and pass $N_1, \ldots, N_n$ as arguments to the result of the transformation. We write $\Sigma_T$ for the signature $\Sigma_1 + \Sigma_2 + \Sigma_Q$. Notice also that the right-hand part of a rule is a term that is built only with constants of $\Sigma_2$, states from $\Sigma_Q$ and variables of type $o_1$. Thus, in order for this term to have a type in types($\Sigma_2$), it is necessary that the variables of type $o_1$ only occur as...
the first argument of a state in $\Sigma_Q$. Finally, remark that we did not put any requirement
on the type of the initial state. So as to restrict our attention to transducers as they are
usually understood, it suffices to add the requirement that the initial state is of type $o_1 \rightarrow o_2$.
However, we consider as well that transducers may produce programs instead of first order
terms.

The linearity constraint on $M$ affects both bound variables and the free variables
$x_1, \ldots, x_n$, meaning that all of the subtrees $x_1, \ldots, x_n$ are used in computing the output.
That will be important for the composition of two transducers because if the first
transducer fails in a branch of its input tree then the second transducer, applied to that tree,
must fail too. This restriction forcing the use of input subtrees does not reduce the model’s
expressivity because we can always add a state $q$ which visits the subtree but only produces
the identity function on type $o_2$ (this state then has type $A_q = o_1 \rightarrow o_2 \rightarrow o_2$).

Almost linear high-order deterministic top-down transducer with regular look-ahead
(HODTR_{al}) are defined similarly, with the distinction that a term $M$ appearing as a right-
hand side of a rule should be almost linear.

As we are concerned with the size of the composition of transducers, we wish to relax
a bit the notion of HODTR_{lin}. Indeed, when composing HODTR_{lin} we may have to
determine the look-ahead so as to obtain a HODTR_{lin}, which may cause an exponential
blow-up of the look-ahead. However if we keep the look-ahead non-deterministic, the
transducer stays deterministic in the weaker sense that only one rule of the transducer
can apply when it is actually run. For this we adopt a slightly relaxed notion of determin-
istic transducer that we call high-order weakly deterministic top-down transducer with
regular look-ahead (HOWDTR_{lin}). They are similar to HODTR_{lin} but they can have non-
deterministic automata as look-ahead with the proviso that when $q(a x_1 \ldots x_n)(p_1, \ldots, p_n) \rightarrow
M[x_1, \ldots, x_n]$ and $q(a x_1 \ldots x_n)(p'_1, \ldots, p'_n) \rightarrow M'[x_1, \ldots, x_n]$ are two distinct rules of the
transducer then it must be the case that for some $i$ there is no tree that is recognized by
both $p_i$ and $p'_i$. This property guarantees that when transforming a term at most one rule
can apply for every possible state. Notice that it suffices to determinize the look-ahead so as
to obtain a HODTR_{lin} from a HOWDTR_{lin}, and therefore the two models are equivalent.

Given a HODTR_{al}, a HODTR_{al} or a HOWDTR_{lin} $T$, we write $T : \Sigma_1 \rightarrow \Sigma_2$ to mean
that the input signature of $T$ is $\Sigma_1$ and its output signature is $\Sigma_2$.

A transducer $T$ induces a notion of reduction on terms. A $T$-redex is a term of the form
$q(a M_1 \ldots M_n)$ if and only if $q(a x_1 \ldots x_n)(p_1, \ldots, p_n) \rightarrow M[x_1, \ldots, x_n]$ is a rule of $T$ and
(the $\beta$-normal forms of) $M_1, \ldots, M_n$ are respectively accepted by $T$ with the states $p_1, \ldots, p_n$.
In that case, a $T$-contractum of $q(a M_1 \ldots M_n)$ is $M[M_1, \ldots, M_n]$. Notice that $T$-contracta
are typed terms and that they have the same type as their corresponding $T$-redices. The
relation of $T$-contraction relates a term $M$ and a term $M'$ when $M'$ is obtained from $M$
by replacing one of its $T$-redex with a corresponding $T$-contractum. We write $M \rightarrow_T M'$
when $M$ $T$-contracts to $M'$. The relation of $\beta$-reduction is confluent, and so is the relation
of $T$-reduction as transducers are deterministic, moreover, the union of the two relations is
terminating. It is not hard to prove that it is also locally confluent and thus confluent. It
follows that $\rightarrow_{\beta,T}$ (which is the union of $\rightarrow_{\beta}$ and $\rightarrow_T$) is confluent and strongly normalizing.
Given a term $M$ built on $\Sigma_T$, we write $|M|_T$ to denote its normal form modulo $=_{\beta,T}$.

