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PARALLEL COMPUTATION**

K. AEHLIG, J. JOHANNSEN,  
H. SCHWICHTENBERG and S. TERWIJN

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# Linear Ramified Higher Type Recursion and Parallel Computation

Klaus Aehlig<sup>1,\*</sup>, Jan Johannsen<sup>2,\*\*</sup>, Helmut Schwichtenberg<sup>1,\*\*\*</sup>, and  
Sebastiaan A. Terwijn<sup>3,†</sup>

<sup>1</sup> Mathematisches Institut, Ludwig-Maximilians-Universität München,  
Theresienstraße 39, 80333 München, Germany  
{aehlig,schwicht}@rz.mathematik.uni-muenchen.de,  
Tel.: +49 89 2394 { -4415, -4413}

<sup>2</sup> Institut für Informatik, Ludwig-Maximilians-Universität München  
Oettingenstraße 67, 80538 München, Germany  
jjohanns@informatik.uni-muenchen.de,  
Tel.: +49 89 2178 2209, Fax: +49 89 2178 2238

<sup>3</sup> Department of Mathematics and Computer Science, Vrije Universiteit Amsterdam,  
De Boelelaan 1081a, 1081 HV Amsterdam, The Netherlands  
terwijn@cs.vu.nl, Tel.: +31 20 4447753

**Abstract.** A typed lambda calculus with recursion in all finite types is defined such that the first order terms exactly characterize the parallel complexity class NC. This is achieved by use of the appropriate forms of recursion (concatenation recursion and logarithmic recursion), a ramified type structure and imposing of a linearity constraint.

**Keywords:** higher types, recursion, parallel computation, NC, lambda calculus, linear logic, implicit computational complexity

## 1 Introduction

One of the most prominent complexity classes, other than polynomial time, is the class NC of functions computable in parallel polylogarithmic time with a polynomial amount of hardware. This class has several natural characterizations in terms of circuits, alternating Turing machines or parallel random access machines, as used in this work. It can be argued that NC is the class of efficiently parallelizable problems, just as polynomial time is often viewed as the correct formalization of feasible sequential computation.

Machine-independent characterizations of computational complexity classes are not only of theoretical, but recently also of increasing practical interest. Besides

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indicating the robustness and naturality of the classes in question, they also provide guidance for the development of programming languages [10].

The earliest such characterizations, starting with Cobham’s function algebra for polynomial time [8], used recursions with explicit bounds on the growth of the defined functions. Function algebra characterizations in this style of parallel complexity classes, among them NC, were given by Clote [7] and Allen [1].

More elegant *implicit* characterizations, i.e., without any explicitly given bounds, but instead using logical concepts like ramification or tiering, have been given for many complexity classes, starting with the work of Bellantoni and Cook [4] and Leivant [13] on polynomial time. In his thesis, Bellantoni [2] gives such a characterization of NC using a ramified variant of Clote’s recursion schemes. A different implicit characterization of NC, using tree recursion, was given by Leivant [14]. Other parallel complexity classes, viz. parallel logarithmic and polylogarithmic time, were given implicit characterizations by Bellantoni [3], Bloch [6] and Leivant and Marion [15].

In order to apply the approach within the functional programming paradigm, one has to consider functions of higher type, and thus extend the function algebras by a typed lambda calculus. To really make use of this feature, it is desirable to allow the definition of higher type functions by recursion. Higher type recursion was originally considered by Gödel [9] for the analysis of logical systems. Systems with recursion in all finite types characterizing polynomial time were given by Bellantoni et al. [5] and Hofmann [11], based on the first-order system of Bellantoni and Cook [4].

We define an analogous system that characterizes NC while allowing an appropriate form of recursion, viz. logarithmic recursion as used by Bellantoni [2], in all finite types. More precisely, our system is a typed lambda calculus which allows two kinds of function types, denoted  $\sigma \multimap \tau$  and  $\Box\sigma \multimap \tau$ , and two sorts of variables of the ground type  $\iota$ , the *complete* ones in addition to the usual ones, which are called incomplete for emphasis. A function of type  $\Box\sigma \multimap \tau$  can only be applied to complete terms of type  $\sigma$ , i.e., terms containing only complete free variables.

It features two recursion operators LR and CR, the latter corresponding to Clote’s [7] concatenation recursion on notation, which can naturally only be applied to first-order functions. The former is a form of recursion of logarithmic length characteristic of all function algebra representations of NC, and here can be applied to functions of all  $\Box$ -free types. The function being iterated as well as the numerical argument being recurred on have to be complete, i.e., the type of LR is  $\sigma \multimap \Box(\Box\iota \multimap \sigma \multimap \sigma) \multimap \Box\iota \multimap \sigma$  for  $\sigma$   $\Box$ -free.

The crucial restriction, justifying the use of linear logic notation, is a linearity constraint on variables of higher types: all higher type variables in a term must occur at most once.

The main new contribution in the analysis of the complexity of the system is a strict separation between the term, i.e., the program, and the numerical context, i.e., its input and data. Whereas the runtime may depend polynomially on the former, it may only depend polylogarithmically on the latter.

To make use of this conceptual separation, the algorithm that unfolds recursions computes, given a term and context, a recursion-free term *plus a new context*. In particular, it does not substitute numerical parameters, but only uses them for unfolding; in some cases, including the reduction of CR, it extends the context. This way, the growth of terms in the elimination of recursions is kept under control. In earlier systems that comprised at least polynomial time this strict distinction was not necessary, since the computation time there may depend on the *input* superlinearly. Note that any reasonable form of computation will depend at least linearly on the size of the *program*.

As opposed to the first-order system of Bellantoni [2], the numerical argument that governs a concatenation recursion must be complete in our system, the type of CR is  $(\iota \multimap \iota) \multimap \Box \iota \multimap \iota$ . The reason is that the amount of hardware required depends exponentially on the number of CR in a term, thus we must not allow duplications of this constant during the unfolding of LR. The only way to avoid this is by the more restrictive typing. This weaker form of concatenation recursion nevertheless suffices to include all of NC, when the set of base functions is slightly extended.

A further feature of this work is the usage of a tree data structure to store numerals during the computation. Whereas trees are used as the principal data structure in other characterizations of parallel complexity classes [14, 15], our system works with usual binary numerals, and trees are only used in the implementation.

## 2 Formal Definition of the System

We use simple types with two forms of abstraction over a single base type  $\iota$ , i.e. our types are given by the grammar

$$\sigma, \tau ::= \iota \mid \sigma \multimap \tau \mid \Box \sigma \multimap \tau$$

As the intended semantics for our base type are the binary numerals we have the constants 0 of type  $\iota$  and  $s_0$  and  $s_1$  of type  $\iota \multimap \iota$ . Moreover we add the constants half, len of type  $\iota \multimap \iota$ , bit, drop of type  $\iota \multimap \iota \multimap \iota$  and sm of type  $\iota \multimap \iota \multimap \iota \multimap \iota$  for the corresponding base functions. We allow case-distinction for arbitrary types, so we have a constant  $d_\sigma$  of type  $\iota \multimap \sigma \multimap \sigma \multimap \sigma$  for *every* type  $\sigma$ . Growth is added to the system via the constant #, recursion via the constant LR and parallelism via the constant CR. Their types are

$$\begin{array}{lll} \# & : & \Box \iota \multimap \iota \\ \text{CR} & : & (\iota \multimap \iota) \multimap \Box \iota \multimap \iota \\ \text{LR}_\sigma & : & \sigma \multimap \Box(\Box \iota \multimap \sigma \multimap \sigma) \multimap \Box \iota \multimap \sigma \quad \sigma \text{ } \Box\text{-free} \end{array}$$

Terms are built from variables and constants via abstraction and typed application. We have incomplete variables of every type, denoted by  $x, y, \dots$  and complete variables of ground type, denoted by  $\mathbf{x}, \mathbf{y}, \dots$ . All our variables and

terms have a fixed type and we add type superscripts to emphasize the type:  $x^\sigma$ ,  $\mathbf{x}^\iota$ ,  $t^\sigma$ . So terms are given by the grammar

$$s, t, \dots ::= c \mid x^\sigma \mid \mathbf{x}^\iota \mid (\lambda x^\sigma . t^\tau)^{\sigma \multimap \tau} \mid (\lambda \mathbf{x}^\iota . t^\tau)^{\square \sigma \multimap \tau} \mid (t^{\sigma \multimap \tau} s^\sigma)^\tau \mid (t^{\square \sigma \multimap \tau} s^\sigma)^\tau$$

where in the last case we require  $s$  to be complete; a term is called *complete* if all its free variables are. It should be noted that, although we cannot form terms of type  $\square \sigma \multimap \tau$  with  $\sigma \neq \iota$  directly via abstraction it is still important to have that type in order to express, for example, that the first argument of **LR** must not contain free incomplete variables.

