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A Logical account of PSPACE

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Abstract
We propose a characterization of PSPACE by means of a type assignment for an extension of lambda calculus with a conditional construction. The type assignment \( \text{STA}_B \) is an extension of STA, a type assignment for lambda-calculus inspired by Lafont’s Soft Linear Logic.

We extend STA by means of a ground type and terms for booleans. The key point is that the elimination rule for booleans is managed in an additive way. Thus, we are able to program polynomial time Alternating Turing Machines. Conversely, we introduce a call-by-name evaluation machine in order to compute programs in polynomial space. As far as we know, this is the first characterization of PSPACE which is based on lambda calculus and light logics.

1. Introduction
The argument of this paper fits in the so-called Implicit Computational Complexity topic, in particular on the design of programming languages with bounded computational complexity. We want to use a ML-like approach, so having a \( \lambda \)-calculus like language, and a type assignment system for it, where the types guarantee, besides the functional correctness, also complexity properties. So types can be used in a static way in order to check the correct behaviour of the programs, also with respect to the resource usage. If the considered resource is the time, the natural choice is to use as types formulae of the light logics, which characterize some classes of time complexity. Light Linear Logic (LLL) of Girard [Gir98], and Soft Linear Logic (SLL) of Lafont [Laf04] characterize polynomial time, while Elementary Linear Logic (EAL) characterizes elementary time. The characterization is based on the fact that cut-elimination in these logics is performed in a number of steps which depends in a polynomial or elementary way from the initial size of the proof (while the degree of the proof, i.e., the nesting of exponential rules, is fixed). Moreover all these logics are also complete with respect to the related complexity class.

The good properties of such logics have been fruitfully used in order to design type assignment systems for \( \lambda \)-calculus which are correct and complete with respect to the polynomial or elementary complexity bound. Namely every well typed term \( \beta \)-reduces to normal form in a number of steps which depends in a polynomial or elementary way from its size, and moreover all functions with the corresponding complexity are representable by a well typed term. Examples of polynomial type assignment systems are in [BT04] and [GR07], based respectively on LAL (an affine variant of LLL designed by Asperti and Roversi [AR02]) and on SLL, and an example of an elementary type assignment system is in [CDLRDR05].

Here we use the same approach for studying space complexity, in particular we build a type system for a \( \lambda \)-calculus like language, in such a way that well typed terms are correct and complete for PSPACE. More precisely, every well typed program reduces in polynomial space and all decision functions computable in polynomial space are computed by well typed programs. There is no previous logical characterization of PSPACE from which we can start. But we will use the fact that polynomial space computations coincide with polynomial time alternating Turing machine computations (APTIME) [Sav70, CKS81]. In particular

\[ \text{PSPACE} = \text{NSPACE} = \text{APTIME} \]

So we will start from the type assignment STA for \( \lambda \)-calculus presented in [GR07], which is based on SLL, in the sense that in STA both types are a proper subset of SLL formulae, and type assignment derivations correspond, through the Curry-Howard isomorphism, to a proper subset of SLL derivations. STA is correct and complete (in the sense said before) with respect to polynomial time computations. Then we design a type assignment system (\( \text{STA}_B \)), where the types are STA types plus a type \( B \) for booleans, and the language \( \Lambda_B \) is an extension of \( \lambda \)-calculus with two boolean constants and a conditional constructor. The elimination rule for conditional is the following:

\[ \Gamma \vdash M : B \quad \Gamma \vdash \Psi_0 : A \quad \Gamma \vdash \Psi_1 : A \]
\[ \Gamma \vdash \text{if} \ M \ \text{then} \ \Psi_0 \ \text{else} \ \Psi_1 : A \quad (\text{BE}) \]

In the if-rule above, contexts are managed in an additive way, that is with free contractions. From a computational point of view, this intuitively means that a computation can repeatedly fork into subcomputations and the result is obtained by a backward computation from all subcomputation results.

While the time complexity result for STA is not related to a particular evaluation strategy, here, for characterizing space complexity, the evaluation should be done carefully. Indeed, a call-by-value evaluation can construct exponential size term. So we define a call-by-name evaluation machine, inspired by Krivine’s machine [Kri07] for \( \lambda \)-calculus, where substitutions are made only on head variables. This machine is equipped with a memory device thanks to which the space used is easily determined, as the dimension of the maximal machine configuration. Then we prove that, if the machine takes a program (i.e., a closed term well typed with a ground type) as input, then each configuration is bounded in a polynomial way in the size of the input. So every program is evaluated by the machine in polynomial space. Conversely, we encode every polynomial time alternating Turing machine by a term of \( \text{STA}_B \). The simulation relies on a higher order representation of a parameter substitution recurrence schema which was used in [LM94].

\( \text{STA}_B \) is the first characterization of PSPACE through a type assignment system. A proposal for a similar characterization has been made by Terui [Ter00], but the work has never been completed.

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There are previous implicit characterizations of polynomial space computations. The characterizations in [LM94, LM97] and [Oti01] are based on ramified recursions over binary words. In finite model theory, PSPACE is captured by first order queries with a partial fixed point operator [Var82, AV89]. The reader may consult the recent book [GKL+07]. Finally there are some algebraic characterizations like the one [Goe92] or [Jon01] but which are, in essence, over finite domains.

An example of a characterization of a complexity space class through a light logic is in [Sch07] where a logical system characterizing logarithmic space computations is defined, the Stratified Bounded Affine Logic (SBAL). Logarithmic space soundness is proved by considering only proofs of certain sequents to represent the functions computable in logarithmic space.

Our characterization is strongly based on the additive rule (BE). A similar tool has been used by Maurel's Non Deterministic Light Logic (nLLL) [Mau03] in order to characterize non deterministic polynomial time. More precisely nLLL introduces an explicit sum characterizing logarithmic space computations. The characterizations in [LM94, LM97] and [Goe92] or [Jon01] but this does not relate to the task of designing programming language with an intrinsically polynomial computational bound.

Outline of the paper In Section 2 the system STA_B is introduced and the proofs of subject reduction and strong normalization properties are given. In Section 3 the operational semantics of STA_B program is defined, through an abstract evaluation machine. In Section 4 we show that STA_B programs can be executed in polynomial time. In Section 5 the completeness for PSPACE is proved. In Section 6 some complementary argument are considered. The Appendix contains the most technical proofs.

2. Soft Type Assignment system with Booleans

In this section the type assignment STA_B is presented, and its properties are proved. STA_B is an extension of the type system STA for λ-calculus introduced in [GR07], which assigns to terms of the λ-calculus a proper subset of formulae of Lafont's Soft Linear Logic [Laf04]. STA has been proved to be correct and complete for polynomial time computations. STA_B is obtained from STA by extending both the calculus and the set of types. The calculus is the λ-calculus extended by boolean constants 0, 1 and an if constructor, types are the types of STA plus a constant type B for booleans.

Definition 1.
1. The set Λ_B of terms is defined by the following grammar:
   
   \[ M ::= x \mid 0 \mid 1 \mid λx.M \mid MM \mid if \ M \ then \ B \ else \ M \]
   
   where \( x \) ranges over a countable set of variables and \( B = \{0, 1\} \) is the set of booleans.

2. The set \( T \) of \( B \) types is defined as follows:
   
   \[ A ::= B \mid α \mid σ → γ \mid ∀α.A \quad \text{(Linear Types)} \]
   
   \[ σ ::= A \mid !σ \]
   
   where \( α \) ranges over a countable set of type variables and \( B \) is the only ground type.