Then we write rel($T$) for the relation:
$$\left\{ (M, |q_0 M|_T) \mid M \text{ is a closed term of type } o_1 \text{ and } |q_0 M|_T \in \Lambda(\Sigma_2) \right\}.$$
Notice that when $|q_0 M|_T$ contains some states of $T$, as it is usual, the pair $(M, |q_0 M|_T)$
is not in the relation.

Given a finite set of trees $L_1$ on $\Sigma_1$ and $L_2$ included in $\Lambda^{\Sigma_2}$, we respectively write $T(L_1)$
and $T^{-1}(L_2)$ for the image of $L_1$ by $T$ and the inverse image of $L_2$ by $T$. 

We give an example of a HODTR\textsubscript{lin} $T$ that computes the result of additions of numeric expressions (numbers being represented in unary notation). For this we use an input tree signature with type $o_1$, and constants $Z^{o_1}$, $S^{o_1}$ and $\text{add}^{o_1 \to o_1 \to o_1}$ which respectively denote zero, the successor function and addition. The output signature is similar but different to avoid confusion: it uses the type $o_2$ and constants $O^{o_2}$, $N^{o_2 \to o_2}$ which respectively denote zero and successor.

We do not really need the look-ahead automaton for this computation, so we omit it for this example. We could have a blank look-ahead automaton $\lambda$ with one state $l$ and rules:

- $\lambda(Z) = l$, $\lambda(Sl) = l$, $\lambda(\text{add}l l) = l$; which would not change the result of the transducer.

The transducer has two states: $q_0$ of type $o_1 \to o_2$ (the initial state), and $q_1$ of type $o_1 \to o_2 \to o_2$. The rules of the transducer are the following:

- $q_0(Z) \to O$, $q_0(Sx) \to N(q_i x O)$,
- $q_0(\text{add}xy) \to q_i x (q_i y O)$,
- $q_1(Z) \to \lambda x.x$,
- $q_1(Sx) \to \lambda y.N(q_i x y)$,
- $q_1(\text{add}xy) \to \lambda z.q_i x (q_i y z)$.

As an example, we perform the transduction of the following term $\text{add}(S(SZ))(S(SSZ))$:

- $q_0(\text{add}(S(SZ))(S(SSZ))) \to_T (q_i(SSZ))(q_i(S(SSZ)))O$,
- $\to_T (\lambda y_1.N((\lambda y_2.N((\lambda x.x)y_2))y_1)((\lambda y_3.N((\lambda y_4.N((\lambda x.x)y_3)y_4))y_4))O$,
- $\to_\beta N(N(N(N(O))))$.

The state $q_i$ transforms a sequence of 4 symbols $S$ into a $\lambda$-term of the form $\lambda x.N^n(x)$, and the $\text{add}$ maps both its children into such terms and composes them. The state $q_0$ simply applies $O$ to the resulting term.

Note that our reduction strategy here has consisted in first computing the $T$-reduces and then reducing the $\beta$-reduces. This makes the computation simpler to present. As we mentioned above a head-reduction strategy would lead to the same result.

The order of the HODTR\textsubscript{lin} $T$ is $\max\{|\text{order}(A_q)| q \in Q\}$. Before going further, we want to discuss how our framework relates to other transduction models. More specifically how the notion of order of transformations generalizes the DTOP and MTT transduction models:

- If we relax the constraint of linearity of our transducers, then DTOP and MTT can be seen as non-linear transducers of order 0 and 1 respectively. In contrast of these, we chose to study the constraint of linearity instead of the constraint of order and, in this paper, we will explore the benefits of this approach. Firstly we will explain why increasing the order beyond order 3 does not increase the expressivity of neither HODTR\textsubscript{lin} nor HODTR\textsubscript{al}.

Next we will show how HODTR\textsubscript{lin} and HOWDTR\textsubscript{lin} both capture the expressivity of tree transformations defined by monadic second order logic. Lastly, we will prove that, contrary to MTT, the class of HODTR\textsubscript{lin} transformations is closed under composition, we will give an algorithm for computing the composition of HODTR\textsubscript{lin} and HOWDTR\textsubscript{lin}, and explain why using HOWDTR\textsubscript{lin} avoids an exponential blow-up in the size of the composition transducer.

