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A Calculus for Dynamic Loading

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A Calculus for Dynamic Loading

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We present the load-calculus, used to model dynamic loading, and prove it sound. The calculus extends the polymorphic λ-calculus with a load primitive that dynamically loads terms that are closed, with respect to values. The calculus is meant to approximate the process of dynamic loading in TAL/Load [4], a version of Typed Assembly Language [7] extending with dynamic linking. To model the key aspects of TAL, the calculus contains references and facilities for named types. Loadable programs may refer to named types defined by the running program, and may export new types to code loaded later. Our approach follows the framework initially outlined by Glew et. al [3]. This calculus has been implemented in the TALx86 [6] version of Typed Assembly Language, and is used to implement a full-featured dynamic linking library, DLpop [4].

Comments

At the time of publication, the author Stephanie C. Weirich was affiliated with Cornell University. Currently June 2007, she is a faculty member in the Department of Computer Information and Science at the University of Pennsylvania.
A Calculus for Dynamic Loading

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February 6, 2001

Abstract

We present the load-calculus, used to model dynamic loading, and prove it sound. The calculus extends the polymorphic $\lambda$-calculus with a load primitive that dynamically loads terms that are closed, with respect to values. The calculus is meant to approximate the process of dynamic loading in TAL/Load [4], an version of Typed Assembly Language [7] extending with dynamic linknig. To model the key aspects of TAL, the calculus contains references and facilities for named types. Loadable programs may refer to named types defined by the running program, and may export new types to code loaded later. Our approach follows the framework initially outlined by Glew et. al [3]. This calculus has been implemented in the TALx86 [6] version of Typed Assembly Language, and is used to implement a full-featured dynamic linking library, DLpop [4].

1 Introduction

The purpose of this report is prove the soundness of a simple calculus for dynamic loading, designed as a theoretical basis for dynamic linking in Typed Assembly Language [7, 6, 3]. Dynamic loading is provided by a simple primitive load, which converts the binary representation of some closed\footnote{By closed, we mean that there are no free value variables; there may be free type labels, as we describe shortly.} term into the term itself. This calculus is meant to approximate an implementation of dynamic loading in Typed Assembly Language, and so the language provides references and named types, in addition to load and lambda-terms.

Here is a small example of the use of load. Consider the following program (using OCaml-style [5] syntax):

\begin{verbatim}
let f f2 =
  let x = 1 in
  (3, f2 x)
\end{verbatim}
Assuming \( f_2 \) has type \( \text{int} \rightarrow \text{int} \), then \( f \) has type \( (\text{int} \rightarrow \text{int}) \rightarrow \text{int} \times \text{int} \). We could load this (closed) program in another program. Assuming that the binary representation of this program is stored in the file “f”:

```ml
let g () =
  let load_suc f = f (function x -> x + 1) in
  let load_fail = (3,4) in
  load [(\text{int} \rightarrow \text{int}) \rightarrow \text{int} \times \text{int}] ("f",load_suc,load_fail)
```

When \( g \) is executed, it will call \( \text{load} \). If \( \text{load} \) succeeds, it will call \( \text{load} \_\_\_\_\_\text{suc} \) with the loaded function of type \( \text{int} \rightarrow \text{int} \), in this case the function \( f \). If \( \text{load} \) fails (because of either a type or format error), then \( \text{load} \_\_\_\_\_\text{fail} \) is executed instead. The result of evaluating this program, assuming “f” is well-formed, is \( (3,2) \).

In order to properly accommodate named types, we define the notion of a type heap, which maps type labels to types, where the type label corresponds to the named type and the type it maps to is the implementation of that type. A program has two type heaps, the current type heap, and the imported type heap. Labels within the imported type heap correspond to types not defined by the current program. Additionally, a type label in the imported type heap could be undefined, corresponding to a type whose representation is defined externally. In the ML terminology, an imported type whose representation is known essentially corresponds to manifest type, while one whose representation isn’t known corresponds to an opaque type, the consequence of which is that values of that type may only be used abstractly. For example, we can (roughly) modify the two programs above as follows:

```ml
extern namedtype t = int \times int
let f f2 =
  let x = 1 in
  roll [t] (3, f2 x)

Here externally is used to approximate a manifest type defined externally, and namedtype indicates that \( t \) is a unique name for the type.

namedtype t = int \times int
let g () =
  let load_suc f = f (function x -> x + 1) in
  let load_fail = roll [t] (3,4) in
  let x = load [(\text{int} \rightarrow \text{int}) \rightarrow \text{int} \rightarrow t]
    ("f",load_suc,load_fail) in
  unroll x
```
Here, the running program defines the named type t, which is matched up at load
time with the imported type t defined in the other program. We use roll and
unroll to convert to and from named types.

We could also define opaque named types in both the running program and the
loaded code, and this is well-typed as long as the values of those types are used
abstractly (that is, they are never part of a roll or unroll expression, which would
reveal their representation). For instance, we could modify the loaded program as:

```
extern namedtype t
let f (f2:t->t) (x:t) =
  (f2 x, f2 x)
```

Now the function f has type \((t \to t) \to t \times t\). The running program could
become:

```
namedtype t = int * int
let g () =
  let load_suc f = f
  (function x -> let (y,z) = unroll x in roll [t] (y+1,z+1)) in
  let load_fail = (roll [t] (3,4),roll [t] (4,5)) in
  let x = load [(t -> t) -> t -> t]
  (*"f",load_suc,load_fail) in
  unroll [t] x
```

The converse is also possible. For instance,

```
namedtype t = int * int
let f x y =
  roll [t] (x,y)
```

Now the function f has type \(\text{int} \to \text{int} \to t\). The running program could become:

```
extern namedtype t
let g () =
  let load_suc f = (f 1 2; ()) in
  let load_fail = () in
  load [(int -> int -> t] (*"f",load_suc,load_fail)
```

Note that after the value of type t is created, it is discarded. We could easily have
defined other functions in the loaded code to manipulate values of type t. We could
also combine these two programs to allow recursively defined named types across
modules.

The remainder of this report develops the calculus which allows such programs
to be written in a well-typed manner. We define the syntax, a static and operational
semantics, and finally a type-soundness theorem.
2 Syntax

The syntax of the load-calculus is shown in Figure 1. A program $P$ consists of a type interface $\Theta$, a heap $H$, and an expression to evaluate $e$. The heap $H$ stores reference cell values, and the expression $e$ represents the program’s computation. The interesting part is the type interface, which consists of two type heaps $X_I$ and $X_H$ that defined the named types of the program. $X_I$ contains named types imported by the program (to be resolved later during a linking phase), while $X_H$ contains named types defined by the program, respectively.

A type heap is a finite map; it maps each type label $l$ in its domain to a type heap value $X$, which is either a type $\tau$ or $\perp$; the latter indicates an undefined (unresolved) type label. We write $X(l)$ to denote $\chi$ in the heap $X = \{\ldots, l = \chi, \ldots\}$. For the heap $X = \{l_1 = \chi_1, \ldots, l_n = \chi_n\}$, $\text{dom}(X)$ refers to the set $\{l_1, \ldots, l_n\}$ and $\text{rng}(X) = \{\chi_1, \ldots, \chi_n\}$.

Most types $\tau$ are standard, particularly base type $\text{int}$, function types $\tau \rightarrow \tau$, reference types $\tau \text{ ref}$, variable types $\alpha$ and universally-quantified types $\forall \alpha.\tau$. We
use the type label $l$ itself to represent a named type defined in the type heap.

Most expressions are standard, particularly integers $i$, variables $x$, value abstractions $\lambda x : \tau . e$ and applications $e_1 e_2$, type abstractions $\Delta \alpha . e$ and applications $e[\tau]$, reference construction $\text{ref } e$, reference assignment $\text{assign } e_1 e_2$, and reference deconstruction (dereference) $! e_1$. We assume all $\lambda$-bound variables are unique. To coerce an expression $e$ to named type $l$, we provide a coercion $\text{roll } e$; $\text{unroll}$ performs the reverse operation. For example, say the type heap $X_H$ has the form $\{ \text{filehandle} = \text{int} \}$, indicating that the named type $\text{filehandle}$ is defined to have type $\text{int}$. To coerce the integer 1 to have type $\text{filehandle}$, we would do $\text{roll } \text{filehandle } 1$. Converting it back to an integer would simply require an $\text{unroll}$; i.e. $\text{unroll } (\text{roll } \text{filehandle } 1)$. Note that named types are also permitted to be abstract, such that this $\text{unroll}$ operation is not permitted; this will be clear in the presentation of the static semantics.

