

NASA/CR-1999-209730
ICASE Report No. 99-47



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National Aeronautics and
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Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Contract NAS1-97046

November 1999

PROOF-TERM SYNTHESIS ON DEPENDENT-TYPE SYSTEMS VIA EXPLICIT SUBSTITUTIONS

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Abstract. Typed λ -terms are used as a compact and linear representation of proofs in intuitionistic logic. This is possible since the Curry-Howard isomorphism relates proof trees with typed λ -terms. The proofs-as-terms principle can be used to check a proof by type checking the λ -term extracted from the complete proof tree. However, proof trees and typed λ -terms are built differently. Usually, an auxiliary representation of unfinished proofs is needed, where type checking is possible only on complete proofs. In this paper we present a proof synthesis method for dependent-type systems where typed open terms are built incrementally at the same time as proofs are done. This way, every construction step, not just the last one, may be type checked. The method is based on a suitable calculus where substitutions as well as meta-variables are first-class objects.

Key words. proof synthesis, higher-order unification, explicit substitutions, dependent types, lambda-calculus

Subject classification. Computer Science

1. Introduction. Thanks to the proofs-as-terms paradigm, a method of *proof* synthesis consists in finding a *term* of a given type. Since the set of λ -terms is enumerable, a complete method for proof synthesis in a framework where type checking is decidable consists in enumerating and type checking all the terms. Of course, this method is impractical for implementations. A smart enumeration of terms must take typing information and properties of the λ -calculus into account. In [38], Zaionc presents an algorithm for proof construction in the propositional intuitionistic and classical logics via the simply-typed λ -calculus, and Dowek shows in [12, 13] a complete term enumeration algorithm for the type systems of the Barendregt's cube.

Although the Curry-Howard isomorphism relates proofs with terms, proof construction and term synthesis do not necessarily go in the same direction. A natural deduction proof, for example, is driven by a bottom-up procedure, while term synthesis procedures go in a top-down manner. For instance, to prove a proposition B by *Modus-Ponens*, we assume $A \rightarrow B$ and A as hypotheses, and then we continue recursively trying to prove these two propositions. Eventually, we will get the axioms and the proof is finished. In contrast, to synthesize a term of type B , we start with the axioms to set up the variables, and then go down to the conclusion where the final term has the form $(M N)$ with M a term of type $A \rightarrow B$ and N a term of type A .

These two different construction mechanisms, bottom-up proof construction and top-down term synthesis, coexist in some theorem provers based on the proof-as-term paradigm. For example, in the proof assistant system Coq [3] proofs under construction, also called *incomplete proofs*, are represented as proof-trees. When the proof is done, a λ -term, that is, a *complete proof-term*, is synthesized. The soundness of

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the system relies on the type checker, which is a very small piece of code. However, if something goes wrong with the proof-tree construction, for example because a procedure manipulating a proof-tree is bugged, the problem is detected when the type checking of the *complete* proof-term takes place. That means, at the very last step of the proof-term synthesis.

A uniform representation of complete and incomplete proofs allows to identify the proof construction and term synthesis mechanisms. Furthermore, if such a representation supports an effective type-checking procedure, type inconsistencies can be detected during the whole process of the proof-term construction. In [28], Magnusson proposes an extension to the λ -calculus with place-holders and explicit substitutions to represent incomplete proofs. Her ideas were implemented in the theorem prover Alf [2], but a complete meta-theoretical study of the system and its properties is missing.

A term with place-holders is called an *open term*. Since several place-holders can appear in an open term, it is convenient to name them. In the λ -calculus with de Bruijn indices, named place-holders are just variables of the free-algebra of terms. In order to distinguish place-holders from variables of the λ -calculus, the former are called *meta-variables*. As a convention in this paper, meta-variables are written with the last uppercase letters of the alphabet: X, Y, \dots

The open term $\lambda x:A.Y$, can be seen as a proof-term of $A \rightarrow B$ provided that there exists a term of type B in the right context to replace Y . By using this replacement mechanism, also called *instantiation*, an incomplete proof becomes a complete one. In contrast to substitution of variables in the λ -calculus, instantiation of meta-variables is a first-order substitution that does not care about capture of variables. In the previous example the *instantiation* of Y with x results in the term $\lambda x:A.x$, while the *substitution* of x for Y in $\lambda x:A.Y$ results in $\lambda z:A.x$. Notice that unless A and B represent the same type, the resulting terms in both cases may be ill-typed.

As pointed out in [28, 15], open terms in the λ -calculus reveal new challenges. Assume, for example, that an open term is involved in a β -redex. The β -rule can create substitutions applied to meta-variables that cannot be effective while the meta-variables are not instantiated. In this case, a notation for suspended substitutions should be provided. Since the $\lambda\sigma$ -calculus of explicit substitutions was introduced in [1], several other variants of explicit substitutions calculi have been proposed; among others [1, 36, 26, 23, 6, 27, 11, 24, 30, 18, 32]. The study of explicit substitution calculi showed up to be more complicated than that of the λ -calculus. For some of the explicit substitution calculi, questions about confluence, normalization and type checking are still open.

In [31, 33], we propose a variant of $\lambda\sigma$, called $\lambda\Pi_{\mathcal{L}}$, for dependent-type theories like $\lambda\Pi$ [20] and the Calculus of Constructions [8, 9]. The $\lambda\Pi_{\mathcal{L}}$ -calculus is confluent and weakly normalizing on well-typed expressions. The $\lambda\Pi_{\mathcal{L}}$ -system does not enjoy confluence on the full set of open expressions, that is, $\lambda\Pi_{\mathcal{L}}$ is no longer confluent when meta-variables on the sort of substitutions are considered, and it does not preserve strong normalization, that is, arbitrary reductions on well-typed expressions may not terminate. However, we claim in this paper that the $\lambda\Pi_{\mathcal{L}}$ -calculus is suitable as a framework to represent incomplete proof-terms in a constructive logic.

In this paper we describe a proof-term synthesis method for $\lambda\Pi$ and the Calculus of Construction via the $\lambda\Pi_{\mathcal{L}}$ -calculus. The method uses the incomplete proof-term paradigm proposed in [33]. It is strongly inspired by that proposed by Dowek in [12, 13] for the Cube of Type Systems. In contrast to Dowek's method, our method combines both the bottom-up approach for proof construction, and the top-down synthesis of terms. In other words, proof-terms are synthesized at the same time that proofs are constructed. Since type checking is decidable in $\lambda\Pi_{\mathcal{L}}$, the soundness of the proof construction can be guaranteed step by step. From

a practical point of view, implementation errors in procedures manipulating incomplete-proofs are detected by the type checker at any moment during the proof-construction process. The type checker of $\lambda\Pi_{\mathcal{L}}$ is still simple. In fact, we have implemented it, in the object-oriented functional language OCaml, in about 50 lines. We have also implemented a higher-order unification algorithm for ground expressions. The soundness of the whole implementation relies in the small piece of code corresponding to the type checker.

The rest of this section gives an overview to the dependent-type systems in which we are interested, the λP -calculus and the Calculus of Constructions, and to the $\lambda\sigma$ -calculus of explicit substitutions. For a more comprehensive explanation on both subjects, we refer to [20, 9] and [1]. In Section 2, we present the $\lambda\Pi_{\mathcal{L}}$ -calculus and its dependent-type systems. In Section 3, we describe our method of proof synthesis. The soundness and completeness of the method are proved in Section 4. The last section presents related work and summarizes this work.

1.1. Dependent-type systems. The Dependent Type theory, namely λP [20], is a conservative extension of the simply-typed λ -calculus. It allows a finer stratification of terms by generalizing the function space type. In fact, in λP , the type of a function $\lambda x:A.M$ is $\Pi x:A.B$ where B (the type of M) may depend on x . Hence, the type $A \rightarrow B$ of the simply-typed λ -calculus is just a notation in λP for the product $\Pi x:A.B$ where x does not appear free in B .

From a logical point of view, the λP -calculus allows representation of proofs in the first-order intuitionistic logic using universal quantification. Via the types-as-proofs principle, a term of type $\Pi x:A.B$ is a proof-term of the proposition $\forall x:A.B$.

Terms in λP can be variables: x, y, \dots , applications: $(M N)$, abstractions: $\lambda x:A.M$, products: $\Pi x:A.B$, or one of the sorts: *Type*, *Kind*.¹ Notice that terms and types belong to the same syntactical category. Thus, $\Pi x:A.B$ is a term, as well as $\lambda x:A.M$. However, terms are stratified in several levels according to a type discipline. For instance, given an appropriate context of variable declarations, $\lambda x:A.M : \Pi x:A..B$, $\Pi x:A..B : \textit{Type}$, and $\textit{Type} : \textit{Kind}$. The term *Kind* cannot be typed in any context, but it is necessary since a circular typing as $\textit{Type} : \textit{Type}$ leads to the Girard's paradox [19].

Typing judgments in λP have the form

$$\Gamma \vdash M : A$$

where Γ is a *context* of variable declarations, that is, a set of type assignments for free variables. We use the Greek letters Γ, Δ to range over contexts. Since types may be ill-typed, typing judgments for contexts are also necessary. The notation

$$\vdash \Gamma$$

captures that types in Γ are well-typed. The λP -type system is given in Figure 1.1.

The Calculus of Constructions [8, 9] extends the λP -calculus with polymorphism and constructions of types. It is obtained by replacing the rules (Prod) and (Abs) as shown in Figure 1.2.

In a higher-order logic, as λP or the Calculus of Constructions, it may happen that two types syntactically different are the same module β -conversion. The rule (Conv) uses the equivalence relation \equiv_{β} which is defined as the reflexive and transitive closure of the relation induced by the β -rule:

$(\lambda x:A.M N) \longrightarrow M[N/x]$. We recall that $M[N/x]$ is just a notation for the atomic substitution of the free occurrences of x in M by N , with renaming of bound variables in M when necessary.

¹The names *Type* and *Kind* are not standard, other couples of names used in the literature are: $(\textit{Set}, \textit{Type})$, $(\textit{Prop}, \textit{Type})$ and $(*, \square)$.

$$\begin{array}{c}
\frac{}{\vdash \{\}} \text{ (Empty)} \\
\\
\frac{\vdash \Gamma}{\Gamma \vdash \text{Type} : \text{Kind}} \text{ (Type)} \\
\\
\frac{\Gamma \vdash A : \text{Type} \quad x \text{ does not appear in } \Gamma \quad \Gamma \cup \{x : A\} \vdash B : s \quad s \in \{\text{Kind}, \text{Type}\}}{\Gamma \vdash \Pi x:A. B : s} \text{ (Prod)} \\
\\
\frac{\Gamma \vdash M : \Pi x:A. B \quad \Gamma \vdash N : A}{\Gamma \vdash (M N) : A[N/x]} \text{ (Appl)} \\
\\
\frac{\Gamma \vdash A : s \quad s \in \{\text{Kind}, \text{Type}\} \quad x \text{ is a fresh variable}}{\vdash \Gamma \cup \{x : A\}} \text{ (Var-Decl)} \\
\\
\frac{\vdash \Gamma \quad (x : A) \in \Gamma}{\Gamma \vdash x : A} \text{ (Var)} \\
\\
\frac{\Gamma \vdash A : \text{Type} \quad x \text{ does not appear in } \Gamma \quad \Gamma \cup \{x : A\} \vdash M : B \quad \Gamma \cup \{x : A\} \vdash B : s \quad s \in \{\text{Kind}, \text{Type}\}}{\Gamma \vdash \lambda x:A. M : \Pi x:A. B} \text{ (Abs)} \\
\\
\frac{\Gamma \vdash M : A \quad \Gamma \vdash B : s \quad s \in \{\text{Kind}, \text{Type}\} \quad A \equiv_{\beta} B}{\Gamma \vdash M : B} \text{ (Conv)}
\end{array}$$

FIG. 1.1. *The λP -system*

$$\begin{array}{c}
\frac{x \text{ does not appear in } \Gamma \quad \Gamma \cup \{x : A\} \vdash B : s \quad s \in \{\text{Kind}, \text{Type}\}}{\Gamma \vdash \Pi x:A. B : s} \text{ (Prod)} \\
\\
\frac{x \text{ does not appear in } \Gamma \quad \Gamma \cup \{x : A\} \vdash M : B \quad \Gamma \cup \{x : A\} \vdash B : s \quad s \in \{\text{Kind}, \text{Type}\}}{\Gamma \vdash \lambda x:A. M : \Pi x:A. B} \text{ (Abs)}
\end{array}$$

FIG. 1.2. *The rules (Prod) and (Abs) of the Calculus of Constructions*

1.2. Explicit substitutions. The $\lambda\sigma$ -calculus [1] is a first-order rewrite system with two sorts of expressions: *terms* and *substitutions*. Well-formed expressions in the $\lambda\sigma$ -calculus are defined by the following grammar.

$$\begin{array}{ll}
\mathbf{Terms} & M, N ::= \underline{1} \mid (M N) \mid \lambda M \mid M[S] \\
\mathbf{Substitutions} & S, T ::= id \mid \uparrow \mid M \cdot S \mid S \circ T
\end{array}$$

The $\lambda\sigma$ -calculus is presented in Figure 1.3.