### 3 Order reduction and expressiveness

In this section we outline a construction that transforms a transducer of HODTR\textsubscript{lin} or HODTR\textsubscript{al} into an equivalent linear or almost linear transducer of order $\leq 3$. These two constructions are similar and central to proving that HODTR\textsubscript{lin} and HODTR\textsubscript{al} are respectively equivalent to Monadic Second Order Transductions from trees to trees (MSOT) and to Monadic Second Order Transductions from trees to terms (i.e. trees with sharing) (MSOTS).

We will later show that there are translations between HODTR\textsubscript{lin} of order 3 and attribute tree
Linear High-Order Deterministic Tree transducers with Regular look-ahead

The central idea in the construction consists in decomposing λ-terms \( M \) into pairs \( \langle M', \sigma \rangle \) where \( M' \) is a pure λ-term and \( \sigma \) is a substitution of variables with the following properties:

- \( M = \beta M' . \sigma \),
- the free variables of \( M' \) have at most order 1,
- for every variable \( x \), \( \sigma(x) \) is a closed λ-term,
- the number of free variables in \( M' \) is minimal.

In such a decomposition, we call the term \( M' \) a template. In case \( M \) is of type \( A \), linear or almost linear, it can be proven that \( M' \) can be taken from a finite set [14]. The linear case is rather simple, but the almost linear case requires some precaution as one needs first to put \( M \) in syntactically almost linear form and then make the decomposition. Though the almost linear case is more technical the finiteness argument is the same in both cases and is based on proof theoretical arguments in multiplicative linear logic which involves polarities in a straightforward way.

The linear case conveys the intuition of decompositions in a clear manner. One takes the normal form of \( M \) and then delineates the largest contexts of \( M \), i.e. first order terms that are made only with constants and that are as large as possible. These contexts are then replaced by variables and the substitution \( \sigma \) is built accordingly. The fact that the contexts are chosen as large as possible makes it so that no introduced variable can have as argument a term of the form \( xM_1 \ldots M_n \) where \( x \) is another variable introduced in the process. Therefore, the new variables introduced in the process bring one negative atom and several (possibly 0) positive ones and all of them need to be matched with positive and negative atoms in the type of \( M \) as, under these conditions, they cannot be matched together.

This explains why there are only finitely many possible templates for a fixed type.

**Theorem 1.** For all type \( A \) built on tree signature \( \Sigma \), the set of templates of closed linear (or almost linear) terms of type \( A \) is finite.

Moreover, the templates associated with a λ-term can be computed compositionally (i.e. from the templates of its parts). As a result, templates can be computed by the look-ahead of \( \text{HODTR}_{\text{lin}} \) or of \( \text{HODTR}_{\text{al}} \). When reducing the order, we enrich the look-ahead with template information while the substitution that is needed to reconstruct the produced term is outputted by the new transducer. The substitution is then performed by the initial state used at the root of the input tree which then outputs the same result as the former transducer. The substitution can be seen as a tuple of order 1 terms. It is represented as a tuple using Church encoding, i.e. a continuation. This makes the transducer we construct be of order 3.

**Theorem 2.** Any \( \text{HODTR}_{\text{lin}} \) (resp. \( \text{HODTR}_{\text{al}} \)) has an equivalent \( \text{HODTR}_{\text{lin}} \) (resp. \( \text{HODTR}_{\text{al}} \)) of order 3.

The proof of this result shows that every \( \text{HODTR}_{\text{lin}} \) (or \( \text{HODTR}_{\text{al}} \)) can be seen as mapping trees to tuples of contexts and combining these contexts in a linear (resp. almost linear) way. This understanding of \( \text{HODTR}_{\text{lin}} \) and of \( \text{HODTR}_{\text{al}} \) allows us to prove that they are respectively equivalent to Attribute Tree Transducers with Single Use Restriction (\( \text{ATT}_{\text{sur}} \)); and to Attribute Tree Transducers (\( \text{ATT} \)). Then, using [2], we can conclude with the following expressivity result:

**Theorem 3.** \( \text{HODTR}_{\text{lin}} \) are equivalent to MSOT and \( \text{HODTR}_{\text{al}} \) are equivalent to MSOTS.
The full proofs of these are rather technical and are not detailed here, but they appear in the full version of the article. The proof that HODTR$_{lin}$ are equivalent to MSOT could have been simpler by using the equivalence with MTT with the single-use restricted property instead of ATT, but we would still need to use ATT to show that HODTR$_{al}$ are equivalent to MSOTS.

