Plugging-in Proof Development
Environments using Locks in LF

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We present two extensions of the LF Constructive Type Theory featuring monadic locks. A lock is a monadic type construct that captures the effect of an external call to an oracle. Such calls are the basic tool for plugging-in and gluing together, different metalanguages and proof development environments. Oracles can be invoked either to check that a constraint holds or to provide a witness. The systems are presented in the canonical style developed by the “CMU School”. The first system, CLLF\textsubscript{P}, is the canonical version of the system LLF\textsubscript{P}, presented earlier by the authors. The second system, CLLF\textsubscript{P?}, features the possibility of invoking the oracle to obtain also a witness satisfying a given constraint. In order to illustrate the advantages of our new frameworks, we show how to encode logical systems featuring rules which deeply constrain the shape of proofs. The locks mechanisms of CLLF\textsubscript{P} and CLLF\textsubscript{P?} permit to factor out naturally the complexities arising from enforcing these “side conditions”, which severely obscure standard LF encodings. We discuss Girard’s Elementary Affine Logic, Fitch-Prawitz Set theory, call-by-value λ-calculi, and functions, both total and even partial.

1. Introduction

This work is an extended version of (Honsell et al. 2015) and is part of an ongoing research programme, (Honsell et al. 2012; Honsell 2013; Honsell et al. 2014; Honsell et al. 2016), aiming to define a simple Universal Meta-language for Logics, extending the Constructive Type Theory LF, that can support the effects of plugging-in and integrating different proof development environments.

The basic idea underpinning these logical frameworks is to allow for the user to express explicitly the invocation of external tools and to uniformly record their effects by means of a new monadic type-constructor $L_{M,\sigma}[\cdot]$, called a lock. More specifically, locks permit to

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express the fact that, in order to obtain a term of a given type, it is necessary, beforehand, to verify a constraint, which is written in the form of a meta-predicate on a typing judgement $\mathcal{P}(\Gamma \vdash_\Sigma M : \sigma)$. There are no limitations on how the external proof search tools can supply such evidence. These can even make use of oracles or exploit some other epistemic source, such as diagrams, physical analogies, or explicit computations in the spirit of Poincaré Principle (Barendregt et al. 2002; Kerber 2006). We can say, therefore, that locks subsume different proof attitudes, such as “proof-irrelevant” approaches, where one is interested only in knowing that some evidence does exist, as well as approaches relying on powerful terminating metalanguages. Indeed, locks allow for a straightforward accommodation of many different proof cultures within a single Logical Framework, which can otherwise be embedded only very deeply (Boulton et al. 1992; Hirschkoff 1997) or axiomatically (Honsell et al. 2001).

Pragmatically, using lock constructors, one can factorize the goal, produce pieces of evidence using different proof environments, and finally glue them back together, using the unlock operator, which releases the locked term in the calling framework. Clearly, the task of checking the validity of external evidence relies entirely on the external tool which has been plugged-in. Our framework limits itself to recording in the proof term that there has been a recourse to an external tool, by means of an unlock destructor. Of course one can, separately, check the adequacy of the external tool (see (Honsell et al. 2016) for a more detailed discussion on this point).

Departing from our earlier work, we focus in this paper on systems presented in canonical format. This format, introduced by the “CMU School”, (Watkins et al. 2002; Harper and Licata 2007), makes use only of terms in normal form, while definitional equality is subsumed by hereditary substitution. This format streamlines the proofs of the “adequacy” of the encodings of the object logics. The canonical format is usually rigidly “syntax directed” and it produces a unique derivation for each derivable judgement. In our case this does not hold any longer, but we still have a weak form of syntax directedness that allows for decidability. Uniqueness of derivations is lost, but inversions of a derivation can still be performed exhaustively.

All effective Locks can be encoded deeply in plain LF in a stand-alone signature, at least in principle. Doing this however, obscures the flow of the logical argument with cumbersome syntactic checks, when using the stand-alone signature. Locks can therefore be viewed also a structuring tool for factoring logic signatures in modules.

In this paper, first, we discuss the canonical system CLLF$_P$ and the correspondence to its non-canonical counterpart LLF$_P$ presented in (Honsell et al. 2016).

The second, and completely innovative, contribution of this paper is to show how locks can be used to accommodate, not only the request to an external tool for specific evidence, but also for a witness to be further used by the calling environment, satisfying a given property. This feature is exhibited by the new system CLLF$_P$ (see Section 3), where locks act as binding operators while unlocks act as substitutions.

In order to illustrate the usefulness and the expressive power of CLLF$_P$, we show how to encode logical systems featuring rules which constrain severely the shape of proofs. Constraints may concern the “shape” or the “number” of assumptions in proofs, as in Modal Logic or Light Linear Logic, (Girard 1998; Baillot et al. 2007); the very “form”
of proofs as in Fitch-Prawitzconsistent Set-Theory (FPST), (Prawitz 1965), or in proof-functional connectives (Pottinger 1980; Barbanera and Martini 1994); dynamic aspects of terms, as in restricted λ-calculi. Standard LF encodings of these systems are very obscure because of the machinery necessary for rendering these “side conditions”. On the other hand CLLFₚ and CLLFₚ? can capitalize on locks, which permit to structure the encodings and factor out naturally such complexities. Finally, in Subsection 4.4, we show how to encode functions, both total and even partial functions in CLLFₚ?.

The paper is organized as follows: in Section 2 we present the syntax, the type system and the metatheory of CLLFₚ, whereas CLLFₚ? is introduced in Section 3. Section 4 is devoted to the presentation and discussion of examples and case studies. Finally, connections with related work in the literature appear in Section 5.

2. The Canonical System CLLFₚ

In this section, we present the system CLLFₚ which is the canonical counterpart of LLFₚ (Honsell et al. 2016) in the style of (Watkins et al. 2002; Harper and Licata 2007). In canonical systems one deals only with terms in normal form, either canonical objects or atomic objects. Hence definitional equality is identity. The added value of canonical systems is that one can streamline results of adequacy for object logics. Indeed terms, in the meta-language of proofs, which are not in normal form, are not very meaningful, unless we are interested in recording the use of lemmata and, possibly higher-order, derivable rules. To define a system in canonical form, the standard procedure for deriving typing rules based on the introduction-elimination-equality rule-pattern needs to be rephrased. Introduction rules correspond to type checking rules of canonical objects, whereas elimination rules correspond to type synthesis rules of atomic objects. Equality rules are not explicit but are embedded in the rules of hereditary substitution.

2.1. Syntax and Type System for CLLFₚ

The syntax of CLLFₚ is presented in Figure 1. The judgements of CLLFₚ are the following:

```latex
\begin{align*}
\mathcal{K} \in \cal{K} & \quad \mathcal{K} ::= \text{type} | \Pi x:\sigma.\mathcal{K} & \quad \text{Kinds} \\
\alpha \in \cal{F}, & \quad \alpha ::= a | \alpha N & \quad \text{Atomic Families} \\
\sigma, \tau, \rho \in \cal{F} & \quad \sigma ::= \alpha | \Pi x:\sigma.\tau | \mathcal{L}_N^\sigma[\rho] & \quad \text{Canonical Families} \\
A \in \cal{O}, & \quad A ::= c | x | AM | \mathcal{U}_N^0[A] & \quad \text{Atomic Objects} \\
M, N \in \cal{O} & \quad M ::= A | \lambda x.M | \mathcal{L}_N^0[M] & \quad \text{Canonical Objects} \\
\Sigma \in \cal{S} & \quad \Sigma ::= \emptyset | \Sigma, a:K | \Sigma, c:\sigma & \quad \text{Signatures} \\
\Gamma \in \cal{C} & \quad \Gamma ::= \emptyset | \Gamma, x:\sigma & \quad \text{Contexts}
\end{align*}
```

Fig. 1. Syntax of CLLFₚ
The type system for CLLFᵣ is shown in Figure 2. For a discussion of the monadic interpretation of locks and unlocks see Section 2.3.

The judgements Σ sig, and ⊢Σ Γ, and Γ ⊢Σ K are as in Section 2.1 of (Honsell et al. 2013), whereas the remaining ones are peculiar to the canonical style. Informally, the judgment Γ ⊢Σ M ⇐ σ uses σ to check the type of the canonical term M, while the judgment Γ ⊢Σ A ⇒ σ uses the type information contained in the atomic term A and Γ to synthesize σ. Without loss of generality, predicates P in CLLFᵣ are defined only on judgements of the shape Γ ⊢Σ M ⇐ σ.

The rules (A·App) and (F·App), and (O·Nested·Unlock) and (F·Nested·Unlock) make use of the notion of Hereditary Substitution, defined in Figures 4 and 5. Hereditary Substitution computes the substitution of a normal form into another, performing β-reductions and Unlock-Lock reductions (UL-reductions), i.e. U_L^P[L^K_N[M]] → M, in the rules (S·O·App·H) and (S·O·Unlock·H), when a redex would result from the substitution. The general form of the hereditary substitution judgement is T[M/x]_ρ = T', where M is the term being substituted, x is the variable being substituted for, T is the term being substituted into, T' is the result of the substitution, ρ is the simple-type of M, and t ∈ {K, F, F_a, O, O_a} denotes the syntactic class (i.e., kinds, canonical and atomic families, canonical and atomic objects) under consideration. We give the rules of the Hereditary Substitution in the style of (Harper and Licata 2007), where the erasure function to simple types is necessary to ensure the decidability of the existence of a hered-

Notice that, in the rule (O·Atom) of the type system (Figure 2), the syntactic restriction of the classifier to atomic ensures that canonical forms are long βη₄U₅-normal forms for the appropriate notion of long βη₄-normal form, which extends the standard one to lock-types (Definition 2.4). Hence, since the judgement x:Πz:a.a ⊢Σ x ⇐ Πz:a.a is not derivable, as ΠΣΣz:a.a is not atomic, then ⊢Σ Λx.x ⇐ Πx:(Πz:a.a)Πz:a.a is not derivable either. On the other hand, ⊢Σ Λx.λy.xy ⇐ Πx:(Πz:a.a).Πz:a.a, where a is a family constant of kind Type, is derivable. Analogously, for lock-types, the judgement x:Σ |_N,a[P] ⊢Σ x ⇐ Σ |_N,a[P] is not derivable, since Σ |_N,a[P] is not atomic. Consequently, ⊢Σ Λx.x ⇐ Πx:Σ |_N,a[P].Σ |_N,a[P] is not derivable either. However, x:Σ |_N,a[P] ⊢Σ Σ |_N,U_L^P[x] ⇐ Σ |_N,a[P] is derivable, if ρ is atomic. Hence, the judgment ⊢Σ Λx.Σ |_N,U_L^P[x] ⇐ Πx:Σ |_N,a[P].Σ |_N,a[P] is derivable. Notice that the unlock constructor takes an atomic term as its main ar-
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in LF

Valid signatures
\[
\begin{array}{c}
\emptyset \vdash \Sigma \quad \Sigma \vdash a : K \quad \Sigma, a : K \vdash \emptyset \\
\hline \\
\Sigma \vdash \Sigma \quad \Sigma \vdash a : K \\
\hline \\
\Sigma, a : K \vdash \Sigma \\
\end{array}
\]

