Space-Efficient Manifest Contracts

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Abstract
The standard algorithm for higher-order contract checking can lead to unbounded space consumption and can destroy tail recursion, altering a program’s asymptotic space complexity. While space efficiency for gradual types—contracts mediating untyped and typed code—is well studied, sound space efficiency for manifest contracts—contracts that check stronger properties than simple types, e.g., “is a natural” instead of “is an integer”—remains an open problem.

We show how to achieve sound space efficiency for manifest contracts with strong predicate contracts. The essential trick is breaking the contract checking down into coercions; structured, blame-annotated lists of checks. By carefully preventing duplicate coercions from appearing, we can restore space efficiency while keeping the same observable behavior.

Categories and Subject Descriptors D.3.3 [Software]: Programming Languages—Language Constructs and Features

Keywords contracts; pre- and post-conditions; function proxy; coercions; space efficiency

1. Introduction
Types are an extremely successful form of lightweight specification: programmers can state their intent—e.g., plus is a function that takes two numbers and returns another number—and then type checkers can ensure that a program conforms to the programmer’s intent. Types can only go so far though: division is, like addition, a function that takes two numbers and returns another number... so long as the second number isn’t zero. Conventional type systems do a good job of stopping many kinds of errors, but most type systems cannot protect partial operations like division and array indexing. Advanced techniques—singleton and dependent types, for example—can cover many of these cases, allowing programmers to use types like “non-zero number” or “index within bounds” to specify the domains on which partial operations are safe. Such techniques are demanding: they can be difficult to understand, they force certain programming idioms, and they place heavy constraints on the programming language, requiring purity or even strong normalization.

Contracts are a popular compromise: programmers write type-like contracts of the form \( \text{Int} \rightarrow \{ x : \text{Int} \mid x \neq 0 \} \rightarrow \text{Int} \), where the predicates \( x \neq 0 \) are written in code. These type-like specifications can then be checked at runtime [5]. Models of contract calculi have taken two forms: latent and manifest [12]. We take the manifest approach here, which means checking contracts with casts, written \( \langle T_1 \Rightarrow T_2 \rangle \ e \). Checking a predicate contract (also called a refinement type, though that term is overloaded) like \( \{ x : \text{Int} \mid x \neq 0 \} \) on a number \( n \) involves running the predicate \( x \neq 0 \) with \( n \) for \( x \). Casts from one predicate contract to another, \( \{ x : B \mid e_1 \} \Rightarrow \{ x : B \mid e_2 \} \), take a constant \( k \) and check to see that \( e_2[k/x] \) is true. It’s hard to know what to do with function casts at runtime: in \( \langle T_{11} \Rightarrow T_{12} \Rightarrow T_{21} \Rightarrow T_{22} \rangle \ e \), we know that \( e \) is a \( T_{11} \rightarrow T_{12} \), but what does that tell us about treating \( e \) as a \( T_{21} \rightarrow T_{22} \)? Findler and Felleisen’s insight is that we must defer checking, waiting until the cast value \( e \) gets an argument [5]. These deferred checks are recorded on the value by means of a function proxy, i.e., \( \langle T_{11} \Rightarrow T_{12} \Rightarrow T_{21} \Rightarrow T_{22} \rangle \ e \) is a value when \( e \) is a value; applying a function proxy unwraps it contravariantly. We check the domain contract \( T_1 \) on \( e \), run the original function \( f \) on the result, and then check that result against the codomain contract \( T_2 \):

\[
\langle T_{11} \Rightarrow T_{12} \Rightarrow T_{21} \Rightarrow T_{22} \rangle \ e_1 \quad \Rightarrow \quad \langle T_{12} \Rightarrow T_{22} \rangle \ e_2 \quad \Rightarrow \quad \langle T_{21} \Rightarrow T_{11} \rangle \ e_1 (\langle T_{21} \Rightarrow T_{11} \rangle \ e_2)
\]

Findler and Felleisen neatly designed a system for contract checking in a higher-order world, but there is a problem: contract checking is space inefficient [15]. Contract checking’s space inefficiency can be summed up as follows: function proxies break tail calls. Calls to an unproxied function from a tail position can be optimized to not allocate stack frames. Proxied functions, however, will unwrap to have codomain contracts—breaking tail calls. We discuss other sources of space inefficiency below, but breaking tail calls is the most severe. Consider factorial written in accumulator passing style. The developer may believe that the following can be compiled to use tail calls:

\[
\text{fact : } \{ x : \text{Int} \mid x \geq 0 \} \rightarrow \{ x : \text{Int} \mid x \geq 0 \} \rightarrow \{ x : \text{Int} \mid x \geq 0 \}
= \lambda x : \{ x : \text{Int} \mid x \geq 0 \} . \lambda y : \{ y : \text{Int} \mid y \geq 0 \} . \text{fact} (x * y)
\]

A cast insertion algorithm [29] might produce the following non-tail recursive function:

\[
\text{fact} =
\{ x : \text{Int} \mid x \geq 0 \} \rightarrow \{ y : \text{Int} \mid y \geq 0 \} \rightarrow \{ z : \text{Int} \mid z \geq 0 \}
= \lambda x : \{ x : \text{Int} \mid x \geq 0 \} . \lambda y : \{ y : \text{Int} \mid y \geq 0 \} . \text{fact} (x * y)
\]

