

Coq Coq CORRECT!

Verification of Type Checking and Erasure for Coq, in Coq

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Coq is built around a well-delimited kernel that performs typechecking for definitions in a variant of the Calculus of Inductive Constructions (CIC). Although the metatheory of CIC is very stable and reliable, the correctness of its implementation in Coq is less clear. Indeed, implementing an efficient type checker for CIC is a rather complex task, and many parts of the code rely on implicit invariants which can easily be broken by further evolution of the code. Therefore, on average, one critical bug has been found every year in Coq. This paper presents the first implementation of a type checker for the kernel of Coq, which is proven correct in Coq with respect to its formal specification. Note that because of Gödel's incompleteness theorem, there is no hope to prove completely the correctness of the specification of Coq inside Coq (in particular strong normalisation or canonicity), but it is possible to prove the correctness of the implementation assuming the correctness of the specification. Our work is based on the METACOQ project [Anand et al. 2018; Sozeau et al. 2019] which provides metaprogramming facilities to work with terms and declarations at the level of this kernel. Our type checker is based on the specification of the typing relation of the Polymorphic, Cumulative Calculus of Inductive Constructions (PCUIC) at the basis of Coq and the verification of a relatively efficient and sound type-checker for it. In addition to the kernel implementation, an essential feature of Coq is so-called *extraction* [Letouzey 2004]: the production of executable code in functional languages from Coq definitions. We present a verified version of this subtle type-and-proof erasure step, therefore enabling the verified extraction of a safe type-checker for Coq.

Additional Key Words and Phrases: proof assistants, type checker, certification

1 INTRODUCTION

Since the introduction of the Calculus of Inductive Constructions (CIC) and the first implementation of the Coq proof assistant, very few issues have been found in the underlying theory of Coq. There have been several debates on which set of axioms are consistent altogether. For instance, the fact that the sort `Set` of sets was impredicative by default has been changed to maintain compatibility with the axiom of excluded middle. But globally, the type theory supporting the Coq proof assistant is very stable and reliable. This is however far to be the case for the implementation of the kernel of Coq, for which on average one critical bug is found every year. The interested reader can directly jump to <https://github.com/coq/coq/blob/master/dev/doc/critical-bugs>, where the list of the critical bugs that have been found in the Coq proof assistant is maintained. For instance, one can find there that for some time, there was a substitution missing in the body of a `let` in the definition of `match`, somewhere in the code, which could lead to a proof of `False`.

Fortunately, all those critical bugs are very tricky to exhibit, and would be very unlikely to happen by accident, but still a malicious developer could exploit them to produce very hard to detect fake formalisations. At a time where certificates obtained from proof assistants such as Coq are gaining traction in the safety & security industry, this looks like a bad joke.

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However, implementing and maintaining an efficient and bug free type checker for CIC is a very complex task, mainly due to the fact that the implementation relies on many invariants which are not always explicit and easy to break by modifying the code or adding new functionality.

“In this paper, we describe the first implementation of a type checker for the core language of Coq, which is proven correct in Coq with respect to an entirely formal specification of the calculus.”

We would like to mention right away that we are not claiming to prove the consistency of Coq in Coq, which would obviously contradict Gödel’s second incompleteness theorem stating that no consistent axiomatic system which includes Peano arithmetic can prove its own consistency. Therefore, it is not possible to prove the consistency of the kernel of Coq using Coq, but it is perfectly possible to prove the correctness of an implementation of a type-checker *assuming the consistency of the theory*.

In practice, our formalisation assumes strong normalisation of the reduction of CIC; and this even serves as the basis for the implementation of algorithmic conversion, which is defined by recursion on the strong normalisation assumption. We also assume other properties of the metatheory such as principality, type-preservation and alpha-equivalence of typing (their proofs are in progress). This is the only Achilles heel of our formalisation, the correctness of the specification of the metatheory: If the metatheory fulfills the well-known, assumed properties, then there is no error in the implementation. Note that if one of the assumed properties would not be true, the implementation might be wrong – but there would be a much more serious problem to fix in Coq’s metatheory. Without entering into philosophical debates, we argue that this work provides important assurances about the correctness of the system, that is complimentary to the many theoretical studies of variants of the Calculus of Constructions and Martin-Löf Type Theory from the literature [Coquand and Huet 1988; Martin-Löf 1998], of which none is as close to the calculus actually implemented in Coq as our work. True believers in computation and type theory might actually enjoy the relatively small, formal specification of the calculus implemented in Coq (a few pages for the typing and reduction rules), which we show confluent. To avoid unnecessary complications, we work with a mildly simplified version of Coq’s core language we call PCUIC (for Predicative Calculus of CUmulative Inductive Construction), and show an equivalence with the implemented version (up-to representation of strings and arrays). Note that the kernel of Coq also includes a module system and efficient conversion algorithms that we exclude for now. We start by separating the specification of the type system of PCUIC from its implementation. This allows us to get for instance a very direct definition of the consistency of a polymorphic universe hierarchy, without the notion of graph of universes or acyclicity. The implementation involves the more clever and efficient graph representation, whose acyclicity check is orthogonal to the rest of the type checker. Therefore, we can replace a naive implementation (as we have currently) by a more efficient one, such as the incremental cycle detection algorithm of Bender et al. [2015], actually used in the Coq kernel, while being sure not to break anything in the type checker.

Finally, to get a correct and efficient type checking algorithm, we need to extract it to an efficient language such as OCAML. In order to maintain the correctness guarantees on the extracted code, we derive a proven correct type and proof erasure algorithm. Note that the current extraction mechanism available in Coq is not able to extract our implemented type checker because it produces an ill-typed term, which strengthens the need for certified extraction.

Outline of the paper. Section 2 presents the specification of PCUIC and its metatheory. Section 3 describes the implementation of a proven correct type-checker for PCUIC. Section 4 explains type and proof erasure for PCUIC. Section 5 discusses related work. Section 6 put everything together and discusses future work.

```

Inductive term : Set :=
| tRel (n : ℕ)
| tSort (u : universe)
| tProd (na : name) (A B : term)
| tLambda (na : name) (A t : term)
| tLetIn (na : name) (b B t : term)
| tApp (u v : term)
| tConst (k : kername) (ui : universe_instance)
| tInd (ind : inductive) (ui : universe_instance)
| tConstruct (ind : inductive) (n : ℕ) (ui : universe_instance)
| tCase (indn : inductive * ℕ) (p c : term) (brs : list (ℕ * term))
    (* # of parameters/type info/discriminee/branches *)
| tProj (p : projection) (c : term)
| tFix (mfix : mfixpoint term) (idx : ℕ)
| tCoFix (mfix : mfixpoint term) (idx : ℕ).

```

Fig. 1. Syntax of PCUIC

The complete Coq formalisation can be found as supplementary materials. In the remaining of the text, we refer to PCUIC: MyFile to depict the file PCUICMyFile.v in the development. ¹

2 PCUIC: COQ'S CORE CALCULUS

As a type system, PCUIC is an extension of the Predicative Calculus of (Co)-Inductive Constructions, a Pure Type System with an infinite hierarchy of universes Type_i and an impredicative sort Prop , extended with inductive and co-inductive type families. The system also includes *universe* polymorphism [Sozeau and Tabareau 2014], making it flexible in handling constructions that are generic in universes. Timany and Sozeau [2017] show the consistency (with a pen and paper proof) of a variant of the calculus with eliminators for polymorphic and cumulative inductive types.

As a programming language, PCUIC is a standard pure dependent λ -calculus extended with a let-in construct for local definitions, case analysis and projections of datatypes and (co)-recursion operators. We will see in § 2.3.2 that the seemingly innocuous addition of local definitions significantly complicates the metatheory of the system. The definitional equality of the system is the congruence closure of the standard $\beta_i\zeta\delta\mu\nu$ -reductions of each elimination/introduction pairs of λ -abstraction and case analysis, let reduction, unfolding of constants and (co)-fixpoints. The system is parametric over universes, hence traditional α -equality of terms, which simply ignores name annotations, is extended with cumulativity or equality of universes and everything must respect this subtyping notion. We will also study subrelations of definitional equality geared towards evaluation of programs (closed terms) for the erasure procedure (§4).

The specification of PCUIC in Coq follows the pattern of the specification of the kernel of Coq inside Coq itself, as described in the METACOQ project [Anand et al. 2018; Sozeau et al. 2019]. We briefly explain the syntax and typing judgments of PCUIC and refer the reader to [Sozeau et al. 2019] for a more complete explanation.

2.1 Definition of the Syntax and Environments

The syntax of PCUIC is defined in Figure 1. This inductive type is a direct representation of the `constr` datatype used in the implementation of Coq terms in OCaml. The only difference is that PCUIC’s application `tApp` is binary—while it is n -ary in OCaml, and that PCUIC has no type cast constructor². The constructor `tRel` represents variables—using de Bruijn indices implemented as natural numbers—bound by abstractions (introduced by `tLambda`), dependent products (introduced by `tProd`) and local definitions (introduced by `tLetIn`). The type name is a printing annotation. Sorts are represented with `tSort`, which takes a universe as argument. A universe can be either `Prop`, `Set` or a more complex expression representing one of the `Type` universes. The details are given in Section 2.2.1.

The three constructors `tConst`, `tInd` and `tConstruct` represent references to constants declared in a global environment. The first is for definitions or axioms, the second for inductive types, and the last for constructors of inductive types. `tCase` represents pattern-matchings, `tProj` primitive projections, `tFix` fixpoints and `tCoFix` cofixpoints.

In PCUIC, the meaning of a term is relative to global environment which is constant through a typing derivation, and to a local context which may vary.

The *local context* consists of a list of declarations written in *snoc* order: we use the notation Γ, d for adding d to the head of Γ . $x :_d A$ is a declaration without a body (as introduced by `tLambda`) and $x := t :_d A$ is a declaration with a body (as introduced by `tLetIn`). The *global environment* consists of two parts: a list of declarations, properly ordered according to dependencies, and possibly some additional universe declarations (used to type check the body of a new declaration) A declaration is either the declaration of a constant (a definition or an axiom, depending on the presence or absence of a body) or of a block of mutual inductive types (which brings both the inductive types and their constructors to the context). We do not go into details here, mutual inductives types are described as in [Sozeau et al. 2019]

2.2 Definition of Typing

The typing rules of PCUIC are defined as the inductive family typing (Figure 2). We do not detail the rules for inductive types as they introduce a significant additional level of bureaucracy. We refer the interested reader to the Coq formalisation.

The type of typing relation is of type

$$\text{typing} : \text{global_env_ext} \rightarrow \text{context} \rightarrow \text{term} \rightarrow \text{term} \rightarrow \text{Type}$$

and we use the notation $\Sigma ; \Gamma \vdash t : T$ for typing $\Sigma \Gamma t T$.