3. A context is a set of assumptions of the shape \( x : α \), where all variables are different. We use \( Γ, Δ \) to denote contexts. dom(Γ) = \{\( x \mid x : σ \in Γ \)\} and \( Γ#Δ \) means \( \text{dom}(Γ) \cap \text{dom}(Δ) = \emptyset. \)

Table 1. The Soft Type Assignment system with Booleans

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x : A \vdash x : A )</td>
<td>( \text{Ax} )</td>
</tr>
<tr>
<td>( Γ \vdash M : σ )</td>
<td>( \text{w} )</td>
</tr>
<tr>
<td>( Γ, x : A \vdash M : σ )</td>
<td>( \text{Ax} )</td>
</tr>
<tr>
<td>( Γ \vdash M : σ → γ )</td>
<td>( \text{Ax} )</td>
</tr>
<tr>
<td>( Γ \vdash M : σ → γ )</td>
<td>( \text{Ax} )</td>
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<td>( \text{Ax} )</td>
</tr>
</tbody>
</table>

4. STA_B proves judgments of the shape \( Γ \vdash M : σ \) where \( Γ \) is a context, \( M \) is a term, and \( σ \) is a \( B \) type. The rules are given in Table 1.

5. Derivations are denoted by \( Γ \vdash M : σ \) denotes a derivation \( Γ \vdash M : σ \) has precedence on conclusion \( Γ \vdash M : σ \). We let \( Γ \vdash M : σ \) abbreviate \( 0 \vdash M : σ \).

Note that while all rules in STA have a multiplicative treatment of contexts, the rule \( (BE) \) of STA_B is additive and so contraction is free.

Notation 1. Terms are ranged over by \( M, N, V, P \). As usual terms are considered up to \( α \)-equivalence, namely a bound variable can be renamed provided no free variable is captured. Moreover \( M[\alpha/x] \) denotes the capture-free substitution of all free occurrences of \( x \) in \( M \) by \( V \). \( FV(M) \) denotes the set of free variables of \( M \), \( FV(x, M) \) the number of free occurrences of the variable \( x \) in \( M \).

Type variables are ranged over by \( α, β \), linear types by \( A, B, C \), and types by \( σ, τ, μ \). denotes the syntactical equality both for types and terms (modulo renaming of bound variables). As usual → associates to the right and has precedence on \( ∀ \), while \( ! \) has precedence on everything else. \( σ[\alpha/x] \) denotes the capture free substitution in \( σ \) of all occurrences of the type variable \( α \) by the linear type \( A \). \( FTV(Γ) \) denotes the set of free type variables occurring in the assumptions of the context \( Γ \).

We stress that each type is of the shape \( !∀α.A \) where \( ∀α.A \) is an abbreviation for \( ∀α1...∀αm.A \), and \( !∀α.A \) is an abbreviation for \( !∀α1...∀αm.A \) n-times. In particular \( !∀α.A \equiv σ. \)

We have the following standard properties for a natural deduction system.

Lemma 1 (Free variable lemma).

1. \( Γ \vdash M : σ \) implies \( FV(M) \subseteq \text{dom}(Γ) \).
2. \( Γ \vdash M : σ, Δ \subseteq Γ \) and \( FV(M) \subseteq \text{dom}(Δ) \) imply \( Δ \vdash M : σ \).
3. \( Γ \vdash M : σ, Δ \subseteq Δ \) implies \( Δ \vdash M : σ \).

The functional behaviour of \( Λ_B \) is described in the next definition.
Definition 2. The reduction relation $\rightarrow_{\beta} \subseteq \Lambda \times \Lambda$ is the contextual closure of the following rules:

\[
(\lambda x. M) N \rightarrow_{\beta} M[N/x]
\]

if 0 then M else N → M

if 1 then M else N → N

$\rightarrow_{\beta}$ denotes the reflexive and transitive closure of $\rightarrow_{\beta}$. In what follows, we will need to talk about proofs modulo commutations of rules.

Definition 3. Let $\Pi$ and $\Pi'$ be two derivations in $\text{STA}_B$, proving the same conclusion: $\Pi \rightsquigarrow \Pi'$ denotes the fact that $\Pi'$ is obtained from $\Pi$ by commuting or deleting some rules.

The Generation Lemma connects the shape of a term with its possible typings, and will be useful in the sequel.

Lemma 2 (Generation lemma).

1. $(\forall) \Gamma \vdash \lambda x: \sigma. M : \forall \alpha \sigma$

2. $(\forall) \Gamma \vdash \lambda x: \sigma. M : \sigma \rightarrow \Delta$

3. $(\forall) \Gamma \vdash M : \sigma \rightarrow \Delta$ implies there is $\nu$ such that $\nu \vdash \nu \rightarrow \nu'$, whose last rule is $\delta$ (if $\delta$).

4. $(\forall) \Gamma \vdash M : \sigma \rightarrow \Delta$ implies there is $\nu$ such that $\nu \vdash \nu \rightarrow \nu'$, whose last rule is $(\delta)$. The substitution lemma will be the key lemma to show that $\text{STA}_B$ enjoys the subject reduction property.

Lemma 3 (Substitution lemma). Let $(\forall) \Gamma, x : \mu \vdash M : \sigma$ and $(\forall) \Delta \vdash N : \mu$ such that $\Gamma \# \Delta$. Then there exists $(\forall) \Gamma, \Delta \vdash M[N/x] : \sigma$.

Proof. Since the proof is quite involved, we postpone it to Appendix A.1.

We can finally prove the main property of this section.

Lemma 4 (Subject Reduction). Let $\Gamma \vdash M : \sigma$ and $M \rightarrow_{\beta} N$. Then $\Gamma \vdash N : \sigma$.

Proof. The case of a →_δ reduction is easy, the one of →_β reduction follows by Lemma 3.

By strong normalization of STA we have the following.

Lemma 5 (Strong Normalization). Let $\Gamma \vdash M : \sigma$ then $M$ is strongly normalizing with respect to the reduction $→_{\beta}$.

Nevertheless due to the additive rule $(B E)$, $\text{STA}_B$ is no more correct for polynomial time, since terms with exponential number of reductions can be typed this way.

Example 1. Consider for $n \in \mathbb{N}$ terms $M_n$ of the shape:

\[(\lambda f. \lambda x. f^n(x))(\lambda x. \text{if } x \text{ then } x \text{ else } x)0\]

It is easy to verify that for each $M_n$, there exist reduction sequences of length exponential in $n$.

3. Structural Operational Semantics

In this section the operational semantics of terms of $\Lambda_B$ will be given, through an evaluation machine, defined in SOS style, performing the evaluation according to the leftmost outermost strategy. The machine, if restricted to $\lambda$-calculus, is quite similar to the Krivine machine[Kri97], since $\beta$-reduction is not an elementary step, but the substitution of a term to a variable is performed one occurrence at a time. The evaluation machine is related to the type assignment system $\text{STA}_B$ in the sense that, when it starts on an empty memory, all the programs (closed terms of ground type) can be evaluated.

Definition 4. The set $\mathcal{P}$ of $\text{STA}_B$ programs is the set of closed terms typable by the ground type, i.e. $\mathcal{P} = \{ \mathcal{H} \ | \ \mathcal{M} \vdash \mathcal{B} \}$.

