

# Notes on type systems

Vladimir Voevodsky

Started September 08, 2009

## Contents

<b>1</b>	<b>Introduction</b>	<b>2</b>
<b>2</b>	<b>Essentially algebraic theories</b>	<b>2</b>
<b>3</b>	<b>The main hierarchy</b>	<b>2</b>
1	Contextual categories . . . . .	2
2	$\Pi$ -contextual categories . . . . .	12
3	Impredicative $\Pi$ -universe structures. . . . .	16
4	Predicative $\Pi$ -universe structures. . . . .	17
5	Universes with Martin-Loef identity types. . . . .	17
<b>4</b>	<b>Contextual categories defined by universes in 1-categories</b>	<b>17</b>
<b>5</b>	<b>Universes in the category of simplicial sets</b>	<b>26</b>
1	Well-ordered morphisms of simplicial sets . . . . .	26
2	Well-ordered simplicial sets . . . . .	32
<b>6</b>	<b>Type systems</b>	<b>33</b>
1	Systems of expressions . . . . .	33
2	Type systems . . . . .	36
3	Rules and parsing schemes in contextual categories . . . . .	43
4	Weak intermediate type systems . . . . .	46
<b>7</b>	<b>The system of Coq</b>	<b>46</b>
1	A type system CIC0 . . . . .	46
2	Representing inductive definitions in Coq as combinations of elementary ones . . . . .	52
3	Interpretations of inductive definitions in lccc's . . . . .	58

# 1 Introduction

## 2 Essentially algebraic theories

## 3 The main hierarchy

### 1 Contextual categories

**Contextual categories.** It will be important for us to distinguish two notions of a category. What is understood by a category by most practicing mathematicians i.e. a category up to an equivalence, will be called, when an explicit distinction is needed, a category of level 1. A category as a combinatorial object i.e. a category up to an isomorphism will be called a set-level category. A set-level category  $C$  is a pair of sets  $Mor(C)$  and  $Ob(C)$  with an additional structure. The structure is given by four maps

$$\partial_0, \partial_1 : Mor(C) \rightarrow ob(C)$$

$$Id : ob(C) \rightarrow Mor(CC)$$

and the composition map

$$\circ : Mor(CC)_{\partial_1} \times_{\partial_0} Mor(CC) \rightarrow Mor(CC)$$

which satisfy the well known conditions.

A contextual category is a set-level category with additional structure of the form

1. an object  $pt$ ,
2. a map  $ft : Ob(C) \rightarrow Ob(C)$ ,
3. for each  $X \in Ob(C)$  a morphism  $p_X : X \rightarrow ft(X)$ ,
4. for each  $X \in Ob(C)$  and each morphism  $f : Y \rightarrow ft(X)$  an object  $f^*X$  and a morphism  $q(f, X) : f^*X \rightarrow X$ ,

which satisfies the following conditions:

1.  $ft(pt) = pt$ ,
2.  $pt$  is a final object,
3. for  $X \in Ob(C)$  and  $f : Y \rightarrow ft(X)$  one has  $ft(f^*X) = Y$  and the square

$$\begin{array}{ccc} f^*X & \xrightarrow{q(f,X)} & X \\ \text{[2009.10.14.eq1]} \downarrow & & \downarrow p_X \\ Y & \xrightarrow{f} & ft(X) \end{array} \quad (1)$$

is a pull-back square,

4. for  $X \in ob(C)$  one has  $id_{ft(X)}^*(X) = X$  and  $q(id_{ft(X)}, X) = id_X$ ,

5. for  $X \in ob(C)$ ,  $f : Y \rightarrow ft(X)$  and  $g : Z \rightarrow Y$  one has  $(fg)^*(X) = g^*(f^*(X))$  and  $q(fg, X) = q(f, X)q(g, f^*X)$ .

This definition differs from the original definition of Cartmell and Streicher (see [3], [8, Def. 1.2, p.47]) since we do not require the existence, for every  $X \in ob(C)$  of a natural number  $n$  such that  $ft^n(X) = pt$  and do consider  $f^*X$  and  $q(f, X)$  for  $X = pt$ . These changes allow us to consider contextual categories as models of a quasi-equational theory  $CC$  described below and in particular they ensure that the free contextual categories with various additional structures exist. If we required the morphism  $ft$  to be "bounded" in the sense mentioned above then there would be no free categories - for example what would be the smallest  $n$  for which  $ft^n(X) = pt$  in the free contextual category generated by  $X$ ?

In practice this is not important since for free contextual categories with "good" structures whose generators are of finite "height" so are all the objects. Allowing canonical pull-back squares with  $X = pt$  leads to the fact that for any  $Y \in Ob(C)$  we get the object  $(p^Y)^*(pt)$  (where  $p^Y : Y \rightarrow pt$ ) which has the property that  $ft((p^Y)^*(pt)) = Y$  and  $p_{(p^Y)^*(pt)}$  is an isomorphism. This is different from the Cartmell-Streicher categories and requires us to modify slightly the construction of the contextual category associated with a type system.

**Contextual subcategories.** A subcategory  $CC'$  of a contextual category  $CC$  is called contextual subcategory if it is closed, in the obvious sense under the operations which define the contextual structure on  $CC$  and such that the canonical squares which belong to  $CC'$  are pull-back squares in  $CC'$ . A contextual subcategory is called non-trivial if it contains at least one other element than  $pt$ . A contextual subcategory of a contextual category is itself a contextual category with respect to the induced structure. The following elementary result plays a key role in many constructions of type theory:

**Proposition 1.1** [2009.10.15.prop1] *Let  $CC$  be a contextual category. Then for any family  $CC_\alpha$  of contextual subcategories of  $CC$ , the intersection  $CC' = \bigcap_\alpha CC_\alpha$  is a contextual sub-category.*

**Proof:** The only condition to check is that a canonical square which belongs to  $CC'$  is a pull-back square in  $CC'$ . This follows from the definition of pull-back squares and the fact that fiber products of sets commute with intersections of sets.

**Corollary 1.2** [2009.10.15.cor1] *Let  $CC$  be a contextual category,  $C_0$  a set of objects of  $CC$  and  $C_1$  a set of morphisms of  $CC$ . Then there exists the smallest contextual subcategory  $[C_1, C_0]$  which contains  $C_0$  and  $C_1$ . It is called the contextual subcategory generated by  $C_0$  and  $C_1$ .*

Let  $CC$  be a contextual category. Let  $ob(CC)$  be as usually the set of objects of  $CC$  and let  $\tilde{ob}(CC)$  be the set of pairs of the form  $(X, s)$  where  $X \in ob(CC)$  and  $s : ft(X) \rightarrow X$  is a section of the canonical morphism  $p_X : X \rightarrow ft(X)$ .

**Lemma 1.3** [2009.10.15.11] *Let  $CC$  be a contextual category and  $CC', \tilde{CC}''$  be two contextual subcategories such that  $ob(CC') = ob(\tilde{CC}'')$  (as subsets of  $ob(CC)$ ) and  $\tilde{ob}(CC') = \tilde{ob}(\tilde{CC}'')$  (as subsets of  $\tilde{ob}(CC)$ ). Then  $CC' = \tilde{CC}''$ .*

**Proof:** For any contextual category we have a canonical decomposition  $ob(CC) = \coprod_n ob_n(CC)$  such that  $ob_0(CC) = \{pt\}$  is the distinguished final object and for  $\Gamma \in ob_n$  and  $n > 0$ ,  $ft(\Gamma) \in ob_{n-1}$ .

Let  $f : Y \rightarrow X$  be a morphism in  $CC'$ . We want to show that it belongs to  $CC''$ . Proceed by induction on  $m$  where  $X \in ob_m$ . For  $m = 0$  the assertion is obvious. Suppose that  $m > 0$ . Since  $CC$  is a contextual category we have a commutative diagram

$$\begin{array}{ccccc}
Y & \xrightarrow{s_f} & (p_X f)^* X & \xrightarrow{q(p_X f, X)} & X \\
\text{[2009.11.07.oldeq1]} \downarrow & & \downarrow p' & & \downarrow p \\
Y & \xrightarrow{=} & Y & \xrightarrow{p_X f} & ft(X)
\end{array} \tag{2}$$

such that  $f = q(p_X f, X) s_f$ . Since the right hand side square is a canonical one,  $((p_X f)^* \Gamma', s_f) \in \tilde{ob}(CC)$  and  $ft(X) \in ob_{m-1}(CC)$ , the inductive assumption implies that  $f \in CC''$ .

**Remark 1.4** In Lemma 1.3, it is sufficient to assume that  $\tilde{ob}(CC') = \tilde{ob}(CC'')$ . The condition  $ob(CC') = ob(CC'')$  is then also satisfied. Indeed, let  $X \in ob(CC')$ . Then  $p_X^* X$  is the product  $X \times X$  in  $CC$ . Consider the diagonal section  $\Delta_X : X \rightarrow p_X^* X$  of  $p_{p_X^*(X)}$ . Since  $CC'$  is assumed to be a contextual subcategory we conclude that  $\Delta_X \in \tilde{ob}(CC') = \tilde{ob}(CC'')$  and therefore  $X \in ob(CC'')$ . It is however more convenient to think of contextual subcategories in terms of both subsets  $ob$  and  $\tilde{ob}$ .

Let  $CC$  be a contextual category. Let us say that a pair of subsets  $C \subset ob(CC)$ ,  $\tilde{C} \subset \tilde{ob}(CC)$  is saturated if there exists a contextual subcategory  $CC'$  such that  $C = ob(CC')$  and  $\tilde{C} = \tilde{ob}(CC')$ . By Lemma 1.3 we have a bijection between contextual subcategories of  $CC$  and saturated pairs  $(C, \tilde{C})$ .

Let us introduce the following notations. Let  $X \in ob(CC)$  and  $i \geq 0$ . Denote by  $p_{X,i}$  the composition of the canonical projections  $X \rightarrow ft(X) \rightarrow \dots \rightarrow ft^i(X)$  such that  $p_{X,0} = Id_X$  and  $p_{X,1} = p_X$ . For  $f : Y \rightarrow ft^i(X)$  denote by  $q(f, X, i) : f^*(X, i) \rightarrow X$  the morphism defined inductively by the rule

$$\begin{aligned}
f^*(X, 0) &= Y & q(f, X, 0) &= f, \\
f^*(X, i+1) &= q(f, ft(X), i)^*(X) & q(q(f, ft(X), i), X) &.
\end{aligned}$$

In other words,  $q(f, X, i)$  is the canonical pull-back of the morphism  $f : Y \rightarrow ft^i(X)$  with respect to the sequence of canonical projections  $X \rightarrow ft(X) \rightarrow \dots \rightarrow ft^i(X)$ .

Let  $i \geq 1$ ,  $f : Y \rightarrow ft^i(X)$  be a morphism and  $s : ft(X) \rightarrow X$  an element of  $\tilde{ob}(CC)$ . Denote by  $f^*(s, i)$  the element of  $ob(CC)$  of the form  $f^*(ft(X), i-1) \rightarrow f^*(X, i)$  which is the pull-back of  $s$  with respect to  $q(f, ft(X), i-1)$ .

**Proposition 1.5** [2009.10.15.prop2] *A pair  $(C, \tilde{C})$  is saturated if and only if it satisfies the following conditions:*

1.  $pt \in C$ ,
2. if  $X \in C$  then  $ft(X) \in C$ ,
3. if  $(s : ft(X) \rightarrow X) \in \tilde{C}$  then  $X \in C$ ,
4. if  $(s : ft(X) \rightarrow X) \in \tilde{C}$ ,  $X' \in C$ ,  $i \geq 1$  and  $ft^i(X) = ft(X')$  then  $q(p_{X'}, ft(X), i-1)^*(s) \in \tilde{C}$ ,

5. if  $(s_1 : ft(X) \rightarrow X) \in \tilde{C}$ ,  $i \geq 1$  and  $(s_2 : ft^{i+1}(X) \rightarrow ft^i(X)) \in \tilde{C}$  then  $q(s_2, ft(X), i-1)^*(s_1) \in \tilde{C}$ ,
6. if  $X \in C$  then the diagonal  $s_{id_X} : X \rightarrow (p_X)^*(X)$  is in  $\tilde{C}$ .

Conditions (4) and (5) are illustrated by the following diagrams:

$$\begin{array}{ccccccc}
p_{X'}^*(ft(X), i-1) & \xrightarrow{q(p_{X'}, ft(X), i-1)} & ft(X) & & s_2^*(ft(X), i-1) & \xrightarrow{q(s_2, ft(X), i-1)} & ft(X) \\
\downarrow q(p_{X'}, ft(X), i-1)^*(s) & & \downarrow s & & \downarrow q(s_2, ft(X), i-1)^*(s_1) & & \downarrow s_1 \\
p_{X'}^*(X, i) & \xrightarrow{q(p_{X'}, X, i)} & X & & s_2^*(X, i) & \xrightarrow{q(s_2, X, i)} & X \\
\downarrow & & \downarrow p_X & & \downarrow & & \downarrow p_X \\
p_{X'}^*(ft(X), i-1) & \xrightarrow{q(p_{X'}, ft(X), i-1)} & ft(X) & & s_2^*(ft(X), i-1) & \xrightarrow{q(s_2, ft(X), i-1)} & ft(X) \\
\downarrow & & \downarrow & & \downarrow & & \downarrow \\
\dots & & \dots & & \dots & & \dots \\
\downarrow & & \downarrow & & \downarrow & & \downarrow \\
X' & \xrightarrow{p_{X'}} & ft^i(X) & & ft^{i+1}(X) & \xrightarrow{s_2} & ft^i(X)
\end{array}$$

**Proof:** The "only if" part of the proposition is straightforward. Let us prove that for any  $(C, \tilde{C})$  satisfying the conditions of the proposition there exists a contextual subcategory  $CC'$  of  $CC$  such that  $C = ob(CC')$  and  $\tilde{C} = \tilde{ob}(CC')$ .

For a morphism  $f : Y \rightarrow X$  let  $ft(f) = p_X f : Y \rightarrow ft(X)$ . Any morphism  $f : Y \rightarrow X$  in  $CC$  has a canonical representation of the form  $Y \xrightarrow{s_f} X_f \xrightarrow{q_f} X$  where  $X_f = ft(f)^*(X)$ ,  $q_f = q(ft(f), X)$  and  $s_f : Y \rightarrow X_f$  is the section of the canonical projection  $X_f \rightarrow Y$  corresponding to  $f$ .

Define a candidate subcategory  $CC'$  setting  $ob(CC') = C$  and defining the set  $Mor(CC')$  of morphisms of  $CC'$  inductively by the conditions:

1.  $Y \rightarrow pt$  is in  $Mor(CC')$  if and only if  $Y \in C$ ,
2.  $f : Y \rightarrow X$  is in  $Mor(CC')$  if and only if  $X \in ob(C)$ ,  $ft(f) \in Mor(CC')$  and  $s_f \in \tilde{C}$ .

(note that the for  $(f : Y \rightarrow X) \in Mor(CC')$  one has  $Y \in C$  since  $s_f : Y \rightarrow X_f$ ).

Let us show that if the condition of the proposition are satisfied then  $(ob(CC'), Mor(CC'))$  form a contextual subcategory of  $CC$ .

The subset  $ob(CC')$  contains  $pt$  and is closed under  $ft$  map by the first two conditions. The following lemma shows that  $Mor(CC')$  contains identities and the compositions of canonical projections.

**Lemma 1.6 [2009.10.16.11]** *Under the assumptions of the proposition, if  $X \in C$  and  $i \geq 0$  then  $p_{X,i} : X \rightarrow ft^i(X)$  is in  $Mor(CC')$ .*

**Proof:** By definition of contextual categories there exists  $n$  such that  $ft^n(X) = pt$ . Then  $p_{X,n} \in Mor(CC')$  by the first constructor of  $Mor(CC')$ . By induction it remains to show that if  $X \in C$

and  $p_{X,i} \in \text{Mor}(CC')$  then  $p_{X,i-1} \in \text{Mor}(CC')$ . We have  $ft(p_{X,i-1}) = p_{X,i}$  and  $s_{p_{X,i-1}}$  is the pull-back of the diagonal  $ft^{i-1}(X) \rightarrow (p_{ft^{i-1}(X)})^*(ft^{i-1}(X))$  with respect to the canonical morphism  $X \rightarrow ft^{i-1}(X)$ . The diagonal is in  $\tilde{C}$  by condition (6) and therefore  $s_{p_{X,i-1}}$  is in  $\tilde{C}$  by repeated application of condition (4).

**Lemma 1.7 [2009.10.16.13]** *Under the assumptions of the proposition, let  $X \in C$ ,  $(s : ft(X) \rightarrow X) \in \tilde{C}$ ,  $i \geq 0$ , and  $(f : Y \rightarrow ft^i(X)) \in \text{Mor}(CC')$ . Then  $q(f, ft(X), i-1)^*(s) : ft(f^*(X, i)) \rightarrow f^*(X, i)$  is in  $\text{Mor}(CC')$ .*

**Proof:** Suppose first that  $ft^i(X) = pt$ . Then  $f = p_{Y,n}$  for some  $n$  and the statement of the lemma follows from repeated application of condition (4). Suppose that the lemma is proved for all morphisms to objects of length  $j-1$  and let the length of  $ft^i(X)$  be  $j$ . Consider the canonical decomposition  $f = q_f s_f$ . The morphism  $q_f$  is the canonical pull-back of  $ft(f)$  and therefore the pull-back of  $s$  relative to  $q_f$  coincides with its pull-back relative to  $ft(f)$  which is  $\tilde{C}$  by the inductive assumption. The pull-back of an element of  $\tilde{C}$  with respect to  $s_f$  is in  $\tilde{C}$  by condition (5).

**Lemma 1.8 [2009.10.16.14]** *Under the assumptions of the proposition, let  $g : Z \rightarrow Y$  and  $f : Y \rightarrow X$  be in  $\text{Mor}(CC')$ . then  $fg \in \text{Mor}(CC')$ .*

**Proof:** If  $X = pt$  the the statement is obvious. Assume that it is proved for all  $f$  whose codomain is of length  $< j$  and let  $X$  be of length  $j$ . We have  $ft(fg) = ft(f)g$  and therefore  $ft(fg) \in \text{Mor}(CC')$  by the inductive assumption. It remains to show that  $s_{fg} \in \tilde{C}$ . We have the following diagram whose squares are canonical pull-back squares

$$\begin{array}{ccccc} X_{fg} & \longrightarrow & X_f & \longrightarrow & X \\ \downarrow & & \downarrow & & \downarrow p_X \\ Z & \xrightarrow{g} & Y & \xrightarrow{ft(f)} & ft(X) \end{array}$$

which shows that  $s_{fg} = g^*(s_f)$ . Therefore,  $s_{fg} \in \text{Mor}(CC')$  by Lemma 1.7.

**Lemma 1.9 [2009.10.16.15]** *Under the assumptions of the proposition, let  $X \in C$  and let  $f : Y \rightarrow ft(X)$  be in  $\text{Mor}(CC')$ , then  $f^*(X) \in C$  and  $q(f, X) \in \text{Mor}(CC')$ .*

**Proof:** Consider the diagram

$$\begin{array}{ccccc} f^*(X) & \xrightarrow{q(f,X)} & X & & \\ s_{q(f,X)} \downarrow & & \downarrow s_{Id_X} & & \\ q(f, X)^*(X) & \longrightarrow & p_X^*(X) & \longrightarrow & X \\ \downarrow & & \downarrow & & \downarrow \\ f^*(X) & \xrightarrow{q(f,X)} & X & \longrightarrow & ft(X) \\ p_{f^*(X)} \downarrow & & \downarrow p_X & & \\ Y & \xrightarrow{f} & ft(X) & & \end{array}$$

where the squares are canonical. By condition (6) we have  $s_{Id} \in \tilde{C}$ . Therefore, by Lemma 1.7, we have  $s_{q(f,X)} \in \tilde{C}$ . In particular,  $q(f,X)^*(X) \in C$  and therefore  $f^*(X) = ft(q(f,X)^*(X)) \in C$ . The fact that  $q(f,X) \in Mor(CC')$  follows from the fact that  $s_{q(f,X)} \in \tilde{C}$  and  $ft(q(f,X)) = f \circ p_{f^*(X)}$  is in  $Mor(CC')$  by previous lemmas.

**Lemma 1.10** [2009.10.16.16] *Under the assumptions of Lemma 1.9, the square*

$$\begin{array}{ccc} f^*(X) & \xrightarrow{q(f,X)} & X \\ p_{f^*(X)} \downarrow & & \downarrow p_X \\ Y & \xrightarrow{f} & ft(X) \end{array}$$

is a pull-back square in  $CC'$ .

**Proof:** We need to show that for a morphism  $g : Z \rightarrow f^*(X)$  such that  $p_{f^*(X)}g$  and  $q(f,X)g$  are in  $Mor(CC')$  one has  $g \in Mor(CC')$ . We have  $ft(g) = p_{f^*(X)}g$ , therefore by definition of  $Mor(CC')$  it remains to check that  $s_g \in \tilde{C}$ . The diagram

$$\begin{array}{ccccc} (f^*Y)_g & \longrightarrow & f^*Y & \xrightarrow{q(f,X)} & X \\ \downarrow & & \downarrow & & \downarrow \\ Z & \xrightarrow{ft(g)} & Y & \xrightarrow{f} & ft(X) \end{array}$$

shows that  $s_g = s_{q(f,X)g}$  and therefore  $s_g \in Mor(CC')$ .

To finish the proof of the proposition it remains to show that  $ob(CC') = C$  and  $\tilde{ob}(CC') = \tilde{C}$ . The first assertion is tautological. The second one follows immediately from the fact that for  $(s : ft(X) \rightarrow X) \in \tilde{ob}(CC)$  one has  $ft(s) = Id_{ft(X)}$  and  $s_s = s$ .

**The sequent axiomatics of contextual categories.** Proposition 1.5 suggests that a contextual category  $CC$  can be reconstructed from the sets  $ob(CC)$  and  $\tilde{ob}(CC)$  together with the structures on these sets which correspond to the conditions of the proposition. Let us show that it is indeed the case. Let  $B = ob(CC)$  and  $\tilde{B} = \tilde{ob}(CC)$ . We will further write  $B_n$  for  $ob(CC)_n$  such that  $B_0 = \{pt\}$ ,  $ft : B_n \rightarrow B_{n-1}$  for the  $ft$  map and  $ft^i : B_n \rightarrow B_{n-i}$  for the  $i$ -th iteration of  $ft$ . Let  $\partial : \tilde{B} \rightarrow B$  be the map which assigns to a pair  $(X, s : ft(X) \rightarrow X) \in \tilde{ob}(CC)$  the object  $X$ . It takes values in  $B_{\geq 1} = \coprod_{n \geq 1} B_n$ . Let  $\delta : B_{\geq 1} \rightarrow \tilde{B}$  be the map which sends  $X$  to the diagonal section of the projection  $p_X^* X \rightarrow X$ . We will also write  $\tilde{B}_i$  for  $(X, s)$  such that  $X \in B_i$  with the obvious meaning assigned to  $\tilde{B}_{\geq i}$  etc. Finally, for  $X \in B_i$  where  $i \geq 1$  we will write  $\tilde{B}(X)$  or  $\tilde{B}_i(X)$  for the set of  $r \in \tilde{B}$  such that  $\partial(r) = X$ .

In addition let us consider the following maps given for all  $m \geq n \geq 0$ :

1.  $T : (B_{n+1})_{ft} \times_{ft^{m+1-n}} (B_{m+1}) \rightarrow B_{m+2}$ , which sends  $(Y, X)$  such that  $ft(Y) = ft^{m+1-n}(X)$  to  $p_Y^*(X, m+1-n)$ ,
2.  $\tilde{T} : (B_{n+1})_{ft} \times_{ft^{m+1-n}\partial} (\tilde{B}_{m+1}) \rightarrow \tilde{B}_{m+2}$ , which sends  $(Y, r)$  such that  $ft(Y) = ft^{m+1-n}\partial(r)$  to  $p_Y^*(r, m+1-n)$ ,

3.  $S : (\tilde{B}_{n+1})_{\partial} \times_{ft^{m+1-n}} (B_{m+2}) \rightarrow B_{m+1}$ , which sends  $(s, X)$  such that  $\partial(s) = ft^{m+1-n}(X)$  to  $s^*(X, m+1-n)$ ,
4.  $\tilde{S} : (\tilde{B}_{n+1})_{\partial} \times_{ft^{m+1-n}\partial} (\tilde{B}_{m+2}) \rightarrow \tilde{B}_{m+1}$ , which sends  $(s, r)$  such that  $\partial(s) = ft^{m+1-n}\partial(r)$  to  $s^*(r, m+1-n)$ .

Note that we have

$$\begin{aligned}
ft(T(Y, X)) &= \begin{cases} T(Y, ft(X)) & \text{if } l(Y) - l(X) \geq 1 \\ Y & \text{if } l(Y) - l(X) = 0 \end{cases} \\
\partial(\tilde{T}(Y, r)) &= T(Y, \partial(r)) \\
ft(S(s, X)) &= \begin{cases} S(s, ft(X)) & \text{if } l(\partial(s)) - l(X) \geq 1 \\ Y & \text{if } l(\partial(s)) - l(X) = 0 \end{cases} \\
\partial(\tilde{S}(s, r)) &= S(s, \partial(r))
\end{aligned} \tag{3}$$

and

$$[\mathbf{2009.12.27.eq1}] \partial(\delta(X)) = T(X, X) \tag{4}$$

Let us denote by

$$\begin{aligned}
T_j &: (B_{n+j})_{ft^j} \times_{ft^{m+1-n}} (B_{m+1}) \rightarrow B_{m+1+j} \\
\tilde{T}_j &: (B_{n+j})_{ft^j} \times_{ft^{m+1-n}\partial} (\tilde{B}_{m+1}) \rightarrow \tilde{B}_{m+1+j}
\end{aligned}$$

the maps which are defined inductively by

$$T_j(Y, X) = \begin{cases} X & \text{if } j = 0 \\ T(Y, X) & \text{if } j = 1 \\ T_{j-1}(ft(Y), X) & \text{if } j > 1 \end{cases} \quad \tilde{T}_j(Y, r) = \begin{cases} r & \text{if } j = 0 \\ \tilde{T}(Y, r) & \text{if } j = 1 \\ \tilde{T}_{j-1}(ft(Y), r) & \text{if } j > 1 \end{cases} \tag{5}$$

Let  $f : Y \rightarrow X$  be a morphism such that  $Y \in B_n$  and  $X \in B_m$ . Define a sequence  $(s_1(f), \dots, s_m(f))$  of elements of  $\tilde{B}_{n+1}$  inductively by the rule

$$(s_1(f), \dots, s_m(f)) = (s_1(ft(f)), \dots, s_{m-1}(ft(f)), s_f) = (s_{ft^{m-1}(f)}, \dots, s_{ft(f)}, s_f)$$

where  $ft(f) = p_X f$ ,  $s_f$  is defined by the diagram (2) and for  $m = 0$  we start with the empty sequence. This construction can be illustrated by the following diagram for  $f : Y \rightarrow X$  where



$X \in B_4$ :

$$\begin{array}{ccccccccc}
Y & \xrightarrow{s_4(f)} & Z_{4,3} & \longrightarrow & Z_{4,2} & \longrightarrow & Z_{4,1} & \longrightarrow & T_n(Y, X) & \longrightarrow & X \\
& & \downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\
& & Y & \xrightarrow{s_3(f)} & Z_{3,2} & \longrightarrow & Z_{3,1} & \longrightarrow & T_n(Y, ft(X)) & \longrightarrow & ft(X) \\
& & & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\
& & & & Y & \xrightarrow{s_2(f)} & Z_{2,1} & \longrightarrow & T_n(Y, ft^2(X)) & \longrightarrow & ft^2(X) \\
& & & & & & \downarrow & & \downarrow & & \downarrow \\
& & & & & & Y & \xrightarrow{s_1(f)} & T_n(Y, ft^3(X)) & \longrightarrow & ft^3(X) \\
& & & & & & & & \downarrow & & \downarrow \\
& & & & & & & & Y & \longrightarrow & pt
\end{array} \tag{6}$$

which is completely determined by the condition that the squares are the canonical ones and the composition of morphisms in the  $i$ -th arrow from the top is  $ft^i(f)$ . For the objects  $Z_i^j$  we have:

$$\begin{aligned}
Z_{4,1} &= S(s_1(f), T_n(Y, X)) & Z_{4,2} &= S(s_2(f), Z_{4,1}) & Z_{4,3} &= S(s_3(f), Z_{4,2}) \\
Z_{3,1} &= S(s_1(f), T_n(Y, ft(X))) & Z_{3,2} &= S(s_2(f), Z_{3,1}) \\
Z_{2,1} &= S(s_1(f), T_n(Y, ft^2(X)))
\end{aligned} \tag{7}$$

A simple inductive argument similar to the one in the proof of Lemma 1.3 show that if  $f, f' : Y \rightarrow X$  are two morphisms such that  $X \in B_m$  and  $s_i(f) = s_i(f')$  for  $i = 1, \dots, m$  then  $f = f'$ . Therefore, we may consider the set  $Mor(CC)$  of morphisms of  $CC$  as a subset in  $\prod_{n,m \geq 0} B_n \times B_m \times \tilde{B}_{n+1}^m$ .