Context rules
\[
\begin{array}{c}
\Sigma \vdash \emptyset \\
\hline \\
\Sigma \vdash \Sigma \\
\hline \\
\Sigma, a : K \vdash \Sigma \\
\end{array}
\]

Atomic Family rules
\[
\begin{array}{c}
\Sigma \vdash a \in \Sigma \\
\hline \\
\Sigma \vdash a \in \Sigma \\
\hline \\
\Sigma, a \in \Sigma \\
\end{array}
\]

Canonical Family rules
\[
\begin{array}{c}
\Gamma \vdash \Sigma \vdash a \in \Sigma \\
\hline \\
\Gamma \vdash \Sigma \vdash a \in \Sigma \\
\hline \\
\Gamma \vdash \Sigma \vdash \tau \in \Sigma \\
\end{array}
\]

Canonical Object rules
\[
\begin{array}{c}
\Gamma \vdash \Sigma \vdash \alpha \in \Sigma \\
\hline \\
\Gamma \vdash \Sigma \vdash \alpha \in \Sigma \\
\hline \\
\Gamma \vdash \Sigma \vdash M \in \tau \\
\end{array}
\]

Kind rules
\[
\begin{array}{c}
\Gamma \vdash \Sigma \vdash a \in \Sigma \\
\hline \\
\Gamma \vdash \Sigma \vdash a \in \Sigma \\
\hline \\
\Gamma \vdash \Sigma \vdash \tau \in \Sigma \\
\end{array}
\]

In Definition 2.4, we formalize the notion of \( \eta \)-expansion of a judgement, together with correspondence theorems between \( \text{LLF}_P \) and \( \text{CLLF}_P \).

The rules \( (\text{F-Nested-Unlock}) \) and \( (\text{O-Nested-Unlock}) \) in Figure 2 apparently break

gument, thus avoiding the creation of possible \( \mathcal{L} \)-redexes under substitution. Moreover, as unlocks can only receive locked terms in their body, no abstractions can ever arise.
In this paper, we present \( \text{CLLF}_p \) à la Curry, following closely (Harper and Licata 2007), while in (Honsell et al. 2016) we presented the non canonical system \( \text{LLF}_p \) in a fully-typed style, i.e. à la Church. Namely, in \( \text{LLF}_p \) the canonical forms \( \lambda x : \sigma.M \), \( \mathcal{L}_{\sigma,M}^p[N] \), and \( \mathcal{U}_{\mathcal{M},\sigma}^p[N] \) carry type information. We could have made that choice also for \( \text{CLLF}_p \) (as we did in (Honsell et al. 2015)), the type rules would then have been, e.g.:
Substitution in Atomic Objects
\[
\frac{c[M_0/x_0]_{\rho_0}^\circ}{(S\text{-}O\text{-Const})} \quad \frac{x[M_0/x_0]_{\rho_0}^\circ = M_0 : \rho_0}{(S\text{-}O\text{-Var-H})} \quad \frac{x \neq x_0}{(S\text{-}O\text{-Var})}
\]
\[
A_1[M_0/x_0]_{\rho_0}^\circ = \lambda x.M_1' : \rho_2 \rightarrow \rho \quad M_2[M_0/x_0]_{\rho_0}^\circ = M_2' \quad M_1'[M_2'/x_0]_{\rho_0}^\circ = M' \quad (S\text{-}O\text{-App-H})
\]
\[
\frac{(A_1 M_2)[M_0/x_0]_{\rho_0}^\circ = M' : \rho}{(S\text{-}O\text{-App})}
\]
\[
M[M_0/x_0]_{\rho_0}^\circ = M' \quad A[M_0/x_0]_{\rho_0}^\circ = \mathcal{L}_{M'}^P [M_1] : \mathcal{L}_{M',\sigma'}^P [\rho] \quad (S\text{-}O\text{-Unlock-H})
\]
\[
\frac{M[M_0/x_0]_{\rho_0}^\circ = M'}{U_{M_1}^M [A][M_0/x_0]_{\rho_0}^\circ = U_{M'}^M [A']} \quad (S\text{-}O\text{-Unlock})
\]

Substitution in Canonical Objects
\[
\frac{A[M_0/x_0]_{\rho_0}^\circ = A'}{(S\text{-}O\text{-R})} \quad \frac{A[M_0/x_0]_{\rho_0}^\circ = M' : \rho}{(S\text{-}O\text{-R-H})} \quad \frac{M[M_0/x_0]_{\rho_0}^\circ = M'}{(S\text{-}O\text{-Abs})}
\]
\[
\frac{A[M_0/x_0]_{\rho_0}^\circ = A'}{A[M_0/x_0]_{\rho_0}^\circ = M' : \rho} \quad \frac{M[M_0/x_0]_{\rho_0}^\circ = M'}{\lambda x.M[M_0/x_0]_{\rho_0}^\circ = \lambda x.M'} \quad (S\text{-}O\text{-Lock})
\]

Substitution in Contexts
\[
\frac{[M_0/x_0]_{\rho_0}^\circ = \emptyset}{(S\text{-}Ctxt\text{-Empty})} \quad \frac{x_0 \neq x \quad x \notin \text{Fv}(M_0) \quad \Gamma[M_0/x_0]_{\rho_0}^\circ = \Gamma' \quad \sigma[M_0/x_0]_{\rho_0}^\circ = \sigma'}{(S\text{-}Ctxt\text{-Term})}
\]

Fig. 5. Hereditary substitution, objects and contexts of CLLF

\[
\frac{\Gamma, x : \sigma \vdash \tau}{\Gamma \vdash \lambda x : \sigma. M \equiv \Pi x : \sigma. \tau} \quad (O\text{-Abs}) \quad \frac{\Gamma \vdash \sigma \quad \Gamma \vdash \tau}{\Gamma \vdash \sigma} \quad (O\text{-Lock})
\]

In this paper we use a Curry-style syntax of terms because it is more suitable for implementations in that it simplifies the notation. While, as remarked in (Honsell et al., 2015), the typeful syntax à la Church allows for a more direct comparison with non-canonical systems. Indeed, there is a correspondence between the two systems. In Theorem 2.9 we prove by induction on derivations that any provable judgement in the system where object terms are à la Curry has a unique type decoration of its object subterms, which turns it into a provable judgement in the version à la Church. Vice versa, any provable judgement in the version à la Church can forget the types in its object subterms, yielding a provable judgement in the version à la Curry.
2.3. Discussion: Locks and Monads

In (Honsell et al. 2016) we introduced lock-types following the paradigm of Constructive Type Theory (à la Martin-Löf), i.e. via introduction, elimination, and equality rules. In the present paper, the system is in canonical format, hence lock-types are introduced by:

— a lock constructor for building canonical objects \( \mathcal{L}_S^p[M] \) of type \( \mathcal{L}_S^p[\sigma] \), via the type checking rule (O-Lock);

— an unlock destructor, \( \mathcal{U}_S^p[M] \), for building atomic objects, whose type is synthesized by the atomic rule (O-Unlock)

— rules in the definition of hereditary substitution, allowing the elimination of the lock-type constructor under the condition that a specific predicate \( P \) is verified, possibly externally, on a judgement.

The specific rules taken from Figures 2, 4, and 5 are:

\[
\text{(O-Lock)} \quad \frac{\Gamma \vdash \Sigma \ M \equiv \rho \quad \Gamma \vdash \Sigma \ N \equiv \sigma}{\Gamma \vdash \Sigma \ \mathcal{L}_S^p[M] \equiv \mathcal{L}_S^p[\sigma]}
\]

\[
\text{(O-Unlock)} \quad \frac{\Gamma \vdash \Sigma \ A \Rightarrow \mathcal{L}_N^p[\rho] \quad \Gamma \vdash \Sigma \ N \equiv \sigma \quad \mathcal{P}(\Gamma \vdash \Sigma \ N \equiv \sigma)}{\Gamma \vdash \Sigma \ \mathcal{U}_S^p[A] \Rightarrow \rho}
\]

\[
\text{(S-O-Unlock-H)} \quad \sigma[M_0/x_0]_{\rho_0} = \sigma' \quad M[M_0/x_0]_{\rho_0} = M' \quad A[M_0/x_0]_{\rho_0} = \mathcal{L}_M^p[M_1]:\mathcal{L}_M^p[\sigma',[\rho]]
\]

\[
\mathcal{U}_S^p[A][M_0/x_0]_{\rho_0} = M_1: \rho
\]

Lock type constructors have a natural monadic reading/behaviour, i.e. any object can be "frozen" by a lock in a lock-type and locks are idempotent. Hence we can speak of the \( \mathcal{L}_S^p[\cdot] \)-monad, see (Honsell et al. 2014; Honsell et al. 2016) for more details. Therefore, we can manipulate locked terms without necessarily establishing first the predicate, provided an outermost lock is present. This increases the flexibility of the system, and allows for reasoning under the assumption that the verification is successful, as well as for postponing tests and hence reducing the number of verifications. This is one of the most fruitful advantages of using locks, indeed. The rules which make all this work are:

\[
\text{(F-Nested-Unlock)} \quad \frac{\Gamma, x: \tau \vdash \Sigma \ \mathcal{L}_{S,\sigma}^p[\rho] \ \text{type} \quad \Gamma \vdash \Sigma \ A \Rightarrow \mathcal{L}_{S,\sigma}^p[\tau] \quad \rho[\mathcal{U}_{S,\sigma}^p[A]/x]_{(\tau)} = \rho'} \quad x \in \text{Fv}(\rho)}{\Gamma \vdash \Sigma \ \mathcal{L}_{S,\sigma}^p[\rho'] \ \text{type}}
\]

\[
\text{(O-Nested-Unlock)} \quad \frac{\Gamma, x: \tau \vdash \Sigma \ \mathcal{L}_S^p[M] \equiv \mathcal{L}_S^p[\sigma] \quad x \in \text{Fv}(M) \cup \text{Fv}(\rho)}{\Gamma \vdash \Sigma \ A \Rightarrow \mathcal{L}_S^p[\tau] \quad \rho[\mathcal{U}_S^p[A]/x]_{(\tau)} = \rho' \quad M[\mathcal{U}_S^p[A]/x]_{(\tau)} = M'}{\Gamma \vdash \Sigma \ \mathcal{L}_S^p[M'] \equiv \mathcal{L}_S^p[\rho']}\]

The (O-Nested-Unlock)-rule is the counterpart of the elimination rule for monads, since the standard destructor of monads (cf. (Moggi 1989)) \( \text{let}_{\mathcal{U}_S^p[A]/x} x = A \) in \( N \) can be expressed in our context by \( N[\mathcal{U}_S^p[A]/x] \). This works since the \( \mathcal{L}_S^p[\cdot] \)-monad satisfies the property \( \text{let}_{\mathcal{U}_S^p[A]/x} x = A \) in \( N \rightarrow N[\mathcal{U}_S^p[A]/x] \) provided \( x \) occurs guarded in \( N \), i.e. within some subterm whose type is locked by \( \mathcal{L}_S^p[\cdot] \). Namely, we do not need to check repeatedly...
the constraint but we do need to do it at least once. The rule \((F\cdot\text{Nested}\cdot\text{Unlock})\) takes care of the elimination rule for monads at the level of types.