It is easy to check that a $\text{STA}_B$ term is of the following shape:

\[M \equiv \lambda x_1 \ldots x_n. C_1 \cdots C_m\]

where $\beta$ is either a boolean $b$, a variable $x$, a redex $(\lambda x. M) P$, or a subterm of the shape if $P$ then $M$ else $N$.

In particular, if a term is a program, then its shape is as before, but with the condition that the number $n$ of initial abstractions is equal to 0. Moreover if $\beta$ is a boolean $b$ then the number $m$ of arguments is equal to 0. We will use this characterization of programs to design the evaluation machine $K_B$.

$K_B$ uses two memory devices, the $m$-context and the $B$-context, that memorize respectively the assignments to variables and the control.

Definition 5. Let $\mathcal{A}$ be a sequence of variable assignments of the shape $x_i := M_i$ where all variables $x$ are distinct. The set of $m$-contexts is denoted by $\text{Ctx}_m$.

2. The cardinality of an $m$-context $\mathcal{A}$, denoted by $|\mathcal{A}|$, is the number of variable assignments in $\mathcal{A}$.

3. The size of an $m$-context $\mathcal{A}$, denoted by $|\mathcal{A}|$, is the sum of the size of each variable assignment in $\mathcal{A}$, where a variable assignment $x := M$ has size $|M| + 1$, and $|\mathcal{A}|$ is the number of symbols of $\mathcal{A}$.

4. Let $\circ$ be a distinguished symbol. The set $\text{Ctx}_B$ of $B$-contexts is defined by the following grammar:

\[C[0] := 0 \mid (C[0] \text{ if } C[0] \text{ then } N \cdot \ldots \cdot N)\]

5. The size of a $B$-context $C[0]$ denoted by $|C[0]|$ is the size of the term obtained by replacing the symbol $\circ$ by a variable. The cardinality of a $B$-context $C[0]$, denoted by $|B[0]|$, is the number of nested $B$-contexts in it.

Notation 2. $\epsilon$ denotes the empty $m$-context and $A_1 \otimes A_2$ denotes the concatenation of the $m$-contexts $A_1$ and $A_2$. $\{x := M \mid A\}$ denotes the fact that $x := M$ is in the $m$-context $A$. $\text{FV}(A) = \{x \mid x \in \text{FV}(C) \in A\}$ is the set of all free variables in $A$.

In general we omit the hole $\circ$ and we range over $B$-contexts by $C$. $\text{FC}(C) = |\text{FC}(C)|$ for every closed term $M$.

Note that variable assignments in $m$-contexts are ordered; this fact allows us to define the following closure operation.

Definition 6. Let $A = \{x_1 := M_1, \ldots, x_n := M_n\}$ be an $m$-context.

Then $(\cdot)^A : \Lambda_B \rightarrow \Lambda_B$ is the map associating to each term $M$ the term $M[M_1/x_1] \cdots [M_n/x_n]$. $K_B$ is defined in Table 2. Some comments are in order. The rules will be commented bottom-up, which is the natural direction of the evaluation flow.

Rule $(\lambda x. M)$ is obvious. Rule $(\beta)$ applies when the head of the subject is a $\beta$-redex: then the association between the bound variable and the argument is remembered in the $m$-context and the body of the term in functional position is evaluated. Note that an $\alpha$-rule is always performed. Rule $(\text{h})$ replaces the head occurrence of the head variable by the term associated with it in the $m$-context. Rules $(\text{if } 0)$ and $(\text{if } 1)$ perform the $\delta$ reductions. Here the evaluation naturally erases part of the subject, but the erased information is
reductions, while the m-context completes the machine on the same term of Example 1.

Lemma 6.

1. Let $M \in \mathcal{P}$ and $\Pi :: C, A \models N \Downarrow b' \in \Pi$. Then $(C[N])^A, (N)^A \in \mathcal{P}$.

2. Let $M \in \mathcal{P}$ and $\Pi :: M \Downarrow b$. For each $C, A \models N \Downarrow b' \in \Pi$

$$
M \rightarrow^*_{\delta \beta} (C[N])^A \rightarrow^*_{\delta \beta} b
$$

Table 2. The Abstract Machine $K_B^C$

<table>
<thead>
<tr>
<th>Example 2. In Table 5 we present an example of $K_B^C$ computation on the same term of Example 1.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Note that by Definition 7.1 a term $M$ evaluates only if it is a program and there exists $b$ such that $\models M \Downarrow b$. We stress here, that the machine $K_B^C$ is complete with respect to programs, in the sense that all the programs can be evaluated.</td>
</tr>
</tbody>
</table>

Theorem 1.

$M \in \mathcal{P}$ implies $M \Downarrow$

Proof. By induction on the reduction to normal form using Lemma 5.

3.1 A small step version of $K_B^C$

In Table 3 we depict a small step version of the machine $K_B^C$. The rules are similar to the rules in Table 2 but the use of a garbage collector procedure described in Table 4 which is needed in order to maintain the desired complexity property. In fact the small step machine can be easily shown equivalent to the big step one. The small step machine explicit the evaluation order clarifying that every configuration depends uniquely on the previous one (thanks to the B-context). So the space necessary to evaluate a program turns out to be the maximum space used by one of its configurations.

Nevertheless, the big step machine has the advantage of being more abstract and this make it easy to prove the complexity properties. In fact, the garbage collector procedure make more difficult the proofs of such properties for the small step machine. For this reason in what follows we will work on the big step machine.

3.2 Space Measures

We can now define the space effectively used to evaluate a term. The remarks in the previous section allows us to consider the following definition.

Definition 8. Let $\phi \triangleright C, A \models M \Downarrow b$ be a configuration then its size denoted $|\phi|$ is the sum $|C| + |A| + |M|$. Let $\Pi :: C, A \models M \Downarrow b$ be a computation, then its space occupation denoted $\text{space}(\Pi)$ is the maximal size of a configuration in $\Pi$.

In particular since there is a one-to-one correspondence between a program $M$ and its computation $\Pi :: [\phi], \epsilon \models M \Downarrow b$, we will usually write $\text{space}(M)$ in place of $\text{space}(\Pi)$. In order to have polynomial space soundness we will show that for each $M \in \mathcal{P}$ there exists a polynomial $P(X)$ such that $\text{space}(M) \leq P(|M|)$. The result will be proved in next section.
Example 3. By returning to the computation of Example 2 it is
worth noting that to pass from the configuration \( \phi \) to the con-
figuration \( \psi \) all necessary information are already present in the
configuration \( \phi \) itself. We can view such a step as a \( \sigma \rightarrow \sigma \) step
\( (\text{if } 0 \text{ then } x_1 \text{ else } x_1)^{A_2} \rightarrow (x_1)^{A_2} \) noting that
\((x_1)^{A_2} = (x_1)^{A_2}\). In fact this can be generalized, so in this sense we don’t
need neither mechanism for backtracking nor the memorization of
parts of the computation tree.

In what follows we will introduce some relations between the
size of the contexts and the behaviour of the machine, which will be
useful later.

Definition 9. Let \( \Pi \) be a computation and \( \phi \in \Pi \) a configuration.

- \( \#_\beta (\phi) \) denotes the number of applications of the \( (\beta) \) rule in
  path(\( \phi \)).
- \( \#_h (\phi) \) denotes the number of applications of the \( (h) \) rule in
  path(\( \phi \)).
- \( \#_u (\phi) \) denotes the number of applications of \( (\text{if } 0) \) and \( (\text{if } 1) \)
rules in path(\( \phi \)).