In $\lambda\sigma$, free and bound variables are represented by de Bruijn indices. They are encoded by means of the constant $\underline{1}$ and the substitution \uparrow . We write \uparrow^n as a shorthand for $\overbrace{\uparrow \circ \dots \circ \uparrow}^{n\text{-times}}$. We overload the notation \underline{i} to

$(\lambda M N)$	\longrightarrow	$M[N \cdot id]$	(Beta)
$(M N)[S]$	\longrightarrow	$(M[S] N[S])$	(Application)
$(\lambda M)[S]$	\longrightarrow	$\lambda M[\underline{1} \cdot (S \circ \uparrow)]$	(Lambda)
$M[S][T]$	\longrightarrow	$M[S \circ T]$	(Clos)
$\underline{1}[M \cdot S]$	\longrightarrow	M	(VarCons)
$M[id]$	\longrightarrow	M	(Id)
$(S_1 \circ S_2) \circ T$	\longrightarrow	$S_1 \circ (S_2 \circ T)$	(Ass)
$(M \cdot S) \circ T$	\longrightarrow	$M[T] \cdot (S \circ T)$	(Map)
$id \circ S$	\longrightarrow	S	(Idl)
$S \circ id$	\longrightarrow	S	(Idr)
$\uparrow \circ (M \cdot S)$	\longrightarrow	S	(ShiftCons)
$\underline{1} \cdot \uparrow$	\longrightarrow	id	(VarShift)
$\underline{1}[S] \cdot (\uparrow \circ S)$	\longrightarrow	S	(SCons)

FIG. 1.3. *The $\lambda\sigma$ -calculus [1]*

represent the $\lambda\sigma$ -term corresponding to the index i , i.e.,

$$\underline{i} = \begin{cases} \underline{1} & \text{if } i = 1 \\ \underline{1}[\uparrow^n] & \text{if } i = n + 1. \end{cases}$$

An explicit substitution denotes a mapping from indices to terms. Thus, id maps each index i to the term \underline{i} , \uparrow maps each index i to the term $\underline{i+1}$, $S \circ T$ is the composition of the mapping denoted by T with the mapping denoted by S (notice that the composition of substitution follows a reverse order with respect to the usual notation of function composition), and finally, $M \cdot S$ maps the index 1 to the term M , and recursively, the index $i + 1$ to the term mapped by the substitution S on the index i .

2. A Framework to Represent Incomplete Proof-Terms. The important elements of our framework are: explicit substitutions, open terms, and dependent types. A simply-typed version of $\lambda\sigma$ on open terms has been studied in [15]. In [31, 33], we propose the $\lambda\Pi_{\mathcal{L}}$ -calculus which is a dependent-typed version of a variant of $\lambda\sigma$. The $\lambda\Pi_{\mathcal{L}}$ -calculus is confluent and weakly normalizing on well-typed terms.

As usual in explicit substitution calculi, expressions of $\lambda\Pi_{\mathcal{L}}$ are structured in terms and substitutions. The $\lambda\Pi_{\mathcal{L}}$ -calculus admits meta-variables only on the sort of terms.

The set of well-formed expressions in $\lambda\Pi_{\mathcal{L}}$ is defined by the following grammar:

Natural numbers	n	$::=$	$0 \mid n + 1$
Meta-variables	χ	$::=$	$X \mid Y \mid \dots$
Sorts	s	$::=$	$Kind \mid Type$
Terms	A, B, M, N	$::=$	$\underline{1} \mid s \mid \Pi_A.B \mid \lambda_A.M \mid$ $(M N) \mid M[S] \mid \chi$
Substitutions	S, T	$::=$	$\uparrow^n \mid M \cdot_A S \mid S \circ T$

An expression in $\lambda\Pi_{\mathcal{L}}$ is *ground* if it does not contain meta-variables. A ground expression is also *pure* if it does not contain explicit substitutions (other than those representing de Bruijn indices).

$(\lambda_A.M N)$	\longrightarrow	$M[N \cdot_A \uparrow^0]$	(Beta)
$(\lambda_A.M)[S]$	\longrightarrow	$\lambda_{A[S]}.M[\underline{1} \cdot_A (S \circ \uparrow^1)]$	(Lambda)
$(\Pi_A.B)[S]$	\longrightarrow	$\Pi_{A[S]}.B[\underline{1} \cdot_A (S \circ \uparrow^1)]$	(Pi)
$(M N)[S]$	\longrightarrow	$(M[S] N[S])$	(Application)
$M[S][T]$	\longrightarrow	$M[S \circ T]$	(Clos)
$\underline{1}[M \cdot_A S]$	\longrightarrow	M	(VarCons)
$M[\uparrow^0]$	\longrightarrow	M	(Id)
$(M \cdot_A S) \circ T$	\longrightarrow	$M[T] \cdot_A (S \circ T)$	(Map)
$\uparrow^0 \circ S$	\longrightarrow	S	(IdS)
$\uparrow^{n+1} \circ (M \cdot_A S)$	\longrightarrow	$\uparrow^n \circ S$	(ShiftCons)
$\uparrow^{n+1} \circ \uparrow^m$	\longrightarrow	$\uparrow^n \circ \uparrow^{m+1}$	(ShiftShift)
$\underline{1} \cdot_A \uparrow^1$	\longrightarrow	\uparrow^0	(Shift0)
$\underline{1}[\uparrow^n] \cdot_A \uparrow^{n+1}$	\longrightarrow	\uparrow^n	(ShiftS)
$Type[S]$	\longrightarrow	$Type$	(Type)

FIG. 2.1. *The $\lambda\Pi_{\mathcal{L}}$ -rewrite system*

In dependent-type systems, object terms and type terms are in the same syntactical category. In this paper, for readability, we use the uppercase letters A, B, \dots to denote type terms, that is, terms of type (kind) *Type* or *Kind*, and M, N, \dots to denote object terms, that is, terms of type A where A is a type term.

The equivalence relation $\equiv_{\lambda\Pi_{\mathcal{L}}}$ is defined as the symmetric and transitive closure of the relation induced by the rewrite system in Figure 2.1. As usual, we denote by $\xrightarrow{\lambda\Pi_{\mathcal{L}}^*}$ the reflexive and transitive closure of $\lambda\Pi_{\mathcal{L}}$.

The system $\Pi_{\mathcal{L}}$ is obtained by dropping the rule (Beta) from $\lambda\Pi_{\mathcal{L}}$. As shown by Zantema [40], the $\Pi_{\mathcal{L}}$ -calculus is strongly normalizing.

LEMMA 2.1. *The $\Pi_{\mathcal{L}}$ -calculus is terminating.*

Proof. See [33]. The proof uses the semantic labeling technique [39]. \square

The set of normal-forms of an expression x (term or substitution) is denoted by $(x)\downarrow_{\Pi_{\mathcal{L}}}$.

The $\lambda\Pi_{\mathcal{L}}$ -calculus, just as $\lambda\sigma$, uses the composition operation to achieve confluence on terms with meta-variables. The rules (Idr) and (Ass) of $\lambda\sigma$ are not necessary in $\lambda\Pi_{\mathcal{L}}$.

We adopt the notation \dot{i} as a shorthand for $\underline{1}[\uparrow^n]$ when $i = n + 1$. In contrast to $\lambda\sigma$, \uparrow^n is not a shorthand but an explicit substitution in $\lambda\Pi_{\mathcal{L}}$. Indeed, \uparrow^0 replaces *id* and \uparrow^1 replaces \uparrow . In general, \uparrow^n denotes the mapping of each index i to the term $i + n$. Using \uparrow^n , the non-left-linear rule (SCons) of $\lambda\sigma$, which is responsible of confluence and typing problems [11, 5, 33], can be dropped of the $\lambda\Pi_{\mathcal{L}}$ -calculus. Notice that we do not assume any meta-theoretical property on natural numbers. They are constructed with 0 and $n + 1$. Arithmetic calculations on indices are embedded in the rewrite system.

A *context* in $\lambda\Pi_{\mathcal{L}}$ is a list of types. The empty context is written ϵ . A context with head A and rest Γ is written $A.\Gamma$. In that case, A is the type of the index 1, the head of Γ (if Γ is not empty) is the type of the index 2, and so on. In a dependent-type theory with de Bruijn indices, the order in which variables are declared in a context is important. In fact, in the context $A.\Gamma$, the indices in A are relative to Γ .

The type of a substitution is a context. This choice seems natural since substitutions denote mapping from indices to terms, and contexts are list of types. In fact, if the type of a substitution S is the context

$A.\Delta$, the type of the term mapped by the substitution S on the index 1 is A , and so for the rest of indices.

2.1. Meta-variables. As we have said, meta-variables are first-class objects in $\lambda\Pi_{\mathcal{L}}$. Just as variables, they have to be declared in order to keep track of possible dependences between terms and types.

A meta-variable declaration has the form $X:\Gamma A$, where Γ and A are, respectively, a context and a type assigned to the meta-variable X . The pair (Γ, A) is unique (modulo $\equiv_{\lambda\Pi_{\mathcal{L}}}$) for each meta-variable. This requirement is enforced by the type system.

A list of meta-variable declarations is called a *signature*. We use the Greek letter Σ to range over signatures. The empty signature is written ϵ . A signature with head $X:\Gamma A$ and rest Σ is written $X:\Gamma A. \Sigma$. We overload the notation $\Sigma_1. \Sigma_2$ to write the concatenation of the signatures Σ_1 and Σ_2 .

The order of the meta-variable declarations is important. In a signature $X_1:\Gamma_1 A_1. \dots . X_n:\Gamma_n A_n$, the type A_i and the context Γ_i , $0 < i \leq n$, may depend only on meta-variables X_j , $i < j \leq n$. The indices in A_i are relative to the context Γ_i .

The main operation on meta-variables is *instantiation*. The instantiation of a meta-variable X with a term M in an expression y (term or substitution) replaces all the occurrences of X in y by M .

DEFINITION 2.2 (Instantiation). *The instantiation of a meta-variable X with a term M in an expression y , denoted $y\{X/M\}$, is defined by induction over the structure of y as follows.*

- $s\{X/M\} = s$, if $s \in \{\text{Kind}, \text{Type}\}$.
- $\perp\{X/M\} = \perp$.
- $X\{X/M\} = M$.
- $Y\{X/M\} = Y$, if $Y \neq X$.
- $(\Pi_A.B)\{X/M\} = \Pi_{A\{X/M\}}.B\{X/M\}$.
- $(\lambda_A.N)\{X/M\} = \lambda_{A\{X/M\}}.N\{X/M\}$.
- $(N_1 N_2)\{X/M\} = (N_1\{X/M\}) N_2\{X/M\}$.
- $(N[S])\{X/M\} = N\{X/M\}[S\{X/M\}]$.
- $\uparrow^n\{X/M\} = \uparrow^n$.
- $(N \cdot_A S)\{X/M\} = N\{X/M\} \cdot_{A\{X/M\}} S\{X/M\}$.
- $(S \circ T)\{X/M\} = S\{X/M\} \circ T\{X/M\}$.

Application of instantiations extends to context and signatures, that is, $\Gamma\{X/M\}$ and $\Sigma\{X/M\}$, in the obvious way. In the case of signatures, the application $\Sigma\{X/M\}$ also removes the declaration of X in Σ , if any.

In contrast to substitution of variables, instantiation of meta-variables allows capture of variables. Moreover, instantiations are not first-class objects, i.e., the application of an instantiation is atomic and external to the $\lambda\Pi_{\mathcal{L}}$ -calculus.

2.2. Type annotations. Type annotations in substitutions are introduced with the rules (Beta), (Lambda), and (Pi), and then propagated with the rule (Map). They can also be eliminated with the rules (VarCons), (ShiftCons), and (Shift0). Notice that the type annotation that is propagated by the rule (Map):

$$(M \cdot_A S) \circ T \longrightarrow M[T] \cdot_A (S \circ T)$$

is A , not $A[T]$. Type annotations in substitutions act as remainder of types when substitutions are distributed under abstractions and products. As shown in [33], they are necessary to preserve typing in $\lambda\Pi_{\mathcal{L}}$ -reductions.

2.3. η -conversion. In this paper we consider a calculus without η -conversion. Although, extensional versions of explicit substitution calculi have been studied for ground terms [24], work is necessary to understand the interaction of the η -rule with explicit substitutions, dependent types, and meta-variables.

$$\begin{array}{c}
\frac{}{\vdash \epsilon; \epsilon} \text{ (Empty)} \qquad \frac{\Sigma; \Gamma \vdash A : s \quad s \in \{Kind, Type\}}{\vdash \Sigma; A.\Gamma} \text{ (Var-Decl)} \\
\\
\frac{\vdash \Sigma; \Gamma \quad X \text{ is a fresh meta-variable}}{\vdash X :_{\Gamma} Kind. \Sigma} \text{ (Meta-Var-Decl}_1\text{)} \\
\\
\frac{\Sigma; \Gamma \vdash A : s \quad s \in \{Kind, Type\} \quad X \text{ is a fresh meta-variable}}{\vdash X :_{\Gamma} A. \Sigma} \text{ (Meta-Var-Decl}_2\text{)}
\end{array}$$

FIG. 2.2. *Valid signatures and contexts*

2.4. Dependent types. In $\lambda\Pi_{\mathcal{L}}$, we consider typing assertions having one of the following forms:

$$\vdash \Sigma; \Gamma$$

to capture that the context Γ is valid in the signature Σ ,

$$\Sigma; \Gamma \vdash M : A$$

to capture that the term M has type A (the type M has the kind A) in $\Sigma; \Gamma$, and

$$\Sigma; \Gamma \vdash S \triangleright \Delta$$

to capture that the substitution S has the type Δ in $\Sigma; \Gamma$. The scoping rules for variables and meta-variables are as follows. Contexts Γ , Δ , and expressions M , A , S may depend on any meta-variable declared in the respective signature Σ . Indices in M , A and S are relative to their respective context Γ .

Typing rules for signatures, contexts, and expressions are all mutually dependent. Valid signatures and contexts are defined by the typing rules in Figure 2.2.

Valid $\lambda\Pi_{\mathcal{L}}$ -expressions the λP -system are defined by the typing rules in Figure 2.3. In the case of the Calculus of Constructions, the rules (Prod), (Abs), and (Cons) are modified as indicated in Figure 2.4. Finally, conversion rules, on both systems, are defined in Figure 2.5.