The fact that we can express the effects of the elimination rule for monads directly, makes us do away with the tedious permutative reductions which normally arise in dealing with monadic \textit{let} constructors. As we anticipated in Section 2.1, it is precisely the monadic flavour of the above rules, however, that breaks the strict syntax directedness of \(\text{CLLF}_P\), which can be recovered, nevertheless, in a weaker form sufficient for all practical purposes.

### 2.4. The Metatheory of \(\text{CLLF}_P\)

The type system \(\text{CLLF}_P\) is legitimately a Logical Framework in that it is decidable (Theorem 2.6), provided the predicates \(P\) are themselves decidable. Moreover, it captures the expressive power of \(\text{LLF}_P\) in the sense of the Soundness and Correspondence Theorems 2.8 and 2.9. Soundness implies that every valid judgement \(J\) in \(\text{CLLF}_P\) is, up to unique type decoration of \(\lambda\)-s and lock/unlocks, a valid judgement in \(\text{LLF}_P\). Correspondence claims that a judgement \(J\) is valid in \(\text{LLF}_P\) if and only if there exists a valid judgment \(J'\) in \(\text{CLLF}_P\) which morally is the long \(\eta\)\(L\)-expansions of the \(\beta\)U-normal forms of all its components. We will clarify this point when discussing the above mentioned Theorems, without spelling out all the details because they belong to the Logical Frameworks’ folklore.

Throughout this section we capitalize, whenever possible, on the seminal work (Harper and Licata 2007) and the canonical version of the system introduced in (Honsell et al. 2013). Indeed, all the proofs follow the standard patterns used in those papers. The only remark-worthy differences w.r.t. the approach of (Harper and Licata 2007) are the need to take care of the lock and unlock constructors and the fact that we drop the subordination relation from the typing system, taking the strongest one as implicit (for the details, see Section 2.4 of (Harper and Licata 2007)).

We start by studying the basic properties of hereditary substitution and the type system. First of all, we need to assume that the predicates are well-behaved in the sense of Definition 1 (Honsell et al. 2013). In the context of canonical systems, this notion needs to be rephrased as follows:

**Definition 2.1 (Well-behaved predicates for canonical systems).**

A finite set of predicates \(\{P_i\}_{i\in I}\) is well-behaved if each \(P\) in the set satisfies the following conditions, provided all the judgements involved are valid:

1. **Closure under signature and context weakening and permutation:**
   - (a) If \(\Sigma\) and \(\Omega\) are valid signatures such that \(\Sigma \subseteq \Omega\) and \(P(\Gamma \vdash_{\Sigma} N \Leftarrow \sigma)\), then \(P(\Gamma \vdash_{\Omega} N \Leftarrow \sigma)\).
   - (b) If \(\Gamma\) and \(\Delta\) are valid contexts such that \(\Gamma \subseteq \Delta\) and \(P(\Gamma \vdash_{\Sigma} N \Leftarrow \sigma)\), then \(P(\Delta \vdash_{\Sigma} N \Leftarrow \sigma)\).

2. **Closure under hereditary substitution:** If \(P(\Gamma, x:\sigma', \Gamma' \vdash_{\Sigma} N \Leftarrow \sigma)\) and \(\Gamma \vdash_{\Sigma} N' \Leftarrow \sigma'\), then \(P(\Gamma, \Gamma'[N'/x]_{(\sigma')} \vdash_{\Sigma} N[N'/x]_{(\sigma')} \Leftarrow \sigma[N'/x]_{(\sigma')}\).

As canonical systems do not feature reductions, the “classical” third constraint for well-
behaved predicates (closure under reduction) is not needed here. Moreover, the second condition (closure under substitution) becomes “closure under hereditary substitution”.

Lemma 2.1 (Head substitution size).
If $A[M_0/x_0]_{t_0}^O = M:\rho$, then $\rho$ is a subexpression of $\rho_0$.

Proof. The proof proceeds by induction on the derivation of $A[M_0/x_0]_{t_0}^O = M:\rho$. Hence, the applicable rules are $(S\cdot O\cdot \text{Var} \cdot H)$, $(S\cdot O\cdot \text{App} \cdot H)$, and $(S\cdot O\cdot \text{Unlock} \cdot H)$. The only difference w.r.t. (Harper and Licata 2007) is represented by the latter case, where, by induction hypothesis, we have that $\mathcal{L}_{F_\rho \cdot t_\rho}[\rho]$ is a subexpression of $\rho_0$, whence also $\rho$ is a subexpression of $\rho_0$. □

Lemma 2.2 (Uniqueness of substitution and synthesis).

1. It is not possible that $A[M_0/x_0]_{t_0}^O = A'$ and $A[M_0/x_0]_{t_0}^O = M:\rho$.
2. For any $T$ in any category $t \in \{K, F_a, F, O_a, O\}$, if $T[M_0/x_0]_{t_0}^O = T'$, and $T[M_0/x_0]_{t_0}^O = T''$, then $T' = T''$.
3. If $\Gamma \vdash_{\Sigma} A \Rightarrow \sigma$, and $\Gamma \vdash_{\Sigma} A \Rightarrow \sigma'$, then $\sigma = \sigma'$.
4. If $\Gamma \vdash_{\Sigma} \alpha \Rightarrow K$, and $\Gamma \vdash_{\Sigma} \alpha \Rightarrow K'$, then $K = K'$.

Proof. These claims follow directly from the definition of hereditary substitution (see Figures 4 and 5) and the $\mathbf{CLLF}_\rho$ type system (see Figure 2). □

So far, we can state and prove the following lemma about the decidability of hereditary substitution:

Lemma 2.3 (Decidability of hereditary substitution).

1. For any $T$ in $\{K, F_a, F, O_a, O\}$, and any $M$, $x$, and $\rho$, it is decidable whether there exists a $T'$ such that $T[M/x]_{t_0}^O = T'$ or there is no such $T'$.
2. For any $M$, $x$, $\rho$, and $A$, it is decidable whether there exists an $A'$, such that $A[M/x]_{t_0}^O = A'$, or there exist $M'$ and $\rho'$, such that $A[M/x]_{t_0}^O = M' : \rho'$, or there are no such $A'$ and $M'$.

Proof. This is the lemma for which erasure to simple types (Figure 3) plays a crucial role. As in (Harper and Licata 2007), the proof proceeds first with a mutual lexicographic induction on the simple type $\rho$, the terms $M$ and $A$, and an order allowing inductive calls to clauses for atomic terms from clauses of canonical terms (when, of course, the terms and the simple types involved are the same), in order to prove claim 1 for canonical terms (i.e., $T \in \mathcal{O}$) and claim 2. Then, another induction on $M$ is carried out to prove the remaining clauses of the first part about $F$, $F_a$, $K$, and $O$.

Lemma 2.4 (Composition of hereditary substitution). Let $x \neq x_0$ and $x \notin \text{Fv}(M_0)$. Then:

1. For all $T_1$ in $\{K, F_a, F, O_a, O\}$, if we have that $M_2[M_0/x_0]_{t_0}^O = M'_2$, $T_1[M_2/x]_{t_2}^O = T'_1$, and $T_1[M_0/x_0]_{t_0}^O = T'_1$, then there exists a $T$: $T_1'[M_0/x_0]_{t_0}^O = T$, and $T_1'[M_2/x]_{t_2}^O = T$.
2. If $M_2[M_0/x_0]_{t_0}^O = M'_2$, $A_1[M_2/x]_{t_2}^O = M : \rho$, and $A_1[M_0/x_0]_{t_0}^O = A$, then there exists an $M'$: $M[M_0/x_0]_{t_0}^O = M'$, and $A[M_2/x]_{t_2}^O = M' : \rho$. □
3 If 

\[ M_2[M_0/x_0]^\rho_0 = M'_2, A_1[M_2/x]^\rho_2 = A, \text{ and } A_1[M_0/x_0]^\rho_0 = M : \rho, \]

then there exists an \( M' : A[M_0/x_0]^\rho_0 = M' : \rho, \text{ and } M[M_2/x]^\rho_2 = M' \).

**Proof.** These claims are proved following the same pattern of (Harper and Licata 2007), by means of mutual induction on \( \text{size}(\rho_0) + \text{size}(\rho_2) \) and on the derivation of the substitution of \( M_2 \) (where \( \text{size}(a) = 1 \) and \( \text{size}(\rho_1 \rightarrow \rho_2) = 1 + \text{size}(\rho_1) + \text{size}(\rho_2) \)).

Then, by induction on derivations, similar to the one in (Harper and Licata 2007) p.14–15, we can prove:

**Theorem 2.5 (Transitivity).** Let \( \Sigma \), \( \Gamma, x_0 : \rho_0, \Gamma' \) and \( \Gamma' \vdash \Sigma M_0 \equiv \rho_0 \), and assume that all predicates are well-behaved. Then,

1. There exists a \( \Gamma'' : \Gamma'[M_0/x_0]^{\rho_0} = \Gamma'' \) and \( \vdash \Sigma \), \( \Gamma, \Gamma'' \).
2. If \( \Gamma, x_0 : \rho_0, \Gamma'' \vdash \Sigma K \) then there exists a \( K' : [M_0/x_0]^{\rho_0} K = K' \) and \( \Gamma, \Gamma'' \vdash \Sigma K' \).
3. If \( \Gamma, x_0 : \rho_0, \Gamma'' \vdash \Sigma \sigma \text{ type} \), then there exists a \( \sigma' : [M_0/x_0]^{\rho_0} \sigma = \sigma' \) and \( \Gamma, \Gamma'' \vdash \Sigma \sigma' \text{ type} \).
4. If \( \Gamma, x_0 : \rho_0, \Gamma'' \vdash \Sigma M \equiv \sigma, \Gamma, x_0 : \rho_0, \Gamma'' \vdash \Sigma M' \equiv \sigma \).

**Theorem 2.6 (Decidability of typing).** If predicates in \( \text{CLLF}_\mathcal{P} \) are decidable, then all of the judgements of the system are decidable.

**Proof.** By induction on the complexity of judgements we reconstruct derivations when possible. The only cases which differ from the proof in (Honsell et al. 2013) are those regarding the rules (\( F\)-Nested-UnLock) and (\( O\)-Nested-UnLock), and (\( F\)-Lock) and (\( O\)-Lock) (see Figure 2). We proceed as outlined before in discussing the weak form of syntax directedness of the system. Namely rules (\( F\)-Lock) and (\( O\)-Lock) are inverted only when the arguments to the locks are \( U^F_{\mathcal{P}}[\cdot] \)-free. This excludes the possibility of reconstructing derivations which lock terms with the predicate \( \mathcal{P} \) which have subterms of the shape \( U^F_{\mathcal{P}}[\cdot] \), when we already know the predicate \( \mathcal{P} \) to hold, i.e. we have used already rule (\( O\)-Unlock). It is immediate to check that such proofs do not restrict the class of derivable judgments. Similarly, when we have to choose a suitable \( A \) in rules (\( F\)-Nested-UnLock) and (\( O\)-Nested-UnLock), we inspect \( M' \) searching for all the occurrences of subterms of the shape \( U^F_{\mathcal{P}}[A] \), and we choose any \( A \) which is itself \( U^F_{\mathcal{P}}[\cdot] \)-free, say the leftmost in \( M' \). This provides a principled deterministic procedure, which does not require any back-tracking. It is tedious but straightforward to check that the proofs which are excluded do not extend the class of derivable judgments.