Tail-call optimization is essential for usable functional languages. Space inefficiency has been one of two significant obstacles for pervasive use of higher-order contract checking. (The other is state, which we do not treat here.)
In this work, we show how to achieve semantics-preserving space efficiency for non-dependent contract checking. Our approach is inspired by work on gradual typing [27], a form of (manifest) contracts designed to mediate dynamic and simple typing—that is, gradual typing (a) allows the dynamic type, and (b) restricts the predicates in contracts to checks on type tags. Herman et al. [15] developed the first space-efficient gradually typed system, using Henglein’s coercions [14]; Siek and Wadler [28] devised a related system supporting blame. The essence of the solution is to allow casts to merge: given two adjacent casts \((T_3 \Rightarrow T_4)^{c_1} \rangle e\), we must somehow combine them into a single cast. Siek and Wadler annotate their casts with an intermediate type representing the greatest lower bound of the types encountered. Such a trick doesn’t work in our more general setting: simple types plus dynamic form a straightforward lattice using type precision as the ordering, but it’s less clear what to do when we have arbitrary predicate contracts.

We define two modes of a single calculus, \(\lambda_H\). The classic mode is just the conventional, inefficient semantics; the \(\tilde{\lambda}\)­­edic (mode) annotates casts with refinement types and function coercions—a new form of coercion inspired by Greenberg [9]. The coercions keep track of checking so well that the type indices and blame labels on casts are unnecessary:

\[
\langle T_3 \Rightarrow T_4 \rangle^* (\langle T_1 \Rightarrow T_2 \rangle^* \langle T_3 \Rightarrow T_4 \rangle^* e) \quad \longrightarrow \quad \langle T_1 \rangle^{\text{join}(c_1, c_2)} \quad \langle T_3 \rangle^* e
\]

These coercions form a skew lattice: refinement lists have ordering constraints that break commutativity. Eide­­tic \(\lambda_E\) is space efficient and observationally equivalent to the classic mode.

Eide­t­­tic \(\lambda_E\) is the first manifest contract calculus that is both sound and space efficient with respect to the classic semantics—a result contrary to Greenberg [9], who conjectured that such a result is impossible. We believe that space efficiency is a critical step towards the implementation of practical languages with manifest contracts.

We do not prove a blame theorem [30], since we lack the clear separation of dynamic and static typing found in gradual typing. We conjecture that such a theorem could be proved. Our model has two limits worth mentioning: we do not handle dependency, a common and powerful feature in manifest systems; and, our bounds for space efficiency are galactic—they establish that contracts consume constant space, but do nothing to reduce that constant [20]. Our contribution is showing that sound space efficiency is possible where it was believed to be impossible [9]; we leave evidence that it is practicable for future work.

Our proofs are available in the extended version [10], Appendices A–C.

Readers who are very familiar with this topic can read Figures 1, 2, and 3 and then skip directly to Section 4. Readers who understand the space inefficiency of contracts but aren’t particularly familiar with manifest contracts can skip Section 2 and proceed to Section 3.

2. Function proxies

Space inefficient contract checking breaks tail recursion—a show­­stopping problem for realistic implementations of pervasive contract use. Racket’s contract system [22], the most widely used higher-order contract system, takes a “macro” approach to contracts: contracts typically appear only on module interfaces, and aren’t checked within a module. Their approach comes partly out of a philosophy of breaking invariants inside modules but not out of them, but also partly out of a need to retain tail recursion within modules. Space inefficiency has shaped the way their contract system has developed. They do not use our “micro” approach, wherein annotations and casts permeate the code.

Tail recursion aside, there is another important source of space inefficiency: the unbounded number of function proxies. Hierarchies of libraries are a typical example: consider a list library and a set library built using increasingly sorted lists. We might have:

\[
\begin{align*}
\text{null} : \alpha &\to \text{List} \to \text{Bool} \to \text{true} = \ldots \\
\text{head} : \{x: \alpha \mid \text{not} (\text{null} x)\} &\to \alpha = \ldots \\
\text{empty} : \alpha &\to \text{Set} \to \text{Bool} \to \text{true} = \text{null} \\
\text{min} : \{x: \alpha \mid \text{not} (\text{empty} x)\} &\to \alpha = \text{head}
\end{align*}
\]

Our code reuse comes with a price: even though the precondition on \text{min} is effectively the same as that on \text{head}, we must have two function proxies, and the non-emptiness of the list representing the set is checked twice: first by checking empty, and again by checking null (which is the same function). Blame systems like those in Racket encourage modules to declare contracts to avoid being blamed, which can result in redundant checking like the above when libraries requirements imply sub-libraries’ requirements.