Reference values are stored in the value heap $H$. Value heaps are finite maps mapping value labels $L$ to values. We write $H(L)$ to denote $v$ in the heap $H = \{ L = v, \ldots \}$. For the heap $H = \{ L_1 = v_1, \ldots, L_n = v_n \}$, $\text{dom}(H)$ refers to the set $\{ L_1, \ldots, L_n \}$ and $\text{rng}(H) = \{ v_1, \ldots, v_n \}$. If $H = \{ L = v, \ldots \}$, then let $H[L = v']$ be the heap $\{ \ldots, L = v', \ldots \}$; this operation is undefined if $L \notin H$.

3 Dynamic Semantics

In this section we present the rules for the model of computation in the load-calculus.

3.1 Linking

A running program may dynamically link in other programs as it runs using $\text{load}$. The $\text{load}$ expression models the loading of object files in TAL/Load, but varies slightly from its presentation in [4]. Here, $\text{load}$ takes 'integers' as its first two arguments (representing the bytes of a program and a type heap mask, explained more below) and alternative branches for a successful load and failure.

When a running program dynamically loads another program into it, both the value and type heaps of the two programs must be merged. This process is called $\text{linking}$. We first define linking for type heaps, and then for value heaps.

Stated informally, linking two type heaps together yields a resulting heap (1) whose exports are the disjoint union of the source exports, and (2) whose imports are the merge of the imports minus the exports. Type heap linking is well-formed if the imports agree with each other (that is, they don't define any named types whose definitions conflict), and the exports are disjoint. Using the operations and predicates on type heaps and type heap values shown in Figure 2, type heap linking is defined formally as:
Figure 2: Type heaps and type heap values: operators and predicates

Definition 3.1 (Type Heap Linking)
\[
\begin{align*}
X_1 \sim X_2 & \quad X_1 \sqsubseteq X_2 \\
X_1 \sim X_2 & \quad X_1 \sqsubseteq X_2 \\
X_1 \sqsubseteq X_2 & \quad X_1 \sqsubseteq X_2
\end{align*}
\]
\[
(X_1 \uplus X_2) \cup (X_1 \uplus X_2) = (X_1 \uplus X_2) \cup (X_1 \uplus X_2)
\]

Value heap linking is essentially the same as type heap linking, minus the requirements and operations concerning imported values. This is because value heaps are required to be closed (i.e., self-contained), so there is no import heap and linking them together just becomes disjoint union. This requirement is in contrast to typical definitions of value heap (or term-level) linking (e.g., [3, 1, 2]); we make it because we expect value linking to occur in the term language itself.

Definition 3.2 (Value Heap Linking)
\[
\frac{H_1 \cup H_2}{H_1 \cup H_2} (H_3 = H_1 \cup H_2)
\]

where
- \( H_1 \cup H_2 \) dom\( (H_1) \) and dom\( (H_2) \) are disjoint
- \( H_1 \cup H_2 \) Union of disjoint maps, defined if \( H_1 \mid H_2 \)
3.2 Operational Semantics

We define the operational semantics for the load-calculus using a one-step reduction operator $\rightarrow$, following a call-by-value discipline. The most interesting construct is load; its operational rules appear in Figure 3. The first two (term) arguments to load are the integers $h$, specifying the type heap mask to use during linking, and $i$, specifying the program to load. We use $\hat{a}$ as some function that maps integer arguments to programs or type heaps, as appropriate, modeling a filesystem. The argument $\hat{a}$ is a type heap that is more restrictive than the running program’s type export heap. It is used by the caller to limit the definitions that may be seen by the loaded code, if desired; as such, we refer to it as a type heap mask. The second two arguments to load are the success and failure expressions. If load - success is used, then the success expression is applied to the loaded program expression $e$; otherwise the expression $e_3$ is used (i.e., when using load - failure). The type argument to $\tau$ to load indicates the expected type of the expression in the loaded program.

For load to succeed, three conditions must be met. First, value heap linking $H_1 \text{ link } H_2 \Rightarrow H_3$ must succeed, combining the running program’s value heap $H_1$ and the loaded program’s value heap $H_2$ to produce heap $H_3$. Second, $X^{\phi}_H \vdash \hat{a} : \tau$, indicating that the program to be loaded $\hat{a}$ is well-formed in the context of the running program’s export heap, having type $\tau$, matching the type argument passed to load. Program well-formedness is presented as part of the ‘static’ semantics in the next subsection. Finally, type heap linking $(X^0_f, X) \text{ link } (X^0_f, X^0_H) \Rightarrow (X^3, X')$ must succeed. Rather than linking the running program’s type interface $(X^0_f, X^0_H)$ with the loaded program’s interface, we link $(X^0_f, X)$ instead, thereby replacing the export type heap $X^0_H$ with $X$, which is the type heap indicated by $\hat{a}$. This type heap must be the same as or more restrictive than the program’s export type heap, as required by the conditions $X^0_H \leq X$ and $X^0_f \mid (X^0_H - X)$. This linking operation produces export heap $X'$, which is merged with the program export heap in the new program: $X^3 = X' \oplus X^0_H$.

The remaining operational rules for the calculus are shown in Figure 4. We define $e[e'/x]$ as the capture-avoiding substitution of the term $e'$ for each occurrence of the variable $x$ in the term $e$. These rules are basically standard. In particular, $\beta$ performs function application via substitution; $\text{unroll}$ guarantees that a value that has been coerced to a named type cannot be examined until it has been unrolled; $\text{ref}$ causes the ‘allocation’ of a unique value label $L$ in the value heap and stores the value $v$ there; $\text{deref}$ extracts the value $v$ mapped to by value label $L$ in the value heap; $\text{assign}$ overwrites the existing mapping for value label $L$ in the value heap with one from $L$ to $v$ (recall that the operation $H[L = v]$ requires that $L$ be defined in $H$); $\text{tapp}$ performs type application via substitution. The remaining rules are congruence rules. One oddity is that the success and failure expressions in the
congruence rules are not call-by-value; they are left unevaluated until the actual loading operation takes place. Then only one of them will evaluate, based on the result. Note that we require a type-passing semantics because the type argument passed to load is used at runtime; we use type-erasure semantics in TAL/Load by introducing $\lambda_R$-style term representations for types, as explained in the next section.

4 Static Semantics

As is standard, the static semantics is used to statically check that a program is well-formed. In addition, the operational rule for load requires that well-formedness be checked at runtime, before a program can be dynamically loaded into the running program. Informally, program well-formedness is defined as follows. The program type interface components $X_I$ and $X_H$ must be disjoint and well-formed; the value heap $H$ must be well-typed in the context of the type interface; and the program expression $e$ must be well-typed in the context of both the type and value heaps. In the case that the program is being loaded dynamically, its type export heap labels $X_H$ must be disjoint from those of the running program $X_P$. This is stated formally below.

**Definition 4.1 (Program well-formedness)**

\[
\begin{align*}
\vdash X_I \cup X_H & \quad X_I \cup X_H \vdash \Phi \\
X_I \cup X_H \vdash H : \Phi & \quad X_I \cup X_H ; \Phi ; \vdots \vdash e : \tau \\
\hline
X_P \vdash ((X_I,X_H),H,e) : \tau & \quad (X_H | X_P)
\end{align*}
\]

Figure 3: Operational rules for load
Figure 4: Operational rules, excluding load

\( (\Theta, H, e) \mapsto (\Theta', H', e') \)

