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Binders Unbound

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Binders Unbound

Abstract
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Disciplines
Computer Sciences

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Abstract
Implementors of compilers, program refactorers, theorem provers, proof checkers, and other systems that manipulate syntax know that dealing with name binding is difficult to do well. Operations such as $\alpha$-equivalence and capture-avoiding substitution seem simple, yet subtle bugs often go undetected. Furthermore, their implementations are tedious, requiring “boilerplate” code that must be updated whenever the object language definition changes.

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Categories and Subject Descriptors D.2.3 [Coding Tools and Techniques]; D.1.1 [Applicative (Functional) Programming]; E.1 [Data Structures]

General Terms Algorithms, Languages.

Keywords generic programming, Haskell, name binding, patterns

1. Introduction
Name binding is one of the most annoying parts of language implementations. Although functional programming languages such as Haskell and ML excel at the implementation of type checkers, compilers, and interpreters, there is an impedance mismatch between the free structure provided by algebraic datatypes and the syntax identified up to $\alpha$-equivalence that we actually want to model. Although there are many techniques for implementing name binding, they require subtle invariants that pervade the system. Implementation flaws cause bugs that are difficult to track down. Furthermore, the implementations themselves are tedious, requiring boilerplate that must be maintained as the implemented language evolves. While such boilerplate is straightforward, it causes friction for developers who just want to get the job done.

And all this work is for something so “obvious” that it is often elided from language definitions!

There has been much research towards solving this problem. Recently introduced languages and tools provide primitive support for variable-binding, based on first-order \cite{6, 22, 30, 31} and higher-order representations \cite{18, 20}. These tools handle the details behind the scenes, relieving programmers of the tedium and subtle bugs described above. However, these tools must also satisfy the practical needs of programmers, and here they fall short:

Expressiveness: These tools provide binding specification languages that specify what variables are bound where. As unary lexical scoping (binding a single variable in a single location) is not sufficient for many applications, many of these tools support a language for patterns in binding specifications. Despite this flexibility, it is still not enough—there are patterns that we would like to use that cannot be defined by existing specification languages.

Availability: Programmers want to write code in their language, and they want to do it directly. Tools that are wrappers for existing languages are preferred to completely new systems, but such tools still require update with each new version of the language. Libraries are more stable and have the added benefit of simple distribution, some degree of portability and familiar syntax.

Choice of implementations: These tools each provide only one implementation for any given binding specification. However, name binding involves a number of different operations and some implementations may favor one over the other. Programmers should be able to swap out implementations (or write their own) if they find one that works better with their application.

In this paper, we present a new domain-specific language, UNBOUND, for specifying binding structure that addresses these issues. Concretely, our contributions are as follows:

- We describe a small, compositional set of abstract combinators which form the entire basis for UNBOUND. This interface succinctly characterizes our specification language.
- We show, via examples (§ 2, § 3), that UNBOUND is nonetheless expressive. In particular, it supports multiple atom types,
pattern binders, type annotations, recursive binders, and nested binders. The last are necessary to model telescopes and are not supported by any existing specification language.

• We give a formal semantics for our specification language (§ 4) based on a locally nameless representation and prove its correctness (§ 5). Our choice of representation leads to a simple semantics and straightforward metatheory. Alternative meanings are also possible; the simplicity of ours makes it a good reference for more sophisticated implementations.

• We have implemented our framework as a Haskell library (§ 6), using Haskell’s generic programming support to automatically derive standard operations. Our library is available for download from Hackage,1 along with extensive documentation and examples. (Note GHC 7 is required.)

Although UNBOUND is designed for object language implementation, this specification language and semantics are also appropriate for formal object language reasoning. That application is beyond the scope of this paper; we discuss the connections to mechanized metatheory in § 8 and § 9.

2. The UNBOUND Specification Language

We begin with a simple UNBOUND specification.2 Functional programmers are accustomed to using algebraic datatypes to specify the abstract syntax of a programming language. UNBOUND introduces type combinators that encode binding structure into the algebraic datatype itself. For example, to represent the untyped lambda calculus, we use the E datatype below:

```haskell
data E = Var N | Lam (Bind N E) | App E E
```

The abstract type Name (provided by UNBOUND) represents variables, and is indexed by the type of values which can be substituted for them (here, E). For convenience, we define N as a synonym for Name E. Lambda abstractions are represented using the type Bind N E, indicating a name paired with an expression in which the name is bound. Application does not involve binding, so it is simply a pair of E values as expected.

UNBOUND uses this datatype definition to derive standard operations for working with syntax, such as α-equivalence, free variable calculation, and capture-avoiding substitution. For example, suppose we want to implement parallel reduction for untyped lambda calculus terms. This operation looks throughout a term for β- and η-reductions, even under lambda abstractions, transforming it into a simpler form. An implementation is shown in Figure 1. The signatures for the UNBOUND-derived operations that this code relies on are at the top of the figure. All of these functions are automatically derived by UNBOUND.

The function red has three cases. (Note that the Fresh constraint on m also implies a Monad constraint, enabling the use of do-notation.) The Var case is trivial. The Lam case must handle the possibility of η-reduction, so we must break the lambda into its two constituent parts—its bound variable, and its body. Note that the type Bind N E is abstract, so we cannot use pattern matching to extract its components. Instead, the monadic unbind operation decomposes the binding, ensuring that the name x does not conflict with other names currently in scope.

```haskell
red :: Fresh m ⇒ (Bind N E) → m (N, E)
```

Figure 1. Parallel reduction for E

<table>
<thead>
<tr>
<th>T ∈ T</th>
<th>Name T</th>
<th>Names for Ts</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Regular datatype containing only terms</td>
<td></td>
</tr>
<tr>
<td>Bind P T</td>
<td>Bind pattern P in body T</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>P ∈ P</th>
<th>Name T</th>
<th>Single binding name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rp</td>
<td>Regular datatype containing only patterns</td>
<td></td>
</tr>
<tr>
<td>Embed T</td>
<td>Embedded term (§ 3.1)</td>
<td></td>
</tr>
<tr>
<td>Rebind P P</td>
<td>Nested binding pattern (§ 3.2)</td>
<td></td>
</tr>
<tr>
<td>Rec P</td>
<td>Recursive binding pattern (§ 3.3)</td>
<td></td>
</tr>
</tbody>
</table>

3. Beyond single binding

A key feature of UNBOUND is that programmers are not limited to binding a single variable at a time. Instead, the bind con-

---

1 http://hackage.haskell.org/package/unbound/
2 While our examples are presented in Haskell, using our Haskell library, the examples themselves are language neutral.
constructor takes a pattern containing variables and abstracts over all of them. A large class of types may be used as patterns. As a simple example, lists of names are patterns. If we wanted to allow the syntax \(\lambda x \ y \ z \to \ldots\) as a convenient shorthand for \(\lambda x \to \lambda y \to \lambda z \to \ldots\), where \(x\), \(y\), and \(z\) are distinct names,\(^3\) we could change our definition of \(E\) to the following:

\[
\text{data } E = \text{Var } N \\
| \text{Lam } (\text{Bind } [N] E) \\
| \text{App } E E
\]

In general, UNBOUND uses two sorts of types: those that may be used as \(\text{patterns}\), where names are binding occurrences, and those that are \(\text{terms}\), where names are references to binding sites. Figure 2 summarizes these two classes, written \(P\) and \(T\) respectively. The Bind type combinator takes a pattern type as its first argument and a term type as its second argument and returns a term type. Other term types include Name (representing free variables) and regular datatypes—those built using unit, base types, sums, products, and least fixpoint—that contain only term types. By convention, we use the metavariable \(P\) for pattern types and \(T\) for term types.