Or consider a library of drawing primitives based around painters, functions of type \text{Canvas} \Rightarrow \text{Canvas}. An underlying graphics library offers basic functions for manipulating canvases and functions over canvases, e.g., \text{primFlipH} is a painter transformer—of type \text{Canvas} \Rightarrow \text{Canvas} that flips the generated images horizontally. A wrapper library may add derived functions while re-exporting the underlying functions with refinement types specifying a canvas’s square dimensions, where \text{SquareCanvas} = \{x \mid \text{Canvas} \to \text{width}(x) = \text{height}(x)\}:

\[
\text{flipH} p = (\text{Canvas} \Rightarrow \text{Canvas} \Rightarrow \text{SquareCanvas})^l \\
(\text{primFlipH} ((\text{SquareCanvas} \Rightarrow \text{SquareCanvas} \Rightarrow \text{Canvas} \Rightarrow \text{Canvas})^l p))
\]

The wrapper library only accepts painters with appropriately refined types, but must strip away these refinements before calling the underlying implementation—which demands \text{Canvas} \Rightarrow \text{Canvas} painters. The wrapper library then has to cast these modified functions back to the refined types. Calling \text{flipH} (\text{flipH} p) yields:

\[
(\text{Canvas} \Rightarrow \text{Canvas} \Rightarrow \text{SquareCanvas} \Rightarrow \text{SquareCanvas})^l \\
(\text{primFlipH} ((\text{SquareCanvas} \Rightarrow \text{SquareCanvas} \Rightarrow \text{Canvas} \Rightarrow \text{Canvas})^l ((\text{Canvas} \Rightarrow \text{SquareCanvas} \Rightarrow \text{SquareCanvas})^l p)))
\]

That is, we first cast \(p\) to a plain painter and return a new painter \(p’\). We then cast \(p’\) into and then immediately out of the refined type, before continuing on to flip \(p’\). All the while, we are accumulating many function proxies beyond the wrapping done by the underlying implementation of \text{primFlipH}. Redundant wrapping can become quite extreme, especially for continuation-passing programs.

Function proxies are the essential problem: nothing bounds their accumulation. Unfolding unboundedly many function proxies creates stacks of unboundedly many checks—which breaks tail calls. A space-efficient scheme for manifest contracts bounds the number of function proxies that can accumulate.

3. Classic manifest contracts

The standard manifest contract calculus, \(\lambda_C\), is originally due to Flanagan [7]. We give the syntax for the non-dependent fragment in Figure 1. We have highlighted in yellow the four syntactic forms relevant to contract checking. This paper paper discusses two modes of \(\lambda_H\): classic \(\lambda_C\), mode \(\tilde{\lambda}\), and eidetic \(\lambda_E\), mode \(E\). Each of these languages uses the syntax of Figure 1, while the typing rules
and operational semantics are indexed by the mode \( m \). The proofs and metatheory are also mode-indexed. In an extended version of this work, we develop two additional modes with slightly different properties from eidetic \( \lambda_H \), filling out a “framework” for space-efficient manifest contracts [10]. We omit the other two modes here to save space for eidetic \( \lambda_H \), which is the only mode that is sound with respect to classic \( \lambda_H \).

The metavariable \( B \) is used for base types, of which at least \( \text{Bool} \) must be present. There are two kinds of types. First, predicate contracts \( \{x:B \mid e\} \), also called refinements of base types or just refinement types, denotes constants \( k \) of base type \( B \) such that \( e[k/x] \) holds—that is, such that \( e[k/x] \longrightarrow^m \text{true} \) for any mode \( m \). Function types \( T_1 \rightarrow T_2 \) are standard.

The terms of \( \lambda_H \) are largely those of the simply-typed lambda calculus; variables, constants \( k \), abstractions, applications, and operations should all be familiar. The first distinguishing feature of \( \lambda_H \)'s terms is the \textit{cast}, written \( \langle T_1 \mapsto T_2 \rangle e \). Here \( e \) is a term of type \( T_1 \); the cast checks whether \( e \) can be treated as a \( T_2 \)—if \( e \) doesn’t cut it, the cast will use its label \( l \) to raise the uncatchable exception \( \#l \), read “blame \( l \)”. Our casts also have annotations \( \alpha \).

Classic doesn’t need annotations—we write \( \bullet \) and say “none”. Eidetic \( \lambda_H \) uses coercions \( c \), based on coercions in Henglein [14]. We explain coercions in greater detail in Section 4, but they amount to lists of blame-annotated refinement types \( r \) and function coercions.

The three remaining forms—aactive checks, blame, and coercion stacks—only occur as the program evaluates. Casts between refinement types are checked by \textit{active checks} \( \{x:B \mid e_1\}, e_2, k \). The first term is the type being checked—necessary for the typing rule. The second term is the current status of the check; it is an invariant that \( e_1[k/x] \longrightarrow^m \text{true} \). The final term is the constant being checked, which is returned wholesale if the check succeeds. When checks fail, the program raises \textit{blame}, an uncatchable exception written \( \#l \). A \textit{coercion stack} \( \{x:B \mid e_1\}, s, r, k, e^* \) represents the state of checking a coercion; we only use it in eidetic \( \lambda_H \), so we postpone discussing it until Section 4.

3.1 Core operational semantics

Our mode-indexed operational semantics for our manifest calculi comprise three relations: \( \text{val}_m e \) identifies terms that are values in mode \( m \) (or \( m \)-values), \( \text{result}_m e \) identifies \( m \)-results, and \( e_1 \longrightarrow^m e_2 \) is the small-step reduction relation for mode \( m \). Figure 2 defines the core rules. The rules for classic \( \lambda_H (m = C) \) are in salmon; the shared space-efficient rules are in \textit{periwinkle}. To save space, we pass over standard rules.