4 Composition of HODTR$_{lin}$

As we are interested in limiting the size of the transducer that is computed, and even though our primary goal is to compose HODTR$_{lin}$, this section is devoted to the composition of HOWDTR$_{lin}$. Indeed, working with non-deterministic look-aheads allows us to save the possibly exponential cost of determinizing an automaton.

4.1 Semantic analysis

Let $T_1 = (\Sigma_Q, \Sigma_1, \Sigma_2, q_0, R_1, A_1)$ and $T_2 = (\Sigma_P, \Sigma_2, \Sigma_3, p_0, R_2, A_2)$ be two Linear High-Order Weakly Deterministic tree Transducers with Regular look-ahead. The rules of $T_1$ can be written: $q(a, x) \rightarrow (\ell) \rightarrow M(q_1, x_1) \cdots (q_n, x_n)$ where $q, q_1, \ldots, q_n \in Q$ are states of $T_1$, $\ell = \ell_1, \ldots, \ell_n$ are states of $A_1$ and the $\lambda$-term $M$ is of type $A_{q_1} \rightarrow \cdots \rightarrow A_{q_n} \rightarrow A$. Our goal is to build a HOWDTR$_{lin}$ $T ::= \Sigma_1 \rightarrow \Sigma_3$ that does the composition of $T_1$ and $T_2$, so we want to replace a rule such as that one with a new rule which corresponds to applying $T$ to the term $M$.

In order to do so, we need, for each $o_2$ tree in $M$, to know the associated state $\ell \in L_2$ of $T_2$'s look-ahead, and the state $p \in P$ of $T_2$ which is going to process that node. So with any such tree we associate the pair $(p, \ell)$. In this case we call $(p, \ell)$ the token which represents the behavior of the tree. In general, we want to associate tokens not only with trees, but also with $\lambda$-terms of higher order. For example, we map an occurrence of a symbol $a \in \Sigma_2$ of type $o_2 \rightarrow o_2 \rightarrow o_2$, whose arguments $x_1$ and $x_2$ (of type $o_2$) respectively have look-ahead states $\ell_1$ and $\ell_2$ and are processed by states $p_1$ and $p_2 \in P$ of $T_2$, to the token $(p_1, \ell_1) \leadsto (p_2, \ell_2) \leadsto (p, \ell)$, where $(p, \ell)$ is the token of the tree $a x_1 x_2$ (of type $o_2$). We formally define tokens as follows:

\begin{definition}
The set of semantic tokens $[A]$ over a type $A$ built on atomic type $o_2$ is defined by induction:

$[o_2] = \{ (p, \ell) \mid p \in P, \ell \in L_2 \}$

$[A \rightarrow B] = \{ f \leadsto g \mid f \in [A], g \in [B] \}$

\end{definition}

Naturally, the semantic token associated with a $\lambda$-term $M$ of type $A$ built on atomic type $o_2$ will depend on the context where the term $M$ appears. For example a tree of atomic type $o_2$ can be processed by any state $p \in P$ of $T_2$, and a term of type $A \rightarrow B$ can be applied to any argument of type $A$. But for any such $M$ taken out of context, there exists a finite set of possible tokens for it. For example, a given tree of type $o_2$ can be processed by any state $p \in P$ depending on the context, but it has always the same look-ahead $\ell \in L_2$.

In order to define the set of possible semantic tokens for a term, we use a system of derivation rules. The following derivation rules are used to derive judgments that associate a term with a semantic token. So a judgment $\Gamma \vdash M : f$ associates term $M$ with token $f$, where $\Gamma$ is a substitution which maps free variables in $M$ to tokens. The rules are:

\begin{align*}
\frac{\Gamma, p(a \mathcal{Z})/\ell_1, \ldots, \ell_n \vdash T_2 \rightarrow M(p_1, x_1) \cdots (p_n, x_n)}{
\Gamma \vdash a : (p_1, \ell_1) \leadsto \cdots \leadsto (p_n, \ell_n) \leadsto (p, \ell)}
\end{align*}
\[
\begin{align*}
&\Gamma_1 \vdash M : f \to g \\
\Gamma_1, \Gamma_2 \vdash MN : g
\end{align*}
\]

Using this system we can derive, for any term \( M^A \), all the semantic tokens that correspond to possible behaviours of \( M^A \) when it is processed by \( T_2 \).

