

# A Dependently-typed Intermediate Language with General Recursion

Foo Bar Baz

The University of Foo  
{foo,bar,baz}@foo.edu

## Abstract

*This is gonna to be written later.*

**Categories and Subject Descriptors** D.3.1 [Programming Languages]: Formal Definitions and Theory

**General Terms** Languages, Design

**Keywords** Dependent types, Intermediate language

## 1. Introduction

*These are definitely drafts and only some main points are listed in each section.*

a) Motivations:

- Because of the reluctance to introduce dependent types<sup>1</sup>, the current intermediate language of Haskell, namely System  $F_C$  [11], separates expressions as terms, types and kinds, which brings complexity to the implementation as well as further extensions [13, 14].
- Popular full-spectrum dependently typed languages, like Agda, Coq, Idris, have to ensure the termination of functions for the decidability of proofs. No general recursion and the limitation of enforcing termination checking make such languages impractical for general-purpose programming.
- We would like to introduce a simple and compiler-friendly dependently typed core language with only one hierarchy, which supports general recursion at the same time.

b) Contribution:

- A core language based on Calculus of Constructions (CoC) that collapses terms, types and kinds into the same hierarchy.
- General recursion by introducing recursive types for both terms and types by the same  $\mu$  primitive.

<sup>1</sup>This might be changed in the near future. See <https://ghc.haskell.org/trac/ghc/wiki/DependentHaskell/Phase1>.

- Decidable type checking and managed type-level computation by replacing implicit conversion rule of CoC with generalized fold/unfold semantics.
- First-class equality by coercion, which is used for encoding GADTs or newtypes without runtime overhead.
- Surface language that supports datatypes, pattern matching and other language extensions for Haskell, and can be encoded into the core language.

c) Related work:

- Henk [5] and one of its implementation [7] show the simplicity of the Pure Type System (PTS). [8] also tries to combine recursion with PTS.
- Zombie [2, 9] is a language with two fragments supporting logics with non-termination. It limits the  $\beta$ -reduction for congruence closure [10].
- $\Pi\Sigma$  [1] is a simple, dependently-typed core language for expressing high-level constructions<sup>2</sup>. UHC compiler [6] tries to use a simplified core language with coercion to encode GADTs.
- System  $F_C$  [11] has been extended with type promotion [14] and kind equality [13]. The latter one introduces a limited form of dependent types into the system<sup>3</sup>, which mixes up types and kinds.

## 2. Overview

**BRUNO: Jeremy: can you give this section a go and start writing it up? I think this section should be your priority for now.**

We begin this section with an informal introduction to the main features of  $\lambda C_\beta$ . We show how it can serve as a simple and compiler-friendly core language with general recursion and decidable type system. The formal details are presented in §3.

### 2.1 Calculus of Constructions

$\lambda C_\beta$  is based on the *Calculus of Constructions* ( $\lambda C$ ) [4], which is a higher-order typed lambda calculus. One “unconventional” feature of  $\lambda C$  is the so-called *conversion* rule as shown below:

$$\frac{\Gamma \vdash e : \tau_1 \quad \Gamma \vdash \tau_2 : s \quad \tau_1 =_\beta \tau_2}{\Gamma \vdash e : \tau_2} \text{ TCC.CONV}$$

The conversion rule allows one to derive  $e : \tau_2$  from the derivation of  $e : \tau_1$  and the  $\beta$ -equality of  $\tau_1$  and  $\tau_2$ . Note that in

<sup>2</sup>But the paper didn’t give any meta-theories about the language.

<sup>3</sup>Richard A. Eisenberg is going to implement kind equality [13] into GHC. The implementation is proposed at <https://phabricator.haskell.org/D808> and related paper is at <http://www.cis.upenn.edu/~eir/papers/2015/equalities/equalities-extended.pdf>.

$\lambda C$ , the use of this rule is implicit in that it is automatically applied during type checking to all non-normal form terms. To illustrate, let us consider a simple example. Suppose we have a built-in base type  $\text{Int}$  and

$$f \equiv \lambda x : (\lambda y : \star.y) \text{Int}.x$$

Without the conversion rule,  $f$  cannot be applied to, say 3 in  $\lambda C$ . Given that  $f$  is actually  $\beta$ -convertible to  $\lambda x : \text{Int}.x$ , the conversion rule would allow the application of  $f$  to 3 by implicitly converting  $\lambda x : (\lambda y : \star.y) \text{Int}.x$  to  $\lambda x : \text{Int}.x$ .