The expressiveness of UNBOUND is determined by \(P\), the collection of types that can be used as patterns. These types include Names, of course, as well as regular datatypes that contain only other pattern types. This means that some types, such as \(\text{Int}\) and \(\text{String}\), can be used as both terms and patterns. We describe the three remaining UNBOUND pattern combinators (Embed, Rebind and Rec) in more detail in the next subsections.

As a more sophisticated example of pattern binding, consider adding pattern matching to the \(E\) language with a case statement. Each branch is encoded as \(\text{Bind } Pat\ E\), where \(Pat\) is a new datatype representing object-language patterns. Every name occurring in a \(Pat\) will be bound in the respective body.

\[
\text{data } Pat = PV\text{ar } N | \text{PCon String } [Pat] \\
\text{data } E = \ldots \\
| \text{Con String } [E] \quad \text{-- data constructors} \\
| \text{Case } E \ [\text{Bind } Pat\ E] \quad \text{-- pattern matching}
\]

It is not hard to check that \(Pat\) is a valid pattern type (since it contains only Names and Strings), justifying its use as the first argument to Bind.

3.1 Embedding terms in patterns

In many situations it is convenient to be able to embed terms within patterns. Such embedded terms do not bind variables along with the rest of the pattern. For example, suppose we wanted to extend our \(E\) language with simple let-binding, let \(x=e_1\) in \(e_2\). Here \(e_1\) is bound in \(e_2\) but not in \(e_1\).

A semantically correct encoding puts the \(e_1\) in the abstract syntax before binding \(x\) in \(e_2\), “lifting” \(e_1\) outside the binding so it does not participate.

\[
\text{type } E_1 = E \\
\text{type } E_2 = E \\
\text{data } E = \ldots \\
| \text{Let } E_1 \ (\text{Bind } N\ E_2)
\]

(We use the type synonyms \(E_1\) and \(E_2\) to indicate which sub-terms of \text{Let} correspond to \(e_1\) and \(e_2\).) However, this encoding forces us to write the terms in an unnatural order; moreover, it fails to express the relationship between the name being let-bound and its definition. We can craft a more satisfying solution using the embedding combinator Embed provided by UNBOUND:

\[
\text{data } E = \ldots \\
| \text{Let } (\text{Bind } (N, \text{Embed } E_1)\ E_2)
\]

Embed may only occur within pattern types, where it serves as an “escape hatch” for embedding terms which do not bind any names. Note that a term type within an Embed may itself contain pattern types (inside the left-hand side of Bind) which may contain Embedded term types, and so on.

This formulation with Embed also enables us to extend our let expressions to multiple bindings, by using a pattern list:

\[
\text{data } E = \ldots \\
| \text{Let } [E] \ (\text{Bind } [N]\ E)
\]

Without Embed, we could encode this binding specification by “unzipping” the list of name-definition pairs and lifting the definitions outside of the Bind:

\[
\text{data } E = \ldots \\
| \text{Let } [E] \ (\text{Bind } [N]\ E)
\]

But this example is even worse than the corresponding encoding of let with a single binding. Not only does it force us to use an unnatural order and fail to encode the relationship between names and their respective definitions, it also admits “junk” terms with lists of different lengths. Embed enables an encoding where names and their definitions are paired, as they should be.

3.2 Nested binding

Consider now a let* construct, let* \(x_1=e_1, \ldots, x_n=e_n\) in \(e\), where each \(x_i\) is bound in \(e\) and also in all the \(e_j\) with \(j > i\). One way to encode this pattern is by iterating the encoding for single let bindings discussed above:

\[
\text{data } \text{LetList} = \text{Body } E \\
| \text{Binding } (\text{Bind } (N, \text{Embed } E\ )\ \text{LetList}) \\
\text{data } E = \ldots \\
| \text{LetStar } \text{LetList}
\]

This succeeds in capturing the binding structure of let*, and may be sufficient for some purposes. However, it does have one major drawback: in order to extract the body of the let* expression, we must first recurse through all the bindings. It is more convenient to encode a let* expression by \textit{pairing} a list of bindings and a body, so the body can be accessed without first processing the bindings. As a first try, we could write

\[
\text{data } E = \ldots \\
| \text{LetStar } (\text{Bind } ((N, \text{Embed } E)\ ) E)
\]

but this is just the multiple binding example from the previous subsection. With this specification, the \(x_i\) are bound \textit{only} in the body of the let*, not in the definitions of subsequent variables. We evidently want a way to \textit{nest} additional binding structure within the pattern of the outermost Bind.

UNBOUND provides a novel \textit{rebinding} pattern combinator for precisely this purpose. Rebind \(P_1\ P_2\) acts like the pattern type \((P_1, P_2)\), except that \(P_1\) also scopes over \(P_2\), so the binders in \(P_1\) may be referred to by terms embedded within \(P_2\). (The fact that \(P_1\) scopes over \(P_2\) in this way has no effect on the pattern portion of \(P_2\).) For example, consider the specification

\[
\text{type } N_1 = \text{Name } E \\
\text{type } N_2 = \text{Name } E \\
\text{Bind } (\text{Rebind } N_1 (N_2, \text{Embed } E_1))\ E_2
\]

Here \(N_1\) and \(N_2\) are bound in \(E_2\), and additionally \(N_1\) is also bound within \(E_1\).

Using rebinding, we can faithfully encode the binding structure of let* as follows:
data Let = Nil | Cons (Rebind (N, Embed E) Let)

data E = ... | LetStar (Bind Let E)

All the names within the sequence of definitions are bound in the body of the let* expression (Bind Let E); additionally, each name (paired with its definition as an embedded term) is bound within any Embeds occurring in the remainder of the sequence—that is, within the definitions of subsequent names.

Telescopes A particularly important example of a binding pattern that requires Rebind is a telescope. Telescopes were invented by de Bruijn [9] to model dependently-type systems. They are used frequently in specifications of dependently-typed languages, including Epigram [15] and Agda [17].

A telescope, $\Delta$, is a sequence of variables paired with their types:

$$x_1 : A_1, \ldots, x_n : A_n.$$ 

However, each variable scopes over the types that occur later in the telescope. For example, here $x_1$ may occur in $A_2$, $A_3$, and so on. The name telescope comes from the optical device, which is built as a sequence of segments that slide into one another.

Telescopes are used for "aggregate binding". For example, consider the following (very simple) fragment of a dependently-typed language. In this language, functions can take multiple parameters and be applied to multiple arguments. However, because of dependent types, the type of each parameter is allowed to mention earlier parameters.

$$A, B, M, N ::= x \mid \Pi \Delta. B \mid \lambda \Delta. M \mid M (N_1 \ldots N_n)$$

Telescopes gather together all of the parameters of the function in both its definition ($\lambda \Delta. M$) and its type ($\Pi \Delta. B$). Because telescopes are essentially typing contexts, the typing rule for abstractions merely appends the telescope to the current typing context:

$$\Gamma, \Delta \vdash M : B \quad \Gamma \vdash \lambda \Delta. M : \Pi \Delta. B$$

Type checking the multi-applications requires an auxiliary judgment that determines if the vector of arguments “fits into” the telescope.

$$\Gamma \vdash N_1 : A \Gamma \vdash N_2 \ldots N_n : \Delta[x \mapsto N_1]$$

This judgment verifies that all of the arguments have the right types. Computing the result type of the application requires substituting all of the arguments for each binding variable in the telescope.

$$\Gamma \vdash M : \Pi \Delta. A \Gamma \vdash N_1 \ldots N_n : \Delta$$

$$\Gamma \vdash M(N_1 \ldots N_n) : B[x_1 \ldots x_n \mapsto N_1 \ldots N_n]$$

This fragment demonstrates the important features of telescopes. Sometimes they are used as binding patterns and sometimes they are used as the types of vectors, independent of binding. Implementing this language using traditional unary binding would be tiresome because one would have to traverse the entire telescope to see the body of the function or the body of the dependent type. That is not so much of an issue in this simple example, but the semantics of features like inductive families (with eliminators based on induction principles or dependent pattern matching) is greatly simplified by the aggregate binding that telescopes provide.