The cardinality of the contexts is a measure of the number of
some rules performed by the machine.

Lemma 7. Let \( \Pi ::= M \Downarrow b \). Then for each configuration \( \phi \triangleright \)
\( C, A \models P \), \( b' \in \Pi \):

1. \( \#(A_1) = \#_\beta (\phi) \)
2. \( \#(C_1) = \#_u (\phi) \)

The following is an important property of the machine \( k_B^C \).

Property 1. Let \( M \in \mathcal{P} \) and \( \Pi ::= M \Downarrow b \) then for each \( \phi \triangleright C, A \models P \Downarrow b' \in \Pi \) if \( x_j \models N_j \) \( \models A_1 \) then \( N_j \) is an instance (possibly
with fresh variables) of a subterm of \( M \).

Proof. The property is proven by contradiction. Take the configu-
ration \( \phi \) with minimal path from it to the root of \( \Pi \), such that in its
m-context \( A_{\phi} \) there is \( x_j \models N_j \), where \( N_j \) is not an instance of a subterm of \( M \). Let \( p \) be the length of this path. Since the only rule
that make the m-context grow is a \( (\beta) \) rule we are in a situation like the
following:

\[
\begin{align*}
(C, A) & \triangleright (\lambda x.M)V_1 \cdots V_n \\
(C, A) & \triangleright (\lambda x.M)[x := N] \triangleright M[x'/x] V_1 \cdots V_n \\
(C, A) & \triangleright (\text{if } 0 \text{ then } N_0\text{ else } N_1) \triangleright \cdots \triangleright (\text{if } 0 \text{ then } N_0\text{ else } N_1) \triangleright M[0] \triangleright M[1] \triangleright M[1] \triangleright M[1] \\
(C, A) & \triangleright (\lambda x.M)V_1 \cdots V_n \\
(C, A) & \triangleright (\lambda x.M)[x := N] \triangleright M[x'/x] V_1 \cdots V_n \\
(C, A) & \triangleright (\text{if } 0 \text{ then } N_0\text{ else } N_1) \triangleright \cdots \triangleright (\text{if } 0 \text{ then } N_0\text{ else } N_1) \triangleright M[0] \triangleright M[1] \triangleright M[1] \\
(C, A) & \triangleright (\lambda x.M)V_1 \cdots V_n
\end{align*}
\]

Table 3. The small step machine \( k_B^C \)

| clear \((C, e, M) = \varepsilon \) |
| clear \((C, M) = A' \) \( x \in \text{FV}(C) \cup \text{FV}(M) \cup \text{FV}(A) \) |
| clear \((C, [x := N][A, M]) = [x := N][A'] \) |

Table 4. The garbage collector procedure

Example 5. Let \( \Pi = P \Downarrow b \) then for each \( \phi \triangleright C, A \models P \Downarrow b' \in \Pi \) if \( x_j \models N_j \) \( \models A_1 \) then \( N_j \) is an instance (possibly
with fresh variables) of a subterm of \( M \).

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(C, A) & \triangleright (\lambda x.M)V_1 \cdots V_n \\
(C, A) & \triangleright (\lambda x.M)[x := N] \triangleright M[x'/x] V_1 \cdots V_n \\
(C, A) & \triangleright (\text{if } 0 \text{ then } N_0\text{ else } N_1) \triangleright \cdots \triangleright (\text{if } 0 \text{ then } N_0\text{ else } N_1) \triangleright M[0] \triangleright M[1] \triangleright M[1] \\
(C, A) & \triangleright (\lambda x.M)V_1 \cdots V_n \\
(C, A) & \triangleright (\lambda x.M)[x := N] \triangleright M[x'/x] V_1 \cdots V_n \\
(C, A) & \triangleright (\text{if } 0 \text{ then } N_0\text{ else } N_1) \triangleright \cdots \triangleright (\text{if } 0 \text{ then } N_0\text{ else } N_1) \triangleright M[0] \triangleright M[1] \triangleright M[1] \\
(C, A) & \triangleright (\lambda x.M)V_1 \cdots V_n
\end{align*}
\]

The next lemma gives upper bounds to the size of the m-
context, of the B-context and of the subject of a configuration.

Lemma 8. Let \( M \in \mathcal{P} \) and \( \Pi ::= M \Downarrow b \) then for each configuration \( \phi \triangleright C, A \models P \Downarrow b' \in \Pi \):

\[
\begin{align*}
\#(A_1) & = \#_\beta (\phi) \\
\#(C_1) & = \#_u (\phi)
\end{align*}
\]
1. \(|A| \leq \#s(\phi)(|M| + 1)\)
2. \(|s| \leq (\#s(\phi) + 1)|s|\)
3. \(|c| \leq \#s(\phi)(\max\{|\mathcal{M}||\mathcal{M} \vdash \phi \rightarrow A \Rightarrow \mathcal{M} \vdash \phi \rightarrow A'' \in \Pi|\})\)

Proof. 1. By inspection of the rules of Table 2 it is easy to verify that m-contexts can grow only by applications of the \((\beta)\) rule. So the conclusion follows by Lemma 7 and Property 1.

2. By inspection of the rules of Table 2 it is easy to verify that the subject can grow only by substitutions through applications of the \((h)\) rule. So the conclusion follows by Property 1.

3. By inspection of the rules of Table 2 it is easy to verify that B-contexts can grow only by applications of \((\text{if } 0)\) and \((\text{if } 1)\) rules. So the conclusion follows directly by Lemma 7.

4. **PSpace Soundness**

In this section we will show that STA\(_B\) is correct for polynomial space computation, namely each program typable through a derivation with degree \(d\) can be executed on the machine \(K_{\text{sp}}^d\) in space polynomial in its size, where the maximum exponent of the polynomial is \(d\).

The degree of a derivation counts the maximum nesting of applications of the rule \((\text{sp})\) in it. So considering fixed degrees we get PSpace Soundness. Considering a fixed \(d\) is not a limitation. Indeed until now, in STA\(_B\) programs we do not distinguish between the program code and input data. But it will be shown in Section 5 that data types are typable through derivations with degree 0. Hence the degree can be considered as a real characteristic of the program code.

Moreover every STA\(_B\) program can be typed through derivations with different degrees, nevertheless for each program there is a sort of minimal derivation for it, with respect to the degree. So we can stratify programs with respect to the degree of their derivations, according to the following definition.

**Definition 10.**

1. The degree \(d(\nu)\) of \(\nu\) is the maximum nesting of applications of rule \((\text{sp})\) in \(\nu\).
2. For each \(d \in \mathbb{N}\) the set \(\mathcal{P}_d\) is the set of STA\(_B\) programs typable through derivation with degree \(d\).

\[\mathcal{P}_d = \{\mathcal{M} | (\nu) \vdash \mathcal{M} : \mathcal{B} \wedge d(\nu) = d\}\]

Clearly \(\mathcal{P}\) corresponds to the union for \(n \in \mathbb{N}\) of the different \(\mathcal{P}_n\). Moreover if \(\mathcal{M} \in \mathcal{P}_d\) then \(\mathcal{M} \in \mathcal{P}_{d'}\) for every \(d \geq d'\).

This section is divided into two subsections. In the first, we will prove an intermediate result, namely we will give the notion of space weight of a derivation, and we will prove that the subject reduction does not increment it. Moreover this result is extended to the machine \(K_{\text{sp}}^d\). In the second part the soundness with respect to PSpace will be proved.