## 2.2 Explicit Type Conversion Rules

**BRUNO:** Contrast our calculus with the calculus of constructions. Explain fold/unfold.

In contrast to the implicit reduction rules of  $\lambda C$ ,  $\lambda C_\beta$  makes it explicit as to when and where to convert one type to another. To achieve that, it makes type conversion explicit by introducing two operations:  $\text{cast}^\uparrow$  and  $\text{cast}_\downarrow$ .

In order to have a better intuition, let us consider the same example from §2.1. In  $\lambda C_\beta$ ,  $f$  3 is intended as an ill-typed application. Instead one would like to write the application as

$$f (\text{cast}^\uparrow [(\lambda y : \star.y) \text{Int}] 3)$$

The intuition is that,  $\text{cast}^\uparrow$  is actually doing type conversion since the type of 3 is  $\text{Int}$  and  $(\lambda y : \star.y) \text{Int}$  can be reduced to  $\text{Int}$ .

The dual operation of  $\text{cast}^\uparrow$  is  $\text{cast}_\downarrow$ . The use of  $\text{cast}_\downarrow$  is better explained by another similar example. Suppose that

$$g \equiv \lambda x : \text{Int}.x$$

and term  $z$  has type

$$(\lambda y : \star.y) \text{Int}$$

$g z$  is again an ill-typed application, while  $g (\text{cast}_\downarrow z)$  is type correct because  $\text{cast}_\downarrow$  reduces the type of  $z$  to  $\text{Int}$ .

## 2.3 Decidability and Strong Normalization

**BRUNO:** Informally explain that with explicit fold/unfold rules the decidability of the type system does not depend on strong normalization.

The decidability of the type system of  $\lambda C$  depends on the normalization property for all constructed terms [3]. However strong normalization does not hold with general recursion. This is simply because due to the conversion rule, any non-terminating term would force the type checker to go into an infinitely loop (by constantly applying the conversion rule without termination), thus rendering the type system undecidable.

With explicit type conversion rules, however, the decidability of the type system no longer depends on the normalization property. In fact  $\lambda C_\beta$  is not strong normalizing, as we will see in later sections. The ability to write non-terminating terms motivates us to have more control over type-level computation. To illustrate, let us consider a contrived example. Suppose that  $d$  is a “dependent type” where

$$d : \text{Int} \rightarrow \star$$

so that  $d\ 3$  or  $d\ 100$  all yield the same type. With general recursion at hand, we can image a term  $z$  that has type

$$d \text{ loop}$$

where  $\text{loop}$  stands for any diverging computation and of type  $\text{Int}$ . What would happen if we try to type check the following application:

$$(\lambda x : d\ 3.x) z$$

Under the normal typing rules of  $\lambda C$ , the type checker would get stuck as it tries to do  $\beta$ -equality on two terms:  $d\ 3$  and  $d \text{ loop}$ , where the latter is non-terminating.

This is not the case for  $\lambda C_\beta$ : (i) it has no such conversion rule, therefore the type checker would do syntactic comparison between the two terms instead of  $\beta$ -equality in the above example; and (ii) one would need to write infinite number of  $\text{cast}_\downarrow$ ’s to make the type checker loop forever (e.g.,  $(\lambda x : d\ 3.x)(\text{cast}_\downarrow(\text{cast}_\downarrow \dots z))$ ), which is impossible in reality.

In summary,  $\lambda C_\beta$  achieves the decidability of type checking by explicitly controlling type-level computation, which is independent of the normalization property, while supporting general recursion at the same time.

## 2.4 Unifying Recursive Types and Recursion

**BRUNO:** Show how in  $\lambda C_\beta$  recursion and recursive types are unified. Discuss that due to this unification the sensible choice for the evaluation strategy is call-by-name.

Recursive types arise naturally if we want to do general recursion.  $\lambda C_\beta$  differs from other programming languages in that it unifies both recursion and recursive types by the same  $\mu$  primitive.