The typing rules are standard rules of the Calculus of Inductive Constructions or Martin-Löf Type Theory, and each constructor corresponds to a typing inference rule. For instance, `type_Prod` corresponds to the inference rule for dependent product:

$$\frac{\Sigma ; \Gamma \vdash A : s_1 \quad \Sigma ; \Gamma, x : A \vdash B : s_2}{\Sigma ; \Gamma \vdash \Pi x : A. B : \text{sort_of_product}(s_1, s_2)}$$

where `sort_of_product` is the maximum of the two levels when s_2 is not `Prop` and `Prop` otherwise (to account for impredicativity). Note that the typing rules use substitution and lifting operations of de Bruijn indexes (`lift0`, `subst`, ...), their definitions are standard. The constructor `type_Rel` corresponds to the case of variables. `type_Lambda` is the introduction of dependent functions,

¹The remaining admitted lemmas on the metatheory are summarized in the file PCUIC: AdmittedLemmata.

²Casts are only necessary to inform the kernel about which conversion algorithm to use, while we only implement one such algorithm. The implementation actually also includes constructors for existential variables instantiated at a given term substitution and named variables (hypothesis names in goals): they are treated as atoms everywhere and are not typeable.

Inductive typing ($\Sigma : \text{global_env_ext}$) ($\Gamma : \text{context}$): $\text{term} \rightarrow \text{term} \rightarrow \text{Type} :=$

- | type_Rel n decl :
 $\text{All_local_env} (\text{lift_typing typing } \Sigma) \Gamma \rightarrow$
 $\text{nth_error } \Gamma n = \text{Some decl} \rightarrow$
 $\Sigma ; \Gamma \vdash \text{tRel } n : \text{lift}_0 (\text{S } n) \text{ decl.}(\text{decl_type})$
- | type_Sort l :
 $\text{All_local_env} (\text{lift_typing typing } \Sigma) \Gamma \rightarrow$
 $\text{LevelSet.In } l (\text{global_ext_levels } \Sigma) \rightarrow$
 $\Sigma ; \Gamma \vdash \text{tSort } l : \text{tSort} (\text{super } l)$
- | type_Prod na A B s1 s2 :
 $\Sigma ; \Gamma \vdash A : \text{tSort } s1 \rightarrow$
 $\Sigma ; \Gamma, na :_a A \vdash B : \text{tSort } s2 \rightarrow$
 $\Sigma ; \Gamma \vdash \text{tProd } na A B : \text{tSort} (\text{sort_of_product } s1 s2)$
- | type_Lambda na A t s1 B :
 $\Sigma ; \Gamma \vdash A : \text{tSort } s1 \rightarrow$
 $\Sigma ; \Gamma, na :_a A \vdash t : B \rightarrow$
 $\Sigma ; \Gamma \vdash \text{tLambda } na A t : \text{tProd } na A B$
- | type_LetIn na b B t s1 A :
 $\Sigma ; \Gamma \vdash B : \text{tSort } s1 \rightarrow$
 $\Sigma ; \Gamma \vdash b : B \rightarrow$
 $\Sigma ; \Gamma, na := b :_d B \vdash t : A \rightarrow$
 $\Sigma ; \Gamma \vdash \text{tLetIn } na b B t : \text{tLetIn } na b B A$
- | type_App t na A B u :
 $\Sigma ; \Gamma \vdash t : \text{tProd } na A B \rightarrow$
 $\Sigma ; \Gamma \vdash u : A \rightarrow$
 $\Sigma ; \Gamma \vdash \text{tApp } t u : B\{0 := u\}$
- | type_Cumul t A B :
 $\Sigma ; \Gamma \vdash t : A \rightarrow$
 $(\text{isWfArity typing } \Sigma \Gamma B + \{s \ \& \ \Sigma ; \Gamma \vdash B : \text{tSort } s\}) \rightarrow$
 $\Sigma ; \Gamma \vdash A \leq B \rightarrow \Sigma ; \Gamma \vdash t : B$

| ... (* remaining definitions for constants, inductive and coinductive types *)
where " $\Sigma ; \Gamma \vdash t : T$ " := (typing $\Sigma \Gamma t T$).

Inductive cumul ($\Sigma : \text{global_env_ext}$) ($\Gamma : \text{context}$): $\text{term} \rightarrow \text{term} \rightarrow \text{Type} :=$

- | cumul_refl t u : $\text{leq_term} (\text{global_ext_constraints } \Sigma) t u \rightarrow \Sigma ; \Gamma \vdash t \leq u$
- | cumul_red_l t u v : $\text{fst } \Sigma ; \Gamma \vdash t \rightsquigarrow v \rightarrow \Sigma ; \Gamma \vdash v \leq u \rightarrow \Sigma ; \Gamma \vdash t \leq u$
- | cumul_red_r t u v : $\Sigma ; \Gamma \vdash t \leq v \rightarrow \text{fst } \Sigma ; \Gamma \vdash u \rightsquigarrow v \rightarrow \Sigma ; \Gamma \vdash t \leq u$

where " $\Sigma ; \Gamma \vdash t \leq u$ " := (cumul $\Sigma \Gamma t u$).

Definition leq_term ϕ t u := eq_term_upto_univ (eq_universe ϕ) (leq_universe ϕ) t u.

Fig. 2. Excerpt of typing rules

```
Inductive ConstraintType : Set := Lt | Le | Eq.
```

```
Definition univ_constraint : Set := Level * ConstraintType * Level.
```

```
Record valuation :=
{ valuation_mono : string → positive ;
  valuation_poly : ℕ → ℕ }.
```

```
Definition val (v : valuation) (l : Level) : Z := match l with
| lProp ⇒ -1
| lSet ⇒ 0
| Level s ⇒ Zpos (v.(valuation_mono) s)
| Var x ⇒ Z.of_ℕ (v.(valuation_poly) x) end.
```

Fig. 3. Definition of constraints and valuations

type_App its usual application. type_Sort is the rule for typing universes. Here super l morally means $l+1$. type_LetIn is the typing rule for introduction of `tLetIn`. Finally, type_Cumul is the rule for cumulativity. It says that if $t : A$ and A is a subtype of B where B is a type (or a well-formed arity, see Section 2.2.3 for more details) then $t : B$. It relies on the cumulativity (or subtyping) relation, which depends on definitional equality and the cumulativity of the universe hierarchy. Conversion is defined as cumulativity in both directions. Basically, A is a subtype of B , written $A \leq B$, when A and B respectively reduce to A' and B' and A' is equal to B' up to α -equivalence and cumulativity (this is checked syntactically using `leq_term`). To make this precise, we need to define the specification of the universe hierarchy and reduction.

2.2.1 *Universes*. There are four kinds of level for a universe.

```
Inductive Level : Set := lProp | lSet | Level (_ : string) | Var (_ : ℕ).
```

Level s are monomorphic universes with name s (i.e. traditional global universes), while Var n represents a polymorphic universe, where n is the DeBruijn level of the corresponding variable in an ordered universe context. Then, a universe is technically encoded as non empty list of pairs (l,b) of a level l and a boolean b , the boolean being true meaning that we are talking about the universe above l in the hierarchy (“ $l+1$ ”).

```
Definition universe := non_empty_list (Level * ℬ).
```

This list is interpreted as encoding the maximum of its elements to represent so-called “algebraic” universes like $\text{Type}_{\max(u, v+1)}$.

Constraints and valuations. To allow for a flexible and modular account of universes, Coq implements typical ambiguity and universe polymorphism. The universe hierarchy is hence not fixed but rather maintained using an extensible (“elastic”, as coined by its designer Gérard Huet) set of universe levels and associated `universe_constraints` which say that a level is smaller (Lt), smaller or equal (Le) or equal (Eq) to another level, as described in Figure 3. In the Coq type checker, consistency of the universe hierarchy is checked using an acyclicity criterion on the graph induced by the constraints. However, this characterisation of consistency is quite far from the mathematical model, which says that universe levels are integers. To keep the specification as close as possible to the meta theory, we therefore introduce the notion of valuation on universe levels, which associates

-1 to $lProp$, 0 to $lSet$, a positive number to monomorphic universes (a monomorphic universe can neither be $lProp$ nor $lSet$) and a natural number to polymorphic universes (a polymorphic universe cannot be $lProp$). Note that we start the hierarchy at -1 to stick to Coq usual convention, but the starting point is arbitrary.

Then a valuation *satisfies* a set of constraints when:

```
Inductive satisfies0 (v : valuation) : univ_constraint → Prop :=
| satisfies0_Lt l l' : val v l < val v l' → satisfies0 v (l, Lt, l')
| satisfies0_Le l l' : val v l ≤ val v l' → satisfies0 v (l, Le, l')
| satisfies0_Eq l l' : val v l = val v l' → satisfies0 v (l, Eq, l').
```

Definition `satisfies v : constraints → Prop := For_all (satisfies0 v).`

The universe hierarchy is consistent when there exists a valuation which satisfies its set of constraints:

Definition `consistent ctrs := ∃ v, satisfies v ctrs.`

Cumulativity. The notion of subtyping on types is defined as definitional equality up to cumulativity on universes, which states that `Level l` is a subtype of `Level l'` (super `l`). To realize cumulativity, we specify when a universe `u` is smaller than a universe `u'` for a given set of constraints φ by saying that for any valuation which satisfies φ , the value of `u` is smaller than the value of `u'`. Formally, it is defined as

Definition `leq_universe (φ : constraints) u u' :=`
 $\forall v : \text{valuation}, \text{satisfies } v \varphi \rightarrow (\text{val } v u \leq \text{val } v u').$