- \((\Theta, H, (\lambda x: \tau . e) \ v) \mapsto (\Theta, H, e[v/x]) \) (beta)
- \((\Theta, H, \text{unroll}(\text{roll}_1 v)) \mapsto (\Theta, H, v) \) (unroll)
- \((\Theta, H, \text{ref} \ v) \mapsto (\Theta, H \cup \{L = v\}, L) \) (ref)
  where \( L \notin \text{dom}(H) \)
- \((\Theta, H, !L) \mapsto (\Theta, H, v) \) (deref)
  where \( H(L) = v \)
- \((\Theta, H, \text{assign} L \ v) \mapsto (\Theta, H[L = v], v) \) (assign)
- \((\Theta, H, (\Lambda \alpha . e)[\tau]) \mapsto (\Theta, H, e[\tau/\alpha]) \) (tapp)

\[
\begin{aligned}
&\begin{cases}
(\Theta, H, e e_2) \mapsto (\Theta', H', e' e_2) \\
(\Theta, H, v_1 e) \mapsto (\Theta', H', v_1 e') \\
(\Theta, H, \text{roll}_1 e) \mapsto (\Theta', H', \text{roll}_1 e') \\
(\Theta, H, \text{unroll} e) \mapsto (\Theta', H', \text{unroll} e') \\
(\Theta, H, \text{load}[\tau] e e_1 e_2 e_3) \mapsto (\Theta', H', \text{load}[\tau] e' e_1 e_2 e_3) \\
(\Theta, H, \text{ref} e) \mapsto (\Theta', H', \text{ref} e') \\
(\Theta, H, !e) \mapsto (\Theta', H', !e') \\
(\Theta, H, \text{assign} e e_2) \mapsto (\Theta', H', \text{assign} e' e_2) \\
(\Theta, H, \text{assign} v e) \mapsto (\Theta', H', \text{assign} v e') \\
(\Theta, H, e[\tau]) \mapsto (\Theta', H', e'[\tau])
\end{cases}
\end{aligned}
\]
Figure 5: Well-formedness for types, type heaps, contexts, value heap typings, and value heaps

<table>
<thead>
<tr>
<th>Rule</th>
<th>Description</th>
</tr>
</thead>
</table>
| $X; \Delta \vdash \tau$ | $X; \Delta \vdash \text{int}$ \hspace{1cm} $\alpha \in \Delta$ \hspace{1cm} $l \in \text{dom}(X)$ \hspace{1cm} $X; \Delta \vdash l$
| | $X; \Delta \vdash \tau' \quad X; \Delta \vdash \tau$ \hspace{1cm} $X; \Delta \vdash \tau$ \hspace{1cm} $X; \Delta, \alpha \vdash \tau$ \hspace{1cm} $(\alpha \notin \Delta)$
| $\vdash X$ | $(\text{for each } \tau \in \text{rng}(X))$
| $X; \Delta \vdash \Gamma$ | $X; \Delta \vdash \cdot$
| | $X; \Delta \vdash \Gamma \quad X; \Delta \vdash \tau$
| $X \vdash \Phi$ | $X; \cdot \vdash \tau$ \hspace{1cm} $(\text{for each } \tau \in \text{rng}(\Phi))$
| $X \vdash H : \Phi$ | $X; \Phi; \cdot \vdash H(L) : \Phi(L)$ \hspace{1cm} $(\text{for each } L \in \text{dom}(H))$

Figure 5 presents well-formedness conditions for types, type heaps, contexts, value heap typings, and value heaps. Types are checked for well-formedness in relation to a type heap $X$ and a type variable context $\Delta$. The former is used to make sure that a named type $l$ is present in the type heap, and the latter is used to make sure a type variable $\alpha$ is properly quantified. A type heap $X$ is well-formed if all of the types mentioned in its range are well-formed. This rule in combination with the one for named types allows named types to be mutually recursive. Note that a well-formed type heap is closed; all of the labels appearing in its range are defined in the type heap itself.

Like type heaps, a value heap typing $\Phi$ is well-formed if all of the types mentioned in its range are well-formed. A value heap is well-formed if the values therein may be typed with a given value heap typing. Value typing is checked via the expression typing relation, shown in Figure 6.
Most of expression typing rules are standard. Noteworthy are the rules for load, and roll and unroll. As mentioned in the operational semantics, the first two term arguments, which are mapped at runtime to a type heap 'context' and a program, respectively, must have type int. The type argument \( \tau' \) indicates the expected type of the loaded program's term component. The third term argument is the 'success-expression' which is applied to the loaded code, so it must take an argument of type \( \tau' \), returning a result of type \( \tau \). The final term argument is the 'failure-expression' which is executed if loading fails; its type must match the return type \( \tau \) of the success condition so that the overall type of the load expression will be \( \tau \).

We use unroll to coerce an expression \( e \) having some named type \( l \). The result has type \( \tau \), where \( l \) maps to \( \tau \) in the type heap \( X \). We use roll to coerce an expression \( e \) to named type \( l \); if \( e \) has type \( \tau \) then the type heap \( X \) must map \( l \) to \( \tau \). The semantics allows for named types to be opaque (abstract). In particular, the expression unroll : \( \tau \) is only well-typed if \( X(l) = \tau \). To make \( l \) abstract, we set \( X(l) \) to \( \bot \), forbidding the coercion to the implementation type. In practice, label \( l \) is made abstract to loaded code by mapping it to \( \bot \) in the type heap mask \( X \) during loading.
\[
X;\Phi;\Delta;\Gamma \vdash e : \tau
\]

\[
X;\Phi;\Delta;\Gamma \vdash e_0 : \text{int}
\]
\[
X;\Phi;\Delta;\Gamma \vdash e_1 : \text{int}
\]
\[
X;\Phi;\Delta;\Gamma \vdash e_2 : \tau' \rightarrow \tau
\]
\[
X;\Phi;\Delta;\Gamma \vdash e_3 : \tau
\]
\[
\frac{\text{load}[\tau'] \ e_0 \ e_1 \ e_2 \ e_3 : \tau}{X;\Phi;\Delta;\Gamma \vdash \text{load}[\tau']}
\]

\[
X;\Phi;\Delta;\Gamma \vdash i : \text{int}
\]
\[
X;\Phi;\Delta;\Gamma \vdash x : \Gamma(x)
\]
\[
X;\Phi;\Delta;\Gamma \vdash L : \Phi(L) \text{ ref}
\]

\[
\frac{X;\Phi;\Delta;\Gamma \vdash e : l}{X;\Phi;\Delta;\Gamma \vdash \text{unroll } e : \tau}
\]
\[
(X(l) = \tau)
\]
\[
\frac{X;\Phi;\Delta;\Gamma \vdash e : \tau}{X;\Phi;\Delta;\Gamma \vdash \text{roll}_l e : l}
\]
\[
(X(l) = \tau)
\]

\[
X;\Phi;\Delta;\Gamma, x:\tau' \vdash e : \tau
\]
\[
X;\Phi;\Delta;\Gamma \vdash \lambda x : \tau'. e : \tau' \rightarrow \tau
\]

\[
X;\Phi;\Delta;\Gamma \vdash e_1 : \tau' \rightarrow \tau
\]
\[
X;\Phi;\Delta;\Gamma \vdash e_2 : \tau'
\]

\[
X;\Phi;\Delta;\Gamma \vdash e_1 \ e_2 : \tau
\]

\[
\frac{X;\Phi;\Delta;\Gamma \vdash e : \tau}{X;\Phi;\Delta;\Gamma \vdash \text{ref } e : \tau \text{ ref}}
\]
\[
X;\Phi;\Delta;\Gamma \vdash e : \tau \text{ ref}
\]
\[
\frac{X;\Phi;\Delta;\Gamma \vdash !e : \tau}{X;\Phi;\Delta;\Gamma \vdash !e : \tau}
\]

\[
X;\Phi;\Delta;\Gamma \vdash e_1 : \tau \text{ ref}
\]
\[
X;\Phi;\Delta;\Gamma \vdash e_2 : \tau
\]
\[
X;\Phi;\Delta;\Gamma \vdash \text{assign } e_1 \ e_2 : \tau
\]

Figure 6: Expression typing
5 Properties of the formal system

The important formal property of this system is that it is type-safe (this property is also called type-soundness). In particular, if a program is well-typed, it will execute in a well-defined fashion indefinitely, or until it completes with a particular value. Formally stated:

**Theorem 5.1 (Type Safety)** If \( \vdash (\Theta, H, e) : \tau \) and \( (\Theta, H, e) \rightarrow^* (\Theta', H', e') \) then either \( e' \) is a value or may be further reduced by some rule of the operational semantics.

Note that \( \rightarrow^* \) is the multi-step reduction relation, indicating one or more applications of the single-step relation \( \rightarrow \). Type safety is proven using the standard technique of showing subject reduction and progress:

**Lemma 5.2 (Subject Reduction)** If \( \vdash (\Theta, H, e) : \tau \) and \( (\Theta, H, e) \rightarrow (\Theta', H', e') \) then \( \vdash (\Theta', H', e') : \tau \).