*Recursive types.* In the literature on type systems, there are two approaches to recursive types. One is called *equi-recursive*, the other *iso-recursive*.  $\lambda C_\beta$  takes the latter approach since it is more intuitive to us with regard to recursion. The *iso-recursive* approach treats a recursive type and its unfolding as different, but isomorphic. In  $\lambda C_\beta$ , this is witnessed by first  $\text{cast}^\uparrow$ , then  $\text{cast}_\downarrow$ . A classic example of recursive types is the so-called “hungry” type:  $H = \mu\sigma : \star. \text{Int} \rightarrow \sigma$ . A term  $z$  of type  $H$  can accept any number of numeric arguments and return a new function that is hungry for more, as illustrated below:

$$\begin{aligned} \text{cast}_\downarrow z : \text{Int} \rightarrow H \\ \text{cast}_\downarrow (\text{cast}_\downarrow z) : \text{Int} \rightarrow \text{Int} \rightarrow H \\ \text{cast}_\downarrow (\text{cast}_\downarrow \dots z) : \text{Int} \rightarrow \text{Int} \rightarrow \dots \rightarrow H \end{aligned}$$

*Recursion.* The same  $\mu$  primitive can also be used to define recursive functions, e.g., the factorial function:

$$\mu f : \text{Int} \rightarrow \text{Int}. \lambda x : \text{Int}. \text{if } (x == 0) \text{ then } 1 \text{ else } x * f (x - 1)$$

This is reflected by the dynamic semantics of the  $\mu$  primitive:

$$\mu x : T. E \longrightarrow E[x := \mu x : T. E]$$

which is exactly doing recursive unfolding of the same term.

Due to the unification, the *call-by-value* evaluation strategy does not fit in our setting. In call-by-value evaluation, recursion can be expressed by the recursive binder  $\mu$  as  $\mu f : T \rightarrow T. E$  (note that the type of  $f$  is restricted to function types). Since we don’t want to pose restrictions on the types, the *call-by-name* evaluation is a sensible choice.

## 2.5 Encoding Datatypes

**BRUNO:** Informally explain how to encode recursive datatypes and recursive functions using datatypes.

With the explicit type conversion rules and the  $\mu$  primitive, it is straightforward to encode recursive datatypes and recursive functions using datatypes. While inductive datatypes can be encoded using either the Church or the Scott encoding, we adopt the Scott encoding as it is more fit with our unified recursive types. We demonstrate the encoding method using a simple datatype as a running example: the natural numbers.

The datatype declaration for natural numbers is:

$$\text{data Nat} = \text{Zero} \mid \text{Suc } (n : \text{Nat})$$

In the Scott encoding, the encoding of the  $\text{Nat}$  type reflects how its two constructors are going to be used. Since  $\text{Nat}$  is a recursive datatype, we have to use recursive types at some point to reflect its recursive nature. As it turns out, the  $\text{Nat}$  type can be simply

represented as

$$\mu X : \star. \Pi b : \star. b \rightarrow (X \rightarrow b) \rightarrow b$$

As can be seen, in the function type  $b \rightarrow (X \rightarrow b) \rightarrow b$ ,  $b$  corresponds to the type of the Zero constructor, and  $X \rightarrow b$  corresponds to the type of the Suc constructor. The intuition is that any use of the datatype being defined in the constructors is replaced with the recursive type, except for the return type, which is a type variable for use in the recursive functions.

Now its two constructors can be encoded correspondingly as below:

```
let Zero : Nat = cast↑[Nat] (λ(b : ★)(z : b)(f : Nat → b). z) in
let Suc : Nat → Nat = λ(n : Nat). cast↑[Nat] (λ(b : ★)(z : b)
  (f : Nat → b). f n) in
```

Thanks to the explicit type conversion rules, we can make use of the  $\text{cast}^\uparrow$  operation to do type conversion between the recursive type and its unfolding.

As the last example, let us see how we can define recursive functions using the Nat datatype. A simple example would be recursively adding two natural numbers, which can be defined as below:

$$\mu f : \text{Nat} \rightarrow \text{Nat} \rightarrow \text{Nat}. \lambda n : \text{Nat}. \lambda m : \text{Nat}. \\ (\text{cast}_\downarrow n) \text{Nat } m (\lambda n' : \text{Nat}. \text{Suc } (f n' m))$$

As we can see, the above definition quite resembles case analysis common in modern functional programming languages. (Actually we formalize the encoding of case analysis in §5.)