### 4.1 Space and STA\(_B\)

We need to define measures of both terms and proofs, which are an adaptation of those given by Lafont in [Laf04].

**Definition 11.**

1. The rank of a rule \((m)\):

\[\Gamma, x_1 : \sigma, \ldots, x_n : \sigma \vdash M : \sigma \vdash \text{M} : \mu \quad (m)\]

is the number \(k \leq n\) of variables \(x_i\) such that \(x_i\) belongs to the free variables of \(\mathcal{M}\). Let \(r\) be the the maximum rank of a rule \((m)\) in \(\mathcal{V}\). The rank \(r(\nu)\) of \(\nu\) is the maximum of 1 and \(r\).

2. Let \(r\) be a natural number. The space weight \(\delta(\nu, r)\) of \(\nu\) with respect to \(r\) is defined inductively as follows.

(a) If the last applied rule is \((Ax), (B_j I), (B_k I)\) then \(\delta(\nu, r) = 1\).
(b) If the last applied rule is \((\neg I)\) with premise a derivation \(\delta\), then \(\delta(\nu, r) = \delta(\delta, r) + 1\).
(c) If the last applied rule is \((\text{sp})\) with premise a derivation \(\delta\), then \(\delta(\nu, r) = r(\delta, r)\).
(d) If the last applied rule is \((\neg E)\) with premises \(\delta\) and \(\delta\) then \(\delta(\nu, r) = \delta(\delta, r) + \delta(\delta, r) + 1\).
(e) If the last applied rule is:

\[\frac{(\delta) \Gamma \vdash M : B \quad (\mathcal{M}_0) \vdash \mathcal{M}_0 : A \quad (\mathcal{M}_1) \vdash \mathcal{M}_1 : A}{\Gamma \vdash \text{if } \mathcal{M}_0 \text{ then } \mathcal{M}_0 \text{ else } \mathcal{M}_1 : A}\]

then \(\delta(\nu, r) = \max\{\delta(\delta, r), \delta(\delta, r), \delta(\delta, r)\} + 1\).
(f) In every other case \(\delta(\nu, r) = \delta(\delta, r)\) where \(\delta\) is the unique premise derivation.

In order to prove that the subject reduction does not increase the space weight of a derivation, we need to rephrase the Substitution Lemma taking into account this measure.

**Lemma 9** (Weighted Substitution Lemma). Let \((\nu) \Gamma, x : \mu \vdash \sigma\) and \(\delta(\nu) \Delta \vdash \mathcal{N} : \mu\) such that \(\Gamma \vdash \Delta \vdash M[x] : \sigma\) such that if \(r \geq r(\nu)\):

\[\delta(\delta, r) \leq \delta(\nu, r) + \delta(\sigma, r)\]

Proof. We postpone the proof to Appendix A.2.

We are now ready to show that the space weight \(\delta\) gives a bound on the number of both \(\beta\) and \(\text{if}\) rules in a computation path of the machine \(K_{\text{sp}}^d\).

**Lemma 10.** Let \(\mathcal{M} \in \mathcal{P}\) and \(\Pi ::= \mathcal{M} \Downarrow \mathcal{B}.

1. Consider an occurrence in \(\Pi\) of the rule:

\[\frac{\mathcal{C}, A \otimes (x := \mathcal{N}) \vdash \mathcal{M}[x/x]\mathcal{V}_1 \cdots \mathcal{V}_m \Downarrow \mathcal{B}}{\mathcal{C}, \mathcal{A} \vdash \mathcal{M}[x/x]\mathcal{V}_1 \cdots \mathcal{V}_m \Downarrow \mathcal{B} \quad (\beta)}\]

Then, for every derivations \((\Delta) \vdash (\mathcal{C}, A) \vdash (\mathcal{V}_1 \cdots \mathcal{V}_m) : \mathcal{B}\) there exists a derivation \((\mathcal{C}) : \Gamma \vdash (\mathcal{V}_1 \cdots \mathcal{V}_m) : \mathcal{B}\) such that for every \(r \geq r(\Delta)\):

\[\delta(\delta, r) > \delta(\nu, r)\]

2. Consider an occurrence in \(\Pi\) of an \text{if}\) rule as:

\[\frac{\mathcal{C}', \mathcal{A} \vdash \mathcal{M} \Downarrow \mathcal{B}}{\mathcal{C}', \mathcal{A} \vdash \text{if } \mathcal{M} \Downarrow \mathcal{M}_0 \text{ else } \mathcal{M}_1 \Downarrow \mathcal{B}}\]

where \(\mathcal{C}' \equiv C'[\text{if } \mathcal{M} \text{ then } \mathcal{M}_0 \text{ else } \mathcal{M}_1 \Downarrow \mathcal{B}].\) Then, for each derivation \((\delta) \vdash (\mathcal{C}', \mathcal{A}) \vdash (\mathcal{V}_1 \cdots \mathcal{V}_m)\): \(B\) there are derivations \((\mathcal{C}) \vdash (\mathcal{V}_1 \cdots \mathcal{V}_m) : \mathcal{B}\) such that for every \(r \geq r(\nu)\):

\[\delta(\delta, r) > \delta(\nu, r)\]

Proof.

1. It suffices to consider the case where \(m = 0\) and to prove that, if \(\Gamma \vdash (\mathcal{C}, \mathcal{A}) : \Gamma \vdash M[x] : \sigma\) with \(r(\nu) \geq r(\mathcal{V})\) such that for \(r \geq r(\mathcal{V})\):

\[\delta(\nu, r) > \delta(\mathcal{V}, r)\]

Since \((\forall R), (\forall L), (\sigma)\) and \((\sigma)\) rules don’t change the \(\delta\) measure we can without loss of generality assume that we are in a
situation like the following:
\[
(\Diamond) \quad \Gamma, x : \sigma \vdash M : A \\
\Gamma \vdash \lambda x : \Sigma : \sigma \rightarrow \Delta \\
\vdash \lambda (x : \Sigma) : \sigma \rightarrow \Delta \\
\vdash \Gamma, x : \sigma \vdash M[n/x] : A
\]

where $\Gamma \Delta \Sigma$ and $n \geq 0$. Clearly we have $\delta(\Sigma, r) = \delta(\emptyset, r) + 1 + \delta(\emptyset, r)$. By Lemma 9 we have $(\Delta')' \Gamma \vdash M[n/x] \sigma$ such that $\delta(\Sigma', r) \leq \delta(\emptyset, r) + \delta(\emptyset, r)$. Hence, the conclusion follows.

2. Easy, by definition of $\delta$. \hfill \square

Since it is easy to verify that $\Sigma$ rules leave the space weight unchanged, a direct consequence of the above lemma is the following.

**Lemma 11.** Let $(\Sigma') \Gamma \vdash M : B$ and $\Pi ::= M \because B$. Then for each \( \phi \triangleright \Sigma, \Lambda \vdash M \triangleright B' \in \Pi \) $\triangleright r \geq r(\Sigma')$

\( \#_{3}(\phi) + \#_{4}(\phi) \leq \delta(\Sigma, r) \)

Now we are ready to prove that subject reduction does not increase the space weight.

