# Matching Power 

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#### Abstract

In this paper we give a new simpler and uniform presentation of the rewriting calculus also called Rho Calculus. In addition to its simplicity, this reformulation explicitly allows us to encode complex structures such as lists, sets, and objects. We provide extensive examples of calculus use and we focus on its properties and its ability to represent some object oriented calculi, namely the Lambda Calculus of Objects of Fisher, Honsell, and Mitchell, and the Object Calculus of Abadi and Cardelli. This enlightens the capabilities of the rewriting calculus based language ELAN to be used as a logical as well as powerful semantical framework. In summa, we intend to show that the Rho Calculus represents a lingua franca to encode many paradigms of computations.


## 1 Introduction

Matching is a feature provided implicitly in many, and explicitly in few, programming languages. In this paper, by making matching a "first class" concept, we present, experiment with, and show the expressive power of a new version of the rewriting calculus, also called Rho Calculus ( $\rho C a l$ ).

The ability to discriminate patterns is one of the main basic mechanisms the human reasoning is based on; as one commonly says "one picture is better than a thousand explanations". Indeed, the ability to recognize patterns, i.e. pattern matching, is present since the beginning of information processing modeling. Instances of it can be traced back to pattern recognition and it has been extensively studied when dealing with strings [30], trees [23] or feature objects [2].

Matching occurs implicitly in many languages through the parameter passing mechanism but often as a very simple instance, and explicitly in languages like PROLOG and ML where it can be quite sophisticated 32|31. It is somewhat astonishing that one of the most common model of computation, the lambda calculus, uses only trivial pattern matching. This has been extended, initially for programming concerns, either by the introduction of patterns in lambdacalculi 3739, or by the introduction of matching and rewrite rules in functional programming languages. And indeed, many works address the integration of term rewriting with lambda calculus, either by enriching first-order rewriting with higher-order capabilities, or by adding to lambda calculus algebraic features allowing one, in particular, to deal with equality in an efficient way. In the
first case, we find the works on CRS [29] and other higher-order rewriting systems 4133, in the second case the works on combination of lambda calculus with term rewriting [34|5|20|26], to mention only a few.

Embedding more information in the matching process makes it appropriate to deal with complex tasks like program transformations [24] or theorem proving 36. In that direction, matching in elaborated theories has been also studied extensively, either in equational theories [25]6] or in higher-order logic [15]35, where it is still an open problem at order five.

Matching allows one to discriminate between alternatives. Once the patterns are recognized, the action to be taken on the appropriate pattern should be described, and this is what rewriting is designed for. The corresponding pattern is thus rewritten in an appropriate instance of a new one. The mechanism that describes this process is the rewriting calculus. Its main design concept is to make all the basic ingredients of rewriting explicit objects, in particular the notions of rule application and result. By making the application explicit, the calculus emphasizes on one hand the fundamental role of matching, and on the other hand the intrinsic higher-order nature of rewriting. By making the results explicit, the Rho Calculus has the ability to handle non-determinism in the sense of sets of results: an empty set of results represents an application failure, a singleton represents a deterministic result and a set with more than one element represents a non-deterministic choice between the elements of the set.

Rewriting is central in several programming languages developed since the seventies. Amongst the main ones let us mention OBJ [22], ASF+SDF [14], Maude [13], CafeOBJ [19] and ELAN [27|4|38] which has been at the origin of some of the main concepts of the rewriting calculus. In turn, the Rho Calculus provides a natural semantics to such languages, and in particular to ELAN, covering the notion of rule application strategy, an important concept of the language.

The Rho Calculus offers a broad spectrum of applications due to the two fundamental parameters of the calculus: the theory modulo which matching is performed, and the structure under which the results of a rule application are returned. Adjusting these parameters to various situations permits us to easily describe in a uniform but still appropriately tuned manner many calculi, namely: lambda calculus, term rewriting and object calculi.

The contributions of this paper are therefore the following:

- First a description of a new version of the Rho Calculus introduced in [7|8|12 is given. We provide here a simplified version of the evaluation rules of the calculus as well as a generic and explicit handling of result structures, a point left open in the previous works;
- Second, we provide a broad set of examples showing the expressiveness of the Rho Calculus obtained mainly thanks to its "matching power" and how this makes it suitable to uniformly model various paradigms of computation;
- Third, we show how the matching power of the Rho Calculus allows us to encode two major object-calculi which have strongly influenced the typetheoretical research of the last five years: the Object Calculus ( $\varsigma \mathcal{O} b j$ ) of Abadi
and Cardelli 1 and the Lambda Calculus of Objects of Fisher, Honsell, and Mitchell [18 ( $\lambda$ Obj). Moreover, we show two examples in Rho Calculus that cannot be encoded in the above calculi.

Road Map of the Paper. The paper is structured as follows: in Section 2, we present the syntax and the small-step semantics of the Rho Calculus; Section 3 presents a plethora of examples describing the power of matching; Section 4 presents the encoding of the Lambda Calculus of Objects and of the Object Calculus in the Rho Calculus. Conclusions and further works are finally discussed in Section 5 . An extended version of the paper can be found in [10.

## 2 Syntax and Semantics

Notational Conventions. In this paper, the symbol $t$ ranges over the set $\mathcal{T}$ of terms, the symbols $S, X, Y, Z, \ldots$ range over the infinite set $\mathcal{V}$ of variables, the symbols null, $\oplus, \circ, a, b, \ldots, z, 0,1,2, \ldots$ range over the infinite set $\mathcal{C}$ of constants of fixed arity. All symbols can be indexed. The symbol $\equiv$ denotes syntactic identity of objects like terms or substitutions. We work modulo $\alpha$-conversion, and we follow the Barendregt convention [3], saying that free and bound variables have different names.

### 2.1 Syntax

The syntax of the $\rho C a l$ is defined as follows:

$$
\begin{array}{rlrl}
\mathcal{T}::= & a|X| \mathcal{T} \rightarrow \mathcal{T}|\mathcal{T} \cdot \mathcal{T}| & & \text { plain terms } \\
& & \text { null } \mid \mathcal{T}, \mathcal{T} & \\
\text { structured terms }
\end{array}
$$

The main intuition behind this syntax is that a rewrite rule $\mathcal{T} \rightarrow \mathcal{T}$ is an abstraction, the left-hand-side of which determines the bound variables and some pattern structure. The application of a $\rho C$ al-term on another $\rho C$ al-term is represented by " $\bullet$ ". The terms can be grouped together into a structure built using the "," operator and, according to the theory behind this operator, different structures can be obtained. The term null denotes an empty structure.