**Lemma 5.3 (Progress)** If \( \vdash (\Theta, H, e) : \tau \) and \( e \) is not a value, then there exists a \( (\Theta', H', e') \) such that \( (\Theta, H, e) \rightarrow (\Theta', H', e') \).

Stated informally, subject reduction indicates that if a given program has a type \( \tau \), and it may take (at least) one reduction step, then the resulting program, after applying the reduction rule, still has type \( \tau \). Progress indicates that if a well-typed program cannot take an evaluation step, then it must be a value having type \( \tau \). The following chapter presents proofs for these properties.

6 Proofs

Our presentation of the proofs of soundness is bottom-up, starting with properties of the system needed for the final proof. We start with properties of type heaps, then properties of value heaps, then properties of type derivations, and finally the proof of type-safety.

6.1 Properties of Type Heaps

All of the Lemmas (and their corollaries) developed in this subsection are for the purpose of proving the load case of the subject reduction, in Section 6.4.

**Lemma 6.1 (Type Heap Equalities)** Suppose \( A, B, C, D \) are type heaps, then

1. \( (A \oplus B) \oplus C = A \oplus (B \oplus C) \)
2. \((A \oplus B) = (B \oplus A)\)

3. if \(A \mid B\) then \(A \oplus B = A \cup B\)

4. if \(A \not\lesssim C, B \not\lesssim D, A \sim B\) and \(C \sim D, A \mid D, B \mid C\), then \((A \oplus B) \not\lesssim (C \oplus D)\)

5. if \(B \not\lesssim A\) then \((A - B) \oplus B = A \oplus B\).

6. if \(A \leq B\) then \(A \not\lesssim B\)

7. if \(A \leq B\) then \(A \oplus B = A\)

8. if \(A \not\lesssim B\) then \(A \sim B\)

9. if \(B \leq A\) and \(C \mid (B - A)\) then \(C - B = C - A\)

**Proof of 4**  This fails if for some \(l\), \((A \oplus B)(l) = \bot\) and \((C \oplus D)(l) = \tau\). Assume \(A(l) = \bot\). Then \(C(l) = \bot\), if \(l \in \text{dom}(C)\) as \(A \not\lesssim C\). Furthermore \(l \not\in \text{dom}(D)\) as \(A \mid D\). So \((C \oplus D)(l) = \bot\) if anything. Analogous reasoning if \(B(l) = \bot\).

**Proof of 5**  If \(l \in A\) and not in \(B\) then trivially \((A \oplus B)(l) = ((A - B) \cup B)(l)\), likewise if \(l \in B\) and not \(A\), and if \(A(l) = B(l)\). Suppose \(A(l) = \bot\) and \(B(l) = \tau\), then \((A \oplus B)(l) = \tau\) and \((A - B)(l)\) is undefined so \((A - B) \cup B(l) = \tau\). The reverse case, where \(A(l) = \tau\) and \(B(l) = \bot\) cannot happen by assumption.

**Proof of 9**  As \(C\) does not include labels in \(B\) that are not in \(A\), then removing the labels from \(C\) that are in \(B\) is the same as removing only the ones from \(A\).

**Lemma 6.2 (Type Heap Merge)**  If \(X_A\) and \(X_B\) then \(X_A \oplus X_B\).

**Lemma 6.3 (Type Heap Weakening)**  Suppose \(X \oplus X'\) is well-defined.

1. If \(X; \Delta \vdash \tau\) then \((X \oplus X'); \Delta \vdash \tau\)

2. If \(X \vdash \Phi\) then \(X \oplus X' \vdash \Phi\)

3. If \(X; \Phi; \Delta; \Gamma \vdash \epsilon : \tau\) then \(X \oplus X'; \Phi; \Delta; \Gamma \vdash \epsilon : \tau\).

4. If \(X \vdash H : \Phi\) then \(X \oplus X' \vdash H : \Phi\)

**Proof**

1. Proof is by induction on \(X; \Delta \vdash \tau\). If \(\tau = \alpha\) then \((X \oplus X'); \Delta \vdash \alpha\). If \(\tau = \text{int}\) then \((X \oplus X'); \Delta \vdash \text{int}\). If \(\tau = l\) then \(l\) is still in the domain of \(X \oplus X'\) (though its range might change), so \((X \oplus X'); \Delta \vdash l\). The remaining cases follow by induction.
2. We are given that for each $\tau \in \text{rng}(\Phi)$, $X \vdash \tau$. It follows by 1 that $X \oplus X' \vdash \tau$.

3. Proof is by induction on $X; \Phi; \Delta; \Gamma \vdash e : \tau$. This follows trivially or by induction for every rule except: If $e$ is an abstraction or a type application, then Part 1 is also needed to verify the type added to the context. If $e$ is unroll $e'$ or roll $e'$ then we note that because $X(l) = \tau$, then by the definition of $X \oplus X'$, $(X \oplus X')(l) = \tau$ as well, and the rest follows by induction.

4. We are given that for each $L \in \text{dom}(H)$ that $X; \Phi; ; \vdash H(L) : \Phi(L)$. It follows by 3 that $X \oplus X'; \Phi; ; \vdash H(L) : \Phi(L)$.

**Corollary 6.4** Suppose $X \uplus X'$ is well-defined.

1. If $X; \Delta \vdash \tau$ then $X \uplus X'; \Delta \vdash \tau$

2. If $X \vdash \Phi$ then $X \uplus X' \vdash \Phi$

3. If $X; \Phi; \Delta; \Gamma \vdash e : \tau$ then $X \uplus X'; \Phi; \Delta; \Gamma \vdash e : \tau$.

4. If $X \vdash H : \Phi$ then $X \uplus X' \vdash H : \Phi$

**Lemma 6.5 (Type Heap Redundancy Elimination)** If $X \leq X'$ and $X \oplus X'' \vdash \tau$ then $X \oplus (X'' - X') \vdash \tau$

**Proof**

(Sketch) Any label in $X''$ that is also in $X'$ will also be in $X$ as that type heap contains all of the labels of $X'$. Therefore subtracting out the redundant labels will not interfere with type well-formedness.

### 6.2 Properties of Value Heaps

The Lemmas (and their corollaries) developed in this subsection are used in the proof of subject reduction for the load and ref cases.

**Lemma 6.6 (Value Heap Weakening)** If $X \vdash \Phi$, $X \vdash H : \Phi$, $X; \Phi; ; \vdash e : \tau$ and given some $L' \notin \text{dom}(\Phi)$ and some type $\tau'$ such that $X; \vdash \tau'$, then

1. $X \vdash (\Phi \cup \{L' : \tau'\})$

2. $X \vdash H : (\Phi \cup \{L' : \tau'\})$

3. $X; (\Phi \cup \{L' : \tau'\}); ; \vdash e : \tau$

**Proof**
1. We must show that for all $\tau \in \text{rng}(\Phi \uplus \{L': \tau\})$, $X \vdash \tau$. If $\tau \in \text{rng}(\Phi)$, then this is true by inversion of $X \vdash \Phi$. If $\tau \not\in \text{rng}(\Phi)$ then $\tau = \tau'$, and we are given that $X;\cdot \vdash \tau'$.

2. This follows trivially by assumption, since we have not changed the domain of $H$.

3. Proof by induction on $X;\Phi;\cdot \vdash e : \tau$. Follows trivially or by induction. In the abstraction and type application cases, we need to use $1$ for the introduction of the new type, and for $e = L$, we have $\Phi(L) = \tau = (\Phi \uplus \{L': \tau\})(L)$.

**Corollary 6.7** If $X \vdash \Phi$ and $X \vdash H : \Phi$, and given some $\Phi'$ such that $X \vdash \Phi'$ and $\Phi | \Phi'$, then

1. $X \vdash (\Phi \uplus \Phi')$
2. $X \vdash H : (\Phi \uplus \Phi')$
3. $X; (\Phi \uplus \Phi');\cdot \vdash e : \tau$

**Lemma 6.8** *(Value Heap Redundancy Elimination)* If $X \vdash H : \Phi$, and there exists some $L' \in \text{dom}(\Phi)$ s.t. $L' \not\in \text{dom}(H)$, then $X \vdash H : \{L : \tau | L : \tau \in \Phi, L \neq L'\}$.

**Proof**

We must show that for all $L \in \text{dom}(H), H(L) = \{(L : \tau | L : \tau \in \Phi, L \neq L')\}(L)$. But this is obvious, since we have only removed a label from $\Phi$ that was not in $H$.