**Property 2.** Let $(\Sigma') \Gamma \vdash M : \sigma$ and $M \triangleright_{\bar{\lambda}_{3} \bar{\lambda}} N$. Then there exists $(\Sigma')' \Gamma \vdash M : \sigma$ with $r(\Sigma') \geq r(\Sigma')$ such that for each $r \geq r(\Sigma')$

\( \delta(\Sigma, r) \geq \delta(\Sigma', r) \)

**Proof.** By Lemma 9 and definition of $\delta$, noting that a reduction inside an $\texttt{if}$ can leave $\delta$ unchanged. \hfill \square

The previous result can be extended to the machine $K_{n}$ in the following way.

**Property 3.** Let $(\Sigma) \Gamma \vdash M : B$ and $\Pi ::= M \because B$. For each configuration $\phi \triangleright \Sigma, \Lambda \vdash M \triangleright B' \in \Pi$ such that $\Sigma \neq \emptyset$ there exist derivations $(\emptyset) \vdash (C[K])^{4} : B$ and $(\Sigma) \vdash (K)_{n} : \Sigma$ such that $\emptyset$ is a proper subderivation of $\emptyset$ and for each $r \geq r(\Sigma)$

\( \delta(\Sigma, r) \geq \delta(\emptyset, r) \)

**4.2 Proof of PSPACE Soundness**

As we said in the previous section, the space used by the machine $K_{n}$ is the maximum space used by its configurations. In order to give an account of this space, we need to measure how the size of a term can increase during the evaluation. The key notion for doing it is that of number of the sliced occurrence of a variable, which takes into account that in performing an $\texttt{if}$ reduction a subterm of the subject is erased. In particular by giving a bound on the number of sliced occurrence we obtain a bound on the number of applications of the $\ell$ rule in a path.

**Definition 12.** The number of sliced occurrences $n_{s}(x, M)$ of the variable $x$ occurring free in $M$ is defined as:

\( n_{s}(x, M) = n_{s}(x, y) = n_{s}(x, 0) = n_{s}(x, 1) = 0, \)

\( n_{s}(x, M) = n_{s}(x, M) + n_{s}(x, N), \)

\( n_{s}(x, \lambda x.M) = n_{s}(x, M), \)

\( n_{s}(x, \texttt{if } M \texttt{ then } N \texttt{ else } N) = \max\{n_{s}(x, M), n_{s}(x, N), n_{s}(x, N)\} \)

A type derivation gives us some informations about the number of sliced occurrences of a free variable $x$ in its subject $M$.

**Lemma 12.** Let $(\Sigma) \Gamma \vdash M : \sigma$ and $\Phi ::= M \because \sigma$ such that $\sigma$ is a proper subderivation of $\emptyset$ and for each $r \geq r(\Sigma)$

\( \delta(\Sigma, r) \geq \delta(\emptyset, r) \)

**Proof.** By induction on $n$.

Case $n = 0$. The conclusion follows easily by induction on $(\Sigma)$. Base case is trivial. In the case $(\Sigma)\end{equation} ends by $\texttt{(BE)}$ conclusion follows by $n_{s}(x, M)$ definition and induction hypothesis. The other cases follow directly from the induction hypothesis remembering the side condition $\Gamma \neq \emptyset$ in $(\emptyset)$ case.
Case $n > 0$. By induction on $(\nu)$. Base case is trivial. Let the last rule of $(\nu)$ be:

\[
(\nu) \Gamma, x : !^n A, \ldots, x_m : !^{m-1} A \vdash \mu : \nu (m)
\]

where $n(x, M) \leq \text{rk}(\nu)^n$ for $i \leq i \leq m$. Hence in particular,

\[
n_{so}(x, M) \leq m \times \text{rk}(\nu)^n.
\]

By Lemma 13 for every $n > 0$ the conclusion follows directly by induction hypothesis.

The lemma above is essential to prove the following remarkable lemma. The next lemma gives a bound on the dimensions of all the variables.

\[
\text{Lemma 13.} \quad \Gamma, x : !^n A \vdash \sigma \quad \text{and} \quad M \to_{n\beta} N. \quad \text{Then} \quad n_{so}(x, N) \leq \text{rk}(\nu)^n.
\]

Lemma 14. Let $M \in \mathcal{P}_d$ and $\Pi := \vdash \mu \downarrow b$ then for each

\[
\phi \vdash C, A = \vdash \mu \downarrow b'.
\]

\[
\#_d(\phi) \leq \#(|A|^d).
\]

Proof. For each $y := x \in A$ the variable $y$ is a fresh copy of a variable $x$ originally bound in $M$ hence $M$ contains a subterm $(\lambda x.P)Q$ and there exists a derivation $(\nu) x : !^m A \vdash : B$. Hence by Lemma 13 for every $P'$ such that $P \rightarrow_{n\beta} P'$ we have $n_{so}(x, P') \leq \text{rk}(\nu)^n$. In particular the number of applications of $\mu$ rules on the variable $y$ is bounded by $\text{rk}(\nu)^n$. Since $|M| \geq \text{rk}(\nu)$ and $d \geq n$ the conclusion follows.

The following lemma relates the space weight with both the size of the term and the degree of the derivation.

\[
\text{Lemma 15.} \quad (\nu) \Gamma, x : !^n A \vdash \sigma \quad \text{then} \quad \#_d(\phi) \leq \#(|A|^d).
\]

Proof. 1. By induction on $(\nu)$. Base cases are trivial. Cases $(sp), (m), (u), (\forall \ell)$ and $(\forall E)$ follow directly by induction hypothesis. The other cases follow by definition of $\delta$.

2. By induction on $(\nu)$. Base cases are trivial. Cases $(sp), (m), (u), (\forall \ell)$ and $(\forall E)$ follow directly by induction hypothesis. The other cases follow by definition of $\delta$ and $d$.

3. By definition of rank it is easy to verify that $\text{rk}(\nu) \leq |M|$, hence by the previous two points the conclusion follows.

The next lemma gives a bound on the dimensions of all the components of a machine configuration, namely the term, the m-context and the B-context.

\[
\text{Lemma 16.} \quad \Gamma \vdash \Pi \quad \text{and} \quad \Pi := \vdash \mu \downarrow b. \quad \text{Then for each} \quad \phi \vdash C, A = \vdash \mu \downarrow b'. \quad \text{Then}\]

\[|M| \leq (|A|)^{|d+1}|b| 
\]

\[|C| \leq (|C|)^{|d+2}|b| 
\]

\[|C| \leq (|C|)^{|d+3}|b| 
\]

Proof. 1. By Lemma 8.1, Lemma 11 and Lemma 15.3.

2. By Lemma 8.2, Lemma 14, Lemma 7.1, Lemma 11 and Lemma 15.3.

3. By Lemma 8.3, the previous point of this lemma, Lemma 7.2, Lemma 11 and Lemma 15.3.

Theorem 2 (Polynomial Space Soundness).

\[
\text{Let} \quad M \in \mathcal{P}_d, \quad \text{then} \quad |\mu| \leq |M|^{|d+3}.
\]

5. **PSPACE completeness**

It is well known that the class of problem decidable by a Deterministic Turing Machine (DTM) in space polynomial in the length of the input coincides with the class of problems decidable by an Alternating Turing Machine (ATM) [CKS81] in time polynomial in the length of the input.

In [GR07] it has been shown that polytime DTM are definable by $\lambda$-terms typable in STA. Analogously here we will show that polytime ATM are definable by programs of $\text{ST}_{AB}$. We achieve such a result considering a notion of function programmable in $\text{ST}_{AB}$. We will consider the same representation of data types as in STA, in particular data types typable through derivations with degree 0. (We will recall it briefly but we refer to [GR07] for more details.) Finally we show that for each polytime ATM $M$ we can define a recursive evaluation procedure which behaves as $\mathcal{M}$.