In the following we omit the type subscripts at the constants  $d_\sigma$  and  $\mathbf{LR}_\sigma$  if the type is obvious or irrelevant. Moreover we identify  $\alpha$ -equal terms. As usual application associates to the left. A *binary numeral* is either 0, or of the form  $s_{i_1}(\dots(s_{i_k}(s_1 0)))$ . The semantics of  $\iota$  as binary numerals (rather than binary words) is given by the conversion rule  $s_0 0 \mapsto 0$ . In the following definitions we identify binary numerals with the natural number they represent. The base functions get their usual semantics, i.e. we add conversion rules  $\text{len } n \mapsto \lceil \log_2(n+1) \rceil =: \|n\|$ ,  $\text{drop } n m \mapsto \lfloor \frac{n}{2^{\|m\|}} \rfloor$ ,  $\text{half } n \mapsto \lfloor \frac{n}{2^{\lceil \|n\|/2 \rceil}} \rfloor$ ,  $\text{bit } n i \mapsto \lfloor \frac{n}{2^i} \rfloor \bmod 2$ ,  $\text{sm } w m n \mapsto 2^{\|m\| \cdot \|n\|} \bmod 2^{\|w\|}$ . Moreover, we add the conversion rules

$$\begin{array}{lll} d_\sigma 0 & \mapsto & \lambda x^\sigma y^\sigma . x \\ d_\sigma (s_i n) & \mapsto & \lambda x_0^\sigma x_1^\sigma . x_i \\ \# n & \mapsto & s_0^{\|n\|^2} (s_1 0) \\ \mathbf{CR } h 0 & \mapsto & 0 \\ \mathbf{CR } h (s_i n) & \mapsto & d_{(\iota \multimap \iota)} (h (s_i n)) s_0 s_1 (\mathbf{CR } h n) \\ \mathbf{LR } g h 0 & \mapsto & g \\ \mathbf{LR } g h n & \mapsto & h n (\mathbf{LR } g h (\text{half } n)) \end{array}$$

Here we always assumed that  $n$ ,  $m$  and  $s_i n$  are binary numerals, and in particular that the latter does not reduce to 0. In the last rule,  $n$  has to be a binary numeral different from 0.

As usual the reduction relation is the closure of  $\mapsto$  under all term forming operations and equivalence is the symmetric, reflexive, transitive hull of the reduction relation. As all reduction rules are correct with respect to the intended semantics and obviously all closed normal terms of type  $\iota$  are numerals, closed terms  $t$  of type  $\iota$  have a unique normal form that we denote by  $t^{\text{nf}}$ .

As usual, lists of notations for terms/numbers/... that only differ in successive indices are denoted by leaving out the indices and putting an arrow over the notation. It is usually obvious where to add the missing indices. If not we add a dot wherever an index is left out. Lists are inserted into formulae “in the natural way”, e.g.,  $\overrightarrow{hm} = hm_1, \dots, hm_k$  and  $x \overrightarrow{t} = ((x t_1) \dots t_k)$  and  $|g| + |\overrightarrow{s}| = |g| + |s_1| + \dots + |s_k|$ .

As already mentioned, we are not interested in all terms of the system, but only in those fulfilling a certain linearity condition.

**Definition 1.** A term  $t$  is called *linear*, if every variable of higher type in  $t$  occurs at most once.

### 3 Soundness

**Definition 2.** The length  $|t|$  of a term  $t$  is inductively defined as follows: For a variable  $x$ ,  $|x| = 1$ , and for any constant  $c$  other than  $d$ ,  $|c| = 1$ , whereas  $|d| = 3$ . For complex terms we have the usual clauses  $|r s| = |r| + |s|$  and  $|\lambda x.r| = |r| + 1$ .

The length of the constant  $d$  is motivated by the desire to decrease the length of a term in the reduction of a  $d$ -redex.

**Definition 3.** For a list  $\bar{n}^\rightarrow$  of numerals, define  $|\bar{n}^\rightarrow| := \max(|\bar{n}^\rightarrow|)$ .

**Definition 4.** A context is a list of pairs  $(x, n)$  of variables of type  $\iota$  and numerals, where all the variables are distinct. If  $\bar{x}^\rightarrow$  is a list of distinct variables of type  $\iota$  and  $\bar{n}^\rightarrow$  a list of numerals of the same length, then we denote by  $\bar{x}^\rightarrow; \bar{n}^\rightarrow$  the context  $(\bar{x}, \bar{n})^\rightarrow$ .

**Definition 5.** For every symbol  $c$  of our language and term  $t$ ,  $\#_c(t)$  denotes the number of occurrences of  $c$  in  $t$ . For obvious esthetic reasons we abbreviate  $\#_\#(t)$  by  $\#(t)$ .

**Definition 6.** A term  $t$  is called *simple* if  $t$  contains none of the constants  $\#$ , CR or LR.

#### Bounding the Size of Numerals

**Lemma 1.** Let  $t$  be a simple, linear term of type  $\iota$  and  $\bar{x}^\rightarrow; \bar{n}^\rightarrow$  a context, such that all free variables in  $t$  are among  $\bar{x}^\rightarrow$ . Then for  $t^* := t[\bar{x}^\rightarrow := \bar{n}^\rightarrow]^{\text{nf}}$  we have  $|t^*| \leq |t| + |\bar{n}^\rightarrow|$ .

*Proof.* By induction on  $|t|$ . We distinguish cases according to the form of  $t$ .

Case 1:  $t$  is  $x \bar{r}^\rightarrow$  for a variable  $x$ . Since  $x$  must be of type  $\iota$ ,  $\bar{r}^\rightarrow$  must be empty, and  $t^*$  is just one of the numerals in  $\bar{n}^\rightarrow$ .

Case 2:  $t$  is  $c \bar{r}^\rightarrow$  for a constant  $c$ . Here we have four subcases, depending on the constant  $c$ .

Case 2a:  $c$  is 0, so  $\bar{r}^\rightarrow$  is empty and  $t$  is already normal.

Case 2b:  $c$  is  $s_i$ , so  $t$  is  $c r$  for a term  $r$  of type  $\iota$ . Let  $r^* := r[\bar{x}^\rightarrow := \bar{n}^\rightarrow]^{\text{nf}}$ , by the induction hypothesis we have  $|r^*| \leq |r| + |\bar{n}^\rightarrow|$ , and therefore we get  $|t^*| \leq |r^*| + 1 \leq |t| + |\bar{n}^\rightarrow|$ .

Case 2c:  $c$  is one of the constants  $\text{len}$ ,  $\text{half}$ ,  $\text{drop}$ ,  $\text{bit}$  or  $\text{sm}$ , so  $t$  is  $c r \bar{s}^\rightarrow$  for terms  $r, \bar{s}^\rightarrow$  of type  $\iota$ . Let  $r^* := r[\bar{x}^\rightarrow := \bar{n}^\rightarrow]^{\text{nf}}$ , by the induction hypothesis we have  $|r^*| \leq |r| + |\bar{n}^\rightarrow|$ , and therefore we get  $|t^*| \leq |r^*| \leq |t| + |\bar{n}^\rightarrow|$ .