2.2.2 Reduction. Reduction of PCUIC terms is defined in Figure 4 (congruence rules are omitted and can be found in the Coq development). Rule `red_beta` allows a λ -abstraction to consume its argument to reduce. This is the usual β -reduction. A `let` expression can be unfolded as a substitution right away using Rule `red_zeta` (this is called ζ -reduction). It can also be unfolded later, by reducing a reference to the `let`-binding (Rule `red_re1`, included in the δ -reduction in Coq terminology). This is what changes from the usual treatment of `let x := t in b` bindings in ML-style programming languages: we can transparently access the definiens `t` of a `let` inside its body `b`. The rule verifies that the `i`th variable in Γ corresponds to a definition and replaces the variable with it. It needs to be lifted as the body was defined in a smaller context. Rule `red_iota` describes how a `match` expression can be reduced when the scrutinee is a constructor. `mkApps` is just application extended to a list of arguments. Herein, `iota_red` basically picks the branch corresponding to the constructor and applies it to the indices of the inductive. Even after they are checked to be terminating (Section 2.2.4), fixed-points cannot be unfolded indefinitely. There is a syntactic guard to only unfold a fixed-point when its recursive argument is a constructor. `unfold_fix mfix idx` allows to recover both the body (`fn`) and the index of the recursive argument (`narg`) while `is_constructor narg args` checks that the given recursive argument is indeed an applied constructor. Mutual fixpoints are represented by a block of (anonymous) mutually recursive definitions `mfix` from which one can project each recursive definition by the index `idx`. Rules `red_cofix_case` and `red_cofix_proj` describe how co-fixed-points can also be unfolded, when they are forced by a pattern-matching or projection. Rule `red_delta` allows for δ -reduction, which unfolds a constant (from the global environment Σ). It can only be done if a definition is indeed found and has a body. To account for polymorphic universes, its universes (if it is universe polymorphic) are then instantiated. Finally, there is the rule `red_proj` to reduce the projection of the constructor of a record to the corresponding field.

```

Inductive red1 (Σ : global_declarations) (Γ : context) : term → term → Type :=
| red_beta na t b a : Σ ; Γ ⊢ tApp (tLambda na t b) a ∼ b {0 := a}
| red_zeta na b t b' : Σ ; Γ ⊢ tLetIn na b t b' ∼ b' {0 := b}
| red_rel i body : option_map decl_body (nth_error Γ i) = Some (Some body) →
  Σ ; Γ ⊢ tRel i ∼ lift0 (S i) body
| red_iota ind pars c u args p brs :
  Σ ; Γ ⊢ tCase (ind, pars) p (mkApps (tConstruct ind c u) args) brs ∼
  iota_red pars c args brs
| red_fix mfix idx args narg fn : unfold_fix mfix idx = Some (narg, fn) →
  is_constructor narg args = true →
  Σ ; Γ ⊢ mkApps (tFix mfix idx) args ∼ mkApps fn args
| red_cofix_case ip p mfix idx args narg fn brs :
  unfold_cofix mfix idx = Some (narg, fn) →
  Σ ; Γ ⊢ tCase ip p (mkApps (tCoFix mfix idx) args) brs ∼
  tCase ip p (mkApps fn args) brs
| red_cofix_proj p mfix idx args narg fn :
  unfold_cofix mfix idx = Some (narg, fn) →
  Σ ; Γ ⊢ tProj p (mkApps (tCoFix mfix idx) args) ∼ tProj p (mkApps fn args)
| red_delta c decl body (isdecl : declared_constant Σ c decl) u :
  decl.cst_body = Some body →
  Σ ; Γ ⊢ tConst c u ∼ subst_instance_constr u body
| red_proj i pars narg args k u arg :
  nth_error args (pars + narg) = Some arg →
  Σ ; Γ ⊢ tProj (i, pars, narg) (mkApps (tConstruct i k u) args) ∼ arg
| ... (* remaining definitions are congruence rules *)
where " Σ ; Γ ⊢ t ∼ u " := (red1 Σ Γ t u).

```

```

Fixpoint mkApps t us := match us with
| nil ⇒ t
| u :: us ⇒ mkApps (tApp t u) us end.

```

Fig. 4. Excerpt of reduction

2.2.3 Well-formed arities. Coq's type theory relies on the notion of well-formed *arities*, which generalise sorts. An arity is a term of the form $\forall \Gamma, s$ where Γ is a local context and s a sort (i.e. a potentially algebraic universe). The types of (co-)inductive declarations must be arities, and the validity property of the system ensures that for every well-typed term $\Sigma; \Gamma \vdash t : T$, T can itself be typed by an arity in the same context. Arities hence categorise types (as opposed to terms), recovering the separation of terms and types that is part of Martin-Löf-style Type Theory presentations [Martin-Löf 1998].

2.2.4 Dealing with Positivity and the Guard Condition. PCUIC is parametrized by the guard conditions on inductive types and on fixpoints which ensure strong normalization. Technically, they are considered as syntactic oracles, treated as axioms. The development does not depend strongly

```

Axiom fix_guard : mfixpoint term →  $\mathbb{B}$ .

Axiom fix_guard_red1 : ∀ Σ Γ mfix mfix' idx,
  fix_guard mfix →
  tFix mfix idx  $\rightsquigarrow$  tFix mfix' idx →
  fix_guard mfix'.

Axiom ind_guard : mutual_inductive_body →  $\mathbb{B}$ .

```

Fig. 5. Axiomatisation of the positivity and guard condition

on those oracles, but the guard condition on fixpoints must be preserved by reduction and substitution in order for PCUIC to satisfy subject reduction for instance. This shows in particular that implementing a new guard condition on fixpoints in CoQ which performs some reduction before the syntactic check requires some care to be compatible with reduction and substitution. Figure 5 describes the oracles and the axiom of stability under reduction of the guard condition on fixpoints. In CoQ, the guard condition for inductive types that is implemented is called strict positivity, and the guard condition for fixpoints is based on recursive calls which must be done on strict sub-terms³. As we cannot prove strong normalisation anyway, we believe that an axiomatic presentation makes more sense as it sheds light on the syntactical properties that must be satisfied by any guard condition on fixpoints. We consider the axioms about the guard condition together with the axiom of strong normalisation of PCUIC (Section 2.3.4) altogether as one axiom on the metatheory.

2.3 Metatheory

The previous section specifies the theory of PCUIC. To implement a type checker for PCUIC and prove it correct, we actually need to formalise also some parts of its metatheory. In particular, we rely on subject reduction, confluence of the conversion and strong normalisation of the reduction.

In this section, we show confluence of the conversion using Tait-Martin-Löf methodology extended to pattern-matching, (co-)fixpoints and contexts containing let-bindings, and a context conversion property showing that typing respects conversion. Validity (the fact that the type in a typing derivation can itself be typed), Subject Reduction and Principality which depend on it are work in progress, and we *assume* strong normalisation, but that assumption is not used in the proof of confluence. Note that because of Gödel's second incompleteness theorem, strong normalisation of PCUIC cannot be proven inside CoQ. Indeed PCUIC and CoQ have the same logical power and proving strong normalisation (with an explicit characterisation of normal forms) is enough to derive canonicity and consistency of PCUIC.

2.3.1 Substitution and Weakenings. PCUIC: Substitution PCUIC: Weakening

The implemented calculus uses standard weakening and (parallel) substitution operations, which we formalise, showing that reduction, cumulativity and typing are all closed by lifting and substitution operations. This gives rise to weakening and substitution theorems. Note that, to substitute into a context with let-ins, one must provide a substitution that matches them. Our notion of well-typed substitution is hence defined as:

```

Inductive subslet Σ (Γ : context) : list term → context → Type :=
| emptyslet : subslet Σ Γ [] []

```

³Actually the condition is slightly more general, but this is beyond the scope of this paper.

$$\begin{aligned}
& | \text{cons_let_ass } \Delta \text{ s na t } T : \text{subsllet } \Sigma \Gamma \text{ s } \Delta \rightarrow \\
& \quad \Sigma ; \Gamma \vdash t : \text{subst}_0 \text{ s } T \rightarrow \text{subsllet } \Sigma \Gamma (t :: \text{s}) (\Delta, \text{na} :_a T) \\
& | \text{cons_let_def } \Delta \text{ s na t } T : \text{subsllet } \Sigma \Gamma \text{ s } \Delta \rightarrow \\
& \quad \Sigma ; \Gamma \vdash \text{subst}_0 \text{ s } t : \text{subst}_0 \text{ s } T \rightarrow \text{subsllet } \Sigma \Gamma (\text{subst}_0 \text{ s } t :: \text{s}) (\Delta, \text{na} := t :_d T).
\end{aligned}$$

There is support to *promote* a traditional substitution matching the assumptions in a context (e.g. a list of arguments to a function whose type might contain let-ins) to a `subsllet` structure. This formalises the tricky manipulations one must perform when working with Coq terms and contexts in ML that developers and plugin writers face.

The global environment also induces a form of weakening by the addition of new inductive or constant declarations (PCUIC: `WeakeningEnv`), simpler from the point of view of typing but trickier w.r.t. universe instantiation (PCUIC: `UnivSubstitution`).

The σ -calculus. Working with this traditional presentation of de Bruijn indexes works a long way, however we hit a difficulty when formalising more complex operations on syntax, like reduction functions as we will see next. To alleviate the difficulties associated with reasoning on the primitive operations, we provide a version of the σ -calculus operations [Abadi et al. 1991; Schäfer et al. 2015] on terms.

We derive the primitives of the σ -calculus (renaming and instantiation) and show their (extensional) equivalence with the traditional lifting and substitution operations. The σ -calculus operations enjoy a rich, clean and decidable equational theory, equivalent to an explicit substitution calculus, and are able to express complex commutations neatly. compared to the tricky lifting and substitution lemmas of “traditional” de Bruijn representations.

We have to extend it to deal with n-ary bindings: \uparrow^n and \cdot_n and show a few tricky lemmas to derive commutation properties with `fix` and `cofix` (PCUIC: `LiftSubst`).

2.3.2 Confluence. Following the Tait-Martin Lőf method [Takahashi 1989], we define parallel reduction for PCUIC, written as $\Gamma, t \Rightarrow \Delta, t'$, in Figure 6. This reduction is just a variant of reduction $\Sigma ; \Gamma \vdash t \rightsquigarrow t'$ where already present redexes can all be reduced together in one single step. Note that the global environment Σ is a parameter of the reduction and not an index because it is fixed during the reduction. Note that a β -redex can be reduced or not, depending on whether the reduction rule `pred_beta` or congruence rule `pred_app` is used. We also add a reflexivity rule for atoms (variables which may not be reduced, universes, inductive types and constructors), thus ensuring that parallel reduction is reflexive.

Dealing with dependent let-bindings. Note that because of let-bindings, we need to take the context explicitly into account during the reduction. This is obtained by adding the `All2_local_env (on_decl pred1) $\Gamma \Gamma'$` predicate in the premises of basic parallel reduction steps (such as the rule `pred_rel_def_unfold` for instance) in order to allow for parallel reduction in the context too.

Thanks to the generalisation to contexts, we can prove a strong substitution lemma which says that the parallel reduction satisfies the property that the reductions performed on two terms M and N can also be done in one step on M where its first de Bruijn variable is substituted by N' , where N reduces to N' in parallel as well.