In the following, we use $\vdash \Sigma$, $\vdash \Gamma$, $\Gamma \vdash M : A$, and $\Gamma \vdash S \triangleright \Delta$ as shorthands for $\vdash \Sigma; \epsilon$, $\vdash \epsilon; \Gamma$, $\epsilon; \Gamma \vdash M : A$, and $\epsilon; \Gamma \vdash S \triangleright \Delta$, respectively.

In this paper, unless otherwise stated, a judgment like $\Sigma; \Gamma \vdash M : A$ refers to the setting of $\lambda\Pi_{\mathcal{L}}$ in the Calculus of Constructions. However, the main properties of $\lambda\Pi_{\mathcal{L}}$ hold in both the Calculus of Constructions and the λP -system. We prove in [31, 33] that $\lambda\Pi_{\mathcal{L}}$ satisfies, among others, the following properties (for the sake of simplicity we show the properties only for typed terms, but they hold in the same way for typed substitutions):

PROPOSITION 2.3 (Sort soundness). *If $\Sigma; \Gamma \vdash M : A$, then either $A = Kind$, or $\Sigma; \Gamma \vdash A : s$, where $s \in \{Kind, Type\}$.*

PROPOSITION 2.4 (Type uniqueness). *If $\Sigma; \Gamma \vdash M : A$ and $\Sigma; \Gamma \vdash M : B$, then $A \equiv_{\lambda\Pi_{\mathcal{L}}} B$.*

$$\begin{array}{c}
\frac{\vdash \Sigma; \Gamma}{\Sigma; \Gamma \vdash \text{Type} : \text{Kind}} \text{(Type)} \\
\\
\frac{\Sigma; \Gamma \vdash A : \text{Type} \quad \Sigma; A.\Gamma \vdash B : s \quad s \in \{\text{Kind}, \text{Type}\}}{\Sigma; \Gamma \vdash \Pi_A.B : s} \text{(Prod)} \\
\\
\frac{\Sigma; \Gamma \vdash M : \Pi_A.B \quad \Sigma; \Gamma \vdash N : A}{\Sigma; \Gamma \vdash (M N) : B[N \cdot_A \uparrow^0]} \text{(Appl)} \\
\\
\frac{\Sigma; \Gamma \vdash S \triangleright \Delta \quad \Sigma; \Delta \vdash A : \text{Kind}}{\Sigma; \Gamma \vdash A[S] : \text{Kind}} \text{(Clos-Kind)} \\
\\
\frac{\vdash \Sigma; \Gamma}{\Sigma; \Gamma \vdash \uparrow^0 \triangleright \Gamma} \text{(Id)} \\
\\
\frac{\Sigma; \Gamma \vdash S \triangleright \Delta_1 \quad \Sigma; \Delta_1 \vdash T \triangleright \Delta_2}{\Sigma; \Gamma \vdash T \circ S \triangleright \Delta_2} \text{(Comp)} \\
\\
\frac{\vdash \Sigma; A.\Gamma}{\Sigma; A.\Gamma \vdash \underline{_} : A[\uparrow^1]} \text{(Var)} \\
\\
\frac{\Sigma; \Gamma \vdash A : \text{Type} \quad \Sigma; A.\Gamma \vdash M : B \quad \Sigma; \Gamma \vdash \Pi_A.B : s \quad s \in \{\text{Kind}, \text{Type}\}}{\Sigma; \Gamma \vdash \lambda_A.M : \Pi_A.B} \text{(Abs)} \\
\\
\frac{\Sigma; \Gamma \vdash S \triangleright \Delta \quad \Sigma; \Delta \vdash M : A \quad \Sigma; \Delta \vdash A : s \quad s \in \{\text{Kind}, \text{Type}\}}{\Sigma; \Gamma \vdash M[S] : A[S]} \text{(Clos)} \\
\\
\frac{\vdash \Sigma; \Gamma \quad X : \Delta A \in \Sigma \quad \Delta \equiv_{\lambda \Pi_C} \Gamma}{\Sigma; \Gamma \vdash X : A} \text{(Meta-Var)} \\
\\
\frac{\vdash \Sigma; A.\Gamma \quad \Sigma; \Gamma \vdash \uparrow^n \triangleright \Delta}{\Sigma; A.\Gamma \vdash \uparrow^{n+1} \triangleright \Delta} \text{(Shift)} \\
\\
\frac{\Sigma; \Gamma \vdash M : A[S] \quad \Sigma; \Gamma \vdash S \triangleright \Delta \quad \Sigma; \Delta \vdash A : \text{Type}}{\Sigma; \Gamma \vdash M \cdot_A S \triangleright A.\Delta} \text{(Cons)}
\end{array}$$

FIG. 2.3. *Valid expressions*

$$\begin{array}{c}
\frac{\Sigma; A.\Gamma \vdash B : s \quad s \in \{\text{Kind}, \text{Type}\}}{\Sigma; \Gamma \vdash \Pi_A.B : s} \text{(Prod)} \\
\\
\frac{\Sigma; \Gamma \vdash M : A[S] \quad \Sigma; \Gamma \vdash S \triangleright \Delta \quad \Sigma; \Delta \vdash A : s \quad s \in \{\text{Kind}, \text{Type}\}}{\Sigma; \Gamma \vdash M \cdot_A S \triangleright A.\Delta} \text{(Cons)} \\
\\
\frac{\Sigma; A.\Gamma \vdash M : B \quad \Sigma; A.\Gamma \vdash B : s \quad s \in \{\text{Kind}, \text{Type}\}}{\Sigma; \Gamma \vdash \lambda_A.M : \Pi_A.B} \text{(Abs)}
\end{array}$$

FIG. 2.4. *The modified rules (Prod), (Abs), and (Cons)*

$$\begin{array}{c}
\Sigma; \Gamma \vdash M : A \\
\Sigma; \Gamma \vdash B : s \\
s \in \{Kind, Type\} \\
\hline
\frac{A \equiv_{\lambda\Pi_{\mathcal{L}}} B}{\Sigma; \Gamma \vdash M : B} \text{ (Conv)}
\end{array}
\qquad
\begin{array}{c}
\Sigma; \Gamma \vdash S \triangleright \Delta_1 \\
\vdash \Sigma; \Delta_2 \\
\hline
\frac{\Delta_1 \equiv_{\lambda\Pi_{\mathcal{L}}} \Delta_2}{\Sigma; \Gamma \vdash S \triangleright \Delta_2} \text{ (Conv-Subs)}
\end{array}$$

FIG. 2.5. *Conversions*

PROPOSITION 2.5 (Subject reduction). *If $M \xrightarrow{\lambda\Pi_{\mathcal{L}}^*} N$ and $\Sigma; \Gamma \vdash M : A$, then $\Sigma; \Gamma \vdash N : A$.*

PROPOSITION 2.6 (Soundness). *If $\Sigma; \Gamma \vdash M : A$, $\Sigma; \Gamma \vdash N : B$ and $M \equiv_{\lambda\Pi_{\mathcal{L}}} N$, then there exists a path of well-typed reductions between A and B .*

PROPOSITION 2.7 (Weak normalization). *If $\Sigma; \Gamma \vdash M : A$, then M is weakly normalizing; therefore, M has at least one $\lambda\Pi_{\mathcal{L}}$ -normal form.*

PROPOSITION 2.8 (Church-Rosser). *If $M_1 \equiv_{\lambda\Pi_{\mathcal{L}}} M_2$, $\Sigma; \Gamma \vdash M_1 : A$, and $\Sigma; \Gamma \vdash M_2 : A$, then M_1 and M_2 are $\lambda\Pi_{\mathcal{L}}$ -joinable, i.e., there exists M such that $M_1 \xrightarrow{\lambda\Pi_{\mathcal{L}}^*} M$ and $M_2 \xrightarrow{\lambda\Pi_{\mathcal{L}}^*} M$.*

COROLLARY 2.9 (Normal forms). *The $\lambda\Pi_{\mathcal{L}}$ -normal form of a well-typed $\lambda\Pi_{\mathcal{L}}$ -term always exists, and it is unique. If M is a well-typed term, we denote by $(M) \downarrow_{\lambda\Pi_{\mathcal{L}}}$ its $\lambda\Pi_{\mathcal{L}}$ -normal form.*

The following proposition states the conditions that guarantee the soundness of instantiation of meta-variables in $\lambda\Pi_{\mathcal{L}}$.

PROPOSITION 2.10 (Instantiation lemma). *Let M be a term such that $\Sigma_1; \Gamma \vdash M : A$, and Σ a signature having the form $\Sigma_2. X:_{\Gamma} A. \Sigma_1$,*

1. *if $\vdash \Sigma; \Delta$, then $\vdash \Sigma\{X/M\}; \Delta\{X/M\}$,*
2. *if $\Sigma; \Delta \vdash N : B$, then*
 $\Sigma\{X/M\}; \Delta\{X/M\} \vdash N\{X/M\} : B\{X/M\}$, *and*
3. *if $\Sigma; \Delta_1 \vdash S \triangleright \Delta_2$, then $\Sigma\{X/M\}; \Delta_1\{X/M\} \vdash S\{X/M\} \triangleright \Delta_2\{X/M\}$.*

Finally, the next property justifies the use of $\lambda\Pi_{\mathcal{L}}$ to build proof-terms in a constructive logic based on a dependent-type system. It states that when the signature is empty, $\lambda\Pi_{\mathcal{L}}$ types as many terms as the λ -calculus does.

PROPOSITION 2.11 (Conservative extension). *Let M, A be pure terms in $\lambda\Pi_{\mathcal{L}}$, and Γ be a context containing only pure terms. Then, $\Gamma \vdash M : A$ in $\lambda\Pi_{\mathcal{L}}$ if and only if $\Gamma \vdash M : A$ in the respective dependent-typed version of the λ -calculus (modulo de Bruijn indices translation).*

3. A Proof Synthesis Method in $\lambda\Pi_{\mathcal{L}}$. We introduce the basic ideas of our technique with an example. For readability, when discussing examples we use named variables and not de Bruijn indices. Nevertheless, we recall that our formalism uses a de Bruijn nameless notation of variables.

Assume a context with the following variable declarations

$$\begin{aligned}
&bool : Type, \\
&nat : Type, \\
&f : nat \rightarrow nat \rightarrow bool, \\
&g : (nat \rightarrow bool) \rightarrow nat, \\
¬ : bool \rightarrow bool, \\
&eq : bool \rightarrow bool \rightarrow Type, \\
&h : \Pi p:(nat \rightarrow bool) \rightarrow bool. \Pi x:nat \rightarrow bool. (eq (p x) (not (p (f (g x))))).
\end{aligned}$$

We address the problem of finding terms X and Y such that $X : (eq\ Y\ Y)$ and $Y : bool$. This problem happens to be a paraphrasing of a formulation given in [14] of the famous Cantor’s theorem that there is not surjection from a set (in this case nat) to its power set (formed by the elements of type $nat \rightarrow bool$). It can be solved, for example using Dowek’s method, by enumerating all the terms Y of type $bool$, and then the terms of type $(eq\ Y\ Y)$.

However, by combining proof construction and term synthesis we can do better. Instead of looking directly for Y , we could claim to know it, and try to find a term of type $(eq\ Y\ Y)$. Then, we use the typing information available for eq to guide the proof-term synthesis.

In our framework, we assume two meta-variable declarations $Y : bool$ and $X : (eq\ Y\ Y)$. Notice that the meta-variable Y appears in the type of X . In fact, in contrast to the simply-typed λ -calculus, in a dependent-typed calculus meta-variables may appear in types and in contexts. Typing rules for open terms should take into account these considerations.

A *solution* to X and Y is a couple of ground terms M, A such that when X is instantiate with M and Y with A , it holds $M : (eq\ A\ A)$ and $A : bool$.

By looking at the context of variables, we notice that a possible instantiation for X should use the variable h . Since we do not know the right arguments p and x to apply h , we declare new meta-variables $X_p : (nat \rightarrow bool) \rightarrow bool$ and $X_x : nat \rightarrow bool$, and proceed to instantiate X with $(h\ X_p\ X_x)$.

At this stage of the development, we have the following situation. Three meta-variables to solve: $Y : bool$, $X_p : (nat \rightarrow bool) \rightarrow bool$, and $X_x : nat \rightarrow bool$, and the incomplete proof-term $(h\ X_p\ X_x)$ of type $(eq\ Y\ Y)$. However, there is something wrong. The type given by the type system to the term $(h\ X_p\ X_x)$ is $(eq\ (X_p\ X_x)\ (not\ (X_p\ (f\ (g\ X_x))))$), which is not convertible to $(eq\ Y\ Y)$. In fact, we should have been more careful with the instantiation of X with $(h\ X_p\ X_x)$. Since two syntactically different types can become equal via instantiation of meta-variables and β -reduction, we can instantiate a meta-variable with a term of different type, but we have to keep track of a set of disagreement types. In our case, if we want to instantiate X with $(h\ X_p\ X_x)$, we have to add the constraint $(eq\ (X_p\ X_x)\ (not\ (X_p\ (f\ (g\ X_x)))) \equiv_{\lambda\Pi_C} (eq\ Y\ Y)$ to the disagreement set.

Thus, the goal is not to find *any* ground instantiation for the meta-variables, but one that reduces the disagreement set to a set of trivial equations of the form $M = M$, where M is a ground term.

If the original proposition holds, eventually we will instantiate all the meta-variables in such a way that the disagreement set is also solved. A possible solution to our example is

$$\begin{aligned} X_x &= \lambda y:nat.(not\ (f\ y\ y)), \\ X_p &= \lambda x:nat \rightarrow bool.(x\ (g\ \lambda y:nat.(not\ (f\ y\ y)))), \\ Y &= (not\ (f\ (g\ \lambda y:nat.(not\ (f\ y\ y))))), \text{ and} \\ X &= (h\ \lambda x:nat \rightarrow bool.(x\ (g\ \lambda y:nat.(not\ (f\ y\ y))))\ \lambda y:nat.(not\ (f\ y\ y))). \end{aligned}$$

That solution was found by our prototype in 209 rounds (including back-tracking steps). Each round corresponds to the instantiation of one meta-variable or the simplification of the disagreement set. This number contrasts with the 1024 rounds that it took our algorithm to find the same solution by first enumerating all the terms of type $bool$.