Case 2d:  $c$  is  $d_\sigma$ , so  $t$  is  $d_\sigma s u_0 u_1 \bar{v}^\rightarrow$ , where  $s$  is of type  $\iota$  and  $u_i$  are of type  $\sigma$ . Depending on the last bit  $i$  of the value of  $s[\bar{x}^\rightarrow := \bar{n}^\rightarrow]$ ,  $t$  reduces to the shorter

term  $t' = u_i \bar{v}^\rightarrow$ , to which we can apply the induction hypothesis obtaining the normal form  $t^*$  with  $|t^*| \leq |t'| + |\bar{n}^\rightarrow| < |t| + |\bar{n}^\rightarrow|$ .

Case 3:  $t$  is  $(\lambda x.r) s \bar{s}^\rightarrow$ . Here we have two subcases, depending on the number of occurrences of  $x$  in  $r$ .

Case 3a:  $x$  occurs at most once, then the term  $t' := r[x := s] \bar{s}^\rightarrow$  is smaller than  $t$ , and we can apply the induction hypothesis to  $t'$ .

Case 3b:  $x$  occurs more than once, and thus is of type  $\iota$ . Then  $s$  is of type  $\iota$ , so we first apply the induction hypothesis to  $s$ , obtaining  $s^* := s[\bar{x}^\rightarrow := \bar{n}^\rightarrow]^{\text{nf}}$  with  $|s^*| \leq |s| + |\bar{n}^\rightarrow|$ . Now we let  $t' := r \bar{s}^\rightarrow$ , and we apply the induction hypothesis to  $t'$  and the context  $\bar{x}^\rightarrow, y; \bar{n}^\rightarrow, s^*$ , so we get

$$|t^*| \leq |t'| + |\bar{n}^\rightarrow, s^*| \leq |t'| + |s| + |\bar{n}^\rightarrow| .$$

The last case, where  $t$  is  $\lambda x.r$ , cannot occur because of the type of  $t$ . □

## Data Structure

We represent terms as parse trees, fulfilling the obvious typing constraints. The number of edges leaving a particular node is called the out-degree of this node. There is a distinguished node with in-degree 0, called the root. Each node is stored in a record consisting of an entry `cont` indicating its kind, plus some pointers to its children. We allow the following kinds of nodes with the given restrictions:

- Variable nodes representing a variable  $x$ . Variable nodes have out-degree 0. Every variable has a unique name and an associated register  $R[x]$ .
- Abstraction nodes  $\lambda x$  representing the binding of the variable  $x$ . Abstraction nodes have out-degree one, and we denote the pointer to its child by `succ`.
- For each constant  $c$ , there are nodes representing the constant  $c$ . These nodes have out-degree 0.
- Application nodes `@` representing the application of two terms. The obvious typing constraints have to be fulfilled. We denote the pointers to the two children of an application node by `left` and `right`.
- Auxiliary nodes  $\kappa_i$  representing the composition of type one. These nodes are labeled with a natural number  $i$ , and each of those nodes has out-degree either 2 or 3. They will be used to form 2/3-trees (as e.g. described by Knuth [12]) representing numerals during the computation. We require that any node reachable from a  $\kappa$ -node is either a  $\kappa$ . node as well or one of the constants  $s_0$  or  $s_1$ .
- Auxiliary nodes  $\kappa'$  representing the identification of type-one-terms with numerals (via “applying” them to 0). The out-degree of such a node, which is also called a “numeral node”, either is zero, in which case the node represents the term 0, or the out-degree is one and the edge starting from this node either points to one of the constants  $s_0$  or  $s_1$  or to a  $\kappa$ . node.
- Finally, there are so-called dummy nodes  $\diamond$  of out-degree 1. The pointer to the child of a dummy node is again denoted by `succ`. Dummy nodes serve to pass on pointers: a node that becomes superfluous during reduction is made

into a dummy node, and any pointer to it will be regarded as if it pointed to its child.

A tree is called a *numeral* if the root is a numeral node, all leaves have the same distance to the root and the label  $i$  of every  $\kappa_i$  node is the number of leaves reachable from that node. By standard operations on 2/3-trees it is possible in sequential logarithmic time to

- split a numeral at a given position  $i$ .
- find out the  $i$ 'th bit of the numeral.
- concatenate two numerals.

So using  $\kappa'$  and  $\kappa$  nodes is just a way of implementing “nodes” labeled with a numeral allowing all the standard operations on numerals in logarithmic time. Note that the length of the label  $i$  (coded in binary) of a  $\kappa_i$  node is bounded by the logarithm of the number of nodes.

### Normalization Algorithms and Their Complexity

**Lemma 2.** *Let  $t$  be a simple, linear term of type  $\iota$  and  $\bar{x}^\lambda; \bar{n}^\lambda$  a context such that all free variables in  $t$  are among the  $\bar{x}^\lambda$ . Then the normal form of  $t[\bar{x}^\lambda := \bar{n}^\lambda]$  can be computed in time  $O(|t| \cdot \log |\bar{n}^\lambda|)$  by  $O(|t| \cdot |\bar{n}^\lambda|)$  processors.*

*Proof.* We start one processor for each of the nodes of the parse-tree of  $t$ , with a pointer to this node in its local register. The registers associated to the variables  $\bar{x}^\lambda$  in the context contain pointers to the respective numerals  $\bar{n}^\lambda$ , and the registers associated to all other variables are initialized with a NULL pointer.

The program operates in rounds, where the next round starts once all active processors have completed the current round. The only processors that will ever do something are those at the application or variable nodes. Thus all processors where  $\text{cont} \notin \{\text{@}, x, \text{d}\}$  can halt immediately. Processors at  $\text{d}$  nodes do not halt because they will be converted to variable nodes in the course of the reduction. The action of a processor at an application node in one round depends on the type of its sons. If the right son is a dummy node, i.e.,  $\text{right.cont} = \diamond$ , then this dummy is eliminated by setting  $\text{right} := \text{right.succ}$ . Otherwise, the action depends on the type of the left son.

- If  $\text{left.cont} = \diamond$ , then eliminate this dummy by setting  $\text{left} := \text{left.succ}$ .
- If  $\text{left.cont} = \lambda x$ , then this  $\beta$ -redex is partially reduced by copying the argument  $\text{right}$  into the register  $\mathbf{R}[x]$  associated to the variable  $x$ . The substitution part of the  $\beta$ -reduction is then performed by the processors at variable nodes. Afterwards, replace the  $\text{@}$  and  $\lambda x$  nodes by dummies by setting  $\text{cont} := \diamond$ ,  $\text{left.cont} := \diamond$  and  $\text{succ} := \text{left}$ .
- If  $\text{left.cont} \in \{\text{s}_i, \text{len}, \text{half}\}$  and the right son is a numeral,  $\text{right.cont} = \kappa'$ , then replace the current node by a dummy, and let  $\text{succ}$  point to a numeral representing the result. In the case of  $\text{s}_i$  and  $\text{half}$ , this can be implemented by 2/3-tree operations using sequential time  $O(\log |\bar{n}^\lambda|)$ .

In the case of `len`, the result is equal to the number  $i$  of leaves of the numeral argument. This value is read off the topmost  $\kappa_i$  node, and a numeral of that value is produced. Since  $i$  is a number of length  $O(\log |\bar{n}^\dagger|)$ , this can also be done in sequential time  $O(\log |\bar{n}^\dagger|)$ .