In UNBOUND, we can represent the language fragment above using Rebind:

$$\text{data } E = \text{Var } N$$

Furthermore, UNBOUND automatically provides all of the machinery necessary for working with telescopes, including calculation of their binding variables, multiple substitution in terms, and substitution through the telescopes.

3.3 Recursive binding

Our $E$ language is looking nice, but what if we want to add some recursion? We can try to encode a letrec construct,

$$\text{letrec } x_1 = e_1, \ldots, x_n = e_n \text{ in } e,$$

where this time, the $x_i$ are bound in $e$ as well as all the $e_i$. This is straightforward if we are willing to lift all the $x_i$ out to the front:

$$\text{data } E = \ldots$$

$$\quad | \text{Letrec } (\text{Bind } [N] ([E], E))$$

However, the problems with this sort of encoding have already been discussed. We would like to encode letrec in such a way that names and definitions are paired.

Rebind doesn’t help, because it forces us to separate binders from the terms over which they scope, just like Bind. We need a way to freely mix patterns and terms bound by the patterns in the same data structure. UNBOUND provides the Rec combinator for this purpose. In Rec $P$, names in the pattern $P$ scope recursively over any terms embedded in $P$ itself. However, Rec $P$ itself is also a pattern, so names in $P$ also scope externally over any term that binds Rec $P$. Intuitively, Rec is just a “recursive” version of Rebind.

An appropriate encoding of letrec is therefore:

$$\text{data } E = \ldots$$

$$\quad | \text{Letrec } (\text{Bind } (\text{Rec } [(N, \text{Embed } E)]) [E])$$

Here the pattern $[(N, \text{Embed } E)]$ scopes over itself—hence all the names are bound in all the definitions—as well as over the body of the letrec.

4. Semantics

In the previous section, we gave a number of examples of specifying different sorts of binding patterns found in programming languages. However, we have been fairly vague about what those specifications actually mean. In this section, we fill in the details by giving it a semantics.

Our semantics comes in two parts. We first define the representation of syntax with binders, and specify smart constructors and destructors that work with this representation. Second, we define the action of UNBOUND operations ($\alpha$-equivalence, free variable calculation and substitution) in terms of this representation. Once we have formally defined this semantics, we prove that it satisfies the properties we expect (§ 5) and discuss the correspondence between it and our concrete Haskell implementation (§ 6).

4.1 Representation

For simplicity, we use a locally nameless representation of terms with binding structure. This representation provides a straightforward semantics for UNBOUND, one that is both simple to implement and simple to reason about. Using a locally nameless representation is an old idea—we give more details about its history later § 8.

A locally nameless representation of terms with binding structure separates bound variables, represented by de Bruijn indices, from free variables, represented by atoms. (Atoms are often taken to be strings, but any countably infinite set with decidable equality
A ::= {x, y, z, ...}

b ::= j@k

t ::= x | b | K t1 ... t_n | Bind p t

p ::= -x | K p1 ... p_n | Rebind p p | Embed t | Rec p

Figure 3. Syntax of atoms, indices, terms, and patterns

will do.) This representation has the advantage that α-equivalence is simply structural equality. Distinguishing bound variables from free variables in this way also means that we do not need to keep track of the current scope of a free variable and shift it as we move from one scope to another, as we would with a purely de Bruijn-indexed representation.

The locally nameless syntax we use to represent terms with binding structure is shown in Figure 3. As in Figure 2, we separate terms from patterns. Terms t have term types T, whereas patterns have pattern types P.

Names that appear in terms can either be free names, x, or bound names, b. Free names are drawn from the set \(A\) of atoms. (In the interest of simplicity, the semantics we describe here only includes a single sort for atoms; extending to multiple atom sorts is straightforward.) Terms also include applications of constructor constants to zero or more subterms. Note that constructor application covers all terms with some regular type \(R\); in the semantics they are all handled in precisely the same way. Indeed, thanks to generic programming, this is actually a faithful reflection of our Haskell implementation, which handles all data constructors other than the special UNBOUND combinator uniformly.

Like terms, patterns can be formed by the application of constructors to subpatterns. Names inside patterns are binders (\( binders \)), whereas here they are playing the role of placeholders with an associated name.

The astute reader may note that we are punning a bit with our syntax: in earlier examples, Bind and friends showed up as types, whereas here they are playing the role of data. The resolution of the apparent inconsistency is that Bind, Embed, Rebind, and Rec are all singleton types with eponymous constructors.

For example, we can define an operation that lists all of the atoms that a pattern will bind as shown below.

\[
\begin{align*}
 binders :: & P \to [A] \\
 binders \ (K \ p_1 \ldots \ p_n) & = \text{binders }p_1 + \ldots + \text{binders }p_n \\
 binders \ (\text{Rebind }p_1 \ p_2) & = \text{binders }p_1 + \text{binders }p_2 \\
 binders \ (\text{Embed }t) & = \emptyset \\
 binders \ (\text{Rec }p) & = \text{binders }p
\end{align*}
\]

Note that even though we are using Haskell-like syntax, this definition is type-directed. It works for any pattern of any pattern type; the type of \( binders \), \( P \to [A] \), is an abbreviation for \( \forall P : P, P \to [A] \). In our Haskell implementation, to be discussed in more detail in § 6, each clause of a definition such as this one corresponds to a method definition in a type class instance.

4.2 Names, indices and patterns

Bound names \( b \) consist of two natural number indices, \( j@k \). The first index \( j \) references a pattern, counting outwards from zero; the second index \( k \) is an offset. It references a particular binder within the given pattern, counting from left to right, also starting from zero. For example, in

\[
\text{Bind }(-x, -y, -z) \quad \text{(Bind }-q \ 1@2)
\]

the bound variable \( 1@2 \) refers to \(-z\), the index-2 binder within the index-1 enclosing pattern.

Therefore, an important part of this representation is the connection between patterns and offsets. We make this connection precise with the operations \( nth \) and \( find \) (although we omit their definitions in the interest of space):

\[
\begin{align*}
 nth &: P \to \mathbb{N} \to \text{Maybe }A \\
 find &: P \to A \to \text{Maybe }[A]
\end{align*}
\]

\( nth \) takes a pattern and a natural number \( n \) and finds the \( nth \) name bound in that pattern, failing if there are not enough binders. \( find \) takes a pattern and a name and finds the first index of that name in the pattern, failing if the name does not occur.

4.3 Close and open

The two most important operations for the locally nameless representation are close and open. The former is used for binding terms: it converts atoms (i.e. free names) to indices (i.e. bound names). The latter does the reverse, replacing indices that resolve to a particular binding location by free names.