Let us show how to describe this subset in terms of the operations introduced above.

**Lemma 1.11** [2009.11.07.11] *An element  $(Y, X, s_1, \dots, s_m)$  of  $B_n \times B_m \times \tilde{B}_{n+1}^m$  corresponds to a morphism if and only if the element  $(Y, ft(X), s_1, \dots, s_{m-1})$  corresponds to a morphism and  $\partial(s_m) = Z_{m,m-1}$  where  $Z_{m,i}$  is defined inductively by the rule:*

$$Z_{m,0} = T_n(Y, X) \quad Z_{m,i+1} = S(s_{i+1}(f), Z_{m,i})$$

**Proof:** Straightforward from the example considered above.

Let us show now how to identify the canonical morphisms  $p_{X,i} : X \rightarrow ft^i(X)$  and in particular the identity morphisms.

**Lemma 1.12** [2009.11.10.11] *Let  $X \in B_m$  and  $0 \leq i \leq m$ . Let  $p_{X,i} : X \rightarrow ft^i(X)$  be the canonical morphism. Then one has:*

$$s_j(p_{X,i}) = \tilde{T}_{m-j}(X, \delta_{ft^{m-j}(X)}) \quad j = 1, \dots, m-i$$

**Proof:** Let us proceed by induction on  $m-i$ . For  $i = m$  the assertion is trivial. Assume the lemma proved for  $i+1$ . Since  $ft(p_{X,i}) = p_{X,i+1}$  we have  $s_j(p_{X,i}) = s_j(p_{X,i+1})$  for  $j = 1, \dots, m-i-1$ . It remains to show that

$$[\mathbf{2009.11.10.eq1}]s_{m-i}(p_{X,i}) = \tilde{T}_i(X, \delta_{ft^i(X)}) \quad (8)$$

By definition  $s_{m-i}(p_{X,i}) = s_{p_{X,i}}$  and (8) follows from the commutative diagram:

$$\begin{array}{ccccc} X & \longrightarrow & ft^i(X) & & \\ s_p \downarrow & & \downarrow \delta_{ft^i(X)} & & \\ p_{X,i+1}^*(ft^i(X)) & \longrightarrow & p_{ft^i(X)}^*(ft^i(X)) & \longrightarrow & ft^i(X) \\ \downarrow & & \downarrow & & \downarrow p_{ft^i(X)} \\ X & \longrightarrow & ft^i(X) & \longrightarrow & ft^{i+1}(X) \end{array}$$

where  $p = p_{X,i}$ .

**Lemma 1.13** [2009.11.10.12] *Let  $(X, s) \in \tilde{B}_{m+1}$ ,  $Y \in B_n$  and  $f : Y \rightarrow ft(X)$ . Define inductively  $(f, i)^*(s) \in \tilde{B}_{n+m+1-i}$  by the rule*

$$\begin{aligned} (f, 0)^*(s) &= \tilde{T}_n(Y, s) \\ (f, i+1)^*(s) &= \tilde{S}(s_{i+1}(f), (f, i)^*(s)) \end{aligned}$$

Then  $f^*(s) = (f, m)^*(s)$ .

**Proof:** It follows from the diagram:

$$\begin{array}{ccccccc} Y & \xrightarrow{s_m(f)} & * & \longrightarrow & \dots & \longrightarrow & * & \longrightarrow & * & \longrightarrow & ft(X) \\ f^*(s) \downarrow & & \downarrow (f, m-1)^*(s) & & & & \downarrow (f, 1)^*(s) & & \downarrow (f, 0)^*(s) & & \downarrow s \\ * & \longrightarrow & * & \longrightarrow & \dots & \longrightarrow & * & \longrightarrow & * & \longrightarrow & X \\ \downarrow & & \downarrow & & & & \downarrow & & \downarrow & & \downarrow \\ Y & \xrightarrow{s_m(f)} & * & \longrightarrow & \dots & \longrightarrow & * & \longrightarrow & * & \longrightarrow & ft(X) \\ & & \downarrow & & & & \downarrow & & \downarrow & & \downarrow \\ & & Y & \xrightarrow{s_{m-1}(f)} & \dots & \longrightarrow & * & \longrightarrow & * & \longrightarrow & ft^2(X) \\ & & & & & & \downarrow & & \downarrow & & \downarrow \\ & & & & & & \dots & & \dots & & \dots \\ & & & & & & \downarrow & & \downarrow & & \downarrow \\ & & & & & & Y & \xrightarrow{s_1(f)} & * & \longrightarrow & ft^{m-1}(X) \\ & & & & & & & & \downarrow & & \downarrow \\ & & & & & & & & Y & \longrightarrow & pt \end{array}$$

**Lemma 1.14** Let  $g : Z \rightarrow Y$ ,  $f : Y \rightarrow X$  and  $X \in B_m$ . Then  $s_i(fg) = g^*s_i(f)$ .

**Proof:** It follows immediately from the equations  $s_{fg} = g^*s_f$  and  $ft(fg) = ft(f)g$ .

**Lemma 1.15** [2009.11.10.14] Let  $f : Y \rightarrow ft(X)$  be a morphism,  $Y \in B_n$  and  $X \in B_{m+1}$ . Define  $(f, i)^*(X)$  inductively by the rule:

$$\begin{aligned} (f, 0)^*(X) &= T_n(Y, X) \\ (f, i+1)^*(X) &= S(s_{i+1}(f), (f, i)^*(X)) \end{aligned}$$

Then  $f^*(X) = (f, m)^*(X)$ .

**Proof:** Similar to the proof of Lemma 1.13.

**Lemma 1.16** [2009.11.10.14] Let  $f : Y \rightarrow ft(X)$  be a morphism,  $Y \in B_n$  and  $X \in B_{m+1}$ . Then

$$s_i(q(f, X)) = \begin{cases} \tilde{T}(f^*X, s_i(f)) & \text{if } i \leq m \\ \tilde{T}(f^*X, \delta_X) & \text{if } i = m+1 \end{cases}$$

**Proof:** We have  $s_i(q(f, X)) = s_{ft^{m+1-i}(q(f, X))}$ . For  $i \leq m$  we have  $ft^{m+1-i}(q(f, X)) = ft^{m-i}(f)p_{f^*X}$ . Therefore,

$$s_{ft^{m+1-i}(q(f, X))} = s_{ft^{m-i}(f)p_{f^*X}} = p_{f^*X}^*s_{ft^{m-i}(f)} = \tilde{T}(f^*X, s_i(f))$$

and for  $i = m+1$  we have

$$s_i(q(f, X)) = s_{q(f, X)} = p_{f^*X}^*(\delta_X) = \tilde{T}(f^*X, \delta_X).$$

The lemmas proved above show that a contextual category can be reconstructed from the pair of sets  $B, \tilde{B}$  connected by the maps  $ft, \partial, \delta, T, \tilde{T}, S$  and  $\tilde{S}$ . While this way of encoding contextual categories may be less convenient than their encoding as a pair of sets  $Ob$  and  $Mor$  connected by the maps  $\partial_0, \partial_1, c$  (composition),  $id, ft$  and  $qpb : (f, X) \mapsto q(f, X)$ , this fact has the following important corollary.

**Proposition 1.17** [2009.11.10.prop1] Let  $CC, CC'$  be two contextual categories. Then there is a natural bijection between contextual functors  $F : CC \rightarrow CC'$  and pairs of maps  $F_0 : ob(CC) \rightarrow ob(CC'), F_1 : \tilde{ob}(CC) \rightarrow \tilde{ob}(CC')$  which commute in the obvious sense with  $ft, \partial, \delta, T, \tilde{T}, S$  and  $\tilde{S}$ .

**Remark 1.18** Notes on the properties of the maps introduced above:

1. for  $Y \in B_{\geq n+2}$ ,  $S(\delta_{ft^{n+1}(Y)}, T(ft^{n+1}(Y), Y)) = Y$ .

**Remark 1.19** The maps  $S$  and  $T$  can be defined as  $ft\partial\tilde{S}\delta$  and  $ft\partial\tilde{T}\delta$  respectively.

## 2 $\Pi$ -contextual categories

The notion of a  $\Pi$ -contextual category is equivalent to the notion of a contextual category with products of families of types from [8]. We use the name  $\Pi$ -contextual categories to emphasize the fact that we are dealing here with an additional structure on a contextual category rather than with a property of such a category.

Let us recall first the following definition.

**Definition 2.1** [2009.11.24.def2] *Let  $\mathcal{C}$  be a 1-category. Let  $g : Z \rightarrow Y$ ,  $f : Y \rightarrow X$  be a pair of morphisms such that for any  $U \rightarrow X$  a fiber product  $U \times_X Y$  exists. A pair*

$$(w : W \rightarrow X, h : W \times_X Y \rightarrow Z)$$

*such that  $g \circ h = pr$  is called a universal pair for  $(f, g)$  if for any  $U \rightarrow X$  the map*

$$Hom_X(U, W) \rightarrow Hom_Y(U \times_X Y, Z)$$

*of the form  $u \mapsto h \circ (u \times Id_Y)$  is a bijection.*

If a universal pair exists then it is easily seen to be unique up to a canonical isomorphism. We denote such a pair by  $(\Pi(g, f), e_{g,f} : \Pi(g, f) \times_X Y \rightarrow Z)$ . Note that if  $f' : Y \rightarrow X$  and  $pr : Y' \times_X Y \rightarrow Y$  is the projection then

$$(\Pi(pr, f), pr' \circ e_{pr,f} : \Pi(g, f) \times_X Y \rightarrow Y') = (\underline{Hom}_X(Y, Y'), ev : \underline{Hom}_X(Y, Y') \times_X Y \rightarrow Y')$$

so that relative internal Hom-objects are particular cases of universal pairs.

**Definition 2.2** [2009.11.24.def1] *A  $\Pi$ -contextual category is a contextual category  $CC$  together with additional data of the form*

1. *for each  $Y \in ob(CC)_{\geq 2}$  an object  $\Pi(Y) \in ob(CC)$  such that  $ft(\Pi(Y)) = ft^2(Y)$ ,*
2. *for each  $Y \in ob(CC)_{\geq 2}$  a morphism  $eval : T(ft(Y), \Pi(Y)) = p_{ft(Y)}^*(\Pi(Y)) \rightarrow Y$  over  $ft(Y)$ ,*

*such that*

- (i) *for any  $f : Z \rightarrow ft^2(Y)$  one has  $f^*(\Pi(Y)) = \Pi(f^*(Y))$  and  $f^*(eval_Y) = eval_{f^*(Y)}$ ,*
- (ii)  *$(\Pi(Y), eval_Y)$  is a universal pair for  $(p_Y, p_{ft(Y)})$ .*

Let us now prove that this definition can be re-written in a less compact but purely equational form. As before let us write  $B_n$  for  $Ob(CC)_n$ ,  $\tilde{B}_n$  for  $\widetilde{Ob}(CC)_n$  etc.

The contextual category is completely determined by the sets  $B_n, \tilde{B}_{n+1}$ ,  $n \geq 0$  and maps  $\partial : \tilde{B}_{n+1} \rightarrow B_{n+1}$ ,  $ft : B_{n+1} \rightarrow B_n$ ,  $\delta : B_n \rightarrow \tilde{B}_{n+1}$  and the maps  $T_{n+1}, \tilde{T}_{n+1}, S_{n+1}, \tilde{S}_{n+1}$  considered above.

Suppose now that we are given a  $\Pi$ -contextual structure on our contextual category. This structure defines maps:

1.  $\Pi : B_{n+2} \rightarrow B_{n+1}$ ,  $n \geq 0$ ,

2.  $\lambda : \tilde{B}_{n+2} \rightarrow \tilde{B}_{n+1}, n \geq 0,$
3.  $ev : (\tilde{B}_{n+1})_{\partial} \times_{ft} (B_{n+2})_{\Pi} \times_{\partial} (\tilde{B}_{n+1}) \rightarrow \tilde{B}_{n+1}, n \geq 0$

as follows. The map  $\Pi$  is the map from Definition 2.2. Since  $(\Pi(Y), eval_Y)$  is a universal pair for  $(p_Y, p_{ft(Y)})$  the mapping

$$\phi_Y : \{f \in \tilde{B}_{n+1} \mid \partial(f) = \Pi(Y)\} \rightarrow \{s \in \tilde{B}_{n+2} \mid \partial(s) = Y\}$$

given by the formula

$$\phi_Y(f) = eval_Y \circ \tilde{T}(ft(Y), f)$$

is a bijection. One defines  $\lambda_Y$  as the inverse to this bijection.

The map  $ev$  sends a triple  $(r, Y, f)$  such that  $\partial(r) = ft(Y)$  and  $\partial(f) = \Pi(Y)$  to

$$ev(r, Y, f) = \tilde{S}(r, eval \circ \tilde{T}(ft(Y), f))$$

as partially illustrated by the following diagram:

$$\begin{array}{ccccc} & & Y & \longleftarrow & S(r, Y) \\ & & p_Y \downarrow & & \downarrow \\ p_{ft(Y)}^*(\Pi(Y)) & \longrightarrow & ft(Y) & \xleftarrow[r]{} & ft^2(Y) \\ & & \downarrow & & \downarrow \\ & & \Pi(Y) & \xrightarrow{p_{\Pi(Y)}} & ft^2(Y) \end{array}$$

**Lemma 2.3** [2009.11.30.11] *Let  $n \geq i \geq 0, Y \in B_{n+2}, g : Z \rightarrow ft^{i+2}(Y)$  and  $f \in \tilde{B}(\Pi(Y))$ . Then one has*

$$g^*(\phi_Y(f), i+2) = \phi_{g^*(Y, i+2)}(g^*(f, i+1))$$

**Proof:** Let  $h_1 = q(g, ft(Y), i+1), h_2 = q(g, ft^2(Y), i+2)$ . Then one has

$$\begin{aligned} g^*(\phi_Y(f), i+2) &= h_1^*(\phi_Y(f)) = h_1^*(eval_Y \circ \tilde{T}(ft(Y), f)) = h_1^*(eval_Y) \circ h_1^*(\tilde{T}(ft(Y), f)) \\ &= eval_{h_1^*(Y)} p_{g^*(ft(Y), i+1)}^*(h_2^*(f)) = \phi_{h_1^*(Y)}(h_2^*(f)) = \phi_{g^*(Y, i+2)}(g^*(f, i+1)). \end{aligned}$$

As an immediate corollary of Lemma 2.3 we have:

**Lemma 2.4** [2009.11.30.12] *Let  $n \geq i \geq 0, Y \in B_{n+2}, g : Z \rightarrow ft^{i+2}(Y)$  and  $r \in \tilde{B}(Y)$ . Then one has*

$$g^*(\lambda(r), i+1) = \lambda(g^*(r, i+2)).$$

**Lemma 2.5** [2009.11.30.13] *Let  $n \geq i \geq 0, Y \in B_{n+2}, g : Z \rightarrow ft^{i+2}(Y), r \in \tilde{B}(ft(Y))$  and  $f \in \tilde{B}(\Pi(Y))$ . Then one has*

$$g^*(ev(r, Y, f), i+1) = ev(g^*(r, i+2), g^*(Y, i+2), g^*(f, i+1))$$

**Proof:** Let  $h_1 = q(g, ft(Y), i + 1)$ ,  $h_2 = q(g, ft(Y), i + 2)$ . Then one has:

$$\begin{aligned}
g^*(ev(r, Y, f), i + 1) &= h_2^*(\tilde{S}(r, eval \circ \tilde{T}(ft(Y), f))) = h_2^*(r^*(eval \circ \tilde{T}(ft(Y), f))) = \\
&= (h_2^*(r))^* h_1^*(eval \circ \tilde{T}(ft(Y), f)) = (h_2^*(r))^*(h_1^*(eval) \circ h_1^* p_{ft(Y)}^*(f)) = \\
&= (g^*(r, i + 2))^*(eval \circ p_{g^*(ft(Y), i + 1)}^*(h_2^*(f))) = ev(g^*(r, i + 2), g^*(Y, i + 2), g^*(f, i + 1)).
\end{aligned}$$

**Proposition 2.6 [2009.11.29.prop1]** *Let  $CC = (B_n, \tilde{B}_n, ft, \partial, \delta)$  be a contextual category. Let further  $(\Pi, eval)$  be a  $\Pi$ -contextual structure on  $CC$ . Then the maps  $\Pi$ ,  $\lambda$ ,  $ev$  defined by this structure satisfy the following conditions:*

1. for  $Y \in B_{n+2}$  one has

- (a)  $ft \Pi(Y) = ft^2(Y)$ ,
- (b) for  $n + 1 \geq i \geq 1$ ,  $Z \in B_{n+2-i}$  such that  $ft(Z) = ft^{i+1}(Y)$ ,  $T(Z, \Pi(Y)) = \Pi(T(Z, Y))$ ,
- (c) for  $n + 1 \geq i \geq 1$ ,  $t \in \tilde{B}_{n+1-i}$  such that  $\partial(t) = ft^{i+1}(Y)$ ,  $S(t, \Pi(Y)) = \Pi(S(t, Y))$ ,

2. for  $s \in \tilde{B}_{n+2}$  one has

- (a)  $\partial \lambda(s) = \Pi \partial(s)$ ,
- (b) for  $n + 1 \geq i \geq 1$ ,  $Z \in B_{n+2-i}$  such that  $ft(Z) = ft^{i+1} \partial(s)$ ,  $\tilde{T}(Z, \lambda(s)) = \lambda(\tilde{T}(Z, s))$ ,
- (c) for  $n + 1 \geq i \geq 1$ ,  $t \in \tilde{B}_{n+1-i}$  such that  $\partial(t) = ft^{i+1} \partial(s)$ ,  $\tilde{S}(t, \lambda(s)) = \lambda(\tilde{S}(t, s))$ ,

3. for  $r \in \tilde{B}_{n+1}$ ,  $Y \in B_{n+2}$  and  $f \in \tilde{B}_{n+1}$  such that  $\partial(r) = ft(Y)$  and  $\partial(f) = \Pi(Y)$  one has

- (a)  $\partial(ev(r, Y, f)) = S(r, Y)$ ,
- (b) for  $n + 1 \geq i \geq 1$ ,  $Z \in B_{n+2-i}$  such that  $ft(Z) = ft^{i+1}(Y)$ ,
$$\tilde{T}(Z, ev(r, Y, f)) = ev(\tilde{T}(Z, r), T(Z, Y), \tilde{T}(Z, f)),$$
- (c) for  $n + 1 \geq i \geq 1$ ,  $t \in \tilde{B}_{n+1-i}$  such that  $\partial(t) = ft^{i+1}(Y)$ ,
$$\tilde{S}(t, ev(r, Y, f)) = ev(\tilde{S}(t, r), S(t, Y), \tilde{S}(t, f)),$$

4. for  $r \in \tilde{B}_{n+1}$ ,  $s \in \tilde{B}_{n+2}$  such that  $ft(\partial(s)) = \partial(r)$

$$ev(r, \partial s, \lambda(s)) = \tilde{S}(r, s)$$

( $\beta$ -reduction),

5. for  $Y \in B_{n+2}$ ,  $f \in \tilde{B}_{n+1}$  such that  $\partial(f) = \Pi(Y)$ ,

$$[2009.11.30.oldeq1] \lambda(ev(\delta_{ft(Y)}, T(ft(Y), Y), \tilde{T}(ft(Y), f))) = f \quad (9)$$

( $\eta$ -reduction).

**Proof:** (1a) Follows from Definition 2.2(1). (1b) Follows from Definition 2.2(i) applied to  $f = q(p_Z, ft^2(Y), i - 1)$ . (1c) Follows from Definition 2.2(i) applied to  $f = q(t, ft^2(Y), i - 1)$ .

(2a) Follows from the definition of  $\lambda$ . (2b) Follows from Lemma 2.4 applied to  $p_Z$ . (2c) Follows from Lemma 2.4 applied to  $t$ .

(3a) Follows from the definition of  $ev$ . (3b) Follows from Lemma 2.5 applied to  $p_Z$ . (3c) Follows from Lemma 2.5 applied to  $t$ .

(4) One has

$$ev(r, \partial s, \lambda(s)) = r^*(eval \circ (p_{ft(Y)}^*(\lambda(s)))) = r^*(\phi_Y(s)) = r^*(s) = \tilde{S}(r, s).$$

(5) Let  $T_1 = T(ft(Y), ft(Y))$  and  $T_2 = T(ft(Y), Y)$ . Then

$$\begin{aligned} ev(\delta_{ft(Y)}, T(ft(Y), Y), \tilde{T}(ft(Y), f)) &= \delta_{ft(Y)}^*(eval_{T_2} \circ p_{T_1}^*(p_{ft(Y)}^*(f))) = \\ &= \delta_{ft(Y)}^*(eval_{T_2}) \circ \delta_{ft(Y)}^* p_{T_1}^* p_{ft(Y)}^*(f) = eval_{\delta_{ft(Y)}^*(T_2)} \circ p_{ft(Y)}^*(f) = eval_Y \circ p_{ft(Y)}^*(f) = \phi_Y(f) \end{aligned}$$

which implies (9) by definition of  $\lambda$ .

The converse to Proposition 2.6 holds as well. Let  $CC = (B_n, \tilde{B}_n, ft, \partial, \delta)$  be a contextual category and let

1.  $\Pi : B_{n+2} \rightarrow B_{n+1}, n \geq 0,$
2.  $\lambda : \tilde{B}_{n+2} \rightarrow \tilde{B}_{n+1}, n \geq 0,$
3.  $ev : (\tilde{B}_{n+1})_{\partial} \times_{ft} (B_{n+2})_{\Pi} \times_{\partial} (\tilde{B}_{n+1}) \rightarrow \tilde{B}_{n+1}, n \geq 0$

be maps satisfying the conclusion of Proposition 2.6. For each  $Y \in \tilde{B}_{n+2}$  define a morphism

$$eval_Y : T(ft(Y), \Pi(Y)) \rightarrow Y$$

by the formula

$$eval_Y = q(p_Z, Y) \circ ev(p_Z^*(\delta_{ft(Y)}), T_2(Z, Y), \delta_Z)$$

where  $Z = p_{ft(Y)}^*(\Pi(Y))$ .

**Proposition 2.7 [2009.11.30.prop2]** *Under the assumption made above the morphisms  $eval_Y$  are well defined and  $(\Pi, eval)$  is a  $\Pi$ -contextual structure on  $CC$ .*

**Proof:** Let us show that  $eval_Y$  is well defined. This requires us to check the following conditions:

1.  $ft^2(Y) = ft(\Pi(Y))$ , therefore  $Z$  is defined,
2.  $ft(Z) = ft\partial(\delta_{ft(Y)})$  since  $ft(Z) = ft(Y)$ , therefore  $p_Z^*(\delta_{ft(Y)})$  is defined,
3.  $ft^2(Z) = ft^2(Y)$ , therefore  $T_2(Z, Y)$  is defined,
4.  $\partial(p_Z^*(\delta_{ft(Y)})) = p_Z^* p_{ft(Y)}^*(ft(Y))$ ,  $ft(T_2(Z, Y)) = T_2(Z, ft(Y)) = p_Z^* p_{ft(Y)}^*(ft(Y))$ ,
5.  $\partial(\delta_Z) = p_Z^*(Z) = p_Z^* p_{ft(Y)}^*(\Pi(Y)) = \Pi_{T_2(Z, Y)}$ , therefore  $ev = ev(p_Z^*(\delta_{ft(Y)}), T_2(Z, Y), \delta_Z)$  is defined,

6.

$$\begin{aligned}
\partial(ev) &= (p_Z^*(\delta_{ft(Y)}))^*(T_2(Z, Y)) = (p_Z^*(\delta_{ft(Y)}))^*T(Z, T(ft(Y), Y)) = \\
&= (p_Z^*(\delta_{ft(Y)}))^*(p_Z)^*((p_{ft(Y)})^*(Y, 2), 2) = (p_Z^*(\delta_{ft(Y)}))^*q(p_Z, p_Y^*(ft(Y)))^*(p_{ft(Y)})^*(Y, 2) = \\
&= (p_Z^*(\delta_{ft(Y)}))^*q(p_Z, p_Y^*(ft(Y)))^*q(p_{ft(Y)}, ft(Y))^*(Y) = \\
&= (q(p_{ft(Y)}, ft(Y))q(p_Z, p_Y^*(ft(Y)))p_Z^*(\delta_{ft(Y)}))^*(Y) = p_Z^*(Y)
\end{aligned}$$

and  $q(p_Z, Y) : p_Z^*(Y) \rightarrow Y$ . Therefore  $eval_Y$  is defined and is a morphism from  $Z$  to  $Y$  as required by Definition 2.2(2).

We leave the verification of the conditions (i) of (ii) of Definition 2.2 for the later, more mechanized version of this paper.

### 3 Impredicative $\Pi$ -universe structures.

**Definition 3.1** [2009.12.04.def1] *Let  $CC = (B, \tilde{B}, \dots, \Pi, \dots)$  be  $\Pi$ -contextual category. An impredicative  $\Pi$ -universe structure on  $CC$  is a collection of data of the form*

1. an object  $\tilde{\Omega} \in B_2$ ,
2. for any  $n \geq 0$ ,  $Y \in B_{n+1}$ ,  $g : Y \rightarrow ft(\tilde{\Omega})$  a morphism  $\pi_\Omega(g) : ft(Y) \rightarrow ft(\tilde{\Omega})$ ,

such that the following conditions hold

- (i) for any  $g$  as above  $\pi_\Omega(g)^*(\tilde{\Omega}) = \pi(g^*(\tilde{\Omega}))$ ,
- (ii) for any  $g$  as above and  $h : Z \rightarrow ft(Y)$  one has

$$\pi_\Omega(g) \circ h = \pi_\Omega(g \circ q(h, Y))$$

The sequent presentation of an impredicative  $\Pi$ -structure looks as follows. Given an impredicative  $\Pi$ -universe  $(\tilde{\Omega}, \pi_\Omega)$  denote by  $\Omega$  the object  $ft(\tilde{\Omega})$ . Note that for any  $Y \in B_n$  and  $Z \in B_1$  the mapping which sends  $s \in \tilde{B}_{n+1}(T_n(Y, Z))$  to  $s \circ q(p_{Y,n}, Z)$  defines a bijection  $\phi_Y : \tilde{B}_{n+1}(T_n(Y, Z)) \rightarrow Hom_{CC}(Y, Z)$ .

For any  $n \geq 0$ ,  $Y \in B_{n+1}$ ,  $s \in \tilde{B}_{n+2}(T_{n+1}(Y, \Omega))$  define  $\Pi_\Omega(s) \in \tilde{B}_{n+1}(T_n(ft(Y), \Omega))$  by the formula

$$\Pi_\Omega(s) = \phi_{ft(Y)}^{-1}(\pi_\Omega(\phi_Y(g))).$$

One verifies immediately that the conditions of Definition 3.1 imply that

1.  $S(\Pi_\Omega(s), T_n(ft(Y), \tilde{\Omega})) = \Pi(S(s, T_{n+1}(Y, \tilde{\Omega})))$ ,
2. for  $n+1 \geq i \geq 1$ ,  $Z \in B_{n+2-i}$  such that  $ft(Z) = ft^i(Y)$ ,  $\tilde{T}(Z, \Pi_\Omega(s)) = \Pi_\Omega(\tilde{T}(Z, s))$ ,
3. for  $n+1 \geq i \geq 1$ ,  $t \in \tilde{B}_{n+1-i}$  such that  $\partial(t) = ft^i(Y)$ ,  $\tilde{S}(t, \Pi_\Omega(s)) = \Pi_\Omega(\tilde{S}(t, s))$ .

Conversely one has:

**Proposition 3.2** [2009.12.4.prop1] *Let  $CC = (B, \tilde{B}, \dots, \Pi, \dots)$  be  $\Pi$ -contextual category. Let  $\tilde{\Omega} \in B_2$ ,  $\Omega = ft(\tilde{\Omega})$  and*

$$\Pi_\Omega : (B_{n+1})_{T_{n+1}(-, \Omega)} \times_{\partial} (\tilde{B}_{n+2}) \rightarrow \tilde{B}_{n+1}$$

*be maps satisfying conditions (1), (2), (3) listed above. Then they correspond to a unique impredicative  $\Pi$ -structure on  $CC$ .*



## 4 Predicative $\Pi$ -universe structures.

**Definition 4.1** [2009.12.1def4] *Let  $CC = (B, \tilde{B}, \dots, \Pi, \dots)$  be  $\Pi$ -contextual category. A predicative  $\Pi$ -universe structure on  $CC$  is a collection of data of the form*

1. an object  $\tilde{\Omega} \in B_2$ ,
2. for any  $f : X \rightarrow ft(\tilde{\Omega})$ ,  $g : f^*(\tilde{\Omega}) \rightarrow ft(\tilde{\Omega})$  a morphism  $\Pi_{\Omega}(f, g) : X \rightarrow ft(\tilde{\Omega})$ ,

such that the following conditions hold

- (i) for any  $f, g$  as above  $\Pi_{\Omega}(f, g)^*(\tilde{\Omega}) = \Pi(g^*(\tilde{\Omega}))$ ,
- (ii) for any  $f, g$  as above and  $h : Z \rightarrow X$  one has

$$\Pi_{\Omega}(f, g) \circ h = \Pi_{\Omega}(f \circ h, g \circ q(h, f^*(\tilde{\Omega})))$$

Note that any impredicative universe structure defines a predicative universe structure by the formula  $\Pi(f, g) = \Pi(g)$ .