We assume that the application operator "•" associates to the left while the " $\rightarrow$ " and the "," operators associate to the right. The priority of the application "•" is higher than that of the " $\rightarrow$ " operator which is in turn of higher priority than the "," operator.

Definition 1 (Some Type Signatures and Abbreviations).
$\rightarrow: \mathcal{T} \times \mathcal{T} \Rightarrow \mathcal{T} \quad t_{1} \cdot t_{2} \quad \triangleq t_{1} \cdot t_{2} \cdot t_{1} \quad$ self-application
$\cdot: \mathcal{T} \times \mathcal{T} \Rightarrow \mathcal{T}$ and $t\left(t_{1} \ldots t_{n}\right) \triangleq t \bullet t_{1} \ldots \bullet t_{n}$ function-application $(n \in \mathbb{N})$
, : $\mathcal{T} \times \mathcal{T} \Rightarrow \mathcal{T} \quad\left(t_{i}\right)^{i=1 \ldots n} \triangleq t_{1}, \ldots, t_{n} \quad$ structure $(n \in \mathbb{N})$
We draw the attention of the reader on the main difference between """ denoting the application, and "." denoting the object-oriented self-application operator.

### 2.2 Matching Theories

An important parameter of the $\rho C a l$ is the matching theory $\mathbb{T}$. We assume theories $\mathbb{T}$ be defined equationally.

## Definition 2 (Matching theories).

- the Empty theory $\mathbb{T}_{\emptyset}$ of equality (up to $\alpha$-conversion) is defined as the following inference rules:

$$
\frac{t_{1}=t_{2} \quad t_{2}=t_{3}}{t_{1}=t_{3}}(\text { Tra }) \quad \frac{t_{1}=t_{2}}{t_{2}=t_{1}}(\text { Sym }) \quad \frac{t_{1}=t_{2}}{t_{3}\left[t_{1}\right]_{p}=t_{3}\left[t_{2}\right]_{p}}(\text { Ctx }) \quad \overline{t=t}(\text { Ref })
$$

where $t_{1}\left[t_{2}\right]_{p}$ denotes the term $t_{1}$ with the term $t_{2}$ at position $p$. The precise definition of $\alpha$-conversion is given in [7].

- the theory of Commutativity $\mathbb{T}_{C(f)}$ (resp. Associativity $\mathbb{T}_{A(f)}$ ) is defined as $\mathbb{T}_{\emptyset}$ plus the following inference rules:

$$
\overline{f\left(t_{1} t_{2}\right)=f\left(t_{2} t_{1}\right)}(\mathrm{Com}) \quad \overline{f\left(f\left(t_{1} t_{2}\right) t_{3}\right)=f\left(t_{1} f\left(t_{2} t_{3}\right)\right)}(\text { Ass })
$$

- the theory of Idempotency $\mathbb{T}_{I(f)}$ is defined as $\mathbb{T}_{\emptyset}$ plus the axiom $f(t)=t$.
- the theory of Neutral Element $\mathbb{T}_{N\left(f^{0}\right)}$ is defined as $\mathbb{T}_{\emptyset}$ plus the following inference rules:

$$
\overline{f(0 t)=t}\left(0_{L}\right) \quad \overline{f(t 0)=t}\left(0_{R}\right)
$$

- the theory of Lambda Calculus of Objects, $\mathbb{T}_{\lambda \text { Obj }}$, is obtained by considering the symbol "," as associative and null as its neutral element, i.e.:

$$
\mathbb{T}_{\lambda \mathcal{O} b j}=\mathbb{T}_{A(,)} \cup \mathbb{T}_{N(, n u l l)}
$$

- the theory of Object Calculus, $\mathbb{T}_{\varsigma \mathcal{O b j}}$, is obtained by considering the symbol "," as associative and commutative and null as its neutral element, i.e.:

$$
\mathbb{T}_{\varsigma \mathcal{O} b j}=\mathbb{T}_{A(,)} \cup \mathbb{T}_{C(,)} \cup \mathbb{T}_{N(, \text { null })}=\mathbb{T}_{\lambda \mathcal{O} b j} \cup \mathbb{T}_{C(,)}
$$

Other interesting theories can be built from the above ones, such as e.g. $\mathbb{T}_{M S e t(f, n i l)}$, and $\mathbb{T}_{\text {Set }(f, n i l)}$ [1110. For the sake of completeness, we include in the paper the definition of syntactic matching, which can also be found in [11] together with some explanatory examples.

Definition 3 (Syntactic Matching). For a given theory $\mathbb{T}$ over $\rho$ Cal-terms:

1. a $\mathbb{T}$-match equation is a formula of the form $t_{1} \ll \mathbb{T} t_{2}$;
2. a substitution $\sigma$ is a solution of the $\mathbb{T}$-match equation $t_{1} \ll \mathbb{T} t_{2}$ if $\sigma t_{1}=\mathbb{T} t_{2}$;
3. a $\mathbb{T}$-matching system is a conjunction of $\mathbb{T}$-match equations;
4. a substitution $\sigma$ is a solution of a $\mathbb{T}$-matching system if it is a solution of all the $\mathbb{T}$-match equations in it;
5. a $\mathbb{T}$-matching system is trivial when all substitutions are solution of it and we denote by $\mathbb{F}$ a $\mathbb{T}$-matching system without solution;
6. we define the function $\mathcal{S o l}$ on a $\mathbb{T}$-matching system T as returning the $\prec$-ordered ${ }^{11}$ ist of all $\mathbb{T}$-matches of T when T is not trivial and the list containing only $\sigma_{\mathbf{i d}}$, where $\sigma_{\mathbf{i d}}$ is the identity substitution, when T is trivial.

$$
\begin{array}{lll}
\diamond_{1}\left(t_{1} \ldots t_{n}\right) \ll \mathbb{T}_{\emptyset} \diamond_{2}\left(t_{1}^{\prime} \ldots t_{m}^{\prime}\right) & \rightsquigarrow \begin{cases}\bigwedge_{i=1 \ldots n} t_{i} \ll \mathbb{T}_{\emptyset} t_{i}^{\prime} & \text { if } \diamond_{1} \equiv \diamond_{2} \text { and } n=m \\
\mathbb{F} & \text { otherwise }\end{cases} \\
\left(X \ll \mathbb{T}_{\emptyset} t\right) \wedge\left(X \ll \mathbb{T}_{\emptyset} t^{\prime}\right) & \rightsquigarrow \begin{cases}X<\mathbb{T}_{\emptyset} t & \text { if } t=\mathbb{T}_{\emptyset} t^{\prime} \\
\mathbb{F} & \text { otherwise }\end{cases} \\
t \ll \mathbb{T}_{\emptyset} X & \text { if } t \notin \mathcal{V} \\
\mathbb{F} \wedge\left(t \ll \mathbb{T}_{\emptyset} t^{\prime}\right) & \rightsquigarrow \mathbb{F}
\end{array}
$$