Lemma `substitution_pred1` $\Gamma \Delta M M' \text{na } A A' N N' : \text{wf } \Sigma \rightarrow$
 $\Gamma, N \Rightarrow \Delta, N' \rightarrow (\Gamma, \text{na} :_a A), M \Rightarrow (\Delta, \text{na} :_a A'), M' \rightarrow \Gamma, M\{0 := N\} \Rightarrow \Delta, M'\{0 := N'\}.$

We actually need a generalised version of this lemma for well-typed substitutions: $\Gamma \vdash s : \Delta$, where Δ is the context we are substituting into and Γ represents the variables needed to type the substitution s . However, as we are doing things in parallel, we need a notion of parallel substitution. To account for let-ins correctly, we need these well-typed substitutions to coherently *preserve* the

```

Inductive pred1 (Γ Δ : context) : term → term → Type :=
| pred_beta na t0 t1 b0 b1 a0 a1 :
  Γ, t0 ≅ Δ, t1 →
  (Γ, na :a t0), b0 ≅ (Δ, na :a t1), b1 → Γ, a0 ≅ Δ, a1 →
  Γ, tApp (tLambda na t0 b0) a0 ≅ Γ, b1 {0:=a1}
| pred_zeta na d0 d1 t0 t1 b0 b1 :
  Γ, t0 ≅ Δ, t1 →
  Γ, d0 ≅ Δ, d1 → (Γ, na :=d d0 t0), b0 ≅ (Δ, na :=d d1 t1), b1 →
  Γ, tLetIn na d0 t0 b0 ≅ Δ, b1 {0:=d1}
| pred_rel_def_unfold i body :
  All2_local_env (on_decl pred1) Γ Δ →
  option_map decl_body (nth_error Δ i) = Some (Some body) →
  Γ, tRel i ≅ Δ, liftt0 (S i) body
| pred_iota ind pars c u args0 args1 p brs0 brs1 :
  All2_local_env (on_decl pred1) Γ Δ →
  All2 (pred1 Γ Δ) args0 args1 →
  All2 (on_Trel_eq (pred1 Γ Δ) snd fst) brs0 brs1 →
  Γ, tCase (ind, pars) p (mkApps (tConstruct ind c u) args0) brs0 ≅
  Δ, iota_red pars c args1 brs1
| pred_app M0 M1 N0 N1 :
  Γ, M0 ≅ Δ, M1 → Γ, N0 ≅ Δ, N1 →
  Γ, tApp M0 N0 ≅ Δ, tApp M1 N1
| pred_atom_refl t :
  All2_local_env (on_decl pred1) Γ Γ' →
  pred_atom t → Γ, t ≅ Γ', t.
(* other cases are omitted *)
where " Γ, t ≅ Δ, u " := (pred1 Γ Δ t u).

```

```

Inductive psubst Γ Γ' : list term → list term → context → context → Type :=
| psubst_empty : psubst Γ Γ' [] [] [] []
| psubsta Δ Δ' s s' na na' t t' T T' : psubst Γ Γ' s s' Δ Δ' →
  pred1 (Γ ++ Δ) (Γ' ++ Δ') T T' → pred1 Γ Γ' t t' →
  psubst Γ Γ' (t :: s) (t' :: s') (Δ, na :a T) (Δ', na' :a T')
| psubstd Δ Δ' s s' na na' t t' T T' : psubst Γ Γ' s s' Δ Δ' →
  pred1 (Γ ++ Δ) (Γ' ++ Δ') T T' → pred1 Γ Γ' (subst0 s t) (subst0 s' t') →
  psubst Γ Γ' (subst0 s t :: s) (subst0 s' t' :: s') (Δ, na :=d t T) (Δ', na' :=d t' T').

```

Fig. 6. Definition of parallel reduction and substitution (assuming a global environment Σ)

definiens of local definitions. The parallel substitution structure $\text{psubst } \Sigma \Gamma \Gamma' s t \Delta \Delta'$ represents two substitutions s and t typed respectively in Γ and Γ' and instantiating respectively contexts Δ and Δ' (Figure 6).

Rule psubst_a simply ensures that the two terms t and t' are in the parallel reduction relation, to instantiate two assumptions. However, the psubst_d assumption rather *forces* the substitution

```

Fixpoint  $\rho \Sigma \Gamma t : \text{term} :=$ 
  match t with
  | tApp (tLambda na T b) u  $\Rightarrow (\rho \text{ na} :_a (\rho \Gamma T) :: \Gamma) b \{0 := \rho \Gamma u\}$ 
  | tLetIn na d t b  $\Rightarrow (\rho \text{ na} := (\rho \Gamma d) :_d (\rho \Gamma t) :: \Gamma) b \{0 := \rho \Gamma d\}$ 
  | tRel i  $\Rightarrow$ 
    match option_map decl_body (nth_error  $\Gamma$  i) with
    | Some (Some body)  $\Rightarrow (\text{lift}_0 (S i) \text{ body})$ 
    | Some None  $\Rightarrow \text{tRel } i$ 
    | None  $\Rightarrow \text{tRel } i$ 
    end
  | tApp t u  $\Rightarrow \text{tApp } (\rho \Gamma t) (\rho \Gamma u)$ 
  | tLambda na t u  $\Rightarrow \text{tLambda na } (\rho \Gamma t) (\rho \text{ na} :_a (\rho \Gamma t) :: \Gamma) u$ 
  | tProd na t u  $\Rightarrow \text{tProd na } (\rho \Gamma t) (\rho \text{ na} :_a (\rho \Gamma t) :: \Gamma) u$ 
  | tVar i  $\Rightarrow \text{tVar } i$ 
  (* other cases are similar *)
end.

```

Fig. 7. Definition of the optimal reduced term $\rho(t)$

to be equal to the appropriately substituted bodies of let-ins. This still allows the reduction of the substituted versions of let-in definiens in the contexts. While types themselves do not participate in reduction, it is essential to also allow their reduction, to get context conversion (of type annotations, not bodies) at the same time as substitution: a context conversion, when restricted to type annotations, is a substitution by the identity.

THEOREM 2.1 (PARALLEL SUBSTITUTION). *The stability by substitution of parallel reduction extends to parallel substitution in the following way:*

*if $\text{psubst } \Sigma \Gamma \Gamma' s t \Delta \Delta'$ and $(\Gamma \ ++ \ \Delta \ ++ \ \Gamma'), M \Rightarrow (\Gamma_1 \ ++ \ \Delta_1 \ ++ \ \Gamma'_1), N$
then $(\Gamma \ ++ \ \Gamma'[s]), (\text{subst } s \ \#|\Gamma'| \ M) \Rightarrow (\Gamma_1 \ ++ \ \Gamma'_1[s']), (\text{subst } s' \ \#|\Gamma'_1| \ N)$.*

The triangle method. Parallel reduction induces a relation which is larger than one-step reduction, but smaller than the reflexive transitive closure of one-step reduction.

$$\rightarrow \subseteq \Rightarrow \subseteq \rightarrow^*$$

Therefore, confluence of parallel reduction is equivalent to confluence of one-step reduction.

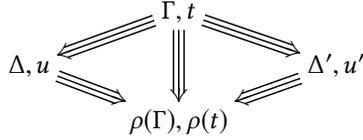
But what is crucial for parallel reduction is that it satisfies the property that there is an *optimal* reduced term $\rho(t)$ for every term t (Smolka [2015] provides a detailed exposition of this). This term is defined by a fixpoint on the syntax, performing as many reduction as possible during its traversal (see Figure 7). The fact that it is optimal is expressed by the following triangle property (for readability, we express the following two properties using commutative diagrams).

THEOREM 2.2 (TRIANGLE PROPERTY). *For every term t and context Γ , we have $\Gamma, t \Rightarrow \rho(\Gamma), \rho(t)$ and for every Δ, u such that $\Gamma, t \Rightarrow \Delta, u$, the following triangle commutes*

$$\begin{array}{ccc}
 \Gamma, t & & \\
 \Downarrow & \searrow & \\
 \Delta, u & \Longrightarrow & \rho(\Gamma), \rho(t)
 \end{array}$$

Parallel reduction is confluent because it is confluent in exactly one step, by using Theorem 2.2 twice.

COROLLARY 2.2.1 (CONFLUENCE OF PARALLEL REDUCTION). *Parallel reduction is confluent. PCUIC: `ParallelReductionConfluence`*



Context Conversion. PCUIC: `ContextConversion`

One can go “out” of parallel-reduction back to the traditional transitive closure of 1-step reduction by forgetting the target contexts (PCUIC: `Confluence`). Due to the action at a distance nature of let-in definiens reduction, we *cannot* get full context conversion from the substitution lemma. We prove only after confluence that for two contexts Γ and Δ , if $\text{red}_{1\text{-ctx}} \Gamma \Delta$ and $\text{red}_1 \Gamma t u$ then there exists a common reduct of t and u using the reflexive-transitive closure of $\text{red}_1 \Delta$.

From this, we define a notion of reductions of contexts and derive a confluence lemma for it: convertible contexts have a common reduct. Finally, this allows to show that cumulativity and typing are preserved by conversion. Although we did not prove it, we believe our formalisation is generic enough to prove an additional strengthening lemma w.r.t. cumulativity.

2.3.3 Subject Reduction & Principality. Type preservation depends on a validity lemma of typing (PCUIC: `Validity`), and the usual inversion properties of the system (PCUIC: `Inversion`). Validity for this calculus is complicated by the fact that not all types have types: algebraic universes cannot be typed. This shows up in the second premise of the cumulativity rule (figure 2). Therefore, we suppose the following properties on the metatheory.

Conjecture `subject_reduction` : $\forall (\Sigma : \text{global_env_ext}) \Gamma t u T,$
 $\text{wf } \Sigma \rightarrow \Sigma ; \Gamma \vdash t : T \rightarrow \text{red } \Sigma \Gamma t u \rightarrow \Sigma ; \Gamma \vdash u : T.$

Note that due to subtyping, the “natural” type of t might be smaller. The general property of cumulativity we assume is:

Conjecture `principal_typing` $\{\Gamma u A B\} : \Sigma ; \Gamma \vdash u : A \rightarrow \Sigma ; \Gamma \vdash u : B \rightarrow$
 $\Sigma C, \Sigma ; \Gamma \vdash C \leq A \times \Sigma ; \Gamma \vdash C \leq B \times \Sigma ; \Gamma \vdash u : C.$

This property together with subject reduction is essential to derive strong enough principles of reasoning on typing derivations up-to reduction (e.g. for sorts for the erasure procedure §4), or to get preservation of typing by conversions, as necessary in the verified conversion checker (§3).

Dealing with co-fixpoints. The subject reduction theorem can hold only for typing derivations where the co-fixpoint introduction rule is forbidden. Indeed, subject reduction fails for co-fixpoints in Coq. This is an explicit design decision: when Giménez [1996] introduced co-inductive types in Coq, he faced the problem that his presentation could either provide type preservation or decidability of type-checking, but not both at the same time. It is known today how to fix the situation, either by forcing the use of co-pattern-matching and “mendler-style” presentations of co-inductives [Abel et al. 2013] or by restricting the dependent elimination of co-inductive “values” to “pure” predicates, as they should rather be seen as computations [Pédrot and Tabareau 2017]. We plan to study the later treatment in future work. To implement this restriction, the whole development is parameterized over a flag structure that allows to configure if the `type_CoFix` rule is allowed or not.

