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The Refined Calculus of Inductive Construction: Parametricity and Abstraction

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Abstract—We present a refinement of the Calculus of Inductive Constructions in which one can easily define a notion of relational parametricity. It provides a new way to automate proofs in an interactive theorem prover like Coq.

I. INTRODUCTION

The Calculus of Inductive Constructions (CIC in short) extends the Calculus of Constructions with inductively defined types. It is the underlying formal language of the Coq interactive theorem prover [1].

In the original presentation, CIC had three kinds of sorts: the impredicative sort of propositions Prop, the impredicative sort of basic informative types Set, and the hierarchy of universes Type₀, Type₁, ... This presentation was not compatible with the possibility to add axioms in the system, since it could lead to inconsistencies [2]. Nowadays, there is no impredicative sort of basic informative types, and Set represents Type₀.

This does not fit well with one of the major original ideas about CIC: the possibility to perform program extraction. Indeed, since the current version of CIC does not separate informative types from non-informative types, extraction needs to normalize its type to guess whether it should be erased or not, and this makes it very uneasy to prove correct [3].

In this paper, we propose a refinement of CIC which reconciles extraction with the possibility to add axioms to the system: CIC_ref, the Refined Calculus of Inductive Constructions. The idea is to split the (Typeᵢ)ᵢ∈N hierarchy into two hierarchies (Setᵢ)ᵢ∈N and (Typeᵢ)ᵢ∈N, one for informative types and one for types without computational content.

This calculus allows us to extend the presentation of parametricity for Pure Type Systems introduced by Bernardy et al. [4] to the Calculus of Inductive Constructions. Parametricity is a concept introduced by Reynolds [5] to study the type abstraction of system F, and the abstraction theorem expresses the fact that polymorphic programs map related arguments to related results. In CIC_ref, we can define a notion of relational parametricity in which the relations’ codomains is the Prop sort of propositions.

II. CIC_ref: THE RINED CALCUUS OF INDUCTIVE CONSTRUCTION

The Refined Calculus of Inductive Constructions is a refinement of CIC where terms are generated by the same grammar as CIC:

\[ A, B, P, Q, F :: \equiv x \mid s \mid \forall x : A.B \mid \lambda x : A.B \mid (A \ B) \mid I \mid \text{case}_i(A, Q, P, F) \mid c \mid \text{fix}(x : A).B \]

where \( s \) ranges over the set \{Prop\} \cup \{Setᵢ, Typeᵢ₊₁ \mid i \in \mathbb{N}\} of sorts and \( x \) ranges over the set of variables. We write \( \text{Ind}^p(I : A, c : C^k) \) to state that \( I \) is a well-formed inductive definition typed with \( p \) parameters, of arity \( A \), with \( k \) constructors \( c_1, \ldots, c_k \) of respective types \( C_1, \ldots, C_k \).

A context \( \Gamma \) is a list of pairs \( x : A \) and the typing rules are the rules of CIC (one can refer to [1] for the complete set of rules), except to type sorts and dependent products. As for CIC, typing fixpoints (for \text{fix} and elimination rules (for case) is subject to restrictions to ensure coherence. We present only the rules which are specific to our type system. Here are the three typing rules to type sorts:

\[ \Gamma \vdash \text{Prop} : \text{Type}_{i+1} \quad \Gamma \vdash \text{Set}_i : \text{Type}_{i+1} \quad \Gamma \vdash \text{Type}_i : \text{Type}_{i+1} \]

The following three typing rules tell which products are authorized in the system. The level of the product is the maximum level of the domain and the codomain:

\[ \Gamma \vdash A : r_i \quad \Gamma, x : A \vdash B : s_j \quad (r, s) \in \{\text{Type}, \text{Set}\} \]

Quantifying over propositions does not rise the level of the product:

\[ \Gamma \vdash A : \text{Prop} \quad \Gamma, h : A \vdash B : s_i \quad s \in \{\text{Type}, \text{Set}, \text{Prop}\} \]

And the sort Prop is impredicative, it means that products in Prop may be built by quantifying over objects whose types inhabit any sort:

\[ \Gamma \vdash A : s \quad \Gamma, x : A \vdash B : \text{Prop} \quad s \in \{\text{Type}, \text{Set}, \text{Prop}\} \]

Finally, as in CIC, the system comes with subtyping rules based on the following inclusion of sorts (where \( i < j \)):

\[ \text{Prop} : \text{Set}_i \quad \text{Set}_i : \text{Set}_j \quad \text{Type}_i : \text{Type}_j \]

One should note that CIC_ref easily embeds into CIC by mapping any Setᵢ and Typeᵢ onto the Typeᵢ of CIC. The coherence of CIC thus implies the coherence of CIC_ref.