Notice that in case the predicates \( \mathcal{P} \) are only semidecidable then the same argument in the above proof yields that the system \( \text{CLLF}_\mathcal{P} \) is semidecidable.

We can now state precisely the relationship between \( \text{CLLF}_\mathcal{P} \) and the system \( \text{LLF}_\mathcal{P} \) in (Honsell et al. 2013). We assume the reader familiar with (Honsell et al. 2013). First, we need to introduce the natural erasure function \( \mathcal{E} \) which removes types from \( \lambda \) abstractions, and turns terms of the form \( \mathcal{L}^F_{\mathcal{P},n}[M] \) into \( \mathcal{L}^F_{\mathcal{P}}[M] \) and \( U^F_{\mathcal{P},n}[M] \) into \( U^F_{\mathcal{P}}[M] \). The function \( \mathcal{E} \) is defined in the obvious way and extends to all syntactic categories.

**Definition 2.2 (Erasure function).** The erasure function \( \mathcal{E} \) maps terms of \( \text{LLF}_\mathcal{P} \) (in
Church-style) into the corresponding terms of $\mathsf{CLLF}_P$ (in Curry-style) as follows:

\[
\begin{align*}
\mathcal{E}(c) &= c \\
\mathcal{E}(x) &= x \\
\mathcal{E}(MN) &= \mathcal{E}(M) \mathcal{E}(N) \\
\mathcal{E}(\lambda x.\sigma. M) &= \lambda x. \mathcal{E}(M) \\
\mathcal{E}(\mathcal{L}_{N,\sigma}[M]) &= \mathcal{L}_{\mathcal{E}(N),\mathcal{E}(\sigma)}[\mathcal{E}(M)] \\
\mathcal{E}(\mathcal{U}_{N,\sigma}[M]) &= \mathcal{U}_{\mathcal{E}(N),\mathcal{E}(\sigma)}[\mathcal{E}(M)]
\end{align*}
\]

Then, $\mathcal{E}$ is naturally extended to type families, kinds, signatures and contexts as follows:

\[
\begin{align*}
\mathcal{E}(a) &= a \\
\mathcal{E}(\Pi x.\sigma. \tau) &= \Pi x. \mathcal{E}(\sigma), \mathcal{E}(\tau) \\
\mathcal{E}(\sigma.N) &= \mathcal{E}(\sigma) \mathcal{E}(N) \\
\mathcal{E}(\mathcal{L}_{N,\sigma}[\tau]) &= \mathcal{L}_{\mathcal{E}(N),\mathcal{E}(\sigma)}[\mathcal{E}(\tau)] \\
\mathcal{E}(\text{type}) &= \text{type} \\
\mathcal{E}(\Pi x.\sigma. K) &= \Pi x. \mathcal{E}(\sigma), \mathcal{E}(K) \\
\mathcal{E}(\Sigma, a; K) &= \mathcal{E}(\Sigma), a. \mathcal{E}(K) \\
\mathcal{E}(\Sigma, c; \sigma) &= \mathcal{E}(\Sigma), c. \mathcal{E}(\sigma) \\
\mathcal{E}(\Gamma, x; \sigma) &= \mathcal{E}(\Gamma), x. \mathcal{E}(\sigma)
\end{align*}
\]

Next, we introduce the crucial notion of a judgement in long $\beta\eta\mathcal{UL}$-normal form ($\beta\eta\mathcal{UL}$-lnf).

**Definition 2.3.** An occurrence $\xi$ of a constant or a variable in a term of an $\mathsf{LLF}_P$ judgement is **fully applied and unlocked** w.r.t. its type or kind $\Pi x: \sigma. \tau, \mathcal{L}_1[\ldots], \mathcal{L}_n[\alpha][\ldots]$, where $\mathcal{L}_1, \ldots, \mathcal{L}_n$ are vectors of locks, if $\xi$ appears only in contexts that are of the form $\mathcal{U}_n[\ldots(\mathcal{U}_1[\mathcal{M}_1]\ldots)\mathcal{M}_n]$, where $\mathcal{M}_1, \ldots, \mathcal{M}_n, \mathcal{U}_1, \ldots, \mathcal{U}_n$ have the same arities of the corresponding vectors of $\Pi$'s and locks.

**Definition 2.4 (Judgements in long $\beta\eta\mathcal{UL}$-normal form).**

1. A term $T$ in a judgement of $\mathsf{LLF}_P$ is in $\beta\eta\mathcal{UL}$-lnf if $T$ is in normal form and every constant and variable occurrence in $T$ is fully applied and unlocked w.r.t. its typing in the judgement.
2. A judgement is in $\beta\eta\mathcal{UL}$-lnf if all terms appearing in it are in $\beta\eta\mathcal{UL}$-lnf.

The concept of a “judgement in $\beta\eta\mathcal{UL}$-lnf” is based on the idea of inverting the standard $\eta$-rule. This is made precise in the following theorem. First we introduce the following two notions of reduction:

\[
\begin{align*}
M \rightarrow_{\eta\text{-long}} \lambda x.\sigma. M x & \quad \text{provided both } M \text{ and } \lambda x.\sigma. M x \text{ are in } \beta\text{-normal form;} \\
M \rightarrow_{\mathcal{L}_\text{long}} \mathcal{L}_{\mathcal{E}(N),\mathcal{E}(\sigma)}[\mathcal{U}_{\mathcal{E}(N),\mathcal{E}(\sigma)}[M]] & \quad \text{provided } M \text{ and } \mathcal{L}_{\mathcal{E}(N),\mathcal{E}(\sigma)}[\mathcal{U}_{\mathcal{E}(N),\mathcal{E}(\sigma)}[M]] \text{ are in } \mathcal{UL}\text{-normal form.}
\end{align*}
\]

**Theorem 2.7.** Let $J$ be a valid judgement in $\mathsf{LLF}_P$. Then, there exists a unique valid judgement $J'$ in $\beta\eta\mathcal{UL}$-lnf such that all terms appearing in $J'$ are $\beta\eta\mathcal{UL}_\text{long}$-reducts of the corresponding terms in $J$.

Theorem 2.7 above is proved by induction on the derivation of judgments in $\beta\mathcal{UL}$-normal form in $\mathsf{LLF}_P$, once the full power of Subject Reduction in $\mathsf{LLF}_P$ has been used
to obtain the “normal form” of a judgement $J$. Actually, Theorem 2.7 yields a function which maps each term $T$ of a valid judgment to its “$\beta\mu\eta_{long}-long-normal$ form” $T^\sharp$.

We are now ready to prove the two fundamental theorems:

**Theorem 2.8 (Soundness).** For any well-behaved predicate $P$ of $\text{CLLF}_P$, we define a corresponding predicate $P'$ in $\text{LLF}_P$ as follows: $P'(\Gamma \vdash_\Sigma M : \sigma)$ holds if and only if $\Gamma \vdash_\Sigma M : \sigma$ is derivable in $\text{LLF}_P$ and $P(E(\Gamma') \vdash_{E(\Sigma')} E(M') \leftarrow E(\sigma'))$ holds in $\text{CLLF}_P$.

Then we have:

1. If $\Sigma\text{ sig}$ is $\text{CLLF}_P$-derivable, then there exists a unique $\Sigma'$, such that $\Sigma'$ sig is $\text{LLF}_P$-derivable and $E(\Sigma') = \Sigma$.
2. If $\vdash_\Sigma \Gamma$ is $\text{CLLF}_P$-derivable, then there exist unique $\Sigma'$, $\Gamma'$, such that $\vdash_\Sigma \Gamma'$ is $\text{LLF}_P$-derivable, and $E(\Sigma') = \Sigma$ and $E(\Gamma') = \Gamma$.
3. If $\Gamma \vdash_\Sigma K$ is $\text{CLLF}_P$-derivable, then there exist unique $\Sigma'$, $\Gamma'$, and $K'$, such that $\Gamma' \vdash_\Sigma K'$ is $\text{LLF}_P$-derivable, and $E(\Sigma') = \Sigma$, $E(\Gamma') = \Gamma$, and $E(K') = K$.
4. If $\Gamma \vdash_\Sigma \alpha \leftarrow K$ is $\text{CLLF}_P$-derivable, then there exist unique $\Sigma'$, $\Gamma'$, $K'$, and $\alpha'$, such that $\Gamma' \vdash_\Sigma \alpha' : K'$ is $\text{LLF}_P$-derivable, and $E(\Sigma') = \Sigma$, $E(\Gamma') = \Gamma$, $E(K') = K$, and $E(\alpha') = \alpha$.
5. If $\Gamma \vdash_\Sigma \sigma$ type is $\text{CLLF}_P$-derivable, then there exist unique $\Sigma'$, $\Gamma'$, and $\sigma'$, such that $\Gamma' \vdash_\Sigma \sigma'$ type is $\text{LLF}_P$-derivable, and $E(\Sigma') = \Sigma$, $E(\Gamma') = \Gamma$, and $E(\sigma') = \sigma$.
6. If $\Gamma \vdash_\Sigma A \Rightarrow \sigma$ is $\text{CLLF}_P$-derivable, then there exist unique $\Sigma'$, $\Gamma'$, $\sigma'$, and $A'$, such that $\Gamma' \vdash_\Sigma A'$ : $\sigma'$ is $\text{LLF}_P$-derivable, and $E(\Sigma') = \Sigma$, $E(\Gamma') = \Gamma$, $E(\sigma') = \sigma$, and $E(A') = A$.
7. If $\Gamma \vdash_\Sigma M \Leftarrow \sigma$ is $\text{CLLF}_P$-derivable, then there exist unique $\Sigma'$, $\Gamma'$, $\sigma'$, and $M'$, such that $\Gamma' \vdash_\Sigma M' : \sigma'$ is $\text{LLF}_P$-derivable, and $E(\Sigma') = \Sigma$, $E(\Gamma') = \Gamma$, $E(\sigma') = \sigma$, and $E(M') = M$.

**Proof.** The proof proceeds by a lengthy, but ultimately straightforward mutual induction on the structure of the $\text{CLLF}_P$ derivations.