The mode-agnostic value rules are straightforward: constants are always values \( V_{\text{CONST}} \), as are lambdas \( V_{\text{ABS}} \). Each mode defines its own value rule for function proxies, \( V_{\text{PROXY}} \). The classic rule, \( V_{\text{PROXYC}} \), says that a function proxy

\[
\langle T_1 \mapsto T_2 \rangle e
\]

is a \( C \)-value when \( e \) is a \( C \)-value. That is, function proxies can wrap lambda abstractions and other function proxies alike. Eidetic \( \lambda_H \) only allows lambda abstractions to be proxied. All of the space-efficient calculi in the literature take our approach, where a function cast applied to a value \( v \) is a value; some space inefficient ones do, too [5, 12, 13]. In other formulations of \( \lambda_H \) in the literature, function proxies are implemented by introducing a new lambda as a wrapper à la Findler and Felleisen’s \textit{wrapp} operator [1, 5, 7, 27]. Such an \( \eta \)-expansion semantics is convenient, since then applications only ever reduce by \( \beta \)-reduction. But it wouldn’t suit our purposes at all: space efficiency demands that we combine function proxies. We can also imagine a third, ungainly semantics that looks into closures rather than having explicit function proxies. Results don’t depend on the mode: \( m \)-values are always \( m \)-results \( (R_{\text{VAL}}) \); blame is always a result, too \( (R_{\text{BLAME}}) \).

\( E_{\text{BETA}} \) applies lambda abstractions via substitution, using a \textit{call-by-value} rule. Note that \( \beta \) reduction in \( m \) requires that the argument is an \( m \)-value. The reduction rule for operations \( (E_{\text{OP}}) \) defers to operations’ denotations \( \text{op} \); since these may be partial (e.g., division), we assign types to operations that guarantee totality (see Section 3.2). That is, partial operations are a potential source of stuckness, and the types assigned to operations must guarantee the absence of stuckness. Robin Milner famously stated that “well typed expressions don’t go wrong” [21]; his programs could go wrong by (a) applying a boolean like a function or (b) conditioning on a function like a boolean. Systems with more base types can go wrong in more ways, some of which are hard to capture in standard type systems. Contracts allow us to bridge that gap. Letting operations get stuck is a philosophical stance—contracts expand the notion of “wrong”.

\( E_{\text{UNWRAP}} \) applies function proxies to values, contravariantly in the domain and covariantly in the codomain. We also split up each cast’s annotation, using \( \text{dom}(a) \) and \( \text{cod}(a) \)—each mode is discussed in its respective section. \( E_{\text{CHECKONEC}} \) turns a cast between refinement types into an active check with the same blame label. We discard the source type—we already know that \( k \) is a \( \{x:B \mid e_1\} \) and substitute the scrutinee into the target type, \( e_2[k/x] \), as the current state of checking. We must also hold onto the scrutinee, in case the check succeeds. We are careful not to apply this rule in eidetic \( \lambda_H \), which must generate annotations before running checks. Active checks evaluate by the congruence rule \( E_{\text{CHECKINNER}} \), which is a single rule that adheres: the predicate returns true, so the whole active check returns the scrutinee \( (E_{\text{CHECKOK}}) \); the predicate returns false, so the whole active check raises blame using the label on the check \( (E_{\text{CHECKFAIL}}) \); or blame was raised during checking, and we propagate it via \( E_{\text{CHECKRAISE}} \). Checks in eidetic \( \lambda_H \) use slightly different forms, described in Section 4.

The core semantics includes several other congruence rules: \( E_{\text{APPL}}, E_{\text{APPR}}, \) and \( E_{\text{OPINNER}} \). Since space bounds rely only on limiting the number of function proxies but also on accumulation of casts on the stack, the core semantics doesn’t include a cast congruence rule. The congruence rule for casts in classic \( \lambda_H, E_{\text{CASTINNERC}} \), allows for free use of congruence. In the space-efficient calculus, the use of congruence is instead limited by the rules \( E_{\text{CASTINNERE}} \) and \( E_{\text{CASTMERGE}} \). Cast arguments only take congruent steps when they aren’t casts themselves. A cast ap-
Values and results

<table>
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<tr>
<th>Val_m e</th>
<th>R_val e</th>
<th>R_blame e</th>
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<td>V_abs</td>
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<tr>
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<td>Val_c (T_11 → T_12) ⋙ T_21 → T_22) e</td>
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Shared operational semantics

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<tr>
<td>Val_m (T_11 → T_12) ⋙ T_21 → T_22) e</td>
<td>Val_m e2</td>
<td>E_op</td>
</tr>
</tbody>
</table>

Figure 2. Core operational semantics of λ_H; classic λ_H rules are salmon; space-efficient rules are periwinkle

plied to another cast merges, using the join function. Each space-efficient calculus uses a different annotation scheme, so each one has a different merge function. We are careful to define join only over coercions, so E.CastMergeE won’t apply on the empty annotation, • (read “none”). We have E.CastMergeE arbitrarily retain the label of the outer cast. This choice is ultimately irrelevant, since ecdic λ_H won’t need to keep track of blame labels on casts themselves (Section 4). In addition to congruence rules, there are blame propagation rules, which are universal: E_AppRaiseE, E_AppRAIsE, E_CastRaise, E_OpRaise. These rules propagate the uncachable exception ⊢ l while obeying call-by-value rules.