**6.3 Properties of Type Derivations**

**Lemma 6.9** *(Type in Type Substitution)* If $X;\Delta, \alpha \vdash \tau$ and $X;\Delta \vdash \tau'$ then $X;\Delta \vdash [\tau'/\alpha]$.

**Proof**

Proof by induction on $X;\Delta, \alpha \vdash \tau$  

Case 1: $X;\Delta, \alpha \vdash l$ or $X;\Delta, \alpha \vdash \text{int}$ follows trivially.

Case 2: $X;\Delta, \alpha \vdash \alpha$ since by assumption $X;\Delta \vdash [\tau'/\alpha]$.

Remaining cases follow by simple induction.

The following lemma is used in the ref case of subject reduction.

**Lemma 6.10** *(Regularity)*
If $X; \Phi; \Delta; \Gamma \vdash v : \tau$, $\vdash X$, $X; \Delta \vdash \Gamma$, and $X \vdash \Phi$, then $X; \Delta \vdash \tau$.

**Proof**

The proof proceeds by induction on the derivation $X; \Phi; \Delta; \Gamma \vdash e : \tau$.

**Case 1:** $X; \Phi; \Delta; \Gamma \vdash i : \text{int}$. Follows directly that $X; \Delta \vdash \text{int}$.

**Case 2:** $X; \Phi; \Delta; \Gamma \vdash L : \Phi(L)$. By assumption $X \vdash \Phi$, and by inversion $X; \cdot \vdash \Phi(L)$.

**Case 3:** $X; \Phi; \Delta; \Gamma \vdash y : \Gamma(y)$. By assumption $X; \Delta \vdash \Gamma$, so $X; \Delta \vdash \Gamma(y)$.

**Case 4:** $X; \Phi; \Delta; \Gamma \vdash \lambda x : \tau'. e : \tau' \rightarrow \tau$. By inversion $X; \Delta \vdash \tau'$. As a result, $X; \Delta \vdash \Gamma, x : \tau'$, as $\tau'$ is well-formed. Therefore, by induction $X; \Delta \vdash \tau$. Thus, $X; \Delta \vdash \tau' \rightarrow \tau$.

**Case 5:** $X; \Phi; \Delta; \Gamma \vdash e_1 e_2 : \tau$. By induction $X; \Delta \vdash \tau' \rightarrow \tau$, and by inversion $X; \Delta \vdash \tau$.

**Case 6:** $X; \Phi; \Delta; \Gamma \vdash \text{load}[\tau'] e_0 e_1 e_2 : \tau$. By induction.

**Case 7:** $X; \Phi; \Delta; \Gamma \vdash \text{roll}_l e : l$. By the rule side-condition $X(l) = \tau$, thus $X; \Delta \vdash \cdot$.

**Case 8:** $X; \Phi; \Delta; \Gamma \vdash \text{unroll} e : \tau$. By the rule side-condition $X(l) = \tau$, and by assumption $\vdash X$, so $X; \cdot \vdash \tau$. By weakening, $X; \Delta \vdash \tau$.

**Case 9:** $X; \Phi; \Delta; \Gamma \vdash \text{ref} e : \tau \text{ ref}$. By induction $X; \Delta \vdash \tau$, so $X; \Delta \vdash \tau \text{ ref}$ follows directly.

**Case 10:** $X; \Phi; \Delta; \Gamma \vdash \text{ref} e : \tau$. By induction $X; \Delta \vdash \tau \text{ ref}$, and by induction again $X; \Delta \vdash \tau$.

**Case 11:** $X; \Phi; \Delta; \Gamma \vdash \text{assign} e_1 e_2 : \tau$. By induction.

**Case 12:** $X; \Phi; \Delta; \Gamma \vdash e : \forall \alpha \tau$. By induction.

**Case 13:** $X; \Phi; \Delta; \Gamma \vdash e[\tau'] : \tau[\tau'/\alpha]$, so by inversion $X; \Phi; \Delta, \alpha ; \Gamma \vdash e : \tau$ and $X; \Delta \vdash \tau'$. By induction $X; \Delta, \alpha \vdash \tau$ and by type in type substitution, $X; \Delta \vdash \tau[\tau'/\alpha]$.

The following two lemmas are used in the proof of substitution, also below.

**Lemma 6.11 (Weakening)** If $X; \Phi; \Delta; \Gamma \vdash e : \tau$ and $x \notin \text{dom}(\Gamma)$ and $\alpha \notin \text{dom}(\Delta)$, then $X; \Phi; \Delta; \Gamma, x : \tau' \vdash e : \tau$, and $X; \Phi; \Delta; \alpha, \Gamma \vdash e : \tau$. Moreover, the latter derivations have the same depth as the former.

**Lemma 6.12 (Permutation)** If $X; \Phi; \Delta; \Gamma \vdash e : \tau$ with $\Gamma'$ is a permutation of $\Gamma$ and $\Delta'$ is a permutation of $\Delta$, then $X; \Phi; \Delta; \Gamma' \vdash e : \tau$, and $X; \Phi; \Delta'; \Gamma \vdash e : \tau$.

Moreover, the latter derivations have the same depth as the former.
Lemma 6.13 (Substitution) If $X; \Phi; \Delta; \Gamma, x: \tau' \vdash e : \tau$ and $X; \Phi; \Delta; \Gamma \vdash e' : \tau'$ then $X; \Phi; \Delta; \Gamma \vdash e[e'/x] : \tau$.

Proof

Proof is by induction on $X; \Phi; \Delta; \Gamma, x: \tau' \vdash e : \tau$.

Case 1: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash i : \text{int}$

Therefore $e[e'/x] = i$, and $X; \Phi; \Delta; \Gamma \vdash i : \text{int}$.

Case 2: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash L : \Phi(L)$.

Therefore $e[e'/x] = L$, and $X; \Phi; \Delta; \Gamma \vdash L : \Phi(L)$.

Case 3: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash y : (\text{int})$. If $y = x$ then $y[e'/x] = e'$. By assumption, $X; \Phi; \Delta; \Gamma \vdash e' : \tau'$, and the result follows from $\tau = \tau'$. Otherwise, $y[e'/x] = y$ and $X; \Phi; \Delta; \Gamma \vdash y : \Gamma(y)$.

Case 4: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash \lambda y: \tau''. e : \tau'' \rightarrow \tau$

Follows by induction (with Weakening and Permutation): $X; \Phi; \Delta; \Gamma, y: \tau'' \vdash e[e'/x] : \tau$. Therefore, $X; \Phi; \Delta; \Gamma \vdash (\lambda y: \tau''. e)[e'/x] : \tau'' \rightarrow \tau$.

Case 5: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash e_1 e_2 : \tau$.

Follows by induction: $X; \Phi; \Delta; \Gamma \vdash e_1[e'/x] : \tau'' \rightarrow \tau$ and $X; \Phi; \Delta; \Gamma \vdash e_2[e'/x] : \tau''$. Therefore, $X; \Phi; \Delta; \Gamma \vdash (e_1 e_2)[e'/x] : \tau$.

Case 6: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash \text{load}[	au''] e_0 e_1 e_2 e_3 : \tau$.

Follows by induction: $X; \Phi; \Delta; \Gamma \vdash e_0[e'/x] : \text{int}, X; \Phi; \Delta; \Gamma \vdash e_1[e'/x] : \text{int}, X; \Phi; \Delta; \Gamma \vdash e_2[e'/x] : \tau'' \rightarrow \tau$, and $X; \Phi; \Delta; \Gamma \vdash e_3[e'/x] : \tau$, so therefore $X; \Phi; \Delta; \Gamma \vdash (\text{load}[	au''] e_0 e_1 e_2 e_3)[e'/x] : \tau$.

Case 7: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash \text{roll}_1 e : l$.

Follows by induction: $X; \Phi; \Delta; \Gamma \vdash e[e'/x] : \tau''$, so $X; \Phi; \Delta; \Gamma \vdash (\text{roll}_1 e)[e'/x] : l$.

Case 8: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash \text{unroll} e : \tau$.

Follows by induction: $X; \Phi; \Delta; \Gamma \vdash e[e'/x] : \tau$, so $X; \Phi; \Delta; \Gamma \vdash (\text{unroll} e)[e'/x] : \tau$.

Case 9: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash \text{ref} e : \tau \text{ ref}$.