Due to the unification of recursive types and recursion, we can use the same  $\mu$  primitive to write both recursive types and recursion with ease.

### 3. The Explicit Calculus of Constructions

**BRUNO: Linus: can you write up this section? I think this section should be your priority. First bring in all results and formalization: syntax; semantics; proofs ... then write text**

In this section, we present a variant of the Calculus of Constructions ( $\lambda C$ ), called *explicit* Calculus of Constructions ( $\lambda C_{\text{exp}}$ ), which is the foundation of our core language  $\lambda C_\beta$ .  $\lambda C_{\text{exp}}$  can be regarded as  $\lambda C_\beta$  without general recursion, so that has more straightforward properties and metatheory. It is suitable for illustrating the core idea of our design, that is to control  $\beta$ -reduction at the type level by introducing *explicit* type conversion semantics. This also brings a benefit to type checking of  $\lambda C_{\text{exp}}$ , that the strong normalization is no long necessary to achieve the decidability of type checking. In the following part of this section, we give explanation of these properties by showing the syntax, static and dynamic semantics and the metatheory of  $\lambda C_{\text{exp}}$ .

#### 3.1 Syntax

The basic syntax of  $\lambda C_{\text{exp}}$  is shown in Figure 1, which gives abstract syntax of expressions, sorts, contexts and values. Just like  $\lambda C$ ,  $\lambda C_{\text{exp}}$  has two main advantages of keeping syntax concise when compared to the System  $F$  families including System  $F_\omega$  and  $F_C$ . One is that  $\lambda C_{\text{exp}}$  uses a single syntactic level to represent terms, types and kinds, which are usually distinguished in System  $F$  families. This brings the economy that we can use a single set of rules for terms, types and kinds uniformly. We use metavariables  $e$  and  $\tau$  when referring to a “term” and a “type” respectively. Note that without distinction of terms, types and kinds, the “term” can be a term, a type or a kind. For example, in  $\alpha : \star$ , the “term”  $\alpha$  is a type and the “type” of  $\alpha$  is  $\star$ , which is a kind.

Another advantage is that  $\lambda C_{\text{exp}}$  includes a product form  $\Pi x : \tau_1. \tau_2$  which is used to represent type of functions from values of

type  $\tau_1$  to values of type  $\tau_2$ . Compared with concepts in System  $F$ ,  $\Pi x : \tau_1. \tau_2$  subsumes both the arrow of function types  $\tau_1 \rightarrow \tau_2$  (if  $x$  does not occur free in  $\tau_2$ ), and the universal quantification  $\forall x : \tau_1. \tau_2$ . Moreover, if  $x$  occurs free in  $\tau_2$ , the product becomes a dependent product, which allows to represent dependent types. The product  $\Pi$  keeps the syntax of  $\lambda C_{\text{exp}}$  simple and expressive at the same time.

The syntax difference of from  $\lambda C$  is that  $\lambda C_{\text{exp}}$  introduces two new explicit type conversion primitives, namely  $\text{cast}^\uparrow$  and  $\text{cast}_\downarrow$  (pronounced as “cast up” and “cast down”), in order to replace the implicit conversion rule of  $\lambda C$ . They represent two directions of type conversion operations:  $\text{cast}_\downarrow$  stands for the reduction of types while  $\text{cast}^\uparrow$  is the inverse. Specifically speaking, suppose we have  $e : \sigma$ , i.e. the type of expression  $e$  is  $\sigma$ .  $\text{cast}^\uparrow[\tau]e$  converts the type of  $e$  to  $\tau$ , if there exists a type  $\tau'$  such that it can be reduced to  $\sigma$  in a single step, i.e.  $\tau \rightarrow \sigma$ .  $\text{cast}_\downarrow e$  represents the one-step-reduced type of  $e$ , i.e.  $(\text{cast}_\downarrow e) : \sigma'$  if  $\sigma \rightarrow \sigma'$ .

The intention of introducing two explicit cast primitives is that we can gain full control of computation at the type level by manually managing the type conversions. Later in §3.3 we will see dropping the implicit conversion rule of  $\lambda C$  simplifies the type checking and leads to syntax-directed typing rules. This also influences the requirements of decidable type checking, that strong normalization is no long necessary.

