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Abstract

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1 Introduction

2 The Untyped Calculus ND

I will be introducing the Untyped Calculus ND, based on ...

2.1 Syntax of the Untyped Calculus ND

Some knowledge of notation is necessary to familiarize oneself with the syntax of the Untyped Calculus. X represents a (possibly empty) sequence $X_1, \dots, X_i, \dots, X_n$.

A pattern match $e.\text{case}\{\overline{K(\bar{x}) \Rightarrow e}\}$ matches a term e against a sequence of clauses, each clause consisting of a constructor and an expression. The expression associated with first constructor that matches the term is the result of the pattern match. For a copattern match $\text{cocase}\{\overline{d(\bar{x}) \Rightarrow e}\}$ the same rules apply, but instead of constructors, the term is matched against destructors.

$e ::=$	x	Variable
	$ \quad K(\bar{e})$	Constructor
	$ \quad e.d(\bar{e})$	Destructor
	$ \quad e.\text{case}\{\overline{K(\bar{x}) \Rightarrow e}\}$	Pattern match
	$ \quad \text{cocase}\{\overline{d(\bar{x}) \Rightarrow e}\}$	Copattern match

Definition 2.1 (Terms of the Calculus ND).

In pattern and copattern matches, every con- or destructor may occur no more than once.

Let's look at some examples to ... All rudimentary datatypes can be constructed through constructors:

The Booleans **True** and **False** are constructors on an empty sequence.

Abstract data types like lists, arrays, records etc. can similarly be defined through constructors:

`Cons(True, Cons(False, Nil))` and `Date(...)`

We can use Pattern matching to represent conditionals: Lik this if statement: "**if** e_1 **then** e_2 **else** e_3 " which is analogous to: $e_1.\text{case}\{\text{True} \Rightarrow e_2, \text{False} \Rightarrow e_3\}$ Or the expression which tests whether a given list contains the number 5: $e.\text{case}\{\}$

2.2 Free Variables, Substitutions, Contexts

Definition 2.2 (Free Variables). The set of free variables of a term e is $\text{FV}(e)$. A term is closed if this set is empty. Free Variables are defined recursively over

the structure of terms as follows:

$$\begin{aligned}
\text{FV}(x) &:= \{x\} \\
\text{FV}(K(e_1, \dots, e_n)) &:= \text{FV}(e_1) \cup \dots \cup \text{FV}(e_n) \\
\text{FV}(e.d(e_1, \dots, e_n)) &:= \text{FV}(e) \cup \text{FV}(e_1) \cup \dots \cup \text{FV}(e_n) \\
\text{FV}(e.\text{case}\{\overline{K(\bar{x}) \Rightarrow e}\}) &:= \text{FV}(e) \cup (\text{FV}(e_1) \setminus \bar{x}) \cup \dots \cup (\text{FV}(e_n) \setminus \bar{x}) \\
\text{FV}(\text{cocase}\{\overline{d(\bar{x}) \Rightarrow e}\}) &:= (\text{FV}(e_1) \setminus \bar{x}) \cup \dots \cup (\text{FV}(e_n) \setminus \bar{x})
\end{aligned}$$

Definition 2.3 (Substitution). A simultaneous substitution σ of the terms e_1, \dots, e_n for the distinct variables x_1, \dots, x_n is defined as follows:

$$\sigma ::= [e_1, \dots, e_n / x_1, \dots, x_n]$$

The set of variables for which the substitution is defined is called the domain. The set of free variables which appear in the substitution is called the range.