The method to solve a set of meta-variables and a disagreement set can be summarized as:

1. Take a meta-variable X to solve. Because eventually, all the meta-variables have to be solved, any of them can be chosen. However, as we will explain later, some typing properties guide the choice of an appropriate meta-variable to solve.
2. By using the type information, propose a term M , probably containing new meta-variables, to

instantiate X .

3. Declare the new meta-variables appearing in M , and add to the disagreement set the typing constraints necessary to guarantee the soundness of the instantiation.
4. Simplify the disagreement set. If a typing constraint is unsatisfiable, backtrack to step 2. Restore the disagreement set to that point.
5. Stop if all the meta-variables are solved and the disagreement set contains only trivial equations. Otherwise, call recursively the procedure.

Our method improves Dowek's method in three ways:

- Proof construction and term synthesis are combined in a single method. Therefore, proof assistant systems based on the proofs-as-terms paradigm can use our framework to represent uniformly proof under construction and proof-terms.
- The first-order setting of the $\lambda\Pi_{\mathcal{L}}$ -calculus eliminates most of the technical problems related to the higher-order aspects of the λ -calculus.
- In Dowek's method, variables, and not meta-variables, are used to represent place-holders. Since, these variables should range over all the set of well-typed terms, the type system where the proof synthesis method is described allows variable declarations where the original type system does not. That type system introduces some technical nuisances [12, 13]. In our framework this is not necessary. Meta-variables and variables have different declaration rules. In particular, meta-variables can be typed in sorts where variables cannot (see rules (Meta-Var-Decl₁), (Meta-Var-Decl₂), and (Var-Decl)).

3.1. The $\lambda\Pi_{\mathcal{L}}$ -calculus with constraints. As we have seen in the informal description of the method, instantiation of meta-variables may need the resolution of a disagreement set. Indeed, the disagreement set is maintained in an extended kind of signatures called *constrained signatures*.

DEFINITION 3.1 (Constrained signatures). *A constraint $M \simeq_{\Gamma} N$ relates two terms M, N , and a context Γ . A constrained signature is a list containing meta-variable declarations and constraint declarations. Formally, they are defined by the following grammar:*

$$\text{Constrained signatures } \Xi ::= \epsilon \mid X :_{\Gamma} A. \Xi \mid M \simeq_{\Gamma} N. \Xi$$

Notice that constraints are declared together with meta-variables. This way, the type system may enforce that a constraint uses only meta-variables that have already been declared in a signature.

DEFINITION 3.2 (Equivalence modulo constraints). *Let Ξ be a constrained signature; we define the relation \equiv_{Ξ} as the smallest equivalence relation compatible with structure such that*

1. *if $M \equiv_{\lambda\Pi_{\mathcal{L}}} N$, then $M \equiv_{\Xi} N$, and*
2. *if $M \simeq_{\Gamma} N \in \Xi$, then $M \equiv_{\Xi} N$.*

We extend the $\lambda\Pi_{\mathcal{L}}$ -calculus to deal with constraints.

DEFINITION 3.3 ($\lambda\Pi_{\mathcal{L}}$ -with constraints). *The type system $\lambda\Pi_{\mathcal{L}}$ with constraints is defined as $\lambda\Pi_{\mathcal{L}}$ in Section 2, where we denote typing judgments by $\vdash \Xi$, $\vdash \Xi; \Gamma$ and $\Xi; \Gamma \vdash M : A$, we add the rule*

$$\frac{\Xi; \Gamma \vdash M_1 : A \quad \Xi; \Gamma \vdash M_2 : A}{\vdash M_1 \simeq_{\Gamma} M_2. \Xi} \text{ (Constraint)}$$

and we replace the rules (Conv), (Conv-Subs), and (Meta-Var) by

$$\begin{array}{c}
\Xi; \Gamma \vdash M : A \\
\Xi; \Gamma \vdash B : s \\
s \in \{Kind, Type\} \\
\hline
\Xi; \Gamma \vdash M : B \quad (Conv)
\end{array}
\qquad
\begin{array}{c}
\Sigma; \Gamma \vdash S \triangleright \Delta \\
\vdash \Sigma; \Delta' \\
\hline
\Sigma; \Gamma \vdash S \triangleright \Delta' \quad (Conv-Subs)
\end{array}$$

$$\begin{array}{c}
\vdash \Sigma; \Gamma \\
X: \Delta A \in \Sigma \\
\hline
\Sigma; \Gamma \vdash X : A \quad (Meta-Var)
\end{array}$$

As expected, a constrained signature Ξ is said to be valid if it holds $\vdash \Xi$.

The $\lambda\Pi_{\mathcal{L}}$ -calculus with constraints does not satisfy most of the typing properties of $\lambda\Pi_{\mathcal{L}}$ given in Section 2. In particular, it is not normalizing (not even weakly). For instance, the non-terminating term $(\lambda x:A.(x x) \lambda x:A.(x x))$ can be typed in a constrained signature containing $A \simeq A \rightarrow A$.

However, we can prove the following properties.

LEMMA 3.4. *Let Ξ be a valid constrained signature and Σ be the signature where we have removed all the constraints of Ξ ,*

1. (a) if $\vdash \Sigma; \Gamma$, then $\vdash \Xi; \Gamma$,
- (b) if $\Sigma; \Gamma \vdash M : A$, then $\Xi; \Gamma \vdash M : A$, and
- (c) if $\Sigma; \Gamma \vdash S \triangleright \Delta$, then $\Xi; \Gamma \vdash S \triangleright \Delta$; and
2. if Ξ does not contain constraints, i.e., $\Sigma = \Xi$, then
 - (a) if $\vdash \Xi; \Gamma$, then $\vdash \Sigma; \Gamma$,
 - (b) if $\Xi; \Gamma \vdash M : A$, then $\Sigma; \Gamma \vdash M : A$, and
 - (c) if $\Xi; \Gamma \vdash S \triangleright \Delta$, then $\Sigma; \Gamma \vdash S \triangleright \Delta$.

Proof. By simultaneous induction on the typing derivations. \square

According to Lemma 3.4, if Ξ' is a prefix of a signature Ξ , and it does not contain constraints, the set of expressions that are typeable in Ξ' satisfies the properties given in Section 2; in particular, these expressions have a $\lambda\Pi_{\mathcal{L}}$ -normal form (Corollary 2.9). This is no longer true if Ξ' contains constraints. We exploit this fact to simplify constrained signatures. Indeed, we define the $\lambda\Pi_{\mathcal{L}}$ -normal form of a constrained signature, with respect to the largest prefix which does not contain a constraint. We will see later that constrained signatures in $\lambda\Pi_{\mathcal{L}}$ -normal form allow us to prune the search space of solutions to meta-variables.

DEFINITION 3.5 (Normal form of a constrained signature). *Let Ξ be a valid constrained signature, the $\lambda\Pi_{\mathcal{L}}$ -normal form of Ξ , denoted by $(\Xi)_{\downarrow \lambda\Pi_{\mathcal{L}}}$, is defined by structural induction on Ξ .*

1. $(\epsilon)_{\downarrow \lambda\Pi_{\mathcal{L}}} = \epsilon$,
2. Ξ has the form $X: \Gamma A. \Xi'$ or $M \simeq_{\Gamma} N. \Xi'$
 - if Ξ' contains constraints,

$$\begin{aligned}
(X: \Gamma A. \Xi')_{\downarrow \lambda\Pi_{\mathcal{L}}} &= X: \Gamma A. (\Xi')_{\downarrow \lambda\Pi_{\mathcal{L}}} \\
(M \simeq_{\Gamma} N. \Xi')_{\downarrow \lambda\Pi_{\mathcal{L}}} &= M \simeq_{\Gamma} N. (\Xi')_{\downarrow \lambda\Pi_{\mathcal{L}}},
\end{aligned}$$

- if Ξ' does not contain constraints,

$$\begin{aligned}
(X: \Gamma A. \Xi')_{\downarrow \lambda\Pi_{\mathcal{L}}} &= X: (\Gamma)_{\downarrow \lambda\Pi_{\mathcal{L}}} (A)_{\downarrow \lambda\Pi_{\mathcal{L}}} \cdot (\Xi')_{\downarrow \lambda\Pi_{\mathcal{L}}} \\
(M \simeq_{\Gamma} N. \Xi')_{\downarrow \lambda\Pi_{\mathcal{L}}} &= (\Xi')_{\downarrow \lambda\Pi_{\mathcal{L}}}, \text{ if } (M)_{\downarrow \lambda\Pi_{\mathcal{L}}} = (N)_{\downarrow \lambda\Pi_{\mathcal{L}}} \\
(M \simeq_{\Gamma} N. \Xi')_{\downarrow \lambda\Pi_{\mathcal{L}}} &= (M)_{\downarrow \lambda\Pi_{\mathcal{L}}} \simeq_{(\Gamma)_{\downarrow \lambda\Pi_{\mathcal{L}}}} (N)_{\downarrow \lambda\Pi_{\mathcal{L}}} \cdot (\Xi')_{\downarrow \lambda\Pi_{\mathcal{L}}}, \text{ otherwise.}
\end{aligned}$$

The $\lambda\Pi_{\mathcal{L}}$ -normal form of a constrained signature preserves typing.

LEMMA 3.6. *Let Ξ be a valid constrained signature,*

1. $\vdash \Xi; \Gamma$ if and only if $\vdash (\Xi) \downarrow_{\lambda\Pi_{\mathcal{L}}}; \Gamma$,
2. $\Xi; \Gamma \vdash M : A$ if and only if $(\Xi) \downarrow_{\lambda\Pi_{\mathcal{L}}}; \Gamma \vdash M : A$, and
3. $\Xi; \Gamma \vdash S \triangleright \Delta$ if and only if $(\Xi) \downarrow_{\lambda\Pi_{\mathcal{L}}}; \Gamma \vdash S \triangleright \Delta$.

Proof. By simultaneous induction on the typing derivations. \square

3.2. The problem. A constrained signature can be seen as a list of goals to be solved. Informally speaking, to solve a signature means to find ground instantiations for all the meta-variables in a way that all the constraints are reduced to trivial equations.

DEFINITION 3.7 (Parallel instantiation). *A parallel instantiation of a constrained signature Ξ is a function Ψ_{Ξ} from meta-variables of Ξ to terms. As usual, the function Ψ_{Ξ} is extended to be applied to arbitrary expressions. When Ξ can be inferred from the context, we simply write Ψ .*

DEFINITION 3.8 (Solution). *Let Ξ be a valid constrained signature, we say that a parallel instantiation Ψ is a solution to Ξ if and only if*

1. for any constraint $M \simeq_{\Gamma} N \in \Xi$, we have $\Psi(\Gamma) \vdash \Psi(M) : A$, $\Psi(\Gamma) \vdash \Psi(N) : A$ and $\Psi(M) \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi(N)$, and
2. for any meta-variable declaration $X :_{\Gamma} A \in \Xi$, we have $\Psi(\Gamma) \vdash \Psi(X) : \Psi(A)$.

In this case we say that Ξ is a solvable signature. Furthermore, if for all meta-variables X in Ξ , $\Psi(X)$ is a $\lambda\Pi_{\mathcal{L}}$ -normal form, we say that Ψ is a normal solution to Ξ .

Notice that according to the previous definition, if Ψ is a solution to a constrained signature Ξ , for all meta-variables X in Ξ , $\Psi(X)$ is a ground term. If Ψ is also normal, then $\Psi(X)$ is pure.

DEFINITION 3.9 (Equivalent solutions). *Let Ψ_1, Ψ_2 be solutions to a valid constrained signature Ξ . They are said to be equivalent, denoted $\Psi_1 \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi_2$, if and only if for all X in Ξ , $\Psi_1(X) \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi_2(X)$.*

To know whether or not a valid constrained signature is solvable is undecidable in the general case. In particular, it requires to decide the existence of solutions for constraints having the form $(X M_1 \dots M_i) \simeq (Y N_1 \dots N_j)$, where X and Y are meta-variables, and to solve the inhabitation problem in a dependent-type system. Those problems are known to be undecidable [29, 4].

Some kinds of signatures can be trivially discharged.

REMARK 1. *If a valid constrained signature Ξ is solvable, then there exists a normal solution to Ξ .*

DEFINITION 3.10 (Failure signature). *Let Ξ be the $\lambda\Pi_{\mathcal{L}}$ -normal form of a valid constrained signature; we say that Ξ is a failure signature if it contains a constraint relating two ground terms in $\lambda\Pi_{\mathcal{L}}$ -normal form which are not identical.*

REMARK 2. *Failure signatures are not solvable.*

The Cantor's theorem example can be described in our formalism as follows. Let $\Gamma =$

$$\begin{aligned} h &: \Pi p : (nat \rightarrow bool) \rightarrow bool. \Pi x : nat \rightarrow bool. (eq (p x) (not (p (f (g x))))) \\ eq &: bool \rightarrow bool \rightarrow Type. not : bool \rightarrow bool. \\ g &: (nat \rightarrow bool) \rightarrow nat. f : nat \rightarrow nat \rightarrow bool. bool : Type. nat : Type, \end{aligned}$$

and $\Xi = X :_{\Gamma} (eq Y Y). Y :_{\Gamma} bool$, the following parallel instantiation Ψ is a solution to Ξ :

$$\begin{aligned} \Psi(Y) &= (not (f (g \lambda y : nat. (not (f y y))))) \\ \Psi(X) &= (h \lambda x : nat \rightarrow bool. (x (g \lambda y : nat. (not (f y y))))) \lambda y : nat. (not (f y y)). \end{aligned}$$

In the process of finding that solution, we have first solved the constrained signature $\Xi' =$

$$X \simeq_{\Gamma} (h X_p X_x). (eq (X_p X_x) (not (X_p (f (g X_x))))) \simeq_{\Gamma} (eq Y Y).$$

$X_x:_{\Gamma} \text{nat} \rightarrow \text{bool}$. $X_p:_{\Gamma} (\text{nat} \rightarrow \text{bool}) \rightarrow \text{bool}$. $X:_{\Gamma} (\text{eq } Y \ Y)$. $Y:_{\Gamma} \text{bool}$,
which has the solution

$$\begin{aligned}\Psi'(X_p) &= \lambda x: \text{nat} \rightarrow \text{bool}. (x (g \ \lambda y: \text{nat}. (\text{not } (f \ y \ y)))) \\ \Psi'(X_x) &= \lambda y: \text{nat}. (\text{not } (f \ y \ y)) \\ \Psi'(Z) &= \Psi(Z), \text{ otherwise.}\end{aligned}$$

It can be verified that, for example, $\Psi'((\text{eq } (X_p \ X_x) (\text{not } (X_p (f (g \ X_x)))))) \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi'(\text{eq } Y \ Y)$.