We call the first operation close, as we are closing the term with respect to the free names listed in a pattern. Likewise, we call the inverse operation open, as we may use it to open up a binder in order to recurse through its subcomponents. These two operations are standard components for working with a locally nameless representation [2, 11]. Here we modify them to close and open terms with respect to a pattern instead of a single variable, and also to close and open the terms embedded inside patterns.

The close operation is defined in Figure 4. It takes as input a natural number level, a pattern, and a term, and returns a new term where free variables matching binders in the pattern have been replaced by bound variables at the given level. In the free variable case, it uses find to look for a matching binder and generate the appropriate index if one is found. We also define a version of close for patterns, closp, whose job is to recurse through patterns looking for Embedded terms to which close can be applied. When recursing under a binder (Bind, Rebind, or Rec), both close and closp increment the current level.

The open operation is also defined in Figure 4. It takes a natural number level, a pattern, and a term, and “opens” the term by interpreting bound variables at the given level as references into the pattern, replacing them by the free variable attached to the referenced binder.\(^4\) Similarly to close, open is mutually defined with a pattern version openp. In the case where a bound variable is found which matches the current level, open uses nth to index into the pattern and pick out the free variable associated with the referenced binder.

We use close p t and open p t as convenient synonyms for close 0 p t and open 0 p t, respectively.

4.4 Constructing terms and patterns

Figure 5 lists the smart constructors and destructors that are part of the interface to the type combinators exported by UNBOUND. In

\(^4\) In the locally nameless literature, open is sometimes defined as bound-variable substitution and generalized to replace bound variables with terms instead of with free variables. Such definitions save effort, since the next step after opening is often to substitute for the new free variable. In that case, the definition of open is a little more complex than what is presented here in order to deal with substituting terms with dangling bound variable references. We prefer our reference semantics to be as simple as possible so we avoid such complications.
ables in a term that references both variables will produce indices
effectively this replaces all free occurrences of variables that ap-
the pattern with respect to itself.

the next two subsections, we discuss the implementations of these operations.
we use close to define the constructors for binding abstractions.
closing a term with respect to the pattern binds the pattern variables
in the term.

\[
\text{bind } p t = \text{Bind } p (\text{close } p t)
\]

Effectively, this replaces all free occurrences of variables that appear
in the pattern with indices. For example, binding a pair of variables
in a term that refers to both variables will produce indices that refer to the same pattern, but at different offsets. In contrast, nesting the binders produces indices that refer to different binding locations, but each one at the same offset (the zeroth variable in the pattern).

\[
\text{bind } (-x, -y) (x, y) = \text{Bind } (-x, -y) (\text{close } x, \text{close } y)
\]

Likewise, for pattern combinators that introduce internal binding,
we also use close to replace occurrences of the bound variable
with indices. Note that in the case of recursive binding, we close
the pattern with respect to itself.

\[
\begin{align*}
\text{close} &: \mathbb{N} \rightarrow P \rightarrow T \rightarrow T \\
\text{close } l p b &= b \\
\text{close } l p x &= \text{case find } p x \text{ of} \\
& \quad \text{Just } i \rightarrow \text{close } i p t \\
& \quad \text{Nothing } \\n\text{close } l p (K t_1 \ldots t_n) &= \text{K (close } l p t_1) \ldots \text{ (close } l p t_n) \\
\text{close } l p (\text{Bind } p' t) &= \text{Bind } (l p p') \text{ (close } l p t) \\
\end{align*}
\]

\[
\begin{align*}
\text{closep} &: \mathbb{N} \rightarrow P \rightarrow P \\
\text{closep } l p x &= -x \\
\text{closep } l p (K p_1 \ldots p_n) &= \text{K (closep } l p p_1) \ldots \text{ (closep } l p p_n) \\
\text{closep } l p (\text{Rebind } p_1 p_2) &= \text{Rebind } (l p p_1) \text{ (close } l p t) \\
\text{closep } l p (\text{Rec } p') &= \text{Rec } (l p p') \\
\text{open} &: \mathbb{N} \rightarrow P \rightarrow T \\
\text{open } l p (j@k) | j \equiv l &= \text{case nth } p k \text{ of} \\
& \quad \text{Just } x \rightarrow x \\
& \quad \text{Nothing } \\n\text{open } l p x &= x \\
\text{open } l p (K t_1 \ldots t_n) &= \text{K (open } l p t_1) \ldots \text{ (open } l p t_n) \\
\text{open } l p (\text{Bind } p' t) &= \text{Bind } (\text{open } l p p') \text{ (open } l p t) \\
\text{openp} &: \mathbb{N} \rightarrow P \rightarrow P \\
\text{openp } l p (K p_1 \ldots p_n) &= \text{K (openp } l p p_1) \ldots \text{ (openp } l p p_n) \\
\text{openp } l p x &= -x \\
\text{openp } l p (\text{Rebind } p_1 p_2) &= \text{Rebind } (\text{openp } l p p_1) \text{ (openp } l p t) \\
\text{openp } l p (\text{Rec } p') &= \text{Rec } (\text{openp } l p p')
\end{align*}
\]

\[
\begin{align*}
\text{bind} &\quad P \rightarrow T \rightarrow \text{Bind } P T \\
\text{unbind} &\quad \text{Fresh } m \Rightarrow \text{Bind } P T \rightarrow m (P, T) \\
\text{rebind} &\quad P_1 \rightarrow P_2 \rightarrow \text{Rebind } P_1 P_2 \\
\text{urebind} &\quad \text{Rebind } P_1 P_2 \rightarrow (P_1, P_2) \\
\text{rec} &\quad P \rightarrow \text{Rec } P \\
\text{urec} &\quad \text{Rec } P \rightarrow P \\
\text{embed} &\quad T \rightarrow \text{Embed } T \\
\text{unembed} &\quad \text{Embed } T \rightarrow T
\end{align*}
\]

Figure 4. close and open

\[
\begin{align*}
\text{string2Name} &\quad \text{String } \rightarrow \text{Name } T \\
\text{name2String} &\quad \text{Name } T \rightarrow \text{String }
\end{align*}
\]

\[
\begin{align*}
\text{bind} (\text{Bind } p t) &= \text{do} \\
& \quad p' \leftarrow \text{freshen } p \\
& \quad \text{return } (p', \text{open } p')
\end{align*}
\]

In contrast, the destructors for Rebind and Rec do not freshen
before opening the rest of the pattern. Instead, they use the preex-
isting names:

\[
\begin{align*}
\text{urebind } (\text{Rebind } p_1 p_2) &= (p_1, \text{openp } p_1 p_2) \\
\text{urec } (\text{Rec } p) &= \text{openp } p p
\end{align*}
\]

\[
\begin{align*}
\text{One might wonder: why the difference?}
\end{align*}
\]

When opening a Bind, we must generate fresh names for its
binders. However, by the time we come to opening a nested bind-
ing, fresh names will have already been chosen for its binders when
the enclosing Bind was opened. Hence there is no need to choose
new names. In fact, we must not choose fresh names, since there
may exist corresponding free variables over which we have no con-
tral. For example, consider the term Bind \(\text{Rebind } p_1 p_2 t\), in
which \(t\) may contain references to binders in \(p_1\). If we use \text{unbind}
to take it apart into \text{Rebind } p'_1 p'_2 and \(t'\), there will now be free vari-
able in \(t'\) which match the names on binders in \(p'_1\). Freshening \(p'_1\)
again when opening the Rebind would destroy this connection, and

4.5 Freshening and unbinding

Unbinding is not quite as straightforward as binding. Given a term
Bind \(p t\), it is only safe to call open \(p t\) if none of the binding
variables of \(p\) clash with existing free variables in \(t\). Therefore,
before opening, we must first freshen \(p\) by assigning suitably fresh
names to its binders. At this point, we leave the precise meaning of
“suitably fresh” open to interpretation; some concrete alternatives
are discussed in § 6.4. We omit the formal definition of freshening
since it is straightforward: it simply walks over a pattern, assigning
a suitably fresh name to each binder encountered, and stopping at
occurrences of Embed, since these are not part of the pattern. In
our implementation, freshening also returns a permutation which
describes how the variables were renamed, but we omit that here.