### 4.2 Unicity of derivation for semantic token judgements

We will later show that we can compute the image of \( M \) from the derivation of the judgement \( \Gamma \vdash M : f \), assuming that \( f \) is the token that represents the behaviour of \( T_2 \) on \( M \). But before that we need to prove that for a given term \( M \) and token \( f \) the derivation of the judgement \( \Gamma \vdash M : f \) is unique:

> **Theorem 5.** For every type \( A \), for every term \( M \) of type \( A \) and every token \( f \in [A] \), there is at most one derivation \( D :: \vdash M : f \).

This theorem relies in part on the fact that tokens form a coherent space, as introduced by Girard in [13]. The full proof of this theorem is not detailed here but can be found in the full version of the article on Hal.

Now that we have shown that there is only one derivation per judgement \( \Gamma \vdash M : f \), we are going to see how to use that derivation in order to compute the term \( N \) that is the image of \( M \) by transducer \( T_2 \).

### 4.3 Collapsing of token derivations

We define a function (we call it collapsing function) which maps every derivation \( D :: \vdash M : f \) to a term \( \overline{D} \) which corresponds to the output of transducer \( T_2 \) on term \( M \) assuming that \( M \) has behaviour \( f \).

> **Definition 6.** Let \( D \) be a derivation. We define \( \overline{D} \) by induction on \( D \), there are different cases depending on the first rule of \( D \):

- If \( D \) is of the form:
  \[
  \frac{p(a \overline{x})(\ell_1, \ldots, \ell_n) \vdash N(p_1 x_1) \ldots (p_n x_n)}{\overline{D} = N}
  \]
  then \( \overline{D} = N \),

- if \( D \) is of the form:
  \[
  \frac{D_1 :: \vdash N_1 : f \to g}{\overline{D} = \overline{D}_1 \overline{D}_2}
  \]
  then \( \overline{D} = \overline{D}_1 \overline{D}_2 \),

- if \( D \) is of the form:
  \[
  \frac{\Gamma \vdash \lambda x^A. N : f \to g}{\overline{D} = \lambda x. \overline{D}}
  \]
  then \( \overline{D} = \lambda x. \overline{D} \),
if $D$ is of the form:

$$f \in [A]$$

$$x^A : f \vdash x^A : f$$

then $\overline{D} = x^T$.

We can check that, for all derivation $D :: \vdash M : f$, the term $\overline{D}$ is of type $T$ given by:

$$\overline{[p,t]} = A_p$$

and $f \vdash o \overline{D} = f \rightarrow \overline{D}$.

Now that we have associated, with any pair $(M, f)$ such that $f$ is a semantic token of term $M$, a term $N = \overline{D}$ which represents the image of $M$ by $T_2$, we need to show that replacing $M$ with $N$ in the computation of transducers leads to the same results.

### 4.4 Construction of the transducer which realizes the composition

We recall some notations: $T_1 = (\Sigma_Q, \Sigma_1, \Sigma_2, q_0, R_1, A_1)$ and $T_2 = (\Sigma_P, \Sigma_2, \Sigma_3, p_0, R_2, A_2)$ are two HOWDTR$_\text{lin}$, $Q = \{q_1, \ldots, q_m\}$ is the set of states of $T_1$ and, for every state $q_i \in Q$, we note $A_q$, the type of $q_i(t)$ when $t$ is a tree of type $o_1$. For all type $A$ built on $o_2$, the set of tokens of terms of type $A$ is noted $[A]$ and is finite.

Previously, we saw how to apply transducer $T_2$ to terms $M$ of type $A$ built on the atomic type $o_2$, so we can apply $T_2$ to terms which appear on the left side of rules of $T_1$: $q(a_\overline{D})(t) \rightarrow M(q_i, x_i), \ldots(q_i, x_n)$. In a rule such as this one, in order to replace term $M$ with term $N = \overline{D}$ where $D$ is the unique derivation of the judgement $\vdash M : f$, we need to know which token $f$ properly describes the behaviour of $T_2$ on $M$. The computation of that token is done in the look-ahead automaton $A$ of $T$.