2.3.4 *Strong Normalisation.* As explained in the beginning of this section, there is no hope to prove strong normalisation of PCUIC inside Coq. However we can state it as an axiom. First, we need to specify the transitive closure of the co-reduction (the opposite of the reduction) as the following inductive type `cored`:

```
Inductive cored  $\Sigma$   $\Gamma$ : term  $\rightarrow$  term  $\rightarrow$  Prop :=
| cored1 :  $\forall$  u v, red1  $\Sigma$   $\Gamma$  u v  $\rightarrow$  cored  $\Sigma$   $\Gamma$  v u
| cored_trans :  $\forall$  u v w, cored  $\Sigma$   $\Gamma$  v u  $\rightarrow$  red1  $\Sigma$   $\Gamma$  v w  $\rightarrow$  cored  $\Sigma$   $\Gamma$  w u.
```

Then, the axiom of normalisation corresponds to the proposition that every well-typed term of PCUIC is accessible for `cored`.

```
Conjecture normalisation :  $\forall$   $\Gamma$  t, welltyped  $\Sigma$   $\Gamma$  t  $\rightarrow$  Acc (cored (fst  $\Sigma$ )  $\Gamma$ ) t.
```

Recall that a relation R is accessible at x when the following inductive type is inhabited.

```
Inductive Acc (A : Type) (R : A  $\rightarrow$  A  $\rightarrow$  Prop) (x : A) : Prop :=
  Acc_intro : ( $\forall$  y : A, R y x  $\rightarrow$  Acc R y)  $\rightarrow$  Acc R x
```

So the axiom `normalisation` means that the relation `cored` is well-founded for well-typed terms, which corresponds to strong normalisation of PCUIC.

3 A VERIFIED CHECKER FOR PCUIC

We now turn to the definition of a type checker for PCUIC and a proof that it is correct with respect to the specification given in Section 2. The main ingredients are the definition of a conversion algorithm relying on strong normalisation and checking consistency of universe constraints using a graph traversal algorithm.

3.1 Defining reduction without fuel

Merely assuming strong normalisation doesn't deliver a terminating algorithm to compute the weak-head normal form of a term. We need to define a measure that allows us to reduce the term, but also to *focus* on a subterm. This becomes even harder when dealing with pattern matching and fixpoint. All the more so for fixpoint where the syntactic guard only allows for the unfolding of fix applied to some arguments if the *recursive* argument is an applied constructor. In order to do this, we need to reduce an argument on the stack, meaning a stack consisting only of applications is not sufficient and we need to remember that we were previously reducing a fixpoint.

We define (see Figure 8) a function `stack_pos` to get a position corresponding to a stack. A stack can be seen as a term with a hole (described by the constructor `Empty`) and a position is a list of choices indicating how to traverse a stack to reach its hole. Positions are given with an order `positionR`. From that we deduce a measure with the lexicographical order of first coreduction and then position relation. However the position relation is only well founded if the two positions are valid positions (defined as `pos t`) in the same term t (we need to know we do not go indefinitely down in the term), since the two positions are a priori different terms, we need to use a dependent lexicographical order `dllexprod`, meaning the second order only makes sense if the first components of the pairs are actually equal.

Finally, we define an order R on tuples of term and stack, where the term under consideration is the zipping of the term in the stack (coarsely filling the term in the hole of the stack) and the position is the position induced by the stack (which is valid with respect to the zipped term).

Using the axiom of strong normalization of PCUIC (Section 2.3.4), we can show that R is accessible for pairs of a term and a stack, whose zipping is well-formed, that is either well-typed or a valid arity.

Inductive stack : Type :=

| Empty
 | App (t : term) (p : stack)
 | Fix (f : mfixpoint term) (n : \mathbb{N}) (args : list term) (p : stack)
 | CoFix (f : mfixpoint term) (n : \mathbb{N}) (args : list term) (p : stack)
 | Case (indn : inductive * \mathbb{N}) (p : term) (brs : list (\mathbb{N} * term)) (p : stack)
 | Proj (p : projection) (p : stack)
 | Prod_l (na : name) (B : term) (p : stack)
 | Prod_r (na : name) (A : term) (p : stack)
 | Lambda_ty (na : name) (b : term) (p : stack)
 | Lambda_tm (na : name) (A : term) (p : stack)
 | coApp (t : term) (p : stack).

Inductive choice := app_l | app_r | case_c | proj_c | lam_ty | lam_tm
 | prod_l | prod_r | let_in.

Definition position := list choice.

Inductive positionR : position \rightarrow position \rightarrow Prop :=
 | positionR_app_lr p q : positionR (app_r :: p) (app_l :: q)
 | positionR_deep c p q : positionR p q \rightarrow positionR (c :: p) (c :: q)
 | positionR_root c p : positionR (c :: p) [].

Definition pos (t : term) := { p : position | validpos t p = true }.

Definition posR {t} (p q : pos t) : Prop := positionR p. π_1 q. π_1 .

Inductive dlexprod {A} {B : A \rightarrow Type}
 (leA : A \rightarrow A \rightarrow Prop) (leB : \forall x, B x \rightarrow B x \rightarrow Prop)
 : sigT B \rightarrow sigT B \rightarrow Prop :=
 | left_lex : \forall x x' y y', leA x x' \rightarrow dlexprod leA leB (x;y) (x';y')
 | right_lex : \forall x y y', leB x y y' \rightarrow dlexprod leA leB (x;y) (x;y').

Definition R_aux Γ := dlexprod (cored Σ Γ) (@posR).

Definition R Γ (u v : term * stack) := R_aux Γ (zip u ; stack_pos (fst u) (snd u))
 (zip v ; stack_pos (fst v) (snd v)).

Fig. 8. Definition of the measures on stacks and terms

Corollary R_Acc : \forall Γ t, wf Σ \rightarrow wellformed Σ Γ (zip t) \rightarrow Acc (R Γ) t.

Definition $\text{Edge} := V * \mathbb{N} * V$.

Definition $\text{RootedGraph} := (V\text{Set} * \text{EdgeSet} * V)$.

Definition $\text{Edges } (G : \text{RootedGraph}) \ x \ y := \sum n, \text{EdgeSet.In } (x, n, y) \ (E \ G)$.

Inductive $\text{Paths } G : V \rightarrow V \rightarrow \text{Type} :=$
 | $\text{paths_refl } x : \text{Paths } x \ x$
 | $\text{paths_step } x \ y \ z : \text{Edges } x \ y \rightarrow \text{Paths } y \ z \rightarrow \text{Paths } x \ z$.

Definition $\text{acyclic } G := \forall x \ (p : \text{Paths } G \ x \ x), \text{weight } G \ p = 0$.

Fig. 9. Definition of acyclicity of graph

3.2 Weak-head normalisation using a stack machine

Using R_Acc , we can define weak-head normalisation using a stack machine which emulates the reduction specified by red_1 (Section 2.2.2). The function is defined by induction on the accessibility proof.

Definition $\text{reduce_stack } \Gamma \ (t : \text{term}) \ (p : \text{stack}) \ (h : \text{wellformed } \Sigma \ \Gamma \ (\text{zip } (t, p)))$
 $: \{ t' : \text{term} * \text{stack} \mid \text{Req } \Sigma \ \Gamma \ t' \ (t, p) \} :=$
 $\text{Fix_F } (R := R \ \Sigma \ \Gamma)$
 $(\text{fun } x \Rightarrow \text{wellformed } \Sigma \ \Gamma \ (\text{zip } x) \rightarrow \{ t' : \text{term} * \text{stack} \mid \text{Req } \Sigma \ \Gamma \ t' \ x \})$
 $(\text{fun } t' \ f \Rightarrow _) \ (x := (t, p)) \ _ \ \text{R_Acc}$.

Here, the relation Req is a generalisation of R where the two pairs of term and stack can also be equal. Thus the definition of reduce_stack is by construction correct with respect to its specification. Technically, the internal definition of the reduction is a bit more involved as it requires to maintain more invariants during the reduction. We refer the interesting reader to the Coq development to get a complete definition of weak-head normalisation.

3.3 Universes: valuation vs acyclicity

The specification of universe consistency (Section 2.2.1) as the existence of a valuation into natural numbers which respects the constraints on the universes does not give rise to a decision procedure. Therefore, in Coq, the implementation of this consistency check is performed using an acyclicity check on the weighted graph induced by the constraints.

Our notion of weighted graph (Figure 9) is parametrised by a type a type V of nodes, an edge between x and y of weight n is represented as a tuple (x, n, y) . Then, a rooted graph G is a set of V -nodes ($V \ G$), a set of edges ($E \ G$) and a particular node ($s \ G$) in V , the root of the graph.

Note that we need our weighted graphs to be rooted because a graph representing a universe hierarchy always contains Set as a the universe smaller than all the other (apart from Prop which is treated separately and not represented in the graph), and this plays a particular role because we thus know that there is only one connected component.

The predicate $\text{Edges } G \ x \ y$ specifies that there is an edge between the two nodes x and y . And the inductive predicate $\text{Paths } G \ x \ y$ specifies the existence of a path between G and x . The acyclicity of a weighted graph can then simply be stated as the fact that all reflexive paths have weight 0.

Now, we turn to the formalisation that the acyclicity of the graph induced by the constraints is equivalent to the existence of a valuation respecting the constraints. First, it is easy to define a notion of correct labelling of a graph (where $\text{labelling} := V \rightarrow \mathbb{N}$), which corresponds to the notion of a valuation satisfying the constraints.

Definition `correct_labelling` ($l : \text{labelling}$) :=
 $l (s G) = 0 \wedge \forall x n y, \text{EdgeSet.In } (x,n,y) (E G) \rightarrow l x + n \leq l y.$

Now it remains to show that acyclicity is equivalent to the existence of a correct labelling. To do so, we will use the notion of longest simple path between two nodes, which provides at the same time a characterisation of acyclicity and a decision procedure to check acyclicity.

A simple path in `SimplePaths` $s x y$ is a path from x to y going only through the nodes in s , without visiting twice the same node, except for the last one which can appear two times (forming a loop then)⁴.

Inductive `SimplePaths` : $V\text{Set} \rightarrow V \rightarrow V \rightarrow \text{Type} :=$
 $| \text{spaths_refl } s x : \text{SimplePaths } s x x$
 $| \text{spaths_step } s s' x y z : \text{DisjointAdd } x s s' \rightarrow \text{Edges } x y$
 $\rightarrow \text{SimplePaths } s y z \rightarrow \text{SimplePaths } s' x z.$

From this notion, it is possible to compute the weight of the longest simple path (or simply `lsp`) between two nodes by taking the maximum of all possible simple paths between x and y .

Definition `lsp` : ($s : V\text{Set}$) ($x y : V$) : $\text{option } \mathbb{N}.$

Note that the function goes to $\text{option } \mathbb{N}$ because there may not be any path between x and y . Thus, the constructor `None` of $\text{option } \mathbb{N}$ corresponds to $-\infty$ when extending the addition, maximum function and comparison to $\text{option } \mathbb{N}$.

We then show that `lsp` $s x y$ is equal to the maximum of weights of simple paths from x to y :

Lemma `lsp_spec_le` $s x y (p : \text{SimplePaths } s x y) : \text{Some } (\text{weight } p) \leq \text{lsp } s x y.$

Lemma `lsp_spec_eq` $s x y n : \text{lsp } s x y = \text{Some } n \rightarrow \exists p : \text{SimplePaths } s x y, \text{weight } p = n.$

With this notion of `lsp`, we can prove that acyclicity is equivalent to the existence of a correct labelling, by showing that acyclicity implies that the weight of the longest simple reflexive path on x is always 0. This allows to derive the fact that the labelling induced by the weight of the longest simple path from the root is correct when the graph is acyclic.