In the rest of this section, we describe a method to find a solution to a constrained signature via refinement steps. In the example above, Ξ' is a refinement of Ξ , and thus, a solution to Ξ can be deduced from a solution to Ξ' .

3.3. The construction steps: Elementary graftings. We want to solve a constrained signature via successive instantiation of meta-variables. Each one of these instantiations is called an *elementary grafting*.²

DEFINITION 3.11 (Grafting). *A grafting is an instantiation of a meta-variable, with possibly new declarations of meta-variables and constraints. Let X be a meta-variable, M be a term, and Ξ' be a constrained signature, the grafting of X with M in Ξ' is denoted by $\{X/\Xi' M\}$.*

Valid graftings (in Ξ) are defined by the following typing rule,

$$\frac{\begin{array}{c} \vdash \Xi \\ \Xi = \Xi_2. X:_{\Gamma} A. \Xi_1 \\ \Xi'. \Xi_1; \Gamma \vdash M : A \\ \vdash \Xi_2. \Xi'. \Xi_1 \end{array}}{\Xi \vdash \{X/\Xi' M\}} \text{ (Grafting)}$$

In the previous definition, Ξ' contains *only* the additional meta-variables and constraints that are necessary to type M . However, $\Xi_2. \Xi'. \Xi_1$ is a conservative extension of Ξ , i.e., all the expressions that are typeable in Ξ , are typeable in $\Xi_2. \Xi'. \Xi_1$, too. In particular, it holds $\vdash \Xi'. \Xi_1$.

The grafting $\{X/\Xi' M\}$ can be applied to an expression or a context in the same way as the instantiation $\{X/M\}$. However, only valid grafting can be applied to constrained signatures. Let Ξ be a valid constrained signature, the application of the grafting $\{X/\Xi' M\}$ to Ξ , instantiates the meta-variable X with M in Ξ , and installs Ξ' in the right place of Ξ .

DEFINITION 3.12 (Application of grafting). *Let $\Xi = \Xi_2. X:_{\Gamma} A. \Xi_1$ such that $\Xi \vdash \{X/\Xi' M\}$,*

$$\Xi\{X/\Xi' M\} = (\Xi_2. \Xi'. \Xi_1)\{X/M\}.$$

The application of a valid grafting preserves typing.

LEMMA 3.13. *Let Ξ be a valid constrained signature such that $\Xi \vdash \{X/\Xi' M\}$,*

1. *if $\vdash \Xi; \Gamma$, then $\vdash \Xi\{X/\Xi' M\}; \Gamma\{X/M\}$,*
2. *if $\Xi; \Gamma \vdash M : A$, then $\Xi\{X/\Xi' M\}; \Gamma\{X/M\} \vdash M\{X/M\} : A\{X/M\}$, and*
3. *if $\Xi; \Gamma \vdash S \triangleright \Delta$, then $\Xi\{X/\Xi' M\}; \Gamma\{X/M\} \vdash S\{X/M\} \triangleright \Delta\{X/M\}$.*

Proof. By induction on the typing derivations. The proof uses Proposition 2.10. \square

The reduction to $\lambda\Pi_{\mathcal{L}}$ -normal form of a constrained signature preserves its valid graftings.

²In Dowek's method, they are called *elementary substitutions*.

LEMMA 3.14. *Let Ξ be a valid constrained signature, $\Xi \vdash \{X/\Xi' M\}$ if and only if $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}} \vdash \{X/\Xi' M\}$.*

Proof. We show that $\Xi \vdash \{X/\Xi' M\}$ implies $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}} \vdash \{X/\Xi' M\}$. The other direction is similar. By Lemma 3.6, $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$ is a valid constrained signature. By Definition 3.5, Ξ and $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$ declare exactly the same meta-variables, then, by hypothesis, meta-variables declared in Ξ' are not in Ξ . Since Ξ has the form $\Xi'_2. X:\Gamma A'. \Xi'_1$, $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$ has the form $\Xi_2. X:\Gamma A. \Xi_1$, where

1. $\Xi'. \Xi'_1; \Gamma \vdash M : A'$, and
2. $\Xi_1 = (\Xi'_1)\downarrow_{\lambda\Pi_{\mathcal{L}}}$, $A = (A')\downarrow_{\lambda\Pi_{\mathcal{L}}}$.

From (1) and (3), $\Xi'. \Xi'_1; \Gamma \vdash M : A$. Therefore, by Lemma 3.6 and (3), $\Xi'. \Xi_1; \Gamma \vdash M : A$. \square

In our Cantor's theorem example we verify that

$$\Xi \vdash \{X/\Xi'(h X_p X_x)\},$$

where $\Xi = X:\Gamma(eq Y Y). Y:\Gamma bool$, and $\Xi' =$

$$(eq (X_p X_x) (not (X_p (f (g X_x)))))) \simeq_{\Gamma} (eq Y Y). \\ X_x:\Gamma nat \rightarrow bool. X_p:\Gamma(nat \rightarrow bool) \rightarrow bool.$$

In fact, Ξ' contains meta-variables which are not already declared in Ξ (thus, Ξ' can be safely installed in Ξ), X is declared in Ξ , and

$$\Xi'. Y:\Gamma bool \vdash (h X_p X_x) : (eq Y Y).$$

Then, by Definition 3.11,

$$\Xi \vdash \{X/\Xi'(h X_p X_x)\}.$$

Given a constrained signature, the choice of the next meta-variable to solve is crucial. Since properties like confluence and normalization are available for any typeable expression in a prefix of a constrained signature without constraints, meta-variables in those prefixes are very appropriate to solve in the first place. The next property states that such variables exist.

LEMMA 3.15. *Let Ξ be the $\lambda\Pi_{\mathcal{L}}$ -normal form of a valid constrained signature such that $\Xi \neq \epsilon$ and Ξ is not a failure signature. Then, Ξ has the form $\Xi_2. X:\Gamma A. \Xi_1$, where*

1. Ξ_1 does not contain constraints, and
2. $\vdash X:\Gamma A. \Xi_1$.

Proof. The constrained signature Ξ is not empty, then it has at least one element. Assume that the first element is a constraint $M \simeq_{\Gamma} N$. By hypothesis and Lemma 3.6, $\vdash \Xi$. Hence, it holds that $\vdash M \simeq_{\Gamma} N$. By inversion of rule (Constraint), $\Gamma \vdash M : B$ and $\Gamma \vdash N : B$. Since M, N, B are well-typed without meta-variables, they are ground, and by Lemma 3.4, it holds that $\Gamma \vdash M : B$ and $\Gamma \vdash N : B$. Since Ξ is a signature in $\lambda\Pi_{\mathcal{L}}$ -normal form, M and N are not identical. But this is not possible because Ξ is not a failure context. Therefore, the first element of Ξ is not a constraint, and thus, Ξ has the form $\Xi_2. X:\Gamma A. \Xi_1$, where Ξ_1 does not contain constraints. By the typing rules, we have $\vdash X:\Gamma A. \Xi_1$, and thus, by Lemma 3.4, $\vdash X:\Gamma A. \Xi_1$. \square

The type of a meta-variable gives enough information to guess a valid grafting. Assume, for example, that a meta-variable X has a type A . If $A = Kind$, then by inversion of the type rule (Type), X may be instantiate with *Type*. But also, by inversion of the rule (Prod), X may be instantiate with the term $\Pi x:Z.Y$ where Z is a new meta-variable of type one of the sorts $\{Kind, Type\}$, and Y is a new meta-variable of type A (notice that Y should be declared in a context where the variable declaration $x : Z$ exists). This case also applies if $A = Type$.

If A is a product, i.e., $A = \Pi x:A_1.A_2$, by inversion of the rule (Abs), we can instantiate X with the term $\lambda x:A_1.Y$ where Y is a new meta-variable of type A (declared in a context where the variable declaration $x : A_1$ exists).

In any case, and by inversion of the rule (Appl), it is always possible to instantiate X with the term (YZ) , where Y is a meta-variable of type $\Pi x:Y_B.Y_A$, Z is a meta-variable of type Y_B , Y_B is a meta-variable of one of the sorts $\{Kind, Type\}$, Y_A is a meta-variable with the same type as A (declared in a context where the variable declaration $x : Y_B$ exists), and the constraint $A \simeq Y_A[Z \cdot Y_B \uparrow^0]$ is added to the constrained signature. However, since we are interested in solutions modulo $\equiv_{\lambda\Pi_{\mathcal{L}}}$, any normal instantiation of Y has the form $(n M_1 \dots M_i)$ where n is a variable. Using this remark, we simplify the current case by using the variables of the context where the meta-variable X has been declared. Assume a variable declaration $n : \Pi x_1:A_1 \dots \Pi x_j:A_j.B_1$. The meta-variable X can be instantiated with the term $(n X_1 \dots X_i)$ of type B_2 , where $i \leq j$, X_1, \dots, X_i are new meta-variables of the right type (according to the type of n), and the constraint $A \simeq B_2$ is added to the constrained signature. We call this case *imitation*, because it is very similar to the *imitation* rule of higher-order unification algorithms [22].

The imitation case, as it has been described before, is not complete. In a polymorphic type system, as the Calculus of Constructions, if the type of a term M is $\Pi x:A.B$, where B is not a product, the type of $(M N)$ may still be a product. That is, the number of arguments of M is not bounded by the number of products in its type. Take for example the context $O : nat. nat : Type. P : \Pi x:Type.x$. In this context, $(P nat) : nat$, $(P (nat \rightarrow nat) O) : nat$, $(P (nat \rightarrow nat \rightarrow nat) O O) : nat$, \dots . In fact, for any natural number $i > 0$, there exist M_1, \dots, M_i such that $(P M_1 \dots M_i) : nat$.

The fact that the number of arguments of a term is not fixed by its type is called *splitting* [21]. Splitting raises some technical problems in higher-order unification algorithms and so, in proof-synthesis methods [13].

Given the valid judgment $\Sigma; \Gamma \vdash M : \Pi x_1:A_1 \dots \Pi x_i:A_i.B$, where B is not a product, for any $j > 0$, there exists a term N having the form $(M X_1; \dots X_j)$ such that it is well-typed in a constrained signature extending Σ . The term N is called an *imitation of M of grade j* . Furthermore, if $j > i$, $(j - i)$ is the *splitting grade* of N . Otherwise, the splitting grade of N is 0. We describe a method to build imitations of arbitrary splitting grade.

DEFINITION 3.16 (Imitation with splitting). *Let Σ be a signature, without constraints, in $\lambda\Pi_{\mathcal{L}}$ -normal form, M be a term such that $\Sigma; \Gamma \vdash M : A$, and $\Sigma; \Gamma \vdash A : s$ where $s \in \{Kind, Type\}$. For $i \geq 0$, the set of imitations of M of grade i , denoted $[\Sigma; \Gamma \vdash M : A]^i$, is a set of judgments in $\lambda\Pi_{\mathcal{L}}$ with constraints defined by induction on i as follows.*

- If $i = 0$, then $\{\Sigma; \Gamma \vdash M : A\}$.
- If $i > 0$, then for all $\Xi; \Gamma \vdash N : B$ in $[\Sigma; \Gamma \vdash M : A]^{i-1}$, we consider the union of the following set of judgments,³
 - If B has the form $\Pi_{A_1}.A_2$, then

$$\begin{aligned} \{\Xi'. \Xi; \Gamma \vdash N' : B' \mid & \Xi' = X :_{\Gamma} A_1, \\ & X \text{ is a fresh meta-variable,} \\ & N' = (N X), \\ & B' \in (A_2[X \cdot_{A_1} \uparrow^0]) \downarrow_{\Pi_{\mathcal{L}}}\} \end{aligned}$$

³We recall that $\Pi_{\mathcal{L}}$ is strongly normalizing (Lemma 2.1).

– Otherwise — this is the case of splitting,

$$\begin{aligned} \{\Xi'. \Xi; \Gamma \vdash N' : B'\} \quad & \Xi' = B \simeq_{\Gamma} \Pi_{Y_1}. Y_2. X :_{\Gamma} Y_1. Y_2 :_{Y_1. \Gamma} s_2. Y_1 :_{\Gamma} s_1, \\ & X, Y_1, Y_2 \text{ are fresh meta-variables,} \\ & s_1 \in \{Kind, Type\}, \\ & s_2 = s, \\ & N' = (N X), \\ & B' \in (Y_2[X \cdot_{Y_1} \uparrow^0]) \downarrow_{\Pi_{\mathcal{L}}} \end{aligned}$$

We verify that judgments in the set $[\Sigma; \Gamma \vdash M : A]^i$ are valid.