The sequent representation of a predicative  $\Pi$ -universe structure looks as follows.

**Proposition 4.2** [2009.12.4.prop2] *Let  $CC = (B, \tilde{B}, \dots, \Pi, \dots)$  be  $\Pi$ -contextual category. Any predicative  $\Pi$ -universe structure on  $CC$  is uniquely determined by a collection of data of the form*

1. an object  $\tilde{\Omega} \in B_2$  (we will write  $\Omega$  for  $ft(\tilde{\Omega})$ ),
2. a morphism  $\Pi_{\Omega} : \Pi(T_2(\tilde{\Omega}, ft(\tilde{\Omega}))) \rightarrow ft(\tilde{\Omega})$ ,

which satisfies the following conditions.

## 5 Universes with Martin-Loef identity types.

## 4 Contextual categories defined by universes in 1-categories

**Contextual categories**  $CC(\mathcal{C}, p)$ .

**Definition 0.1** [2009.11.1.def1] *Let  $\mathcal{C}$  be a (level 1) category. A universe on  $\mathcal{C}$  is a morphism  $p : \tilde{U} \rightarrow U$  together with a mapping which assigns to any morphism  $f : X \rightarrow U$  in  $\mathcal{C}$  a pull-back square*

$$\begin{array}{ccc} (X, f) & \xrightarrow{Q(f)} & \tilde{U} \\ p_{(X, f)} \downarrow & & \downarrow p \\ X & \xrightarrow{f} & U \end{array}$$

In what follows we will write  $(X, f_1, \dots, f_n)$  for  $(\dots((X, f_1), f_2) \dots, f_n)$ .

Let  $\mathcal{C}$  be a 1-category,  $p$  a universe on  $\mathcal{C}$  and  $pt$  a final object of  $\mathcal{C}$ . For such a triple define a contextual category  $CC = CC(\mathcal{C}, p)$  as follows. Objects of  $CC$  are sequences of the form  $(F_1, \dots, F_n)$

where  $F_1 \in \text{Hom}_{\mathcal{C}}(pt, U)$  and  $F_{i+1} \in \text{Hom}_{\mathcal{C}}((pt, F_1, \dots, F_i), U)$ . Morphisms from  $(G_1, \dots, G_n)$  to  $(F_1, \dots, F_m)$  are given by

$$\text{Hom}_{CC}((G_1, \dots, G_n), (F_1, \dots, F_m)) = \text{Hom}_{\mathcal{C}}((pt, G_1, \dots, G_n), (pt, F_1, \dots, F_m))$$

and units and compositions are defined as units and compositions in  $\mathcal{C}$  such that the mapping  $(F_1, \dots, F_n) \rightarrow (pt, F_1, \dots, F_n)$  is a full embedding of the underlying category of  $CC$  to  $\mathcal{C}$ . The image of this embedding consists of objects  $X$  for which the canonical morphism  $X \rightarrow pt$  is a composition of morphisms which are (canonical) pull-backs of  $p$ . We will denote this embedding by  $int$ .

The final object of  $CC$  is the empty sequence  $()$ . The map  $ft$  sends  $(F_1, \dots, F_n)$  to  $(F_1, \dots, F_{n-1})$ . The canonical morphism  $p_{(F_1, \dots, F_n)}$  is the projection

$$p_{((pt, F_1, \dots, F_{n-1}), F_n)} : ((pt, F_1, \dots, F_{n-1}), F_n) \rightarrow (pt, F_1, \dots, F_{n-1})$$

For an object  $(F_1, \dots, F_{m+1})$  and a morphism  $f : (G_1, \dots, G_n) \rightarrow (F_1, \dots, F_m)$  the canonical pull-back square is of the form

$$\begin{array}{ccc} (G_1, \dots, G_n, F_{m+1}f) & \xrightarrow{q(f)} & (F_1, \dots, F_{m+1}) \\ \text{[2009.10.26.eq3]} \quad p_G \downarrow & & \downarrow p_F \\ (G_1, \dots, G_n) & \xrightarrow{f} & (F_1, \dots, F_m) \end{array} \quad (10)$$

where  $int(p_F) = p((pt, F_1, \dots, F_{n-1}), F_n)$ ,  $int(p_G) = p((pt, G_1, \dots, G_{n-1}), F_{m+1} \circ f)$  and  $q(f)$  is the morphism such that  $p_F q(f) = f p_G$  and  $Q(F_{m+1})int(q(f)) = Q(F_{m+1}f)$ . The unity and composition axioms for the canonical squares follow immediately from the unity and associativity axioms for compositions of morphisms in  $\mathcal{C}$ .

Let  $(\mathcal{C}, p, pt)$  and  $(\mathcal{C}', p', pt')$  be two sets of data as above. Let  $\Phi : \mathcal{C} \rightarrow \mathcal{C}'$  be a functor which takes distinguished squares in  $\mathcal{C}$  to pull-back squares in  $\mathcal{C}'$  and such that  $\Phi(pt) \rightarrow pt'$  is an isomorphism, let further  $\phi : \Phi(U) \rightarrow U'$ ,  $\tilde{\phi} : \Phi(\tilde{U}) \rightarrow \tilde{U}'$  be two morphisms such that

$$\begin{array}{ccc} \Phi(\tilde{U}) & \xrightarrow{\tilde{\phi}} & \tilde{U}' \\ \Phi(p) \downarrow & & \downarrow p' \\ \Phi(U) & \xrightarrow{\phi} & U' \end{array}$$

is a pull-back square. Denote by  $\psi$  the isomorphism  $\psi : pt' \rightarrow \Phi(pt)$ .

Define a functor  $H = H(\Phi, \phi, \tilde{\phi})$  from  $CC(\mathcal{C}, p)$  to  $CC(\mathcal{C}', p')$  as follows. We define by induction on  $n$  objects  $H(F_1, \dots, F_n) \in CC(\mathcal{C}', p')$  and isomorphisms

$$\psi_{(F_1, \dots, F_n)} : int'(H(F_1, \dots, F_n)) \rightarrow \Phi(int(F_1, \dots, F_n))$$

where  $int$  and  $int'$  are the canonical functors  $CC(\mathcal{C}, p) \rightarrow \mathcal{C}$  and  $CC(\mathcal{C}', p') \rightarrow \mathcal{C}'$  respectively.

For  $n = 0$  we set  $H(pt) = pt$  and  $\psi_{()} = \psi$ . For  $n > 0$  let

$$(F'_1, \dots, F'_{n-1}) = H(F_1, \dots, F_{n-1})$$

and let  $F_n : int(F_1, \dots, F_{n-1}) \rightarrow U$ . Define  $F'_n$  as the composition

$$\text{[2009.10.26.eq5]} F'_n : int'(F'_1, \dots, F'_{n-1}) \xrightarrow{\psi_{(F_1, \dots, F_{n-1})}} \Phi(int(F_1, \dots, F_{n-1})) \xrightarrow{\Phi(F_n)} \Phi(U) \xrightarrow{\phi} U' \quad (11)$$

and let  $H(F_1, \dots, F_n) = (F'_1, \dots, F'_{n-1}, F'_n)$ . Then

$$\text{int}'(H(F_1, \dots, F_n)) = (\text{int}'(H(F_1, \dots, F_n)), F'_n)$$

To define

$$\psi_{(F_1, \dots, F_n)} : \text{int}'(H(F_1, \dots, F_n)) \rightarrow \Phi(\text{int}(F_1, \dots, F_n))$$

observe that by our conditions on  $\phi, \tilde{\phi}$  and  $\Phi$  the squares of the diagram

$$\begin{array}{ccccc} \Phi(\text{int}(F_1, \dots, F_n)) & \xrightarrow{\Phi(Q(F_n))} & \Phi(\tilde{U}) & \longrightarrow & \tilde{U}' \\ \downarrow & & \downarrow & & \downarrow \\ \Phi(\text{int}(F_1, \dots, F_{n-1})) & \xrightarrow{\Phi(F_n)} & \Phi(U) & \xrightarrow{\phi} & U' \end{array}$$

are pull-back. Therefore there is a unique morphism  $\psi_{(F_1, \dots, F_n)}$  such that the diagram

$$\begin{array}{ccccccc} \text{int}'(H(F_1, \dots, F_n)) & \xrightarrow{\psi_{(F_1, \dots, F_n)}} & \Phi(\text{int}(F_1, \dots, F_n)) & \xrightarrow{\tilde{\phi}\Phi(Q(F_n))} & \tilde{U}' & & \\ \text{[2009.10.26.eq2]} \quad \downarrow & & \downarrow & & \downarrow & & (12) \\ \text{int}'(H(F_1, \dots, F_{n-1})) & \xrightarrow{\psi_{(F_1, \dots, F_{n-1})}} & \Phi(\text{int}(F_1, \dots, F_{n-1})) & \xrightarrow{\phi\Phi(F_n)} & U' & & \end{array}$$

commutes and

$$\text{[2009.10.26.eq7]} \tilde{\phi}\Phi(Q(F_n))\psi_{(F_1, \dots, F_n)} = Q(\phi\Phi(F_n)\psi_{(F_1, \dots, F_{n-1})}) \quad (13)$$

and this morphism is an isomorphism.

To define  $H$  on morphism we use the fact that morphisms  $\psi_{(F_1, \dots, F_n)}$  are isomorphisms and for  $f : (F_1, \dots, F_n) \rightarrow (G_1, \dots, G_m)$  we set

$$\text{[2009.10.26.eq6]} H(f) = \psi_{(G_1, \dots, G_m)}^{-1} \Phi(f) \psi_{(F_1, \dots, F_n)} \quad (14)$$

The fact that this construction gives a functor i.e. satisfies the unity and composition axioms is straightforward.

It remains to verify that this functor respects the contextual structure. It is clear that it respects the length function and the  $ft$  maps. The fact that it takes the canonical projections to canonical projections is equivalent to the commutativity of the left hand side square in (12).

Consider a canonical square of the form (10). Its image is a square of the form

$$\begin{array}{ccc} (G'_1, \dots, G'_n, G'_{n+1}) & \xrightarrow{H(q(f))} & (F'_1, \dots, F'_{m+1}) \\ \text{[2009.10.26.eq4]} \quad H(p_G) \downarrow & & \downarrow H(p_F) \\ (G'_1, \dots, G'_n) & \xrightarrow{H(f)} & (F'_1, \dots, F'_m) \end{array} \quad (15)$$

We already know that the vertical arrows are canonical projections. Therefore, in order to prove that (15) is a canonical square in  $CC(\mathcal{C}', p')$  we have to show that  $G'_{n+1} = F'_{m+1} \text{int}(H(f))$  and

$$\text{[2009.10.26.eq8]} Q(F'_{m+1} \text{int}(H(q(f)))) = Q(F'_{m+1} \text{int}(H(f))) \quad (16)$$

By (11) we have

$$\begin{aligned} G'_{n+1} &= \phi\Phi(F_{m+1}f)\psi_{(G_1,\dots,G_n)} \\ F'_{m+1} &= \phi\Phi(F_{m+1})\psi_{(F_1,\dots,F_m)} \end{aligned}$$

and by (14)

$$\begin{aligned} \text{int}(H(f)) &= \psi_{(F_1,\dots,F_m)}^{-1}\Phi(f)\psi_{(G_1,\dots,G_n)} \\ \text{int}(H(q(f))) &= \psi_{(F_1,\dots,F_{m+1})}^{-1}\Phi(q(f))\psi_{(G_1,\dots,G_n,F_{m+1}f)} \end{aligned}$$

Therefore the relation  $G'_{n+1} = F'_{m+1}\text{int}(H(f))$  follows immediately and the relation (16) follows by application of (13).

Our construction of  $H$  shows that if  $\Phi$  is a full embedding and  $\phi$  and  $\tilde{\phi}$  are isomorphisms then  $H$  is an isomorphism of contextual categories. This implies in particular that considered up to a canonical isomorphism  $CC(\mathcal{C}, p)$  depends only on the equivalence class of the pair  $(\mathcal{C}, p)$  i.e. that our construction maps level 1 pairs  $(\mathcal{C}, p)$  to contextual categories which are at the set level.

Let us describe now an inverse construction which shows that any contextual category is isomorphic to a contextual category of the form  $CC(\mathcal{C}, p)$ . Let  $CC$  be a contextual category. Denote by  $PreShv(CC)$  the 1-category of contravariant functors from the category underlying  $CC$  to  $Sets$ .

Let  $Ty$  be the functor which takes an object  $\Gamma \in CC$  to the set

$$Ty(\Gamma) = \{\Gamma' \in CC \mid ft(\Gamma') = \Gamma\}$$

and a morphism  $f : \Delta \rightarrow \Gamma$  to the map  $\Gamma' \mapsto f^*\Gamma'$ . It is a functor due to the composition and unity axioms for  $f^*$ . Let  $Tm$  be the functor which takes an object  $\Gamma$  to the set

$$Tm(\Gamma) = \{s \in \widetilde{CC} \mid ft\partial(s) = \Gamma\}$$

and a morphism  $f : \Delta \rightarrow \Gamma$  to the map  $s \mapsto f^*(s)$ . Let further  $p : Tm \rightarrow Ty$  be the morphism which takes  $s$  to  $\partial(s)$ . It is well defined as a morphisms of families of sets and forms a morphism of presheaves since  $\partial(f^*(s)) = f^*(\partial(s))$ .

**Proposition 0.2** [2009.12.28.prop1] *For any contextual category  $CC$  there is a natural isomorphism*

$$CC = CC(PreShv(CC), p)$$

**Proof:** We start with the key lemma. (In what follows we identify objects of  $CC$  with the corresponding representable presheaves and, for a presheaf  $F$  and an object  $\Gamma$ , we identify morphisms  $\Gamma \rightarrow F$  in  $PreShv(CC)$  with  $F(\Gamma)$ ).

**Lemma 0.3** [2009.12.28.11] *Let  $\Gamma' \in ob(CC)$  and let  $\Gamma = ft(\Gamma')$ . Then the square*

$$\begin{array}{ccc} \Gamma' & \xrightarrow{\delta_{\Gamma'}} & Tm \\ p_{\Gamma'} \downarrow & & \downarrow p \\ \Gamma & \xrightarrow{\Gamma'} & Ty \end{array}$$

*is a pull-back square.*

**Proof:** We have to show that for any  $\Delta \in CC$  the obvious map

$$[2009.12.28.eq2] Hom(\Delta, \Gamma') \rightarrow Hom(\Delta, \Gamma) \times_{Ty(\Delta)} Tm(\Delta) \quad (17)$$

is a bijection. Let  $f_1, f_2 : \Delta \rightarrow \Gamma'$  be two morphisms such that their images under (17) coincide i.e. such that  $p_{\Gamma'} f_1 = p_{\Gamma'} f_2$  and  $f_1^*(\delta_{\Gamma'}) = f_2^*(\delta_{\Gamma'})$ . These two conditions are equivalent to saying, in the notation introduced above, that  $ft(f_1) = ft(f_2)$  and  $s_{f_1} = s_{f_2}$ . This implies that  $f_1 = f_2$  i.e. that (17) is injective. Let  $f : \Delta \rightarrow \Gamma$  be a morphism and  $s \in Tm(\Delta)$  a section such that  $ft(\partial(s)) = f^*(\Gamma')$ . Then the composition  $q(f, \Gamma')s$  is a morphism  $f' : \Delta \rightarrow \Gamma'$  such that  $p_{\Gamma'} f' = f$ . We also have

$$(f')^*(\delta_{\Gamma'}) = s^*q(f, \Gamma')^*(\delta_{\Gamma'}) = s$$

which proves that (17) is surjective.

To construct the required isomorphism we now choose a universe structure on  $p$  such that the pull-back squares associated with morphisms from representable objects are squares (17). The isomorphism is now obvious.

**Definition 0.4** [2009.12.27.def1] *Let  $CC$  be a contextual category. A closed model of  $CC$  is a collection of data of the following form:*

1. A 1-category  $\mathcal{C}$ ,
2. a universe  $p : \tilde{U} \rightarrow U$  in  $\mathcal{C}$  and a final object  $pt$  of  $\mathcal{C}$ ,
3. a contextual functor  $CC \rightarrow CC(\mathcal{C}, p)$ .

The following proposition shows that any "model" of a contextual category can be viewed as a closed model.

**Proposition 0.5** [2009.12.27.prop1] *Let  $\mathcal{C}$  be a 1-category,  $CC$  be a contextual category and  $M : CC \rightarrow \mathcal{C}$  a functor such that  $M(pt_{CC})$  is a final object of  $\mathcal{C}$  and  $M$  maps distinguished squares of  $CC$  to pull-back squares of  $\mathcal{C}$ . Then there exists a universe  $p_M : \tilde{U}_M \rightarrow U_M$  in  $PreShv(\mathcal{C})$  and a contextual functor  $M' : CC \rightarrow CC(PreShv(\mathcal{C}), p_M)$  such that the square*

$$\begin{array}{ccc} CC & \xrightarrow{M} & \mathcal{C} \\ \downarrow M' & & \downarrow \\ CC(PreShv(\mathcal{C}), p_M) & \xrightarrow{int} & PreShv(\mathcal{C}) \end{array}$$

where the right hand side vertical arrow is the Yoneda embedding, commutes up to a canonical isomorphism.

**Proof:** We will write  $p : \tilde{U} \rightarrow U$  instead of  $p_M : \tilde{U}_M \rightarrow U_M$ . Set

$$\tilde{U} = \coprod_{\Gamma \in CC_{>0}} M(\Gamma) \quad U = \coprod_{\Gamma \in CC_{>0}} M(ft(\Gamma)) \quad p = \coprod_{\Gamma \in CC_{>0}} M(p_\Gamma)$$

Let  $pt$  be final object of  $PreShv(\mathcal{C})$ . Set  $M'(pt_{CC}) = pt$ .

....

**$\Pi$ -universes in lcc categories.** Recall that a (level 1) category  $\mathcal{C}$  is called a lcc (locally Cartesian closed) category if it has fiber products and all the over-categories  $\mathcal{C}/X$  have internal Hom-objects.

**Definition 0.6** [2009.10.27.def1] Let  $\mathcal{C}$  be an lcc category and let  $p_i : \tilde{U}_i \rightarrow U_i$ ,  $i = 1, 2, 3$  be three morphisms in  $\mathcal{C}$ . A  $\Pi$ -structure on  $(p_1, p_2, p_3)$  is a Cartesian square of the form

$$\begin{array}{ccc}
 \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times \tilde{U}_2) & \xrightarrow{\tilde{P}} & \tilde{U}_3 \\
 \text{[Pisq1]} \quad p'_2 \downarrow & & \downarrow p_3 \\
 \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) & \xrightarrow{P} & U_3
 \end{array} \tag{18}$$

such that  $p'_2$  is the natural morphism defined by  $p_2$ . A  $\Pi$ -structure on  $p : \tilde{U} \rightarrow U$  is a  $\Pi$ -structure on  $(p, p, p)$ .

**Remark 0.7** A  $\Pi$ -structure on  $(p_1, p_2, p_3)$  corresponds to the rule

$$\frac{\Gamma, X : U_1, f : X \rightarrow U_2 \vdash}{\Gamma, X : U_1, f : X \rightarrow U_2 \vdash \prod x : X. ev(f, x) : U_3}$$

Let  $\mathcal{C}$  be as above,  $p : \tilde{U} \rightarrow U$  and let  $(\tilde{P}, P)$  be a  $\Pi$ -structure on  $(p, p, p)$ . Let us construct a structure of  $\Pi$ -contextual category on  $CC = CC(\mathcal{C}, p)$ .

We start by recalling some level 1 constructions in  $\mathcal{C}$ .

**Lemma 0.8** [2009.11.24.15] Consider a pair of pull back squares

$$\begin{array}{ccc}
 I_2 & \xrightarrow{\tilde{F}_1} & \tilde{U}_1 & & I_3 & \xrightarrow{\tilde{F}_2} & \tilde{U}_2 \\
 \text{[2009.11.24.eq3]} \downarrow & & \downarrow p_1 & & q_2 \downarrow & & \downarrow p_2 \\
 I_1 & \xrightarrow{F_1} & U_1 & & I_2 & \xrightarrow{F_2} & U_2
 \end{array} \tag{19}$$

Then there exists a unique morphism  $f_{F_1, F_2} : I_1 \rightarrow \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2)$  such that its composition with the natural morphism to  $U_1$  is  $F_1$  and the composition of its adjoint

$$ev \circ (f_{F_1, F_2} \times_{U_1} \tilde{U}_1) : I_2 = I_1 \times_{U_1} \tilde{U}_1 \rightarrow U_1 \times U_2$$

with the projection to  $U_2$  is  $F_2$ .

**Proof:** Follows immediately from the definition of internal Hom-objects.

**Lemma 0.9** [2009.11.24.13] In the notation of Lemma 0.8 let

$$\begin{array}{ccc}
 J_2 & \xrightarrow{\phi_2} & I_2 & & J_3 & \xrightarrow{\phi_3} & I_3 \\
 \downarrow & & \downarrow q_1 & & \downarrow & & \downarrow q_2 \\
 J_1 & \xrightarrow{\phi_1} & I_1 & & J_2 & \xrightarrow{\phi_2} & I_2
 \end{array}$$

be two pull-back squares. Then  $f_{F_1 \phi_1, F_2 \phi_2} = f_{F_1, F_2} \circ \phi_1$ .

**Proof:** Straightforward.

Let  $p_1 : \tilde{U}_1 \rightarrow U_1$ ,  $p_2 : \tilde{U}_2 \rightarrow U_2$  be a pair of morphisms in an lcc  $\mathcal{C}$ . Consider a pull-back square of the form

$$\begin{array}{ccc}
 & Fam_2(p_1, p_2) & \longrightarrow \tilde{U}_2 \\
 \text{[2009.11.24.eq4]} & \downarrow p_{12} & \downarrow p_2 \\
 & \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) \times_{U_1} \tilde{U}_1 & \xrightarrow{pr \circ ev} U_2
 \end{array} \tag{20}$$

where

$$ev : \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) \times_{U_1} \tilde{U}_1 \rightarrow U_1 \times U_2$$

is the canonical morphism.

Then for any two pull-back squares as in Lemma 0.8, the morphism  $f_{F_1, F_2}$  defines factorizations of the pull-back squares (19) of the form

$$\begin{array}{ccccc}
 I_2 & \xrightarrow{f_{F_1, F_2} \times_{U_1} \tilde{U}_1} & \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) \times_{U_1} \tilde{U}_1 & \xrightarrow{pr} & \tilde{U}_1 \\
 q_1 \downarrow & & \downarrow & & \downarrow p_1 \\
 I_1 & \xrightarrow{f_{F_1, F_2}} & \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) & \longrightarrow & U_1
 \end{array}$$

and

$$\begin{array}{ccccc}
 I_3 & \longrightarrow & Fam_2(p_1, p_2) & \longrightarrow & \tilde{U}_2 \\
 q_2 \downarrow & & \downarrow p_{12} & & \downarrow p_2 \\
 I_2 & \xrightarrow{f_{F_1, F_2} \times_{U_1} \tilde{U}_1} & \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) \times_{U_1} \tilde{U}_1 & \xrightarrow{pr \circ ev} & U_2
 \end{array}$$

respectively and joining the left hand side squares of these diagrams we get a diagram with pull-back squares of the form

$$\begin{array}{ccccc}
 I_3 & \longrightarrow & Fam_2(p_1, p_2) & & \\
 q_2 \downarrow & & \downarrow p_{12} & & \\
 I_2 & \xrightarrow{f_{F_1, F_2} \times_{U_1} \tilde{U}_1} & \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) \times_{U_1} \tilde{U}_1 & & \\
 q_1 \downarrow & & \downarrow pr & & \\
 I_1 & \xrightarrow{f_{F_1, F_2}} & \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) & & 
 \end{array}$$

Let

$$g : \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times \tilde{U}_2) \times_{U_1} \tilde{U}_1 \rightarrow Fam_2(p_1, p_2)$$

be the morphism over  $\underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) \times_{U_1} \tilde{U}_1$  whose composition with the projection  $Fam_2(p_1, p_2) \rightarrow \tilde{U}_2$  equals  $pr \circ \tilde{ev}$  where

$$\tilde{ev} : \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times \tilde{U}_2) \times_{U_1} \tilde{U}_1 \rightarrow U_1 \times \tilde{U}_2$$

is the canonical morphism.

**Lemma 0.10** [2009.11.24.12] *The pair*

$$(\underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times \tilde{U}_2) \rightarrow \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2), g)$$

is universal for  $(p_{12}, pr)$ .

**Proof:** For a given  $w : Z \rightarrow \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2)$ , a morphism  $Z \rightarrow \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times \tilde{U}_2)$  over  $\underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2)$  is the same as a morphism  $Z \times_{U_1} \tilde{U}_1 \rightarrow \tilde{U}_2$  such that the adjoint of its composition with  $p_2 : \tilde{U}_2 \rightarrow U_2$  is  $w$ .

A morphism from  $Z$  to the universal pair for  $p_{12}$  over  $\underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2)$  is a morphism  $Z \times_{U_1} \tilde{U}_1 \rightarrow \tilde{U}_2$  whose composition with  $p_2$  is  $(pr \circ ev) \circ (w \times_{U_1} Id_{\tilde{U}_1})$  which coincides with the condition that the composition of its adjoint with  $p_2$  is  $w$ . This can be also seen from the diagram

$$\begin{array}{ccc} & Fam_2(p_1, p_2) & \longrightarrow \tilde{U}_2 \\ & p_{12} \downarrow & \downarrow p_2 \\ \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times \tilde{U}_2) \times_{U_1} \tilde{U}_1 & \longrightarrow \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) \times_{U_1} \tilde{U}_1 & \xrightarrow{pr \circ ev} U_2 \\ \downarrow & \downarrow pr & \\ \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times \tilde{U}_2) & \longrightarrow \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) & \end{array}$$

**Lemma 0.11** [2009.11.24.14] *For two pull back squares as in (19), consider a pull-back square of the form*

$$\begin{array}{ccc} R(F_1, F_2) & \longrightarrow & \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times \tilde{U}_2) \\ \downarrow & & \downarrow \\ I_1 & \xrightarrow{f_{F_1, F_2}} & \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) \end{array}$$

and the morphism

$$g_{F_1, F_2} : R(F_1, F_2) \times_{I_1} I_2 \rightarrow I_3$$

whose composition with the morphism  $I_3 \rightarrow \tilde{U}_2$  coincides with the composition

$$R(F_1, F_2) \times_{I_1} I_2 = R(F_1, F_2) \times_{U_1} \tilde{U}_1 \rightarrow \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times \tilde{U}_2) \times_{U_1} \tilde{U}_1 \xrightarrow{pr \circ ev} \tilde{U}_2$$

Then  $(R(F_1, F_2), g_{F_1, F_2})$  is a universal pair for  $(q_1, q_2)$ .

**Proof:** It follows from Lemma 0.10 and the fact that in a lcc a pull-back of a universal pair is a universal pair.

Let us now construct a  $\Pi$ -contextual structure on  $CC = CC(\mathcal{C}, p)$ . Let  $n \geq 2$  and  $(F_1, \dots, F_n) \in CC$ . Denote  $(pt, F_1, \dots, F_{n-2})$  by  $I$ . Then we have two morphisms  $F_{n-1} : I \rightarrow U$  and  $F_n : (I, F_{n-1}) \rightarrow U$ .

Applying Lemma 0.8 to the corresponding pull-back squares we get a morphism

$$f_{F_{n-1}, F_n} : I \rightarrow \underline{Hom}_U(\tilde{U}, U \times U)$$



Set  $\Pi(F_1, \dots, F_n) = (I, P \circ f_{F_{n-1}, F_n}) = (F_1, \dots, F_{n-2}, P \circ f_{F_{n-1}, F_n})$ . Since the square (18) is a pull-back square there is a unique morphism  $\Pi(F_1, \dots, F_n) \rightarrow \underline{Hom}_U(\tilde{U}, U \times \tilde{U})$  such that the diagram

$$\begin{array}{ccccc} \Pi(F_1, \dots, F_n) & \longrightarrow & \underline{Hom}_U(\tilde{U}, U \times \tilde{U}) & \xrightarrow{\tilde{P}} & \tilde{U} \\ \downarrow & & \downarrow & & \downarrow \\ I & \xrightarrow{f_{F_{n-1}, F_n}} & \underline{Hom}_U(\tilde{U}, U \times U) & \xrightarrow{P} & U \end{array}$$

commutes and the composition of the two upper arrows is  $Q(f_{F_{n-1}, F_n})$ . The left hand side square in this diagram is automatically a pull-back square. Applying to this square Lemma 0.11 we obtain a morphism

$$eval_{(F_1, \dots, F_n)} : (I, F_{n-1}, (P \circ f_{F_{n-1}, F_n}) \circ pr) \rightarrow (I, F_{n-1}, F_n)$$

over  $(I, F_{n-1})$  (where  $pr : (I, F_{n-1}) \rightarrow I$  is the projection).