Lemma `acyclic_labelling` $l : \text{correct_labelling } l \rightarrow \text{acyclic}.$

Lemma `acyclic_lsp` ($HG : \text{acyclic } G$) $s x : \text{lsp } s x x = \text{Some } 0.$

Lemma `lsp_correctness` ($HG : \text{acyclic } G$) :
`correct_labelling` (`fun x => option_get 0 (lsp (V G) (s G) x)`).

In particular, it gives us a decision procedure to check that a graph is acyclic, by simply checking that `lsp (V G) x x` is 0 for every node x in the graph.

Of course, this decision procedure is far from being optimal with respect to complexity, but the rest of the type checker is independent from it, so it can be replaced by a more efficient one (e.g., using Tarjan *et al.* algorithm, as recently formalised in [Guéneau et al. 2019] in the particular case

⁴The usual notion of simple path does not allow such a repetition.

where there is no constraint of the form \leq) as soon as this new procedure implies acyclicity of the graph.

3.4 Cumulativity

To implement the conversion check up to cumulativity, we need to decide when a universe is smaller than another one. This can be rephrased using labelling on graph as

Definition $\text{leq_vertices } n \times y := \forall l, \text{correct_labelling } l \rightarrow l \times + n \leq l \ y.$

Using lsp again, we can prove that when the graph is acyclic, this property can just be tested on one correct labelling, namely the one induced by lsp .

Lemma $\text{leq_vertices_caract } n \times y (\forall y : \text{VSet.In } y (V \ G)) :$
 $\text{leq_vertices } G \ n \times y \leftrightarrow (\text{Some } n \leq \text{lsp } G \times y).$

Using this, we can define the basic brick of the cumulativity check, which says that x is n smaller than y when either y is in the graph of constraints and $\text{lsp } G \times y$ is bigger than n , or y is constraint free, and in that case, n must be 0 and x must be at distance 0 from Set (which is the source of the graph).

Definition $\text{leqb_vertices } n \times y : \mathbb{B} :=$
 $\text{if } \text{VSet.mem } y (V \ G) \text{ then } \text{le_dec } (\text{Some } n) (\text{lsp } G \times y)$
 $\text{else } \text{Nat.eqb } n \ 0 \ \&\& (V.\text{eq_dec } x \ y \ || \ \text{le_dec } (\text{Some } 0) (\text{lsp } G \times (s \ G))).$

Then, conversion up to cumulativity can be implemented again by induction on accessibility of R . We do not detail here the definition of the conversion algorithm which it is optimised to be much more efficient than just comparing the normal forms up to cumulativity. Coarsely, it mimics the conversion algorithm implemented in Coq which consists in

- (1) first weak-head reducing the two terms without δ -reductions (i.e., without unfolding definitions);
- (2) then compare their heads, if they match, compare the subterms;
- (3) if they do not match, check if some computation (pattern-matching or fixpoint)—or just the whole term—is blocked by a definition that could unfold to a value, unfold this value and start comparing again.

All together, this allows for the implementation of the function convert_leq while showing that it is correct with respect to the specification of the conversion of PCUIC.

3.5 Typechecking

Instead of defining typechecking, we directly define type inference, which is decidable in absence of existential variables.⁵ As type inference may fail when the term is not well-typed, we work inside the following error monad.

Inductive $\text{typing_result } (A : \text{Type}) :=$
 $| \text{Checked } (a : A)$
 $| \text{TypeError } (t : \text{type_error}).$

Type inference is thus described as a function which expects a term t in a well-formed environment $\Sigma ; \Gamma$ and returns a type A together with a proof term that $\Sigma ; \Gamma \vdash t : A$. It is thus correct by construction. Note that the returned proof term of typing derivation is squashed (noted $\| X \|$) in **Prop** in order to make sure that it will be erased by extraction. In the definition of type inference, we let $_$ for typing derivation proof terms as they are quite complex to write down. In the development, they have

⁵Type inference is decidable because we use a fully annotated syntax, as opposed to a Curry style one.

```

Fixpoint infer  $\Gamma$  (H $\Gamma$  : || wf_local  $\Sigma$   $\Gamma$  ||) t : typing_result ( { A : term & ||  $\Sigma$ ;  $\Gamma \vdash t : A$  || })
:= match t with
| tRel n  $\Rightarrow$ 
  match nth_error  $\Gamma$  n with
  | Some c  $\Rightarrow$  ret ((lift0 (S n)) (decl_type c); _)
  | None  $\Rightarrow$  raise (UnboundRel n)
  end
| tSort u  $\Rightarrow$ 
  match u with
  | NEL.sing (l, false)  $\Rightarrow$ 
    check_eq_true (LevelSet.mem l (global_ext_levels  $\Sigma$ )) (Msg "undeclared level");
    ret (tSort (Universe.super l); _)
  | _  $\Rightarrow$  raise (Msg "I can't infer the type of an algebraic universe")
  end
| tProd na A B  $\Rightarrow$ 
  s1  $\leftarrow$  infer_type infer  $\Gamma$  H $\Gamma$  A ;
  s2  $\leftarrow$  infer_type infer ( $\Gamma$ , na :a A) _ B ;
  ret (tSort (sort_of_product s1. $\pi_1$  s2. $\pi_1$ ); _)
| tLambda na A t  $\Rightarrow$ 
  s1  $\leftarrow$  infer_type infer  $\Gamma$  H $\Gamma$  A ;
  B  $\leftarrow$  infer ( $\Gamma$ , na :a A) _ t ;
  ret (tProd na A B. $\pi_1$ ; _)
| tLetIn n b b_ty b'  $\Rightarrow$ 
  s  $\leftarrow$  infer_type infer  $\Gamma$  H $\Gamma$  b_ty ;
  X  $\leftarrow$  infer_cumul infer  $\Gamma$  H $\Gamma$  b b_ty _ ;
  b'_ty  $\leftarrow$  infer ( $\Gamma$ , n := b :d b_ty) _ b' ;
  ret (tLetIn n b b_ty b'_ty. $\pi_1$ ; _)
| tApp t u  $\Rightarrow$ 
  ty  $\leftarrow$  infer  $\Gamma$  H $\Gamma$  t ;
  pi  $\leftarrow$  reduce_to_prod  $\Gamma$  ty. $\pi_1$  _ ;
  X  $\leftarrow$  infer_cumul infer  $\Gamma$  H $\Gamma$  u pi. $\pi_2$ . $\pi_1$  _ ;
  ret (pi. $\pi_2$ . $\pi_2$ . $\pi_1$  {0:=u}; _)
  (* other cases are tConst, tInd, tConstruct, tCase, tProj and tFix *)
end

Definition infer_cumul  $\Gamma$  H $\Gamma$  t A (hA : wellformed  $\Sigma$   $\Gamma$  A)
: typing_result (||  $\Sigma$ ;  $\Gamma \vdash t : A$  ||) :=
A'  $\leftarrow$  infer  $\Gamma$  H $\Gamma$  t ;
X  $\leftarrow$  convert_leq  $\Gamma$  A'. $\pi_1$  A _ hA ;
ret _ .

```

Fig. 10. Definition of type inference (excerpt)

been defined using the `Program` command and the possibility to give them after definition time, using tactics to solve obligations. Figure 10 describes the algorithm written in monadic style. For a variable `tRel n`, it checks that it is bound in Γ , and returns its types, and fails otherwise. For sorts `tSort u`, it checks that the universe is not algebraic, that the level is declared, and returns a sort at level above. For dependent products `tProd na A B`, it computes the sort of A and the sort of B in the context extended by $na:A$ and returns the sort at level of the `sort_of_product` of the two sorts. Similarly for typing functions. The case of `tLetIn` and `tApp` are more interesting as they involve bidirectional typechecking. Indeed, for instance in `tApp t u`, one needs to infer the type ty of t , then reduce it to get a type of the term `tProd A B` using the function `reduce_to_prod` and finally check that u as type A . This is done by the function `infer_cumul` which actually infers the principal type A' of u and checks that it is convertible to A . Note again here that the function `infer_cumul` must return a proof that u as type A , whose definition is postponed using `_`. This proof is defined using tactics, combining the proof that u has type A' and the fact that A is a subtype of A' .

Note that we also have an implementation of re-typechecking which does an optimised version of type inference knowing that the term is already well-typed. However, we have not proven completeness of type inference.

4 TYPE AND PROOF ERASURE FOR PCUIC

One of the key features of the Coq proof assistant is extraction, used for instance in the CompCert compiler [Gallium et al. 2008]. The current implementation of extraction [Letouzey 2002] consists of a general procedure to erase types and proofs and several different mechanisms to extract this erased terms into industrial programming languages like OCaml or Scheme. We verify the type and proof erasure procedure for PCUIC w.r.t. big-step call-by-value evaluation⁶

We first introduce the target calculus of erasure, which is a simplified version of PCUIC with one extra constructor \square denoting erased terms. We then define an erasure function \mathcal{E} , using the verified type checker from Section 3. Following Letouzey [2004], we introduce an erasure relation extending the erasure function, prove its correctness and deduce the strongest possible correctness result for the erasure function. We obtain that if a program evaluates to an element of a first-order inductive type (i.e. an inductive type containing no proofs or functions), its erasure evaluates to the same element. As a corollary, we obtain that for a function where the return type is a first-order inductive type, its erasure can be obtained separately, and will still evaluate to the correct value once applied to enough arguments.

Note that, like in the extraction implemented currently in Coq, the rule `Prop ≤ Type` has to be disabled for type-checking (using the flag `structure`) to ensure erasability is stable by expansion.

4.1 The target calculus $\lambda\square$

The target of the type and proof erasure procedure is $\lambda\square$, an untyped λ -calculus, syntactically agreeing with PCUIC, but where all subterms which can only contain types are left out and with an additional constructor \square denoting computationally meaningless erased content. The definition of the terms of $\lambda\square$ is depicted in Figure 11.

The big-step evaluation relation is defined like for PCUIC, with three amendments:

- (1) If $\Sigma \vdash a \triangleright \square$ then $\Sigma \vdash (\text{tApp } a \ t) \triangleright \square$.
- (2) If $\Sigma \vdash a \triangleright \square$ then $\Sigma \vdash \text{eCase } (i, p) \ a \ [(n, t)] \triangleright t \underbrace{\square \dots \square}_{n \text{ times}}$.
- (3) The rule for `tFix` is extended to also apply if the principal argument evaluates to \square .