We can now define unbind as the operation that freshens the
binding variables in the pattern and then opens the body of the binder
with the new pattern.

\[
\begin{align*}
\text{unbind } (\text{Bind } p t) &= \text{do} \\
& \quad p' \leftarrow \text{freshen } p \\
& \quad \text{return } (p', \text{open } p')
\end{align*}
\]

Finally, embed does not need to do any closing, and merely ap-
plies the Embed constructor to the given term. Likewise, unembed
merely returns the nested term.

\[
\begin{align*}
\text{embed } t &= \text{Embed } t \\
\text{unembed } (\text{Embed } t) &= t
\end{align*}
\]
in particular would mean that we could not reassemble the original term using \texttt{rebind} and \texttt{bind}. This is also why we must have \texttt{Bind} and \texttt{Rebind} as distinct combinators: if we used \texttt{Bind} everywhere, \texttt{unbind} would have no way of knowing whether it was opening a top-level \texttt{Bind} (which must first be freshened) or a nested one (which must not be).

4.6 Free variables, \(\alpha\)-equivalence and substitution

Now we come to the real payoff of our representation, as we specify the basic \texttt{Unbind} operations of \(\alpha\)-equivalence, free variable calculation, and capture-avoiding substitution, all shown in Figure 6. Their specifications are entirely straightforward—and, as described in the next section, reasoning about them is not much harder! Their specifications are entirely straightforward—and, as described in the next section, reasoning about them is not much harder!

The \(\alpha\)-equivalence relation on terms is defined mutually with a notion of equivalence for patterns which ignores binders and checks that embedded terms are \(\alpha\)-equivalent. This \(\alpha\)-equivalence relation is essentially structural equality—the only reason it is not precisely structural equality is that name annotations on binders are ignored in \texttt{PEQBINDER}.

Computing free variables is equally straightforward. Since free and bound variables are distinguished syntactically, we need only recurse through terms and patterns collecting all the free variables we find.

Finally, we define substitution into terms and patterns. If we see the free variable we are substituting for, we replace it with the term being substituted; otherwise we simply recurse. We need do nothing special when recursing through binders: since free and bound variables are distinguished syntactically, we are in no danger of mistaking a bound variable for a free variable we should substitute for, or of accidentally capturing any free variables in the substituted term.

5. Metatheory

We’ve now defined a simple semantics for our pattern specification language in terms of a locally nameless representation. But how can we know whether this semantics is at all meaningful? Well, we prove stuff, of course!

In the previous section, we noted how straightforward the definitions of various operations were. Likewise, most of the proofs regarding these operations are also straightforward (but full of fiddly details). We therefore omit most of the proofs and give only brief sketches of a few. The fact that the proofs are straightforward is a testament to the elegance of the locally nameless representation.

There is already a lot of work to draw on from the metatheory of locally nameless representations in the single binder case [1, 2]; much of the metatheory here can be seen as an extension of that prior work.

5.1 Local closure

One important property of the locally nameless representation is that only some terms are good representations. In particular, there is some “junk” in our representation, and we would like to know that we (and users of our library) never need to deal with it. The local closure relation in Figure 7 is an invariant for our representation which excludes terms with “dangling” bound variables. For example, the term \texttt{0} \texttt{0} \texttt{0} \texttt{0}, a bound variable with no surrounding binder, is not locally closed.\footnote{This relation is an extension of McKinna and Pollack’s \texttt{VClosed relation} [16].}

By making the type combinators of our library abstract, we can demonstrate a central property of our interface: \texttt{users of the library can only construct locally closed patterns and terms}.

\begin{figure}[h]
\begin{align*}
\approx &:: T \rightarrow T \rightarrow \text{Bool} \\
x \approx y &:: x \equiv y \\
b_1 \approx b_2 &:: b_1 \equiv b_2 \\
(K s_1 \ldots s_n) \approx (K t_1 \ldots t_n) &:: s_1 \equiv t_1 \wedge \ldots \wedge s_n \equiv t_n \\
\text{Bind} p_1 t_1 &\approx \text{Bind} p_2 t_2 :: p_1 \approx p_2 \wedge t_1 \approx t_2 \\
\approx_p &:: P \rightarrow P \rightarrow \text{Bool} \\
\rightarrow_x &:: \approx_p \rightarrow y \\
\text{Bind} p_1 \ldots p_n &\approx \text{Bind} p_1 \ldots p_n :: p_1 \approx_p q_1 \wedge \ldots \wedge p_n \approx_p q_n \\
\text{Rebind} p_1 p_2 &\approx \text{Rebind} q_1 q_2 :: p_1 \approx_p q_1 \wedge p_2 \approx_p q_2 \\
\text{Embed} t_1 &\approx \text{Embed} t_2 :: t_1 \equiv t_2 \\
\text{Rec} t_1 &\approx \text{Rec} t_2 :: p_1 \approx_p p_2 \\
\text{fv} x &:: T \rightarrow \text{Set A} \\
\text{fv} x &:: \{x\} \\
\text{fv} b &:: \emptyset \\
\text{fv} (K t_1 \ldots t_n) &:: \text{fv} t_1 \cup \ldots \cup \text{fv} t_n \\
\text{fv} (\text{Bind} p t) &:: \text{fv} p \cup \text{fv} t \\
\text{fv}_p &:: P \rightarrow \text{Set A} \\
\text{fv}_p x &:: \emptyset \\
\text{fv}_p (K t_1 \ldots p_n) &:: \text{fv}_p p_1 \cup \ldots \cup \text{fv}_p p_n \\
\text{fv}_p (\text{Rebind} p_1 p_2) &:: \text{fv}_p p_1 \cup \text{fv}_p p_2 \\
\text{fv}_p (\text{Embed} t) &:: \text{fv} t \\
\text{fv}_p (\text{Rec} p) &:: \text{fv}_p p \\
\text{subst} &:: \texttt{t} \rightarrow T \rightarrow T \\
\text{subst} x s y &:: \begin{array}{ll}
\text{otherwise} &:: y \\
\end{array} \\
\text{subst} x s b &:: b \\
\text{subst} x s (K t_1 \ldots t_n) &:: K (\text{subst} x s t_1) \ldots (\text{subst} x s t_n) \\
\text{subst} x s (\text{Bind} p t) &:: \text{Bind} (\text{subst}_p x s p) (\text{subst} x s t) \\
\text{subst}_p &:: \texttt{t} \rightarrow P \rightarrow P \\
\text{subst}_p x s y &:: \begin{array}{ll}
\text{otherwise} &:: \begin{array}{ll}
\end{array} \\
\end{array} \\
\text{subst}_p x s (K t_1 \ldots p_n) &:: K (\text{subst}_p x s p_1) \ldots (\text{subst}_p x s p_n) \\
\text{subst}_p x s (\text{Rebind} p_1 p_2) &:: \text{Rebind} (\text{subst}_p x s p_1) \ldots (\text{subst}_p x s p_2) \\
\text{subst}_p x s (\text{Embed} t) &:: \text{Embed} (\text{subst} x s t) \\
\text{subst}_p x s (\text{Rec} p) &:: \text{Rec} (\text{subst}_p x s p)
\end{align*}
\caption{\(\alpha\)-equivalence, free variables, and substitution}
\end{figure}

Theorem 1 (Constructors and destructors preserve local closure). All exported term and pattern constructors and destructors preserve local closure.