- If `left.cont = @`, `left.left.cont`  $\in \{\text{drop}, \text{bit}\}$  and `right` and `left.right` both point to numerals, then again replace the current node by a dummy, and let `succ` point to a numeral representing the result, which again can be computed by 2/3-tree operations in time  $O(\log |\bar{n}^\dagger|)$ .
- If `left.cont = left.left.cont = @`, `left.left.left.cont = sm` and all of `right`, `left.right` and `left.left.right` point to numerals, then again the current node is replaced by a dummy with `succ` pointing to the result. To compute the result, the lengths  $i$  and  $j$  are read off the second and third argument, and multiplied. As  $i$  and  $j$  are  $O(\log |\bar{n}^\dagger|)$  bit numbers, this can be done in parallel time  $O(\log \log |\bar{n}^\dagger|)$  by  $O(\log^3 |\bar{n}^\dagger|)$  many processors. The product  $i \cdot j$  is compared to the length of the first argument; let the maximum of both be  $k$ . Now the result is a numeral consisting of a one followed by  $k$  zeroes, which can be produced in parallel time  $\log^2 k$  by  $O(k)$  many processors using the square-and-multiply method, which suffices since  $k \leq O(\log |\bar{n}^\dagger|)$ .
- Finally, if `left.cont = d` and `right.cont =  $\kappa'$` , then extract the last bit  $b$  of the numeral at `right`, and create two new variables  $x_0$  and  $x_1$ . Then reduce the `d`-redex by replacing the current node and the right son by abstraction nodes, and the left son by a variable node, i.e., setting `cont :=  $\lambda x_0$` , `right.cont :=  $\lambda x_1$` , `succ.right`, `succ.succ := left` and `left.cont :=  $x_b$` .

A processor with `cont =  $x$`  only becomes active when  $R[x] \neq \text{NULL}$ , and what it does then depends on the type of  $x$ .

If  $x$  is not of ground type, then the variable  $x$  occurs only in this place, so the substitution can be safely performed by setting `cont :=  $\diamond$`  and `succ :=  $R[x]$` .

If  $x$  is of type  $\iota$ , the processor waits until the content of register  $R[x]$  has been normalized, i.e., it acts only if  $R[x].\text{cont} = \kappa'$ . In this case, it replaces the variable node by a dummy, and lets `succ` point to a newly formed copy of the numeral in  $R[x]$ . This copy can be produced in parallel time  $O(\log |\bar{n}^\dagger|)$  by  $|\bar{n}^\dagger|$  processors, since the depth of any numeral is bounded by  $\log |\bar{n}^\dagger|$ .

Concerning correctness, note that the tree structure is preserved since numerals being substituted for type  $\iota$  variables are explicitly copied, and variables of higher type occur at most once. Obviously, no redex is left when the program halts.

For the time bound, observe that every processor performs at most one proper reduction plus possibly some dummy reductions. Every dummy reduction makes one dummy node unreachable, so the number of dummy reductions is bounded by the number of dummy nodes generated. Every dummy used to be a proper node, and the number of nodes is at most  $2|t|$ , so this number is bounded by  $2|t|$ . Thus at most  $4|t|$  reductions are performed, and thus the program ends after at most that many rounds. As argued above, every round takes at most  $O(\log |\bar{n}^\dagger|)$  operations with  $O(|\bar{n}^\dagger|)$  many additional processors.  $\square$

Let  $f(n) \lesssim g(n)$  abbreviate  $f(n) \leq (1 + o(1))g(n)$ , i.e.,  $\limsup_{n \rightarrow \infty} \frac{f(n)}{g(n)} \leq 1$ .

**Lemma 3.** *Let  $t$  be a linear term of  $\square$ -free type and  $\bar{x}^\triangleright; \bar{n}^\triangleright$  a context with all free variables of  $t[\bar{x}^\triangleright := \bar{n}^\triangleright]$  incomplete. Then there are a term  $\text{simp}(t, \bar{x}^\triangleright; \bar{n}^\triangleright)$  and a context  $\bar{y}^\triangleright; \bar{m}^\triangleright$  such that  $\text{simp}(t, \bar{x}^\triangleright; \bar{n}^\triangleright)[\bar{y}^\triangleright := \bar{m}^\triangleright]$  is simple and equivalent to  $t[\bar{x}^\triangleright := \bar{n}^\triangleright]$ , and which can be computed in time  $\lesssim 2^{\#\text{LR}(t)} \cdot |t| \cdot (2^{\#\text{LR}(t)} \cdot \log |\bar{n}^\triangleright|)^{\#\text{LR}(t)+2}$  by  $\lesssim |t| \cdot |\bar{n}^\triangleright|^{2^{\#\text{LR}(t)}(\#\text{CR}(t)+\#\text{LR}(t)+2)}$  processors, such that*

$$|\text{simp}(t, \bar{x}^\triangleright; \bar{n}^\triangleright)| \lesssim |t| \cdot \left(2^{\#\text{LR}(t)} \cdot \log |\bar{n}^\triangleright|\right)^{\#\text{LR}(t)} \quad \text{and} \quad |\bar{m}^\triangleright| \lesssim |\bar{n}^\triangleright|^{2^{\#\text{LR}(t)}}.$$

*Proof.* By induction on  $\#\text{LR}(t)$ , with a side-induction on  $|t|$  show that the following algorithm does it:

By pattern matching, determine in time  $O(|t|)$  the form of  $t$ , and branch according to the form.

- If  $t$  is a variable or one of the constants 0 or d, then return  $t$  and leave  $\bar{x}^\triangleright; \bar{n}^\triangleright$  unchanged.
- If  $t$  is  $c \bar{s}^\triangleright$ , where  $c$  is one of the constants  $s_i$ , drop, bit, len or sm then recursively simplify  $\bar{s}^\triangleright$ , giving  $\bar{s}^{*\triangleright}$  and contexts  $\bar{y}_j^\triangleright; \bar{m}_j^\triangleright$ , and return  $c \bar{s}^{*\triangleright}$  and  $\bar{y}^\triangleright; \bar{m}^\triangleright$ .
- If  $t$  is  $d r \bar{s}^\triangleright$ , then simplify  $r$  giving  $r'$  and  $\bar{y}^\triangleright; \bar{m}^\triangleright$ . Compute the numeral  $r^* := r'[\bar{y}^\triangleright := \bar{m}^\triangleright]^{\text{nf}}$ , and reduce the redex  $d r^*$ , giving  $t'$ , and recursively simplify  $t' \bar{s}^\triangleright$  with context  $\bar{x}^\triangleright; \bar{n}^\triangleright$ .
- If  $t$  is  $\# r$  then simplify  $r$  giving  $r'$  and  $\bar{y}^\triangleright; \bar{m}^\triangleright$ . Compute the numeral  $r^* := r'[\bar{y}^\triangleright := \bar{m}^\triangleright]^{\text{nf}}$ , and return a new variable  $y'$  and the context  $y'; 2^{|r^*|}$ .
- If  $t$  is  $\text{CR} h r$ , then simplify  $r$  giving  $r'$  and  $\bar{y}^\triangleright; \bar{m}^\triangleright$ , and compute the numeral  $r^* := r'[\bar{y}^\triangleright := \bar{m}^\triangleright]^{\text{nf}}$ .

Spawn  $|r^*|$  many processors, one for each leaf of  $r^*$ , by moving along the tree structure of  $r^*$ . The processor at bit  $i$  of  $r^*$  simplifies  $h z$  in the context  $\bar{x}^\triangleright, z; \bar{n}^\triangleright, [r^*/2^i]$ , giving a term  $h_i$  and context  $\bar{y}_i^\triangleright; \bar{m}_i^\triangleright$ , then he computes  $h_i^* := h_i[y_i := m_i]^{\text{nf}}$ , retaining only the lowest order bit  $b_i$ .

The bits  $\bar{b}^\triangleright$  are collected into a 2/3-tree representation of a numeral  $m$ , which is output in the form of a new variable  $z$  and the context  $z; m$ .