III. PARAMETRICITY

We can define a notion of relational parametricity for CIC_ref.
\[ \Theta_I(Q^p, T, \mathcal{F}^n) = \lambda(x: A)(x': A')(x_R: [A] x x') (a: I Q^p x^n) (a': I Q^p x'^n) (a_R: [I] Q Q' Q^p x x' x_R a a'). \]

\[ [T] x x_R x_R a a_R (\text{case}_I(a, Q^p, T, \mathcal{F}^n)) (\text{case}_I(a', Q^p, T', \mathcal{F}^n)) \]

Fig. 1. Relation parametricity for inductive types

**Definition 1** (Parametricity relation). For any inductive
\[ \text{Ind}^p(I : A : c : C) \), we define a fresh inductive symbol \([I] \)
and a family \([I]_i \) of fresh constructor names.

The parametricity translation \([\bullet] \) is defined by induction on
the structure of terms and contexts:

\[ \begin{align*}
[\langle\rangle] & = \langle\rangle \\
[\Gamma, x : A] & = [\Gamma], x : A, x' : A', x_R : [A] x x' \\
[s] & = \lambda(x : s)(x' : s) x \to x' \to s \\
[x] & = x_R \\
[\forall x : A.B] & = \lambda(f : \forall x : A.B) (f' : \forall x' : A'.B'). \\
\forall(x : A)(x' : A')(x_R : [A] x x'). \\
[B](f x) (f' x') \\
[\lambda x : A.B] & = \lambda(x : A)(x' : A') (x_R : [A] x x'). \\
\lambda(x : A)(x' : A')(x_R : [A] x x'). \\
[B] I (A B) & = ([A] B B' [B]) \\
[\text{fix}(x : A).B] & = (\text{fix}(x_R : [A] x x'). [B]) \\
[\text{fix}(x : A).B/x]\text{fix}(x' : A').B'/x'] \\
\text{case}_I(M, Q^p, T, \mathcal{F}^n) ) & = \text{case}_I([M], Q, Q', [Q]^p, \\
\Theta_I(Q^p, T, \mathcal{F}^n)) \]

where Prop = \( \text{Set}_1 \), Prop and Type, = Type, and where \( A' \)
denotes the term \( A \) in which we have replaced each variable
\( x \) by a fresh variable \( x' \). The definition of \( \Theta_I \) is in Fig. 1.

What is new with respect to previous works is the fact
that relations over objects of type Prop or Set, have their
codomain in Prop instead of higher universes. We also formally
define parametricity for inductive types.

Unfortunately, in order to prove the abstraction theorem
below, we need to restrict the strong elimination: we have to
disallow the case destructions used to build objects whose
types are of sort Type when the destructed inductive definition
is not small (small inductive definitions are inductive definitions
which constructors only have arguments of type Prop or
Set, see [6]). We write \( \vdash \) for the derivability where strong
elimination is authorized only over small inductive definitions.

**Theorem 1** (Abstraction theorem). If \( \Gamma \vdash_\ast A : B \) then \( \Gamma \vdash_\ast A : B, \Gamma' \vdash_\ast A' : B' \), and \( \Gamma \vdash_\ast [A] : [B] A A' \).

**IV. APPLICATIONS**

A lot of so-called “free theorems” are consequences of the
abstraction theorem and our framework is expressive enough
to implement most examples that can be found in the literature
(see for instance [4], [7]).

Here we propose a new example inspired by François
Garillot’s thesis [8], in which he remarks that polymorphic
functions operating on groups can only compose elements
using the laws given by the group’s structure, and thus cannot
create new elements.

In our system, we may actually use parametricity theory to
translate this uniformity property. We take an arbitrary group
structure \( H \) defined by its carrier \( : \text{Set}_0 \), a unit element,
a composition law, an inverse and the standard axioms stating
that \( H \) is a group. We define \( \text{fingrp} \) the type of all the
finite subgroups of \( H \) consisting of a list plus stability axioms.
Now consider any term \( Z : \text{fingrp} \to \text{fingrp} \) (examples of
such terms abound: e.g. the center, the normalizer, the derived
subgroup...). The abstraction theorem states that for any
\( R : \alpha \to \alpha \to \text{Prop} \) compatible with the laws of \( H \) and for any
\( G G' = \text{fingrp} \) : \( \text{fingrp} \) \( G G' = \text{fingrp} \) \( (Z G) (Z G') \)
where \( \text{fingrp} \) \( R \) is the relation on subgroups induced by \( R \).
Given this, we can prove the following properties:

- for any \( G, Z G \subseteq G \) (if we take \( R : x y \to x \in G \);
- for any \( G, \) for any \( \phi \) a morphism of \( H, \phi(Z G) = Z \phi(G) \)
  (if we take \( R : x y \to y = \phi(x) \)). It entails that \( Z G \) is a
  characteristic subgroup of \( H \).

For a complete Coq formalization of this, please refer to
the online source code [9].

**V. CONCLUSION**

The system presented here allows to distinguish clearly via
typing which expressions will be computationally meaningful
after extraction. It allows us to define a notion of parametricity
for which relations lie in the sort of propositions. We set here
the theoretical foundation for an implementation of a
Coq tactic that constructs proof terms by parametricity. A first
prototype of such a tactic can be found online [9].

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