Proof. Requires considering the action of each constructor and destructor individually, appealing to a number of properties about the interaction of local closure, open and close.

Theorem 2 (Substitution preserves local closure).

\begin{itemize}
\item If \texttt{LC} \(t\) and \texttt{LC} \(t'\) then \texttt{LC} \texttt{subst} \(x\ t\ t'\).

\item If \texttt{LC} \(t\) and \texttt{LC p} then \texttt{LC subst}_p \(x\ t\ p\).
\end{itemize}

Proof. Straightforward induction using a generalized version of local closure.
If reflexivity, symmetry, and transitivity can each be established straightforward induction on the derivation of $fv$, then $fv t_1 = fv t_2$.

Proof. Straightforward induction on $fv t_1$ along with a similar proof for $fv p$.

Theorem 6 (Substitution respects $\alpha$-equivalence). If $t_1 \approx t_2$, then $fv t_1 = fv t_2$.

Proof. Straightforward induction on the derivation of $t_1 \approx t_2$, along with a similar proof for pattern substitution.

We next specify how the operations of $\alpha$-equivalence, free variable calculation, and substitution interact with Bind. The proofs of these remaining theorems rely on properties about the interactions between close and each of the operations.

The first theorem states the interaction between binding and $\alpha$-equivalence. It states that two bindings are $\alpha$-equivalent when we can freshen two patterns to the same new result, and then show that their bodies are $\alpha$-equivalent under a consistent renaming. Below, $\pi_1$ and $\pi_2$ are the permutations returned by freshen and $\pi_1 \cdot t_1$ is the application of a permutation to a term.

We implement UNBOUND using the REPIL generic programming library [35]. REPIL works by producing generic representation instances for each type. Roughly, a representation instance records the structure of a datatype by analyzing its data declaration. In this case, the call $\$\ derive [\'E\']$ uses Template Haskell [29] to generate the generic representation for $E$. This structure information is used to automatically generate particular functions over $E$ on demand.

The following line in the figure declares $E$ to be an instance of the Alpha type class, which governs $\alpha$-equality, free variable and freshening operations. Happly, default implementations for the methods of Alpha are defined generically. Guided by the occurrences of Bind and Name in the definition of $E$, the default definitions of these methods behave exactly like their specifications in the semantics section.

Capture-avoiding substitution is governed by the Subst class, and requires a tiny bit of work on our part: we must indicate where variables are located in datatypes. Beyond that, the generic default implementation suffices. In general, the type of subst declares that values of type $\xi$ may be substituted for free variables occurring in
values of type \( a \), so the \( \text{Subst} \ E \ E \text{ instance shown declares that} \ E \) values may be substituted for \( \text{Vars} \) in other \( \text{E} \) values.

By making \( \text{Subst} \) a multiparameter type class we have flexibility and safety. Imagine a different declaration of the type \( \text{E} \) variables may be substituted for \( \text{Var} \) the type indices of \( \text{clare that} \ E \text{ isvar} \) give a definition of \( \text{typ} \) function.

The operations \( \text{fv}, \text{bind}, \text{unbind} \) and \( \text{subst} \) are implemented in terms of the \( \text{Alpha} \) and \( \text{Subst} \) type classes. Therefore, Figure 8 provides all the necessary definitions for the parallel reduction example in Figure 1 (which is valid Haskell code).

### 6.1 Multi-sorted names and \( \text{AnyName} \)

Instead of a single homogeneous set of atomic names, \( \text{Unbound} \) has multisorted names. Consider the type declarations in Figure 9. Names are indexed by a type, and the type of \( \text{subst} \) ensures that only things of type \( t \) may be substituted for \( t \)-indexed names. The \( \text{fv}, \text{fv}_p \), and \( \text{bind} \) functions are also polymorphic in their result type, ignoring names whose type index does not match the requested result type. In this way, one may calculate, say, just the free term variables or just the free type variables from an expression. These functions are overloaded, so type inference determines precisely what sort of names will be calculated, and what sort of data structure (list, set, etc.) will be used to collect them.

However, sometimes we would like to know all free names, no matter what their sort. Therefore, \( \text{Unbound} \) also provides the type \( \text{AnyName} \), which existentially hides the type index on a name, and the functions \( \text{fvAny} \) and \( \text{bindersAny} \) which return all appropriate names wrapped in \( \text{AnyName} \) constructors.

### 6.2 The \( \text{Alpha} \) type class

One way in which our implementation differs from our semantics is that while the semantics statically differentiates between terms and patterns, the implementation does not. Due to limitations of \( \text{REPLIB} \), instead of having two type classes \( \text{Term} \) and \( \text{Pattern} \) we must have a single type class \( \text{Alpha} \) which serves both purposes. This conflation means that our implementation cannot statically prevent meaningless types which use a pattern as a term (e.g. \( \text{Embed} \) (\( \text{Embed} \) \( N \)) or a term as a pattern (e.g. \( \text{Bind} \) (\( \text{Bind} \) \( N \) \( E \)) \( E \)).

However, this conflation does have an advantage. Many of the methods of the \( \text{Alpha} \) class are parameterized by \( \text{mode} \) which determines whether the type is being used as a term or a pattern. For example, the \( \alpha \)-equivalence method, called \( \text{aeq} \), is declared as:

\[
\text{aeq} :: \text{AlphaCtx} \rightarrow \text{a} \rightarrow \text{a} \rightarrow \text{Bool}
\]

\[
\text{aeq} = \text{aeqR1 rep1}
\]

The first argument, of type \( \text{AlphaCtx} \), specifies whether \( \alpha \)-equivalence should operate in term or pattern mode, generalizing the \( \approx \) and \( \approx_\beta \) functions shown in Figure 6. The second line of the declaration is the default definition, which calls the datatype-generic function \( \text{aeqR1} \) (not shown) with the type representation \( \text{rep1} \) (derived with Template Haskell). Instances of \( \text{Alpha} \) can override this default implementation. For example, in the \( \text{Name} \) instance, the mode determines whether the names should be compared or always considered equivalent.

\[
\text{instance Alpha Name where}
\]

\[
\text{...}
\]

\[
\text{aeq} c x y | \text{mode} c \equiv \text{Term} = x \equiv y
\]

\[
\text{aeq} c \_ \_ | \text{mode} c \equiv \text{Pat} = \text{True}
\]

Many types (such as products and sums) are parametric in the mode and use the same behavior in both cases.

Overall, the \( \text{Alpha} \) type class includes mode-generalized versions of the operations shown in Figure 9, the predicates for distinguishing between terms and patterns, and the necessary machinery for the locally nameless representation (\( \text{open}, \text{close}, \text{find} \) and \( \text{nth} \)).

### 6.3 Specific instances for \( \text{Alpha} \)

Default implementations for all \( \text{Alpha} \) methods are defined via generic programming, but they may be overridden for greater control or customization. This capability is necessary in practical uses of \( \text{Unbound} \) for specific types.