Fig. 1. Rules for Syntactic Matching

$$
\begin{aligned}
& (\rho)\left(t_{1} \rightarrow t_{2}\right) \bullet t_{3} \mapsto \mathbb{T} \begin{cases}\text { null } & \text { if } t_{1} \ll \mathbb{T} t_{3} \text { has no solution } \\
\sigma_{1} t_{2}, \ldots, \sigma_{n} t_{2} & \text { if } \sigma_{i} \in \operatorname{Sol}\left(t_{1} \ll \mathbb{T} t_{3}\right), \sigma_{1} \prec \sigma_{i+1}, n \leq \infty\end{cases} \\
& \text { ( } \epsilon \text { ) } \quad\left(t_{1}, t_{2}\right) \bullet t_{3} \quad \mapsto \mathbb{T} \quad t_{1} \bullet t_{3}, t_{2} \bullet t_{3} \\
& \text { ( } \nu \text { ) null } \bullet \bullet \quad \mapsto_{\mathbb{T}} \text { null }
\end{aligned}
$$

Fig. 2. Evaluation rules of the $\rho$ Cal.

Notice that when the matching algorithm fails (i.e. returns $\mathbb{F}$ ), the function $\mathcal{S}$ ol returns the empty list. A more detailed discussion on decidability of matching can be found in 812|10.

For example, in $\mathbb{T}_{\emptyset}$, the matching substitution from a $\rho$ Cal-term $t_{1}$ to a $\rho C a l$-term $t_{2}$ can be computed by the rewrite system presented in Figure 1 . where the symbol $\wedge$ is assumed to be associative and commutative, and $\diamond_{1}, \diamond_{2}$ are either constant symbols or the prefix notations of "," or "•" or " $\rightarrow$ ".

Starting from a matching system T , the application of this rule set terminates and returns either $\mathbb{F}$ when there are no substitutions solving the system, or a system $\mathrm{T}^{\prime}$ in "normal form" from which the solution can be trivially inferred 28. This set of rules could be easily extended to matching modulo commutativity, and associativity-commutativity [25].

### 2.3 Operational Semantics

For a given ordering $\prec$ and a theory $\mathbb{T}$, the operational semantics is defined by the computational rules given in Figure 2 . The central idea of the main rule of the calculus $(\rho)$ is that the application of a rewrite rule $t_{1} \rightarrow t_{2}$ at the root (also called top) position of a term $t_{3}$, consists in computing all the solutions of the matching equation $\left(t_{1} \ll \mathbb{T} t_{3}\right)$ in the theory $\mathbb{T}$ and applying all the substitutions from the $\prec$-ordered list returned by the function $\operatorname{Sol}\left(t_{1}<_{\mathbb{T}} t_{3}\right)$ to the term $t_{2}$. When there is no solution for the matching equation $t_{1}<\mathbb{T}_{\mathbb{T}} t_{3}$, the special constant null is

[^0]obtained as result of the application. Notice that, in some theories [17], there could be an infinity of solutions to the matching problem $\left(t_{1}<_{\mathbb{T}} t_{3}\right)$; possible ways to deal with the infinitary case are described in [12].

The other rules $(\epsilon)$ and $(\nu)$ deal with the distributivity of the application on the structures whose constructors are "," and null. When the theory $\mathbb{T}$ is clear from the context, its denotation will be omitted. Worth noticing that if $t_{1}$ is a variable, then the $(\rho)$-rule corresponds exactly to the $\beta$-rule of the lambda calculus.

With respect to the previous presentation of the Rho Calculus [7|8|12], we have modified the notation of the application operator which was denoted [_](-), but more importantly, the evaluation rules have been simplified on one hand and generalized to deal with generic result structures on the other hand.

As usual, we denote by $={ }_{\rho}$ the reflexive, symmetric, transitive, and contextual closure of the reduction $\mapsto_{\mathbb{T}}$ over a theory $\mathbb{T}$. The relation $={ }_{\rho}$ is a congruence relation. When working modulo reasonably powerful theories $\mathbb{T}$, the evaluation rules of the $\rho C a l$ are confluent:

Theorem 1 (Confluence in $\mathbb{T}_{\emptyset}$ ). Given a term $t_{1}$ such that all its abstractions contain no arrow in the first argument, if $t_{1} \mapsto \mathbb{T}_{\emptyset} t_{2}$ and $t_{1} \mapsto \mathbb{T}_{\emptyset} t_{3}$ then there exists a term $t_{4}$ such that $t_{2} \mapsto \mathbb{T}_{\emptyset} t_{4}$ and $t_{3} \mapsto \mathbb{T}_{\emptyset} t_{4}$.

Proof. The proof follows the same lines defined in [9].

## 3 Examples in Rho Calculus

In the following section we present some simple examples intended to help the reader in the understanding of the behavior of the Rho Calculus.

Example 1 ( $\operatorname{In} \mathbb{T}_{\emptyset}$ ).