The fact that this construction satisfies the first condition of Definition 2.2 follows from Lemma 0.9. The fact that it satisfies the second condition of this definition follows from Lemma 0.11.

### $\Sigma$ -universes in lcc categories.

**Definition 0.12** [2009.10.27.def2] *Let  $\mathcal{C}$  be an lcc category and  $p_i : \tilde{U}_i \rightarrow U_i$ ,  $i = 1, 2, 3$  be three morphisms in  $\mathcal{C}$ . A  $\Sigma$ -structure on  $(p_1, p_2, p_3)$  is a diagram of the form*

$$\begin{array}{ccccc} \tilde{U}_2 & \longleftarrow & Fam_{\bullet}(U_1, U_2) & \longrightarrow & \tilde{U}_3 \\ p_2 \downarrow & & \downarrow & & \downarrow p_3 \\ U_2 & \xleftarrow{pr_{U_2} eval} & \tilde{U}_1 \times_{U_1} \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) & & \downarrow p_3 \\ & & \downarrow pr & & \\ & & \underline{Hom}_{U_1}(\tilde{U}_1, U_1 \times U_2) & \xrightarrow{\Sigma} & U_3 \end{array}$$

such that  $p'_2$  is the natural morphism defined by  $p_2$ ,  $eval$  is the canonical evaluation morphism and both the square and the vertical rectangle are Cartesian. A  $\Sigma$ -structure on  $p : \tilde{U} \rightarrow U$  is a  $\Sigma$ -structure on  $(p, p, p)$ .

A  $\Sigma$ -structure on  $(p_1, p_2, p_3)$  corresponds to the rule

$$\frac{\Gamma, X : U_1, f : X \rightarrow U_2 \vdash}{\Gamma, X : U_1, f : X \rightarrow U_2 \vdash \sum x : X. ev(f, x) : U_3}$$

**Definition 0.13** [2009.11.2.def1] *Let  $\mathcal{C}$  be an lcc category and  $p : \tilde{U} \rightarrow U$  be a morphism. A Prop-structure on  $p$  is a collection of data of the following form:*

1. two pull-back squares

$$\begin{array}{ccc} P & \longrightarrow & \tilde{U} \\ \downarrow & & \downarrow p \\ pt & \longrightarrow & U \end{array} \quad \begin{array}{ccc} \tilde{P} & \longrightarrow & \tilde{U} \\ p_0 \downarrow & & \downarrow p \\ P & \longrightarrow & U \end{array}$$

2. a  $\Pi$ -structure on  $(p, p_0, p_0)$ .

A *Prop*-structure on  $p$  corresponds to the rules:

$$\frac{}{x : P \vdash} \quad \frac{}{x : P, y : x \vdash} \quad \frac{\Gamma, f : X \rightarrow P \vdash}{\Gamma, f : X \rightarrow P \vdash \prod x : X. \text{ev}(f, x) : P}$$

## 5 Universes in the category of simplicial sets

### 1 Well-ordered morphisms of simplicial sets

Let  $X, Y$  be simplicial sets. A well-ordered morphism  $p : Y \rightarrow X$  is a pair which consists of a morphism  $Y \rightarrow X$  (also denoted by  $p$ ) and of a function which assigns to each  $n \geq 0$  and each  $\sigma \in X_n$  a well-ordering on  $p^{-1}(\sigma) \subset Y_n$ .

Note that there is a unique well-ordering on any isomorphism but, for example, the morphism  $pt \amalg pt \rightarrow pt$  has uncountably many well-orderings since  $pt_n = pt$  for all  $n$  and we require no compatibility conditions for well orderings of the fibers over different simplexes of the target.

If  $p : Y \rightarrow X, p' : Y' \rightarrow X$  are two well-ordered morphisms then we define a standard isomorphism from  $Y$  to  $Y'$  over  $X$  as an isomorphism over  $X$  such that for each  $n \geq 0$  and each  $\sigma \in X_n$  the bijection  $p^{-1}(\sigma) \rightarrow (p')^{-1}(\sigma)$  is order-preserving. Since there is at most one order-preserving bijection between two well-ordered sets, there is at most one standard isomorphism between two well-ordered simplicial sets over  $X$ .

Let  $WOM(X, < \alpha)$  be the set of standard isomorphism classes of well-ordered simplicial sets  $p : Y \rightarrow X$  over  $X$  such that for each  $n \geq 0$  and each  $\sigma \in X_n$  the fiber  $p^{-1}(\sigma)$  has cardinality  $< \alpha$ . For any  $f : X' \rightarrow X$  the pull-back  $p' : Y' = X' \times_X Y \rightarrow X'$  of a well-ordered morphism has a natural well-ordering which makes  $WOM(X, < \alpha)$  into a functor from  $\Delta^{op}Sets$  to  $Sets$ .

Consider  $WOM(\Delta^n, < \alpha)$ . These sets depend on  $\Delta^n$  functorially and therefore define a simplicial set  $WOM(< \alpha)$ . Let  $\widetilde{WOM}(\Delta^n, < \alpha)$  be the set of pairs  $p : Y \rightarrow \Delta^n, s \in Y_n$  where  $p \in WOM(\Delta^n, < \alpha)$  and  $s \in p^{-1}(\sigma_n)$  where  $\sigma_n$  is the non-degenerate  $n$ -simplex of  $\Delta^n$ . These sets also depend on  $\Delta^n$  functorially and define a simplicial set  $\widetilde{WOM}(< \alpha)$ .

Since  $p^{-1}(\sigma)$  carries a well-ordering the natural projection  $\widetilde{WOM}(< \alpha) \rightarrow WOM(< \alpha)$  carries a natural well-ordering.

**Proposition 1.1** [2009.12.10.pr1] *The morphism  $\widetilde{WOM}(< \alpha) \rightarrow WOM(< \alpha)$  is a universal well-ordered morphism with fibers of cardinality  $< \alpha$ . In particular,  $WOM(< \alpha)$  represents the functor  $WOM(-, < \alpha)$ .*

**Proof:** Straightforward.

Note that  $WOM(< \alpha)$  is obviously a contractible Kan simplicial set for any  $\alpha > 0$ .

Let us consider now the sub-object  $WOF(< \alpha)$  of  $WOM(< \alpha)$  which classifies well-ordered Kan fibrations whose fibers have cardinality  $< \alpha$  and let  $\widetilde{WOF}(< \alpha) \rightarrow WOF(< \alpha)$  be the corresponding universal fibration.

The idea of the proof of the following result and in general the idea to use minimal fibrations is due to A. Bousfield and reached me through Peter May and Rick Jardine.

**Proposition 1.2** [2009.12.8.prop1] *Let  $\alpha$  be an infinite cardinal. Then the simplicial set  $WOF(<\alpha)$  is Kan.*

**Proof:** One can easily see that it is sufficient to show that for any horn inclusion  $\Lambda_k^n \rightarrow \Delta^n$  and any Kan fibration  $p : B \rightarrow \Lambda_k^n$  there exists a pull-back square of the form

$$\begin{array}{ccc} B & \longrightarrow & C \\ \text{[2009.12.8.eq1]} p \downarrow & & \downarrow q \\ \Lambda_k^n & \longrightarrow & \Delta_k^n \end{array} \quad (21)$$

where  $q$  is a Kan fibration whose fibers have cardinality  $< \alpha$ . By Quillen's Lemma ([7]) there is a factorization of  $p$  of the form  $B \xrightarrow{p'} B' \xrightarrow{p''} \Lambda_k^n$  where  $p'$  is a trivial fibration and  $p''$  is a minimal fibration. Since trivial fibrations are surjective, both  $p'$  and  $p''$  have fibers of cardinality  $< \alpha$ . By [5, Cor. 11.7, p.45] the fibration  $p''$  is isomorphic to a fibration  $F \times \Lambda_k^n \rightarrow \Lambda_k^n$  where  $F$  is a Kan simplicial set. Together with Lemma 1.4 it shows that there is a diagram of the form

$$\begin{array}{ccc} B & \longrightarrow & C \\ p' \downarrow & & \downarrow q' \\ F \times \Lambda_k^n & \longrightarrow & F \times \Delta^n \\ \downarrow & & \downarrow \\ \Lambda_k^n & \longrightarrow & \Delta^n \end{array}$$

with pull-back squares such that  $q'$  is a trivial fibration with fibers of cardinality  $< \alpha$ . The external square of this diagram has the required form (21).

**Lemma 1.3** [2009.12.11.11] *Let  $\alpha$  be an infinite cardinal. Let  $p : Y \rightarrow X$  be a map of simplicial sets such that for each  $n \geq 0$ ,  $x \in X_n$  one has  $|p^{-1}(x) \cap Y_n^{nd}| < \alpha$  where  $Y_n^{nd}$  is the subset of non-degenerate simplexes in  $Y_n$ . Then for each  $n \geq 0$ ,  $\sigma \in X_n$  one has  $|p^{-1}(x)| < \alpha$ .*

**Proof:** Since for any surjection  $s$  the map  $s^* : X_m \rightarrow X_n$  is an inclusion and there are only finitely many surjections of the form  $[n] \rightarrow [m]$  (where  $[n] = \{0, \dots, n\}$ ) there exists only finitely many pair-wise distinct pairs  $(x_i, s_i)$  where  $x_1, \dots, x_d \in X_{m_i}$  and  $s : [n] \rightarrow [m_i]$  is a surjection, such that  $s_i^*(x_i) = x$ .

Consider the map

$$\text{[2009.12.11.eq1]} \coprod_i s_i^* : \coprod_i (p^{-1}(x_i) \cap Y_{m_i}^{nd}) \rightarrow p^{-1}(x) \quad (22)$$

If  $y \in p^{-1}(x)$  then there exists  $s : [n] \rightarrow [m]$  and  $y' \in Y_m^{nd}$  such that  $s^*(y') = y$ . Then  $s^*p(y') = ps^*(y') = x$  and therefore  $s = s_i$  for  $i = 1, \dots, d$ . We conclude that the map (22) is surjective and therefore  $|p^{-1}(x)| < \alpha$ .

**Lemma 1.4** [2009.12.8.14] *Let  $\alpha > \aleph_0$  be an cardinal. Let  $j : A \rightarrow X$  be a cofibration (monomorphism) and  $p : B \rightarrow A$  be a trivial Kan fibration with fibers of cardinality  $< \alpha$ . Then there exists a pull-back square of the form*

$$\begin{array}{ccc} B & \longrightarrow & Y \\ \text{[2009.12.8.eq2]} \downarrow & & \downarrow q \\ A & \xrightarrow{j} & X \end{array} \quad (23)$$

such that  $q$  is a trivial Kan fibration with fibers of cardinality  $< \alpha$ .

**Proof:** Define inductively squares

$$\begin{array}{ccc} B & \longrightarrow & B_i \\ \text{[2009.12.8.eq3]} \downarrow & & \downarrow p_i \\ A & \xrightarrow{j} & X \end{array} \quad (24)$$

setting  $p_0 = p$  and defining  $B_{i+1}$  by the push-out square of the form

$$\begin{array}{ccc} \coprod_n \coprod_{Q_{n,i}} \partial\Delta^n & \longrightarrow & B_i \\ \text{[2009.12.11.eq2]} \downarrow & & \downarrow \\ \coprod_n \coprod_{Q_{n,i}} \Delta^n & \longrightarrow & B_{i+1} \end{array} \quad (25)$$

where  $Q_{n,i}$  is the set of commutative squares of the form

$$\begin{array}{ccc} \partial\Delta^n & \longrightarrow & B_i \\ \downarrow & & \downarrow \\ \Delta^n & \longrightarrow & X \end{array}$$

such that its base simplex i.e. the simplex corresponding to the map  $\Delta^n \rightarrow X$  does not belong to  $A$ .

Since for such a map  $f$  one has  $f^{-1}(A) \subset \partial\Delta^n$  the squares (24) are pull-back squares. Define  $Y$  as  $\text{colim } B_i$ . Then one verifies easily that (23) is a pull-back square and  $q$  is a fibration. Let us show that the fibers of  $q$  have cardinality  $< \alpha$ . Since  $\alpha > \aleph_0$  it is sufficient to show that, assuming that the fibers of  $B_i \rightarrow X$  are of cardinality  $< \alpha$ , the fibers of  $B_{i+1}$  are. The squares (25) show that for each  $n$  and  $x \in X_n$  the fiber  $p_{i+1}^{-1}(x) \cap (B_{i+1})_n^{nd}$  is of the form  $(p_i^{-1}(x) \cap (B_i)_n^{nd}) \amalg Q(n, i; x)$  where  $Q(n, i; x)$  is the subset in  $Q(n, i)$  which consists of squares whose base simplex  $\Delta^n \rightarrow X$  is  $x$ . It remains to observe that the number of such squares is  $< \alpha^{n+1}$  and to apply Lemma 1.3.

The category  $\Delta^{op}Sets$  is a topos and in particular an lcc. The relative internal Hom-objects in  $\Delta^{op}Sets$  can be explicitly described as follows.

**Lemma 1.5** [2009.12.8.15] *Let  $p_1 : E_1 \rightarrow B$ ,  $p_2 : E_2 \rightarrow B$  be morphisms of simplicial sets. Consider the simplicial set  $H(p_1, p_2)$  whose set of  $n$ -simplexes is the set of pairs of the form  $(f, \tilde{f})$  where  $f : \Delta^n \rightarrow B$  and  $\tilde{f} : f^*(p_1) \rightarrow p_2$  is a morphism over  $B$ .*

*Let  $H(p_1, p_2) \rightarrow B$  be the morphism  $ev : (f, \tilde{f}) \mapsto f$  and let  $H(p_1, p_2) \times_B E_1 \rightarrow E_2$  be the morphism which sends  $((f, \tilde{f}), \sigma)$  to  $\tilde{f}(\sigma)$ . Then  $(H(p_1, p_2), ev)$  is an internal Hom-object from  $E_1$  to  $E_2$  over  $B$ .*

**Lemma 1.6** [2009.12.8.16] *Let  $p_1 : E_1 \rightarrow B$ ,  $p_2 : E_2 \rightarrow B$  be Kan fibrations. Then  $H(p_1, p_2) \rightarrow B$  is a Kan fibration.*

**Proof:** It follows immediately from definitions and the fact that for a fibration  $p_1 : E_1 \rightarrow B$  and an anodyne morphism  $A \rightarrow X$  over  $B$ , the morphism  $A \times_B E_1 \rightarrow X \times_B E_1$  is anodyne.

**Lemma 1.7** [2009.12.9.11] *Let  $p_1 : E_1 \rightarrow B$ ,  $p_2 : E_2 \rightarrow B$  be Kan fibrations and  $f : E_1 \rightarrow E_2$  a morphism over  $B$  which is a weak equivalence. Then for any  $g : B' \rightarrow B$  the pull-back  $f' : B' \times_B E_1 \rightarrow B' \times_B E_2$  is a weak equivalence.*

**Proof:** Using the factorization of  $f$  into a trivial cofibration and a trivial fibration and the fact that the pull-back of a trivial fibration is a trivial fibration we may assume that  $f$  is a trivial cofibration. A trivial cofibration between two fibrant objects (in the category over  $B$ ) is a homotopy equivalence and the pull-back of a homotopy equivalence is a homotopy equivalence.

**Lemma 1.8** [2009.12.9.13] *Let  $p_1 : E_1 \rightarrow B$ ,  $p_2 : E_2 \rightarrow B$  be Kan fibrations and  $f : E_1 \rightarrow E_2$  a morphism over  $B$ . Suppose that for any  $n \geq 0$  and any simplex  $\sigma : \Delta^n \rightarrow B$  the pull-back  $f_\sigma : \Delta^n \times_B E_1 \rightarrow \Delta^n \times_B E_2$  is a weak equivalence. Then  $f$  is a weak equivalence.*

**Proof:** Replacing  $p_1, p_2$  by minimal fibrations we may assume that  $p_1, p_2$  are minimal. Then our condition implies that  $f_\sigma$  is an isomorphism for each  $\sigma$  and therefore is an isomorphism globally.

Let  $p_1, p_2$  be Kan fibrations as above. Consider the internal Hom-object  $H(p_1, p_2)$ . A morphism  $f : A \rightarrow H(p_1, p_2)$  defines a morphism  $pr(f) : A \rightarrow B$  and a morphism  $fib(f) : A \times_B E_1 \rightarrow A \times_B E_2$ . Let  $Eq(p_1, p_2)_n$  be the subset of simplexes  $\sigma : \Delta^n \rightarrow H(p_1, p_2)$  such that  $fib(\sigma)$  is a weak equivalence. Lemma 1.7 implies that these subsets form a simplicial subset in  $H(p_1, p_2)$  which we denote by  $Eq(p_1, p_2)$  or  $Eq_B(p_1, p_2)$ .

**Lemma 1.9** [2009.12.9.12] *Let  $p_1, p_2$  be Kan fibrations as above and  $f : A \rightarrow H(p_1, p_2)$  a morphism. The  $fib(f)$  is a weak equivalence if and only if  $Im(f) \subset Eq(p_1, p_2)$ .*

**Proof:** Straightforward using Lemmas 1.7 and 1.8.

**Lemma 1.10** [2009.12.9.14] *Let  $p_1, p_2$  be Kan fibrations as above,  $f : E_1 \rightarrow E_2$  a morphism over  $B$  and  $b \in B$ . Assume that  $B$  is connected and that  $p_1^{-1}(b) \rightarrow p_2^{-1}(b)$  is a weak equivalence. Then  $f$  is a weak equivalence.*

**Proof:** In view of Lemma 1.8 we may assume that  $B = \Delta^n$ . Since the pull-back of a weak equivalence along a fibration is a weak equivalence and  $b : \Delta^0 \rightarrow \Delta^n$  is a weak equivalence, we conclude that  $p_1^{-1}(b) \rightarrow E_1$  and  $p_2^{-1}(b) \rightarrow E_2$  are weak equivalences. Therefore, if  $f_b : p_1^{-1}(b) \rightarrow p_2^{-1}(b)$  is a weak equivalence then so is  $f$ .

**Lemma 1.11** [2009.12.9.15] *Let  $p_1, p_2$  be Kan fibrations as above. Then  $Eq(p_1, p_2)$  is a union of connected components of  $H(p_1, p_2)$  i.e. if  $(A, a)$  is a connected pointed simplicial set and  $f : A \rightarrow H(p_1, p_2)$  a morphism such that  $f(a) \in Eq(p_1, p_2)$  then  $Im(f) \subset Eq(p_1, p_2)$ .*

**Proof:** Follows immediately from Lemma 1.10.

Let  $p : E \rightarrow B$  be a fibration. Let  $p_1 : E \times B \rightarrow B \times B$  and  $p_2 : B \times E \rightarrow B \times B$  be the obvious projections. Consider the space  $H(p_1, p_2)$  over  $B \times B$ . The natural isomorphism  $p_1^{-1}(\Delta(B)) = p_2^{-1}(\Delta(B))$  where  $\Delta$  is the diagonal defines a morphism  $B \rightarrow H(p_1, p_2)$  over  $B \times B$  which, by Lemma 1.9, takes values in  $Eq(p_1, p_2)$ . Let us denote this morphism by  $mm_p : B \rightarrow Eq(p_1, p_2)$ .

**Definition 1.12** [2009.12.9.def1] *A Kan fibration  $p : E \rightarrow B$  is called univalent if the morphism  $mm_p : B \rightarrow Eq(p_1, p_2)$  defined above is a weak equivalence.*

**Theorem 1.13** [2009.12.9.th1] *The Kan fibration*

$$p_{fib} : \widetilde{WOF}(< \alpha) \rightarrow WOF(\alpha)$$

*is univalent.*

**Proof:** Let  $E = \widetilde{WOF}(< \alpha)$  and  $B = WOF(< \alpha)$ . Let  $P_1 : E \times B \rightarrow B \times B$ ,  $P_2 : B \times E \rightarrow B \times B$  be the projections. Proposition 1.1 implies easily that the space  $H(P_1, P_2)$  represents the functor which sends  $X$  into the set of (standard isomorphism classes of) triples of the form  $p_1 : Y_1 \rightarrow X$ ,  $p_2 : Y_2 \rightarrow X$ ,  $f : Y_1 \rightarrow Y_2$  where  $p_1, p_2$  are well ordered Kan fibrations with fibers of cardinality  $< \alpha$  and  $f$  is a morphism over  $X$ . The subspace  $Eq(P_1, P_2)$  classifies triples such that  $f$  is a weak equivalence.

Consider now the morphism  $r : B \rightarrow Eq(P_1, P_2) \rightarrow B \times B \xrightarrow{pr_2} B$ . To prove the theorem it is sufficient to show that the composition  $Eq(P_1, P_2) \rightarrow B \rightarrow Eq(P_1, P_2)$  is homotopic to the identity. This composition represents the functor morphism which sends  $(p_1, p_2, f)$  to  $(p_2, p_2, id)$ .

Applying Lemma 1.14 to the universal equivalence of fibrations over  $Eq(P_1, P_2)$  and using the axiom of choice we construct the required homotopy.

**Lemma 1.14** [2009.12.11.13] *Let  $p_1 : Y_1 \rightarrow X$ ,  $p_2 : Y_2 \rightarrow X$  be two Kan fibrations and  $f : Y_1 \rightarrow Y_2$  be a morphism over  $X$  which is a weak equivalence. Then there exists a fibration  $q : Z \rightarrow X \times \Delta^1$  and a morphism  $F : Z \rightarrow Y_2 \times \Delta^1$  over  $X$  such that the fiber of  $F$  over  $X \times \{0\}$  is isomorphic to  $f$  and the fiber over  $X \times \{1\}$  is isomorphic to  $Id_{Y_2}$ .*

*In addition if  $\alpha > \aleph_0$  is a cardinal and the fibers of  $p_1$  and  $p_2$  have cardinality  $< \alpha$  then we can choose  $q$  such that its fibers have cardinality  $< \alpha$ .*

**Proof:** Let  $Y_1 \xrightarrow{p'_1} Y'_1 \xrightarrow{p''_1} X$ ,  $Y_2 \xrightarrow{p'_2} Y'_2 \xrightarrow{p''_2} X$  be factorizations of  $p_1$  and  $p_2$  such that  $p'_i$  is a trivial fibration and  $p''_i$  a minimal fibration which exist by [7]. If  $s_1$  is a section of  $p'_1$  (which exist since all simplicial sets are cofibrant) then  $p'_2 f s_1$  is a weak equivalence between two minimal fibrations over  $X$  and therefore an isomorphism. Let us denote it by  $f' : Y'_1 \rightarrow Y'_2$ .

Applying Lemma 1.4 to the trivial fibration  $p'_1 \amalg p'_2 : Y_1 \amalg Y_2 \rightarrow Y'_1 \amalg Y'_2$  and monomorphism  $j = (i_0 f' \amalg i_1) : Y'_1 \amalg Y'_2 \rightarrow Y'_2 \times \Delta^1$  we obtain a pull-back square of the form

$$\begin{array}{ccc} Y_1 \amalg Y_2 & \xrightarrow{k} & Z \\ p'_1 \amalg p'_2 \downarrow & & \downarrow q \\ Y'_1 \amalg Y'_2 & \xrightarrow{j} & Y'_2 \times \Delta^1 \end{array}$$

Consider now the square

$$\begin{array}{ccc} Y_1 \amalg Y_2 & \xrightarrow{i_0 f \amalg i_1} & Y_2 \times \Delta^1 \\ k \downarrow & & \downarrow p'_2 \times Id \\ Z & \xrightarrow{q} & Y'_2 \times \Delta^1 \end{array}$$

Let us show that it commutes. (The following argument was supplied by Thomas Streicher). It clearly commutes on the  $Y_2$  summand. On the  $Y_1$  summand the corresponding maps are (up to inclusions into  $Y'_2 \times \Delta^1$ ) of the form  $f' \circ p'_1$  and  $p'_2 \circ f$ . Note that a priori it is not clear that  $f' \circ p'_1 = p'_2 \circ f$ . However these two maps are homotopic since in the homotopy category over  $X$ , the morphism  $p'_1$  and therefore its section  $s_1$  are isomorphisms and therefore  $s_1 \circ p'_1$  is homotopic to the identity. On the other hand  $Y'_2$  is a minimal fibration over  $X$  and any two morphisms with values in this simplicial set which are homotopic and coincide after projection to  $X$  are equal.

Since  $k$  is a cofibration (monomorphism) and  $p'_2 \times Id$  is a trivial fibration, there is a morphism  $F : Z \rightarrow Y'_2 \times \Delta^1$  which splits this square into two commutative triangles. One verifies easily that the pair  $(Z, F)$  satisfies the conditions of the lemma.

Let  $p' : E \rightarrow B$ ,  $p : \tilde{U} \rightarrow U$  be two Kan fibrations. For a simplicial set  $X$  denote by  $HInd(p', p)(X)$  the set of pairs  $(\tilde{f}, f)$  where  $\tilde{f} : E \times X \rightarrow \tilde{U}$ ,  $f : B \times X \rightarrow U$  are morphisms such that the square

$$\begin{array}{ccc} E \times X & \xrightarrow{\tilde{f}} & \tilde{U} \\ \text{[2009.12.23.eq1]} p' \times Id_X \downarrow & & \downarrow p \\ B \times X & \xrightarrow{f} & U \end{array} \quad (26)$$

is a homotopy pull-back square i.e. such that  $p \circ \tilde{f} = f \circ (p' \times Id_X)$  and the obvious morphism  $E \times X \rightarrow (B \times X) \times_U \tilde{U}$  is a weak equivalence. Since  $p'$  and  $p$  are fibrations, the composition of a homotopy pull-back square of the form (26) with a pull-back square

$$\begin{array}{ccc} E \times X' & \longrightarrow & E \times X \\ \downarrow & & \downarrow \\ B \times X' & \longrightarrow & B \times X \end{array}$$

defined by any morphism  $f : X' \rightarrow X$ , is a homotopy pull-back square. Therefore  $HInd(p', p)(-)$  is a contravariant functor on  $\Delta^{op}Sets$  and Lemma 1.8 implies easily that it is represented by the simplicial set  $HInd(p', p)$  whose set of  $n$ -simplexes is  $HInd(p', p)(\Delta^n)$ .

**Proposition 1.15** [2009.12.23.prop1] *A Kan fibration  $p : \tilde{U} \rightarrow U$  such that  $U$  is a Kan simplicial set is univalent if and only if for any Kan fibration  $p' : E \rightarrow B$ ,  $(HInd(p', p) \neq \emptyset) \Rightarrow (HInd(p', p) \text{ is contractible})$ .*

**Proof:** Let  $p' : E \rightarrow B$  be a Kan fibration such that  $HInd(p', p) \neq \emptyset$  i.e. such that there exists a pull-back square of the form

$$\begin{array}{ccc} E & \xrightarrow{\tilde{f}} & \tilde{U} \\ p \downarrow & & \downarrow \\ B & \xrightarrow{f} & U \end{array}$$

Let  $X$  be a simplicial set. Then a morphism  $X \rightarrow HInd(p', p)$  is given by a pair of a morphism  $f_X : B \times X \rightarrow U$  and a weak equivalence  $E \times X \rightarrow (B \times X)_{f_X} \times_p \tilde{U}$  over  $B \times X$ . The morphism  $E \times X \rightarrow B \times X$  is canonically isomorphic to the projection  $(B \times X)_{f \circ pr_B} \times_p \tilde{U} \rightarrow B \times X$ . Therefore, morphisms  $X \rightarrow HInd(p', p)$  correspond to morphisms  $B \times X \rightarrow Eq(p \times Id_U, Id_U \times p)$  whose composition with  $Eq(p \times Id_U, Id_U \times p) \xrightarrow{pEq} U \times U \xrightarrow{pr_2} U$  equals  $f \circ pr_B : B \times X \rightarrow B \xrightarrow{f} U$ .

Since  $U$  is assumed to be a Kan simplicial set the morphism  $pr_2 \circ pEq$  is a Kan fibration. If  $p$  is univalent it is a trivial Kan fibration and from the previous description of  $HInd(p', p)$  we conclude that for any cofibration  $X \subset Y$  and a morphism  $F = (\tilde{f}, f) : X \rightarrow HInd(p', p)$  there exists an extension of  $F$  to  $Y$  i.e. that  $HInd(p', p) \rightarrow pt$  is a trivial Kan fibration.

To prove the other implication consider the case when  $B = pt$ . Then our considerations show that  $HInd(p', p)$  is isomorphic to the fiber of  $pr_2 \circ pEq$  over  $f(pt) \in U_0$ . Since any Kan fibrations with contractible fibers is a trivial Kan fibration we conclude that the required implication holds.

## 2 Well-ordered simplicial sets

We consider a triple  $(ST, ST', M)$  where  $ST, ST'$  are ZF-like set-theories and  $M$  is a model of  $ST$  and  $ST'$ . These data defines "the set of all  $ST$  sets" as an  $ST'$ -set. Similarly, these data provides an unambiguous definition for objects such as "the set of isomorphism classes of simplicial sets" etc.

Our first step is to choose a convenient set-level model of the 1-category of simplicial sets.