- $t$  is  $\text{LR} g h m \bar{s}^\triangleright$  then simplify  $m$ , giving  $m'$  and  $\bar{x}_m^\triangleright; \bar{n}_m^\triangleright$ . Normalize  $m'$  in the context  $\bar{x}^\triangleright, \bar{x}_m^\triangleright; \bar{n}^\triangleright, \bar{n}_m^\triangleright$ , giving  $m^*$ . Form  $k$  numerals  $m_i = \text{Half}^i(m^*)$  and sequentially simplify  $\bar{h} m_i^\triangleright$ , giving  $\bar{h}^\triangleright$ . (Of course, more precisely simplify  $h x$  for a new variable  $x$  in the context extended by  $x; m_i$ .) Then form the term

$$t' := h'_0(h'_1 \dots (h'_k g)) \bar{s}^\triangleright$$

and simplify it.

- If  $t$  is of the form  $\lambda x.r$  then recursively simplify  $r$ .
- If  $t$  is of the form  $(\lambda x.r) s \bar{s}^\triangleright$  and  $x$  occurs at most once in  $r$  then recursively simplify  $r[x := s] \bar{s}^\triangleright$ .
- If  $t$  is of the form  $(\lambda x.r) s \bar{s}^\triangleright$  and  $x$  occurs several times in  $r$ , then simplify  $s$  giving  $s'$  and a context  $\bar{y}^\triangleright; \bar{m}^\triangleright$ . Normalize  $s'$  in this context giving the numeral  $s^*$ . Then simplify  $r \bar{s}^\triangleright$  in the context  $\bar{x}^\triangleright, x; \bar{n}^\triangleright, s^*$ .

For correctness, note that **in the case**  $d r \bar{s}^\dagger$  simplifying  $r$  takes time  $\lesssim 2^{\#\text{LR}(r)} \cdot |r| \cdot (2^{\#(r)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(r)+2}$  and uses  $\lesssim |r| \cdot |\bar{n}^\dagger|^{2^{\#(r)}(\#\text{CR}(r)+\#\text{LR}(r)+2)}$  many processors. For the output we have  $|r'| \lesssim |r| \cdot (2^{\#(r)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(r)}$  and  $|\bar{m}^\dagger| \lesssim |\bar{n}^\dagger|^{2^{\#(r)}}$ . Hence the time used to normalize  $r'$  is  $O(|r'| \cdot \log |\bar{m}^\dagger|)$ , which is  $O(|r| \cdot (2^{\#\text{LR}(r)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(r)+1})$ , and the number of processors needed is  $O(|r'| \cdot |\bar{n}^\dagger|) \leq |\bar{n}^\dagger|^{2^{\#(r)+1}}$ . Finally, to simplify  $t' \bar{s}^\dagger$  we need time  $\lesssim 2^{\#\text{LR}(\bar{s}^\dagger)} \cdot (|\bar{s}^\dagger| + 3) \cdot (2^{\#(\bar{s}^\dagger)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(\bar{s}^\dagger)+2}$  and the number of processors is  $\lesssim (|\bar{s}^\dagger| + 3) |\bar{n}^\dagger|^{2^{\#(\bar{s}^\dagger)}(\#\text{CR}(\bar{s}^\dagger)+\#\text{LR}(\bar{s}^\dagger)+2)}$ . Summing up gives an overall time that is  $\lesssim 2^{\#\text{LR}(t)} \cdot (|r| + |\bar{s}^\dagger| + 3) \cdot (2^{\#(t)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(t)+2}$  which is a correct bound since  $|d| = 3$ . Maximizing gives that the overall number of processors is  $\lesssim |t| \cdot |\bar{n}^\dagger|^{2^{\#(t)}(\#\text{CR}(t)+\#\text{LR}(t)+2)}$ . The length of the output term is  $\lesssim (|\bar{s}^\dagger| + 3) \cdot (2^{\#(\bar{s}^\dagger)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(\bar{s}^\dagger)}$ , and the size of the output context is  $\lesssim |\bar{n}^\dagger|^{2^{\#(\bar{s}^\dagger)}}$ , which suffices.

**In the case**  $\#r$  we obtain the same bounds for simplification and normalization of  $r$  as in the previous case. For  $r^*$  we get  $|r^*| = O(|r'| + |\bar{m}^\dagger|) \lesssim |\bar{n}^\dagger|^{2^{\#(r)}}$ . Computing the output now takes time  $\log |r^*|^2 = 2^{\#(r)+1} \cdot \log |\bar{n}^\dagger|$  and  $|r^*|^2 \lesssim |\bar{n}^\dagger|^{2^{\#(r)+1}}$  many processors. Thus the overall time is  $\lesssim 2^{\#\text{LR}(r)} \cdot |r| \cdot (2^{\#(r)+1} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(r)+2}$  and the number of processors is  $\lesssim |\bar{n}^\dagger|^{2^{\#(r)+1}(\#\text{CR}(r)+\#\text{LR}(r)+2)}$ . The length of the output term is 1, and the size of the output context is bounded by  $|r^*|^2 + 1 \lesssim |\bar{n}^\dagger|^{2^{\#(r)+1}}$ , which implies the claim.

**In the case**  $\text{CR}hr$  note that the arguments  $h : \iota \multimap \iota$  and  $r : \iota$  both have to be present, since  $t$  has to be of  $\square$ -free type. We obtain the same bounds for simplification and normalization of  $r$  and the length of the numeral  $r^*$  as in the previous case. Spawning the parallel processors and collecting the result in the end each needs time  $\log |r^*| = 2^{\#(r)} \cdot |\bar{n}^\dagger|$ . The main work is done by the  $|\bar{n}^\dagger|^{2^{\#(r)}}$  many processors that do the simplification and normalization of the step terms. Each of them takes time  $\lesssim 2^{\#\text{LR}(h)} \cdot (|h| + 1) \cdot (2^{\#(h)} \cdot \log |\bar{n}^\dagger, r^*|)^{\#\text{LR}(h)+2} \lesssim 2^{\#\text{LR}(h)} \cdot (|h| + 1) \cdot (2^{\#(h)+\#(r)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(h)+2}$  and a number of subprocessors satisfying  $\lesssim (|h| + 1) \cdot |\bar{n}^\dagger, r^*|^{2^{\#(h)}(\#\text{CR}(h)+\#\text{LR}(h)+2)} \lesssim (|h| + 1) \cdot |\bar{n}^\dagger|^{2^{\#(h)+\#(r)}(\#\text{CR}(h)+\#\text{LR}(h)+2)}$  to compute  $h_i$  and  $\bar{y}_i^\dagger; \bar{m}_i^\dagger$  with  $|h_i| \lesssim (|h| + 1) \cdot (2^{\#(h)} \cdot \log |\bar{n}^\dagger, r^*|)^{\#\text{LR}(h)}$  and  $|\bar{m}_i^\dagger| \lesssim |\bar{n}^\dagger, r^*|^{2^{\#\text{LR}(h)}} \lesssim |\bar{n}^\dagger|^{2^{\#\text{LR}(h)+\#(r)}}$ . Now the normal form  $h_i^*$  is computed in time  $O(|h_i| \cdot \log |\bar{m}_i^\dagger|) \lesssim (|h| + 1) \cdot (2^{\#(h)+\#(r)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(h)+1}$  by  $O(|h_i| \cdot |\bar{m}_i^\dagger|) \lesssim |\bar{n}^\dagger|^{2^{\#(h)+\#(r)+1}}$  many subprocessors. Summing up the times yields that the overall time is  $\lesssim 2^{\#\text{LR}(r)} \cdot |r| \cdot (2^{\#(r)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(r)+2} + 2^{\#\text{LR}(h)} \cdot (|h| + 1) \cdot (2^{\#(h)+\#(r)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(h)+2} \lesssim 2^{\#\text{LR}(t)} \cdot (|r| + |h| + 1) \cdot (2^{\#(t)} \cdot \log |\bar{n}^\dagger|)^{\#\text{LR}(t)+2}$ . The number of subprocessors used by each of the  $|r^*|$  processes is  $\lesssim (|h| + 1) \cdot |\bar{n}^\dagger|^{2^{\#(h)+\#(r)}(\#\text{CR}(h)+\#\text{LR}(h)+2)}$  and multiplying this by the upper bound  $|\bar{n}^\dagger|^{2^{\#(r)}}$  on the number of processes yields that the bound for the total number of pro-

cessor holds. The output term is of length 1, and the length of the output context is bounded by  $|r^*| \lesssim |\bar{n}^\rightarrow|^{2^{\sharp(r)}}$ .