LEMMA 3.17. *Let Σ be a signature in $\lambda\Pi_{\mathcal{L}}$ -normal form, M be a term such that $\Sigma; \Gamma \vdash M : A$, and $\Sigma; \Gamma \vdash A : s$ where $s \in \{Kind, Type\}$. For $i \geq 0$, the elements of $[\Sigma; \Gamma \vdash M : A]^i$ are valid judgments.*

Proof. By induction on i . The base case holds by Lemma 3.4. At the induction step we use the rules (Appl), (Conv), and the fact that the reduction to $\Pi_{\mathcal{L}}$ -normal form preserves the type. \square

We formally define the *elementary graftings*.

DEFINITION 3.18 (Elementary graftings). *Let Ξ be the $\lambda\Pi_{\mathcal{L}}$ -normal form of a valid constrained signature such that $\Xi \neq \epsilon$ and Ξ is not a failure signature. We choose a meta-variable X in Ξ , i.e., $\Xi = \Xi_2. X :_{\Gamma} A. \Xi_1$, such that $\vdash X :_{\Gamma} A. \Xi_1$. Such a meta-variable exists by Lemma 3.15. We define the following graftings by case analysis on A (the cases are not disjoint):*

1. $A = Kind$. We consider the grafting $\{X/\epsilon Type\}$.
2. $A \in \{Kind, Type\}$. For any $s \in \{Kind, Type\}$, we consider the grafting $\{X/\Xi' \Pi_Z. Y\}$, where Z, Y are fresh meta-variables, and $\Xi' = Y :_{Z. \Gamma} A. Z :_{\Gamma} s$.
3. $A = \Pi_{A_1}. A_2$. We consider the grafting $\{X/\Xi' \lambda_{A_1}. Y\}$, where Y is a fresh meta-variable, and $\Xi' = Y :_{A_1. \Gamma} A_2$.
4. $\Xi_1; \Gamma \vdash A : s_1$, $s_1 \in \{Kind, Type\}$. For all variables n in the context Γ , i.e., $1 \leq n \leq |\Gamma|$, such that $\Xi_1; \Gamma \vdash \underline{n} : B$ (B is a $\lambda\Pi_{\mathcal{L}}$ -normal form), and for $i \geq 0$, we consider all the graftings

$$\{X/A \simeq_{\Gamma} A'. \Xi' M\}$$

where $\Xi'. \Xi_1; \Gamma \vdash M : A'$ is in $[\Xi_1; \Gamma \vdash \underline{n} : B]^i$.

All the graftings considered above form the set of elementary graftings of the meta-variable X in Ξ .

Due to the splitting rule, the set of elementary graftings of one meta-variable is potentially infinite. Some of the elementary graftings lead to failure signatures. An early detection of failure signatures allows the pruning of the research space of valid graftings. This is why we use constrained signatures in $\lambda\Pi_{\mathcal{L}}$ -normal form.

We verify that the elementary graftings are valid graftings.

THEOREM 3.19 (Elementary graftings). *Let Ξ be the $\lambda\Pi_{\mathcal{L}}$ -normal form of a valid constrained signature such that $\Xi \neq \epsilon$ and Ξ is not a failure signature. If X is a meta-variable in Ξ such that it is well-typed without constraints, then the elementary graftings of X are valid graftings in Ξ .*

Proof. By Lemma 3.15, Ξ has the form $\Xi_2. X :_{\Gamma} A. \Xi_1$. First, we verify that

$$(3.1) \quad \vdash \Xi_1; \Gamma,$$

$$(3.2) \quad A = Kind \text{ or } \Xi_1; \Gamma \vdash A : s, \quad s \in \{Kind, Type\}.$$

Then, we reason by case analysis on A , and we consider all the elementary graftings of X .

- $A = Kind$. By using Eq. 3.1 with the rule (Type), we get $\Xi_1; \Gamma \vdash Type : Kind$. Therefore, $\Xi \vdash \{X/\epsilon Type\}$.
- $A \in \{Kind, Type\}$. For any $s' \in \{Kind, Type\}$, we consider the grafting $\{X/\Xi \cdot \Pi_Z.Y\}$, where Y, Z are fresh meta-variables, and $\Xi' = Y :_{Z.\Gamma} A, Z :_{\Gamma} s'$. We consider two cases according to the form of s' .
 - $s' = Kind$. We have the derivation

$$\frac{\text{Eq. 3.1}}{\vdash Z :_{\Gamma} Kind. \Xi_1} \text{(Meta-Var-Decl}_1\text{)}$$

- $s' = Type$. We have the derivation

$$\frac{\frac{\text{Eq. 3.1}}{\Xi_1; \Gamma \vdash Type : Kind} \text{(Type)}}{\vdash Z :_{\Gamma} Type. \Xi_1} \text{(Meta-Var-Decl}_2\text{)}$$

In both cases,

$$(3.3) \quad \vdash Z :_{\Gamma} s'. \Xi_1.$$

The derivation continues as follows

$$\frac{\frac{\text{Eq. 3.3}}{Z :_{\Gamma} s'. \Xi_1; \Gamma \vdash Z : s'} \text{(Meta-Var)}}{\vdash Z :_{\Gamma} s'. \Xi_1; Z.\Gamma} \text{(Var-Decl)}$$

Now, we consider two cases according to the form of A .

- $A = Kind$. We have the derivation

$$\frac{\vdash Z :_{\Gamma} s'. \Xi_1; Z.\Gamma}{\vdash Y :_{Z.\Gamma} Kind. Z :_{\Gamma} s'. \Xi_1} \text{(Meta-Var-Decl}_1\text{)}$$

- $A = Type$. We have the derivation

$$\frac{\frac{\vdash Z :_{\Gamma} s'. \Xi_1; Z.\Gamma}{Z :_{\Gamma} s'. \Xi_1; \Gamma \vdash Type : Kind} \text{(Type)}}{\vdash Y :_{Z.\Gamma} Type. Z :_{\Gamma} s'. \Xi_1} \text{(Meta-Var-Decl}_2\text{)}$$

In both cases,

$$(3.4) \quad \vdash Y :_{Z.\Gamma} A. Z :_{\Gamma} s'. \Xi_1.$$

But also

$$\frac{\frac{\text{Eq. 3.4}}{Y :_{Z.\Gamma} A. Z :_{\Gamma} s'. \Xi_1; Z.\Gamma \vdash Y : A} \text{(Meta-Var)}}{Y :_{Z.\Gamma} A. Z :_{\Gamma} s'. \Xi_1; \Gamma \vdash \Pi_Z Y : A} \text{(Prod)}$$

Therefore, $\Xi \vdash \{X/\Xi \cdot \Pi_Z.Y\}$,

- $A = \Pi_{A_1}.A_2$. We consider the grafting $\{X/\Xi \cdot \lambda_{A_1}.Y\}$, where Y is a fresh meta-variable, and $\Xi' = Y :_{A_1.\Gamma} A_2$. As in the previous case we have the derivation

$$\frac{\text{Eq. 3.2} \quad \frac{\dots}{\Xi'. \Xi_1; A_1.\Gamma \vdash Y : A_2}}{\Xi'. \Xi_1 \vdash \lambda_{A_1}.Y : \Pi_{A_1}.A_2} \text{(Abs)}$$

Therefore, $\Xi \vdash \{X/\Xi \cdot \lambda_{A_1}.Y\}$.

- For $1 \leq n \leq |\Gamma|$ such that $\Xi_1; \Gamma \vdash \underline{n} : B$ (B is a $\lambda\Pi_{\mathcal{L}}$ -normal form), we consider all the graftings

$$\{X /_{A \simeq_{\Gamma} A'} \Xi' M\}$$

where $\Xi'. \Xi_1; \Gamma \vdash M : A'$ is in $[\Sigma; \Gamma \vdash \underline{n} : B]^i$, $i \geq 0$. By Lemma 3.17,

$$(3.5) \quad \Xi'. \Xi_1; \Gamma \vdash M : A',$$

$$(3.6) \quad \Xi'. \Xi_1; \vdash A' : s.$$

We also have

$$\text{Eq. 3.5} \quad \frac{\frac{\Xi'. \Xi_1; \Gamma \vdash A : s \quad \Xi'. \Xi_1; \Gamma \vdash A' : s}{\vdash A \simeq_{\Gamma} A'} \text{ (Constraint)}}{A \simeq_{\Gamma} A'. \Xi'. \Xi_1; \Gamma \vdash M : A} \text{ (Conv)}$$

Therefore, $\Xi \sim \{X /_{A \simeq_{\Gamma} A'} \Xi' M\}$.

□

3.4. Splitting in λP . In a calculus without polymorphism, as λP , splitting is not possible. Thus, in that case the number of applications of a variable is fixed by its type. In our version of λP using the $\lambda\Pi_{\mathcal{L}}$ -calculus, splitting is still possible since we allow meta-variables of types and kinds.

However, some simplifications are still possible.

A term having the form $(X[S] M_1 M_i)$ or $(X M_1 M_i)$, $i \geq 0$, where X is a meta-variable is said to be *flexible*. A term having the form *Type*, *Kind*, or $(\underline{n} M_1 M_i)$, $i \geq 0$ is said to be *rigid*. Consider a term M such that $\Xi; \Gamma \vdash M : \Pi_{A_1} \dots \Pi_{A_i} B$ in λP . If B is a $\lambda\Pi_{\mathcal{L}}$ -normal form and it is not a product, it is either flexible or rigid. If B is flexible, the number of applications of n depends on the actual parameters of M . If B is rigid, the number of applications of M cannot be greater than i . In that case, we could consider imitations of M only of grade $j \leq i$, since their splitting grade is 0, the set of such imitations is finite (module renaming of fresh meta-variables).

3.5. Putting everything together: The method. Given a constrained signature Ξ , we solve each meta-variable by exploring the set of its elementary graftings. We can organize the search of elementary graftings as follows.

DEFINITION 3.20 (Search tree). *Let Ξ be a valid constrained signature; we build a search tree of Ξ , where nodes are labeled by constrained signatures in $\lambda\Pi_{\mathcal{L}}$ -normal form and edges by elementary graftings, in the following way:*

- The root is labeled by $(\Xi) \downarrow_{\lambda\Pi_{\mathcal{L}}}$.
- Nodes labeled by the empty signature or by failure signatures are leaves.
- If a node is labeled by a signature Ξ which is not empty or a failure signature, we choose a meta-variable X in Ξ such that it is well-typed in a signature without constraints and for each elementary grafting $\{X /_{\Xi} M\}$ of X , we grow an edge labeled by this elementary signature to a new node labeled by $(\Xi \{X /_{\Xi} M\}) \downarrow_{\lambda\Pi_{\mathcal{L}}}$.

We claim that if there exists a node labeled by the empty signature in a search tree of Ξ , then Ξ is solvable, and a solution can be found by composing sequentially all the elementary graftings along a path in the search tree containing the node labeled by the empty signature. Conversely, if there exists a solution to a constrained signature Ξ , it can be found, modulo $\equiv_{\lambda\Pi_{\mathcal{L}}}$, in a search tree of Ξ . These two properties, *soundness and completeness*, are proved in Section 4.

A semi-algorithm to solve a valid constrained signature is to enumerate the nodes of a search tree to find a leaf labeled by the empty signature. Notice that the enumeration must deal with infinite paths in the tree, but also with infinite branching because the set of elementary graftings of a meta-variable is potentially infinite.

EXAMPLE 1 (Revisited Cantor's theorem example). *Let Γ be the context*

$$h : \Pi p:(nat \rightarrow bool) \rightarrow bool. \Pi x:nat \rightarrow bool. (eq (p x) (not (p (f (g x)))).$$

$$eq : bool \rightarrow bool \rightarrow Type. not : bool \rightarrow bool.$$

$$g : (nat \rightarrow bool) \rightarrow nat. f : nat \rightarrow nat \rightarrow bool. bool : Type. nat : Type,$$

and $\Xi = X :_{\Gamma} (eq Y Y). Y :_{\Gamma} bool$. *Find a solution to Ξ .*

A search tree is built from the root Ξ (notice that it is a $\lambda\Pi_{\mathcal{L}}$ -normal form). Since Ξ does not contain constraints, we can take any meta-variable of Ξ to solve. Let us choose the meta-variable X . The type of X is neither a product nor a sort. Therefore, the only elementary graftings that are possible for this meta-variable are those generated by the imitation step. We instantiate X with an imitation of grade 2 of the variable h (no splitting takes place),

$$\begin{aligned} & \{\Xi; \Gamma \vdash h : \Pi p:(nat \rightarrow bool) \rightarrow bool. \Pi x:nat \rightarrow bool. \\ & \quad (eq (p x) (not (p (f (g x)))))\}^2 = \\ & \{\Xi'. \Xi; \Gamma \vdash (h X_p X_x) : (eq (X_p X_x) (not (X_p (f (g X_x)))))\} \\ & \quad X_x, X_p \text{ are fresh meta-variables,} \\ & \quad \Xi' = X_x :_{\Gamma} nat \rightarrow bool. X_p :_{\Gamma} (nat \rightarrow bool) \rightarrow bool \} \end{aligned}$$

We label an edge with the elementary grafting,

$$\{X/\Xi_1 (h X_p X_x)\},$$

where $\Xi_1 =$

$$(eq (X_p X_x) (not (X_p (f (g X_x))))) \simeq_{\Gamma} (eq Y Y).$$

$$X_x :_{\Gamma} nat \rightarrow bool. X_p :_{\Gamma} (nat \rightarrow bool) \rightarrow bool.$$

This edge points to the constrained signature:

$$(eq (X_p X_x) (not (X_p (f (g X_x))))) \simeq_{\Gamma} (eq Y Y).$$

$$X_x :_{\Gamma} nat \rightarrow bool. X_p :_{\Gamma} (nat \rightarrow bool) \rightarrow bool.$$

$$Y :_{\Gamma} bool.$$

Notice that the meta-variable X is no longer in the signature. Instead, there are new meta-variables X_x and X_p . At this stage, any meta-variable can be chosen. We solve the meta-variable X_x of type $nat \rightarrow bool$. An elementary grafting of this meta-variable is

$$\{X_x/\Xi_2 \lambda y:nat.Z\},$$

where $\Xi_2 = Z :_{y:nat. \Gamma} bool$. We label a new edge with this elementary grafting. It points to the constrained signature:

$$(eq (X_p \lambda y:nat.Z) (not (X_p (f (g \lambda y:nat.Z))))) \simeq_{\Gamma} (eq Y Y).$$

$$Z :_{y:nat. \Gamma} bool. X_p :_{\Gamma} (nat \rightarrow bool) \rightarrow bool.$$

$$Y :_{\Gamma} bool.$$

Eventually, after some iterations an empty signature is obtained. A solution can be found by composing all the elementary graftings along the path of the search tree leading to the empty signature.