3.2 Type system

All modes share a type system, given in Figure 3. All judgments are universal and simply thread the mode through—except for annotation well formedness ⊢ m a |- m T_1 |- m T_2, which is mode specific, and a single ecdic-specific rule given in Figure 4. The type system comprises several relations: context well formedness ⊢ m Γ and type well formedness ⊢ m T; type compatibility |- m T_1 |- m T_2, a mode-less comparison of the skeleton of two types; annotation well formedness ⊢ m a |- m T_1 |- m T_2; and term typing Γ |- m e : T.

Context well formedness is entirely straightforward; type well formedness requires some care to get base types off the ground. We establish as an axiom that the raw type {x : T} is well formed for every base type B (WF_Base); we then use raw types to check that refinements are well formed: {x : B | e} is well formed in mode m if e is well typed as a boolean in mode m when x is a value of type B (WF_Ren). Without WF_Base, WF_Ren wouldn’t have a well formed context. Function types are well formed in mode m when their domains and codomains are well formed in mode m. (Unlike many recent formulations, our functions are not dependent—we leave dependency as future work.) Type compatibility |- m T_1 |- m T_2 identifies types which can be cast to each other: the types must have the same “skeleton”. It is reasonable to try to cast a non-zero integer {x : Int | x ≠ 0} to a positive integer {x : Int | x > 0}, but it is senseless to cast it to a boolean {x : Bool | true} or to a function type T_1 |- m T_2. Every cast must be between compatible types; at their core, λ_H programs are simply typed lambda calculus programs. Type compatibility

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<td>Val_m e4 m e4</td>
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<tr>
<th>e : C (T_1 _ E T_2) e : C (T_1 _ E T_2) e’</th>
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is reflexive, symmetric, and transitive; i.e., it is an equivalence relation.

Our family of calculi use different annotations. All source programs (defined below) begin without annotations—we write the empty annotation \( \bullet \), read "none". The universal annotation well formedness rule just defers to type compatibility (A_NONE); it is an invariant that \( \vdash_m a \parallel T_1 \Rightarrow T_2 \) implies \( \vdash_m T_1 \parallel T_2 \).

As for term typing, the T_VAR, T_ABS, T_OP, and T_CAST rules are entirely conventional. TCLUDE types blame at any (well formed) type. A constant \( k \) can be typed by T_COND at any type \( \{ x: B \mid e \} \) in mode \( m \) if: (a) \( k \) is a \( B \), i.e., \( ty(k) = B \); (b) the type in question is well formed in mode \( m \); and (c), if \( e[k/x] \rightarrow_m \) true. As an immediate consequence, we can derive the following rule typing constants at their raw type, since true \( \rightarrow_m \) true in all modes and raw types are well formed in all modes (WF_BASE):

\[
\Gamma \vdash_m \text{ty}(k) = B \\
\Gamma \vdash_m k : \{ x: B \mid \text{true} \}
\]

This approach to constant typing in a manifest calculus is novel: it offers a great deal of latitude with typing, while avoiding the subtyping of some formulations [7, 12, 17, 18] and the extra rule of others [1]. We assume that \( \text{ty}(k) = \text{Bool} \) iff \( k \in \{ \text{true, false} \} \).

We require in T_OP that \( \text{ty}(op) \) only produces well formed first-order types, i.e., types of the form \( \{ x: B_1 \mid e_1 \} \rightarrow \ldots \rightarrow \{ x: B_n \mid e_n \} \). We require that the type is consistent with the operation’s denotation: \( [op]\{ b_1, \ldots, b_n \} \) is defined iff \( e_i[k/x] \rightarrow_m \) true for all \( m \). For this evaluation to hold for every system we consider, the types assigned to operations can’t involve casts that both (a) stack and (b) can fail. We still do not say this is stringent: the types for operations ought to be simple, e.g. \( \text{ty}([\text{div}] = \{ \text{x:Real} \mid \text{true}\} \rightarrow \{ y: \text{Real} \mid y \neq 0 \} \rightarrow \{ z: \text{Real} \mid \text{true} \} \), and stacked casts only arise in stack-free terms due to function proxies. In general, it is interesting to ask what refinement types to assign to constants, as careless assignments can lead to circular checking (e.g., if division has a codomain cast checking its work with multiplication and vice versa).

The typing rule for casts, T_CAST, relies on the annotation well formedness rule: \( \{ T_1 \rightarrow T_2 \mid e \} \) is well formed in mode \( m \) when \( \vdash_m a \parallel T_1 \Rightarrow T_2 \) and \( e \) is a \( T_1 \). Allowing any cast between compatible base types is conservative: a cast from \( \{ x: \text{Int} \mid x > 0 \} \) to \( \{ x: \text{Int} \mid x \leq 0 \} \) always fails. Earlier work has used SMT solvers to try to statically reject certain casts and eliminate those that are guaranteed to succeed [2, 7, 18]; we omit these checks, as we view them as secondary—a static analysis offering bug-finding and optimization, and not the essence of the system.