Definition 2.4 (Domain and Range of a Substitution). The definitions of Domain and Range of a Substitution are as follows:

$$\begin{aligned}
\text{dom}([e_1, \dots, e_n / x_1, \dots, x_n]) &:= \{x_1, \dots, x_n\} \\
\text{rng}([e_1, \dots, e_n / x_1, \dots, x_n]) &:= \text{FV}(e_1) \cup \dots \cup \text{FV}(e_n)
\end{aligned}$$

What is actually interesting is what happens when we apply a substitution to an expression

Definition 2.5 (Action of a Substitution). The action of a substitution σ on a term e , written as $e\sigma$ and is defined as follows:

$$\begin{aligned}
x[e_1, \dots, e_n / x_1, \dots, x_n] &:= e_i \quad (\text{if } x = x_i) \\
y\sigma &:= y \quad (\text{if } y \notin \text{dom}(\sigma)) \\
(K(e_1, \dots, e_n))\sigma &:= K(e_1\sigma, \dots, e_n\sigma) \\
(e.d(e_1, \dots, e_n))\sigma &:= (e\sigma).d(e_1\sigma, \dots, e_n\sigma) \\
(e.\text{case}\{\overline{K(\bar{x}) \Rightarrow e}\})\sigma &:= (e\sigma).\text{case}\{\overline{K(\bar{y}) \Rightarrow (e\sigma')\sigma}\} \\
(\text{cocase}\{\overline{d(\bar{x}) \Rightarrow e}\})\sigma &:= \text{cocase}\{\overline{d(\bar{y}) \Rightarrow (e\sigma')\sigma}\}
\end{aligned}$$

Where σ' is a substitution that ensures that we don't bind new variables: σ' has the form $[y_1, \dots, y_n / x_1, \dots, x_n]$ and all y_i are fresh for both the domain and the range of σ .

The composition of two substitutions $\sigma_2 \circ \sigma_1$ which is equivalent to first applying the substitution σ_1 , then the substitution σ_2 .

Definition 2.6 (Composition of Substitutions). Given two substitutions

$$\sigma_1 := [e_1, \dots, e_n / x_1, \dots, x_n], \quad \sigma_2 := [t_1, \dots, t_m / y_1, \dots, y_m]$$

Composition is defined as:

$$\sigma_2 \circ \sigma_1 := [e_1 \sigma_2, \dots, e_n \sigma_2, t_j, \dots, t_k / x_1, \dots, x_n, y_j, \dots, y_k]$$

Where j, \dots, k is the greatest sub-range of indices $1, \dots, m$ such that none of the variables y_j to y_k is in the domain of σ_1

2.3 Conversion

Definition 2.7 (Beta-Conversion). A single step of beta-conversion $e_1 \equiv_\beta^1 e_2$ is defined as follows:

$$\begin{aligned} K(\bar{e}).\text{case}\{\dots, K(\bar{x} \Rightarrow e)\} &\equiv_\beta^1 e[\bar{e}/x] & (\beta\text{-Data}) \\ \text{cocase}\{\dots, d(\bar{x} \Rightarrow e, \dots)\}.d(\bar{e}) &\equiv_\beta^1 e[\bar{e}/x] & (\beta\text{-Codata}) \end{aligned}$$

Definition 2.8 (Eta-Conversion for Codata). A single step of eta-conversion $e_1 \equiv_\eta^1 e_2$ is defined as follows:

$$\begin{aligned} e.\text{case}\{K(\bar{x}) \Rightarrow K(\bar{x})\} &\equiv_\eta^1 e & (\eta\text{-Data}) \\ \text{cocase}\{d(\bar{x}) \Rightarrow e.d(\bar{x})\} &\equiv_\eta^1 e \quad (\text{if } \bar{x} \notin \text{FV}(e)) & (\eta\text{-Codata}) \end{aligned}$$

3 The Unification Problem

The Unification Problem is described by a set of equations with expressions on each side $\bar{e} \equiv \bar{e}$ containing unknown unification variables $\alpha^?$, where our goal is to find a simultaneous substitution $[e_1, \dots, e_n / \alpha_1^?, \dots, \alpha_n^?]$ which substitutes expressions for unification variables, such that the sides of the given equations are the same (respectively).

To describe this formally, we need to expand our syntax to be able to represent unification variables.