We define the set of states of $A$ as: $L = L_1 \times [A_{q_1}] \times \cdots \times [A_{q_m}]$

With any tree $t$ (of type $o_1$) we want to associate the look-ahead of $T_1$ on $t$ and, for each state $q_i \in Q$ of $T_1$, a token of $q_i(t)$. The transition function of the look-ahead automaton $A$ is defined by, for all $(t_1, f_1,1, \ldots, f_1,n), \ldots, (t_n, f_m,1, \ldots, f_m,n) \in L$:

$$a(t_1, f_1,1, \ldots, f_1,n) \ldots(t_n, f_m,1, \ldots, f_m,n) \rightarrow t_1(t_1, f_1,1, \ldots, f_1,n) \ldots t_n(t_n, f_m,1, \ldots, f_m,n)$$

where $a \in L_1$ and, for all state $q_i \in Q$, $f_i$ is such that in $T_1$ there exists a rule $q_i(a_\overline{D})(t_1, \ldots, t_n) \rightarrow M(q_i, x_i), \ldots(q_i, x_n)$ and a derivation of the judgement $\vdash M : f_1, t_1 \rightarrow \ldots \rightarrow f_n, t_n \rightarrow f_i$. Note that this look-ahead automaton is non-deterministic in general, but the transducer is weakly deterministic in the sense that, at each step, even if several look-ahead states are possible, only one rule of the transducer can be applied.

We define the set of states $Q'$ of transducer $T$ by:

$$Q' = \{(q, f) | q \in Q, f \in [A] \} \cup \{q_0\}$$

Then we define the set $R$ of rules of transducer $T$ as the set of rules of the form:

$$q(a_\overline{D})(t_1, f_1,1, \ldots, f_1,n) \ldots \rightarrow t_1(t_1, f_1,1, \ldots, f_1,n) \ldots t_n(t_n, f_m,1, \ldots, f_m,n)$$

such that there exists in $T_1$ a rule: $q(a_\overline{D})(t_1, \ldots, t_n) \rightarrow M(q_i, x_1), \ldots(q_i, x_n)$ and $D$ is a derivation of the judgement $\vdash M : f_1, t_1 \rightarrow \ldots \rightarrow f_n, t_n \rightarrow f_i$.

Because of Theorem 5 that set of rules is weakly deterministic.

To that set $R$ we then add rules for the initial state $q_0$, which simply replicate the rules of states of the form $(q_0, (p_0, t))$: for all $a \in \Sigma_1$, all $(t_1, f_1,1, \ldots, f_1,n), \ldots, (t_n, f_m,1, \ldots, f_m,n) \in L$ and all rule in $R$ of the form:

$$(q_0, (p_0, t))(a_\overline{D})(t_1, f_1,1, \ldots, f_1,n) \ldots \rightarrow t_1(t_1, f_1,1, \ldots, f_1,n) \ldots t_n(t_n, f_m,1, \ldots, f_m,n)$$

where $p_0$ is the initial state of $T_2$ and $t \in L_2$ is a state of the look-ahead automaton of $T_2$, we add the rule:

$$q_0(a_\overline{D})(t_1, f_1,1, \ldots, f_1,n) \ldots \rightarrow t_1(t_1, f_1,1, \ldots, f_1,n) \ldots t_n(t_n, f_m,1, \ldots, f_m,n)$$

This set $R$ of rules is still weakly deterministic according to Theorem 5.

We have thus defined the HOWDTR$_\text{lin}$ $T = (\Sigma_{Q'}, \Sigma_1, q_0, p_0, R, A)$. 

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\textbf{Theorem 7.} \( T = T_2 \circ T_1 \)

Finally, we will analyze the complexity of this algorithm and show that using the
algorithm on HOWDTR\textsubscript{lin} instead of HODTR\textsubscript{lin} avoids an exponential blow-up of the size
of the produced transducer.

First the set of states \( Q' \) of \( T \) is of size \( |Q'| = 1 + \Sigma_{q \in Q} |A_q| \) where \( |A_q| \) is the number
of tokens of type \( A_q \). \( |A_q| = (|P| |L_2|)^{|A_q|} \) where \( |P| \) is the number of states of transducer
\( T_2 \). \(|L_2|\) is the number of states of the look-ahead automaton of transducer \( T_2 \) and \( |A_q| \) is
the size of the type \( A_q \). So the size of \( Q' \) is \( O(\Sigma_{q \in Q} (|P| |L_2|)^{|A_q|}) \), that is a polynomial in
the size of \( T_2 \) to the power of the size of types of states of \( T_1 \).