The final rule, T_CHECK, is used for checking active checks, which should only occur at runtime. In fact, they should only ever be applied to closed terms; the rule allows for any well formed context as a technical device for weakening.

Active checks \( \langle \{ x: B \mid e_1 \}, e_2, k \rangle \) arise as the result of casts between refined base types, as in the following classic \( \lambda_H \) evaluation of a successful cast:

\[
\langle \{ x: B \mid e \} \Rightarrow \{ x: B \mid e' \} \rangle \rightarrow_k \langle \{ x: B \mid e' \}, e'[k/x], k \rangle \rightarrow_k \langle \{ x: B \mid e' \}, \text{true}, k \rangle \rightarrow_k k
\]

If we are going to prove type soundness via syntactic methods [32], we must have enough information to type \( k \) at \( \{ x: B \mid e' \} \). For this reason, T_CHECK requires that \( e_1[k/x] \rightarrow_m e_2 \); this way, we know that \( e'[k/x] \rightarrow_m \) true at the end of the previous derivation, which is enough to apply T_COND. The other premises of T_CHECK ensure that the types all match up: that the target refinement type is well formed; that \( k \) has the base type in question; and that \( e_2 \), the current state of the active check, is also well formed.

To truly say that our languages share a syntax and a type system, we highlight a subset of type derivations as source program type
derivations. We show that source programs well typed in one mode are well typed in all the modes [10].

3.1 Definition [Source program]: A source program type derivation obeys the following rules:

- \(\text{T,CONST}\) only ever assigns the type \(\{x:B \mid e\}\). Variations in each mode’s evaluation aren’t reflected in the (source program) type system. (We could soundly relax this requirement to allow \(\{x:B \mid e\}\) such that \(e[k/x] \rightarrow_m^*\) true for any mode \(m\).

- Casts have empty annotations \(\varepsilon = \bullet\). Casts also have blame labels, and not empty blame (also written \(\varepsilon\)).

- \(\text{T,CHECK}, \text{T,STACK}\) (Section 4), and \(\text{T,BLAME}\) are not used—these are for runtime only.

Note that source programs don’t use any of the typing rules that derive modes at once (see Section A.1). To wit, we prove syntactic type weakening, substitution, and regularity—can be proved for all its own progress and preservation lemmas for syntactic type once for all modes. Each mode proves its own canonical forms maintain a clear phase distinction between type checking programs and running them.

3.2 Metatheory

One distinct advantage of having a single syntax with parameterized semantics is that some of the metatheory can be done once for all modes. Each mode proves its own canonical forms lemma—since each mode has a unique notion of value—and its own progress and preservation lemmas for syntactic type soundness [32]. But other standard metatheoretical machinery—weakening, substitution, and regularity—can be proved for all modes at once (see Section A.1). To wit, we prove syntactic type soundness in Appendix A.2 for classic \(\lambda_h\) in just three mode-specific lemmas: canonical forms, progress, and preservation. In every theorem statement, we include a reference to the lemma number where it is proved in the appendix. In PDF versions, this reference is hyperlinked.

Lemma [Classic canonical forms (A.11)]: If \(\emptyset \vdash_e e : T\) and \(\text{val}_e\) then:

- If \(T = \{x:B \mid e'\}\), then \(e = k\) and \(\text{ty}(k) = B\) and \(e'[e/x] \rightarrow_m^*\) true.

- If \(T = T_1 \rightarrow T_2\), then either \(e = \lambda x:T.\ e'\) or \(e = \langle T_{11} \rightarrow T_{12} \rightarrow T_{21} \rightarrow T_{22}\rangle\) for \(e'\).

Lemma [Classic progress (A.12)]: If \(\emptyset \vdash_e e : T\), then either:

1. \(\text{result}_e\), i.e., \(e = \mathbb{F}l\) or \(\text{val}_e\) or
2. there exists an \(e'\) such that \(e \rightarrow _e e'\).

Lemma [Classic preservation (A.13)]: If \(\emptyset \vdash_e e : T\) and \(e \rightarrow _e e'\), then \(\emptyset \vdash_e e' : T\).

4. Eidetic space efficiency

Eidetic \(\lambda_h\) uses coercions. Coercions do two critical things: they retain check order, and they track blame. Our coercions are ultimately inspired by those of Henglein [14]; we discuss the relationship between our coercions and his in related work (Section 7). Recall the syntax of coercions from Figure 1:

\[
\begin{align*}
\text{e} & \ ::= \ r \mid c_1 \rightarrow c_2 \\
\text{r} & \ ::= \ \text{nil} \mid \{x:B \mid e\}, r
\end{align*}
\]

Coercions come in two flavors: blame-annotated refinement lists \(r\)—zero or more refinement types, each annotated with a blame label—and function coercions \(c_1 \rightarrow c_2\). We write them as comma separated lists, omitting the empty refinement list \(\text{nil}\) when the refinement list is non-empty. We define the coercion well formedness rules, an additional typing rule, and reduction rules for eidetic \(\lambda_h\) in Figure 4. To ease the exposition, our explanation doesn’t mirror the rule groupings in the figure.