$e ::=$	$\alpha^?$	Unification variable
	x	Variable
	$K(\bar{e})$	Constructor
	$e.d(\bar{e})$	Destructor
	$e.\text{case}\{\overline{K(\bar{x}) \Rightarrow e}\}$	Pattern match
	$\text{cocase}\{\overline{d(\bar{x}) \Rightarrow e}\}$	Copattern match

In unification, we are not concerned with syntactic equality, but ... equality. Thus, I will use \equiv for unification problems, where two terms are either syntactically equivalent, beta-equivalent or eta-equivalent. This essentially means that two terms are equivalent if they are equivalent after function application and/or are equivalent externally.

For some unification problems, there exists a solution and it is obvious: The solution to $\alpha^? \equiv True$ is $[True/\alpha^?]$

For some unification problems, it is rather obvious that there is no solution on the other hand: There is no mapping of unification variables that make both sides of $True \equiv False$ the same.

Solutions aren't necessarily unique, either. The problem $\alpha^?5 \equiv 5$ has multiple solutions:

$[\mathbf{c} \mathbf{o} \mathbf{c} \mathbf{a} \mathbf{s} \mathbf{e}\{\mathbf{A} \mathbf{p}(x) \Rightarrow x\}/\alpha^?]$ and $[\mathbf{c} \mathbf{o} \mathbf{c} \mathbf{a} \mathbf{s} \mathbf{e}\{\mathbf{A} \mathbf{p}(x) \Rightarrow 5\}/\alpha^?]$, where $\mathbf{A} \mathbf{p}$ is a function applicator. Thus, the two given solutions are the identity function and the constant function 5, which when consuming the argument 5, both give back 5.

The interesting unification problems are those where it is not clear at first sight whether there exists a solution.

3.1 Types Of Solutions

To be able to discuss the algorithm for solving the unification problem, we need to define some helpful concepts first.

Definition 3.1 (Idempotency). A solution σ is idempotent, iff. $\sigma \circ \sigma = \sigma$. Concretely, this means that it doesn't matter how often we apply a solution to a given problem.

For example, $[\lambda x.x/y]$ is idempotent, since:

$$[\lambda x.x/y] \circ [\lambda x.x/y] = [(\lambda x.x)[\lambda x.x/y]/y] = [\lambda x.x/y]$$

On the other hand, the solution $[\lambda y.x/x]$ is not idempotent, since:

$$[\lambda y.x/x] \circ [\lambda y.x/x] = [(\lambda y.x)[\lambda y.x/x]/x] = [\lambda y.y.x/x] \neq [\lambda y.x/x]$$

Definition 3.2 (More General). A solution σ is more general than a solution θ , iff. there exists a mapping τ , such that: $\theta = \tau \circ \sigma$.

For example, for the problem $\alpha x = zx$, both $\sigma_1 = [z/\alpha]$ and $\sigma_2 = [\lambda y.zx, \lambda y.zx/\alpha, z]$ are solutions, but σ_1 is more general than σ_2 , since there exists a substitution $\sigma_3 = [\lambda y.zx/z]$, and:

$$\sigma_3 \circ \sigma_1 = [z[\lambda y.zx/z], \lambda y.zx/\alpha, z] = [(\lambda y.zx), \lambda y.zx/\alpha, z] = \sigma_2$$

Definition 3.3 (Most General). A solution is the most general unifier (mgu), iff. it is more general than all other solutions.

Selbständigkeitserklärung

Hiermit versichere ich, dass ich die vorliegende Bachelorarbeit selbständig und nur mit den angegebenen Hilfsmitteln angefertigt habe und dass alle Stellen, die dem Wortlaut oder dem Sinne nach anderen Werken entnommen sind, durch Angaben von Quellen als Entlehnung kenntlich gemacht worden sind. Diese Bachelorarbeit wurde in gleicher oder ähnlicher Form in keinem anderen Studiengang als Prüfungsleistung vorgelegt.

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