**In the case LR  $ghm \bar{s}^\rightarrow$**  note that, as  $t$  has  $\square$ -free type, all the arguments up to and including the  $m$  have to be present. Moreover,  $h$  is in a complete position, so it cannot contain incomplete free variables, therefore neither can do any of the  $\bar{h}^\rightarrow$ ; so  $t'$  really is linear. Due to the typing restrictions of the LR the step functions  $\bar{h}m^\rightarrow$  have  $\square$ -free type. So in all cases we're entitled to recursively call the algorithm and to apply the induction hypothesis. For calculating  $m^*$  we have the same bounds as in the previous cases. We have  $k \sim \log |m^*| \lesssim 2^{\sharp(m)} \log |\bar{n}^\rightarrow|$ . The time needed for calculating the  $\bar{h}^\rightarrow$  is  $\leq k 2^{\sharp_{LR}(h)} (|h|+1) (2^{\sharp(h)} \log |\bar{n}^\rightarrow, m^*|)^{\sharp_{LR}(h)+2} \lesssim 2^{\sharp_{LR}(h)} (|h|+1) (2^{\sharp(h)+\sharp(m)} \log |\bar{n}^\rightarrow|)^{\sharp_{LR}(h)+3}$ . For the length  $|\bar{h}^\rightarrow|$  we have  $|\bar{h}^\rightarrow| \lesssim (|h|+1) (2^{\sharp(h)} \cdot \log |\bar{n}^\rightarrow, m^*|)^{\sharp_{LR}(h)} \lesssim (|h|+1) (2^{\sharp(h)+\sharp(m)} \log |\bar{n}^\rightarrow|)^{\sharp_{LR}(h)}$  and the length of the numerals  $\bar{n}^\rightarrow$  in the contexts output by the computation of the  $\bar{h}^\rightarrow$  is bounded by  $|\bar{n}^\rightarrow, m^*|^{2^{\sharp(h)}} \lesssim (|\bar{n}^\rightarrow|^{2^{\sharp(m)}})^{2^{\sharp(h)}} = |\bar{n}^\rightarrow|^{2^{\sharp(m)+\sharp(h)}}$ . For the length of  $t'$  we have  $|t'| \leq k |\bar{h}^\rightarrow| + |g| + |\bar{s}^\rightarrow| \lesssim (|h|+|g|+|\bar{s}^\rightarrow|+1) (2^{\sharp(h)+\sharp(m)} \log |\bar{n}^\rightarrow|)^{\sharp_{LR}(h)+1}$ . So the final computation takes time

$$\begin{aligned} &\lesssim 2^{\sharp_{LR}(t')} |t'| (2^{\sharp(t')} \log |\bar{n}^\rightarrow, \bar{n}^\rightarrow|)^{\sharp_{LR}(t')+2} \\ &\lesssim 2^{\sharp_{LR}(g)+\sharp_{LR}(\bar{s}^\rightarrow)} (|h|+|g|+|\bar{s}^\rightarrow|+1) (2^{\sharp(h)+\sharp(m)} \log |\bar{n}^\rightarrow|)^{\sharp_{LR}(h)+1} \\ &\quad \cdot (2^{\sharp(g)+\sharp(\bar{s}^\rightarrow)} \cdot 2^{\sharp(m)+\sharp(h)} \log |\bar{n}^\rightarrow|)^{\sharp_{LR}(g)+\sharp_{LR}(\bar{s}^\rightarrow)+2} \\ &\lesssim 2^{\sharp_{LR}(g)+\sharp_{LR}(\bar{s}^\rightarrow)} (|h|+|g|+|\bar{s}^\rightarrow|+1) (2^{\sharp(t)} \log |\bar{n}^\rightarrow|)^{\sharp_{LR}(h)+1+\sharp_{LR}(g)+\sharp_{LR}(\bar{s}^\rightarrow)+2}. \end{aligned}$$

So summing up all the times one verifies that the time bound holds. The number of processors needed in the final computation is

$$\begin{aligned} &\lesssim |t'| \cdot \left| \bar{n}^\rightarrow, \bar{n}^\rightarrow \right|^{2^{\sharp(t')} (\sharp_{CR}(t')+\sharp_{LR}(t')+2)} \\ &\lesssim (|h|+|g|+|\bar{s}^\rightarrow|+1) (2^{\sharp(h)+\sharp(m)} \log |\bar{n}^\rightarrow|)^{\sharp_{LR}(h)+1} \cdot \\ &\quad (|\bar{n}^\rightarrow|^{2^{\sharp(m)+\sharp(h)}})^{2^{\sharp(g)+\sharp(\bar{s}^\rightarrow)} (\sharp_{CR}(g)+\sharp_{CR}(\bar{s}^\rightarrow)+\sharp_{LR}(g)+\sharp_{LR}(\bar{s}^\rightarrow)+2)} \\ &\leq (|h|+|g|+|\bar{s}^\rightarrow|+1) (|\bar{n}^\rightarrow|^{2^{\sharp(m)+\sharp(h)}})^{2^{\sharp(g)+\sharp(\bar{s}^\rightarrow)} (\sharp_{CR}(g)+\sharp_{CR}(\bar{s}^\rightarrow)+\sharp_{LR}(g)+\sharp_{LR}(\bar{s}^\rightarrow)+2+1)}. \end{aligned}$$

The context finally output is bounded by  $\lesssim \left| \bar{n}^\rightarrow, \bar{n}^\rightarrow \right|^{2^{\sharp(t')}} \lesssim |\bar{n}^\rightarrow|^{2^{\sharp(m)+\sharp(h)+\sharp(t')}}$ .

The length of the final output is bounded by  $\lesssim |t'| \cdot (2^{\sharp(t')} \log |\bar{n}^\rightarrow, \bar{n}^\rightarrow|)^{\sharp_{LR}(t')} \lesssim (|h|+|g|+|\bar{s}^\rightarrow|+1) (2^{\sharp(h)+\sharp(m)} \log |\bar{n}^\rightarrow|)^{\sharp_{LR}(h)+1} (2^{\sharp(t')+\sharp(m)+\sharp(h)} \log |\bar{n}^\rightarrow|)^{\sharp_{LR}(t')} \lesssim (|h|+|g|+|\bar{s}^\rightarrow|+1) (2^{\sharp(t')+\sharp(m)+\sharp(h)} \log |\bar{n}^\rightarrow|)^{\sharp_{LR}(t')+\sharp_{LR}(h)+1}$ .

**In the case  $\lambda x.r$**  note that due to the fact that  $t$  has  $\square$ -free type  $x$  has to be incomplete, so we're entitled to use the induction hypothesis.