As a general intuition, coercions are plans for checking; they contain precisely those types to be checked. Refinement lists are well formed for casts between \(\{x:B \mid e_1\}\) and \(\{x:B \mid e_2\}\) when: (a) every type in the list is a blame-annotated, well formed refinement of \(B\), i.e., all the types are of the form \(\{x:B \mid e\}\) and are therefore similar to the indices; (b) there are no duplicated types in the list; and (c) the target type \(\{x:B \mid e_2\}\) is implied by some other type in the list. Note that the input type for all refinement lists can be any well formed refinement—this corresponds to the intuition that base types have no negative parts, i.e., casts between refinements ignore the type on the left. Finally, we simply write “no duplicates in \(r\)” — it is an invariant during the evaluation of source programs. Function coercions, on the other hand, have a straightforward (contravariant) well formedness rule.

The \E,_COERC, rule translates source-program casts to coercions: \(\text{coerce}(T_1, T_2, l)\) is a coercion representing exactly the checking done by the cast \((T_1 \Rightarrow T_2)\). All of the refinement types in \(\text{coerce}(T_1, T_2, l)\) are annotated with the blame label \(l\), since that’s the label that would be blamed if the cast failed at that type. Since a coercion is a complete plan for checking, a coercion annotation obviates the need for type indices and blame labels. To this end, \E,_COERC drops the blame label from the cast, replacing it with an empty label. We keep the type indices so that we can reuse \E,CASTMERGE\, from the universal semantics, and also as a technical device in the preservation proof.

The actual checking of coercions rests on the treatment of refinement list functions: coercion coercions are expanded as functions are applied by \E,UNWRAP, so they don’t need much special treatment beyond a definition for dom and cod. Eidetic \(\lambda_h\) uses coercion stacks \(\langle\{x:B \mid e_1\}, s, r, k, e_2\rangle^*\) to evaluate refinement lists. Coercion stacks are type checked by \T,STACK\ (in Figure 4). We explain the operational semantics before explaining the typing rule. Coercion stacks are runtime-only entities comprising five parts: a target type, a status, a pending refinement list, a constant scrutinizee, and a checking term. We keep the target type of the coercion for preservation’s sake. The status bit \(s\) is either \(\checkmark\) or \(?\); when the status is \(\checkmark\), we are currently checking or have already checked the target type \(\{x:B \mid e_1\}\); when it is \(?\), we haven’t. The pending refinement list \(r\) holds those checks not yet done. When \(s = ?\), the target type is still in \(r\). The scrutinizee \(k\) is the constant we’re checking; the checking term \(e_2\) is either the scrutinizee \(k\) itself, or it is an active check on \(k\).

The evaluation of a coercion stack proceeds as follows. First, \E,COERCSTACK starts a coercion stack when a cast between refinements meets a constant, recording the target type, setting the status to \(?\), and setting the checking term to \(k\). Then \E,STACKPOP starts an active check on the first type in the refinement list, using its blame label on the active check—possibly updating the status if the type being popped from the list is the target type. The active check runs by the congruence rule \E,STACKINNER, eventually returning \(k\) itself or blame. In the latter case, \E,STACKRAISE propagates the blame. If not, then the scrutinizee is \(k\) once more and \E,STACKPOP can fire again. Eventually, the refinement list is exhausted, and \E,STACKDONE returns \(k\).

Now we can explain \T,STACK’s many jobs. It must recapitulate \A,REFINE, but not exactly—since eventually the target type will be checked and no longer appear in \(r\). The status \(s\) differentiates what our requirement is: when \(s = ?\), the target type is in \(r\). When \(s = \checkmark\), we either know that \(k\) inhabits the target type or that we are currently checking the target type (i.e., an active check of the target type at some blame label reduces to our current checking term).

Finally, we need to define how to merge casts. We use the join operator, which is very nearly concatenation on refinement lists and a contravariant homomorphism on function coercions. It’s not
Coercion implication predicate: axioms
\[ \{x : B \mid e_1\} \supset \{x : B \mid e_2\} \]

(Reflexivity) If \(\Gamma \vdash_E \{x : B \mid e\}\) then \(\{x : B \mid e\} \supset \{x : B \mid e\}\).

(Transitivity) If \(\Gamma \vdash_E \{x : B \mid e_1\} \supset \{x : B \mid e_2\}\) and \(\Gamma \vdash_E \{x : B \mid e_2\} \supset \{x : B \mid e_3\}\) then \(\Gamma \vdash_E \{x : B \mid e_1\} \supset \{x : B \mid e_3\}\).

(Adequacy) If \(\Gamma \vdash_E \{x : B \mid e_1\} \supset \{x : B \mid e_2\}\) then \(\forall k \in K_B. e_1[k] /x/ \rightarrow_E^e\) true implies \(e_2[k] /x/ \rightarrow_E^e\) true.

(Decidability) For all \(\Gamma \vdash_E \{x : B \mid e_1\}\) and \(\Gamma \vdash_E \{x : B \mid e_2\}\), it is decidable whether \(\{x : B \mid e_1\} \supset \{x : B \mid e_2\}\).