**Definition 2.1** [2009.12.8.def1] *A well-ordered simplicial set is a simplicial set  $(X_n)_{n \geq 0}$  together with well orderings  $<$  on each of  $X_n$ .*

Note that the well orderings on  $X_n$  are not assumed to be compatible with the boundary or degeneracy maps. By a morphism between two well-ordered simplicial sets we will mean a morphism between the corresponding simplicial sets without any regard for orderings. A morphism which preserves well-orderings on each of  $X_n$  will be called a standard morphism.

The standard facts about well-ordered sets imply that there is at most one standard isomorphism between any two well-ordered simplicial sets. Therefore, we may consider a set level model  $C$  of  $\Delta^{op}Sets$  where  $ob(C)$  is the set of standard isomorphism classes of well-ordered simplicial sets and  $Mor(X, Y)$  is the set of all morphisms from  $X$  to  $Y$ . The uniqueness of standard isomorphisms implies that the composition of morphisms is well defined.

For well-ordered simplicial sets  $X, Y$  denote by  $X \times Y$  the well-ordered simplicial set whose terms  $X_n \times Y_n$  are well-ordered with respect to the lexicographical ordering such that the projection to  $X$  (but not to  $Y$ ) is a standard morphism.

For  $f : X' \rightarrow X$  and  $p : Y \rightarrow X$  define the standard pull-back square

$$\begin{array}{ccc} f^*(Y, p) & \xrightarrow{q(f, Y, p)} & Y \\ p_f \downarrow & & \downarrow p \\ X' & \xrightarrow{f'} & X \end{array}$$

setting  $f^*(Y, p)$  to be the subset in  $X' \times Y$  defined by the usual equations with the induced well-ordering.



One verifies easily the following results.

**Lemma 2.2 [2009.12.8.11]** *For any  $p$  the morphism  $p_f$  is standard and  $p : Y \rightarrow X$  is standard if and only if  $Id_X^*(p) = p$ .*

**Lemma 2.3 [2009.12.8.12]** *For any  $p : Y \rightarrow X$  and  $g : X'' \rightarrow X'$ ,  $f : X' \rightarrow X$  one has  $(fg)^*(p) = g^*f^*(p)$ ,  $q(fg, Y, p) = q(g, f^*(p), p_f)q(f, Y, p)$  and  $p_{fg} = (p_f)_g$ .*

Note that  $q(f, Y, p)$  need not be standard even if both  $p$  and  $f$  are standard (consider e.g. the case when  $X = pt$ ).

In what follows we choose a well-ordering on the sets  $\Delta_i^n$  and consider the standard simplexes as objects of  $C$  with respect to this ordering.

## 6 Type systems

### 1 Systems of expressions

**Free systems of expressions.** Let  $M$  be a set and let  $T(M)$  be the set of finite rooted trees whose vertices (including the root) are labeled by elements of  $M$  and such that for any vertex the set of edges leaving this vertex is ordered. Note that such ordered trees have no symmetries. We will use the following notations. For  $T \in T(M)$  let  $Vrtx(T)$  be the set of vertices of  $T$  and for  $v \in Vrtx(T)$  let  $lbl(v) = lbl(v)_T \in M$  be the label on  $v$ . We will sometimes write  $v \in T$  instead of  $v \in Vrtx(T)$ . For  $v \in Vrtx(T)$  let  $[v] = [v]_T \in T(M)$  be the subtree in  $T$  which consists of  $v$  and all the vertices under  $v$ . Let  $val(v)$  be the valency of  $v$  i.e. the number of edges leaving  $v$  and  $ch_1(v), \dots, ch_{val(v)}(v) \in Vrtx(T)$  be the "children" of  $v$  i.e. the end points of these edges. Let further  $br_i(v) = [ch_i(v)]$  be the branches of  $[v]$ . We write  $v \leq w$  (resp.  $v < w$ ) if  $v \in [w]$  (resp.  $v \in [w] - w$ ). We say that two vertices  $v$  and  $w$  are independent if  $v \notin [w]$  and  $w \notin [v]$ .

For three sets  $A, B$  and  $Con$  let

$$AllExp(A, B; Con) = T(A \amalg B \amalg (Con \times (\amalg_{n \geq 0} B^n)))$$

Elements of  $AllExp(A, B; Con)$  are called expressions over the alphabet  $Con$  (or with a set of constructors  $Con$ ), free variables from  $A$  and bound variables from  $B$ .

An expression is called unambiguous if it satisfies the following conditions:

1. if  $lbl(v) \in A \amalg B$  then  $val(v) = 0$ ,
2. (a) if  $v < v'$ ,  $lbl(v) = (c; x_1, \dots, x_n)$  and  $lbl(v') = (c'; x'_1, \dots, x'_{n'})$  then  $\{x_1, \dots, x_n\} \cap \{x'_1, \dots, x'_{n'}\} = \emptyset$ ,  
(b) if  $lbl(v) = (c; x_1, \dots, x_n)$  then  $x_i \neq x_j$  for  $i \neq j$ ,
3. if  $lbl(v) = (c; x_1, \dots, x_n)$  and  $lbl(v') \in \{x_1, \dots, x_n\}$  then  $v' \in [v]$ .

The first conditions says that a vertex labeled by a variable is a leaf. The second one is equivalent to saying that if the same variable is bound at two different vertices  $v, v'$  then these vertices are independent i.e.  $[v] \cap [v'] = \emptyset$  and that a vertex can not bind the same variable twice. The third

one says that all the leaves labeled by a bound variable lie under the vertex where it is bound. We let  $UAExp(A, B; Con)$  denote the subset of unambiguous expressions in  $AllExp(A, B; Con)$ . Note that for any  $T \in UAExp(A, B; Con)$  and  $v \in Vrtx(T)$  there is a subset  $Ext(v) \subset B$  such that

$$[v] \in UAExp(A \amalg Ext(v), B \setminus Ext(v); Con)$$

Any triple of maps  $f_{Con} : A \rightarrow A'$ ,  $f_B : B \rightarrow B'$ ,  $f_{Con} : Con \rightarrow Con'$  define a map

$$f_* = (f_A, f_B, f_{Con})_* : AllExp(A, B; Con) \rightarrow AllExp(A', B'; Con')$$

which changes labels in the obvious way. If  $f_B$  is injective then  $f_*$  maps unambiguous expressions to unambiguous ones.

An element  $T$  of  $UAExp(A, B; Con)$  is said to be strictly unambiguous if for any  $v \neq v'$  in  $Vrtx(T)$  such that  $lbl(v) = (c; x_1, \dots, x_n)$  and  $lbl(v') = (c'; x'_1, \dots, x'_{n'})$  one has  $\{x_1, \dots, x_n\} \cap \{x'_1, \dots, x'_{n'}\} = \emptyset$  i.e. if the names of all bound variables are different. We let  $SUAExp(A, B; Con)$  denote the subset of strictly unambiguous expressions in  $UAExp(A, B; Con)$ .

An element  $T$  of  $UAExp(A, B; Con)$  is said to be  $\alpha$ -equivalent to an element  $T'$  of  $UAExp(A, B'; Con)$  if there is a set  $B''$ , an element  $T'' \in UAExp(A, B''; Con)$  and two maps  $f : B'' \rightarrow B$ ,  $f' : B'' \rightarrow B'$  such that  $T = (Id, f, Id)_*(T'')$  and  $T' = (Id, f', Id)_*(T'')$ . The following lemma is straightforward:

**Lemma 1.1** [2009.09.08.11] *For any two sets  $A$  and  $Con$  one has:*

1.  $\alpha$ -equivalence is an equivalence relation,
2. for any set  $B$  and any element  $T \in UAExp(A, B; Con)$  there exists an element  $T' \in UAExp(A, \mathbf{N}; Con)$  such that  $T \overset{\alpha}{\sim} T'$  and  $T'$  is strictly unambiguous,
3. two strictly unambiguous elements  $T, T' \in UAExp(A, B; Con)$  are  $\alpha$ -equivalent if and only if there exists a permutation  $f : B \rightarrow B$  such that  $(Id, f, Id)_*(T) = T'$ .

We let  $Exp_\alpha(A; Con)$  denote the set of  $\alpha$ -equivalence classes in  $\amalg_B UAExp(A, B; Con)$ . In view of Lemma 1.1 this set is well defined and can be also defined as the set of equivalence classes in  $SUAExp(A, \mathbf{N}; Con)$  modulo the equivalence relation generated by the permutations on  $\mathbf{N}$ .

Note that for two  $\alpha$ -equivalent expressions  $T_1, T_2$  and a vertex  $v \in V(T_1) = V(T_2)$  the expressions  $[v]_{T_1}$  and  $[v]_{T_2}$  need not be  $\alpha$ -equivalent since some of the variables which are bound in  $T_1$  may be free in  $[v]$ .

The maps  $(f_A, f_B, f_{Con})_*$  respect  $\alpha$ -equivalence. Therefore for any  $f_A : A \rightarrow A'$  and  $f_{Con} : Con \rightarrow Con'$  there is a well defined map

$$(f_A, f_{Con})_* : Exp_\alpha(A; Con) \rightarrow Exp_\alpha(A'; Con')$$

which make  $Exp_\alpha(-; -)$  into a covariant functors from pairs of sets to sets. In addition there is a well defined notion of substitution on  $Exp_\alpha(-; Con)$  which may be considered as a collection of maps of the form:

$$Exp_\alpha(A; Con) \times \left( \prod_{a \in A} Exp_\alpha(X_a; Con) \right) \rightarrow Exp_\alpha(\amalg_{a \in A} X_a; Con)$$

given for all pairs  $(A; \{X_a\}_{a \in A})$  where  $A$  is a set and  $\{X_a\}_{a \in A}$  a family of sets parametrized by  $A$ . Alternatively, the substitution structure can be seen as a collection of maps

$$Exp_\alpha(Exp_\alpha(A; Con); Con) \rightarrow Exp_\alpha(A; Con)$$

given for all  $A$  and  $Con$ . These maps make the functor  $Exp_\alpha(-; Con)$  into a monad (triple) on the category of sets which functorially depends on the set  $Con$ .

**Example 1.2** [**lambda**] The mapping which sends a set  $X$  to the set of  $\alpha$ -equivalence classes of terms of the untyped  $\lambda$ -calculus with free variables from  $X$  is a sub-triple of  $Exp_\alpha(-; Con)$  where  $Con = \{\lambda, ev\}$ . Elements  $T$  of  $UAEExp(X, \mathbf{N}; \{\lambda, ev\})$  which belong to this sub-triple are characterized by the following "local" conditions:

1. for each  $v \in T$ ,  $lbl(v) \in X \amalg \mathbf{N} \amalg \{ev\} \amalg \{\lambda\} \times \mathbf{N}$
2. if  $lbl(v) \in \{\lambda\} \times \mathbf{N}$  then  $val(v) = 1$
3. if  $lbl(v) = ev$  then  $val(v) = 2$ .

**Example 1.3** [**propositional**] The mapping which sends a set  $X$  to the set of terms of the propositional calculus with free variables from  $X$  is a sub-triple of  $Exp_\alpha(-; C_0)$  where  $C_0 = \{\vee, \wedge, \neg, \Rightarrow\}$ . Elements  $T$  of  $UAEExp(X, \mathbf{N}; C_0)$  which belong to this sub-triple are characterized by the following "local" conditions:

1. for all  $v \in T$ ,  $lbl(v) \in X \amalg C_0$
2. if  $lbl(v) \in \{\vee, \wedge, \Rightarrow\}$  then  $val(v) = 2$
3. if  $lbl(v) = \neg$  then  $val(v) = 1$ .

**Example 1.4** [**multisorted**] Consider first order logic with several sorts  $GS = \{S_1, \dots, S_n\}$ . Let  $GP$  be the set of generating predicates and  $GF$  the set of generating functions. Let  $C_1 = C_0 \amalg \{\forall, \exists\}$  and  $C_2 = C_1 \amalg GP \amalg GF \amalg GS$ . We can identify the  $\alpha$ -equivalence classes of formulas of the first order language defined by  $GS$  and  $GF$  with free variables from a set  $X$  with a subset in  $Exp_\alpha(X, \mathbf{N}; C_2)$ . Vertices which are labeled by  $(\forall; x)$  and  $(\exists; x)$  have valency two. For such a vertex  $v$ , the first branch of  $[v]$  is one vertex labeled by an element of  $GS$  giving the sort over which the quantification occurs and the second branch is the expression which is quantified. Now however, these subsets do not form a sub-triple of  $Exp_\alpha$  since not all substitutions are allowed. By allowing all substitutions irrespectively of the sort we get (for each  $X$ ) a subset in  $Exp_\alpha(X; C_2)$  whose elements will be called pseudo-formulas.

The following operations on expressions are well defined up to the  $\alpha$ -equivalence:

1. If  $T_1, \dots, T_m \in Exp_\alpha(A; Con)$ ,  $a_1, \dots, a_n$  are pair-wise different elements of  $A$  and  $M \in Con$  we will write  $(M, a_1, \dots, a_n)(T_1, \dots, T_m)$  for the expression whose root  $v$  is labeled by  $(M, a_1, \dots, a_n)$ ,  $val(v) = n$  and  $br_i(v) = T_i$ .
2. For  $T_1, T_2 \in Exp_\alpha(A; Con)$  and  $v \in T_1$  we let  $T_1(T_2/[v])$  be the expression obtained by replacing  $[v]$  in  $T_1$  with  $T_2'$  where  $T_2'$  is obtained from  $T_2$  by the change of bound variables such that the bound variables of  $T_2'$  do not conflict with the variables of  $T_1$ .

3. For  $T, R_1, \dots, R_n \in \text{Exp}_\alpha(A; \text{Con})$  and  $y_1, \dots, y_n \in A$  we let  $T(R_1/y_1, \dots, R_n/y_n)$  denote the expression obtained by changing  $R_i$ 's by  $\alpha$ -equivalent  $R'_i$  such that  $\text{bnd}(R'_i) \cap \text{bnd}(R_j)' = \emptyset$  for  $i \neq j$ , changing  $T$  to an  $\alpha$ -equivalent  $T'$  such that  $\text{bnd}(T') \cap (\text{var}(R'_1) \cup \dots \cup \text{var}(R'_n)) = \emptyset$  and then replacing all the leaves of  $T'$  marked by  $y_i$  by  $R'_i$ .

In all the examples considered above, these operations correspond to the usual operations on formulas. The first operation can be used to directly associate expressions in our sense with the formulas. For example, the expression associated with the formula  $\forall x : S.P(x, y)$  in a multi-sorted predicate calculus is  $(\forall, x)(S, P(x, y))$  where as was mentioned above we use the same notation for an element of  $A \amalg B \amalg (\text{Con} \times (\amalg_{n \geq 0} B^n))$  and the one vertex tree with the corresponding label.

Note: about representing elements of  $\text{AllExp}(A, B; \text{Con})$  by linear sequences of elements of  $A \amalg B \amalg \dots$ ??

**Reduction structures.** Another component of the structure present in systems of expressions used in formal systems is the reduction relation. It is very important for our approach to type systems that the reduction relation is defined on all pseudo-formulas and is compatible with the substitution structure even when not all pseudo-formulas are well formed formulas. In what follows we will consider, instead of a particular syntactic system, a pair  $(S, \triangleright)$  where  $S$  is a continuous triple on the category of sets and  $\triangleright$  is a reduction structure on  $S$  i.e. a collection of relations  $\triangleright_X$  on  $S(X)$  given for all finite sets  $X$  satisfying the following two conditions:

1. if  $E \in S(\{x_1, \dots, x_n\})$ ,  $f_1, \dots, f_n, f'_i \in S(\{y_1, \dots, y_m\})$  and  $f_i \triangleright_{\{y_1, \dots, y_m\}} f'_i$  then

$$E(f_1/x_1, \dots, f_i/x_i, \dots, f_n/x_n) \triangleright_{\{x_1, \dots, x_n\}} E(f_1/x_1, \dots, f'_i/x_i, \dots, f_n/x_n),$$

2. if  $E, E' \in S(\{x_1, \dots, x_n\})$ ,  $f_1, \dots, f_n \in S(\{y_1, \dots, y_m\})$  and  $E \triangleright_{\{x_1, \dots, x_n\}} E'$  then

$$E(f_1/x_1, \dots, f_n/x_n) \triangleright_{\{x_1, \dots, x_n\}} E'(f_1/x_1, \dots, f_n/x_n).$$

The following two results are obvious but important.

**Proposition 1.5 [2009.10.17.prop1]** *Let  $S$  be a continuous triple on Sets and  $\triangleright_\alpha$  be a family of reduction structures on  $S$ . Then the intersection  $\bigcap_\alpha \triangleright_\alpha : X \mapsto \bigcap_\alpha \triangleright_{\alpha, X}$  is a reduction structure on  $S$ .*

**Corollary 1.6 [2009.10.17.cor1]** *For any family  $(X_\alpha, \text{pre}_\alpha)$  of pairs of the form  $(X, \text{pre})$  where  $X$  is a set and  $\text{pre}$  is a relation on  $S(X)$  (i.e. a subset of  $S(X) \times S(X)$ ) there exists the smallest reduction structure  $\triangleright = \triangleright(X_\alpha, \text{pre}_\alpha)$  on  $S$  such that for each  $\alpha$  and each  $(f, g) \in \text{pre}_\alpha$  one has  $f \triangleright g$ .*

## 2 Type systems

**Contextual categories defined by a triple.** Let  $S$  be a continuous triple on Sets. Let  $S\text{-cor}$  be the full subcategory of the Kleisli category of  $S$  whose objects are finite sets. Recall, that the set of morphisms from  $X$  to  $Y$  in  $S\text{-cor}$  is the set of maps from  $X$  to  $S(Y)$  i.e.  $S(Y)^X$  (in other words,  $S\text{-cor}$  is the category of free, finitely generated  $S$ -algebras). We will construct two contextual categories  $C(S)$  and  $CC(S)$  which are based on  $(S\text{-cor})^{op}$ .

**Examples:**

1. If  $S = Id$  i.e.  $S(X) = X$  the  $S - cor = FSets$  is the category of finite sets. It is easy to see that the category of finite sets is the free category with finite coproducts generated by one object. Therefore,  $(FSets)^{op}$  can be thought of the free category with finite products generated by one object.
2. Let  $S$  be given by  $S(X) = X \amalg A$  where  $A$  is a set. This corresponds to the system of expressions where all expressions are either variables or constants and the set of constants is  $A$ . The category  $(S - cor)^{op}$  can be thought of as the free category with finite products generated by an object  $U$  and the set  $A$  of morphisms  $pt \rightarrow U$ .

The categories of sets, finite sets or even the category of finite linearly ordered sets and their isomorphisms are all level 1 categories and so is the category  $S - cor$ . We can get a set-level model  $C(S)$  for  $(S - cor)^{op}$  by setting  $ob(C(S)) = \mathbf{N}$  and  $Hom_{C(S)}(n, m) = S(\{1, \dots, n\})^m$ .

The category  $C(S)$  has a contextual structure which is defined as follows. The final object is 0. The map  $ft$  is given by

$$ft(n) = \begin{cases} 0 & \text{if } n = 0 \\ n - 1 & \text{if } n > 0 \end{cases}$$

The canonical projection  $n \rightarrow n - 1$  is given by the sequence  $(1, \dots, n - 1)$ . For  $f = (f_1, \dots, f_m) : n \rightarrow m$  the canonical square build on  $f$  and the canonical projection  $m + 1 \rightarrow m$  is of the form

$$\begin{array}{ccc} n + 1 & \xrightarrow{(f_1, \dots, f_m, n+1)} & m + 1 \\ \downarrow & & \downarrow \\ n & \xrightarrow{(f_1, \dots, f_m)} & m \end{array}$$

Any morphism of triples  $S \rightarrow S'$  defines a contextual functor  $C(S) \rightarrow C(S')$ . Non-trivial contextual subcategories of  $C(S)$  are in one-to-one correspondence with continuous sub-triples of  $S$ .

Note: add notes that a continuous sub-triple of  $S$  is exactly the same as a subcategory in  $S - cor$  which contains all (isomorphism classes of) objects. Intersection of two sub-triples is a sub-triple which allows us to speak of sub-triples (systems of expressions etc.) generated by a set of expressions. For the construction of type systems the category  $S - cor$  is replaced by the contextual category  $CC(S, X)$ .

Note: that continuous triples on  $Sets$  are the same as category structures on  $\mathbf{N}$  which extend the a category structure of finite sets and where the addition remains to be coproduct.

Let now  $CC(S)$  be the set-level category whose set of objects is  $ob(CC(S)) = \amalg_{n \geq 0} ob_n$  where

$$ob_n = S(\emptyset) \times \dots \times S(\{1, \dots, n - 1\})$$

and the set of morphisms is

$$mor(CC(S)) = \prod_{n, m \geq 0} ob_n \times ob_m \times S(\{1, \dots, n\})^m$$

with the obvious domain and codomain maps. The composition of morphisms is defined in the same way as in  $C(S)$  such that the mapping  $ob(CC(S)) \rightarrow \mathbf{N}$  which sends all elements of  $ob_n$  to  $n$ , is a functor. The associativity of compositions follows immediately from the associativity of compositions in  $S - cor$ .

Note that if  $S(\emptyset) = \emptyset$  then  $CC(S) = \emptyset$  and otherwise the functor  $CC(S) \rightarrow (S - cor)^{op}$  is an equivalence, so that in the second case  $C(S)$  and  $CC(S)$  are indistinguishable as level 1 categories. However, as set level categories they are quite different.

The category  $CC(S)$  is given a contextual structure as follows. The final object is the only element of  $ob_0$ , the map  $ft$  is defined by the rule

$$ft(T_1, \dots, T_n) = (T_1, \dots, T_{n-1}).$$

The canonical pull-back square defined by an object  $(T_1, \dots, T_{m+1})$  and a morphism  $(f_1, \dots, f_m) \in S(\{1, \dots, n\})^m$  from  $(R_1, \dots, R_n)$  to  $(T_1, \dots, T_m)$  is of the form

$$\begin{array}{ccc} (R_1, \dots, R_n, T_{m+1}(f_1/1, \dots, f_m/m)) & \xrightarrow{(f_1, \dots, f_m, n+1)} & (T_1, \dots, T_{m+1}) \\ \downarrow & & \downarrow \\ (R_1, \dots, R_n) & \xrightarrow{(f_1, \dots, f_m)} & (T_1, \dots, T_m) \end{array} \quad (27)$$

[2009.11.05.oldeq1]

**Proposition 2.1** [2009.10.01.prop2] *With the structure defined above  $CC(S)$  is a contextual category.*

**Proof:** Straightforward.

Note that the natural projection  $CC(S) \rightarrow C(S)$  is a contextual functor. It's contextual sections are in one-to-one correspondence with  $S(\emptyset)$  such that  $U \in S(\emptyset)$  corresponds to the section which takes the object  $n$  of  $C(S)$  to the object  $(U, \dots, U)$  of  $CC(S)$ .

Any morphism of triples  $S \rightarrow S'$  defines a contextual functor  $CC(S) \rightarrow CC(S')$ . Contextual subcategories of  $CC(S)$ , which are discussed in more detail below, provide an important class of type systems over  $S$ .

There is another construction of a category from a continuous triple  $S$  which takes as an additional parameter a set  $Var$  which is called the set of variables. Let  $F_n(Var)$  be the set of sequences of length  $n$  of pair-wise distinct elements of  $Var$ . Define the category  $CC(S, Var)$  as follows. The set of objects of  $CC(S, Var)$  is

$$ob(CC(S, Var)) = \coprod_{n \geq 0} \coprod_{(x_1, \dots, x_n) \in F_n(Var)} S(\emptyset) \times \dots \times S(\{x_1, \dots, x_{n-1}\})$$

For notational compatibility with the traditional type theory we will write the elements of  $ob(CC(S, X))$  as sequences of the form  $x_1 : E_1, \dots, x_n : E_n$ . The set of morphisms is given by

$$Hom_{CC(S, Var)}((x_1 : E_1, \dots, x_n : E_n), (y_1 : T_1, \dots, y_m : T_m)) = S(\{x_1, \dots, x_n\})^m$$

The composition is defined in such a way that the projection

$$(x_1 : E_1, \dots, x_n : E_n) \mapsto (E_1, E_2(1/x_1), \dots, E_n(1/x_1, \dots, n-1/x_{n-1}))$$

is a functor from  $CC(S, X)$  to  $CC(S)$ . This functor is clearly an equivalence. There is an obvious final object and  $frth$  map on  $CC(S, X)$ . There is however a real problem in making it into a contextual category which is due to the following. Consider an object  $(y_1 : T_1, \dots, y_{m+1} : T_{m+1})$  and a morphism  $(f_1, \dots, f_m) : (x_1 : R_1, \dots, x_n : R_n) \rightarrow (y_1 : T_1, \dots, y_m : T_m)$ . In order for the

functor to  $CC(S)$  to be a contextual functor the canonical square build on this pair should have the form

$$\begin{array}{ccc} (x_1 : R_1, \dots, x_n : R_n, x_{n+1} : T_{m+1}(f_1/1, \dots, f_m/m)) & \xrightarrow{(f_1, \dots, f_m, n+1)} & (y_1 : T_1, \dots, y_{m+1} : T_{m+1}) \\ \downarrow & & \downarrow \\ (x_1 : R_1, \dots, x_n : R_n) & \xrightarrow{(f_1, \dots, f_m)} & (y_1 : T_1, \dots, y_m : T_m) \end{array}$$

where  $x_{n+1}$  is an element of  $X$  which is distinct from each of the elements  $x_1, \dots, x_n$ . Moreover, we should choose  $x_{n+1}$  in such a way the the resulting construction satisfies the contextual category axioms for  $(f_1, \dots, f_m) = Id$  and for the compositions  $(g_1, \dots, g_n) \circ (f_1, \dots, f_m)$ . One can easily see that no such choice is possible for a finite set  $X$ . At the moment it is not clear to me whether or not such it is possible for an infinite  $X$ .

**Contextual subcategories of  $CC(S)$ .** Let  $TS$  be a contextual subcategory of  $CC(S)$ . By Lemma 1.3,  $TS$  is determined by the subsets  $ob(TS)$  and  $\tilde{ob}(TS)$  in  $ob(CC(S))$  and  $\tilde{ob}(CC(S))$ . By definition we have

$$ob(CC(S)) = \coprod_{n \geq 0} S(\emptyset) \times S(\{1\}) \times \dots \times S(\{1, \dots, n-1\}) \times S(\{1, \dots, n\})$$

An element of  $\tilde{ob}(CC(S))$  is given by a pair  $(\Gamma, s)$  where  $\Gamma \in ob(CC(S))$  is an object and  $s : ft(\Gamma) \rightarrow \Gamma$  is a section of the canonical morphism  $p_\Gamma : \Gamma \rightarrow ft(\Gamma)$ . It follows immediately from the definition of  $CC(S)$  that for  $\Gamma = (E_1, \dots, E_{n+1})$ , a morphism  $(f_1, \dots, f_{n+1}) \in S(\{1, \dots, n\})^{n+1}$  from  $ft(\Gamma)$  to  $\Gamma$  is a section of  $p_\Gamma$  if and only if  $f_i = i$  for  $i = 1, \dots, n$ . Therefore, any such section is determined by its last component  $f_{n+1}$  and mapping  $((E_1, \dots, E_{n+1}), (f_1, \dots, f_{n+1}))$  to  $(E_1, \dots, E_n, E_{n+1}, f_{n+1})$  we get a bijection

$$[\mathbf{2009.10.15.eq2}] \tilde{ob}(CC(S)) \cong \coprod_{n \geq 0} S(\emptyset) \times S(\{1\}) \times \dots \times S(\{1, \dots, n-1\}) \times S(\{1, \dots, n\})^2 \quad (28)$$

Let  $Seq_0(TS) = ob(TS)$  and let  $Seq_1(TS)$  be the image of  $\tilde{ob}(TS)$  under the bijection (28). Traditionally, one writes  $E_1, E_2, \dots, E_n \vdash_{TS}$  if  $(E_1, \dots, E_n)$  is in  $Seq_0(TS)$  and  $E_1, E_2, \dots, E_n \vdash_{TS} t : T$  if  $(E_1, \dots, E_n, T, t)$  is in  $Seq_1(TS)$ . When no confusion is possible we will write  $\vdash$  instead of  $\vdash_{TS}$ .

The following result is an immediate corollary of Proposition 1.5.