⁶We leave out the definition of this standard notion (written as $\Sigma; \Gamma \vdash t \triangleright v$) and refer to the file PCUIC:PCUICWcbveval.

```

Inductive eterm : Set :=
| eBox      : term
| eRel      :  $\mathbb{N} \rightarrow$  eterm
| eLambda   : name  $\rightarrow$  eterm  $\rightarrow$  eterm
| eLetIn    : name  $\rightarrow$  eterm (* the eterm *)  $\rightarrow$  eterm  $\rightarrow$  eterm
| eApp      : eterm  $\rightarrow$  eterm  $\rightarrow$  eterm
| eConst    : kername  $\rightarrow$  eterm
| eConstruct: inductive  $\rightarrow$   $\mathbb{N} \rightarrow$  eterm
| eCase     : (inductive *  $\mathbb{N}$ ) (* # of parameters *)
               $\rightarrow$  eterm (* discriminee *)  $\rightarrow$  list ( $\mathbb{N} *$  eterm) (* branches *)  $\rightarrow$  eterm
| eProj     : projection  $\rightarrow$  eterm  $\rightarrow$  eterm
| eFix      : mfixpoint eterm  $\rightarrow$   $\mathbb{N} \rightarrow$  eterm
| eCoFix    : mfixpoint eterm  $\rightarrow$   $\mathbb{N} \rightarrow$  eterm.

```

Fig. 11. Syntax of $\lambda\Box$

4.2 Definition of an erasure function

We now define a type and proof erasure function $\mathcal{E}_{\Sigma \Gamma} : \text{term} \rightarrow \text{eterm}$ which replaces all types and proofs by \Box . Its implementation is based on a Boolean function $\text{is_erasable } \Sigma \Gamma t$ which checks whether a term is *erasable*.

We leave out the implementation of is_erasable and only give its informative type:

Definition $\text{is_erasable } \Sigma (\text{H}\Sigma : || \text{wf } \Sigma ||) \Gamma (\text{H}\Gamma : || \text{wf_local } \Sigma \Gamma ||) (t : \text{term}) :$
 $\text{typing_result } (|| \text{isErasable } \Sigma \Gamma t || + || (\text{isErasable } \Sigma \Gamma t \rightarrow \text{False}) * \text{welltyped } \Sigma \Gamma t ||).$

The definition of the erasure function is depicted in Figure 12.

4.3 Correctness of erasure

Ideally, we would like to prove that if $\Sigma; \Gamma \vdash t \triangleright v$, we have $\mathcal{E}\Sigma \vdash \mathcal{E}_{\Sigma, \Gamma} t \triangleright \mathcal{E}_{\Sigma, \Gamma} v$ for a suitable extension of \mathcal{E} to global environments. However, this already fails on simple counter-examples: the Coq-term $(\text{fun } Z : \text{Type} \Rightarrow (1, \text{fun } x : X \Rightarrow x)) \text{Type}$ has type $\mathbb{N} * (\text{Type} \rightarrow \text{Type})$ and value $(e, \text{fun } x : \text{Type} \Rightarrow x)$. Erasing the term yields $(\text{fun } X \Rightarrow (1, \text{fun } x \Rightarrow x)) \Box$, with value $(1, \text{fun } x \Rightarrow x)$, whereas the erasure of the value is $(1, \Box)$.

Following Letouzey [2004], we fix this problem by setting up a relation $;\vdash \rightsquigarrow_{\mathcal{E}}$ extending the erasure function, which will be closed under weak call-by-value evaluation. For normal terms of first-order inductive types like \mathbb{N} or $\mathbb{N} * \mathbb{N}$, the relation and the function agree and we can still get the strongest result described above on such first-order types.

We define the erasure relation $\Sigma; \Gamma \vdash t \rightsquigarrow_{\mathcal{E}} t'$ as depicted in Figure 13. Essentially, the relation extends the erasure function by nondeterministic rules allowing not to erase a certain part of a term which could be erased.

The only exception here is the tCase rule. If the tCase matches on a proof of a non-informative proposition, the whole case analysis has to be erased. This is necessary because erased discriemees do not contain any information about which branch to use during evaluation. For informative propositions, there is at most one branch where all arguments are proofs and thus can be erased, they can thus be still evaluated (by picking the one available branch, if any).

The erasure relations contains (the graph of) the erasure function:

LEMMA 4.1. *If $\mathcal{E}_{\Sigma, \Gamma} t = \text{Checked } t'$, then $\Sigma; \Gamma \vdash t \rightsquigarrow_{\mathcal{E}} t'$*

```

Equations  $\mathcal{E} \Gamma (H\Gamma : || \text{wf\_local } \Sigma \Gamma ||) (t : \text{term}) : \text{typing\_result } E.\text{term} :=
\mathcal{E} \Gamma H\Gamma t \text{ with } (\text{is\_erasable } \Sigma H\Sigma \Gamma H\Gamma t) :=
\{ \mathcal{E} \Gamma H\Gamma \_ (\text{Checked } (\text{left } \_)) := \text{ret } (E.\text{tBox});
  \mathcal{E} \Gamma H\Gamma \_ (\text{TypeError } t) := \text{TypeError } t ;
  \mathcal{E} \Gamma H\Gamma (\text{tRel } i) \_ := \text{ret } (E.\text{tRel } i) ;
  \mathcal{E} \Gamma H\Gamma (\text{tLambda na b t}) \_ :=
    t'  $\leftarrow$   $\mathcal{E} (:_a \text{ na b } :: \Gamma) \_ t$ ;
    ret (E.tLambda na t')
  \mathcal{E} \Gamma H\Gamma (\text{tApp f u}) \_ :=
    f'  $\leftarrow$   $\mathcal{E} \Gamma H\Gamma f$ ;
    l'  $\leftarrow$   $\mathcal{E} \Gamma H\Gamma u$ ;
    ret (E.tApp f' l');
  \mathcal{E} \Gamma H\Gamma (\text{tCase ip p c brs}) \_ :=
    c'  $\leftarrow$   $\mathcal{E} \Gamma H\Gamma c$ ;
    brs'  $\leftarrow$   $\text{monad\_map } (\text{fun } x \Rightarrow x' \leftarrow \mathcal{E} \Gamma H\Gamma (\text{snd } x); \text{ret } (\text{fst } x, x')) \text{ brs}$ ;
    ret (E.tCase ip c' brs');
  (* ... *)
\}$ 
```

Fig. 12. Erasure function

We can prove global weakening, weakening and substitutivity of the erasure relation:

LEMMA 4.2. *Let $\Sigma ; \Gamma \vdash t : T$ and $\Sigma ; \Gamma \vdash t \rightsquigarrow_{\mathcal{E}} t'$. Then*

- (1) $\Sigma' ; \Gamma \vdash t \rightsquigarrow_{\mathcal{E}} t'$ for Σ' extending Σ .
- (2) $\Sigma ; \Gamma, \Gamma' \vdash t \rightsquigarrow_{\mathcal{E}} t'$.
- (3) If σ erases to σ' pointwisely, then $\Sigma ; \Gamma \vdash t[\sigma] \rightsquigarrow_{\mathcal{E}} t'[\sigma']$.

We will now prove that the erasure relation commutes with weak call-by-value evaluation. First, we establish some properties of erasable terms:

LEMMA 4.3. *The following hold:*

- (1) If t is erasable, $\text{mkApps } t \ L$ is erasable.
- (2) If $\text{tLambda na } T1 \ t$ is erasable, t is erasable.
- (3) If t is erasable and $\Sigma ; \Gamma \vdash t \triangleright v$, then v is erasable.

To state the correctness lemma, we need to extend erasure to global environments Σ . We write $\Sigma \rightsquigarrow_{\mathcal{E}} \Sigma'$ for this straightforward, inductively defined pointwise extension of $\rightsquigarrow_{\mathcal{E}}$.

LEMMA 4.4. *If $\Sigma \rightsquigarrow_{\mathcal{E}} \Sigma'$ and the constant c is bound to declaration d in Σ , then constant c is bound to d' in Σ' with $\Sigma ; \emptyset \vdash d \rightsquigarrow_{\mathcal{E}} d'$.*

PROOF. The proof is by straightforward induction. Note that in the inductive step for $\Sigma = \Sigma_1, c := d, \Sigma_2$, we only know that $\Sigma_1 ; \emptyset \vdash d \rightsquigarrow_{\mathcal{E}} d'$. To prove $\Sigma ; \emptyset \vdash d \rightsquigarrow_{\mathcal{E}} d'$, we need to use global weakening for the erasure relation. \square

We need to prove an introduction lemma and an inversion lemma for erasure on terms built using mkApps . The introduction lemma is easy:

LEMMA 4.5. *If $\Sigma ; \Gamma \vdash \text{mkApps } f \ L : T$, f erases to f' , and L erases to L' pointwise then $\text{mkApps } f \ L$ erases to $\text{mkApps } f' \ L'$.*

Inductive erases (Σ : global_context) (Γ : context) : term \rightarrow E.term \rightarrow Prop :=