Some syntactic sugar

Let $\alpha$ denote composition. In particular $\lambda \in \mathcal{N}$ stands for $\lambda x.M(Nz)$ and $M_1 \circ M_2 \circ \cdots \circ M_n$ stands for $\lambda x.M_i(M_2(M_1(x)) \cdots))$.

Tensor product is definable as $\sigma \otimes \tau \equiv \forall \alpha.(\sigma \to \tau \to \alpha) \to \alpha$. In particular, $\lambda \alpha.\beta$ stands for $\lambda x.\alpha x.\beta$. Let $2$ be $x, y$ in $\mathcal{N}$ stands for $\alpha(x, y)$. Note that, since $\text{ST}_{AB}$ is an affine system, tensor product enjoys some properties of the additive conjunction, as to allow the projectors: as usual $\pi_1(M)$ stands for $M(\lambda x. \lambda y. \alpha)$ and $\pi_2(M)$ stands for $M(\lambda x. \lambda y. \alpha)$. $n$-ary tensor product can be easily defined through the binary one and we use $\sigma^{n}$ to denote $\sigma \odot \cdots \odot \sigma$ $n$-times.

**Natural numbers and strings of booleans**

Natural numbers are represented by Church numerals, i.e. $n \equiv \lambda x.\lambda y.\alpha^n(z)$. Terms defining successor, addition and multiplication are typable by indexed types $\delta_1 \equiv \forall \alpha.!(\alpha \to \alpha) \to \alpha \to \alpha$. We write $\mathcal{N}$ to mean $\mathcal{N}_1$. In particular the following still holds for $\text{ST}_{AB}$:

\[
\text{Lemma 17.} \quad \text{Let} \quad P \quad \text{be a polynomial and } \text{deg}(P) \quad \text{its degree. Then} \quad \text{there is a term} \quad P \quad \text{defining } P \text{ typable as:}
\]

\[
\Gamma \vdash P : !^{\text{deg}(P)} \quad \text{N}_1 \to \text{N}_2^{2 \text{deg}(P)+1}
\]
Strings of boolean are represented as terms of the shape \(\lambda z.\text{cb}_b(\cdots(\text{cb}_{z_2}(\cdots))\cdots)\) where \(b_i \in \{0, 1\}\). Such terms are typable by the indexed type \(S_i \triangleq \forall \alpha.\!! (B \to \alpha \to \alpha) \to \alpha \to \alpha\). Again, we write \(S\) to mean \(S_1\). Moreover there is a term \(\text{len} : S_i \to N\), that gives a string of boolean returns its length.

Note that the data types defined above can be typed in \(\text{STAB}\) by derivations with degree 0.

**Programmable functions** The polynomial time completeness in \([GR07]\) relies on the notion of \(\lambda\)-definability, given in \([Bar84]\), generalized to different kinds of data.

The same can be done here for \(\text{STAB}\), by using a generalization of \(\lambda\)-definability to the set of terms \(\Lambda_B\). Nevertheless this is not sufficient, since we want to show that polynomial time \(\mathcal{A}\)-terms can be defined by programs of \(\text{STAB}\). In fact we have the following definition.

**Definition 13.** Let \(f : S \times \ldots \times S \to B\) and let every string \(s \in S\) be representable by terms \(s^j\). Then, \(f\) is programmable if there exists a term \(\Gamma \in \Lambda_n\), such that \(\Gamma_{s_1} \ldots s_n \in \mathcal{P}\) and:
\[
f(s_1, \ldots, s_n) = b \iff f(s_1, \ldots, s_n) = b
\]

**Booleans connectives** It is worth noting that due to the presence of the \((\mathcal{B}\mathcal{E})\) rule it is possible to define the usual boolean connectives. In fact let \(M\) and \(N\) be two \(\mathcal{B}\mathcal{E}\) terms such that \(M\) and \(N\) are \(\mathcal{B}\mathcal{E}\) terms, \(\Gamma\) the typing context and \(s\) the boolean variable.

We can encode \(\text{A TM}\) configurations by terms of the shape:
\[
\lambda c.\text{cb}_b(\cdots\text{cb}_{s_1}(\cdots))\text{cb}_b\cdot\cdots\cdot\text{cb}_{s_n}(q, k)
\]
where \(\text{cb}_b\) and \(\text{cb}_s\) are respectively the left and right handside words on the \(\mathcal{B}\mathcal{E}\) tape, \(q\) is a tuple of length \(\alpha\) encoding the state and \(k\) is the tensor pair encoding the kind of its state.

**ATMs Configurations** The encoding of Deterministic Turing Machine configuration given in \([GR07]\) can be adapted in order to encode Alternating Turing Machine configurations. In fact an \(\mathcal{A}\)-configuration can be viewed as a \(\mathcal{B}\mathcal{E}\) configuration with an extra information about the state. There are four kinds of state: accepting (\(A\)), rejecting (\(R\)), universal (\(\forall\)) and existential (\(\exists\)). We can encode such information by tensor pairs of booleans. In particular:

\[
\begin{array}{c|c|c|c}
(1, 0) & A & (1, 1) & R \\
(0, 1) & \exists & (0, 0) & \forall
\end{array}
\]

We say that a configuration is accepting, rejecting, universal or existential depending on the kind of its state.

We can encode \(\mathcal{A}\) configurations by terms of the shape:
\[
\lambda c.\text{cb}_b(\cdots\cdots\text{cb}_{s_1}(\cdots))\cdot\cdots\cdot\text{cb}_b(q, k)
\]

\(\text{cb}_b\) and \(\text{cb}_s\) are respectively the left and right handside words on the \(\mathcal{B}\mathcal{E}\) tape, \(q\) is a tuple of length \(\alpha\) encoding the state and \(k\) is the tensor pair encoding the kind of its state. Such terms can be typed as:

\[
\text{ATM}_i \triangleq \forall \alpha.\!! (B \to \alpha \to \alpha) \to ((\alpha \to \alpha)^2 \otimes B^{++^2})
\]

It is easy to adapt the term described in \([GR07]\) dealing with \(\mathcal{M}\) to the case of \(\mathcal{A}\). In particular we have:

\[
\begin{array}{c}
\vdash \text{Init} : S_i \to \text{ATM}_i \\
\vdash \text{Tr}_i : \text{ATM}_i \to \text{ATM}_i
\end{array}
\]

Moreover we have a term:
\[
\text{Kind} \triangleq \lambda x. \exists y (\lambda b. \lambda y. y) x \in (\text{let } s \text{ be } q, k \text{ in } k) \text{ typable as } \vdash \text{Kind} : \text{ATM}_i \to B^2 \text{ which takes a configuration and return its kind. We also have a term: }
\]
\[
\text{Ext} \triangleq \lambda x. \text{let } (\text{Kind } x) \text{ be } 1, x \in x
\]
can be obtained by replacing booleans by words over booleans. In particular, we can add to STA the type $\text{W}$ and the following rules:

$$
\Gamma \vdash \epsilon : \text{W} \\
\Gamma \vdash \bot_0 : \text{W} \\
\Gamma \vdash \top_0 : \text{W} \\
\Gamma \vdash p(M) : \text{W} \\
$$

and the conditional

$$
\Gamma \vdash \mathcal{N} : \text{W} \\
\Gamma \vdash \mathcal{N}_0 : \text{W} \\
\Gamma \vdash \mathcal{N}_1 : \text{W} \\
\Gamma \vdash \mathcal{D}(\mathcal{N}, \mathcal{N}_0, \mathcal{N}_1) : \text{W} \\
$$

The obtained system STA$_W$ equipped with the obvious reduction relation can be shown to be FPSPACE sound following what we have done for STA$_B$. Moreover, analogously to [LM93], completeness for FPSPACE can be proved by considering two distinct data types $S$ (Church representations of Strings) and $\text{W}$ (Flat words over Booleans) as input and output data type respectively. The above is one of the reasons that leads us to consider STA$_B$ instead of the above system.