**Proposition 2.2** [ $\mathbf{2009.10.16.prop3}$ ] *Let  $S$  be a continuous triple on Sets. A pair of subsets  $Seq_0, Seq_1$  of the form*

$$\begin{aligned} Seq_0(TS) &\subset \coprod_{n \geq 0} S(\emptyset) \times S(\{1\}) \times \dots \times S(\{1, \dots, n-1\}) \times S(\{1, \dots, n\}) \\ [\mathbf{2009.10.01.eq3}] \quad Seq_1(TS) &\subset \coprod_{n \geq 0} S(\emptyset) \times S(\{1\}) \times \dots \times S(\{1, \dots, n-1\}) \times S(\{1, \dots, n\})^2 \end{aligned} \quad (29)$$

*defines a contextual subcategory of  $CC(S)$  if and only if the following conditions hold:*

1.  $\vdash$ ,
2. if  $E_1, \dots, E_n \vdash$  then  $E_1, \dots, E_{n-1} \vdash$ ,

3. if  $E_1, \dots, E_n \vdash t : T$  then  $E_1, \dots, E_n, T \vdash$ ,
4. if  $E_1, \dots, E_n \vdash t : T$ ,  $i = 0, \dots, n$  and  $E_1, \dots, E_i, E'_{i+1} \vdash$  then  $E_1, \dots, E_i, E'_{i+1}, E_{i+1}, \dots, E_n(i+2/i+1, \dots, n/n-1) \vdash t(i+2/i+1, \dots, n+1/n) : T(i+2/i+1, \dots, n+1/n)$ ,
5. if  $E_1, \dots, E_n \vdash t : T$ ,  $i = 0, \dots, n-1$  and  $E_1, \dots, E_i \vdash r : E_{i+1}$  then  $E_1, \dots, E_i, E_{i+2}(r/i+1), \dots, E_n(r/i+1, i+1/i+2, \dots, n-2/n-1) \vdash t(r/i+1, i+1/i+2, \dots, n-2/n-1) : T(r/i+1, i+1/i+2, \dots, n-2/n-1)$ ,
6.  $E_1, \dots, E_n \vdash$  then  $E_1, \dots, E_n \vdash n : E_n$ .

Note that conditions (4) and (5) together with condition (6) and condition (3) imply the following

- 4a** if  $E_1, \dots, E_n \vdash$ ,  $i = 1, \dots, n$  and  $E_1, \dots, E_i, E'_{i+1} \vdash$  then  $E_1, \dots, E_i, E'_{i+1}, E_{i+1}, \dots, E_n(i+2/i+1, \dots, n/n-1) \vdash$ ,
- 5a** if  $E_1, \dots, E_n \vdash$ ,  $i = 1, \dots, n$  and  $E_1, \dots, E_i \vdash r : E_{i+1}$  then  $E_1, \dots, E_i, E_{i+2}(r/i+1), \dots, E_n(r/i+1, i+1/i+2, \dots, n-2/n-1) \vdash$ .

**Remark 2.3** [2010.08.07.rem1] If one re-writes the conditions of Proposition 2.2 in the more familiar in type theory form where the variables introduced in the context are named rather than directly numbered one arrives at the following rules:

$$\frac{}{\vdash} \quad \frac{x_1 : E_1, \dots, x_n : E_n \vdash}{x_1 : E_1, \dots, x_{n-1} : E_{n-1} \vdash} \quad \frac{x_1 : E_1, \dots, x_n : E_n \vdash t : T}{x_1 : E_1, \dots, x_n : E_n \vdash}$$

$$\frac{x_1 : E_1, \dots, x_n : E_n \vdash t : T \quad x_1 : E_1, \dots, x_i : E_i, y : F \vdash}{x_1 : E_1, \dots, x_i : E_i, y : F, x_{i+1} : E_{i+1}, \dots, x_n : E_n \vdash t : T}, \quad i = 0, \dots, n$$

$$\frac{x_1 : E_1, \dots, x_n : E_n \vdash t : T \quad x_1 : E_1, \dots, x_i : E_i \vdash r : E_{i+1}}{x_1 : E_1, \dots, x_i : E_i, x_{i+2} : E_{i+2}[r/x_{i+1}], \dots, x_n : E_n[r/x_{i+1}] \vdash t[r/x_{i+1}] : T[r/x_{i+1}]}, \quad i = 0, \dots, n-1$$

$$\frac{x_1 : E_1, \dots, x_n : E_n \vdash}{x_1 : E_1, \dots, x_n : E_n \vdash x_n : E_n}$$

which are similar to (and probably equivalent) the "basic rules of DTT" given in [4, p.585]. The advantage of the rules given here is that they are precisely the ones which are necessary and sufficient for a given collection of contexts and judgements to define a contextual category.

**Lemma 2.4** [2009.11.05.11] *Let  $S$  be as above and let  $Seq_0 = ob(TS)$ ,  $Seq_1 \cong \tilde{ob}(TS)$  be subsets corresponding to a contextual subcategory  $TS$ . Let further  $(E_1, \dots, E_n), (T_1, \dots, T_m) \in ob(TS)$  and  $(f_1, \dots, f_m) \in S(\{1, \dots, n\})^m$ . Then*

$$(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_m))$$

*if and only if  $(f_1, \dots, f_{m-1}) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_{m-1}))$  and*

$$(E_1, \dots, E_n, T_m(f_1/1, \dots, f_{m-1}/m-1), f_m) \in Seq_1$$



**Proof:** Straightforward using the fact that the canonical pull-back squares in  $CC(S)$  are given by (27).

Note: describe all type systems over the triple  $X \mapsto X_+$ . (Note that there are no non-trivial type systems over the identity triple since  $Id(\emptyset) = \emptyset$ . (update Aug. 2010): It does not seem to be a trivial problem. It is not even clear whether there are countably or uncountably many type systems over this triple.

**Remark 2.5** One can also define type systems as sub-quotients rather than just subobjects of  $C_1(S, X)$ . This requires one to consider "type equality sequents" and "term equality sequents" in addition to the type sequents and term sequents which we consider. Some sort of syntactic equality is necessary in order to define well behaved type systems. The question is whether or not one needs to consider context dependent syntactic equalities which make it necessary to pass to equivalence classes on the level of contextual categories. The example of most of the type systems which are practically used suggests that it is sufficient to consider context-independent syntactic equalities (i.e. equivalence classes of abstract expressions) and to use equality types for the context dependent equalities. For the approach with context dependent syntactic equalities see [8].

**Type systems over  $(S, \triangleright)$ .** Let  $S$  be a continuous triple on *Sets* and  $\triangleright$  a relation on  $S$  (see above). One defines type systems over  $(S, \triangleright)$  as follows.

**Definition 2.6 [2009.10.01.def2]** Let  $S$  be a continuous triple on the category of sets. A type system over  $(S, \triangleright)$  is a contextual subcategory  $TS$  of  $CC(S)$  such that

1. if  $(E_1, \dots, E_n) \in ob_n(TS)$ ,  $i = 1, \dots, n$  and  $E'_i \in S(\{1, \dots, i-1\})$  is such that  $E_i \triangleright E'_i$  then  $(E_1, \dots, E'_i, \dots, E_n) \in ob_n(TS)$ ,
2. if  $(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_m))$ ,  $i = 1, \dots, m$  and  $f'_i \in S(\{1, \dots, n\})$  is such that  $f_i \triangleright f'_i$  then  $(f_1, \dots, f'_i, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_m))$ ,
3. if  $(E_1, \dots, E_n), (T_1, \dots, T_m) \in ob(TS)$ ,  $(f_1, \dots, f_m) \in S(\{1, \dots, n\})^m$ ,  $i = 1, \dots, n$  and  $E'_i \in S(\{1, \dots, i-1\})$  is such that  $E_i \triangleright E'_i$  then

$$(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_m))$$

if and only if  $(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E'_i, \dots, E_n), (T_1, \dots, T_m))$ ,

4. if  $(E_1, \dots, E_n), (T_1, \dots, T_m) \in ob(TS)$ ,  $(f_1, \dots, f_m) \in S(\{1, \dots, n\})^m$ ,  $i = 1, \dots, m$  and  $T'_i \in S(\{1, \dots, i-1\})$  is such that  $T_i \triangleright T'_i$  then

$$(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_m))$$

if and only if  $(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T'_i, \dots, T_m))$ ,

We will write  $TS(S, \triangleright)$  for the set of type systems over  $(S, \triangleright)$ . Type systems over  $(S, =)$  are just the contextual subcategories of  $CC(S)$ .

Define relations  $\triangleright_{TS}$  on  $ob(TS)$  and on the sets  $Hom_{TS}(-, -)$

**Proposition 2.7** [2009.10.18.prop1] *Let  $S$  be a continuous triple on Sets and  $\triangleright$  a reduction structure on  $S$ . A pair of subsets  $Seq_0, Seq_1$  of the form (29) defines a type system over  $(S, \triangleright)$  if and only if it satisfies the conditions of Proposition 2.2 together with the following additional conditions:*

1. *if  $(E_1, \dots, E_n) \in Seq_0$ ,  $i = 1, \dots, n$  and  $E_i \triangleright E'_i$  then  $(E_1, \dots, E'_i, \dots, E_n) \in Seq_0$ ,*
2. *if  $(E_1, \dots, E_{n+1}, t) \in Seq_1$  and  $t \triangleright t'$  then  $(E_1, \dots, E_{n+1}, t') \in Seq_1$ ,*
3. *if  $(E_1, \dots, E_{n+1}, t) \in Seq_1$ ,  $i = 1, \dots, n+1$  and  $E_i \triangleright E'_i$  then  $(E_1, \dots, E'_i, \dots, E_{n+1}, t) \in Seq_1$ ,*
4. *if  $(E_1, \dots, E_{n+1}) \in Seq_0$ ,  $i = 1, \dots, n+1$ ,  $E_i \triangleright E'_i$  and  $(E_1, \dots, E'_i, \dots, E_{n+1}, t) \in Seq_1$  then  $(E_1, \dots, E_i, \dots, E_{n+1}, t) \in Seq_1$ .*

**Proof:** Since  $Seq_0 = ob(TS)$  the first condition of the proposition is equivalent to the first condition of Definition 2.6.

Suppose that  $Seq_0$  and  $Seq_1$  correspond to a contextual subcategory  $TS$  satisfying the conditions of Definition 2.6. A sequence  $(E_1, \dots, E_{n+1}, t)$  is in  $Seq_1$  if and only if  $(1, \dots, n, t)$  is a morphism from  $(E_1, \dots, E_n)$  to  $(E_1, \dots, E_{n+1})$  in  $TS$ . If  $(E_1, \dots, E_{n+1}, t) \in Seq_1$  and  $t \triangleright t'$  then  $(E_1, \dots, E_{n+1}, t') \in Seq_1$  by condition (2) of Definition 2.6. If  $(E_1, \dots, E_{n+1}, t) \in Seq_1$ ,  $i = 1, \dots, n$  and  $E_i \triangleright E'_i$  then by  $(E_1, \dots, E'_i, \dots, E_{n+1}, t) \in Seq_1$  conditions (3) and (4) of Definition 2.6. If  $(E_1, \dots, E_{n+1}) \in Seq_0$ ,  $i = 1, \dots, n+1$ ,  $E_i \triangleright E'_i$  and  $(E_1, \dots, E'_i, \dots, E_{n+1}, t) \in Seq_1$  then  $(E_1, \dots, E_i, \dots, E_{n+1}, t) \in Seq_1$  again by conditions (3), (4) of Definition 2.6.

Suppose now that the conditions (1)-(4) of the proposition are satisfied and  $Seq_0, Seq_1$  correspond to a contextual subcategory  $TS$ . Let us show that  $TS$  satisfies conditions (2)-(4) of Definition 2.6. Let  $(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_m))$ ,  $i = 1, \dots, m$  and  $f'_i \in S(\{1, \dots, n\})$  is such that  $f_i \triangleright f'_i$ . Then  $(f_1, \dots, f'_i, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_m))$  by Lemma 2.4, the definition of the reduction structure on  $S$  and conditions (2), (3) of our proposition.

Let  $(E_1, \dots, E_n), (T_1, \dots, T_m) \in ob(TS)$ ,  $(f_1, \dots, f_m) \in S(\{1, \dots, n\})^m$ ,  $i = 1, \dots, n$  and  $E'_i \in S(\{1, \dots, i-1\})$  is such that  $E_i \triangleright E'_i$ . Then

$$(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_m))$$

if and only if  $(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E'_i, \dots, E_n), (T_1, \dots, T_m))$  by obvious induction, Lemma 2.4 and conditions (3), (4) of the proposition.

Similarly, if  $(E_1, \dots, E_n), (T_1, \dots, T_m) \in ob(TS)$ ,  $(f_1, \dots, f_m) \in S(\{1, \dots, n\})^m$ ,  $i = 1, \dots, m$  and  $T'_i \in S(\{1, \dots, i-1\})$  is such that  $T_i \triangleright T'_i$  then

$$(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_m))$$

if and only if  $(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T'_i, \dots, T_m))$ , by obvious induction, Lemma 2.4, the definition of reduction structure and conditions (3), (4) of the proposition.

**Definition 2.8** [2009.11.4.def1] *Let  $S, \triangleright$  and  $TS$  be as above. Let further  $(\mathcal{C}, p)$  be a category with a universe structure. A closed model of  $TS$  with values in  $(\mathcal{C}, p)$  is a contextual functor*

$$M : TS \rightarrow CC(\mathcal{C}, p)$$

*which is compatible with  $\triangleright$  i.e. such that the following conditions hold:*

1. if  $(E_1, \dots, E_n) \in ob(TS)$ ,  $i = 1, \dots, n$  and  $E'_i \in S(\{x_1, \dots, x_{i-1}\})$  is such that  $E_i \triangleright E'_i$  then  $M(E_1, \dots, E_n) = M(E_1, \dots, E'_i, \dots, E_n)$ ,

2. if  $(f_1, \dots, f_m) \in Hom_{TS}((E_1, \dots, E_n), (T_1, \dots, T_m))$ ,  $i = 1, \dots, m$  and  $f'_i \in S(\{1, \dots, n\})$  is such that  $f_i \triangleright f'_i$  then

$$M((f_1, \dots, f_m); (E_1, \dots, E_n); (T_1, \dots, T_m)) = M((f_1, \dots, f'_i, \dots, f_m); (E_1, \dots, E_n); (T_1, \dots, T_m))$$

3. if  $(E_1, \dots, E_n), (T_1, \dots, T_m) \in ob(TS)$ ,  $(f_1, \dots, f_m) \in S(\{1, \dots, n\})^m$ ,  $i = 1, \dots, n$  and  $E'_i \in S(\{1, \dots, i-1\})$  is such that  $E_i \triangleright E'_i$  then

$$M((f_1, \dots, f_m); (E_1, \dots, E_n); (T_1, \dots, T_m)) = M((f_1, \dots, f_m); (E_1, \dots, E'_i, \dots, E_n); (T_1, \dots, T_m))$$

4. if  $(E_1, \dots, E_n), (T_1, \dots, T_m) \in ob(TS)$ ,  $(f_1, \dots, f_m) \in S(\{1, \dots, n\})^m$ ,  $i = 1, \dots, m$  and  $T'_i \in S(\{1, \dots, i-1\})$  is such that  $T_i \triangleright T'_i$  then

$$M((f_1, \dots, f_m); (E_1, \dots, E_n); (T_1, \dots, T_m)) = M((f_1, \dots, f_m); (E_1, \dots, E_n); (T_1, \dots, T'_i, \dots, T_m))$$

... are called the subset of type sequents and the subset of term sequents of a type system. By Lemma 1.3 they uniquely determine the type system.

Elements of  $Seq_0$  are called contexts and elements of  $Seq_1$  are called judgements. Proposition 2.2 shows that for any type system  $TS$  and any  $(E_1, \dots, E_n, t, T)$  in  $Seq_1(TS)$  the sequence  $(E_1, \dots, E_n)$  is in  $Seq_0$  i.e. the first part of a judgement should be a valid context.

One also often uses the notation  $E_1, E_2, \dots, E_n \vdash T : Type$  which is equivalent to  $E_1, E_2, \dots, E_n, T \vdash$ . The meaning assigned to these subsets is as follows:

1.  $E_1, E_2, \dots, E_n \vdash$  means that  $E_1$  is a well formed closed type expression and for  $i > 1$ ,  $E_i(1, \dots, i-1)$  is a well formed type expression in the context where variables  $1, \dots, i-1$  have types  $E_1, \dots, E_{i-1}$  respectively,
2.  $E_1, E_2, \dots, E_n \vdash t : T$  means that  $E_1, E_2, \dots, E_n, T \vdash$  and in the context where variables  $1, \dots, n$  are of the types  $E_1, \dots, E_n$  respectively,  $t(1, \dots, n)$  is a well formed term expression of type  $T(1, \dots, n)$ .

### 3 Rules and parsing schemes in contextual categories

This section contains some unfinished attempts to formulate which structures on a contextual category can be used to prove that it is a free contextual category given by some "generations and relations". It will have to be re-written (Aug. 8, 2010).

**Rules.** Let  $CC = (B, \tilde{B}, \dots)$  be a contextual category. We will write  $Seq$  for  $B \amalg \tilde{B}$ .

**Definition 3.1 [2009.11.11.def1]** A rule of valency  $n$  on  $CC$  is a subset  $R \subset Seq^n \times Seq$ . A rule is called functional if it defines a partial function  $f_R : U_R \rightarrow Seq$ .

**Definition 3.2 [2009.11.11.def2]** A subset  $Sq \subset Seq$  is said to satisfy a rule  $R$  if for any  $(S_1, \dots, S_n; S') \in R$  such that  $S_1, \dots, S_n \in Sq$  one has  $S' \in Sq$ .

Let  $\mathcal{R}$  be a set of rules on  $CC$ . We say that  $Sq \subset Seq(CC)$  satisfies  $\mathcal{R}$  if it satisfies all the rules from  $\mathcal{R}$ . The intersection of all the subsets in  $Seq$  which satisfy  $\mathcal{R}$  is the smallest subset which satisfies  $\mathcal{R}$  and we denote it by  $Seq(\mathcal{R})$ . We will also write  $Seq_0(\mathcal{R})$  and  $Seq_1(\mathcal{R})$  for the intersections of  $Seq(\mathcal{R})$  with  $B$  and  $\tilde{B}$  respectively.

Let us consider the condition on  $\mathcal{R}$  which are required for the pair of subsets  $(Seq_0(\mathcal{R}), Seq_1(\mathcal{R}))$  to be saturated i.e. to correspond to a contextual subcategory.

A contextual subcategory  $CC'$  of  $CC$  satisfies  $\mathcal{R}$  if  $Seq(CC')$  satisfies  $\mathcal{R}$  as a subset of  $Seq(CC)$ .

**Lemma 3.3** [2009.11.11.11] *Let  $CC$  be a contextual category and  $\mathcal{R}$  be a set of rules on  $CC$ . Then there exists the smallest contextual subcategory  $CC(\mathcal{R})$  which satisfies  $\mathcal{R}$ .*

**Proof:** The whole  $CC$  clearly satisfy all possible rules. Consider the intersection of all contextual subcategories which satisfy  $\mathcal{R}$ . It is a contextual subcategory by Proposition 1.1. Since the intersection of any family of subcategories satisfying a rule  $R$  obviously satisfies this rule as well, we conclude that this subcategory satisfies  $\mathcal{R}$ . Since it is clearly the smallest possible subcategory satisfying  $\mathcal{R}$  this proves the lemma.

The contextual subcategory  $CC(\mathcal{R})$  is called the subcategory generated by the set of rules  $\mathcal{R}$ .

### Parsing schemes.

**Definition 3.4** [2009.11.11.def2] *Let  $CC = (B, \tilde{B}, \dots)$  be a contextual category. A parsing scheme  $\zeta$  on  $CC$  is a triple  $n \geq 0$ ,  $U_\zeta \subset Seq$  and  $\zeta : U_\zeta \rightarrow Seq^n$ .*

**Definition 3.5** [2009.12.1.def1] *Let  $R \subset Seq^n \times Seq$  be a rule of valency  $n$  on  $CC$  and  $\zeta = (n, V_\zeta, \zeta)$  be a parsing scheme. Then  $\zeta$  is said to be a strict parsing scheme for  $R$  if one has:*

1. for any  $S \in V_\zeta$ ,  $(\zeta(S), S) \in R$ ,
2. for any  $(S_1, \dots, S_n, S') \in R$ ,  $S' \in V_\zeta$  and  $\zeta(S') = (S_1, \dots, S_n)$ .

*If only the first of the two conditions is satisfied then  $\zeta$  is called a weak parsing scheme for  $R$ .*

Note that if a strict parsing scheme for  $R$  exists then  $R$  is necessarily functional. Note also that all the structures such as  $ft, \delta, T, S, \Pi$  etc. which we considered above are examples of functional rules on  $CC$ .

**Definition 3.6** [2009.12.01.def2]

1. A  $\Pi$ -shaped parsing scheme on  $CC$  is a parsing scheme  $\zeta$  such that  $V_\zeta \subset \coprod_{n \geq 0} B_{n+1}$  and for  $Z \in V_\zeta \cap B_{n+1}$  one has
  - (a)  $\zeta(Z) \in B_{n+2}$ ,
  - (b)  $ft^2(\zeta(Z)) = ft(Z)$ ,
  - (c) for any  $n + 1 \geq i \geq 1$ ,  $A \in B_{n+2-i}$  such that  $ft(A) = ft^i(Z)$  one has  $T(A, Z) \in V_\zeta$  and  $\zeta(T(A, Z)) = T(A, \zeta(Z))$ ,

- (d) for any  $n + 1 \geq i \geq 1$ ,  $a \in \tilde{B}_{n+1-i}$  such that  $\partial(a) = ft^i(Z)$  one has  $S(a, Z) \in V_\zeta$  and  $\zeta(S(a, Z)) = S(a, \zeta(Z))$ .
2. A  $(\Pi, \lambda)$ -shaped pair of parsing schemes on  $CC$  is a  $\Pi$ -shaped parsing scheme  $\zeta$  together with a parsing scheme  $\xi$  such that  $V_\xi \subset \Pi_{n \geq 0} \tilde{B}_{n+1}$  and for  $f \in V_\xi \cap \tilde{B}_{n+1}$  one has:
- (a)  $\xi(f) \in \tilde{B}_{n+2}$ ,
  - (b)  $\partial(f) \in V_\zeta$ ,
  - (c)  $\partial(\xi(f)) = \zeta(\partial(f))$ ,
  - (d) for any  $n + 1 \geq i \geq 1$ ,  $A \in B_{n+2-i}$  such that  $ft(Y) = ft^i(\partial(f))$  one has  $\tilde{T}(A, f) \in V_\xi$  and  $\xi(\tilde{T}(A, f)) = \tilde{T}(A, \xi(f))$ ,
  - (e) for any  $n + 1 \geq i \geq 1$ ,  $a \in \tilde{B}_{n+1-i}$  such that  $\partial(a) = ft^i(\partial(f))$  one has  $\tilde{S}(a, f) \in V_\xi$  and  $\xi(\tilde{S}(a, f)) = \tilde{S}(a, \xi(f))$ .
3. A  $(\Pi, \lambda, ev)$ -shaped triple of parsing schemes is a  $(\Pi, \lambda)$ -pair  $(\zeta, \xi)$  together with a parsing scheme  $\epsilon$  such that  $V_\epsilon \subset \Pi_{n \geq 0} \tilde{B}_{n+1}$ ,  $V_\epsilon \cap V_\zeta = \emptyset$  and for  $s \in V_\epsilon \cap \tilde{B}_{n+1}$  one has:
- (a)  $\epsilon(s) = (f, Y, r) \in \tilde{B}_{n+1} \times B_{n+2} \times \tilde{B}_{n+1}$ ,  $\partial(f) = ft(Y)$ ,  $\partial(r) \in V_\zeta$ ,  $\zeta(\partial(r)) = Y$ ,
  - (b)  $\partial(s) = S(r, Y)$ ,
  - (c) for any  $n + 1 \geq i \geq 1$ ,  $A \in B_{n+2-i}$  such that  $ft(Y) = ft^i(\partial(s))$  one has  $\tilde{T}(A, s) \in V_\epsilon$  and  $\epsilon(\tilde{T}(A, s)) = \tilde{T}(A, \epsilon(s))$ ,
  - (d) for any  $n + 1 \geq i \geq 1$ ,  $a \in \tilde{B}_{n+1-i}$  such that  $\partial(a) = ft^i(\partial(s))$  one has  $\tilde{S}(a, s) \in V_\epsilon$  and  $\epsilon(\tilde{S}(a, s)) = \tilde{S}(a, \epsilon(s))$ .

**Definition 3.7** [2009.12.1.def3] Let  $CC = (B, \tilde{B}, \dots)$  be a contextual category and  $i \geq 1$ . A weakly adapted  $(\delta, i)$ -shaped parsing scheme on  $CC$  is a parsing scheme  $(\varrho, i)$  such that  $V_{(\varrho, i)} \subset \Pi_{n \geq i} \tilde{B}_{n+1}$  and for  $r \in V_{(\varrho, i)} \cap \tilde{B}_{n+1}$  one has

1.  $(\varrho, i)(r) = ft(\partial(r))$ ,
2.  $r = \delta((\varrho, i)(r), i)$  where for  $Y \in B_n$ ,  $\delta(Y, i) = \tilde{T}_{n-i}(Y, \delta(ft^{n-i}(Y)))$ .

Let us define two more classes of parsing schemes.

**Definition 3.8** [2009.12.2.def1] Let  $CC = (B, \tilde{B}, \dots)$  be a contextual category,  $\tilde{\Omega} \in B_2$  and  $\Omega = ft(\tilde{\Omega})$ . Then

1. A weakly adapted  $\Omega$ -shaped parsing scheme is a parsing scheme  $\omega$  such that  $V_\omega \subset \Pi_{n \geq 0} B_{n+1}$  and for  $X \in V_\omega \cap B_{n+1}$  one has
  - (a)  $\omega(X) = ft(X)$ ,
  - (b)  $X = T_n(ft(X), \Omega)$ .
2. A weakly adapted  $\tilde{\Omega}$ -shaped parsing scheme on  $CC$  is a parsing scheme  $\tilde{\omega}$  such that  $V_{\tilde{\omega}} \subset \Pi_{n \geq 0} B_{n+1}$  and for  $X \in V_{\tilde{\omega}} \cap B_{n+1}$  one has
  - (a)  $\tilde{\omega}(X) \in \tilde{B}_{n+1}$ ,

- (b)  $\partial(\tilde{\omega}(X)) = T_n(ft(X), \Omega)$ ,
- (c)  $X = S(\tilde{\omega}(X), T_n(ft(X), \tilde{\Omega}))$ .

3. A very weakly adapted  $(\tilde{\Omega}, \Pi_{\Omega})$ -shaped pair of parsing schemes is a weakly adapted  $\tilde{\Omega}$ -shaped parsing scheme  $\tilde{\omega}$  and a parsing scheme  $\kappa$  such that  $V_{\kappa} \subset \Pi_{n \geq 0} \tilde{B}_{n+1}$  and for  $p \in V_{\kappa} \cap \tilde{B}_{n+1}$  one has

- (a)  $\kappa(p) = (r, s) \in \tilde{B}_{n+1} \times \tilde{B}_{n+2}$ ,  $\partial(s) = T_{n+1}(ft(\partial(s)), \Omega)$ ,  $ft(\partial(s)) \in V_{\tilde{\omega}} \cap \tilde{B}_{n+1}$  and  $r = \omega(ft(\partial(s)))$ ,
- (b)  $ft(\partial(r)) = ft(\partial(p))$ ,
- (c)  $\partial(p) = T_n(ft(\partial(p)), \Omega)$ .

**Lemma 3.9** [2009.11.11.13] *Let  $CC$  and  $\mathcal{R}$  be as above. Let  $CC'$  be a subcategory satisfying  $\mathcal{R}$ . Suppose that there exists a parsing scheme on  $Seq_0(CC') \amalg Seq_1(CC')$  relative to  $\mathcal{R}$ . Then  $CC'$  is generated by  $\mathcal{R}$ .*

**Proof:** Using induction on the length of the parsing tree from  $S \in Seq_0(CC') \amalg Seq_1(CC')$  one can easily see that any such  $S$  belongs to the subcategory generated by  $\mathcal{R}$ .

Let  $\mathcal{R}$  be a collection of rules and let  $Seq(\mathcal{R})$  be the smallest subset in  $Seq$  which satisfies  $\mathcal{R}$ .

## 4 Weak intermediate type systems

**Definition 4.1** [2010.1.19.def1] *A universe scheme  $\mathcal{U}$  is a collection of data of the following form:*

1. a set  $Univ$ ,
2. an element  $*$   $\in Univ$ ,
3. a reflexive, transitive binary relation  $\leq$  on  $Univ$ ,
4. a binary relation  $:$  on  $Univ$ .

## 7 The system of Coq

The goal of these notes is to collect the material needed to prove that the system of inductive constructors and reductions supported by the Coq proof assistant is compatible with the univalent interpretation of type theory. For information about inductive definitions in Coq see [9], [2][p.77] (good notations) and [6].

### 1 A type system CIC0

We start with a subset of current Coq system with a simplified universe structure which we call CIC0. Namely, we will only allow for two universes **Prop** and **Type0** =  $Type(0)$  with **Prop**  $\subset$

**Type0** and **Prop : Type0** but without **Type0 : Type0**. We only allow universal quantification over expressions which type to **Type0** and our **Prop** is impredicative i.e. the product of any family of members of **Prop** again types to **Prop**. We will also use slightly different syntax in our description. We will use  $\prod$  and  $\lambda$  and most notably we will make the evaluation explicit and having three arguments the first of which is the domain of the function to be evaluated. This allows one to have unambiguous  $\eta$ -reduction.