**In the case  $(\lambda x.r) s \bar{s}^\rightarrow$  with several occurrences of  $x$**  in  $r$  note that due to the fact that  $t$  is linear,  $x$  has to be of ground type (since higher

type variables are only allowed to occur once). The time needed to calculate  $s'$  is bounded by  $2^{\#\text{LR}(s)} |s| (2^{\#(s)} \log |\bar{n}^\rightarrow|)^{\#\text{LR}(s)+2}$  and the number of processors is not too high. For the length of  $s'$  we have  $|s'| \lesssim |s| \cdot (2^{\#(s)} \log |\bar{n}^\rightarrow|)^{\#\text{LR}(s)}$  and  $|\bar{m}^\rightarrow| \lesssim |\bar{n}^\rightarrow|^{2^{\#(s)}}$ . So the time for calculating  $s^*$  is bounded by  $\lesssim |s'| \log |\bar{n}^\rightarrow, \bar{m}^\rightarrow| \lesssim |s| \cdot (2^{\#(s)} \log |\bar{n}^\rightarrow|)^{\#\text{LR}(s)+1}$ . For the length of the numeral  $s^*$  we have  $|s^*| \leq |s'| + |\bar{n}^\rightarrow, \bar{m}^\rightarrow| \lesssim |\bar{n}^\rightarrow|^{2^{\#(s)}}$ . So the last computation takes time

$$2^{\#\text{LR}(r \bar{s}^\rightarrow)} \cdot |r \bar{s}^\rightarrow| \left( 2^{\#(r \bar{s}^\rightarrow) + \#(s)} \log |\bar{n}^\rightarrow| \right)^{\#\text{LR}(r \bar{s}^\rightarrow) + 2}.$$

Summing up, the time bound holds. The number of processors needed for the last computation is bounded by  $\lesssim |r \bar{s}^\rightarrow| \cdot |\bar{n}^\rightarrow|^{2^{\#(s) + \#(r \bar{s}^\rightarrow)} (\#\text{CR}(r \bar{s}^\rightarrow) + \#\text{LR}(r \bar{s}^\rightarrow) + 2)}$ . The context finally output is bounded by  $|\bar{n}^\rightarrow, s^*|^{2^{\#(r \bar{s}^\rightarrow)}} \lesssim |\bar{n}^\rightarrow|^{2^{\#(s) + \#(r \bar{s}^\rightarrow)}}$ .

**In all other cases** the bounds trivially hold.  $\square$

**Theorem 1.** *Let  $t$  be a linear term of type  $\bar{\square}^\rightarrow \multimap \iota$ . Then the function denoted by  $t$  is in NC.*

*Proof.* Let  $\bar{n}^\rightarrow$  be an input, given as 2/3-tree representations of numerals, and  $\bar{x}^\rightarrow$  complete variables of type  $\iota$ . Using Lemma 3, we compute  $t' := \text{simp}(t \bar{x}^\rightarrow, \bar{x}^\rightarrow; \bar{n}^\rightarrow)$  and a new context  $\bar{y}^\rightarrow; \bar{m}^\rightarrow$  with  $|t'| \leq (\log |\bar{n}^\rightarrow|)^{O(1)}$  and  $|\bar{m}^\rightarrow| \leq |\bar{n}^\rightarrow|^{O(1)}$  in time  $(\log |\bar{n}^\rightarrow|)^{O(1)}$  by  $|\bar{n}^\rightarrow|^{O(1)}$  many processors.

Then using Lemma 2 we compute the normal form  $t'[\bar{y}^\rightarrow := \bar{m}^\rightarrow]^{\text{nf}}$  in time  $O(|t'| \cdot \log |\bar{m}^\rightarrow|) = (\log |\bar{n}^\rightarrow|)^{O(1)}$  by  $O(|t'| |\bar{m}^\rightarrow|) = |\bar{n}^\rightarrow|^{O(1)}$  many processors.

Hence the function denoted by  $t$  is computable in polylogarithmic time by polynomially many processors, and thus is in NC.  $\square$

## 4 Completeness

Bellantoni [2] defines a two-sorted function algebra  $2\text{CLO}$  characterizing NC, which is an implicit variant of Clote's function algebra  $\mathbf{A}$  [7] that characterizes NC by concatenation recursion and logarithmic recursion with explicit bounds.  $2\text{CLO}$  is a class of functions of two sorts of arguments, the normal inputs written to the left of a separating semicolon, and the safe inputs written to the right. It is defined to be the smallest class of functions that contains the constant zero, projections  $\pi_j^{m,n}(x_1, \dots, x_m; x_{m+1}, \dots, x_{m+n}) = x_j$ , successors  $S_i$ , conditional D, bit test Bit, binary length Len, smash  $\#^!(w; a, b) = 2^{\|a\| \cdot \|b\|} \bmod 2^{\|w\|^2}$  and is closed under the following operations:

- *Safe composition:* from  $g, h$  and  $k$  define  $f(\bar{x}^\rightarrow; \bar{y}^\rightarrow) := g(\bar{h}^\rightarrow(\bar{x}^\rightarrow); \bar{k}^\rightarrow(\bar{x}^\rightarrow; \bar{y}^\rightarrow))$ .
- *Concatenation recursion:* from  $h$  define  $f$  by

$$\begin{aligned} f(\bar{x}^\rightarrow; 0, \bar{a}^\rightarrow) &= 0 \\ f(\bar{x}^\rightarrow; S_i(; b), \bar{a}^\rightarrow) &= S_{h(\bar{x}^\rightarrow; b, \bar{a}^\rightarrow) \bmod 2} (; f(\bar{x}^\rightarrow; b, a)) \quad \text{for } S_i(; b) > 0 \end{aligned}$$

– *Log recursion*: from  $g$  and  $h$  define  $f$  by

$$\begin{aligned} f(0, \vec{x}; \vec{a}) &= g(\vec{x}; \vec{a}) \\ f(y, \vec{x}; \vec{a}) &= h(y, \vec{x}; \vec{a}, f(\text{Half}(\cdot; y), \vec{x}; \vec{a})) \quad \text{for } y > 0 \end{aligned}$$

It is proved in Chapter 7 of Bellantoni’s thesis [2] that this function algebra characterizes NC:

**Theorem 2 (Bellantoni [2]).** *A function  $f(\vec{x})$  is in NC if and only if  $f(\vec{x};) \in 2\text{CLO}$ .*

We now define a modified version of the class  $2\text{CLO}$ , denoted by  $2\text{NC}$ , as the smallest class that contains all the base functions of  $2\text{CLO}$  and additionally the functions  $\text{Half}$  and  $\text{Drop}$  with  $\text{Half}(\cdot; a) = \lfloor a/2^{\lceil \|a\|/2} \rceil$  and  $\text{Drop}(\cdot; a, b) = \lfloor a/2^{\|b\|} \rfloor$ , and is closed under safe composition and log recursion and the following variant of concatenation recursion:

$$\begin{aligned} f(0, \vec{x}; \vec{a}) &= 0 \\ f(S_i(\cdot; y), \vec{x}; \vec{a}) &= S_{h(y, \vec{x}; \vec{a}) \bmod 2}(\cdot; f(y, \vec{x}; \vec{a})) \quad \text{for } S_i(\cdot; y) > 0. \end{aligned}$$

where the input that governs the recursion has to be normal.

**Lemma 4.** *A function  $f(\vec{x})$  is in NC if and only if  $f(\vec{x};) \in 2\text{NC}$ .*

*Proof.* We show how to modify the proof of the corresponding proposition for  $2\text{CLO}$  in [2]. The proof of the “if” direction can be left unchanged, one only has to observe that the functions  $\text{Half}$  and  $\text{Drop}$  are in NC, and that the Bounding Lemma still holds.

For the “only if” part, one has to show that for every function  $f(\vec{x})$  in NC there is a function  $f'(w; \vec{x})$  in  $2\text{NC}$  and a polynomial  $p_f$  such that  $f'(w, \vec{x}) = f(\vec{x})$  for all  $w$  with  $\|w\| \geq p_f(\|\vec{x}\|)$ . This is proved by induction on the definition of  $f$  in Clote’s function algebra  $\mathbf{A}$ .