1. The application of the simple rewrite rule $a \rightarrow b$ to $a$, i.e. $(a \rightarrow b) \bullet a$, is evaluated to $b$ since $\operatorname{Sol}\left(a<\mathbb{T}_{\emptyset} a\right)=\sigma_{\mathbf{i d}}$ and $\sigma_{\mathbf{i d}} b \equiv b$;
2. The matching between the left-hand side of the rule and the argument can also fail and in this case the result of the application is the constant null, i.e.: $(a \rightarrow b) \cdot c \stackrel{\rho}{\mapsto}$ null;
3. When the left-hand side of a rewrite rule is not a ground term, the matching can yield a substitution different from $\sigma_{\mathbf{i d}}$, like in $(X \rightarrow X) \bullet a \stackrel{\rho}{\mapsto}[X / a] X \equiv$ $a$;
4. The non-deterministic application of two rewrite rules is represented by the application of the structure containing the respective rules:
$(X \rightarrow X(a), Y \rightarrow Y(b)) \cdot c \stackrel{\epsilon}{\mapsto}(X \rightarrow X(a)) \cdot c,(Y \rightarrow Y(b)) \cdot c \stackrel{\rho}{\mapsto}[X / c] X(a)$, $[Y / c] Y(b) \equiv c(a), c(b) ;$
5. The selection of the field $c x$ inside the record structure $(c x \rightarrow 0, c y \rightarrow 0)$ evaluates to the term $(0$, null $)$, i.e.: $(c x \rightarrow 0, c y \rightarrow 0) \cdot c x \stackrel{\epsilon}{\mapsto}(c x \rightarrow 0) \cdot c x$, $(c y \rightarrow 0) \cdot c x \stackrel{\rho}{\longmapsto}(0, n u l l)$;
6. Functions are first-class entities in the $\rho C a l:(X \rightarrow(X \bullet a)) \bullet(Y \rightarrow Y) \stackrel{\rho}{\mapsto}$ $(Y \rightarrow Y) \cdot a \stackrel{\rho}{\mapsto} a ;$
7. The lambda calculus with patterns of [37] can be easily represented in the $\rho C a l$. For instance, the lambda-term $\lambda \operatorname{Pair}(X Y) . X$, can be represented and reduced as follows: $(\operatorname{Pair}(X Y) \rightarrow X) \cdot \operatorname{Pair}(a b) \stackrel{\rho}{\mapsto}[X / a] X \equiv a$;
8. Starting from the fixed-point combinators of the lambda calculus, we can define a $\rho C$ Cal-term that applies recursively a given $\rho C a l$-term. We use the classical fixed-point $Y_{\lambda} \triangleq\left(A_{\lambda} A_{\lambda}\right)$ with $A_{\lambda} \triangleq \lambda X . \lambda Y . Y(X X Y)$, which can be translated as $Y_{\rho} \triangleq A_{\rho} \bullet A_{\rho}$ with $A_{\rho} \triangleq X \rightarrow Y \rightarrow Y \bullet(X \bullet X \bullet Y)$. Then: $Y_{\rho} \bullet t \triangleq$ $A_{\rho} \bullet A_{\rho} \bullet t \triangleq(X \rightarrow Y \rightarrow Y \bullet(X \bullet X \bullet Y)) \cdot A_{\rho} \bullet t \stackrel{\rho}{\mapsto}\left(Y \rightarrow Y \bullet\left(A_{\rho} \bullet A_{\rho} \cdot Y\right)\right) \bullet t \stackrel{\rho}{\mapsto}$ $t \bullet\left(A_{\rho} \bullet A_{\rho} \bullet t\right) \triangleq t \bullet\left(Y_{\rho} \bullet t\right)$. Starting from the $Y_{\rho}$ term, we can define more elaborated terms describing, for example, the repeated application of a given term or normalization strategies according to a given rewrite rule [12;
9. Consider the terms car $\triangleq X, Y \quad \rightarrow \quad X, \quad$ and $\quad c d r \triangleq X, Y \quad \rightarrow \quad Y$, and cons $\triangleq X \quad \rightarrow \quad Y \quad \rightarrow \quad(X, Y)$. It is easy to verify that $\operatorname{car}(a, b, c, n u l l) \mapsto a$, and that $c d r(a, b, c, n u l l) \mapsto b, c, n u l l$, and that cons $(d a, b, c, n u l l) \mapsto d, a, b, c, n u l l$.

Example 2 (In $\mathbb{T}_{A}, \mathbb{T}_{C}, \mathbb{T}_{A C}$, and $\left.\mathbb{T}_{N\left(f^{\circ}\right)}\right)$.

1. $\left(\mathbb{T}_{A(\circ)}\right)$ The application of the rewrite rule $\circ(X Y) \rightarrow X$ to $\circ(a \circ(b \circ(c d)))$ reduces, thanks to the associativity of $\circ$, to $(a, \circ(a b), \circ(a \circ(b c)))$;
2. $\left(\mathbb{T}_{C(\oplus)}\right)$ The application of the rewrite rule $\oplus\left(\begin{array}{ll}X & Y\end{array}\right) \rightarrow X$ to $\oplus\left(\begin{array}{ll}a & b\end{array}\right)$ reduces, thanks to the associativity-commutativity of $\oplus$, to $(a, b)$, a structure representing all possible results;
3. $\left(\mathbb{T}_{A C(\oplus)}\right)$ The application of the rewrite rule $\oplus(X \oplus(X Y)) \rightarrow \oplus(X Y)$ to $\oplus(a \oplus(b \oplus(c \oplus(a d))))$ reduces to $\oplus(a \oplus(b \oplus(c d)))$. The search for the two equal elements is done by matching thanks to the associativity-commutativity of the $\oplus$ operator, while the elimination of doubles is performed by the rewrite rule;
4. $\left(\mathbb{T}_{N\left(f^{0}\right)}\right)$ Using a theory with a neutral element allows us to "ignore" variables from the rewrite rules. For example, the rewrite rule $X \oplus a \oplus Y \rightarrow$ $X \oplus b \oplus Y$ replaces an $a$ with a $b$ in a structure built using the " $\oplus$ " operator and containing one or more elements. The application of the previous rewrite rule to $b \oplus a \oplus b$ reduces to $b \oplus b \oplus b$ and the same rule applied to $a$ leads to $b$, since $a=\mathbb{T}_{N\left(\oplus^{0}\right)} 0 \oplus a \oplus 0$.

The next example shows how the object oriented paradigm can be easily captured in the $\mathbb{T}_{\lambda \mathcal{O b j}}$. In particular we focus our example on the usage of the pseudovariable this which is crucial for sending messages inside method bodies. In the $\rho C a l$, a method can be seen as a term of the shape $m \rightarrow S \rightarrow t_{m}$, where $m$ is the name of the method, $S$ is a variable playing the role of this and $t_{m}$ is the body of the method that can contain free occurrences of $S$. Sending a message $m$ to a structure (i.e. an object) $t$ is represented via the alias $t . m$, i.e. $t \cdot m \bullet t$. Intuitively, if the method $m$ exists in the structure $t$, then its body $t_{m}$ can be executed with the binding of $S$ to the object itself. This type of application is also called, in the object-oriented jargon, self-application, and it is fundamental for modeling mutual recursion between methods inside an object.

Example 3 (In $\mathbb{T}_{\lambda \mathcal{O b j}}$ ).