Follows by induction: $X; \Phi; \Delta; \Gamma \vdash e[e'/x] : \tau$, so $X; \Phi; \Delta; \Gamma \vdash (\text{ref} e)[e'/x] : \tau \text{ ref}$.

Case 10: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash ! e : \tau$.

Follows by induction: $X; \Phi; \Delta; \Gamma \vdash e[e'/x] : \tau \text{ ref}$, so $X; \Phi; \Delta; \Gamma \vdash (! e)[e'/x] : \tau$.

Case 11: $X; \Phi; \Delta; \Gamma, x: \tau' \vdash \text{assign} e_1 e_2 : \tau$. 18
Follows by induction: $X; \Phi; \Delta; \Gamma \vdash e_1[e'/x] : \tau \text{ ref}$ and $X; \Phi; \Delta; \Gamma \vdash e_2[e'/x] : \tau$. Therefore, $X; \Phi; \Delta; \Gamma \vdash (\text{assign } e_1 e_2)[e'/x] : \tau$.

Case 12: $X; \Phi; \Delta; \Gamma, x : \tau' \vdash \Lambda \alpha. e : \forall \alpha. \tau$. Follows by induction (with Weakening): $X; \Phi; \Delta, \alpha; \Gamma \vdash e[e'/x] : \tau$, so $X; \Phi; \Delta, \alpha; \Gamma \vdash \Lambda \alpha. e[e'/x] : \forall \alpha. \tau$.

Case 13: $X; \Phi; \Delta, \alpha; \Gamma, x : \tau' \vdash e[\tau'] : \tau[\tau'/\alpha]$. Follows by induction: $X; \Phi; \Delta, \alpha; \Gamma \vdash e[e'/x] : \forall \alpha. \tau$, so $X; \Phi; \Delta, \alpha; \Gamma \vdash (e[e'/x])[\tau'] : \tau[\tau'/\alpha]$.

Lemma 6.14 (Type Substitution) If $\vdash X$ and $X; \Phi; \Delta, \alpha; \Gamma \vdash e : \tau$ and $X; \Delta \vdash \tau'$ then $X; \Phi; \Delta, \alpha; \Gamma \vdash e[\tau'/\alpha] : \tau[\tau'/\alpha]$.

Proof
Proof is by induction on $X; \Phi; \Delta, \alpha; \Gamma \vdash e : \tau$. Most cases are trivial or by induction. Selected cases:

Case 1: $X; \Phi; \Delta, \alpha; \Gamma \vdash \text{load}[\tau''] e_1 e_2 e_3 : \tau$.

By induction: $X; \Phi; \Delta, \alpha; \Gamma \vdash e_0[\tau'/\alpha] : \text{int}, X; \Phi; \Delta, \alpha; \Gamma \vdash e_1[\tau'/\alpha] : \text{int}, X; \Phi; \Delta, \alpha; \Gamma \vdash e_2[\tau'/\alpha] : (\tau'' \rightarrow \tau)[\tau'/\alpha]$, and $X; \Phi; \Delta, \alpha; \Gamma \vdash e_3[\tau'/\alpha] : \tau[\tau'/\alpha]$. By type in type substitution $X; \Delta \vdash \tau''[\tau'/\alpha]$ so therefore $X; \Phi; \Delta, \alpha; \Gamma \vdash ((\text{load}[\tau''] e_0 e_1 e_2 e_3)[\tau'/\alpha] : \tau[\tau'/\alpha]$.

Case 2: $X; \Phi; \Delta, \alpha; \Gamma \vdash \text{roll}_l e : l$.

Follows by induction: $X; \Phi; \Delta, \alpha; \Gamma \vdash e[\tau'/\alpha] : \tau''[\tau'/\alpha]$. As $X(l) = \tau''$ and $\vdash X$ then $X; \cdot \vdash \tau''$. Therefore $X; \Phi; \Delta, \alpha; \Gamma \vdash (\text{roll}_l e)[\tau'/\alpha] : l[\tau'/\alpha]$ since $\tau''$ must be closed.

Case 3: $X; \Phi; \Delta, \alpha; \Gamma \vdash \text{unroll}_l e : \tau[\tau'/\alpha]$.

Follows by induction: $X; \Phi; \Delta, \alpha; \Gamma \vdash e[\tau'/\alpha] : l[\tau'/\alpha]$, so $X; \Phi; \Delta, \alpha; \Gamma \vdash (\text{unroll}_l e)[\tau'/\alpha] : \tau[\tau'/\alpha]$.

The following lemma is used in the proof of progress, to develop type soundness.

Lemma 6.15 (Canonical Forms) If $X; \Phi; \cdot \vdash v : \tau$ and

- $\tau = \text{int}$ then $v = i$.
- $\tau = \tau_1 \rightarrow \tau_2$ then $v = \lambda x : \tau. e$.
- $\tau = l$ then $v = \text{roll}_l(v')$ for some $v'$.
- $\tau = \tau \text{ ref}$ then $v = L$.
- $\tau = \forall \alpha. \tau$ then $v = \Lambda \alpha. e$.

Proof
Proof is by examination of the last step of the typing derivation $X; \Phi; \cdot \vdash v : \tau$. Most rules either require the expression to be a non-value or require a non-empty context. The remaining rules produce each of the types at the correct values.
6.4 Type Soundness

We establish type soundness in the standard manner, by proof of subject reduction and progress.

**Lemma 6.16 (Subject Reduction)** If ⊢ (Θ, H, e) : τ and (Θ, H, e) → (Θ', H', e') then ⊢ (Θ', H', e') : τ

**Proof**

⊢ (Θ', H', e') : τ is proven by showing that, for some Φ'

- (Type-heap well-formedness) ⊢ X'_I ⊢ X'_H
- (Value-heap typing well-formedness) X'_I ⊢ X'_H : Φ'
- (Value-heap well-formedness) X'_I ⊢ H' : Φ'
- (Expression well-formedness) X'_I ⊢ X'_H; Φ'; ; ; e' : τ

For brevity, we refer to these points in the proof as THWF, VHTWF, VHWF, and EWF, respectively, and except when otherwise noted, we assume that Φ' = Φ and that THWF, VHTWF, VHWF hold by assumption. The proof is by induction on the typing derivation ⊢ (Θ, H, e) (for some Φ), and on (Θ, H, e) → (Θ', H', e').

**Case 1:** (beta) (Θ, H, (λx:τ.e''')v) → (Θ, H, e''[v/x]).

As e is an application, by inversion X_I ⊢ X_H; Φ; x : τ' ⊢ e'' : τ, and X_I ⊢ X_H; Φ; ; ; ⊢ v : τ'. EWF follows by substitution: X_I ⊢ X_H; Φ; ; ; ⊢ e''[v/x] : τ.

**Case 2:** (load-success) ((X_I, X_H), H, load[τ][h i e_2 e_3]) → ((X_I, X_H), H, e_2 e)

We must establish each of THWF, VHTWF, VHWF, and EWF. We know the following facts. From this evaluation rule:

1. \( \hat{h} = X \)
2. \( \hat{i} = (X_I^2, X_H^2), H_2, e \)
3. \( X_H^1 \vdash \hat{i} : τ' \)
4. \( (X_I^1, X) \) link \((X_I^2, X_H^2)\) \(\Rightarrow (X_I^3, X')\)
5. \( X_I^3 = X' \oplus X_H^1 \)
6. \( H_1 \) link \(H_2 \Rightarrow H_3 \)
7. \( X_H^1 \leq X \)
8. \( X_H^2 \mid (X_H^1 - X) \)

As linking is well-formed for both value heaps (by 6) and type heaps (by 4):
\begin{enumerate}
\item $X_1^1 \sim X_1^2$
\item $X \mid X_1^2$
\item $X_2^1 \preceq X_1^1$
\item $X \preceq X_1^2$
\item $H_1 \mid H_2$
\end{enumerate}

As the loaded program is well-formed (by 3), for some $\Phi_2$:

\begin{enumerate}
\item $\vdash X_1^2 \cup X_1^2$
\item $X_1^2 \cup X_2^1 \vdash \Phi_2$
\item $X_1^2 \cup X_2^1 \vdash H_2 : \Phi_2$
\item $X_1^2 \cup X_2^1 ; \Phi_2 ; \vdash e : \tau'$
\item $X_1^2 \mid X_1^2$
\end{enumerate}

Since the running program is well-formed, for some $\Phi_1$:

\begin{enumerate}
\item $\vdash X_1^1 \cup X_2^1$
\item $X_1^1 \cup X_2^1 \vdash \Phi_1$
\item $X_1^1 \cup X_2^1 \vdash H_1 : \Phi_1$
\item $X_1^1 \cup X_2^1 ; \Phi_1 ; \vdash \text{load}[\tau] \text{ie} e_3 : \tau$
\item By inversion of this last expression's typing judgement:
\item $X_1^1 \cup X_2^1 ; \Phi_1 ; \vdash i : \text{int}$
\item $X_1^1 \cup X_2^1 ; \Phi_1 ; \vdash e_2 : \tau' \rightarrow \tau$
\item $X_1^1 \cup X_2^1 ; \Phi_1 ; \vdash e_3 : \tau$
\end{enumerate}

We define $\Phi_1$ as the least $\Phi_1$ that satisfies 21, and $\Phi_2$ as the least $\Phi_2$ that satisfies 16. Finally, we define $\Phi_3$ as $\Phi_1 \oplus \Phi_2$, which is well-defined as $\text{dom}(H_1) = \text{dom}(\Phi_1)$, $\text{dom}(H_2) = \text{dom}(\Phi_2)$, and $\vdash H_1 \mid H_2$ by 19.