**Theorem 2.9 (Correspondence).** For any well-behaved predicate $P$ in $\text{LLF}_P$, in the sense of Definition 1 (Honsell et al. 2013) we define a corresponding predicate $P'$ in $\text{CLLF}_P$ such that $P'(E(\Gamma) \vdash_{E(\Sigma)} E(M) \leftarrow E(\sigma))$ holds if $E(\Gamma) \vdash_{E(\Sigma)} E(M) \leftarrow E(\sigma)$ is derivable in $\text{CLLF}_P$ and $P'(\Gamma \vdash_\Sigma M : \sigma)$ holds in $\text{LLF}_P$. Then we have:

1. If $\Sigma\text{ sig}$ is in $\beta\eta\mu\nu\mathcal{L}$-lnf and is $\text{LLF}_P$-derivable, then $E(\Sigma)$ sig is $\text{CLLF}_P$-derivable.
2. If $\vdash_\Sigma \Gamma$ is in $\beta\eta\mu\nu\mathcal{L}$-lnf and is $\text{LLF}_P$-derivable, then $E(\Sigma)$ $\text{CLLF}_P$-derivable.
3. If $\Gamma \vdash_\Sigma K$ is in $\beta\eta\mu\nu\mathcal{L}$-lnf, and is $\text{LLF}_P$-derivable, then $E(\Gamma) \vdash_{E(\Sigma)} E(K)$ is $\text{CLLF}_P$-derivable.
4. If $\Gamma \vdash_\Sigma \alpha : K$ is in $\beta\eta\mu\nu\mathcal{L}$-lnf, except for possibly the head variable/constant of $\alpha$ which is not fully applied, and is $\text{LLF}_P$-derivable, then $E(\Gamma) \vdash_{E(\Sigma)} E(\alpha)$ $\Rightarrow E(K)$ is $\text{CLLF}_P$-derivable.
5. If $\Gamma \vdash_\Sigma \sigma$ type is in $\beta\eta\mu\nu\mathcal{L}$-lnf and is $\text{LLF}_P$-derivable, then $E(\Gamma) \vdash_{E(\Sigma)} E(\sigma)$ type is $\text{CLLF}_P$-derivable.
6. If $\Gamma \vdash_\Sigma A : \alpha$ is in $\beta\eta\mu\nu\mathcal{L}$-lnf, except for possibly the head variable/constant of $A$ which is not fully applied, and is $\text{LLF}_P$-derivable, then $E(\Gamma) \vdash_{E(\Sigma)} E(A) \Rightarrow E(\alpha)$ is $\text{CLLF}_P$-derivable.
7 If $\Gamma \vdash \Sigma M : \sigma$ is in $\beta\eta\mathcal{UL}$-lnf and is $\text{LLF}_P$-derivable, then $\mathcal{E}(\Gamma) \vdash_{\mathcal{E}(\Sigma)} \mathcal{E}(M) \equiv \mathcal{E}(\sigma)$ is $\text{CLLF}_P$-derivable.

**Proof.** The strategy follows closely the one used in the proof of the similar Correspondence Theorem 5.11 in (Honsell et al. 2013), where all items are proved by mutual induction on the complexity of the judgement, where the complexity of a judgement is given by the sum of symbols appearing in it, provided that the complexity of the symbols type and 0 is 1, the complexity of a constant/variable is 2, the complexity of the symbol $\mathcal{U}$ is greater than the complexity of $\mathcal{L}$, and the complexity of the subject of the judgement is the sum of the complexities of its symbols plus the complexity of the normal form of the type of each subterm of the subject, derived in the given context and signature.

We illustrate in full detail the subcase of point 7, when the $\text{LLF}_P$-derivable judgement is $\Gamma \vdash \Sigma \mathcal{L}^p_{S,\sigma}[M]:\theta$. By inspecting the typing rules of $\text{LLF}_P$, we have that $\theta \equiv \mathcal{L}^p_{S',\sigma'}[\rho]$, where $S=_{\beta\eta\mathcal{UL}} S'$ and $\sigma=_{\beta\eta\mathcal{UL}} \sigma'$. Moreover, since the judgement is in $\beta\eta\mathcal{UL}$-lnf, we have that $S \equiv S'$ and $\sigma \equiv \sigma'$. Thus, if neither $M$ nor $\rho$ have subterms of the shape $\mathcal{U}^p_{S,\sigma}[\_]$, we can proceed like in the proof of the analogous Correspondence Theorem of (Honsell et al. 2013). Otherwise, we have that the original introduction rule for our judgement must be $(\Box\text{-GuardedUnlock})$. In that case, there must be a term $M'$ such that $M \equiv M'[^p_{S',\sigma'}][N]/x$ and $\rho \equiv \rho'[^p_{S',\sigma'}][N]/x$ with $S=_{\beta\eta\mathcal{UL}} S''$ and $\sigma=_{\beta\eta\mathcal{UL}} \sigma''$, but it must be that $S \equiv S''$ and $\sigma \equiv \sigma''$, since the judgement is in $\beta\eta\mathcal{UL}$-lnf. Hence, we also have that $\Gamma, x : \tau \vdash \Sigma \mathcal{L}^p_{S,\sigma}[M']:\mathcal{L}^p_{S,\sigma}[\rho']$ and $\Gamma \vdash \Sigma N : \mathcal{L}^p_{S,\sigma}[\tau]$, both judgements in $\beta\eta\mathcal{UL}$-lnf.

By applying the induction hypothesis to the last two judgments, we obtain that $\mathcal{E}(\Gamma), x.\mathcal{E}(\tau) \vdash_{\mathcal{E}(\Sigma)} \mathcal{L}^p_{\mathcal{E}(\Sigma),\mathcal{E}(\sigma)}[\mathcal{E}(M')] \equiv \mathcal{L}^p_{\mathcal{E}(\Sigma),\mathcal{E}(\sigma)}[\mathcal{E}(\rho')]$ and also that $\mathcal{E}(\Gamma) \vdash_{\mathcal{E}(\Sigma)} \mathcal{E}(N) \equiv \mathcal{L}^p_{\mathcal{E}(\Sigma),\mathcal{E}(\sigma)}[\mathcal{E}(\tau)]$ in $\text{CLLF}_P$. Since the latter judgement can only be derived from the rule $(\Box\text{-Atom})$, we also have that $\mathcal{E}(\Gamma) \vdash_{\mathcal{E}(\Sigma)} \mathcal{E}(N) = \mathcal{L}^p_{\mathcal{E}(\Sigma),\mathcal{E}(\sigma)}[\mathcal{E}(\tau)]$ holds in $\text{CLLF}_P$. Now we may apply the rule $(\Box\text{-NestedUnlock})$\footnote{Notice that the extra clause of rule $(\Box\text{-NestedUnlock})$, namely the occurrence of $x$ in either $\mathcal{E}(M')$ or $\mathcal{E}(\rho')$, is granted by the fact that all judgments are in $\beta\eta\mathcal{UL}$-lnf and we are reasoning under the assumption that either $M$ or $\rho$ are not $\mathcal{U}^p_{S,\sigma}[\_]$-free.} to obtain $\mathcal{E}(\Gamma) \vdash_{\mathcal{E}(\Sigma)} \mathcal{L}^p_{\mathcal{E}(\Sigma),\mathcal{E}(\sigma)}[\mathcal{E}(M')][\mathcal{L}^p_{\mathcal{E}(\Sigma),\mathcal{E}(\sigma)}[\mathcal{E}(N)]]/x \equiv \mathcal{L}^p_{\mathcal{E}(\Sigma),\mathcal{E}(\sigma)}[\mathcal{E}(\rho')][\mathcal{L}^p_{\mathcal{E}(\Sigma),\mathcal{E}(\sigma)}[\mathcal{E}(N)]]/x$, which is equivalent to $\mathcal{E}(\Gamma) \vdash_{\mathcal{E}(\Sigma)} \mathcal{E}(\mathcal{L}^p_{\mathcal{E}(\Sigma),\mathcal{E}(\sigma)}[M]) \equiv \mathcal{E}(\mathcal{L}^p_{\mathcal{E}(\Sigma),\mathcal{E}(\sigma)}[\rho]), \text{ i.e., the thesis.}$

So far we do not know yet that the two predicates $P'$ defined in the above Soundness and Correspondence Theorems are well-behaved predicates in $\text{LLF}_P$ and $\text{CLLF}_P$ respectively. This is established in the following:

**Theorem 2.10.** The predicate $P'$ defined in Theorem 2.8 is well-behaved in the sense of Definition 2.1 (Honsell et al. 2013), and the predicate $P'$ defined in Theorem 2.9 is well-behaved in the sense of Definition 2.1.

**Proof.** There is a logical chiasm here. Theorem 2.8 is used to prove that the predicate $P'$ in Theorem 2.9 is well-behaved, whereas Theorem 2.9 is used to prove that the predicate $P'$ in Theorem 2.8 is well-behaved. \hfill $\square$
Plugging-in Proof Development Environments using Locks in LF

\[
\begin{align*}
\Sigma & \in \mathcal{S} \quad \Sigma ::= \emptyset \mid \Sigma, a : K \mid \Sigma, e : \sigma & \text{Signatures} \\
\Gamma & \in \mathcal{C} \quad \Gamma ::= \emptyset \mid \Gamma, x : \sigma & \text{Contexts} \\
K & \in \mathcal{K} \quad K ::= \text{type} \mid \Pi x. \sigma.K & \text{Kinds} \\
\alpha & \in \mathcal{A} \quad \alpha ::= a \mid \alpha N & \text{Atomic Families} \\
\sigma, \tau, \rho & \in \mathcal{F} \quad \sigma ::= \alpha \mid \Pi x. \tau \mid \mathcal{L}^p_\sigma[\rho] & \text{Canonical Families} \\
A & \in \mathcal{A}_A \quad A ::= c \mid x \mid A.M \mid \mathcal{U}_N[A] & \text{Atomic Objects} \\
M, N & \in \mathcal{O} \quad M ::= A \mid \lambda x. M \mid \mathcal{L}^p_\sigma[M] & \text{Canonical Objects}
\end{align*}
\]

Fig. 6. CLLF\(_P\) Syntax

3. The Logical Framework CLLF\(_P\)

The main idea behind CLLF\(_P\) (see Figures 6, 7, and 8) is to “empower” the framework of CLLF\(_P\) by adding to the lock/unlock mechanism the possibility to receive from the external oracle a witness satisfying suitable constraints. Thus, we can pave the way for plugging-in proof development environments beyond proof irrelevance scenarios. In this context, the lock constructor behaves as a binding operator. The new (O-Lock) rule is the following:

\[
\frac{\Gamma, x : \sigma \vdash \Sigma \quad M \leftarrow \rho}{\Gamma \vdash \Sigma \quad \mathcal{L}^p_\sigma[M] \leftarrow \mathcal{L}^p_\sigma[\rho]}
\]

where the variable \(x\) is a placeholder bound in \(M\) and \(\rho\), which will be replaced by the concrete term that will be returned by the external oracle call. The intuitive meaning behind the (O-Lock) rule is, therefore, that of recording the need to delegate to the external oracle the inference of a suitable witness of a given type. Indeed, \(M\) can be thought of as an “incomplete” term which needs to be completed by an inhabitant of a given type \(\sigma\) satisfying the constraint \(\mathcal{P}\). The actual term, possibly synthesized by the external tool, will be “released” in CLLF\(_P\), by the unlock constructor in the (O-UnLock) rule as follows:

\[
\frac{\Gamma \vdash \Sigma \quad A \Rightarrow \mathcal{L}^p_\sigma[\rho] \quad \rho[N/x]^{\mathcal{F}}_{\sigma} = \rho' \quad \Gamma \vdash \Sigma \quad N \Leftarrow \sigma \quad \mathcal{P}(\Gamma \vdash \Sigma \quad N \Leftarrow \sigma)}{\Gamma \vdash \Sigma \quad \mathcal{U}_N[A] \Rightarrow \rho'}
\]

The term \(\mathcal{U}_N[A]\) intuitively means that \(N\) is precisely the synthesized term satisfying the constraint \(\mathcal{P}(\Gamma \vdash \Sigma \quad N \Leftarrow \sigma)\) that will replace all the free occurrences of \(x\) in \(\rho\). This replacement is executed in the (S-O-UnLock-H) hereditary substitution rule (Figure 8).