STA$_B$ and Soft Linear Logic. STA has been introduced as a type assignment counterpart of Soft Linear Logic [Laf04]. The technical notion of height of a variable in a derivation will be useful in the proof of the Substitution Lemma.

A. Technical Proofs

A.1 Proof of Substitution Lemma

The technical notion of height of a variable in a derivation will be useful in the proof of the Substitution Lemma.

Definition 14. Let $\langle \mathcal{N} \rangle \Gamma, x : \tau \vdash M : \sigma$. The height of $x$ in $\mathcal{N}$ is inductively defined as follows:

1. if the last applied rule of $\mathcal{N}$ is:

$$
\frac{x : A \vdash x : A}{\Gamma \vdash x : A} \text{ or } \frac{\Gamma \vdash NI : \sigma}{\Gamma, x : A \vdash NI : \sigma}
$$

then the height of $x$ in $\mathcal{N}$ is 0.

2. if the last applied rule of $\mathcal{N}$ is:

$$
\frac{\bigwedge_i x_i : \tau_i \vdash \mathcal{N}_{i} : \sigma_i}{\Gamma, x : \tau \vdash N : \sigma} \quad \text{(m)}
$$

then the height of $x$ in $\mathcal{N}$ is the max between the heights of $x_i$ in $\mathcal{N}_i$ for $1 \leq i \leq k$ plus one.

3. Let $x : \tau \in \Gamma$ and let the last applied rule $\pi$ of $\mathcal{N}$ be:

$$
\frac{\bigwedge_i x_i : \tau_i \vdash \mathcal{N}_{i} : \sigma_i}{\Gamma, x : \tau \vdash M : B} \quad \text{(c) \quad \Gamma, \mathcal{N}_0 \vdash M : A} \quad \text{or} \quad \Gamma, \mathcal{N}_1 \vdash N : A
$$

Then the height of $x$ in $\mathcal{N}$ is the max between the heights of $x_i$ in $\mathcal{N}_0, \mathcal{N}_1$ and $\mathcal{I}$, respectively plus one.

4. In every other case there is an assumption with subject $x$ both in the conclusion of the rule and in one of its premises $\mathcal{O}$. Then the height of $x$ in $\mathcal{N}$ is equal to the height of $x$ in $\mathcal{O}$ plus one.

Proof of Substitution Lemma. By induction on the height of $x$ in $\mathcal{N}$. Base cases $(Ax)$ and $(\omega)$ are trivial. The cases where $\mathcal{N}$ ends by $\langle \rightarrow \rangle$, $\langle \forall \rangle$, $\langle \forall E \rangle$ and $\langle \Rightarrow E \rangle$ follow directly from the induction hypothesis.

Let $\mathcal{N}$ ends by $(sp)$ rule with premise $\langle \mathcal{N}' \rangle \Gamma', x : \mu' \vdash M : \sigma'$ then by Lemma 2.3 $\vdash \mathcal{O} \Rightarrow \mathcal{O}'$ which is composed by a subderivation ending with an $(sp)$ rule with premise $\langle \mathcal{O}' \rangle \Delta' \vdash \mathcal{N} : \mu'$ followed by a sequence of rules $(\omega)$ and $(\mu)$. By the induction hypothesis we have a derivation $\langle \mathcal{O} \rangle \Gamma', \Delta' \vdash \mathcal{M} *[\mathcal{N}]/[\mathcal{X}] * : \sigma'$. By applying the rule $(sp)$ we obtain a derivation $\langle \mathcal{O} \rangle \Gamma, \Delta \vdash \mathcal{M} *[\mathcal{N}]/[\mathcal{X}] : \sigma$. Let $\mathcal{N}$ ends by $\langle \mathcal{O} \rangle \Gamma, \Delta \vdash \mathcal{M} *[\mathcal{N}]/[\mathcal{X}] : \sigma$.

Let $\mathcal{N}$ end by $(sp)_{0}$ rules $\langle \mathcal{O} \rangle \Gamma, \Delta \vdash \mathcal{M} *[\mathcal{N}]/[\mathcal{X}] : \sigma$.

2. by Lemma 1. $\vdash \mathcal{O} \Rightarrow \mathcal{O}' \Rightarrow \mathcal{O}'$ ending by an $(sp)$ rule with premise $\langle \mathcal{O}' \rangle \Gamma', \Delta' \vdash \mathcal{M} *[\mathcal{N}]/[\mathcal{X}] : \sigma'$ followed by a sequence of rules $(\omega)$ and $(\mu)$.

Consider fresh copies of the derivation $\mathcal{O}'$ i.e. $\langle \mathcal{O}' \rangle \Delta' \vdash \mathcal{N} : \mu'$ where $\mathcal{N}$ and $\Delta'$ are fresh copies of $\mathcal{N}$ and $\Delta'$ $(1 \leq j \leq m)$. By induction hypothesis there is a derivation $\langle \mathcal{O} \rangle \Gamma, \Delta' \vdash \mathcal{M} *[\mathcal{N}]/[\mathcal{X}] : \sigma'$. Finally by applying the rules $(\mu)$ and $(\omega)$ the conclusion follows.
By the induction hypothesis $\delta(\square, r) \leq \delta(\nabla, r) + \delta(\diamondsuit, r)$ and applying (sp):

$$\delta(\square, r) \leq r(\delta(\nabla, r) + \delta(\diamondsuit, r)) = \delta(\nabla, r) + \delta(\diamondsuit, r)$$

If $\nabla$ ends by $(BE)$: $\delta(\nabla, r) = \max_{0 \leq i \leq 2}(\delta(\nabla_i, r)) + 1$. By induction hypothesis we have derivations $\delta(\square, r) \leq \delta(\nabla, r) + \delta(\diamondsuit, r)$ for $0 \leq i \leq 2$ and applying a $(BE)$ rule:

$$\delta(\square, r) \leq \max_{0 \leq i \leq 2}(\delta(\nabla, r) + \delta(\diamondsuit, r)) = \max_{0 \leq i \leq 2}(\delta(\nabla, r)) + \delta(\diamondsuit, r)$$

If $\nabla$ ends by $(m)$: $\delta(\nabla, r) = \delta(\nabla', r)$ and $\delta(\diamondsuit, r) = r\delta(\diamondsuit, r)$.

Clearly $\delta(\nabla', r) = \delta(\diamondsuit, r)$ so $\delta(\square, r) \leq \delta(\nabla', r) + m\delta(\diamondsuit, r)$ and since $r \geq \max(\nabla)$ then:

$$\delta(\square, r) \leq \delta(\nabla', r) + m\delta(\diamondsuit, r) = \delta(\nabla, r) + \delta(\diamondsuit, r)$$

Now the rules $(m)$ and $(w)$ leave the space weight $\delta$ unchanged hence the conclusion follows.

References