For example, suppose we would like to tag variables with source position information in our abstract syntax:

---

6 We do, however, provide dynamic checks \( \text{isPat} \) and \( \text{isTerm} \) that can be used to ensure the invariants are maintained.

7 This capability for overriding generic functions is inspired by the SYB3 library [14].
class Monad m ⇒ Fresh m where
  fresh :: α a → m (Name a)

class Monad m ⇒ LFresh m where
  lfresh :: Rep a ⇒ Name a → m (Name a)
  avoid :: [AnyName] → m a → m a

Figure 10. The Fresh and LFresh type classes

data E = . . .
  | Var SourcePos N

To make E an instance of Alpha, we need SourcePos to also be an instance of Alpha, because it appears inside the E type. If we would like α-equivalence to ignore source positions, we can simply override the default definition of α-equivalence for SourcePos. By identifying all source positions as equivalent, we ensure that expressions appearing in different positions can still be determined to be α-equivalent.

instance Alpha SourcePos where
  aeq' _ _ = True

6.4 Freshness monads

Since the freshen operation relies on the generation of fresh names, operations which make use of it (such as unbind) must execute within a monad. The Fresh type class, shown in Figure 10, governs those monads which can be used for this purpose, and is used to avoid tying users down to one particular monadic constructor.

The Fresh class is quite simple: it requires only a single operation fresh, which takes a name as input and generates a new name (based on the given name) which is guaranteed to be "globally fresh" in some appropriate sense. For example, a simple concrete implementation might keep track of a global counter which is incremented every time fresh is called, appending the new counter value to the given base variable name.

However, this is unsatisfactory in many instances. For example, consider the simple pretty-printer for the untyped lambda calculus shown in Figure 11. If we pass it the term \((λx.x)\), it produces \(\langle x. \langle y_1. \langle z_2 → x. (y_1 z_2) \rangle \rangle \). We can see perfectly well that the numeric suffixes on \(y\) and \(z\) are unnecessary, since the existing names do not clash, but the fresh operation does not have enough information to make this assessment.

For this reason, we also provide the more sophisticated LFresh type class for monads which can generate locally fresh names. LFresh works much like Fresh, but it has more to go on: avoid ns m allows us to specify that the names ns should be avoided by calls to fresh in the subcomputation m. Unlike Fresh, LFresh is not guaranteed to pick globally fresh names; it only guarantees not to pick names proscribed by an enclosing call to avoid. The intention is that it will return its argument unchanged when that name is not specifically to be avoided.

Using LFresh, we can rewrite the pretty-printer so that names are chosen fresh with respect to exactly those names currently in scope. To accomplish this we need only use LFresh instead of Fresh and unbind instead of unbind; unbind generates names for the binder using fresh, then hands the body to a continuation wrapped in a call to avoid.

UNBOUND provides several concrete implementations for Fresh and LFresh, including transformer versions for adding fresh name generation capabilities to existing monads, and instances allowing their use with all the standard monad transformers in the transformers package.\(^8\)

6.5 Simultaneous unbinding

Up to now, we have seen only examples of opening a single abstraction with arbitrary fresh names. However, some situations require simultaneously opening two or more abstractions with the same fresh names. For example, in order to check the convertibility of two LF II-types, we must open them with the same fresh name and recursively check the convertibility of the bodies.

In order to simultaneously open two abstractions Bind \(p_1 t_1\) and Bind \(p_2 t_2\), we require only that \(p_1\) and \(p_2\) have the same number of binders. Requiring a stronger match between \(p_1\) and \(p_2\) would be unnecessarily limiting. For example, continuing our LF checking example, \(p_1\) and \(p_2\) might contain type annotations which are convertible but not α-equivalent.

Therefore, UNBOUND provides a function unbind2 that simultaneously opens two related bindings.

\[
\begin{align*}
  \text{unbind2} :: (\text{Fresh} m, \text{Alpha} p_1, \text{Alpha} p_2, \\
  \text{Alpha} t_1, \text{Alpha} t_2) \Rightarrow \\
  \text{Bind} p_1 t_1 \rightarrow \text{Bind} p_2 t_2 \rightarrow \\
  m \rightarrow (p_1 t_1, p_2 t_2)
\end{align*}
\]

\[
\begin{align*}
  \text{unbind2} (B p_1 t_1) (B p_2 t_2) = \text{do} \\
  \text{case mkPerm (bindersAny} p_1 \text{) (bindersAny} p_2 \text{) of} \\
  \text{Just} \pi \rightarrow \text{do} \\
  (p'_1, p'_2) \leftarrow \text{freshen} p_1 \\
  \text{return} (\text{Just} (p'_1, \text{open} p'_1 t_1, \\
  \text{swaps} (\pi \circ \pi) p_2, \text{open} p'_2 t_2)) \\
  \text{Nothing} \rightarrow \text{return Nothing}
\end{align*}
\]

This function works by first matching the binding variables of the two patterns together to create a permutation \(\pi\). This operation will fail if the patterns bind different numbers of variables. Next, it freshens the first pattern \(p_1\) and uses the result to open \(t_1\) and \(t_2\). Finally, it must compose the permutation from freshening \(p_1\) with that from the match, and use the new permutation to rename the second pattern.

\(^8\)http://hackage.haskell.org/package/transformers
7. Discussion

7.1 Nominal semantics

We have presented a semantics for the UNBOUND specification language in terms of a locally nameless representation, but this is not our only possible choice. UNBOUND could also be specified via an equivalent nominal semantics [19], and we are working in parallel on a nominal-style Haskell implementation. Such an alternative semantics would provide differences in running time/space, but otherwise would behave identically to the locally nameless version. In future work, we plan to formalize the precise connection between the two formulations and prove their equivalence with respect to the abstract interface provided by the library.

Although a nominal semantics might appear more natural to think about, in our experience the locally nameless semantics is far easier to understand when it comes to generalized binding patterns, especially with nesting. Therefore, an important contribution of this work is the identification of a simple semantics for pattern binding.

7.2 Coml-style specifications

François Pottier’s Coml system [22] features a single-argument abstraction constructor, inside which patterns and terms (both bound and unbound) can be mixed. Directly inside an abstraction is a pattern, with terms embedded via outer (indicating a term outside the scope of the pattern) or inner (indicating that the pattern binds names in the term). Coml’s abstraction constructor (p) is easily definable with UNBOUND as Bind (Rec p ()). Within that pattern, occurrences of Embed are analogous to occurrences of inner in Coml. To account for Coml’s outer scope specification, we generalize the Embed combinator by adding a natural number subscript. When encountering Embedn0 while doing an open or close operation, we decrement the level by n. Hence, Embedn corresponds to the original Embed, and Embedn1 corresponds to Coml’s outer construct, since it shifts the scope of an embedded term out to the next enclosing level.

In UNBOUND we implemented indexed embedding by adding a new type combinator Shift. This type increments the index of its argument, so Shift (Embed T) corresponds to Embed 0 T, and Shift (Shift (Embed T)) is Embed 1 T. Operationally, all Shift does is decrement the binding level when the pattern is opened or closed so that variables will resolve to an outer scope.

7.3 UNBOUND in practice

We have been using UNBOUND in the TRELLEYS project, in the context of type checking and evaluation of an experimental dependently-typed language. In this context, UNBOUND support for telescopes is essential. Our experience with TRELLEYS has allowed us to find and correct a few bugs in our implementation of UNBOUND, but for the most part the use of UNBOUND has been unremarkable, in the sense that it seems to “just work”. The only drawback to using UNBOUND is the lack of pattern matching for the abstract type Bind.