It is important to note that the set \( |A_q| \) of tokens of type \( A_q \) is where HOWDTR\textsubscript{lin} and
HODTR\textsubscript{lin} differ in their complexity: the deterministic alternative to the weakly deterministic
\( T \) would require to store with the state not a single token, but a set of two-by-two coherent
tokens, that would bring the size of \( Q' \) to \( 1 + \Sigma_{q \in Q} 2^{|A_q|} \) which would be exponential in the
size of \( T_2 \) and doubly exponential in the size of types of \( T_1 \).

Then there is the look-ahead automaton: its set of states is \( L = L_1 \times [A_{q_1}] \times \cdots \times [A_{q_m}] \).
So the number of states is in \( O(\Sigma_{q \in Q} (|P| |L_2|)^{|A_q|}) \). The size of the set of rules of the
look-ahead automaton is in \( O(\Sigma_{a(n) \in \Sigma_1} |L|^{n+1}) \) where \( n \) is the arity of the constant \( a(n) \).

Finally there is the set \( R \) of rules of \( T \). For every judgement \( \vdash M : f_{1,t} \circ f_{2,s} \cdots \circ f_{n,1} \rightarrow \circ f \), finding a derivation \( D \) of that judgement and computing the corresponding \( \overline{D} \) is in \( O(|M|^2) \)
time where \( |M| \) is the size of \( M \). The number of possible rules is in \( O(\Sigma_{a(n) \in \Sigma_1} (|Q'|)^{n+1}) \).

So computing \( R \) is done in time \( O(|R|^2 \Sigma_{a(n) \in \Sigma_1} (|Q'|)^{n+1}) \) where \( R \) is the set of rules of \( T_1 \).
With a fixed input signature \( \Sigma_1 \), the time complexity of the algorithm computing \( T \) is a
polynomial in the sizes of \( T_1 \) and \( T_2 \), with only the sizes of types of states of \( T_1 \) as exponents.

Note that, as our model generalizes other classes of transducers, it is possible to perform
their composition in our setting. Thanks to results of Theorem 2, it is then possible to reduce
the order of the result of the composition, and obtain a HODTR\textsubscript{lin} that can be converted
back in those other models. This methods gives an important insight on the composition
procedure for those other formalisms.

In comparison, the composition algorithms for equivalent classes of transductions are
either not direct or very complex as they essentially perform composition and order reduction
at once. For instance, composition of single used restricted MTT is obtained through MSO
([11]). High-level tree transducers [12] go through a reduction to iterated pushdown tree
transducers and back. The composition algorithm for Streaming Tree Transducers described
in [1] is direct, but made complex by the fact that the algorithm hides this reduction of order.

The double-exponential complexity of composition of HODTR\textsubscript{lin} compares well to the
non-elementary complexity of composition in equivalent non-MSOT classes of transducers.
Although the simple exponential complexity of composition in MSOT is better, we should
account for the fact that the MSOT model does not attempt to represent the behavior of
programs.

\section{Conclusion and future work}

In this paper we have presented a new mechanical characterization of Monadic Second Order
Transductions. This characterization is based on simply typed \( \lambda \)-calculus which allows us to
generalize with very few primitives most of the mechanisms used to compute the output in
the transducer literature. The use of higher-order allows us to propose an arguably simple
algorithm for computing the composition of linear higher-order transducers which coincide
with MSOT. The correctness of this algorithm is based on denotation semantics (coherence
spaces) of λ-calculus and the heart of the proof uses logical relations. Thus, the use of
λ-calculus allows us to base our work on standard tools and techniques rather than developing
our own tools as is often the case when dealing with transducers. Moreover, this work sheds
some light on how composition is computed in other formalisms. Indeed, we argue that for
MTT_{sur}, STT, or ARR_{sur}, the composition must be the application of our composition
algorithm followed by the order reduction procedure that we use to prove the equivalence
with logical transductions.

The notion of higher-order transducer has already been studied [12, 18, 16], however,
there is still some work to be done to obtain direct composition algorithms. We plan to
generalize our approach of the linear case to the general one and devise a semantic based
partial evaluation for the composition of higher-order transducers.
References