4. Soundness and Completeness.

4.1. Soundness. We claim that if $\Xi_1 \xrightarrow{\theta_1} \Xi_2 \xrightarrow{\theta_2} \dots \xrightarrow{\theta_{n-1}} \Xi_n$ is a path of the search tree of a valid constrained signature Ξ , such that $\Xi_1 = (\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$ and $\Xi_n = \epsilon$, the sequential composition of the graftings $\theta_1, \dots, \theta_{n-1}$ results in a solution to Ξ .

The proof of this statement goes as follows. First, we describe which lists of grafting are valid with respect to a valid constrained signature. These lists are called *sequential graftings*. Next, we characterize the sequential graftings that lead to an empty signature. They are called *derivations*. The key points of the proof are:

1. The sequential composition of the graftings in a derivation of Ξ is a solution to Ξ .
2. A path from the root of a search tree of Ξ leading to an empty signature is a derivation of Ξ .

The soundness theorem is a consequence of (1) and (2).

DEFINITION 4.1 (Sequential grafting). *A list $\psi = \langle \theta_1, \dots, \theta_i \rangle$, $i \geq 0$, of graftings is a sequential grafting of a valid constrained signature Ξ if and only if*

- ψ is the empty list, i.e., $i = 0$, or
- $\Xi \sim \theta_1$ and $\langle \theta_2, \dots, \theta_i \rangle$ is a sequential grafting of $\Xi\theta_1$.

The application of ψ to Ξ , is defined as $\Xi\psi = ((\Xi\theta_1)\dots)\theta_i$. We overload this notation to apply sequential graftings to expressions and contexts.

DEFINITION 4.2 (Derivation). *A sequential grafting ψ of a valid constrained signature Ξ is called a derivation of Ξ if and only if $(\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}} = \epsilon$.*

REMARK 3. *Failure signatures do not have derivations.*

DEFINITION 4.3 (Sequential composition). *Let ψ be a sequential grafting of a valid constrained signature Ξ . The sequential composition of ψ , denoted by $\tilde{\psi}$, is the parallel instantiation defined for all X in Ξ as $\tilde{\psi}(X) = X\psi$.*

The next propositions are proved at the end of this section. They are the key proving the soundness theorem.

PROPOSITION 4.4. *If ψ is a derivation of a valid constrained signature Ξ , then $\tilde{\psi}$ — the sequential composition of ψ — is a solution to Ξ .*

PROPOSITION 4.5. *Let $\Xi_1 \xrightarrow{\theta_1} \Xi_2 \xrightarrow{\theta_2} \dots \xrightarrow{\theta_{n-1}} \Xi_n$, $n \geq 0$, be a path of a search tree of a valid constrained signature Ξ such that $\Xi_1 = (\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$, then the list of graftings $\psi = \langle \theta_1, \dots, \theta_{n-1} \rangle$ is a sequential grafting of Ξ , and for $0 < i \leq n$, $\Xi_i = (\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$.*

THEOREM 4.6 (Soundness). *Let $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}} \xrightarrow{\psi} \epsilon$ be a path of a search tree of a valid constrained signature Ξ , the sequential composition of ψ is a solution to Ξ .*

Proof. By Proposition 4.5, ψ is a sequential grafting of Ξ , and $\epsilon = (\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$. Therefore, by Definition 4.2, ψ is a derivation of Ξ . Finally, by Proposition 4.4, the sequential composition of ψ , i.e., $\tilde{\psi}$, is a solution to Ξ . \square

The rest of this section is dedicated to the proof of Proposition 4.4 and Proposition 4.5.

First, we prove that sequential graftings preserve typing.

LEMMA 4.7. *Let ψ be a sequential grafting of a valid constrained signature Ξ ,*

1. *if $\vdash \Xi; \Gamma$, then $\vdash \Xi\psi; \Gamma\psi$,*
2. *if $\Xi; \Gamma \sim M : A$, then $\Xi\psi; \Gamma\psi \sim M\psi : A\psi$, and*
3. *if $\Xi; \Gamma \sim S \triangleright \Delta$, then $\Xi\psi; \Gamma\psi \sim S\psi \triangleright \Delta\psi$.*

Proof. We reason by induction on the length of the list ψ and Lemma 3.13. \square

Proposition 4.4. If ψ is a derivation of a valid constrained signature Ξ , then $\tilde{\psi}$ is a solution to Ξ .

Proof. Since Ξ is a valid constrained signature, for any constraint $M_1 \simeq_{\Gamma} M_2$ and meta-variable declaration $X :_{\Delta} A$ in Ξ ,

$$(4.1) \quad \Xi; \Gamma \vdash M_1 : B,$$

$$(4.2) \quad \Xi; \Gamma \vdash M_2 : B,$$

$$(4.3) \quad \Xi; \Delta \vdash X : A.$$

Because ψ is a sequential grafting of Ξ , and by Lemma 4.7,

$$(4.4) \quad \Xi\psi; \Gamma\psi \vdash M_1\psi : B\psi,$$

$$(4.5) \quad \Xi\psi; \Gamma\psi \vdash M_2\psi : B\psi,$$

$$(4.6) \quad \Xi\psi; \Delta\psi \vdash X\psi : A\psi.$$

By Lemma 3.6,

$$(4.7) \quad (\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}; \Gamma\psi \vdash M_1\psi : B\psi,$$

$$(4.8) \quad (\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}; \Gamma\psi \vdash M_2\psi : B\psi,$$

$$(4.9) \quad (\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}; \Delta\psi \vdash X\psi : B\psi.$$

By Definition 4.3, $\Gamma\psi = \tilde{\psi}(\Gamma)$, $\Delta\psi = \tilde{\psi}(\Delta)$, $M_1\psi = \tilde{\psi}(M_1)$, and $M_2\psi = \tilde{\psi}(M_2)$. Since ψ is a derivation of Ξ , $(\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}} = \epsilon$. Thus, $M_1 \simeq_{\Gamma} M_2$ is not in $(\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$. Hence, $(M_1\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$ and $(M_2\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$ are identical ground terms (otherwise the constraint could not be discharged). Therefore, $\tilde{\psi}$ is a solution to Ξ . \square

LEMMA 4.8. For all valid constrained signature Ξ , ψ is a sequential grafting of Ξ if and only if ψ is a sequential grafting of $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$.

Proof. By induction on the length of ψ . If ψ is the empty list, then the conclusion is trivial by Definition 4.1. Otherwise, we use the induction hypothesis, and Lemma 3.14. \square

LEMMA 4.9. For all valid constrained signature Ξ , if ψ is a sequential grafting of $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$, then $((\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}} = (\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$.

Proof. By induction on the length of ψ . The base case is trivial. At the induction step we use equational reasoning on $\lambda\Pi_{\mathcal{L}}$. \square

Proposition 4.5. For all $n \geq 0$, if $\Xi_1 \xrightarrow{\theta_1} \Xi_2 \xrightarrow{\theta_2} \dots \xrightarrow{\theta_{n-1}} \Xi_n$ is a path of a search tree of a valid constrained signature Ξ such that $\Xi_1 = (\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$, the list of graftings $\psi = \langle \theta_1, \dots, \theta_{n-1} \rangle$ is a sequential grafting of Ξ , and for $0 < i \leq n$, $\Xi_i = (\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$.

Proof. By induction on n . The base case is trivial. Assume that $n > 0$ and take $\psi' = \langle \theta_2, \dots, \theta_i \rangle$. By construction, θ_1 is an elementary grafting of a meta-variable in Ξ_1 . Thus, by Theorem 3.19, θ_1 is a valid grafting of Ξ_1 and $\Xi_2 = (\Xi_1\theta_1)\downarrow_{\lambda\Pi_{\mathcal{L}}}$ is well-defined. By induction hypothesis, ψ' is a sequential grafting of $\Xi_1\theta_1$, and $\Xi_i = (\Xi_1\langle \theta_1\psi' \rangle)\downarrow_{\lambda\Pi_{\mathcal{L}}} = (\Xi_1\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$. By Definition 4.1, ψ is a sequential grafting of $\Xi_1 = (\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$. Therefore, by Lemma 4.8, ψ is a sequential grafting of Ξ , and by Lemma 4.9, $\Xi_i = (\Xi\psi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$. \square

4.2. Completeness. The completeness property states that if there is a solution Ψ to a constraint signature Ξ , there exists a derivation ψ of Ξ , such that $\tilde{\psi} \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi$. This claim is proved by induction on the size of Ψ .

DEFINITION 4.10 (Size of a pure term). *The size of a pure term defined by induction over the structure of terms is as follows.*

- $|s| = 1$, if $s \in \{Kind, Type\}$.
- $|\underline{n}| = 1$.
- $|(M N)| = |M| + |N| + 1$.
- $|\lambda_A.M| = |A| + |M| + 1$.
- $|\Pi_A.B| = |A| + |B| + 1$.

DEFINITION 4.11 (Size of a parallel instantiation). *Let Ψ be a parallel instantiation of a constrained signature Ξ , the size of Ψ , denoted by $|\Psi|$, is the sum of the sizes of $\Psi(X)$ for all X in Ξ .*

LEMMA 4.12. *Let Ξ be a valid constrained signature in $\lambda\Pi_{\mathcal{L}}$ -normal form, if Ψ is a normal solution of Ξ , then there exists a search tree of Ξ with a derivation ψ , such that $\tilde{\psi} \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi$.*

Proof. By induction on the size of Ψ_{Ξ} .⁴ Since Ψ_{Ξ} is a solution to Ξ , Ξ is not a failure signature. If $\Xi = \epsilon$, the empty list is a derivation of Ξ . Otherwise, take the first meta-variable declared in Ξ , namely $X :_{\Gamma} A$. This meta-variable exists by Lemma 3.15. Notice that A and Γ do not depend on any other meta-variable or constraint. We reason by case analysis on $M = \Psi_{\Xi}(X)$. Since Ξ is a constrained signature in $\lambda\Pi_{\mathcal{L}}$ -normal form and Ψ is a normal solution, M, A, Γ are ground $\lambda\Pi_{\mathcal{L}}$ -normal forms.

- $M = Type$. In this case, $A = Kind$. Consider the elementary grafting of X , $\theta = \{X/\epsilon Type\}$. Let $\Xi_1 = (\Xi\theta)\downarrow_{\lambda\Pi_{\mathcal{L}}}$, Ξ_1 is well-defined by Lemma 3.13 and Theorem 3.19. We check that $\Psi'_{\Xi_1}(X) = \Psi_{\Xi}(X)$, $X \in \Xi_1$, is a normal solution of Ξ_1 , and that $|\Psi'_{\Xi_1}| < |\Psi_{\Xi}|$.
- $M = \Pi_{A_1}.A_2$. In this case, $A \in \{Kind, Type\}$ and $\Gamma \vdash A_1 : s$, $s \in \{Kind, Type\}$. Consider the elementary grafting of X , $\theta = \{X/\Xi'\Pi_Z.Y\}$, where Z, Y are fresh meta-variables, and $\Xi' = Y :_{Z.\Gamma} A$. $Z :_{\Gamma} s$. Let $\Xi_1 = (\Xi\theta)\downarrow_{\lambda\Pi_{\mathcal{L}}}$. We check that

$$\Psi'_{\Xi_1}(W) = \begin{cases} A_1 & \text{if } W = Z \\ A_2 & \text{if } W = Y \\ \Psi_{\Xi}(W) & \text{otherwise} \end{cases}$$

is a normal solution of Ξ_1 , and that $|\Psi'_{\Xi_1}| < |\Psi_{\Xi}|$.

- $M = \lambda_{A_1}.N$. In this case, $A \in \Pi_{A_1}.A_2$ and $\Gamma \vdash N : A_2$. Consider the elementary grafting of X , $\theta = \{X/\Xi'\lambda_{A_1}.Y\}$, where Y is a fresh meta-variable, and $\Xi' = Y :_{A_1.\Gamma} A_2$. Let $\Xi_1 = (\Xi\theta)\downarrow_{\lambda\Pi_{\mathcal{L}}}$. We check that

$$\Psi'_{\Xi_1}(W) = \begin{cases} A_2 & \text{if } W = Y \\ \Psi_{\Xi}(W) & \text{otherwise} \end{cases}$$

is a normal solution of Ξ_1 , and that $|\Psi'_{\Xi_1}| < |\Psi_{\Xi}|$.

- $M = (\underline{n} M_1 \dots M_i)$. In this case, $\Gamma \vdash \underline{n} : B$, B (in $\lambda\Pi_{\mathcal{L}}$ -normal form) is a product, $\Gamma \vdash A : s$, and $s \in \{Kind, Type\}$. Consider the elementary grafting of X , $\theta = \{X/A \simeq_{\Gamma} A'. \Xi'(\underline{n} X_1 \dots X_i)\}$ where $\Xi'; \Gamma \vdash (\underline{n} X_1 \dots X_i) : A'$ is in $[\Gamma \vdash \underline{n} : B]^i$. Let $\Xi_1 = (\Xi\theta)\downarrow_{\lambda\Pi_{\mathcal{L}}}$. We check that

$$\Psi'_{\Xi_1}(W) = \begin{cases} M_j & \text{if } W = X_j, 0 < j \leq i \\ \Psi_{\Xi}(W) & \text{otherwise} \end{cases}$$

⁴In this proof, the index of Ψ is relevant.

is a normal solution of Ξ_1 , and that $|\Psi'_{\Xi_1}| < |\Psi_{\Xi}|$.