Similarly to CLLF\(_P\), it is possible also in CLLF\(_P\) to “postpone” or delay the verification of an external predicate in a lock, provided an outermost lock is present. Whence, the synthesis of the actual inhabitant \(N\) can be delayed, thanks to the (F-Nested-UnLock) and (O-Nested-UnLock) rules, see Figure 7.

The Metatheory of CLLF\(_P\) follows closely that of CLLF\(_P\) as far as decidability. We do not state a Correspondence Theorem since we did not introduce a non-canonical version of CLLF\(_P\). This could have been done similarly to CLLF\(_P\).
### Signature rules

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>$\emptyset \vdash \Sigma$</td>
<td>$(S-Empty)$</td>
</tr>
<tr>
<td>$\Sigma \vdash K, a \notin \text{Dom}(\Sigma)$</td>
<td>$(S-Kind)$</td>
</tr>
<tr>
<td>$\Sigma, a: K \vdash$</td>
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</tr>
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### Kind rules

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<tr>
<td>$\vdash_\Sigma \Gamma$</td>
<td>$(K-Type)$</td>
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<tr>
<td>$\vdash_\Sigma \Pi x: \sigma.K$</td>
<td>$(K-Pi)$</td>
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### Atomic Family rules

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<tr>
<td>$\vdash_\Sigma \Gamma, \alpha: K \in \Sigma$</td>
<td>$(A-Const)$</td>
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<tr>
<td>$\Gamma \vdash_\Sigma \alpha \Rightarrow \Pi x: \sigma.K_1$</td>
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</tr>
<tr>
<td>$\Gamma \vdash_\Sigma M \Leftarrow \sigma$</td>
<td></td>
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<tr>
<td>$K_1[M/x]_{\sigma^-} = K$</td>
<td>$(A-App)$</td>
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<td>$\Gamma \vdash_\Sigma \alpha M \Rightarrow K$</td>
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</table>

### Canonical Family rules

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<td>$\vdash_\Sigma \Gamma \Rightarrow \alpha \Rightarrow \text{type}$</td>
<td>$(F-Atom)$</td>
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<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \Pi x: \sigma.\tau \Rightarrow \text{type}$</td>
<td>$(F-Pi)$</td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \Pi x: \sigma.\tau \Rightarrow \text{type}$</td>
<td>$(F-Lock)$</td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \text{Nested-Unlock}$</td>
<td></td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td></td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td></td>
</tr>
<tr>
<td>$\rho[U^\sigma_\varepsilon[A]/y]_{\epsilon^-} = \rho'$</td>
<td>$x \in \text{Fv}(\rho)$</td>
</tr>
</tbody>
</table>

### Context rules

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\vdash_\Sigma \Gamma \vdash_\Sigma \sigma \Rightarrow \text{type}$</td>
<td></td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \vdash_\Sigma \sigma \Rightarrow \text{type}$</td>
<td></td>
</tr>
</tbody>
</table>

### Atomic Object rules

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td>$(O-Const)$</td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td>$(O-Var)$</td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td>$(O-App)$</td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td>$(O-Unlock)$</td>
</tr>
</tbody>
</table>

### Canonical Object rules

<table>
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<th>Rule</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td>$(O-Atom)$</td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td>$(O-Abs)$</td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td>$(O-Lock)$</td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td>$(O-Nested-Unlock)$</td>
</tr>
<tr>
<td>$\vdash_\Sigma \Gamma \Rightarrow \varepsilon \Rightarrow \text{type}$</td>
<td></td>
</tr>
</tbody>
</table>

---

Fig. 7. The CLLF$_{F\pi}$ Type System
Substitution in Canonical Families

Substitution in Atomic Objects

Substitution in Canonical Objects

Fig. 8. CLLF P, Hereditary Substitution: changes w.r.t. CLLF P

4. Benchmarking the Frameworks

In order to illustrate the advantages of CLLF P, we show how to encode logical systems featuring rules which constrain severely the shape of proofs. Constraints may concern the “shape” or the “number” of assumptions in proofs, as in Modal Logic or Light Linear Logic, (Girard 1998; Baillot et al. 2007); the very “form” of proofs as in Fitch-Prawitzconsistent Set-Theory (FPST), (Prawitz 1965), or in logics with proof-functional connectives (Pottinger 1980; Barbanera and Martini 1994); dynamic aspects of terms, as in restricted $\lambda$-calculi. Standard LF encodings of these systems are very obscure because of the machinery necessary for rendering these “side conditions”. On the other hand CLLF P and CLLF P can capitalize on locks, thus permitting to structure the encodings and factor out naturally such complexities.

The crucial step in encoding a logical system in CLLF P or CLLF P is the definition of the predicates involved in locks in such a way that they are well-behaved. Predicates defined on closed terms are usually unproblematic. The difficulties arise from enforcing the properties of closure under hereditary substitution and closure under signature and context extension, when predicates are defined on open terms. To be able to streamline the definition of well-behaved predicates we introduce the following definition:

**Definition 4.1.** Given a signature $\Sigma$, let $\Lambda_{\Sigma}$ (respectively, $\Lambda_{\Sigma}^{c}$) be the set of CLLF P terms (respectively, closed CLLF P terms) definable using constants from $\Sigma$. A skeleton for the term $M$ is a term $N[x_1, \ldots, x_n] \in \Lambda_{\Sigma}$, all whose free variables (called holes of the skeleton) are in $\{x_1, \ldots, x_n\}$, such that $M \equiv N[M_1/x_1, \ldots, M_n/x_n]$ for suitable terms $M_1, \ldots, M_n$.

It is intuitive that properties referring only to the skeleton of a given term are invariant under substitution.
4.1. Elementary Affine Logic

In this section we give a shallow encoding of Elementary Affine Logic as presented in (Baillot et al. 2007). “Shallow” in this context means that we delegate to the meta-language as much as possible. This example needs to deal with two problematic side conditions. The first, which arises also in modal logic, concerns “rules of proof”, i.e., rules whose premises depend on no assumptions. The second is the constraint that an assumption can occur at most once. We will exemplify how locks can express these global syntactic constraints on the proof of the premises occurring in the promotion rule (Prom) of Elementary Affine Logic.

Definition 4.2 (Elementary Affine Logic (Baillot et al. 2007)). Elementary Affine Logic can be specified by the following rules:

\[
\begin{align*}
\frac{}{A \vdash_{EAL} A} & \quad (\text{Var}) \\
\frac{\Gamma, A \vdash_{EAL} B}{\Gamma \vdash_{EAL} A \rightarrow B} & \quad (\text{Weak}) \\
\frac{\Gamma \vdash_{EAL} A}{\Gamma, A \vdash_{EAL} A} & \quad (\text{Abst}) \\
\frac{\Delta \vdash_{EAL} A \rightarrow B}{\Gamma, \Delta \vdash_{EAL} B} & \quad (\text{Appl}) \\
\frac{\Gamma \vdash_{EAL} A \rightarrow B}{\Gamma, \Delta \vdash_{EAL} B} & \quad (\text{Prom}) \\
\end{align*}
\]

Definition 4.3 (CLLF signature \( \Sigma_{EAL} \) for Elementary Affine Logic). The following constants are introduced:

\[
\begin{align*}
o & : \text{Type} \\
\rightarrow & : o \rightarrow \text{Type} \\
\neg & : o \rightarrow o \\
! & : o \\
\end{align*}
\]

\[
\begin{align*}
c_{\text{appl}} & : \Pi A, B : o. \text{T}(A) \rightarrow \text{T}(A \rightarrow B) \rightarrow \text{T}(B) \\
c_{\text{abstr}} & : \Pi A, B : o. \Pi x : (\text{T}(A) \rightarrow \text{T}(B)) \rightarrow \text{L}_{x,T(A),T(B)}^{\text{Light}}[\text{T}(A \rightarrow B)] \\
c_{\text{promV}_1} & : \Pi A, B : o. \Pi x : (\text{T}(A) \rightarrow \text{T}(B)) \rightarrow \text{L}_{x,T(A),T(B)}^{\text{Closed}}[\text{T}(A) \rightarrow \text{T}(B)] \\
c_{\text{promV}_2} & : \Pi A, B : o. \text{V}(A) \rightarrow \text{T}(!A) \rightarrow \text{V}(B)
\end{align*}
\]

where \( o \) is the type of propositions, \( \neg \) and \( ! \) are the obvious syntactic constructors, \( T \) is the basic judgement, and \( \text{V}(\cdot) \) is an auxiliary judgement. The predicates involved in the locks are defined as follows:

- \( \text{Light}(\Gamma \vdash_{\Sigma_{EAL}} x \ll T(A) \rightarrow T(B)) \) holds iff \( A \) is not of the shape \( !A \) then the bound variable of \( x \) occurs at most once in the normal form of \( x \).
- \( \text{Closed}(\Gamma \vdash_{\Sigma_{EAL}} x \ll T(A)) \) holds iff \( x \) has a skeleton whose free variables are only of type \( o \), i.e., no variables of type \( T(B) \), for any \( B : o \).

A few remarks are mandatory. The promotion rule in (Baillot et al. 2007) is in effect a family of natural deduction rules with a growing number of assumptions. Our encoding achieves this via the auxiliary judgement \( \text{V}(\cdot) \), which permits to mimic stepwise the application of the promotion rule, as it is illustrated in the following schema (for the sake
of readability and simplicity we drop the lock notation):

\[
T(A_1) \rightarrow \ldots \rightarrow T(A_n) \rightarrow T(A) \quad \text{(first hypothesis of the promotion rule on paper)}
\]
\[
T(A_1) \rightarrow T(A_2) \rightarrow \ldots \rightarrow T(A_n \rightarrow A) \quad \text{(via an application of } \text{c_abstr)}
\]
\[
\vdots
\]
\[
T(A_1 \rightarrow (A_2 \rightarrow \ldots \rightarrow (A_n \rightarrow A) \ldots )) \quad \text{(via } n \text{-applications of } \text{c_abstr)}
\]
\[
T(!A_1) \rightarrow V(A_2 \rightarrow \ldots \rightarrow V(A_n \rightarrow V(A)) \quad \text{(via an application of } \text{c_promV}_1)
\]
\[
\vdots
\]
\[
T(!A_1) \rightarrow T(!A_2) \rightarrow \ldots \rightarrow T(!A_n) \rightarrow V(A) \quad \text{(via } n \text{-applications of } \text{c_promV}_2)
\]
\[
T(!A_1) \rightarrow T(!A_2) \rightarrow \ldots \rightarrow T(!A_n) \rightarrow T(A) \quad \text{(via an application of } \text{c_val)}
\]

Hence, starting from the hypothesis that \( T(A) \) follows from \( T(A_1), \ldots, T(A_n) \) (first hypothesis of the promotion rule of the object logic) and knowing that \( T(!A_1), \ldots, T(!A_n) \) also hold (the remaining hypotheses of the promotion rule), we can infer that \( T(A) \) holds (conclusion of the promotion rule). Notice that only after the last step we have fully represented the intended semantics of the promotion rule. Of course at each step where \( \text{c_abstr}, \text{c_promV}_1, \) and \( \text{c_promV}_2 \) are applied one must verify the constraints imposed by the corresponding locks. They are not shown explicitly in the above derivation sketch for the sake of readability.