1. This example presents a simple object $t$ with only one method $a$ that do not effectively use the variable $S$. Let $t \triangleq a \rightarrow S \rightarrow b$. Then, $t . a \triangleq t \cdot a \bullet t \stackrel{\rho}{\mapsto}\left(\sigma_{\mathbf{i d}}(S \rightarrow b)\right) \bullet t \equiv(S \rightarrow b) \bullet t \stackrel{\rho}{\mapsto} b ;$
2. This example presents an object $t$ with a non-terminating method $\omega$. Let $t \triangleq \omega \rightarrow S \rightarrow S . \omega$. Then, $t . \omega \stackrel{\rho}{\mapsto}(S \rightarrow S . \omega) \bullet t \stackrel{\rho}{\mapsto} t . \omega \mapsto \ldots ;$
3. We consider another object with a non-terminating behavior consisting of two methods ping and pong, one calling the other via the variable $S$. Let $t \triangleq($ ping $\rightarrow S \rightarrow$ S.pong, pong $\rightarrow S \rightarrow$ S.ping $)$. Then, t.ping $\triangleq t \bullet$ ping $\bullet t \stackrel{\epsilon}{\mapsto}$ $(($ ping $\rightarrow S \rightarrow$ S.pong $) \bullet$ ping,$($ pong $\rightarrow S \rightarrow$ S.ping $) \bullet$ ping $) \bullet t \stackrel{\rho}{\mapsto}(S \rightarrow$ S.pong $) \bullet t$, null $=\mathbb{T}_{\lambda \text { Oбb }}(S \rightarrow S$.pong $) \bullet t \stackrel{\rho}{\mapsto}$ t.pong $\mapsto t$. ping $\mapsto \ldots$

In the above example, we can notice how natural the use of matching is for directly selecting the method name. Starting from these simple examples, we can now imagine how matching can be use in its full generality (i.e. allowing variables as well as appropriate equational theories) in order to deal with more general objects and methods. The purpose of the rest of this paper is to make these aspects precise.

## 4 Object-Based in Rho Calculus

In this section we focus on two major object-calculi which have influenced the type-theoretical research of the last five years:

- The Lambda Calculus of Objects of Fisher, Honsell, and Mitchell [18;
- The Object Calculus of Abadi and Cardelli [1].

Both calculi are prototype-based i.e. they are based on the notion of "objects" and not of "classes". Nevertheless, classes can be easily encoded as suitable objects. Those calculi have been extensively studied in a "typed" setting where the main objective was to conceive sound type systems capturing the unfortunate runtime error message-not-understood which happen when we send a message $m$ to an object which do not have the method $m$ in its interface.

As previously shown in Example [3, structured-terms are well suited to represent objects and to model the special "metavariable" this. In order to support the intuition, we start by showing the way some classical examples of objects can be easily expressed in the $\rho C a l$.

Example 4 (A Point Object Encoding in $\mathbb{T}_{\lambda \text { Obj }}$ ). Given the symbols val, get, set and $v$ (used to denote pairs), an object Point is encoded in $\rho C a l$ by val $\rightarrow S \rightarrow v(11)$, get $\rightarrow S \rightarrow S . v a l$, set $\rightarrow S \rightarrow v(X Y) \rightarrow\left(S\right.$, val $\left.\rightarrow S^{\prime} \rightarrow v(X Y)\right)$ The term Point represents an object with an attribute val and two methods get and set. The method get gives access to the attribute, while method set is used for modifying the attribute by adding the new value at the end of the object. In this context, it is easy to check that Point.get $\mapsto v(11)$, and Point.set $(v(2) 2)) \mapsto$ Point, (val $\rightarrow S^{\prime} \rightarrow v(22)$ ), and Point.set $(v(2) 2)$ ).get $\mapsto v(11), v(22)$. Worthy of notice is that:

1. The call Point.set(v(2 2)) produces a result which consists of the old Point and the new (modified) value for the attribute val, i.e. val $\rightarrow S^{\prime} \rightarrow v(22)$;
2. The call Point.set $\left(v\left(\begin{array}{ll}2 & 2\end{array}\right)\right.$ ).get produces a structure composed of two elements, the former representing the value of val before the execution of set (i.e. before a side effect), and the latter one after the execution of set;
3. A trivial strategy to recover determinism is to consider only the last value from the list of results, i.e. $v(22)$. From this point of view, the $\rho C a l$ can be also understood as a formalism to study side effects in imperative calculi;
4. A way to fix imperative features is to modify the encoding of the method set by considering the term $\operatorname{kill}_{n} \triangleq(X, n \rightarrow Z, Y) \rightarrow X, Y$, and by defining the new object Point ${ }_{i m p}$ as val $\rightarrow \ldots$, get $\rightarrow \ldots$, set $\rightarrow S \rightarrow v(X Y) \rightarrow\left(\right.$ kill $_{\text {val }}(S)$, val $\left.\rightarrow S^{\prime} \rightarrow v(X Y)\right)$ such that Point $_{\text {imp }}$. get $\longmapsto v(11)$, and Point ${ }_{\text {imp }} . \operatorname{set}(v(22)) \mapsto v a l \rightarrow S^{\prime} \rightarrow$ $v(2)$, get $\rightarrow \ldots$, set $\rightarrow \ldots$, and Point imp $^{\text {. }}$.set $(v(2)$ ).get $\mapsto v(2$ 2);
5 . The moral of this example is that the encoding of objects into the $\rho C a l$ can strongly modify the behavior of a computation.

In the next example we present the encoding of the Fisher, Honsell, and Mitchell fixed-point operator [18] and its generalization in the $\rho C a l$.

Example 5 (A Fixed Point Object). Assume symbols rec and $f$. The fixed-point object $F i x_{f}$ for $f$ can be represented in the $\rho C a l$ as $F i x_{f} \triangleq r e c \rightarrow S \rightarrow f(S . r e c)$. It is not hard to verify that Fix $_{f} . r e c \mapsto f\left(\right.$ Fix $\left._{f} . r e c\right)$. This fixed point can be generalized as $F i x \triangleq \operatorname{rec} \rightarrow S \rightarrow X \rightarrow X(S \cdot r e c(X))$ and its behavior will be Fix.rec $(f) \mapsto f($ Fix.rec $(f))$.

### 4.1 The Lambda Calculus of Objects

We now present a translation of the Lambda Calculus of Objects of Fisher, Honsell, and Mitchell [18] into the $\rho C a l$. This calculus is an untyped lambda calculus with constants enriched with object primitives. A new object can be created by modifying and/or extending an existing prototype object; the result is a new object which inherits all the methods and fields of the prototype. This calculus is trivially computationally complete, since the lambda calculus is built in the calculus itself. The syntax and the small-step semantics of $\lambda \mathcal{O} b j$ we present in this paper are inspired by the work of 21.