TRELLEYS is an ideal client for UNBOUND, in that it is a prototype language with a greater emphasis on semantics than performance. Because UNBOUND is implemented using generic programming, it will be slower than a hand-coded implementation [25]. If necessary, we could easily replace the generic definitions with hand-coded operations by overriding the Alpha type class instances.

The locally nameless representation does have some performance concerns with respect to its use of open and close. While the standard operations fv, subst, and ≈· are linear in the size of terms, operations that are defined in the freshness monad must open and close the terms for each binding level, which could be expensive. Although we have not had any difficulties of this sort in TRELLEYS (our experiments are still small) it is possible that with larger programs and deeper binding depths, these operations could dominate. To mitigate this difficulty, UNBOUND supports an “experts-only” interface, where critical operations can be written directly over the terms (in a manner similar to our implementations of fv, subst and · ≈ ·).

We have not explored the interaction of UNBOUND with standard optimizations [28]. For example, by caching free names, an implementation of substitution could stop early if the name being substituted for is not cached. If we remove names from bound patterns (which are preserved only for error messages) the locally nameless representation interacts nicely with hash-consing, as all α-equivalent terms have the same representation.

We are also working on bringing our nominal implementation of UNBOUND up to date with our reference locally nameless implementation. Both implementations provide the same interface to clients. When using the LFresh monad, the nominal implementation could avoid freshening when unbinding patterns if the patterns were already “sufficiently” fresh. However, there are trade-offs involved; for example, α-equivalence can be more expensive with the nominal version.

One important contribution of UNBOUND is that it provides an abstract interface to name binding. Clients can write their code against this interface, and, depending on their particular application, choose the most appropriate implementation. Importantly, our locally nameless implementation provides a simple reference semantics for this interface, and alternative implementations may use this semantics to prove their correctness.

8. Related Work

Locally nameless representation. The locally nameless representation dates back to the introduction of de Bruijn indices, and is mentioned in the conclusion of de Bruijn’s paper [8]. The key idea is even older. It rests on the separation of names into two distinct classes: variables (for locally bound variables) and parameters (for free, or globally bound variables) and goes back to Kleene [13], Prawitz [24] and Gentzen [10]. The full history of the locally nameless representation is outside the scope of this paper, but we refer to Aydemir et al [2] and Charguéraud [4] which discusses it in detail. Instead, we focus on the interaction between this representation, generic programming and binding specifications.

Charguéraud’s paper [4] also gives several examples of locally nameless representations of languages with specific binding forms, including binding a list of variables, pattern matching (with embedded terms), and recursive bindings. However, he does not consider a compositional framework for describing generalized binding.

Zappa Nardelli’s locally nameless backend [36] for the OTT tool [27] automatically generates definitions for the Coq proof assistant given a specification of a language (with single binding only). These definitions include a locally nameless representation of the syntax, open and close operations, α-equivalence, substitution, and free variable calculation. The LNgen tool of Aydemir and Weirich [1] augments this output with generic proofs about this representation, including many of the properties of § 5.

Tools for general bindings. Cirstea et al. [7] define the ρ-calculus, a λ-calculus-like system for expressing rewriting strategies, which features generic binders represented by any term. Herman and Wand define a specification language for binding structure in the service of α-converting Scheme programs containing macros [12]. Although it only allows single variables as binding patterns, it is flexible about the subterms in which each variable should be bound.

The OTT tool provides an expressive specification language for generalized binding in programming languages. In conjunction
with a specification of the abstract syntax, OTT allows the definition of `bindspecs` functions that arbitrarily select the binding variables that appear in terms and bind them elsewhere in the abstract syntax. They give a semantics of this specification language using a representation with concrete variable names [26] and show that under appropriate conditions, their concrete substitution functions respect α-equivalence and coincide with capture-avoiding substitution.

Inspired by the OTT specification language, Urban and Kaliszyk recently extended the Nominal Isabelle proof assistant with support for general bindings [34]. Their system works by using the OTT binding specifications (with some restrictions) to define α-equivalence classes of syntax with binders which they use to model nominal-logic specifications. While a direct comparison is difficult, their restrictions prevent variables from being bound by two different bindspecs, which seems necessary for telescopes. On the other hand, they also add two forms of `set` bindings to their specifications, allowing binders to be equivalent up to permutation and weakening of their patterns.

As discussed in § 7.2, there is a close connection between `UNBOUND` and Francois Pottier’s Coml system [22], based on a nominal semantics for binding. One major difference is that Coml explicitly does not include support for nested binders. Another difference is that Coml is an external tool that performs a preprocessing step, whereas `UNBOUND` is a library. However, this is not a fundamental difference; Coml could be made into a library as well if OCaml had better support for generic programming (likewise, `UNBOUND` could be ported to languages without support for generic programming by making it into an external tool).

Cheney’s FreshLib [6] is a Haskell library which served as an inspiration for `UNBOUND`. Like `UNBOUND`, it uses generic programming to automatically define α-equivalence and substitution functions (although FreshLib is based on a nominal semantics for name binding, so the generic operations that establish its semantics are different). FreshLib also supports some forms of generalized binding, but does not give a generic treatment of patterns.

Other tools based on nominal logic include FreshML [31] and FreshOCaml [30]. However, they support limited forms of binding patterns which do not include embeddings, recursive or nested bindings. Likewise, the Haskell Nominal Toolkit [3] is a library that supports single binding for a fixed term structure.

9. Future work

Although we believe `UNBOUND` is useful in its current state, there are several directions in which we would like to extend it.

Other forms of “exotic” binding

Cheney [5] gives a catalogue of “exotic” binding, renaming, and structural congruence situations. Although `UNBOUND` can express many of these examples, we hope to extend `UNBOUND` with better support for “global” binding, such as that used for objects and modules. Furthermore, we would also like to add support for set binding similar to Nominal Isabelle [34]. However, implementing `unbind_2` in the presence of such bindings is a nontrivial task.

Better static distinction between names and patterns

As discussed in § 6.2, an infelicity of our current design is the ability to get terms and patterns mixed up. `UNBOUND` inherits this limitation from REPLIB; it is possible that an alternative framework for generic programming would perform better in this respect.

Scoping

`UNBOUND` does not keep track of the scope of names once they have been unbound. While this laxity leads to a familiar and flexible interface, it does not rule out bugs that could occur from names escaping their scope. Pottier et al. have made progress in this respect [21, 23], and we would like to explore a variant interface for `UNBOUND` that provides this tighter control.

Mechanized metatheory

The `UNBOUND` specification language seems ideal for incorporation into tools like Ott, LNgen and Nominal Isabelle that assist in the formalization of programming language metatheory. Indeed, locally nameless representations have already proved useful for that sort of reasoning.

However, in the context of formal reasoning, we must be more careful about scoping. Allowing bound names to escape their scope can lead to unsoundness (see Urban [32]). Such functions violate the “Freshness Condition for Binders”, a side condition required for all function definitions in Nominal Isabelle [33]. Adapting `UNBOUND` to mechanized reasoning would require a similar side condition for function definitions.

10. Conclusion

`UNBOUND` is an expressive specification language for generalized binding structures, defined with a simple compositional semantics, proven correct, and immediately available to the GHC user community. Because it supports the rapid development of typecheckers, compilers, and interpreters, it is a valuable tool for exploration in programming language design. Furthermore, we hope that the design of `UNBOUND` itself will be a model for future work on library support for expressive binding structure.

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