Adequacy for this signature can be achieved only in the format of (Honsell et al. 2013), namely:

**Theorem 4.1 (Adequacy for Elementary Affine Logic).** if \( A_1, \ldots, A_n \) are the atomic formulas occurring in \( B_1, \ldots, B_m, A \), then \( B_1 \ldots B_m \vdash_{EAL} A \) iff there exists \( M \) and \( A_1:o, \ldots, A_n:o, x_1:T(B_1), \ldots, x_m:T(B_m) \vdash_{\Sigma_{EAL}} \forall \in T(A) \) (where \( \forall \) and \( \exists \) represent the encodings of, respectively, \( A \) and \( B \) in \( \text{CLLF}_P \), for \( 1 \leq i \leq m \)) and all variables \( x_1 \ldots x_n \) occurring more than once in \( M \) have type of the shape \( T(B_i) \equiv T(!C_i) \) for some suitable formula \( C_i \).

The check on the context of the Adequacy Theorem is *external* to the system \( \text{CLLF}_P \), but this is in the nature of results which relate *internal* and *external* concepts. For example, the very concept of \( \text{CLLF}_P \) context, which appears in any adequacy result, is external to \( \text{CLLF}_P \). Of course, this check is internalized if the term is closed.

### 4.2. Fitch Set Theory à la Prawitz - FPST

In this section, we present the encoding of a formal system of remarkable logical, as well as historical, significance namely the system of consistent Naïve Set Theory, introduced by Fitch (Fitch 1952). Since Naïve Set Theory à la Cantor is inconsistent, Fitch’s idea was to prevent the derivation of inconsistencies from the unrestricted *abstraction* rule, by restricting the rules of the system to premises which are the conclusions of *normalizable deductions*. Fitch system was presented in Natural Deduction style by Prawitz (Prawitz 1965), with some modifications and improvements. Normalizable proofs in this setting are defined as usual, namely all elimination rules come before the introduction rules in all the principal branches of the proof.
Fitch-Prawitz Set Theory, FPST, is therefore a rather intriguing, albeit unexplored, set theoretic system. Of course, some intuitive rules are not derivable. For instance *modus ponens* does not hold and if \( t \in \lambda x. A \) then we do not have necessarily that \( A[t/x] \) holds. Similarly, the *transitivity* of implication does not hold. However FPST is a very expressive type system which “encompasses” many kinds of quantification, provided normalization is preserved. Moreover Fitch has shown, see *e.g.* (Fitch 1952), that a large portion of ordinary Mathematics can be carried out in FPST.

In principle, the normalizability side-condition in Fitch-Prawitz system can be captured in LF, but only very deeply. Hence, that encoding becomes extremely cumbersome and obscure, and hence it violates the *de Bruijn simplicity criterion*, making the proof of adequacy less “reliable”. See (Honsell 2015) for more discussions on this point. An encoding in CLLF\(_P\), on the other hand, factors out the machinery for enforcing the side-condition, breaking the task into a number of more elementary steps.

The encoding of the global constraint of normalizability of a proof in FPST at rule-application time, illustrates beautifully the *bag of tricks* that CLLF\(_P\) supports. Checking that a proof term is normalizable would be the obvious predicate to use in the corresponding lock-type, but this would not be a well-behaved predicate if free variables, *i.e.* assumptions, could be freely replaced. We need to sterilize them, *i.e.* make them behave as axioms in the proof. To this end, we introduce a distinction between generic judgements, which cannot appear as conclusions of rule applications, but which can be *assumed* and *discharged*, and apodictic judgements, which are directly involved in proof rules. In order to make use of generic judgements, one has to downgrade them to an apodictic one. This is achieved by a suitable coercion function. Once the distinction between judgments has been made, in Adequacy Theorems we consider only terms whose free judgement variables are of the generic type. No apodictic assumptions can be made at all.

For simplicity, here we only give the crucial rules for implication and for *set-abstraction*, and the corresponding elimination rules, of the system of Fitch (see (Prawitz 1965)), as presented by Prawitz. The full system of FPST, together with its encoding, and an extensive model-theoretic study of that system appear in (Honsell et al. 2016).

**Definition 4.4 (Fitch Prawitz Set Theory, FPST).** The critical rules of FPST are the following:

\[
\begin{align*}
\Gamma, A \vdash_{FPST} B & \quad \Gamma \vdash_{FPST} A \supset B \quad (\supset I) \\
\Gamma \vdash_{FPST} A[T/x] & \quad \Gamma, T \in \lambda x. A \quad (\lambda I) \\
\end{align*}
\]

\[
\begin{align*}
\Gamma \vdash_{FPST} A & \quad \Gamma \vdash_{FPST} A \supset B \quad (\supset E) \\
\Gamma \vdash_{FPST} T \in \lambda x. A & \quad \Gamma \vdash_{FPST} A[T/x] \quad (\lambda E)
\end{align*}
\]

The intended meaning of the term \( \lambda x. A \) is the set \( \{ x \mid A \} \). In Fitch’s system, FPST, conjunction and universal quantification are defined as usual, while negation is defined constructively, but it still allows for the usual definitions of disjunction and existential quantification. What makes FPST *consistent* is that not all standard deductions in FPST are legal. A *legal deduction* in FPST is defined, as a standard deduction which is *normalizable* in the usual sense of Natural Deduction, namely it can be transformed in a derivation where all elimination rules occur before introductions.
In the following definition we introduce the signature encoding the rules of FPST given above.

**Definition 4.5 (CLLFₚ signature Σ_{FPST} for Fitch Prawitz Set Theory).** The following constants are introduced:

\[
\begin{align*}
o & : \text{Type} \\
l &: \text{Type} \\
V & : o \to \text{Type} \\
\lambda_{\text{intro}} : \Pi A : o. (V(A) \to T(A)) \\
\lambda_{\text{elim}} : \Pi A : o. \Pi x : \epsilon(T(A) \times \epsilon(lam A)) \to T(\epsilon \times (lam A)) \\
\epsilon & : l \to o \to l \\
\sigma_{\text{intro}} : \Pi A, B : o. (V(A) \to T(B)) \to (T(A \supset B)) \\
\supset & : o \to o \to o \\
\epsilon_{\text{elim}} & : \Pi A, B : o. \Pi x : T(A). \Pi y : T(A \supset B) \to \lambda^{\text{Fitch}}_{\langle x, y \rangle, T(A) \times T(A \supset B)}[T(B)]
\end{align*}
\]

where \( o \) is the type of propositions, \( \supset \) and the “membership” predicate \( \epsilon \) are the syntactic constructors for propositions, \( \lambda_{\text{intro}} \) is the “abstraction” operator for building “sets”, \( T \) is the apodictic judgement, \( \delta \) is the coercition function, and \( (x, y) \) denotes the encoding of pairs, whose type is denoted by \( \sigma \times \tau \), e.g. \( \lambda x : \sigma \to \tau \to \rho. \ u x y : (\sigma \to \tau \to \rho) \to \rho \). The predicate in the lock is defined as follows:

\[
\text{Fitch}(\Gamma \vdash_{\Sigma_{\text{FPST}}} (x, y) \iff T(A) \times T(A \supset B))
\]

holds iff \( x \) and \( y \) have skeletons in \( \Lambda_{\Sigma_{\text{FPST}}} \), all the holes of which have either type \( o \) or are guarded by a \( \delta \), and hence have type \( V(A) \), and, moreover, the proof derived by combining the skeletons of \( x \) and \( y \) is normalizable in the natural sense. Clearly, this predicate is only semidecidable.

The rules concerning the other logical operators, which are not given here, are encoded using only the apodictic judgement \( T(\cdot) \). The notion of **normalizable proof** is the standard notion used in natural deduction. The predicate \( \text{Fitch} \) is well-behaved because it considers terms only up-to holes in the skeleton, which can have either type \( o \) or are of generic judgement type and hence cannot be substituted by any term representing a proof which could spoil normalizability. Adequacy for this signature can be achieved in the format of (Honsell et al. 2013):

**Theorem 4.2 (Adequacy for Fitch-Prawitz Naive Set Theory).** If \( A_1, \ldots, A_n \) are the atomic formulas occurring in \( B_1, \ldots, B_m, A \), then \( B_1 \ldots B_m \vdash_{\text{FPST}} A \) iff there exists a normalizable \( M \) such that \( A_1 : o, \ldots, A_n : o, x_1 : V(B_1), \ldots, x_m : V(B_m) \vdash_{\Sigma_{\text{FPST}}} M \iff T(A) \) (where \( A \) and \( B_i \) represent the encodings of, respectively, \( A \) and \( B_i \) in \( \text{CLLF}_p \), for \( 1 \leq i \leq m \)).

In (Honsell et al. 2016) we have given several applications of the theory FPST. In particular we have shown that a strong Fixed Point Theorem holds, which permits to define inductive sets, i.e. types. Interestingly there is a natural inductive definition of the set \( \Lambda \) of \( \lambda \)-terms to which only normalizable terms belong. Since deriving that a term belongs to a set in FPST amounts to typing a term, this definition is implicitly a typing system for \( \lambda \)-terms which types only normalizing terms. The reason is that there is a natural reflection of the metatheoretic normalizability of the FPST derivation of the typing judgement \( M \in \Lambda \) and the fact that the term represented by \( M \) is indeed normalizable! The reader should refer to (Honsell et al. 2016) for more details.
4.3. A Normalizing call-by-value $\lambda$-calculus

In order to illustrate further how to deal with free variables in defining well-behaved predicates, in this section we sketch how to express in $\text{CLLF}_P$ a call-by-value $\lambda$-calculus where $\beta$-reductions fire only if the operator is normal and delete arguments only if normal, namely

$$(\lambda x.M)N \to M[N/x]$$

provided, $M$ normal and, if $x \notin M$ then $N$ normal.

This calculus is correct w.r.t. the observational semantics defined as follows:

$$M =_i N \iff \forall C. C[M] \Downarrow_i \iff C[N] \Downarrow_i$$

where $P \Downarrow_i$ holds if the leftmost innermost reduction strategy terminates. In this theory, for example, the terms $(\lambda z.((\lambda x.\lambda y.y)(zz))(\lambda x.xx))$ and $(\lambda x.\lambda y.y)((\lambda x.xx)(\lambda x.xx))$ are not equated.