For simplicity of notation we will use named free variables (instead of the free variables being always named by natural numbers as in Proposition 2.2). We will also use "vector notation" writing  $\vec{x} : \vec{E}$  for  $x_1 : E_1, \dots, x_n : E_n$  etc. and write  $\Gamma$  to denote any valid context. To distinguish the names of variables and constructors (including constants) from the symbols which denote expressions we will use bold face for the former (except for  $\prod$ ,  $\lambda$  etc. where no ambiguity is possible). Since writing out the three-argument evaluation expressions would make the text very hard to read we will often write  $\mathbf{ev}(f, \vec{x})$  instead of  $\mathbf{ev}(X_1, \dots, \mathbf{ev}(X_i, \dots, \mathbf{ev}(X_1, f, x_1), \dots, x_i), \dots, x_n)$  where  $X_i$  is the type of  $x_i$ .

**Remark 1.1 [2010.08.08.rem1]** Note that if one does not include the substitution rules of Proposition 2.2 explicitly, the context and judgement formation rules should be such that the variables introduced by a context "above the line" can appear in the expressions "below the line" either among the context variables or among the bounded variables of the expressions. If a variable introduced in a context "above the line" appears in an expression below the line as a free variable such a rule will be unstable under the substitution of this variable by an expression.

The basic context and judgement formation rules in CIC0 are as follows.

### Basic rules

$$\frac{\mathbf{x}_1 : E_1, \dots, \mathbf{x}_n : E_n \vdash}{\mathbf{x}_1 : E_1, \dots, \mathbf{x}_n : E_n \vdash \mathbf{x}_i : E_i} \quad i = 1, \dots, n$$

### The universe structure

$$\frac{\Gamma \vdash}{\Gamma, \mathbf{T} : \mathbf{Type0} \vdash} \quad \frac{\Gamma \vdash T : \mathbf{Type0}}{\Gamma, \mathbf{t} : T \vdash} \quad \frac{\Gamma \vdash}{\Gamma, \mathbf{P} : \mathbf{Prop} \vdash} \quad \frac{\Gamma \vdash P : \mathbf{Prop}}{\Gamma, \mathbf{p} : P \vdash}$$

$$\frac{\Gamma \vdash}{\Gamma \vdash \mathbf{Prop} : \mathbf{Type0}} \quad \frac{\Gamma \vdash P : \mathbf{Prop}}{\Gamma \vdash P : \mathbf{Type0}}$$

### Underlying $\lambda$ -calculus

$$\frac{\Gamma, \mathbf{t1} : T1, \mathbf{t2} : T2 \vdash}{\Gamma, \mathbf{t3} : \prod \mathbf{t1} : T1.T2 \vdash}$$

$$\frac{\Gamma \vdash T1 : \mathbf{Type0} \quad \Gamma, \mathbf{t1} : T1 \vdash T2 : \mathbf{Type0}}{\Gamma \vdash \prod \mathbf{t1} : T1.T2 : \mathbf{Type0}}$$

$$\frac{\Gamma, \mathbf{t1} : T1 \vdash T2 : \mathbf{Prop}}{\Gamma \vdash \prod \mathbf{t1} : T1.T2 : \mathbf{Prop}}$$

$$\frac{\Gamma, \mathbf{t1} : T1 \vdash t2 : T2}{\Gamma \vdash \lambda \mathbf{t1} : T1.t2 : \prod \mathbf{t1} : T1.T2} \quad \frac{\Gamma \vdash f : \prod \mathbf{t1} : T1.T2 \quad \Gamma \vdash t : T1}{\Gamma \vdash \mathbf{ev}(T1, f, t) : T2[t/\mathbf{t1}]}$$

$\beta$ -reduction :  $\mathbf{ev}(T1, \lambda \mathbf{t1} : T1.t2, t) \searrow t2[t/\mathbf{t1}]$       $\eta$ -reduction :  $\lambda \mathbf{t1} : T1.\mathbf{ev}(T1, f, \mathbf{t1}) \searrow f$

Note that the  $\beta$ - and  $\eta$ -reductions are defined on the level of the system of expressions.

### Inductive types (Ia)

$$\frac{\Gamma \vdash}{\Gamma \vdash \emptyset : \mathbf{Prop}}$$

$$\frac{\Gamma, \mathbf{t} : T \vdash \quad \Gamma \vdash x : \emptyset}{\Gamma \vdash \epsilon(x, T) : T} \quad (\text{resp. } \frac{\Gamma \vdash T : \mathbf{Type0} \quad \Gamma \vdash x : \emptyset}{\Gamma \vdash \epsilon(x, T) : T} )$$

$$\frac{\Gamma, \mathbf{t1} : T1 \vdash \quad \Gamma, \mathbf{t2} : T2 \vdash}{\Gamma, \mathbf{t} : \Pi(T1, T2) \vdash} \quad (\text{resp. } \frac{\Gamma \vdash T1 : \mathbf{Type0} \quad \Gamma \vdash T2 : \mathbf{Type0}}{\Gamma \vdash \Pi(T1, T2) : \mathbf{Type0}} )$$

### Inductive types (II)

What follows is just an explicit form of a general inductive construction of the CIC with additional restrictions on the "sizes" of the relevant type expressions and with the condition that in the constructors all the non-recursive components are grouped together and placed in front of the "recursive" ones. The input ("above the line") data for a general inductive definition in a context  $\Gamma \vdash$  looks as follows:

1. integers:  $na \geq 0$  (the number of "pseudo-params") and  $nc \geq 0$  (the number of constructors),
2. for each  $i = 1, \dots, nc$  and integer  $nd^{(i)} \geq 0$ ,
3. a valid context  $(\Gamma, \mathbf{a}_1 : A_1, \dots, \mathbf{a}_{na} : A_{na} \vdash)$
4. for each  $i = 1, \dots, nc$  a valid context of the form  $(\Gamma, \vec{\mathbf{b}}^{(i)} : \vec{B}^i \vdash)$ , such that each  $B_j^{(i)}$  types to  $\mathbf{Type0}$  in the context where it is defined,
5. for each  $i = 1, \dots, nc$  and each  $j = 1, \dots, na$  a valid judgement of the form

$$(\Gamma, \vec{\mathbf{b}}^{(i)} : B^{(i)} \vdash m_j^{(i)} : A_j[m_1^{(i)}/\mathbf{a}_1, \dots, m_{j-1}^{(i)}/\mathbf{a}_{j-1}]),$$



6. for each  $i = 1, \dots, nc$  and each  $j = 1, \dots, nd^{(i)}$  a valid context of the form  $(\Gamma, \vec{\mathbf{b}}^{(i)} : \vec{B}^{(i)}, \vec{\mathbf{d}}^{(i),j} : \vec{D}^{(i),j} \vdash)$ , such that each expression  $D_k^{(i),j}$  types to **Type0** in the context where it is defined,

7. for each  $i = 1, \dots, nc$ ,  $j = 1, \dots, nd^{(i)}$  and  $k = 1, \dots, na$  a valid judgement of the form

$$(\Gamma, \vec{\mathbf{b}}^{(i)} : B^{(i)}, \vec{\mathbf{d}}^{(i),j} : \vec{D}^{(i),j} \vdash q_k^{(i),j} : A_j[q_1^{(i),j}/\mathbf{a}_1, \dots, q_{k-1}^{(i),j}/\mathbf{a}_{k-1}])$$

For simplicity of notation we will write simply  $A, B, D, q$  and  $m$  for  $\vec{\mathbf{a}} : \vec{A}, (\vec{\mathbf{b}}^{(1)} : \vec{B}^{(1)}), \dots, (\vec{\mathbf{b}}^{(nc)} : \vec{B}^{(nc)})$  etc. To further simplify the matter we will write  $BID$  ("Basic Input Data") for the sequence  $(na; nc; nd^{(1)}, \dots, nd^{(nc)}; A; B; D; q; m)$  which has to be included in the notation for every object generated by the inductive construction.

The output consists of the following objects:

1. A valid judgement of the form  $(\Gamma \vdash \mathbf{IT}(BID) : \prod \vec{\mathbf{a}} : \vec{A}. \mathbf{Type0})$ . Note that the expression  $\mathbf{IT}(BID)$  bounds the variables  $\mathbf{a}_1, \dots, \mathbf{a}_{na}, \vec{\mathbf{b}}^{(i)}$  and  $\vec{\mathbf{d}}^{(i),j}$ .

2. For each  $i = 1, \dots, nc$  a valid judgement of the form

$$\begin{aligned} \Gamma \vdash \mathbf{c}(i, BID) : \prod \vec{\mathbf{b}}^{(i)} : \vec{B}^{(i)}, \\ \prod \mathbf{z}_1^{(i)} : (\prod \vec{\mathbf{d}}^{(i),1} : \vec{D}^{(i),1}, \mathbf{ev}(\mathbf{IT}(BID), \vec{q}^{(i),1})), \\ \dots, \\ \prod \mathbf{z}^{(i),nd^{(i)}} : (\prod \vec{\mathbf{d}}^{(i),nd^{(i)}} : \vec{D}^{(i),nd^{(i)}}, \mathbf{ev}(\mathbf{IT}(BID), \vec{q}^{(i),nd^{(i)}})), \\ \mathbf{ev}(\mathbf{IT}(BID), \vec{m}^{(i)}) \end{aligned}$$

where each  $\mathbf{c}(i, BID)$  again bounds all of the variables  $\mathbf{a}_1, \dots, \mathbf{a}_{na}, \vec{\mathbf{b}}^{(i)}$  and  $\vec{\mathbf{d}}^{(i),j}$ .

3. A valid judgement of the form

$$\Gamma \vdash \mathbf{rect}(\vec{\mathbf{a}}\vec{\mathbf{r}}, \mathbf{r}, BID) : \mathbf{Trect}(\vec{\mathbf{a}}\vec{\mathbf{r}}, \mathbf{r}, BID)$$

where

$$\begin{aligned} \mathbf{Trect}(\vec{\mathbf{a}}\vec{\mathbf{r}}, \mathbf{r}, BID) &:= \\ &= \prod P : \left( \prod \vec{\mathbf{a}}\vec{\mathbf{r}} : \vec{A}, \mathbf{ev}(\mathbf{IT}(BID), \vec{\mathbf{a}}\vec{\mathbf{r}}) \rightarrow \mathbf{Type0} \right), \\ (RC^{(1)} - > \dots - > RC^{(nc)} - > \prod \vec{\mathbf{a}}\vec{\mathbf{r}} : \vec{A}, \prod \mathbf{r} : \mathbf{ev}(\mathbf{IT}(BID), \vec{\mathbf{a}}\vec{\mathbf{r}}), \mathbf{ev}(\mathbf{ev}(P, \vec{\mathbf{a}}\vec{\mathbf{r}}), \mathbf{r})) \end{aligned}$$

and

$$\begin{aligned} RC^{(i)} &= \prod \vec{\mathbf{b}}^{(i)} : \vec{B}^{(i)}, \\ \prod \mathbf{z}_1^{(i)} &: (\prod \vec{\mathbf{d}}^{(i),1} : \vec{D}^{(i),1}, \mathbf{ev}(\mathbf{IT}(BID), \vec{q}^{(i),1})), \\ \prod \mathbf{y}_1^{(i)} &: (\prod \vec{\mathbf{d}}^{(i),1} : \vec{D}^{(i),1}, \mathbf{ev}(\mathbf{ev}(P, \vec{q}^{(i),1}), \mathbf{ev}(\mathbf{z}_1^{(i)}, \vec{\mathbf{d}}^{(i),1}))), \\ &\dots \\ \prod \mathbf{z}_{nd^{(i)}}^{(i)} &: (\prod \vec{\mathbf{d}}^{(i),nd^{(i)}} : \vec{D}^{(i),nd^{(i)}}, \mathbf{ev}(\mathbf{IT}(BID), \vec{q}^{(i),nd^{(i)}})), \\ \prod \mathbf{y}_{nd^{(i)}}^{(i)} &: (\prod \vec{\mathbf{d}}^{(i),nd^{(i)}} : \vec{D}^{(i),nd^{(i)}}, \mathbf{ev}(\mathbf{ev}(P, \vec{q}^{(i),nd^{(i)}}), \mathbf{ev}(\mathbf{z}_{nd^{(i)}}^{(i)}, \vec{\mathbf{d}}^{(i),nd^{(i)}}))), \\ &\mathbf{ev}(\mathbf{ev}(P, \vec{m}^{(i)}), \mathbf{ev}(\mathbf{ev}(\mathbf{c}(i, BID), \vec{\mathbf{b}}^{(i)}), \vec{\mathbf{z}}^{(i)})). \end{aligned}$$

4. The constructions **IT**, **c** and **rect** satisfy the following reduction rule which is called  $\iota$ -reduction:

Note that with the previous definition (which we will call  $P$ -definition) one can not use inductive elimination to define functions from inductive types to "large types". E.g. given a type expression  $T$  there is no way to define a function  $f : \text{nat} \rightarrow \text{Type0}$  such that  $f n = T^n$ .

Alternatively we can define the  $Q$ -form of inductive constructions as follows. The input data is the same. The output data is of the form:

1. A valid judgement of the form  $(\Gamma \vdash \mathbf{IT}(BID) : \prod \vec{\mathbf{a}} : \vec{A}.\mathbf{Type0})$ .
2. For each  $i = 1, \dots, nc$  a valid judgement of the form

$$\begin{aligned} \Gamma \vdash \mathbf{c}(i, BID) : \prod \vec{\mathbf{b}}^{(i)} : \vec{B}^{(i)}, \\ \prod \mathbf{z}_1^{(i)} : (\prod \vec{\mathbf{d}}^{(i),1} : \vec{D}^{(i),1}, \mathbf{ev}(\mathbf{IT}(BID), \vec{q}^{(i),1})), \\ \dots, \\ \prod \mathbf{z}_{nd^{(i)}}^{(i)} : (\prod \vec{\mathbf{d}}^{(i),nd^{(i)}} : \vec{D}^{(i),nd^{(i)}}, \mathbf{ev}(\mathbf{IT}(BID), \vec{q}^{(i),nd^{(i)}})), \\ \mathbf{ev}(\mathbf{IT}(BID), \vec{m}^{(i)}) \end{aligned}$$

3. For any valid context of the form

$$(\Gamma, \vec{\mathbf{a}}\mathbf{r} : \vec{A}, \mathbf{r} : \mathbf{ev}(\mathbf{IT}(BID), \vec{\mathbf{a}}\mathbf{r}), \mathbf{x} : Q \vdash)$$

a valid judgement of the form

$$\Gamma \vdash \mathbf{rect}(\vec{\mathbf{a}}\mathbf{r}, \mathbf{r}, Q, BID) : \mathbf{TrectQ}(\vec{\mathbf{a}}\mathbf{r}, \mathbf{r}, Q, BID)$$

where

$$\mathbf{TrectQ}(\vec{\mathbf{a}}\mathbf{r}, \mathbf{r}, Q, BID) := RCQ^{(1)} \rightarrow \dots \rightarrow RCQ^{(nc)} \rightarrow \prod \vec{\mathbf{a}}\mathbf{r} : \vec{A}, \prod \mathbf{r} : \mathbf{ev}(\mathbf{IT}(BID), \vec{\mathbf{a}}\mathbf{r}), Q$$

and

$$\begin{aligned} RCQ^{(i)} &= \prod \vec{\mathbf{b}}^{(i)} : \vec{B}^{(i)}, \\ \prod \mathbf{z}_1^{(i)} &: (\prod \vec{\mathbf{d}}^{(i),1} : \vec{D}^{(i),1}, \mathbf{ev}(\mathbf{IT}(BID), \vec{q}^{(i),1})), \\ \prod \mathbf{y}_1^{(i)} &: (\prod \vec{\mathbf{d}}^{(i),1} : \vec{D}^{(i),1}, Q[\vec{q}^{(i),1}/\vec{\mathbf{a}}\mathbf{r}, \mathbf{ev}(\mathbf{z}_1^{(i)}, \vec{\mathbf{d}}^{(i),1})/\mathbf{r}]), \\ &\dots \\ \prod \mathbf{z}_{nd^{(i)}}^{(i)} &: (\prod \vec{\mathbf{d}}^{(i),nd^{(i)}} : \vec{D}^{(i),nd^{(i)}}, \mathbf{ev}(\mathbf{IT}(BID), \vec{q}^{(i),nd^{(i)}})), \\ \prod \mathbf{y}_{nd^{(i)}}^{(i)} &: (\prod \vec{\mathbf{d}}^{(i),nd^{(i)}} : \vec{D}^{(i),nd^{(i)}}, Q[\vec{q}^{(i),nd^{(i)}}/\vec{\mathbf{a}}\mathbf{r}, \mathbf{ev}(\mathbf{z}_{nd^{(i)}}^{(i)}, \vec{\mathbf{d}}^{(i),nd^{(i)}})/\mathbf{r}]), \\ &Q[\vec{m}^{(i)}/\vec{\mathbf{a}}\mathbf{r}, \mathbf{ev}(\mathbf{ev}(\mathbf{c}(i, BID), \vec{\mathbf{b}}^{(i)}), \vec{\mathbf{z}}^{(i)})/\mathbf{r}]. \end{aligned}$$

4. The constructions **IT**, **c** and **rect** satisfy the following  $\iota$ -reduction rule:

Finally, there is the following  $R$ -form of inductive constructions which is stronger than the previous two. The input data is the same but without the restriction on  $B$  and  $D$  to be small. The output data is of the form:

1. A valid context of the form  $(\Gamma, \vec{\mathbf{a}}\mathbf{r} : \vec{A}, \mathbf{r} : \mathbf{ITR}(\vec{\mathbf{a}}\mathbf{r}, BID) \vdash)$ ,
2. For each  $i = 1, \dots, nc$  a valid judgement of the form

$$\begin{aligned} \Gamma \vdash \mathbf{c}(i, BID) : \prod \vec{\mathbf{b}}^{(i)} : \vec{B}^{(i)}, \\ \prod \mathbf{z}_1^{(i)} : (\prod \vec{\mathbf{d}}^{(i),1} : \vec{D}^{(i),1}, \mathbf{ITR}(BID)[\vec{q}^{(i),1}/\vec{\mathbf{a}}\mathbf{r}]), \\ \dots, \\ \prod \mathbf{z}_{nd^{(i)}}^{(i)} : (\prod \vec{\mathbf{d}}^{(i),nd^{(i)}} : \vec{D}^{(i),nd^{(i)}}, \mathbf{ITR}(BID)[\vec{q}^{(i),nd^{(i)}}/\vec{\mathbf{a}}\mathbf{r}]), \\ \mathbf{ITR}(BID)[\vec{m}^{(i)}/\vec{\mathbf{a}}\mathbf{r}] \end{aligned}$$

3. For any valid context of the form

$$(\Gamma, \vec{\mathbf{a}}\mathbf{r} : \vec{A}, \mathbf{r} : \mathbf{ITR}(BID), \mathbf{x} : Q \vdash)$$

a valid judgement of the form

$$\Gamma \vdash \mathbf{rect}(\vec{\mathbf{a}}\mathbf{r}, \mathbf{r}, Q, BID) : \mathbf{TrectR}(\vec{\mathbf{a}}\mathbf{r}, \mathbf{r}, Q, BID)$$

where

$$\begin{aligned} \mathbf{TrectR}(\vec{\mathbf{a}}\mathbf{r}, \mathbf{r}, Q, BID) := \\ RCQ^{(1)} - > \dots - > RCQ^{(nc)} - > \prod \vec{\mathbf{a}}\mathbf{r} : \vec{A}, \prod \mathbf{r} : \mathbf{ITR}(BID), Q \end{aligned}$$

and

$$\begin{aligned} RCQ^{(i)} = \prod \vec{\mathbf{b}}^{(i)} : \vec{B}^{(i)}, \\ \prod \mathbf{z}_1^{(i)} : (\prod \vec{\mathbf{d}}^{(i),1} : \vec{D}^{(i),1}, \mathbf{ITR}(BID)[\vec{q}^{(i),1}/\vec{\mathbf{a}}\mathbf{r}]), \\ \prod \mathbf{y}_1^{(i)} : (\prod \vec{\mathbf{d}}^{(i),1} : \vec{D}^{(i),1}, Q[\vec{q}^{(i),1}/\vec{\mathbf{a}}\mathbf{r}, \mathbf{ev}(\mathbf{z}_1^{(i)}, \vec{\mathbf{d}}^{(i),1})/\mathbf{r}]), \\ \dots \\ \prod \mathbf{z}_{nd^{(i)}}^{(i)} : (\prod \vec{\mathbf{d}}^{(i),nd^{(i)}} : \vec{D}^{(i),nd^{(i)}}, \mathbf{ITR}(BID)[\vec{q}^{(i),nd^{(i)}}/\vec{\mathbf{a}}\mathbf{r}]), \\ \prod \mathbf{y}_{nd^{(i)}}^{(i)} : (\prod \vec{\mathbf{d}}^{(i),nd^{(i)}} : \vec{D}^{(i),nd^{(i)}}, Q[\vec{q}^{(i),nd^{(i)}}/\vec{\mathbf{a}}\mathbf{r}, \mathbf{ev}(\mathbf{z}_{nd^{(i)}}^{(i)}, \vec{\mathbf{d}}^{(i),nd^{(i)}})/\mathbf{r}]), \\ Q[\vec{m}^{(i)}/\vec{\mathbf{a}}\mathbf{r}, \mathbf{ev}(\mathbf{ev}(\mathbf{c}(i, BID), \vec{\mathbf{b}}^{(i)}), \vec{\mathbf{z}}^{(i)})/\mathbf{r}]. \end{aligned}$$

4. The constructions  $\mathbf{ITR}$ ,  $\mathbf{c}$  and  $\mathbf{rect}$  satisfy the following  $\iota$ -reduction rule:

In the case of  $R$ -form we also have an extra rule which says that if  $B$  and  $D$  are small (type to  $Type0$ ) then  $(\Gamma, \vec{\mathbf{a}} : \vec{A} \vdash \mathbf{ITR}(\vec{\mathbf{a}}, BID) : Type0)$  is a valid judgement.

The Coq syntax for an inductive definition with these input data and values in a sort  $s$  (where  $s = Prop, Set$  or  $Type$ ) would look as follows:

Inductive  $X : \text{forall } \vec{\mathbf{a}} : \vec{A}, s := c^{(1)} : C^{(1)} \mid \dots \mid c^{(nc)} : C^{(nc)}$ .

Where

$$C^{(i)} := \text{forall } \vec{\mathbf{b}}^{(i)} : \vec{B}^{(i)}, \\ \text{forall } \mathbf{z}_1^{(i)} : (\text{forall } \vec{\mathbf{d}}_1^{(i)} : \vec{D}_1^{(i)}, X \vec{q}_1^{(i)}), \dots, \text{forall } \mathbf{z}_{nd^{(i)}}^{(i)} : (\text{forall } \vec{\mathbf{d}}_{nd^{(i)}}^{(i)} : \vec{D}_{nd^{(i)}}^{(i)}, X \vec{q}_{nd^{(i)}}^{(i)}), \\ X \vec{m}^{(i)}.$$

We will use below the notation  $C^{(i)}$  for the direct analog of this expression in  $CIC0$  as well. To write this analog explicitly one has to replace all "forall  $w : W$ ," with " $\prod w : W$ ," and write our three-arguments  $\mathbf{ev}(\dots, \dots, \dots)$  wherever applications occur. For example,  $X \vec{m}^{(i)}$  will look as follows:

$$\mathbf{ev}(X, \vec{m}^{(i)}) = \mathbf{ev}(A_{na}[m_1^{(i)}/\mathbf{a}_1, \dots, m_{na-1}^{(i)}/\mathbf{a}_{na-1}], \dots, \mathbf{ev}(A_j[m_1^{(i)}/\mathbf{a}_1, \dots, m_{j-1}^{(i)}/\mathbf{a}_{j-1}], \dots \\ \dots, \mathbf{ev}(A_1, X, m_1^{(i)}), \dots, m_j^{(i)}), \dots, m_{na}^{(i)})$$

**Example 1.2** The following list gives the form of our  $BID$  for some of the inductive constructions which are often used in Coq.

1. To define natural numbers  $nat$  one takes  $na = 0$ ,  $nc = 2$ ,  $nd^{(1)} = 0$ ,  $nd^{(2)} = 1$ ,  $\vec{B}^{(1)} = ()$  (empty sequence),  $\vec{B}^{(2)} = ()$ ,  $\vec{D}_1^{(2)} = ()$ .
2. To define binary trees one takes  $na = 0$ ,  $nc = 2$ ,  $nd^{(1)} = 0$ ,  $nd^{(2)} = 2$ ,  $\vec{B}^{(1)} = ()$ ,  $\vec{B}^{(2)} = ()$ ,  $\vec{D}_1^{(2)} = ()$ ,  $\vec{D}_2^{(2)} = ()$ .
3. Given  $(\Gamma \vdash T : \mathbf{Type0})$  one defines the equality types for  $T$  using the input data of the form  $na = 2$ ,  $nc = 1$ ,  $nd^{(1)} = 0$ ,  $\vec{A} = (\mathbf{t1} : T, \mathbf{t2} : T)$ ,  $\vec{B}^{(1)} = (\mathbf{t} : T)$ ,  $\vec{m}^{(1)} = (\mathbf{t}, \mathbf{t})$ .
4. Given  $(\Gamma \vdash T1 : \mathbf{Type0})$  and  $(\Gamma, \mathbf{t1} : T1 \vdash T2 : \mathbf{Type0})$  one defines the dependent sum (in the standard notation  $\sum \mathbf{t1} : T1.T2$ ) using the input data  $na = 0$ ,  $nc = 1$ ,  $nd^{(1)} = 0$ ,  $\vec{B}^{(1)} = (\mathbf{t1} : T1, \mathbf{t2} : T2)$ .
5. empty, unit, unions.

## 2 Representing inductive definitions in Coq as combinations of elementary ones

In Coq an inductive definition with parameters is just a combination of an inductive definition without parameters in a wider context with the dependent product and abstraction. For a detailed translation see Appendix A. In what follows we will discuss only inductive definitions of the basic Calculus of Inductive Constructions as described in [9], [6] and [2, pp.77-80].

Recall, that in the notation of CIC one writes  $(a : A)$  for what in Coq is *forall*  $a : A$ , and in the standard type-theoretic notation  $\prod a : A$ . and  $[a : A]$  for what in Coq is *fun*  $a : A \Rightarrow$  and in the standard type-theoretic notation  $\lambda a : A$ .

A general expression for an inductive type in a context  $\Gamma$  is of the form  $I(X : \vec{A}s)\{C^{(1)}, \dots, C^{(nc)}\}$  where  $\vec{A}s$  is an "arity" i.e. a valid type expression in  $\Gamma$  of the form

$$(\vec{a} : \vec{A})s = (a_1 : A_1) \dots (a_{na} : A_{na})s$$

where  $s$  is a sort and each  $C^{(k)}$  is a type expression defined in the context  $\Gamma, X : \vec{A}s$  which has the form of a "type of constructor expression" (cf. [2, p.77]).

In Coq inductive type of the form  $I(X : \vec{A}s)\{C^{(1)}, \dots, C^{(nc)}\}$  is introduced using the following syntax:

Inductive X: forall a\_1:A\_1, forall a\_2:A\_2, ... ,forall a\_na:A\_na, s := cc\_1 : C\_1 | ... | cc\_nc : C\_nc .

**Lemma 2.1 [2010.1.19.12]** *Any type of constructor expression  $C$  in variable  $X$  of type  $\vec{A}s$  can be written in a unique way in the form:*

$$\begin{aligned} C = & (z_{1,1} : (\vec{d} : \vec{D}_{1,1}) X \vec{q}_{1,1}) \dots (z_{1,nd_1} : (\vec{d} : \vec{D}_{1,nd_1}) X \vec{q}_{1,nd_1})(b_1 : B_1) \\ & (z_{2,1} : (\vec{d} : \vec{D}_{2,1}) X \vec{q}_{2,1}) \dots (z_{2,nd_2} : (\vec{d} : \vec{D}_{2,nd_2}) X \vec{q}_{2,nd_2})(b_2 : B_2) \\ & \dots \dots \dots \\ & (b_{nb} : B_{nb})(z_{nb,1} : (\vec{d} : \vec{D}_{nb,1}) X \vec{q}_{nb,1}) \dots (z_{nb,nd_{nb}} : (\vec{d} : \vec{D}_{nb,nd_{nb}}) X \vec{q}_{nb,nd_{nb}}) X \vec{m} \end{aligned}$$

where  $B_i$ ,  $\vec{D}_{i,j}$ ,  $\vec{q}_{i,j}$  and  $\vec{m}$  do not depend on  $X$  i.e. can be defined in a context which does not contain  $X$ .