Syntax and Operational Semantics. The syntax of the calculus is defined as follows:

$$
\begin{aligned}
M, N::= & \lambda X . M|M N| X|c| \\
& \rangle|\langle M \leftarrow n=N\rangle|\langle M \leftarrow n=N\rangle| M \Leftarrow n \mid \operatorname{Sel}(M, m, N)
\end{aligned}
$$

The small-step semantics is defined by $(\leftarrow *$ denote either $\leftarrow$ or $\leftarrow)$ :

$$
\begin{array}{lll}
(\lambda X . M) N & \mapsto_{\lambda \mathcal{O b j}}[X / N] M & \operatorname{Sel}(\langle M \leftarrow * n=N\rangle, n, P) \mapsto_{\lambda \mathcal{O b j}} N P \\
M \Leftarrow m & \mapsto_{\lambda \mathcal{O b j}} \operatorname{Sel}(M, m, M) & \operatorname{Sel}(\langle M \leftarrow * n=N\rangle, m, P) \mapsto_{\lambda \mathcal{O b j}} \operatorname{Sel}(M, m, P)
\end{array}
$$

The main operation on objects is method invocation, whose reduction is defined by the second rule. Sending a message $m$ to an object $M$ containing a method $m$ reduces to $\operatorname{Sel}(M, m, M)$. More generally, in the expression $\operatorname{Sel}(M, m, N)$, the term $N$ represents the receiver (or recipient) of the message, the constant $m$ is the message we want to send to the receiver of the message, and the term $M$ is (or reduces to) a proper sub-object of $N$.

By looking at the last two rewrite rules, one may note that the Sel function "scans" the recipient of the message until it finds the definition of the method we want to use; when it finds the body of the method, it applies this body to the recipient of the message. The operational semantics in [18] was based on a more elaborate bookkeeping relation which transforms the receiver (i.e. an ordered list of methods) into another equivalent object where the method we are calling is always the last overridden one.

As a simple example of the calculus, we show an object which has the capability to extend itself simply by receiving a message which encodes the method to be added.

Example 6 (An object with "self-extension"). Consider the object Self_ext 21] $\left\langle\left\rangle \leftarrow a d d \_n=\lambda S .\left\langle S \leftarrow n=\lambda S^{\prime} .1\right\rangle\right\rangle\right.$. If we send the message add_n to Self_ext, then we get Self_ext $\Leftarrow a d d_{-} n \mapsto_{\lambda O b j} S e l\left(S e l f_{-} e x t, a d d_{-} n, S e l f_{-} e x t\right) \mapsto_{\lambda O b j}$ $\left(\lambda S .\left\langle S \leftarrow n=\lambda S^{\prime} .1\right\rangle\right)$ Self_ext $\mapsto_{\lambda \mathcal{O b j}}\left\langle\right.$ Self_ext $\left.\leftarrow n=\lambda S^{\prime} .1\right\rangle$, resulting in the method $n$ being added to Self_ext.

The Translation of $\lambda \mathcal{O} b j$ into $\rho \boldsymbol{C a l}$. The translation of a $\lambda \mathcal{O} b j$-term into a corresponding $\rho$ Cal-term is quite trivial and can be done in the theory $\mathbb{T}_{\lambda \mathcal{O b j}}$ where the symbol "," is associative and null is its neutral element. Intuitively, an object in $\lambda \mathcal{O} b j$ is translated into a simple structure in $\rho C a l$. The choice we made for object override is an imperative one, i.e. we delete the method we are overriding using the kill function defined in Example 4. The translation is defined as follows:

$$
\begin{array}{ll}
\llbracket c \rrbracket & \triangleq c \\
\llbracket X \rrbracket & \triangleq X \\
\llbracket \lambda X . M \rrbracket & \triangleq X \rightarrow \llbracket M \rrbracket \\
\llbracket M N \rrbracket & \triangleq \llbracket M \rrbracket \bullet \llbracket N \rrbracket
\end{array}
$$

$$
\llbracket\rangle \rrbracket \quad \triangleq \text { null }
$$

$$
\llbracket\langle M \leftarrow n=N\rangle \rrbracket \triangleq \operatorname{kill}_{n}(\llbracket M \rrbracket), n \rightarrow \llbracket N \rrbracket
$$

$$
\llbracket\langle M \leftrightarrow n=N\rangle \rrbracket \triangleq \llbracket M \rrbracket, n \rightarrow \llbracket N \rrbracket
$$

$$
\llbracket M \Leftarrow m \rrbracket \quad \triangleq \quad \triangleq \llbracket M \rrbracket \cdot m \triangleq \llbracket M \rrbracket \cdot m \bullet \llbracket M \rrbracket
$$

$$
\llbracket \operatorname{Sel}(M, m, N) \rrbracket \triangleq \llbracket M \rrbracket \bullet m \bullet \llbracket N \rrbracket
$$

For instance, Example 7 shows an example of a simple computation in $\lambda \mathcal{O} b j$ and the corresponding translation into $\rho C a l$, and Example 8 presents the translation of the Self_ext object into $\rho C a l$.

Example 7 (A Simple Computation). Let Point be the simple diagonal point $\left\langle\langle\rangle \leftrightarrow x=\lambda S . S \Leftarrow y\rangle \leftrightarrow y=\lambda S .1\rangle\right.$. Then Point $\Leftarrow x \mapsto_{\lambda O b}$ Sel(Point, x, Point) $\mapsto_{\lambda \mathcal{O} b j} \operatorname{Sel}(\langle\langle \rangle \leftrightarrow x=\lambda S . S \Leftarrow y\rangle, x$, Point $) \mapsto_{\lambda}$ Obj $(\lambda S . S \Leftarrow y)$ Point $\mapsto_{\lambda \mathcal{O} b j}$ Point $\Leftarrow y \mapsto_{\lambda \mathcal{O} b j} \operatorname{Sel}\left(\right.$ Point, $y$, Point) $\mapsto_{\lambda \mathcal{O} b j}$ ( $\lambda$ S.1)Point $\mapsto_{\lambda \text { Obj }} 1$.

The above computation in $\lambda \mathcal{O} b j$ can be easily translated into a corresponding computation in $\rho$ Cal using $t \triangleq \llbracket$ Point $\triangleq \triangleq x \rightarrow S \rightarrow S . y, y \rightarrow S \rightarrow 1$ as follows: $\llbracket$ Point $\Leftarrow x \rrbracket \triangleq t . x \triangleq(x \rightarrow S \rightarrow S . y, y \rightarrow S \rightarrow 1) \bullet x \bullet t \mapsto(S \rightarrow S . y, n u l l) \bullet t=\mathbb{T}_{\lambda} \mathcal{O O} j$ $(S \rightarrow S . y) \bullet t \mapsto t . y \triangleq(x \rightarrow S \rightarrow S . y, y \rightarrow S \rightarrow 1) \bullet y \bullet t \mapsto(n u l l, S \rightarrow 1) \bullet t=\mathbb{T}_{\lambda} \mathcal{O} b, ~$ $(S \rightarrow 1) \bullet t \mapsto 1$.