- erases_tRel : $\forall i : \mathbb{N}, \Sigma; \Gamma \vdash \text{tRel } i \rightsquigarrow_{\mathcal{E}} \text{E.tRel } i$
- | erases_tVar : $\forall n : \text{ident}, \Sigma; \Gamma \vdash \text{tVar } n \rightsquigarrow_{\mathcal{E}} \text{E.tVar } n$
- | erases_tLambda : $\forall (na : \text{name}) (b t : \text{term}) (t' : \text{E.term}),$
 $\Sigma; (;_a na b :: \Gamma) \vdash t \rightsquigarrow_{\mathcal{E}} t' \rightarrow$
 $\Sigma; \Gamma \vdash \text{tLambda } na b t \rightsquigarrow_{\mathcal{E}} \text{E.tLambda } na t'$
- | erases_tLetIn : $\forall (na : \text{name}) (t_1 : \text{term}) (t_1' : \text{E.term})$
 $(T t_2 : \text{term}) (t_2' : \text{E.term}),$
 $\Sigma; \Gamma \vdash t_1 \rightsquigarrow_{\mathcal{E}} t_1' \rightarrow$
 $\Sigma; (;_d na t_1 T :: \Gamma) \vdash t_2 \rightsquigarrow_{\mathcal{E}} t_2' \rightarrow$
 $\Sigma; \Gamma \vdash \text{tLetIn } na t_1 T t_2 \rightsquigarrow_{\mathcal{E}} \text{E.tLetIn } na t_1' t_2'$
- | erases_tApp : $\forall (f u : \text{term}) (f' u' : \text{E.term}),$
 $\Sigma; \Gamma \vdash f \rightsquigarrow_{\mathcal{E}} f' \rightarrow$
 $\Sigma; \Gamma \vdash u \rightsquigarrow_{\mathcal{E}} u' \rightarrow \Sigma; \Gamma \vdash \text{tApp } f u \rightsquigarrow_{\mathcal{E}} \text{E.tApp } f' u'$
- | erases_tConst : $\forall (kn : \text{kername}) (u : \text{universe_instance}),$
 $\Sigma; \Gamma \vdash \text{tConst } kn u \rightsquigarrow_{\mathcal{E}} \text{E.tConst } kn$
- | erases_tConstruct : $\forall (kn : \text{inductive}) (k : \mathbb{N}) (n : \text{universe_instance}),$
 $\Sigma; \Gamma \vdash \text{tConstruct } kn k n \rightsquigarrow_{\mathcal{E}} \text{E.tConstruct } kn k$
- | erases_tCase1 : $\forall (\text{ind} : \text{inductive}) (\text{npar} : \mathbb{N}) (T c : \text{term})$
 $(\text{brs} : \text{list } (\mathbb{N} * \text{term})) (c' : \text{E.term})$
 $(\text{brs}' : \text{list } (\mathbb{N} * \text{E.term})),$
 Informative $\Sigma \text{ind} \rightarrow$
 $\Sigma; \Gamma \vdash c \rightsquigarrow_{\mathcal{E}} c' \rightarrow$
 All2
 $(\text{fun } (x : \mathbb{N} * \text{term}) (x' : \mathbb{N} * \text{E.term}) \Rightarrow$
 $\Sigma; \Gamma \vdash \text{snd } x \rightsquigarrow_{\mathcal{E}} \text{snd } x' * \text{fst } x = \text{fst } x') \text{brs } \text{brs}' \rightarrow$
 $\Sigma; \Gamma \vdash \text{tCase } (\text{ind}, \text{npar}) T c \text{brs} \rightsquigarrow_{\mathcal{E}} \text{E.tCase } (\text{ind}, \text{npar}) c' \text{brs}'$
- | erases_tProj : $\forall (p : (\text{inductive} * \mathbb{N}) * \mathbb{N}) (c : \text{term}) (c' : \text{E.term}),$
 $\text{let } \text{ind} := \text{fst } (\text{fst } p) \text{ in}$
 Informative $\Sigma \text{ind} \rightarrow$
 $\Sigma; \Gamma \vdash c \rightsquigarrow_{\mathcal{E}} c' \rightarrow \Sigma; \Gamma \vdash \text{tProj } p c \rightsquigarrow_{\mathcal{E}} \text{E.tProj } p c'$
- | erases_tFix : $\forall (\text{mfix} : \text{mfixpoint term}) (n : \mathbb{N}) (\text{mfix}' : \text{list } (\text{E.def E.term})),$
 All2
 $(\text{fun } (d : \text{def term}) (d' : \text{E.def E.term}) \Rightarrow$
 $\text{dname } d = \text{E.dname } d'$
 $* \text{rarg } d = \text{E.rarg } d'$
 $* \Sigma; \Gamma ++ \text{PCUICLiftSubst.fix_context } \text{mfix} \vdash$
 $\text{dbody } d \rightsquigarrow_{\mathcal{E}} \text{E.dbody } d') \text{mfix } \text{mfix}' \rightarrow$
 $\Sigma; \Gamma \vdash \text{tFix } \text{mfix } n \rightsquigarrow_{\mathcal{E}} \text{E.tFix } \text{mfix}' n$
- | erases_box : $\forall t : \text{term}, \text{Is_Type_or_Proof } \Sigma \Gamma t \rightarrow \Sigma; \Gamma \vdash t \rightsquigarrow_{\mathcal{E}} \text{E.tBox}$

where " $\Sigma ; \Gamma \vdash s \rightsquigarrow_{\mathcal{E}} t$ " := (erases $\Sigma \Gamma s t$).

Fig. 13. Erasure relation

The inversion case has to be set up very carefully, because of the non-determinism in the erasure relation:

LEMMA 4.6. *If $\Sigma; \Gamma \vdash \text{mkApps } f \ L : T$ and $\Sigma; \Gamma \vdash \text{mkApps } f \ L \rightsquigarrow_{\mathcal{E}} t$ then either*

- (1) *$t = \text{mkApps } f' \ L'$ for $\Sigma; \Gamma \vdash f \rightsquigarrow_{\mathcal{E}} f'$ and L pointwisely erasing to L' .*
- (2) *or $L = L_1 L_2$ with $\text{mkApps } f L_1$ erasable, L_2 pointwisely erasing to L'_2 and $t = \text{mkApps } \square \ L'_2$.*

This now suffices to prove the correctness theorem of the erasure relation:

THEOREM 4.7. *Let Σ be a well-formed global environment erasing to Σ' . Let $\Sigma; \Gamma \vdash t : T$ erasing to t' and evaluating to v . Then there exists v' s.t. $\Sigma; \Gamma \vdash t' \triangleright v'$ and $\Sigma; \Gamma \vdash v \rightsquigarrow_{\mathcal{E}} v'$.*

We conclude with two non-formalised observations. We call a type first-order if it is a non-propositional inductive type where all parameters and all arguments of constructors are of a first-order type. On elements such types, the erasure relation is clearly functional, because there is no erasable content. We thus have the following:

LEMMA 4.8. *Let $\Sigma; \Gamma \vdash t : T$ for T a fully-applied first-order inductive type. If $\Sigma; \Gamma \vdash t \rightsquigarrow_{\mathcal{E}} t'$ and $\mathcal{E}_{\Sigma, \Gamma} t$ is defined, then $t' = \mathcal{E}_{\Sigma, \Gamma} t$.*

COROLLARY 4.8.1. *Let $\Sigma; \Gamma \vdash t : T$ and T be a first-order type.*

If $\mathcal{E}_{\Sigma, \Gamma} t = t'$, $\Sigma; \Gamma \vdash t \triangleright v$, and $\mathcal{E}_{\Sigma, \Gamma} v = v'$, then $\Sigma; \Gamma \vdash v \triangleright v'$.

In particular, this observation entails that our type and proof erasure function supports separate compilation:

COROLLARY 4.8.2. *Let $\Sigma; \Gamma \vdash \text{mkApps } f \ L : T$, where T is a first-order type. Then the value of $\text{mkApps}(\mathcal{E}f)(\mathcal{E}L)$ is the erasure of the value of $\text{mkApps } f \ L$.*

5 RELATED WORK

Abel et al. [2018] present a normalization-by-evaluation algorithm for deciding definitional equality in an idealized dependent type theory with only one universe and natural numbers, verified in a larger type theory with inductive-recursive types. Their methodology provides correctness and completeness results and deals with η -laws by comparing $\beta\eta$ -long normal forms. While we only have correctness for now, our algorithm is certainly more efficient as it does not necessarily need to go to normal forms, which is crucial for performance in practice. Strub et al. [2012] provide a methodology to build a self-certifying type-checker for a large subset of F^* , whose metatheory is formalised in Coq. Our work is complementary in the sense that it reduces the trusted-code base involved in that methodology to the specification of PCUIC, and no longer to its ML kernel implementation. $\mathcal{C}\text{euf}$ [Mullen et al. 2018] formalise a subset of Coq and provide a verified compiler from this language to Assembly code.

Hupel and Nipkow [2018] implement a verified extraction from Isabelle/HOL into CakeML. The first phase of their compiler consists of a proof-producing translation implemented in Standard ML, translating terms of Isabelle/HOL into a deeply embedded term language. The second part of their compiler is a verified translation from the deeply embedded language into CakeML. Myreen and Owens [2014] implement a certifying extraction from HOL light code to CakeML. Their approach can translate programs in a state-and-exception monad into stateful ML code and was used to extract the verified HOL-light compiler to CakeML. Forster and Kunze [2019] report on a certifying translation from a subset of Coq to the weak call-by-value λ -calculus. Their extraction is implemented in the METACOQ framework as well, but they produce correctness proofs for their extract in Coq's tactic language LTac. Runtime proof erasure / ICC* [Barras and Bernardo 2008] Glondou [2012] verifies the syntactic proof given by Letouzey [2004] in Coq. They formalises a

correctness proof w.r.t. arbitrary small-step reduction, but work in a slightly idealised calculus with no exploitable correspondence to the actual implementation of Coq. They do not consider a verified type-checker or the verification of an executable type and proof erasure function.

6 CONCLUSION AND FUTURE WORK

The whole development we presented includes the translation from MetaCoq’s syntax (proven correct), specification of typing (trusted with respect to strong normalisation), metatheory (whose proofs are ongoing), verified checker and conversion and erasure phase (that have been proven correct w.r.t. the metatheory). The whole development is about 17kLoc of specifications, 30kLoc of proofs and 3kLoc of documentation and relies only on the strong normalization axiom, parameters for the guard, and uses of proof irrelevance, which are not known to be inconsistent together. The development runs with Coq 8.8 [Team 2018] in about 10min on a modern laptop. It extensively uses the EQUATIONS package [Sozeau and Mangin 2019] and its dependent elimination tactics. It also relies crucially on the view technique introduced by McBride and McKinna [2004] to factor cases and the support of EQUATIONS for well-founded recursion.

From these specifications and implementations, a number of applications are possible. Certified translations and plugins were surveyed in [Sozeau et al. 2019], we focus here on what our contributions bring in addition.

6.1 METACOQ + CERTICOQ + COMPCERT

Originally, the CERTICOQ compiler [Anand et al. 2017] (a verified compiler from GALLINA programs down to COMPCERT’s C-light) used a rather crude methodology to perform extraction: it expected a quoted input term to have all its maximal subterms of sort `Prop` marked by casts, and then proceeded with an unsafe erasure phase. We put this foremost part of the system on a stronger footing by having not only implemented the extraction in Coq relying on a safe type checker, but also proven that it correctly implements erasure. The theorem we prove can be linked to the correctness of the compiler pipeline resulting in an observational equivalence from a weak call-by-value evaluated term in the $\lambda\Box$ language to C-light semantics. Compiling the code with COMPCERT and linking it with a verified garbage collector provides a maximally safe evaluation chain for Coq’s dependently-typed programming language.

However, at the time of writing this paper, we cannot use Coq’s extraction mechanism to produce a verified version of the checker in OCAML, as the extraction produces an ill-typed term! This term comes from the definition of the convertibility check (§3.4), which uses dependent elimination to produce a variadic function type, when deciding to act as a comparison of terms, stacks or in fallback mode. We hence cannot report on experiments with the extracted code yet.

6.2 Future Work

With respect to Coq’s currently implemented type theory, we depart by not considering η -laws for functions and primitive record types in our specification of definitional equality. We also leave out the module system: thankfully, it is orthogonal to the term language. We leave these extensions to future work.

In future, we want to extend PCUIC and erasure to also handle the sort `SProp` [Gilbert et al. 2019], implemented in Coq 8.10. Since `SProp` is a proof-irrelevant analogue to `Prop`, adapting erasure is almost trivial: `SProp` can be erased like `Prop` and no special care has to be taken for eliminations.

We also want to extend our account of erasure to other evaluation orders (most notably call-by-name evaluation to be able to target lazy languages). Currently, we support axioms which do not block call-by-value evaluation — which is rarely the case. Letouzey [2004] introduces a semantic account of erasure correctness, which would allow the treatment of axioms. We want to verify such

a semantic correctness theorem, allowing us to argue the consistency of (at least) propositional axioms like functional extensionality or Markov's principle.

Another exciting endeavor is to refine the specification to fit into the standard models of dependent type theory, beginning with the set theoretic model developed by [Barras \[1999\]](#). A first step towards this goal will be to tackle the difficult guard and productivity conditions.

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