$e, \tau$	$::=$	Expressions
	$x$	Variable
	$s$	Sort
	$e_1 e_2$	Application
	$\lambda x : \tau. e$	Abstraction
	$\Pi x : \tau_1. \tau_2$	Product
	$\text{cast}^\uparrow[\tau]e$	Cast up to type
	$\text{cast}_\downarrow e$	Cast down by reduction
$s, t$	$::=$	Sorts
	$\star$	Star
	$\square$	Square
$\Gamma$	$::=$	Contexts
	$\emptyset$	Empty
	$\Gamma, x : \tau$	Variable binding
$v$	$::=$	Values
	$\lambda x : \tau. e$	Abstraction
	$\Pi x : \tau_1. \tau_2$	Product
	$\text{cast}^\uparrow[\tau]e$	Cast up

Figure 1. Syntax of  $\lambda C_{\text{exp}}$

#### 3.2 Syntactic sugar

**LINUS: This part can be moved to the next section for  $\lambda C_\beta$ .**

To keep the core language minimal and simplify the translation of surface language, we use syntactic sugar shown in Figure 2 for  $\lambda C_{\text{exp}}$ .

Let binding for  $x = e_2$  in  $e_1$  is equivalent to the substitution of  $x$  in  $e_1$  with  $e_2$ , which can be reduced from  $(\lambda x : \tau. e_1) e_2$ .

The syntactic sugar for the function type is discussed in §3.1 for the functionality of the product  $\Pi$ . The product  $\Pi x : \tau_1. \tau_2$  can also be simply denoted by  $\Pi_\cdot : \tau_1. \tau_2$ , where the underscore stands for an anonymous variable.

Let binding	$\text{let } x : \tau = e_2 \text{ in } e_1$	$\triangleq (\lambda x : \tau. e_1) e_2$
Function type	$\tau_1 \rightarrow \tau_2$	$\triangleq \Pi x : \tau_1. \tau_2$ ( $x$ does not occur free in $\tau_2$ )

Figure 2. Syntactic sugar

### 3.3 Type system

The type system for  $\lambda C_{\text{exp}}$  contains typing judgements and operational semantics. Figure 3 lists operational semantics for  $\lambda C_{\text{exp}}$  that defines rules for one-step reduction, including the  $\beta$ -reduction rule and  $\text{cast}_{\downarrow}$  rules. The expressions will be reduced by applying rules one or more times. Rule S\_CASTDOWN prevents the reduction from stalling with  $\text{cast}_{\downarrow}$  and continues to reduce the inner expression. Rule S\_CASTDOWNUP states that  $\text{cast}_{\downarrow}$  cancels the  $\text{cast}^{\uparrow}$  of an expression.

$e \longrightarrow e'$	One-step reduction
$\frac{}{(\lambda x : \tau. e_1) e_2 \longrightarrow e_1[x \mapsto e_2]}$	S.BETA
$\frac{e_1 \longrightarrow e'_1}{e_1 e_2 \longrightarrow e'_1 e_2}$	S.APP
$\frac{e \longrightarrow e'}{\text{cast}_{\downarrow} e \longrightarrow \text{cast}_{\downarrow} e'}$	S_CASTDOWN
$\frac{}{\text{cast}_{\downarrow} (\text{cast}^{\uparrow} [\tau] e) \longrightarrow e}$	S_CASTDOWNUP

Figure 3. Operational semantics of  $\lambda C_{\text{exp}}$

Figure 4 lists the typing judgements to check the validity of expressions. Most rules are straightforward and similar with the ones in  $\lambda C$ . For example, rule T\_AX states that the “type” of sort  $\star$  is a kind. This is derived from an axiom in  $\lambda C$ , that the highest sort is  $\square$ , making the type system predicative. Rule T\_PI allows us to type dependent products. There are four possible combinations of types of  $\tau_1$  and  $\tau_2$  in a product  $\Pi x : \tau_1. \tau_2$ , i.e.  $(s, t) \in \{\star, \square\} \times \{\star, \square\}$ . For some  $(\lambda x : \tau_1. e) : (\Pi x : \tau_1. \tau_2)$ , when  $(s, t) = (\star, \square)$ ,  $x : \tau_1 : \star$ ,  $e : \tau_2 : \square$ , so  $x$  is a term and  $e$  is a type. Thus, we have a type depending on a term which means the product is a dependent type.