Example 8 (Translation of Self_ext). The object Self_ext can be easily translated in the $\rho C a l$ as $t_{1} \triangleq \llbracket S e l f_{-} e x t \rrbracket \triangleq a d d_{-} n \rightarrow S \rightarrow\left(S, n \rightarrow S^{\prime} \rightarrow 1\right)$. Then: $\left(t_{1} \cdot a d d_{-} n\right) \cdot n \mapsto\left(\left(S \rightarrow\left(S, n \rightarrow S^{\prime} \rightarrow 1\right)\right) \bullet t_{1}\right) \cdot n \mapsto\left(t_{1}, n \rightarrow S^{\prime} \rightarrow 1\right) \cdot n \triangleq$ $\underbrace{\left(a d d \_n \rightarrow \ldots, n \rightarrow S^{\prime} \rightarrow 1\right)}_{t_{2}} . n \mapsto n u l l,\left(S^{\prime} \rightarrow 1\right) \bullet t_{2}=\mathbb{T}_{\lambda \text { OOb }}\left(S^{\prime} \rightarrow 1\right) \bullet t_{2} \mapsto 1$

The translation into the $\rho C a l$ can be proved correct when the theory $\mathbb{T}_{\lambda \mathcal{O b j}}$ is considered:

Theorem 2 (Translation of $\lambda \mathcal{O b j}$ into $\rho C a l$ ). If $M \mapsto_{\lambda \mathcal{O} b j} N$, then $\llbracket M \rrbracket \mapsto \mathbb{T}_{\lambda \text { Obj }} \llbracket N \rrbracket$.

### 4.2 The Object Calculus

The Object Calculus [1] is a calculus where the only existing entities are the objects; it is computationally complete since $\lambda$-calculus, fixed points and complex structures can be easily encoded within it. A large collection of variants (functional and imperative, typed and untyped) for this calculus are presented in the book and in the literature.

Syntax and Operational Semantics. The syntax of the object calculus is defined as follows:

$$
a, b::=X \quad\left|\left[m_{i}=\varsigma(X) b_{i}\right]^{i=1 \ldots n}\right| \text { a.m } \mid \text { a.m }:=\varsigma(X) b
$$

Let $a \triangleq\left[m_{i}=\varsigma(X) b_{i}\right]^{i=1 \ldots n}$; the small-step semantics is:

$$
\left.\begin{array}{lll}
a \cdot m_{j} & \mapsto_{\varsigma \mathcal{O} b j}[X / a] b_{j} & j=1 \ldots n \\
a \cdot m_{j}:=\varsigma(X) b & \mapsto_{\varsigma} \mathcal{O} b j
\end{array} m_{i}=\varsigma(X) b_{i}, m_{j}=\varsigma(X) b\right]^{i=1 \ldots n \backslash\{j\}}{ }^{2}=1 \ldots n
$$

The Translation into $\boldsymbol{\rho} \boldsymbol{C a l}$. The translation of an $\varsigma \mathcal{O} b j$-term into a corresponding $\rho C$ al-term is quite similar to the one of $\lambda \mathcal{O} b j$, and can be done in the theory $\mathbb{T}_{\varsigma \mathcal{O b j}}$ where the symbol "," is associative and commutative, and null is its neutral element. Given the function $\operatorname{kill}_{m} \triangleq(X, m \rightarrow Y) \rightarrow X$, and the alias $\left(t_{1} \cdot m:=t_{2}\right) \triangleq\left(k i l l_{m}\left(t_{1}\right), m \rightarrow t_{2}\right)$, the translation is defined as follows:

$$
\begin{array}{lll}
\llbracket X \rrbracket & \left.\triangleq X m_{i}=\varsigma(X) b_{i}\right]^{i=1 \ldots n} \rrbracket & \triangleq\left(m_{i} \rightarrow X \rightarrow \llbracket b_{i} \rrbracket\right)^{i=1 \ldots n} \\
\llbracket a . m_{j} \rrbracket \triangleq \llbracket a \rrbracket \cdot m_{j} & \llbracket a . m:=\varsigma(X) b \rrbracket & \triangleq \llbracket a \rrbracket \cdot m:=X \rightarrow \llbracket b \rrbracket
\end{array}
$$

As a simple example, we present the usual Abadi and Cardelli's encoding of the Point class [1].

Example 9 (A Point Class). The object PClass is defined in $\varsigma \mathcal{O b j}$ as follows:

$$
\left[\text { new }=\varsigma(S) o, v a l=\lambda S^{\prime} \cdot v(11), \text { get }=\lambda S^{\prime} \cdot\left(S^{\prime} \cdot v a l\right), \text { set }=\lambda S^{\prime} \cdot \lambda N . S^{\prime} \cdot v a l:=N\right]
$$

with $o \triangleq\left[v a l=\varsigma\left(S^{\prime}\right)(S . v a l)\left(S^{\prime}\right)\right.$, get $=\varsigma\left(S^{\prime}\right)(S . g e t)\left(S^{\prime}\right)$, set $\left.=\varsigma\left(S^{\prime}\right)(S . s e t)\left(S^{\prime}\right)\right]$, and it is translated into the $\rho C a l$ as follows:

$$
\begin{aligned}
& \text { new } \rightarrow S \rightarrow t, \text { val } \rightarrow S \rightarrow S^{\prime} \rightarrow v(11) \text {, } \\
& \text { get } \rightarrow S \rightarrow S^{\prime} \rightarrow S^{\prime} \cdot v a l, \text { set } \rightarrow S \rightarrow S^{\prime} \rightarrow v(X Y) \rightarrow\left(S^{\prime} \cdot v a l:=S^{\prime \prime} \rightarrow v(X Y)\right) \\
& \text { with } t \triangleq\left(\text { val } \rightarrow S^{\prime} \rightarrow(S . v a l) \bullet S^{\prime}, \text { get } \rightarrow S^{\prime} \rightarrow(S . g e t) \bullet S^{\prime}, \text { set } \rightarrow S^{\prime} \rightarrow(\text { S.set }) \bullet S^{\prime}\right)
\end{aligned}
$$