In all the cases $|\Psi'_{\Xi_1}| < |\Psi_{\Xi}|$, then by induction hypothesis, there exists a search tree of Ξ_1 with a derivation ψ_1 , such that $\tilde{\psi}_1 \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi'_{\Xi_1}$. Then, $\psi = \langle \theta, \psi_1 \rangle$ is a derivation of Ξ . Since $\Psi_{\Xi}(X) = \Psi'_{\Xi_1}(X\theta)$, for all $X \in \Xi$, $\Psi_{\Xi}(X) \equiv_{\lambda\Pi_{\mathcal{L}}} X\langle \theta, \psi_1 \rangle = X\psi$. Therefore, $\tilde{\psi} \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi_{\Xi}$. \square

THEOREM 4.13 (Completeness). *Let Ξ be a valid constrained signature, if Ψ is a solution of Ξ , then there exists a search tree of Ξ with a derivation ψ , such that $\tilde{\psi} \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi$.*

Proof. If Ψ is a solution of Ξ , by Lemma 3.6 and Definition 3.8, Ψ is a solution of $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$ too. By Remark 1, the parallel instantiation $\Psi'(X) = (\Psi(X))\downarrow_{\lambda\Pi_{\mathcal{L}}}$, $X \in \Xi$, is a normal solution of $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$. Hence, by Lemma 4.12, there exists a search tree of $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$ with a derivation ψ , such that $\tilde{\psi} \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi'$. Therefore, $\tilde{\psi} \equiv_{\lambda\Pi_{\mathcal{L}}} \Psi$. By Definition 3.20, a search tree of Ξ is a search tree of $(\Xi)\downarrow_{\lambda\Pi_{\mathcal{L}}}$. \square

5. Related Work and Summary. Automatic proof synthesis is at the basis of proof assistant systems. A complete method for search of proof trees based on resolution and unification was formulated by Robinson [37] for the first-order logic, and by Huet [21] for the higher-order logic. In type systems, higher-order unification (HOU) algorithms are known for the simply-typed λ -calculus [22] and for the $\lambda\Pi$ -calculus of dependent types [17, 35].

For the cube-type systems, Dowek [12, 13] reformulates the unification procedure and generalizes it as a method of term enumeration. Recently, Cornes [10] proposed an extension of Dowek's method to the Calculus of Constructions with Inductive Types.

Dowek, Hardin, and Kirchner [15] propose a first-order presentation of Huet's HOU algorithm based on explicit substitutions and typed meta-variables. This algorithm is generalized to solve higher-order equational unification by Kirchner and Ringeissen [25], and restricted to the case of higher-order patterns by Dowek, Hardin, Kirchner, and Pfenning in [16]. The algorithm for pattern unification via explicit substitutions has been extended (without proof) to dependent types, and implemented in the Twelf system [34].

On the other hand, Briaud [7] shows how HOU can be considered as a typed narrowing in the $\lambda\nu$ -calculus of explicit substitutions. Magnusson [28] presents a unification algorithm in Martin-Löf's type theory with explicit substitutions. This algorithm solves first-order unification problems, but leaves unsolved the flexible-flexible constraints.

Our main contribution is the presentation of Dowek's method of proof synthesis in a suitable theory with explicit substitutions and meta-variables. This way, proof-terms can be built incrementally as the proofs are done, and each construction step is guaranteed by the type system.

Just as in [12, 13], the method presented here is sound and complete. Thus, it can be seen as a semi-algorithm for ground higher-order unification in λP and the Calculus of Constructions. Although, the implementation issues are out of the scope of this paper, a preliminary version of our method has been implemented in OCaml, and it is electronically available by contacting the author.

The underlying theory of the method proposed here is the $\lambda\Pi_{\mathcal{L}}$ -calculus. We believe that the same ideas can be applied to other formalisms satisfying at least the same typing properties as $\lambda\Pi_{\mathcal{L}}$, that is, confluence, weak-normalization, subject reduction, and instantiation lemma. The $\lambda\Pi_{\mathcal{L}}$ -calculus has some features that are useful for our proof-synthesis method and they seem to be in unification issues:

- It is a finite first-order rewriting system. In particular, some properties as soundness and completeness of the method are much simpler to prove.
- It uses general composition of substitutions and simultaneous substitutions. In [33], we discuss efficiency improvements to the method based on these features.
- Since substitutions distribute under abstractions and products, normal forms have a simple charac-

terization. For example, the normal form of a type has the form $\Pi_{A_1} \dots \Pi_{A_i}.A$ where A is not a product.

Finally, notice that $\lambda\Pi_{\mathcal{L}}$ does not handle the η -rule. Extensional versions of explicit substitution calculi have been studied for ground terms [24]. However, work is necessary to understand the interaction with dependent types and meta-variables.

Acknowledgments. Many persons have contributed to this work with useful remarks and suggestions, in particular Gilles Dowek, Delia Kesner, Nikolaj Bjørner, and the anonymous referees. The author is very grateful to them.

REFERENCES

- [1] M. ABADI, L. CARDELLI, P.-L. CURIEN, AND J.-J. LÉVY, *Explicit substitution*, Journal of Functional Programming, 1 (1991), pp. 375–416.
- [2] T. ALTENKIRCH, V. GASPEL, B. NORDSTRÖM, AND B. VON SYDOW, *A User's Guide to ALF*, Chalmers University of Technology, Sweden, May 1994.
- [3] B. BARRAS, S. BOUTIN, C. CORNES, J. COURANT, J. FILLIATRE, E. GIMÉNEZ, H. HERBELIN, G. HUET, C. MUÑOZ, C. MURTHY, C. PARENT, C. PAULIN, A. SAÏBI, AND B. WERNER, *The Coq Proof Assistant Reference Manual – Version V6.1*, Tech. Report 0203, INRIA, August 1997.
- [4] M. BEZEM AND J. SPRINGINTVELD, *A simple proof of the undecidability of inhabitation in λP* , Journal of Functional Programming, 6 (1996), pp. 757–761.
- [5] R. BLOO, *Preservation of Termination for Explicit Substitution*, PhD thesis, Eindhoven University of Technology, 1997.
- [6] R. BLOO AND K. H. ROSE, *Preservation of strong normalisation in named lambda calculi with explicit substitution and garbage collection*, in Proceedings of CSN-95: Computer Science in the Netherlands, Nov. 1995.
- [7] D. BRIAUD, *Higher order unification as a typed narrowing*, tech. report, CRIN Report 96-R-112, 1996.
- [8] T. COQUAND, *Une Théorie de Constructions*, thèse de doctorat, U. Paris VII, 1985.
- [9] T. COQUAND AND G. HUET, *The Calculus of Constructions*, Information and Computation, 76 (1988), pp. 96–120.
- [10] C. CORNES, *Conception d'un langage de haut niveau de représentation de preuves: récurrence par filtrage de motifs, unification en présence de types inductif primitifs. synthèse de lemmes d'inversion*, thèse de doctorat, Université Paris VII, 1997.
- [11] P.-L. CURIEN, T. HARDIN, AND J.-J. LÉVY, *Confluence properties of weak and strong calculi of explicit substitutions*, Journal of the ACM, 43 (1996), pp. 362–397.
- [12] G. DOWEK, *Démonstration automatique dans le calcul des constructions*, thèse de doctorat, U. Paris VII, 1991.
- [13] —, *A complete proof synthesis method for type systems of the cube*, Journal of Logic and Computation, 3 (1993), pp. 287–315.
- [14] —, *Automated theorem proving in first-order logic modulo: On the difference between type theory and set theory*, in First-order Theorem Proving '98, 1998, pp. 1–21.
- [15] G. DOWEK, T. HARDIN, AND C. KIRCHNER, *Higher-order unification via explicit substitutions (extended abstract)*, in Proceedings of the Tenth Annual IEEE Symposium on Logic in Computer Science, San Diego, California, 26–29 June 1995, IEEE Computer Society Press, pp. 366–374.

- [16] G. DOWEK, T. HARDIN, C. KIRCHNER, AND F. PFENNING, *Unification via explicit substitutions: The case of higher-order patterns*, in Proceedings of the Joint International Conference and Symposium on Logic Programming, M. Maher, ed., Bonn, Germany, Sept. 1996, MIT Press.
- [17] C. ELLIOTT, *Higher-order unification with dependent types*, in Proceedings of the International Conference on Rewriting Techniques and Applications (RTA-89), N. Dershowitz, ed., vol. 355 of LNCS, Chapel Hill, North Carolina, Apr. 1989, Springer-Verlag, pp. 121–136.
- [18] M. C. F. FERREIRA, D. KESNER, AND L. PUEL, *Lambda-calculi with explicit substitutions and composition which preserve beta-strong normalization*, in Algebraic and Logic Programming, 5th International Conference, ALP'96, M. Hanus and M. Rodríguez-Artalejo, eds., vol. 1139 of Incs, Aachen, Germany, 25–27 Sept. 1996, Springer, pp. 284–298.
- [19] J.-Y. GIRARD, *Interprétation Fonctionnelle et Élimination des Compures de l'Arithmétique d'Ordre Supérieur*, thèse de doctorat, Université Paris VII, 1972.
- [20] R. HARPER, F. HONSELL, AND G. PLOTKIN, *A framework for defining logics*, Journal of the Association for Computing Machinery, 40 (1993), pp. 143–184.
- [21] G. HUET, *Constrained Resolution A Complete Method for Higher Order Logic*, PhD thesis, Case Western Reserve University, 1972.
- [22] ———, *A unification algorithm for typed lambda calculus*, Theoretical Computer Science, 1 (1975), pp. 27–57.
- [23] F. KAMAREDDINE AND A. RÍOS, *A lambda-calculus à la De Bruijn with explicit substitutions*, LNCS, 982 (1995), pp. 45–62.
- [24] D. KESNER, *Confluence properties of extensional and non-extensional λ -calculi with explicit substitutions (extended abstract)*, in Proceedings of the Seventh International Conference on Rewriting Techniques and Applications (RTA-96), H. Ganzinger, ed., vol. 1103 of LNCS, New Brunswick, New Jersey, 1996, Springer-Verlag, pp. 184–199.
- [25] C. KIRCHNER AND C. RINGEISSEN, *Higher order equational unification via explicit substitutions*, in Proceedings of the International Conference PLILP/ALP/HOA'97, vol. 1298 of LNCS, Southampton (England), September 1997, Springer.
- [26] P. LESCANNE, *From $\lambda\sigma$ to $\lambda\nu$ a journey through calculi of explicit substitutions*, in Proceedings of the 21st Annual ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages, January 1994, pp. 60–69.
- [27] P. LESCANNE AND J. ROUYER-DEGLI, *Explicit substitutions with de Bruijn's levels*, in Proceedings of the International Conference on Rewriting Techniques and Applications (RTA-95), J. Hsiang, ed., vol. 914 of LNCS, Chapel Hill, North Carolina, 1995, Springer-Verlag, pp. 294–308.
- [28] L. MAGNUSSON, *The Implementation of ALF—A Proof Editor Based on Martin-Löf's Monomorphic Type Theory with Explicit Substitution*, PhD thesis, Chalmers University of Technology and Göteborg University, Jan. 1995.
- [29] D. MILLER, *Unification under a mixed prefix*, Journal of Symbolic Computation, 14 (1992), pp. 321–358.
- [30] C. MUÑOZ, *Confluence and preservation of strong normalisation in an explicit substitutions calculus (extended abstract)*, in Proceedings of the Eleventh Annual IEEE Symposium on Logic in Computer Science, New Brunswick, New Jersey, July 1996, IEEE Computer Society Press, pp. 440–447.
- [31] ———, *Dependent types with explicit substitutions: A meta-theoretical development*, in Types for Proofs and Programs, Proceedings of the International Workshop TYPES'96, vol. 1512 of LNCS, Aussois, France, 1997, pp. 294–316.

- [32] ———, *A left-linear variant of $\lambda\sigma$* , in Proc. International Conference PLILP/ALP/HOA'97, vol. 1298 of Lecture Notes in Computer Science, Southampton (England), September 1997, Springer, pp. 224–234.
- [33] ———, *Un calcul de substitutions pour la représentation de preuves partielles en théorie de types*, thèse de doctorat, Université Paris VII, 1997. English version available as INRIA research report RR-3309.
- [34] F. PFENNING AND C. SCHÜRMAN, *Twelf user's guide, 1.2. edition*, Tech. Report CMU-CS-1998-173, Carnegie Mellon University, September 1998.
- [35] D. PYM, *A unification algorithm for the $\lambda\Pi$ -calculus*, International Journal of Foundations of Computer Science, 3 (1992), pp. 333–378.
- [36] A. RÍOS, *Contributions à l'étude de λ -calculs avec des substitutions explicites*, thèse de doctorat, Université Paris VII, 1993.
- [37] J. A. ROBINSON, *A machine-oriented logic based on the resolution principle*, Journal of the ACM, 12 (1965), pp. 23–41.
- [38] M. ZAIONC, *Mechanical procedure for proof construction via closed terms in typed λ calculus*, Journal of Automated Reasoning, 4 (1988), pp. 173–190.
- [39] H. ZANTEMA, *Termination of term rewriting by semantic labelling*, Fundamenta Informaticae, 24 (1995), pp. 89–105.
- [40] ———, *Termination of ϕ and Π_ϕ by semantic labeling*. Personal communication, 1996.