The difference from  $\lambda C$  for typing rules of  $\lambda C_{\text{exp}}$  is that rule T\_CASTUP and T\_CASTDOWN are added to check the type conversion primitives  $\text{cast}^{\uparrow}$  and  $\text{cast}_{\downarrow}$ , and the implicit type conversion rule of  $\lambda C$  is removed, which is the rule as follows:

$$\frac{\Gamma \vdash e : \tau_1 \quad \Gamma \vdash \tau_2 : s \quad \tau_1 =_{\beta} \tau_2}{\Gamma \vdash e : \tau_2} \quad \text{TCC.CONV}$$

This rule is necessary for  $\lambda C$  because of the premise requirements of the application rule T\_APP:

$$\frac{\Gamma \vdash e_1 : (\Pi x : \tau_2. \tau_1) \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau_1[x \mapsto e_2]} \quad \text{T_APP}$$

Consider the following two cases of the term  $e_1 e_2$ :

- $e_2$  can be an arbitrary term so its type  $\tau_2$  is not necessary in normal form which might break the type checking of  $e_1$ , e.g. suppose  $e_1 : \sigma \rightarrow \tau$  and  $e_2 : \tau_2$ , where  $\tau_2$  is an application  $(\lambda x : \star. x) \sigma$ . By TCC.CONV,  $(\lambda x : \star. x) \sigma$  is  $\beta$ -equivalent to  $\sigma$ , thus  $e_2 : \sigma$  and we can further use T\_APP to achieve  $e_1 e_2 : \tau$ .

- The type of  $e_1$  should be a product expression according to the premise. But without the conversion rule, the term fails to type check if the type of  $e_1$  is an expression which can further evaluate to a product, e.g.  $\Pi y : ((\lambda x : \star. x) \tau_2). \tau_1$ . After applying TCC.CONV, the type of  $e_1$  is converted to its  $\beta$ -equivalence  $\Pi x : \tau_2. \tau_1$ . Thus we can further apply the T\_APP.

We need to show that explicit type conversion rules with cast primitives can also satisfy the premises of rule T\_APP. Still consider the above two cases:

- Given  $e_1 : \sigma \rightarrow \tau$  and  $e_2 : (\lambda x : \star. x) \sigma$ , we do the application by term  $e_1 (\text{cast}_{\downarrow} e_2)$ . Since  $(\lambda x : \star. x) \sigma \longrightarrow \sigma$ ,  $\text{cast}_{\downarrow} e_2 : \sigma$ , the term  $e_1 (\text{cast}_{\downarrow} e_2)$  type-checks with the rule T\_APP.
- Given  $e_1 : (\Pi y : ((\lambda x : \star. x) \tau_2). \tau_1)$  and  $e_2 : \tau_2$ , we do the application by term  $e_1 (\text{cast}^{\uparrow} [(\lambda x : \star. x) \tau_2] e_2)$ . Noting that  $(\lambda x : \star. x) \tau_2 \longrightarrow \tau_2$ , the term conforms to rule T\_CASTUP. Thus  $\text{cast}^{\uparrow} [(\lambda x : \star. x) \tau_2] e_2 : ((\lambda x : \star. x) \tau_2)$  and the term  $e_1 (\text{cast}^{\uparrow} [(\lambda x : \star. x) \tau_2] e_2)$  can be type-checked by the rule T\_APP.

Therefore, it is feasible to replace implicit conversion rules of  $\lambda C$  with explicit type conversion rules.

$\Gamma \vdash e : \tau$	Expression typing
$\frac{}{\emptyset \vdash \star : \square}$	T_AX
$\frac{\Gamma \vdash \tau : s}{\Gamma, x : \tau \vdash x : \tau}$	T_VAR
$\frac{\Gamma \vdash e : \tau_2 \quad \Gamma \vdash \tau_1 : s}{\Gamma, x : \tau_1 \vdash e : \tau_2}$	T_WEAK
$\frac{\Gamma \vdash e_1 : (\Pi x : \tau_2. \tau_1) \quad \Gamma \vdash e_2 : \tau_2}{\Gamma \vdash e_1 e_2 : \tau_1[x \mapsto e_2]}$	T_APP
$\frac{\Gamma, x : \tau_1 \vdash e : \tau_2 \quad \Gamma \vdash (\Pi x : \tau_1. \tau_2) : s}{\Gamma \vdash (\lambda x : \tau_1. e) : (\Pi x : \tau_1. \tau_2)}$	T_LAM
$\frac{\Gamma \vdash \tau_1 : s \quad \Gamma, x : \tau_1 \vdash \tau_2 : t}{\Gamma \vdash (\Pi x : \tau_1. \tau_2) : t}$	T_PI
$\frac{\Gamma \vdash e : \tau_2 \quad \Gamma \vdash \tau_1 : s \quad \tau_1 \longrightarrow \tau_2}{\Gamma \vdash (\text{cast}^{\uparrow} [\tau_1] e) : \tau_1}$	T_CASTUP
$\frac{\Gamma \vdash e : \tau_1 \quad \Gamma \vdash \tau_2 : s \quad \tau_1 \longrightarrow \tau_2}{\Gamma \vdash (\text{cast}_{\downarrow} e) : \tau_2}$	T_CASTDOWN