It is not hard to verify that $\llbracket P C l a s s \rrbracket . n e w \mapsto \mathbb{T}_{\varsigma} \mathcal{O}_{b j}$ Point $_{\text {imp }}$.
As another example, we present the Abadi and Cardelli's fixed point object operator. To do this we recall the usual encoding of lambda calculus in $\varsigma \mathcal{O} b j$ :

$$
\begin{array}{ll}
\llbracket S \rrbracket & \triangleq S \\
\llbracket M N \rrbracket & \triangleq \llbracket M \rrbracket \circ \llbracket N \rrbracket
\end{array} \quad \llbracket \lambda S . M \rrbracket \triangleq[\arg =\varsigma(S) S . \operatorname{sig}, v a l=\varsigma(S)[S . \arg / S] \llbracket M \rrbracket]
$$

and the alias $p \circ q \triangleq(p . a r g:=\varsigma(S) q) . v a l$, which represents the encoding of the function application.
Example 10 (Another Fixed-Point Object). In $\varsigma \mathcal{O} b j$, the generic fixed-point object $F i x \triangleq\left[\arg =\varsigma(S) S . a r g, v a l=\varsigma(S)\left((S . a r g) \cdot a r g:=\varsigma\left(S^{\prime}\right)\right.\right.$ S.arg $\left.) . v a l\right]$, can be translated into $\rho C a l$ as:

$$
F i x \triangleq \arg \rightarrow S \rightarrow S . a r g, v a l \rightarrow S \rightarrow\left(k i l l_{\text {arg }}(S . a r g), \text { arg } \rightarrow S^{\prime} \rightarrow \text { S.arg }\right) . v a l
$$

Using the aliases $t_{1} \circ t_{2} \triangleq\left(t_{1} \cdot \arg :=S \rightarrow t_{2}\right) \cdot v a l$, and Fix $f \triangleq$ Fix.arg $:=$ $S \rightarrow f$, we can prove that Fix $\circ f \equiv$ Fix $_{f}$. val $\mapsto\left(\left(\right.\right.$ Fix $_{f}$.arg $)$.arg $:=S^{\prime} \rightarrow$ Fix $\left.x_{f} . v a l\right) . v a l \mapsto\left(f . a r g:=S^{\prime} \rightarrow F i x \circ f\right) . v a l \equiv f \circ(F i x \circ f)$.
The translation into the $\rho C a l$ can be proved correct when the theory $\mathbb{T}_{\varsigma \mathcal{O} b j}$ is considered:
Theorem 3 (Translation of $\varsigma \mathcal{O} b j$ into $\rho C a l$ ). If $M \mapsto_{\varsigma \mathcal{O} b j} N$, then $\llbracket M \rrbracket \mapsto \mathbb{T}_{\text {sObj }} \llbracket N \rrbracket$.
The following example show that the expressivity of $\rho C a l$ is strictly stronger than the two previous calculi of objects as they cannot be translated neither in $\lambda$ Obj nor in $\varsigma \mathcal{O} b j$. In fact, we can easily consider "labels" and "bodies" as first-class entities that can be passed as function arguments.
Example 11 (The Daemon and the Para object).

1. Assume Daemon be set $\rightarrow S \rightarrow X \rightarrow\left(X\right.$, set $\left.\rightarrow S^{\prime} \rightarrow Y \rightarrow\left(Y, S^{\prime}\right)\right)$. The set method of Daemon is used to create an object completely from scratch by receiving from outside all the components of a method, namely, the labels and the bodies. Once the object is installed, it has the capability to extend itself upon the reception of the same message set. In some sense the "power" of Daemon has been inherited by the created object. Then: Daemon.set $(x \rightarrow S \rightarrow 3) \triangleq$ Daemon $\bullet$ set $\bullet$ Daemon $\bullet(x \rightarrow S \rightarrow 3) \mapsto(X \rightarrow$ $\left(X\right.$, set $\left.\left.\rightarrow S^{\prime} \rightarrow Y \rightarrow\left(Y, S^{\prime}\right)\right)\right) \bullet(x \rightarrow S \rightarrow 3) \mapsto x \rightarrow S \rightarrow 3$, set $\rightarrow S^{\prime} \rightarrow$ $Y \rightarrow\left(Y, S^{\prime}\right) \triangleq t$, and $t \cdot \operatorname{set}(y \rightarrow S \rightarrow 4) \mapsto y \rightarrow S \rightarrow 4, t$.
2. Assume Para be $a \rightarrow S \rightarrow b, \operatorname{par}(X) \rightarrow S \rightarrow S . X$. This object has a method $\operatorname{par}(X)$ which seeks for a method name that is assigned to the variable $X$ and then sends this method to the object itself. Then: Para. $(\operatorname{par}(a)) \triangleq \operatorname{Para} \cdot(\operatorname{par}(a)) \cdot$ Para $\mapsto(S \rightarrow S . a) \cdot$ Para $\mapsto$ Para.$a \mapsto b$.

## 5 Conclusions and Further Work

We have presented a new version of the Rho Calculus and shown that its embedded matching power permits us to uniformly and naturally encode various calculi including the Lambda Calculus of Objects and the Object Calculus.

This presentation of the Rho Calculus inherits from the ideas and concepts of the first proposed one [7] [12], it simplifies the rules of the calculus and improves the way the results are handled. This allows us first to encode object oriented calculi in a very natural and simple way but further to design new powerful object oriented features, like parameterized methods or self creating objects. Based on this new generic approach, an implementation of objects is under way in the Rho-based language ELAN [16]. More generally, rewrite based languages like ASF+SDF, CafeOBJ, Maude, or ELAN, could benefit from a Rho-based semantics that gives a first class status to rewrite rules and to their application.

We are now planning to work on several directions. First, on giving a big step semantics in order to define a deterministic evaluation strategy when needed. Then, the calculus could be further generalized by the explicit use of constraints. For the moment, the ( $\rho$ ) rule calls for the solutions set of the relevant matching constraint. This could be replaced by an appropriate constrained term, in the spirit of constraint programming. We are also exploring an elaborated type system allowing in particular to type self-applications. As we have seen, the applications of the framework are numerous; a track that we have not yet mention in this paper concerns encoding concurrency in the spirit of the early work of Viry [40].

Independently of these ongoing works, we believe that the matching power of the Rho Calculus could be widely used, thanks to its expressiveness and simplicity, as a new model of computation.

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[^0]:    ${ }^{1}$ We consider a total order $\prec$ on the set of substitutions 11.