To prove well-formedness of the new program we must establish:

\begin{itemize}
\item \((\text{THWF}): \vdash X_1^3 \cup X_1^3\)
\end{itemize}

By definition, this is\((X_1^1 \oplus X_1^2) - (X \cup X_1^2)) \cup ((X \cup X_1^2) \cup X_1^3)\). The expression \((X_1^1 \oplus X_1^2)\) is well-defined by 9, \((X \cup X_1^2)\) is well-defined by 10. As \(X_1^1 \preceq X\) and \(X \mid X_1^2\), then \((X \cup X_1^2) \cup X_1^3\) is well-defined, and equal to \(X_1^3 \oplus X_1^3\). Finally, the whole thing is well-defined if there is no label defined in \(X_1^3 \oplus X_1^3\), not defined in \(X\) but defined in \(X_1^3\). However, 8 and 19 guarantee that fact.

Therefore, \(X_1^3 \cup X_1^3\)
= ((X^1_L + X^2_L) - (X^3_H) \cup (X^3_H \cap X^1_H)) \cup (X^2_H \cap X^1_H) 
= ((X^1_L + X^2_L) - (X^3_H) \cup (X^3_H \cap X^1_H)) \cup (X^2_H \cap X^1_H)

by reasoning above

= (X^1_L + X^2_L) \cup (X^1_H \cap X^2_H)

as X^2_L \cap (X^3_H - X) and X^1_L \cap X^3_H

the restriction from type mask X

can’t remove more labels

By Lemma 6.1 (5), since (X^3_H \cap X^2_H) \leq (X^2_L \cap X^1_L) by 11, 12, and

Lemma 6.1 (4) = (X^1_L + X^2_L) \leq (X^1_L + X^2_L) by commutativity

by associativity and commutivity

By 19, \vdash (X^1_L + X^1_H), and by 14, \vdash (X^2_L + X^2_H). So by lemma 6.2, the whole
thing is well formed.

\bullet (VHTWF): X^3_L \cup X^3_H \vdash \Phi_3

This is equivalent to X^3_L \cup X^3_H \vdash (\Phi_1 \cup \Phi_2). Consider some L : \tau \in \Phi_3; there
are two possibilities:

1. L : \tau \in \Phi_1. By 20, X^1_L \cup X^1_H \vdash \Phi_1, so X^1_L \cup X^1_H \vdash \tau. As X^1_L \mid X^1_H,
   this is equivalently X^1_L \cap X^1_H \vdash \tau. By 6.3 (type heap weakening),
   (X^1_L \cap X^1_H) \cap (X^2_L \cap X^2_H) \vdash \tau, which we have shown in the proof of
   THWF is equivalent to X^3_L \cup X^3_H \vdash \tau.

2. L : \tau \in \Phi_2. By 15, X^2_L \cup X^2_H \vdash \Phi_2, so X^2_L \cup X^2_H \vdash \tau. By similar
   weakening as above we may conclude X^3_L \cup X^3_H \vdash \tau.

\bullet (VHWF): X^3_L \cup X^3_H \vdash H_3 : \Phi_3 This is equivalent to X^3_L \cup X^3_H \vdash (H_1 \cup H_2) : 
(\Phi_1 \cup \Phi_2). Consider some L \in H_3; there are two possibilities:

1. (L \equiv v) \in H_1. By 21, X^1_L \cup X^1_H \vdash H_1 : \Phi_1, so X^1_L \cup X^1_H; \Phi_1; \vdash v : \tau, where \Phi_1(L) = \tau. By 6.3 as in VHTWF, (X^1_L \cup X^1_H) \cap (X^2_L \cup
   X^2_H); \Phi_1; \vdash v : \tau.

2. (L \equiv v) \in H_2. X^3_L \cup X^3_H; \Phi_3; \vdash v : \Phi_3(L) follows by similar reasoning.

\bullet (EWF): X^3_L \cup X^3_H; \Phi_3; \vdash e_2 e : \tau

We know X^1_L \cup X^1_H; \Phi_1; \vdash e_2 e : \tau' \rightarrow \tau and X^1_L \cup X^1_H; \Phi_1; \vdash e_3 : \tau. By
the same weakening argument as above, X^3_L \cup X^3_H; \Phi_3; \vdash e_2 e : \tau' \rightarrow \tau, and
X^3_L \cup X^3_H; \Phi_3; \vdash e_3 : \tau. Therefore, we may conclude our well-formedness result.

Case 3:  (load-failure) ((X_I, X_H), H_1, load[\tau'] h i e_2 e_3) \mapsto ((X_I, X_H), H_1, e_3)

EWF follows directly as X_I \cup X_H; \Phi; \vdash e_2 e_3 : \tau.

Case 4:  (unroll) ((X_I, X_H), H, unroll(roll_I v)) \mapsto ((X_I, X_H), H, v)

We must have concluded (during the typing derivation of X_I \cup X_H; \Phi; \vdash unroll(roll_I v) : \tau) that X_I \cup X_H; \Phi; \vdash roll_I v : I (where (X_I \cup X_H)(I) = \tau), and again X_I \cup X_H; \Phi; \vdash v : \tau, which proves EWF.
Case 5: (ref) \(((X_I, X_H), H, \text{ref } v) \mapsto ((X_I, X_H), H \cup \{ L = v \}, L)\)

THWF follows by assumption. We show VHTWF and VHWF as follows. Consider the typing derivation of \(X_I \cup X_H; \Phi; \cdot \vdash \text{ref } v : \tau\) by inversion \(\tau = \tau' \text{ ref}\) and \(X_I \cup X_H; \Phi; \cdot \vdash \cdot v : \tau'\), for some \(\Phi\). We may assume that \(L \notin \text{dom}(\Phi)\) by value-heap redundancy elimination since \(L \notin H\) (by the side-condition on the evaluation rule). Therefore we choose \(\Phi' = \Phi \cup \{ L : \tau' \}\).

To show VHTWF, we must show that \(X_I \cup X_H \vdash \Phi'\). Consider an arbitrary \(L' \in \text{dom}(\Phi')\):

- if \(L' \in \text{dom}(\Phi)\) then \(X_I \cup X_H \vdash (\Phi \cup \{ L : \tau' \})(L')\) by assumption and value-heap weakening.
- if \(L' = L\) then to show \(X_I \cup X_H \vdash \Phi \cup \{ L : \tau' \}\)(L'), we must show that \(X_I \cup X_H \vdash \tau'.\) This follows because by the typing derivation of \(X_I \cup X_H; \Phi; \cdot \vdash \text{ref } v : \tau\) we must have previously concluded that \(X_I \cup X_H; \Phi; \cdot \vdash \cdot v : \tau'\).

By Lemma 6.10, \(X_I \cup X_H \vdash \tau'\).

To show VHWF, we must show that \(X_I \cup X_H \vdash (H \cup \{ L = v \}) : \Phi'\). Consider an arbitrary \(L' \in \text{dom}(H \cup \{ L = v \})\):

- if \(L' \in \text{dom}(H)\) then \(X_I \cup X_H \vdash (H \cup \{ L : \tau' \})(L')\) by assumption and value-heap weakening.
- if \(L' = L\) then to show \(X_I \cup X_H \vdash H(L) : (\Phi \cup \{ L : \tau' \})(L')\), we must show that \(X_I \cup X_H \vdash \cdot v : \tau'\). But this follows by assumption, as noted above.