**Definition 4.6 (Normalizing call-by-value $\lambda$-calculus, $\Sigma_{\lambda N}$).** The following constants are introduced:

$$o : \text{Type} \quad \text{Eq : } o \to o \to \text{Type} \quad \text{app : } o \to o \to o$$

$$v : \text{Type} \quad \text{var : } v \to o \quad \text{lam : } (v \to o) \to o$$

$$\text{refl} : \Pi M : o. (\text{Eq } M \ M)$$

$$\text{symm} : \Pi M,N : o. (\text{Eq } N \ M) \to (\text{Eq } M \ N)$$

$$\text{trans} : \Pi M,N,P : o. (\text{Eq } M \ N) \to (\text{Eq } N \ P) \to (\text{Eq } M \ P)$$

$$\text{eq.app} : \Pi M,N,M',N' : o. (\text{Eq } M \ N) \to (\text{Eq } M' \ N') \to (\text{Eq } (\text{app } M \ M')(\text{app } N \ N'))$$

$$\text{c.beta} : \Pi M : o \to o, N : o. \text{C}^\text{P}M_\text{eq}(\langle M,N \rangle, \langle o \to o \rangle, o) \times o [\text{Eq } (\text{app } (\text{lam } \lambda x : v. M(\text{var } x)) \ N) \ (M N)]$$

$$\text{csiv} : \Pi M,N : (v \to o). (\Pi x : v. (\text{Eq } (M x)(N x))) \to (\text{Eq } (\text{lam } M)(\text{lam } N))$$

where the predicate $\text{P}^\text{M}$ holds on $\Gamma \vdash_{\Sigma_{\lambda N}} \langle M, N \rangle \subseteq (o \to o) \times o$ if both $M$ and $N$ have skeletons in $\Lambda_{\Sigma_{\lambda N}}$ whose holes are guarded by a var (to prevent applications to non-normalizing terms of type $o$) and, moreover, $M$ is “normal” and if $x \notin M$ then $N$ is “normal”, where “normal” is intended in the natural sense.

Notice the role of $v$, which is akin to that of generic judgements in the FPST. Open terms are encoded by terms whose free variables are all of type $v$. All this is made explicit in the following adequacy result for this signature, which can be achieved only in the format of (Honsell et al. 2013), namely:

**Theorem 4.3 (Adequacy for Normalizing call-by-value $\lambda$-calculus).** if $v_1, \ldots, v_n$ are the variables occurring in $A_1, B_1, \ldots, A_m, B_m, A, B$, then

$$A_1 =_{\lambda v_1} B_1, \ldots, A_m =_{\lambda v_m} B_m \vdash_{\lambda N} A =_{\lambda} B$$

iff there exists $M$ and $v_1 : v, \ldots, v_n : v$ such that

$$v_1 : v, \ldots, v_n : v, x_1 : \text{Eq } A_1, B_1, \ldots, x_n : \text{Eq } A_n, B_n \vdash_{\Sigma_{\lambda N}} M \subseteq \text{Eq } A B$$
4.4. Square roots of natural numbers in $\text{CLLF}_{P?}$

In this section we give a general method for a straightforward encoding of function evaluation in $\text{CLLF}_{P?}$ encompassing even partial functions. It is well-known that logical frameworks based on Constructive Type Theory do not permit the latter, because all the expressible functions in such frameworks are total. On the other hand in $\text{CLLF}_{P?}$ we have the possibility of reasoning on function evaluation by delegating their computation to external oracles, and getting back their possible outputs, via the lock-unlock mechanism of $\text{CLLF}_{P?}$.

We briefly outline how to define numerical functions. Consider the usual representation of natural numbers by means of a constant $0$ representing zero and the symbol $S$ representing the successor, and constants for the classical arithmetical operations $+$ and $\ast$, and a predicate $\text{eval}$ to express evaluation. Thus we have the signature:

$$\begin{align*}
nat & : \text{type} \\
0 & : \text{nat} \\
S & : \text{nat}\rightarrow\text{nat} \\
\text{plus} & : \text{nat}\rightarrow\text{nat}\rightarrow\text{nat} \\
\text{minus} & : \text{nat}\rightarrow\text{nat}\rightarrow\text{nat} \\
\text{mult} & : \text{nat}\rightarrow\text{nat}\rightarrow\text{nat} \\
\text{eval} & : \text{nat}\rightarrow\text{nat}\rightarrow\text{type}
\end{align*}$$

In order to encode the evaluation of arithmetical expressions on natural numbers to the corresponding results (e.g., to establish the derivation that a term with type $(\text{eval} (\text{mult} (S (S 0)) (S (S 0))) (S (S (S (S 0))))$ evaluates to $4$) in plain LF we would need a number of suitable rule constants of appropriate type $\text{eval}$, which mimic the evaluation algorithm. In $\text{CLLF}_{P?}$ we can instead simply introduce the single constant

$$\text{multiply} : \Pi x : \text{nat}, y : \text{nat}. \text{L}_{\text{nat}\rightarrow\text{nat}}[(\text{eval} (\text{mult} x y) z)]$$

where the external predicate $M(\Gamma, x : \text{nat}, y : \text{nat} \vdash \Sigma z \leftarrow \text{nat})$ holds if and only if $z = x \ast y$. The predicate is clearly well-behaved both in the case in which the external tool computes a ground term or a symbolic one, provided the syntax is compatible with $\text{CLLF}_{P?}$.

Remarkably this same principle applies also to partial functions. We give the example of integer square root. Namely we introduce the constant $\text{sqroot} : \text{nat}\rightarrow\text{nat}$, and the corresponding rule:

$$\text{sqrt} : \Pi x : \text{nat}. \text{L}_{\text{nat}\rightarrow\text{nat}}[\text{SORT}]$$

where the external predicate $\text{SORT}(\Gamma, x : \text{nat} \vdash \Sigma y \leftarrow \text{nat})$ holds if and only if $x = y \ast y$ holds. This is precisely the specification of the square root of $x$ in the domain of natural numbers.

Notice that the user does not have to provide “deep” specifications of the computation algorithms for multiplication or square root in the framework $\text{CLLF}_{P?}$. Indeed, their semantics is implicit in the definition of the predicates $M$ and $\text{SORT}$, which rely entirely on the external oracle. A single rule constant is enough in all cases.

This example highlights the flexibility of $\text{CLLF}_{P?}$ in incorporating uniformly the effects of executing external code. Of course, this can be a specialized software performing the computation very efficiently. But the approach is beneficial especially in avoiding to spell out in detail the formalization of the execution of complicated, possibly non-terminating, symbolic procedures.
5. Related work and Future Perspectives

Building a universal proof metalanguage where different tools and formalisms can be “plugged in” and “glued together” is a long standing goal that has been extensively explored in a vast and inspiring literature on Logical Frameworks by (Barthe et al. 2003; Pfenning and Schürmann 1999; Watkins et al. 2002; Schack-Nielsen and Schürmann 2008; Cousineau and Doye 2007; Boespflug et al. 2012; Nanevski et al. 2008; Pientka et al. 2008; Pientka et al. 2010; Honsell et al. 2007; Honsell et al. 2012; Honsell 2013; Wang and Chaudhuri 2015; Battel and Felty 2015). Recent work by Chicani et al. on FPC (Chihani et al. 2015; Chihani and Miller 2016; Blanco et al. 2017) and Dedukti (Cousineau and Doye 2007; Boespflug et al. 2012) is very promising. Our approach follows the tradition of generic proof languages and proof development environments and tries to stick to the spirit of De Bruijn’s minimality criterion, in that the reliability of each system is independently established. In our approach, the logical engine of the metalanguage has to be very simple, in order to be reliable as much as possible. This, however, must not prevent us from using more sophisticated tools to streamline the proof development. In our approach we achieve this by calling external tools. The responsibility for the validity of the proof certificates produced by the external tools, in any case, remains with them. If we do not trust the external tools, we can always check the proof certificates which they produced at a later moment, separately, and possibly once and for all. But the Lock mechanism allows us also to reason “up-to” external certificates, thus reducing the number of necessary external calls. On a somewhat related ground, in recent years new proof attitudes have been considered which support e.g. optimistic concurrency vs pessimistic concurrency, fast and loose programming and reasoning, as in delayed termination checking (Danielsson et al. 2006; Casinghino et al. 2014). These proof attitudes rely on heuristics, which means that if, but only if, we have reached a point that we deem significant, we go back and thoroughly check whether the evidence which has been assumed is indeed available or reliable. CLLF can support this proof attitude. Locks, in this case, do the bookkeeping. The approach in (Chihani et al. 2015; Chihani and Miller 2016; Blanco et al. 2017) is somewhat complementary to ours, allowing for exporting proof certificates, but more work needs to be done for a thorough comparison of the two approaches.

The clear-cutting monadic structure and properties of the lock/unlock mechanism of our system go back to Moggi’s notion of computational monads (Moggi 1989). Our system can be seen as a generalization, to a family of dependent lax operators, of Moggi’s partial λ-calculus (Moggi 1988) and of the work carried out in (Fairtlough and Mendler 1997; Mendler 1991) (which is also the original source of the term “lax”). A correspondence between lax modalities and monads in functional programming was pointed out also in (Alechina et al. 2001; Garg and Tschantz 2008). On the other hand, although the connection between constraints and monads in logic programming was considered in the past, e.g., in (Nanevski et al. 2008; Fairtlough et al. 1997; Fairtlough and Mendler 2001), to our knowledge, our systems are the first attempts to establish a clear correspondence between side conditions and monads in a higher-order dependent-type theory. And this has a clear bearing on logical frameworks.
Locks do not add any logical power “per se” to LF provided the external tools can be encoded in LF. Locks are valuable especially in structuring signatures, and hence in suggesting what to factor out and delegate to external modules. Clearly, if the predicates are not decidable, decidability of the system is lost.

Of course, there are a lot of interesting points of contact with other systems in the literature which should be explored further. For instance, in (Nanevski et al. 2008), the authors introduce a contextual modal logic, where the notion of context is rendered by means of monadic constructs. We only point out that, as we did in our system, they could have also simplified their system by doing away with the let construct in favor of a deeper substitution.

Schröder-Heister has discussed in a number of papers, see e.g. (Schroeder-Heister 2012b; Schroeder-Heister 2012a), various restrictions and side conditions on rules and on the nature of assumptions that one can add to logical systems to prevent the arising of paradoxes. There are some potential connections between his work and ours, which should be explored. It would be interesting to compare his requirements on side conditions being “closed under substitution” to our notion of well-behaved predicate. Similarly, there are commonalities between his distinction between specific and unspecific variables, and our treatment of free variables in well-behaved predicates and the distinction between generic and apodictic judgements. The system LFSC, presented in (Stump 2008; Stump et al. 2012), is more reminiscent of our approach as “it extends LF to allow side conditions to be expressed using a simple first-order functional programming language”. Indeed, the author factors the verifications of side-conditions out of the main proof. The task is delegated to the type checker, which runs the code associated with the side-condition, verifying that it yields the expected output. The proposed machinery is focused on providing improvements for SMT solvers.

Practical implementations of CLLF and especially CLLF need to be experimented with. Moreover, it would be important to develop the possibility of introducing and capitalizing on a logical algebra of well-behaved predicates. For instance, it would be interesting to compare CLLF with the system Why3 (Filliâtre 2013), in the field of program verification based on Hoare’s Logic.

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References