Figure 4. Typing rules of  $\lambda C_{\text{exp}}$

### 3.4 Decidability and soundness without strong normalization

The conversion rule of  $\lambda C$  is not syntax-directed because it can be implicitly applied at any time in a derivation. The  $\beta$ -equality premise of the rule also leads to the decidability of type checking relying on the strong normalization property of  $\lambda C$ . Suppose strong normalization does not hold in the type system, then we can find a type  $\tau_1$  such that there exists at least one reduction sequence which does not terminate. Notice that any type  $\tau_2$  in such reduction sequence holds for  $\tau_1 =_{\beta} \tau_2$ . Thus we can constantly apply the conversion rule without termination and the type checking will not stop, which means the type checking is undecidable.

Requiring strong normalization to achieve the decidability of type checking makes it impossible to combine general recursion with  $\lambda C$ , because general recursion might cause nontermination

which simply breaks the strong normalization property. So we use explicit type conversion rules by cast operations to relax the constraints of achieving decidable type checking. We have the following theorem:

**Theorem 3.1** (Decidability of type checking for  $\lambda C_{\text{exp}}$ )  
*Let  $\Gamma$  be an environment,  $e$  and  $\tau$  be expressions of  $\lambda C_{\text{exp}}$  such that  $\Gamma \vdash \tau : s$ . Then the problem of knowing if one has  $\Gamma \vdash e : \tau$  is decidable.*

*Proof.* By induction on typing rules in Figure 4. □

Notice that new explicit type conversion rules are syntax-directed and do not include the  $\beta$ -equality premise but one-step reduction instead. Because checking if one term is one-step-reducible to the other is always decidable by enumerating the reduction rules, type checking using these rules are always decidable. Therefore the proof of decidability for  $\lambda C_{\text{exp}}$  does not rely on the strong normalization. This also implies the possibility of introducing general recursion into the system with decidable type checking.

Also for obtaining the soundness of  $\lambda C_{\text{exp}}$ , the proof does not need the strong normalization by combining the following two theorems:

**Theorem 3.2** (Subject Reduction)  
*If  $\Gamma \vdash e : \tau$  and  $e \rightarrow e'$  then  $\Gamma \vdash e' : \tau$ .*

*Proof.* By induction on rules in Figure 3. □

**Theorem 3.3** (Progress)  
*If  $\emptyset \vdash e : \tau$  then either  $e$  is a value  $v$  or there exists  $e'$  such that  $e \rightarrow e'$ .*

*Proof.* By induction on rules in Figure 4. □

## 4. The Explicit Calculus of Constructions with Recursion

**BRUNO:** Linus and Jeremy, I think you should do this section together. Most work is on Linus though since he needs to work out the proofs. Jeremy is mostly for Linus to consult with here :).

This section shows how to extend  $\lambda C\beta$  with recursion. This extension allows the calculus to account for both: 1) recursive definitions; 2) recursive types. The extension preserves the decidability and soundness of the type system.

## 5. Surface language

**BRUNO:** Jeremy, I think you should write up this section.

- Expand the core language with datatypes and pattern matching by encoding.
- Give translation rules.
- Encode GADTs and maybe other Haskell extensions? GADTs seems challenging, so perhaps some other examples would be datatypes like *Fixf*, and *Monad* as a record. Could formalize records in Haskell style.

## 6. Related Work

## 7. Conclusion

Conclusion and related work.

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## A. Appendix Title

Additional proof goes here.