Finally, to show EWF, we note that \(X_I \cup X_H; (\Phi \cup \{ L : \tau' \}); H \cup \{ L = v \} \vdash L : \tau' \text{ ref}\).

Case 6: (deref) \(((X_I, X_H), H, !L) \mapsto ((X_I, X_H), H, H(L))\).

By inversion, \(X_I \cup X_H; \Phi; \cdot \vdash L : \tau \text{ ref}\), and furthermore that \(\Phi(L) = \tau\). By program well-formedness, \(X_I \cup X_H \vdash H : \Phi\), which implies that \(X_I \cup X_H; \Phi; \cdot \vdash H(L) : \Phi(L) = \tau\), which is the desired result.

Case 7: (assign) \(((X_I, X_H), H, \text{assign } L v) \mapsto ((X_I, X_H), H[L = v], v)\).

THWF and VHTWF follow by assumption for \(\Phi' = \Phi\). To show VHWF, we must show that \(X \cup X_H \vdash H[L = v] : \Phi'\). Consider some \(L' \in H[L = v]\):

- if \(L' \neq L\), then \(X_I \cup X_H \vdash (H[L = v])(L') : \Phi'(L')\) follows by assumption (since \(H\) has not changed at these labels).
- if \(L' = L\), then we must show that \(X_I \cup X_H \vdash \cdot v : \Phi'(L)\). But by inversion \(X_I \cup X_H; \Phi; \cdot \vdash L : \tau \text{ ref}\) which implies (again by inversion) that \(\Phi'(L) = \tau\). Also by inversion \(X_I \cup X_H; \Phi; \cdot \vdash \cdot v : \tau\), which gives the desired result.
Finally, for \( EWF \) we must show that \( X_I \parallel X_H; \Phi'; \vdash u : \tau \). This follows trivially by inversion.

**Case 8:** \((\text{tapp}) (\Theta, H, (\Lambda \alpha.e)[\tau]) \rightarrow (\Theta, H, e[\tau/\alpha])\), of type \( \tau'[\tau/\alpha] \).

By inversion, \( X_I \parallel X_H; \Phi'; \vdash (\Lambda \alpha.e) : \forall \alpha.\tau \) and \( X_I \parallel X_H; \vdash \tau' \). Doing this again we get \( X_I \parallel X_H; \Phi; \vdash e : \tau \). We may now apply type substitution to conclude \( X_I \parallel X_H; \Phi; \vdash e[\tau'[\alpha] : \tau'[\tau/\alpha] \]

**Case 9:** (congruence rules) Follow by induction of \((\Theta, H, e) \rightarrow (\Theta', H', e')\).

**Lemma 6.17** If \( X_I \parallel X_H; X_I \parallel X_H \vdash \Phi, X_I \parallel X_H \vdash H : \Phi, X_I \parallel X_H; \Phi; \vdash e : \tau \), and \( e \) is not a value, then there exists an \(((X'_I, X'_H), H', e')\) such that \(((X_I, X_H), H, e) \rightarrow ((X'_I, X'_H), H', e')\).

**Proof**

Proof is by induction on \( X_I \parallel X_H; \Phi; \vdash e : \tau \) and on \(((X_I, X_H), H, e) \rightarrow ((X'_I, X'_H), H', e')\). We will only consider the expression typing rules in which \( e \) is not a value:

**Case 1:** \((\text{app}) e = e_1 e_2\)

Three cases:

- \( e_1 \) is not a value
  
  By induction, there exists an \(((X'_I, X'_H), H', e'_1)\) such that \(((X_I, X_H), H, e_1) \rightarrow ((X'_I, X'_H), H', e'_1)\). By congruence, \(((X_I, X_H), H, e_1 e_2) \rightarrow ((X'_I, X'_H), H', e'_1 e_2)\).

- \( e_2 \) is not a value
  
  By induction, there exists an \(((X'_I, X'_H), H', e'_2)\) such that \(((X_I, X_H), H, e_2) \rightarrow ((X'_I, X'_H), H', e'_2)\). By congruence, \(((X_I, X_H), H, e_1 e_2) \rightarrow ((X'_I, X'_H), H', e'_1 e'_2)\).

- \( e_1 \) and \( e_2 \) are values.
  
  By canonical forms, \( e_1 = \lambda x : \tau'.e \). Therefore, by beta reduction, \(((X_I, X_H), H, e_1 e_2) \) steps to \(((X_I, X_H), H', e[e_2/x])\).

**Case 2:** \((\text{load}) e = \text{load}[\tau'] e_0 e_1 e_2 e_3\)

If either of the first two arguments is not a value, then by induction there exists a \(((X'_I, X'_H), H', e'_1)\) such that \(((X_I, X_H), H, e_1) \rightarrow ((X'_I, X'_H), H', e'_1)\). Therefore, by congruence, load can take a step.

Otherwise, \( e_0 \) and \( e_1 \) are values and by canonical forms, some integers \( h, i \). If the conditions for load-success hold (i.e. \( h \) is the representation of a type heap and \( i \) is the representation of well-typed program that is link-compatible with \( h \) and the current type heap) then \(((X_I, X_H), H, \text{load}[\tau'] e_1 e_2 e_3) \rightarrow ((X'_I, X'_H), H', e_2 e)\).
If not, the load-fail step rule applies and \(((X_I, X_H), H, \text{load}[\tau'] e_0 e_1 e_2 e_3) \mapsto ((X_I, X_H), H, e_3)\).

**Case 3:** (unroll) \(e = \text{unroll} e_1\).

If \(e_1\) is not a value, congruence rule applies. Otherwise \(e_1\) must be a value of type \(\tau\), so by canonical forms, \(e_1 = \text{roll}(v)\). By the unroll reduction, \(((X_I, X_H), H, \text{unroll}(\text{roll}(v))) \mapsto ((X_I, X_H), H, v)\).

**Case 4:** (ref) \(e = \text{ref} e_1\).

If \(e_1\) is not a value, congruence rule applies. Otherwise, by the ref reduction, \(((X_I, X_H), H, \text{ref} v) \mapsto ((X_I, X_H), H \uplus \{L = v\}, L)\).

**Case 5:** (deref) \(e = !e_1\).

If \(e_1\) is not a value, congruence rule applies. Otherwise \(e_1\) must be a value of type \(\tau'\), so by canonical forms, \(e_1 = L\). By inversion, \(L \in \text{dom}(H)\), and by the deref reduction, \(((X_I, X_H), H, !L) \mapsto ((X_I, X_H), H, H(L))\).

**Case 6:** (assign) \(e = \text{assign} e_1 e_2\).

If \(e_1\) and/or \(e_2\) are not values, congruence rule applies. Otherwise, \(e_1\) is a value of type \(\tau'\), so by canonical forms, \(e_1 = L\). By inversion, \(L \in \text{dom}(H)\), and by the assign reduction, \((\Theta, H, \text{assign} L v) \mapsto (\Theta, H[L = v], v)\).

**Case 7:** (tapp) \(e = e_1[\tau]\).

If \(e_1\) is not a value, congruence rule applies. Otherwise \(e_1\) is of type \(\forall \alpha . \tau\), so by canonical forms, \(e_1 = \Lambda \alpha . e'\), so by tapp reduction \((\Theta, H, e_1[\tau]) \mapsto (\Theta, H.e'[\tau/\alpha])\).

**Corollary 6.18 (Progress)** If \(\vdash (\Theta, H, e) : \tau\) and \(e\) is not a value, then there exists \(a (\Theta', H', e')\) such that \((\Theta, H, e) \mapsto (\Theta', H', e')\).

We say that a term is **stuck** if it is not a value and if no rule of the operational semantics applies to it. Type safety requires that no well-typed term can become stuck:

**Theorem 6.19 (Type Safety)** If \(\vdash (\Theta, H, e) : \tau\) and \((\Theta, H, e) \mapsto^* (\Theta', H', e')\) then \((\Theta', H', e')\) is not stuck.

**Proof**
Proof is by induction on the number of steps of execution \(((\Theta, H, e) \mapsto^* (\Theta', H', e'))\) using Progress to show there is a new state and Subject Reduction to show that that new state is well typed.
References