We only have to change those parts of the proof of this claim where concatenation recursion is used, which has to be replaced by our modified form. In the case of  $f$  defined by log recursion, concatenation recursion is only used to define the function  $\text{Half}$ , which we have added as a base function.

We define some useful functions in  $2\text{NC}$ :

$$\begin{aligned} \text{ones}(0; \cdot) &= 0 \\ \text{ones}(S_i(\cdot; y); \cdot) &= S_1(\cdot; \text{ones}(y)) \\ \llbracket \|y\| \leq \|b\| \rrbracket &= D(\cdot; \text{Bit}(\cdot; \text{ones}(y)), \text{Len}(b)), 1, 0 \end{aligned}$$

here in  $\llbracket \|y\| \leq \|b\| \rrbracket$  the input  $y$  is normal and  $b$  is safe.

$$\begin{aligned} \text{rev}(0; a) &= 0 \\ \text{rev}(S_i(\cdot; y); a) &= S_{\text{Bit}(a, \text{Len}(\cdot; y))}(\cdot; \text{rev}(y; a)) \end{aligned}$$

Here  $rev(y; a)$  outputs the low order  $\|y\|$  bits of  $a$  in reverse order. Now let  $f$  be defined by concatenation recursion in  $\mathbf{A}$ :

$$\begin{aligned} f(0, \bar{x}^\triangleright) &= g(\bar{x}^\triangleright) \\ f(s_i(y), \bar{x}^\triangleright) &= s_{h_i(y, \bar{x}^\triangleright)}(f(y, \bar{x}^\triangleright)) \end{aligned}$$

and let  $g'$  and  $h'$  be obtained by the induction hypothesis. We define

$$\begin{aligned} h'(w; y, \bar{x}^\triangleright) &= \mathbf{D}(\cdot; u, h'_0(w; y, \bar{x}^\triangleright), h'_0(w; y, \bar{x}^\triangleright)) \\ aux(z, w; y, \bar{x}^\triangleright) &= \mathbf{D}(\cdot; [\|z\| \leq \|y\|], h'(w; \mathbf{Drop}(\cdot; y, z), \bar{x}^\triangleright), \mathbf{Bit}(\cdot; g'(w; \bar{x}^\triangleright), \|z\| - \|y\|)) \\ \hat{f}(0, w; y, \bar{x}^\triangleright) &= 0 \\ \hat{f}(S_i(\cdot; z), w; y, \bar{x}^\triangleright) &= S_{aux(z, w; y, \bar{x}^\triangleright)}(\cdot; \hat{f}(z, w; y, \bar{x}^\triangleright)) \\ \tilde{f}(z, w; y, \bar{x}^\triangleright) &= rev(z; \hat{f}(z, w; y, \bar{x}^\triangleright)) \\ f'(w; y, \bar{x}^\triangleright) &= \tilde{f}(w, w; y, \bar{x}^\triangleright) \end{aligned}$$

where in the second line,  $\|z\| - \|y\|$  is computed as  $\mathbf{Len}(\cdot; \mathbf{Drop}(\cdot; z, y))$ . Now one can argue as in [2] that  $f'(w; y, \bar{x}^\triangleright) = f(y, \bar{x}^\triangleright)$  as long as  $\|w\| > \|y\| + \|g(\bar{x}^\triangleright)\|$ , so we define  $p_f(\|y\|, \|\bar{x}^\triangleright\|) = \|y\| + p_g(\|\bar{x}^\triangleright\|) + 1$ .  $\square$

Now we can prove that our term system can denote all functions in NC.

**Theorem 3.** *For every function  $f(\bar{x}^\triangleright; \bar{y}^\triangleright)$  in  $2\text{NC}$ , there is a closed linear term  $t_f$  of type  $\square \bar{\tau}^\triangleright \multimap \bar{\tau}^\triangleright \multimap \iota$  that denotes  $f$ .*

*Proof.* For every base function of  $2\text{NC}$  other than  $\#'$  there is a constant of type  $\bar{\tau}^\triangleright \multimap \iota$  denoting it. For  $\#'$ , we define

$$t_{\#'} := \lambda \mathbf{w} a b . sm(\mathbf{drop}(\# w)(s_1 0)) a b : \square \iota \multimap \iota \multimap \iota \multimap \iota$$

A projection function  $\pi_j^{m,n}$  is denoted by the term

$$\lambda \mathbf{x}_1 \dots \mathbf{x}_m x_{m+1} \dots x_{m+n} \cdot z_j$$

where  $z_j$  is  $\mathbf{x}_j$  for  $j \leq m$  and  $x_j$  for  $j > m$ .

*Safe composition:* Let  $f(\bar{x}^\triangleright; \bar{y}^\triangleright) := g(\bar{h}^\triangleright(\bar{x}^\triangleright); \bar{k}^\triangleright(\bar{x}^\triangleright; \bar{y}^\triangleright))$ . By induction we have terms  $t_g$ ,  $t_{h_i}$  and  $t_{k_j}$  denoting the functions  $g$ ,  $h_i$  and  $k_j$ . Then we define

$$t_f := \lambda \bar{\mathbf{x}}^\triangleright \bar{\mathbf{y}}^\triangleright \cdot t_g(t_{h_1} \bar{\mathbf{x}}^\triangleright) \dots (t_{h_m} \bar{\mathbf{x}}^\triangleright) (t_{k_1} \bar{\mathbf{x}}^\triangleright \bar{\mathbf{y}}^\triangleright) \dots (t_{k_n} \bar{\mathbf{x}}^\triangleright \bar{\mathbf{y}}^\triangleright)$$

*Concatenation recursion:* Let  $f$  be defined by concatenation recursion from  $h$ , and let  $t_h$  be a term that denotes  $h$ . We define  $t'_h := \lambda \bar{\mathbf{x}}^\triangleright \bar{\mathbf{a}}^\triangleright \bar{\mathbf{y}}^\triangleright \cdot t_h \bar{\mathbf{x}}^\triangleright \bar{\mathbf{y}}^\triangleright \bar{\mathbf{a}}^\triangleright$ , and using this, we can define a term  $t_f$  denoting  $f$  as

$$t_f = \lambda \mathbf{y}^\triangleright \bar{\mathbf{x}}^\triangleright \bar{\mathbf{a}}^\triangleright \cdot \mathbf{CR}(t_h \bar{\mathbf{x}}^\triangleright \bar{\mathbf{a}}^\triangleright) \mathbf{y}$$

*Log recursion:* Let  $f$  be defined by log recursion from  $g$  and  $h$ , and let  $t_g$  and  $t_h$  denote  $g$  and  $h$ , respectively. We first define a term  $t'_h$  of type  $(\bar{\tau}^\triangleright \multimap \iota) \multimap \square \iota \multimap (\bar{\tau}^\triangleright \multimap \iota)$  with free variables  $\bar{\mathbf{x}}^\triangleright$  by

$$t'_h = \lambda \mathbf{m}^\triangleright v \bar{\tau}^\triangleright \multimap \iota \bar{\mathbf{b}}^\triangleright \cdot t_h \mathbf{m} \bar{\mathbf{x}}^\triangleright \bar{\mathbf{b}}^\triangleright (v \bar{\mathbf{b}}^\triangleright),$$

and by use of this we define a term  $t_f$  denoting  $f$  by

$$t_f = \lambda \mathbf{n}^t \bar{\mathbf{x}}^{\lambda^t} \bar{\mathbf{a}}^{\lambda^t} . (\text{LR}_{\tau \rightarrow \rightarrow \circ^t} (t_g \bar{\mathbf{x}}^{\lambda^t}) t'_h \mathbf{n}) \bar{\mathbf{a}}^{\lambda^t} .$$

One verifies easily that all constructed terms are linear, so this completes the proof.  $\square$

From Theorems 3 and 1 we immediately get our main result:

**Corollary 1.** *A number-theoretic function  $f$  is in NC if and only if it is denoted by a linear term of our system.*

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