Since  $z_{k,l}$  can only appear in a context which contains  $X$  we get the following observation:

**Lemma 2.2 [2010.1.14.11]** *In a type of constructor expression of the form given above  $\vec{D}_{i,j}$ ,  $\vec{q}_{i,j}$ ,  $\vec{m}$  and  $B_i$  do not depend on  $z_{k,l}$ .*

The dependencies between different sub-terms of  $C$  can be visualized by the following diagram:

$$\begin{array}{ccc} (\Gamma, B_1, \dots, B_i, \vec{D}_{i,1}), \dots, (\Gamma, B_1, \dots, B_i, \vec{D}_{i,nd_i}) & & (\Gamma, \vec{D}_{1,1}), \dots, (\Gamma, \vec{D}_{1,nd_1}) \\ \downarrow & & \downarrow \\ \dots \longrightarrow & (\Gamma, B_1, \dots, B_i) & \longrightarrow \dots \longrightarrow & (\Gamma) \end{array} \quad (30)$$

The sequences  $\vec{q}_{i,j}$  correspond to morphisms  $(\Gamma, B_1, \dots, B_i, \vec{D}_{i,j}) \rightarrow (\Gamma, \vec{A})$  over  $\Gamma$  and the sequence  $\vec{m}$  to a morphism  $(\Gamma, \vec{B}) \rightarrow (\Gamma, \vec{A})$  over  $\Gamma$ .

Due to the structure of the dependencies diagram (30), the expression

$$[2010.1.21.eq2] C' = (\vec{b} : \vec{B})(z_{1,1} : (\vec{d} : \vec{D}_{1,1}) X \vec{q}_{1,1}) \dots (z_{nb,nd_{nb}} : (\vec{d} : \vec{D}_{nb,nd_{nb}}) X \vec{q}_{nb,nd_{nb}}) X \vec{m} \quad (31)$$

is well formed in  $(\Gamma, X : \vec{A}s)$  and there is a canonical bijection between the terms of type  $C$  and terms of type  $C'$ .

The inductive machinery of Coq defines for any collection of contexts of the form

$$[2010.1.21.eq1](\Gamma, \vec{a} : \vec{A}, s), \quad (\Gamma, X : \vec{A} s, C^{(1)} : s''), \dots (\Gamma, X : \vec{A} s, C^{(nc)} : s'') \quad (32)$$

where  $C^{(k)}$  are of the form described above, a term  $I = I(X : \vec{A} s)\{C^{(1)}, \dots, C^{(nc)}\}$  of type  $(\vec{a} : \vec{A})s$  in  $\Gamma$ , a sequence of terms  $c^{(k)}$  of types  $C^{(k)}[I/X]$  for  $k = 1, \dots, nc$  in  $\Gamma$  and, for each "admissible" sort  $s'$  a "recursor" term  $I_{rec}$  (again in  $\Gamma$ ). The type of this term is

$$[2010.1.17.eq1]I_{rec} : (Q : (\vec{a} : \vec{A})(r : I \vec{a})s')(f_1 : \Delta\{I/X, C^{(1)}, Q, c^{(1)}/c\}) \dots \\ \dots (f_{nc} : \Delta\{I/X, C^{(nc)}, Q, c^{(nc)}/c\})(\vec{a} : \vec{A})(r : I \vec{a})Q \vec{a} r. \quad (33)$$

where for  $C$  of the form given above and defined for a variable  $X$ ,  $\Delta\{X, C, Q, c\}$  is the type expression in the context  $(\Gamma, X : (\vec{a} : \vec{A})s, Q : (\vec{a} : \vec{A})(r : X \vec{a})s', c : C)$  of the form:

$$(z_{1,1} : (\vec{d} : \vec{D}_{1,1})X \vec{q}_{1,1})(y_{1,1} : (\vec{d} : \vec{D}_{1,1})Q \vec{q}_{1,1}(z_{1,1} \vec{d})) \dots (z_{1,nd_1} : (\vec{d} : \vec{D}_{1,nd_1})X \vec{q}_{1,nd_1}) \\ (y_{1,nd_1} : (\vec{d} : \vec{D}_{1,nd_1})Q \vec{q}_{1,nd_1}(z_{1,nd_1} \vec{d}))(b_1 : B_1) \\ (z_{2,1} : (\vec{d} : \vec{D}_{2,1})X \vec{q}_{2,1})(y_{2,1} : (\vec{d} : \vec{D}_{2,1})Q \vec{q}_{2,1}(z_{2,1} \vec{d})) \dots (z_{2,nd_2} : (\vec{d} : \vec{D}_{2,nd_2})X \vec{q}_{2,nd_2}) \\ (y_{2,nd_2} : (\vec{d} : \vec{D}_{2,nd_2})Q \vec{q}_{2,nd_2}(z_{2,nd_2} \vec{d}))(b_2 : B_2) \\ \dots \\ (b_{nb} : B_{nb})(z_{nb,1} : (\vec{d} : \vec{D}_{nb,1})X \vec{q}_{nb,1})(y_{nb,1} : (\vec{d} : \vec{D}_{nb,1})Q \vec{q}_{nb,1}(z_{nb,1} \vec{d})) \dots \\ (z_{nb,nd_{nb}} : (\vec{d} : \vec{D}_{nb,nd_{nb}})X \vec{q}_{nb,nd_{nb}})(y_{nb,nd_{nb}} : (\vec{d} : \vec{D}_{nb,nd_{nb}})Q \vec{q}_{nb,nd_{nb}}(z_{nb,nd_{nb}} \vec{d})) \\ Q \vec{m} (c z_{1,1} \dots z_{1,nd_1} b_1 z_{2,1} \dots z_{2,nd_2} b_2 \dots b_{nb} z_{nb,1} \dots z_{nb,nd_{nb}})$$

([2, p.78] uses the notation  $\Delta\{I, X, C_k, Q, c\}$  for  $\Delta\{I/X, C^{(k)}, Q, c\}$ ). Because of the structure of the dependency diagram (30) the expression

$$\Delta'\{X, C, Q, c\} = (\vec{b} : \vec{B})(z_{1,1} : (\vec{d} : D_{1,1}) X \vec{q}_{1,1})(y_{1,1} : (\vec{d} : \vec{D}_{1,1})Q \vec{q}_{1,1}(z_{1,1} \vec{d})) \dots \\ \dots (z_{nb,nd_{nb}} : (\vec{d} : D_{nb,nd_{nb}}) X \vec{q}_{nb,nd_{nb}})(y_{nb,nd_{nb}} : (\vec{d} : \vec{D}_{nb,nd_{nb}})Q \vec{q}_{nb,nd_{nb}}(z_{nb,nd_{nb}} \vec{d})) \\ (Q \vec{m} (c' \vec{b} z_{1,1} \dots z_{nb,nd_{nb}}))$$

where  $c'$  is the term of  $C'$  corresponding to  $c$ , is a well defined type expression and its terms are in a canonical bijection with the terms of  $\Delta\{X, C, Q, c\}$ . For a term  $f$  of  $\Delta\{X, C, Q, c\}$  we will denote by  $f'$  the corresponding term of  $\Delta'\{X, C, Q, c\}$  (note that our  $\Delta'\{\dots\}$  is not to be confused with  $\Delta'[\dots]$  used in [2, p.79]). We will also write  $I'_{rec}$  for the term of the type

$$(Q : (\vec{a} : \vec{A})(r : I \vec{a})s')(f'_1 : \Delta'\{I/X, C^{(1)}, Q, c^{(1)}/c\}) \dots \\ \dots (f'_{nc} : \Delta'\{I/X, C^{(nc)}, Q, c^{(nc)}/c\})(\vec{a} : \vec{A})(r : I \vec{a})Q \vec{a} r.$$

corresponding to  $I_{rec}$ .

The data produced by an inductive definition satisfies the  $\iota$ -reduction(s). For an inductive definition of the form given above and expressed in the form of (definitional) equalities in the context

$$(\Gamma, Q : (\vec{a} : \vec{A})(r : I \vec{a})s', \\ f'_1 : \Delta'\{I/X, C^{(1)}, Q, c^{(1)}/c\}, \dots, f'_{nc} : \Delta'\{I/X, C^{(nc)}, Q, c^{(nc)}/c\},$$

$$\vec{b} : \vec{B}, z_{1,1} : (\vec{d} : \vec{D}_{1,1}) I \vec{q}_{1,1}, \dots, z_{nb,nd_{nb}} : (\vec{d} : \vec{D}_{nb,nd_{nb}}) I \vec{q}_{nb,nd_{nb}}$$

(i.e. using the ordering of variables  $b_i$  and  $z_{i,j}$  corresponding to  $C'$  and  $\Delta'$ ) they take the following form (for  $i = 1, \dots, nc$ ):

$$\begin{aligned} & [\mathbf{2010.1.19.eq1}] I'_{rec} Q \vec{f}' \vec{m} (c'^{(i)} \vec{b} \vec{z}) = \\ & = f'_i \vec{b} z_{0,1} ([\vec{d} : \vec{D}_{0,1}] (I'_{rec} Q \vec{f}' \vec{q}_{0,1} (z_{0,1} \vec{d}))) \dots \\ & \dots z_{nb,nd_{nb}} ([\vec{d} : \vec{D}_{nb,nd_{nb}}] (I'_{rec} Q \vec{f}' \vec{q}_{nb,nd_{nb}} (z_{nb,nd_{nb}} \vec{d}))). \end{aligned} \quad (34)$$

Let us consider inductive constructions in Coq of the following particular forms (following the syntax of Coq we write Type for any sort, note that several occurrences of Type in the same expression may actually refer to different sorts):

Inductive unit : Type := tt:unit.

Inductive Sum (T:Type) (Pf:T-> Type) : Type := pair: (forall t:T, forall x: Pf t, Sum T Pf).

Sum\_rect: forall (T : Type) (Pf : T -> Type) (P : Sum T Pf -> Type), (forall (t : T) (x : Pf t), P (pair T Pf t x)) -> forall s : Sum T Pf, P s

Inductive emptytype : Type := .

Inductive Union (T1:Type) (T2:Type) : Type := ii1: T1 -> Union T1 T2 | ii2: T2 -> Union T1 T2.

Union\_rect: forall (T1 T2 : Type) (P : Union T1 T2 -> Type), (forall t : T1, P (i1 T1 T2 t)) -> (forall t : T2, P (i2 T1 T2 t)) -> forall u : Union T1 T2, P u

Inductive Eq (T:Type): T -> T-> Type := ideq: forall t:T, eq T t t .

Eq\_rect: forall (T : Type) (P : forall t t0 : T, Eq T t t0 -> Type), (forall t : T, P t t (ideq T t)) -> forall (y y0 : T) (m : Eq T y y0), P y y0 m

Inductive IC(A:Type)(B:Type)(Df:B->Type)(q:forall b:B, forall d: Df b, A)(m:forall b:B, A) : A -> Type :=

cic: forall b:B, ((forall d: Df b, IC A B Df q m (q b d)) -> IC A B Df q m (m b)).

IC\_rect: forall (A B : Type) (Df : B -> Type) (q : forall b : B, Df b -> A) (m : B -> A) (P : forall a : A, IC A B Df q m a -> Type), (forall (b : B) (i : forall d : Df b, IC A B Df q m (q b d)), (forall d : Df b, P (q b d) (i d)) -> P (m b) (cic A B Df q m b i)) -> forall (y : A) (i : IC A B Df q m y), P y i

Inductive IP0(B:Type)(Df:B->Type) : Type :=

cip0: forall b:B, ((forall d: Df b, IP0 B Df) -> IP0 B Df).

Inductive IP(A:Type)(Bf:forall a:A,Type)(Df:forall a:A, forall b: Bf a, Type)(q: forall a:A, forall b: Bf a, forall d: Df a b, A) (a:A): Type :=

cip: forall b: Bf a, forall f: (forall d: Df a b, (IP A Bf Df q (q a b d))), (IP A Bf Df q a).

IP\_rect: forall (A : Type) (Bf : A -> Type) (Df : forall a : A, Bf a -> Type) (q : forall (a : A) (b : Bf a), Df a b -> A) (P : forall a : A, IP A Bf Df q a -> Type), (forall (a : A) (b : Bf a) (f : forall d : Df a b, IP A Bf Df q (q a b d)), (forall d : Df a b, P (q a b d) (f d)) -> P a (cip A Bf Df q a b f)) -> forall (a : A) (i : IP A Bf Df q a), P a i

Let us show how to construct an interpretation of Coq in itself which transforms any inductive definition into a sequence of definitions of forms *unit*, *Sum*, *emptytype*, *Union*, *Eq* and *IP*. Definitions of the form *IC* will be used for an intermediate step in the construction.

Given any context of the form  $\Gamma, \vec{x} : \vec{T}$  where  $\vec{x} = (x_1, \dots, x_n)$  and  $\vec{T} = T_1, \dots, T_n$  we can form a new context  $\Gamma, x : \Sigma(\vec{x} : \vec{T})$  where  $\Sigma(\vec{x} : \vec{T})$  is defined by repeated application of the construction *Sum* such that for  $n = 1$  we have  $\Sigma(x : T) = T$  and for  $n > 1$ ,

$$\Sigma(\vec{x} : \vec{T}) = \text{Sum } T_1 (fun x_1 : T_1 => \Sigma((x_2, \dots, x_n) : (T_2, \dots, T_n)))$$

For  $n = 0$  we set  $\Sigma(\vec{x} : \vec{T}) = \text{unit}$ .

Similarly given a sequence of contexts of the form  $\Gamma, x_i : T_i$  where  $i = 1, \dots, n$  we can define a context  $\Gamma, x : \amalg_i T_i$  where for  $n = 1$  we have  $\amalg T = T$  and for  $n > 1$ ,

$$\amalg_i T_i = \text{Union } T_1 (\amalg_i T_{i+1})$$

For  $n = 0$  we set  $\amalg_i T_i = \text{emptytype}$ .

Given any arity  $\vec{A}$ s of the form  $(\vec{a} : \vec{A})s$  define  $A$  as  $\Sigma(\vec{a} : \vec{A})$  and  $A$  s as  $(a : A)s$ . Given any  $C$  of the form given above let us define the following:

$$B = \Sigma(\vec{b} : \vec{B})$$

(in the context  $\Gamma$ ),

$$D'_{i,j} = \Sigma(\vec{d} : \vec{D}_{i,j})$$

in the context  $\Gamma, b : B$  where  $\vec{D}'_{i,j}$  are obtained from  $\vec{D}_{i,j}$  by replacing  $b_1 : B_1, \dots, b_i : B_i$  with the corresponding projections of  $b : B$  and

$$D' = \amalg_{i,j} D'_{i,j}$$

also in the context  $\Gamma, b : B$ . The sequences  $\vec{q}_{i,j}$  define a function  $qf : (\Gamma, b : B, d' : D') \rightarrow (\Gamma, a : A)$  over  $\Gamma$  and the sequence  $\vec{m}$  defines a function  $mf : (\Gamma, b : B) \rightarrow (\Gamma, a : A)$  over  $\Gamma$ .

Suppose now that we have a sequence of type of constructor expressions  $C^{(1)}, \dots, C^{(nc)}$  in a variable  $X$  of arity  $\vec{A}$ s. Denote by  $B^{(k)}, D'^{(k)}, qf^{(k)}, mf^{(k)}$  where  $k = 1, \dots, nc$  the objects defined above which correspond to the expression  $C^{(k)}$ . Let us do the groupings again. Set  $BB = \amalg_k B^{(k)}$ . Then there are functions of the form  $Df^{(k)} : BB \rightarrow \text{Type}$  such that for  $b : B_j, j \neq k$  one has  $Df^{(k)}_{i_j} b = \emptyset$  and for  $b : B_k$  one has  $Df^{(k)}_{i_k} b = D'^{(k)}$ . Set  $DD = \amalg_k Df^{(k)} b$  such that we have a valid context  $(\Gamma, bb : BB, dd : DD)$ . The morphisms  $qf^{(k)}$  and  $mf^{(k)}$  define now morphisms  $qf : (\Gamma, bb : BB, dd : DD) \rightarrow (\Gamma, a : A)$  and  $mf : (\Gamma, bb : BB) \rightarrow (\Gamma, a : A)$  over  $\Gamma$  which we represent by terms  $\Gamma \vdash q : (bb : BB)(dd : DD)A$  and  $\Gamma \vdash m : BB \rightarrow A$ .

This construction provides for any inductive definition  $I(X : \vec{A}s)\{\vec{C}\}$  of the form permitted in Coq a set-up consisting of valid contexts and sequents of the form:

$$\begin{aligned} & \mathbf{[2010.1.18.eq2]}(\Gamma, a : A), \quad (\Gamma, bb : BB, dd : DD) \\ & (\Gamma \vdash q : (bb : BB)(dd : DD)A), \quad (\Gamma \vdash m : BB \rightarrow A) \end{aligned} \tag{35}$$

where  $BB, DD, q$  and  $m$  are expressions which use only the dependent sum and disjoint union constructions and the original expressions  $\vec{A}$  and  $\vec{C}$ . If  $q' : \sum((bb, dd) : (BB, DD)) \rightarrow A$  is adjoint



to  $q$  then our data can be shown in the form of a diagram:

$$\begin{array}{c} \sum((bb, dd) : (BB, DD)) \xrightarrow{q'} A \\ \text{pr}_1 \downarrow \\ BB \\ m \downarrow \\ A \end{array}$$

When  $na = 0$  i.e.  $A = \text{unit}$  we can ignore  $q$  and  $m$  and we obtain the diagram

$$\sum((bb, dd) : (BB, DD)) \xrightarrow{\text{pr}_1} BB$$

**Proposition 2.3** [2010.1.18.prop1] *Let  $I(X : \vec{A}s)\{\vec{C}\}$  be a valid inductive definition in Coq in a context  $\Gamma$ .*

*If  $na > 0$ , consider the type  $I = ICABB(\text{fun } bb : BB \Rightarrow DD)qm$  where  $A, BB, DD, q$  and  $m$  are defined based on  $\vec{A}s$  and  $\vec{C}$  as explained above. Then there is a term expression based on  $IC_{\text{rect}}ABB(\text{fun } bb : BB \Rightarrow DD)qm$  of type (33) in  $\Gamma$  and this expression satisfies the same reduction rules as (33).*

*If  $na = 0$ , consider the type  $I = IP0BB(\text{fun } bb : BB \Rightarrow DD)$ . Then there is a term expression based on  $IP0_{\text{rect}}BB(\text{fun } bb : BB \Rightarrow DD)$  of type (33) in  $\Gamma$  and this expression satisfies the same reduction rules as (33).*

**Example 2.4** [2010.8.4.ex1] *Let us consider the construction described above in the case of the standard definition of natural numbers:*

Inductive nat : Type := O : nat | S : nat -> nat.

We have  $s = \text{Type}$ ,  $A = \text{unit}$ ,  $nc = 2$ ,

$$\begin{aligned} C^{(1)} &= \text{nat} & B^{(1)} &= \text{unit} & D^{(1)} &= \text{emptytype} \\ C^{(2)} &= (z_{0,1}^{(2)} : \text{nat}) \text{nat} & B^{(2)} &= \text{unit} & D^{(2)} &= \text{unit} \end{aligned}$$

When we group  $C^{(1)}$  and  $C^{(2)}$  together we get:

$$BB = \text{Union unit unit}$$

The explicit forms for  $Df1 = Df^{(1)}$  and  $Df2 = Df^{(2)}$  in Coq are:

```
Fixpoint Df1 (bb:BB) Type :=
match bb:BB with
ii1 tt1 => emptytype |
ii2 tt2 => emptytype
end.
```

```
Fixpoint Df2 (bb:BB) Type :=
match bb:BB with
ii1 tt1 => unit |
```

ii2 tt2 => emptytype  
end.

and  $DD$  (in the context  $(\Gamma, \text{bb}:B)$ ) is of the form  $\text{Union } (Df1 \text{ bb}) (Df2 \text{ bb})$ . Therefore, our construction would replace the usual definition of  $\text{nat}$  by

Definition  $\text{nat}' := \text{IP0 BB } (\text{fun bb:BB} => \text{Union } (Df1 \text{ bb}) (Df2 \text{ bb}))$ .

which is equivalent to the one of the form

$\text{nat}' : \text{Type} := (\text{Union nat}' \text{ unit}) \rightarrow \text{nat}'$ .

Proposition 2.3 can be informally summarized by saying that the procedure described above allows one to express any inductive definition of  $\text{Coq}$  as a combination of a number of dependent sums, dependent products and a single inductive definition of the form  $\text{IC}$ .

We will show now how to transform, using  $eq$ , a definition of the form  $\text{IC}$  into an equivalent (in the sense clarified by Proposition 2.5 below) inductive definition of the form  $\text{IP}$ .

Consider a set-up of the form (35). In the context  $\Gamma, a : A$  define  $B' = \Sigma b : B, eq A a (m b)$ . Consider the term sequent

$$(\Gamma, a : A, b' : B', d' : D[(pr1 b')/b] \vdash q (pr1 b') d' : A)$$

This sequent is of the form which can serve as an input for the construction of  $\text{IP}$ . Set

$$I = \text{IP } A B f' D f' q'$$

where  $B f' = (\text{fun } a => B')$ ,  $D f' = (\text{fun } a => (\text{fun } b' => D[(pr1 b')/b]))$  and  $q' = (\text{fun } a => (\text{fun } b' => (\text{fun } d' => a (pr1 b') d')))$ .

**Proposition 2.5 [2010.1.25.prop1]** *In the notations introduced above, there exists a term expression in  $\Gamma$  based on  $\text{IP}_{rect} A B f' D f' q'$  which has the same type as  $\text{IC}_{rect} A B (\text{fun } b : B => D) q m$  and satisfies the same  $\iota$ -reduction property.*

### 3 Interpretations of inductive definitions in lccc's

To get started let us consider an interpretation  $[-]$  of the calculus of construction (with some universes) in a lccc  $\mathcal{C}$  which is compatible with dependent products.

We start by interpreting dependent sums (which can be seen in  $\text{Coq}$  as inductive definitions with one strictly positive constructor) in the usual way. After they are interpreted we can always replace an expression of the form  $(x_1 : T_1)(x_2 : T_2)\dots(x_n : T_n)T_{n+1}$  by  $(x : (\sum x_1 : T_1, \dots, \sum x_{n-1} T_{n-1}, T_n)) T_{n+1}$  i.e. to replace all sequences of dependent products by a single dependent product parametrized by a dependent sum.

We also interpret inductive definitions with several constructors of the form  $T_i \rightarrow I$  where  $T_i$ 's do not depend on  $I$  as disjoint unions.

Using this reduction and also identifications of  $\text{Prop}$  and  $\text{Set}$  with subtypes of  $\text{Type}$  we may assume that a general inductive definition is of the form  $X = \text{Ind}(X : A \rightarrow \text{Type})\{C_1, \dots, C_n\}$  where  $C_i = (z_i : B_i) X m_i$ ,  $X$  is not present in  $m_i$  and  $B_i$  is a dependent sum of the form

$$\mathbf{[2009.1.8.eq1]} B_i = \sum z_{i,0} : B_{i,0}, \sum z_{i,1} : B_{i,1}, \sum \dots, B_{i,n_i} \quad (36)$$

where  $B_{i,j}$  does not depend on  $X$  or is of the form  $(y_{i,j} : D_{i,j}) X q_{i,j}$  where  $D_{i,j}$  and  $q_{i,j}$  do not depend on  $X$ .

Presumably, these conditions imply in particular that if  $B_{i,j} = (y_{i,j} : D_{i,j}) X q_{i,j}$  and  $k > j$  then  $B_{i,k}$  does not depend on  $z_{i,j}$ . Therefore, we can collect all the terms  $B_{i,j}$  which do not depend on  $X$  into  $B_{i,0}$  and assume that for  $j > 0$  the term  $B_{i,j}$  is of the form  $(y_{i,j} : D_{i,j}) X q_{i,j}$ . Note that these terms do not depend on each other for various  $j_1, j_2 > 0$ .

Suppose we have already interpreted everything "before" this definition. By passing to the slice category we may assume that we work in an empty context. Then  $[B_{i,0}]$  is an object of  $\mathcal{C}$  and each of the  $[D_{i,j}]$  is a family of objects over  $[B_{i,0}]$ . Let  $E_{i,j} = \sum z_{i,0} : B_{i,0}, D_{i,j}$ . Then  $[p_{i,j}] : [E_{i,j}] \rightarrow [B_{i,0}]$  is the map whose fibers give this family and  $[q_{i,j}]$  can be seen as a morphism  $[q_{i,j}] : [E_{i,j}] \rightarrow A$ .

Let  $Tot(X) = \sum a : A, Xa$ . Then  $[Tot(X)]$  is an object over  $[A]$  and  $[B_i]$  as an object over  $[B_{i,0}]$  is  $\prod_j [p_{i,j}]_* [q_{i,j}]^* ([Tot(X)]/[A])$ . By taking disjoint union of the types  $E_{i,j}$  for  $j > 0$  we may collect them into one type  $E_i$  and the maps  $p_{i,j}$  and  $q_{i,j}$  into two maps  $p_i : E_i \rightarrow B_{i,0}$ ,  $q_i : E_i \rightarrow A$ .

Since  $m_i$  does not depend on  $X$  it means in particular that, as a function  $B_i \rightarrow A$  it only depends on  $z_{i,0}$  i.e. that  $m_i$  is a function  $B_{i,0} \rightarrow A$ . Summing things up we find that each constructor  $C_i$  defines three morphisms  $p_i : E_i \rightarrow B_{i,0}$ ,  $q_i : E_i \rightarrow A$  and  $m_i : B_{i,0} \rightarrow A$  of which  $p_i$  is a "display map" (i.e. the canonical morphism  $E_i \rightarrow ft(E_i)$ ):

$$\begin{array}{ccc} E_i & \xrightarrow{q_i} & A \\ & \downarrow p_i & \\ A & \xleftarrow{m_i} & B_{i,0} \end{array}$$

and for  $X : A \rightarrow Type$ , a term  $c_i$  of type  $C_i(X)$  is a morphism  $(p_i)_*(q_i)^*(Tot(X)/A) \rightarrow (m_i)^*(Tot(X)/A)$ .

We conclude that an interpretation of such a term is a morphism

$$[p_i]_* [q_i]^* ([Tot(X)]/[A]) \rightarrow [m_i]^* ([Tot(X)]/[A])$$

or equivalently by adjunction a morphism of the form

$$[m_i]_{\#} [p_i]_* [q_i]^* ([Tot(X)]) \rightarrow [Tot(X)]$$

over  $[A]$ . We can further collect these morphisms together for different  $i$  setting

$$E = \amalg_i E_i \quad B = \amalg_i B_{i,0} \quad q = \amalg_i q_i \quad p = \amalg_i p_i \quad m = \amalg_i m_i$$

and define a functor  $F(X') = [m]_{\#} [p]_* [q]^*(X')$  from  $\mathcal{C}/[A]$  to itself.

An inductive definition introduces the following data:

1. an object  $I$  such that  $ft(I) = A$ ,
2. a morphism  $c_X : p_* q^*(I) \rightarrow m^*(I)$  over  $A$ ,
3. a mapping which assigns to any pair  $(P, c_P)$  where  $P$  is an object such that  $ft(P) = I$  and  $c_P : p_* q^*(I) \rightarrow m^*(P)$ , a section  $s : I \rightarrow P$  of  $p_P$  such that  $m^*(s) c_X = c_P (p_* q^*(s))$ .

It is not difficult to show now that an initial algebra for  $F$  provides an interpretation for  $I$  with all of its recursors. However, in the case of the univalent models this is not a satisfactory interpretation since for a fibration  $X' \rightarrow [A]$  the morphism  $F(X') \rightarrow [A]$  needs not be a fibration unless  $[m]$  happened to be a fibration.

In order to overcome this difficulty one re-writes any inductive definition as a combination of dependent sums, disjoint unions, equivalence types and  $IP$  constructions as explained above. A univalent (compatible with the equivalence axiom) interpretation of dependent sums, disjoint unions and equivalence types is known. We obtain a univalent interpretation of  $IP$  types using [1, Th. 5.6] since the  $IP$  construction can be interpreted as the initial algebra of a functor which takes Kan fibrations to Kan fibrations and which depends on its parameters in a way which respects weak equivalences.

## References

- [1] Michael Abbott, Thorsten Altenkirch, and Neil Ghani. Categories of containers. In *In Proceedings of Foundations of Software Science and Computation Structures*, 2003.
- [2] Frédéric Blanqui. Type theory and rewriting. In *Ph. D. Thesis*, pages 1–139. Orsay, 2001.
- [3] John Cartmell. Generalised algebraic theories and contextual categories. *Ann. Pure Appl. Logic*, 32(3):209–243, 1986.
- [4] Bart Jacobs. *Categorical logic and type theory*, volume 141 of *Studies in Logic and the Foundations of Mathematics*. North-Holland Publishing Co., Amsterdam, 1999.
- [5] Peter May. *Simplicial objects in algebraic topology*. Van Nostrand, 1968.
- [6] Christine Paulin-Mohring. Inductive definitions in the system Coq; rules and properties. In *Typed lambda calculi and applications (Utrecht, 1993)*, volume 664 of *Lecture Notes in Comput. Sci.*, pages 328–345. Springer, Berlin, 1993.
- [7] Daniel G. Quillen. The geometric realization of a Kan fibration is a Serre fibration. *Proc. Amer. Math. Soc.*, 19:1499–1500, 1968.
- [8] Thomas Streicher. *Semantics of type theory*. Progress in Theoretical Computer Science. Birkhäuser Boston Inc., Boston, MA, 1991. Correctness, completeness and independence results, With a foreword by Martin Wirsing.
- [9] B. Werner. Une thorie des constructions inductives. In *Thse de Doctorat*, 1994.