Coercion well formedness and term typing
\[ \Gamma \vdash m \parallel T_1 \Rightarrow T_2 \quad \Gamma \vdash m : E \]

Values and operational semantics
\[ \text{val}_E e \quad e_1 \rightarrow_E e_2 \]

Cast translation and coercion operations
\[ \text{dom}(c_1 \rightarrow c_2) = c_1 \quad \text{cod}(c_1 \rightarrow c_2) = c_2 \]

In Figure 4, we only give the axioms for \(\supset\): it must be an adequate, decidable pre-order. Syntactic type equality is the simplest implementation of the \(\supset\) predicate, but the reflexive transitive closure of any adequate decidable relation would work.

By way of example, consider a cast from \(T_1 = \{x:\text{Int} \mid x \geq 0\}\) to \(T_2 = \{x:\text{Int} \mid \text{true}\}\). For brevity, we refer to the domains as \(T_1\) and the codomains as \(T_2\). We find that \(\langle T_1 \Rightarrow T_2 \rangle\) \(v_1\) \(v_2\) steps in classic \(\lambda_H\) to:

\[ \{x : \text{Int} \mid x \geq 0\} \Rightarrow \{x : \text{Int} \mid x \geq 0\} \]

\[ (v_1 (\{x : \text{Int} \mid \text{true}\} \Rightarrow \{x : \text{Int} \mid x \geq 0\}) v_2) \]
Recalling that between casts and polarity is not a new one [4, 9, 13, 15, 31].

While negative positions are checked covariantly—newest (outermost) cast first. Consider the classic $\lambda_0$ term:

$$
T_1 = \{x : \text{Int} \mid e_{11} \} \rightarrow \{x : \text{Int} \mid e_{21} \}
$$

$$
T_2 = \{x : \text{Int} \mid e_{12} \} \rightarrow \{x : \text{Int} \mid e_{22} \}
$$

$$
T_3 = \{x : \text{Int} \mid e_{13} \} \rightarrow \{x : \text{Int} \mid e_{23} \}
$$

$$
e = \langle T_1 \Rightarrow T_2 \rangle^1 \langle T_3 \Rightarrow T_2 \rangle^1 v
$$

Note that the casts run inside-out, from old to new in the positive position, but they run from the outside-in, new to old, in the negative position.

$$
e v' \rightarrow c \{x : \text{Int} \mid e_{22} \} \Rightarrow \{x : \text{Int} \mid e_{22} \}^1
$$

$$
\langle \{x : \text{Int} \mid e_{23} \} \Rightarrow \{x : \text{Int} \mid e_{23} \}^1 v
$$

The key observation for eliminating redundant checks is that only the check run first can fail—there’s no point in checking a predicate contract twice on the same value. So eidetic $\lambda_0$ merges like so:

$$
e \rightarrow^\text{E} \langle T_2 \rangle^1 \langle x : \text{Int} \mid e_{11} \rangle \Rightarrow \{x : \text{Int} \mid e_{23} \}^1 v
$$

where

$$
c = \text{join}(\{x : \text{Int} \mid e_{12} \}, \{x : \text{Int} \mid e_{13} \})
$$

$$
= \{x : \text{Int} \mid e_{12} \} \vee \{x : \text{Int} \mid e_{13} \} \Rightarrow \{x : \text{Int} \mid e_{22} \}
$$

The coercion merge operator eliminates the redundant codomain check, choosing to keep the one with blame label $l_i$. Choosing $l_i$ makes sense here because the codomain is a positive position and $l_i$ is the older, innermost cast. We construct a similar example for merges in negative positions.

$$
T_1 = \{x : \text{Int} \mid e_{11} \} \rightarrow \{x : \text{Int} \mid e_{21} \}
$$

$$
T_2 = \{x : \text{Int} \mid e_{12} \} \rightarrow \{x : \text{Int} \mid e_{22} \}
$$

$$
T_3 = \{x : \text{Int} \mid e_{13} \} \rightarrow \{x : \text{Int} \mid e_{23} \}
$$

$$
e' = \langle T_1 \Rightarrow T_2 \rangle^1 \langle T_3 \Rightarrow T_2 \rangle^1 v
$$

Again, the unfolding runs the positive parts inside-out and the negative parts outside-in when applied to a value $v'$:

$$
\langle x : \text{Int} \mid e_{22} \rangle \Rightarrow \{x : \text{Int} \mid e_{23} \}^1
$$

$$
\langle \{x : \text{Int} \mid e_{23} \} \Rightarrow \{x : \text{Int} \mid e_{11} \}^1 v
$$

$$
\langle \{x : \text{Int} \mid e_{12} \} \Rightarrow \{x : \text{Int} \mid e_{13} \}^1 v
$$

$$
\langle \{x : \text{Int} \mid e_{13} \} \Rightarrow \{x : \text{Int} \mid e_{12} \}^1 v
$$

Running the example in eidetic $\lambda_0$, we reduce the redundant checks in the domain:

$$
e' \rightarrow E \langle T_2 \rangle^1 \langle x : \text{Int} \mid e_{11} \rangle \Rightarrow \{x : \text{Int} \mid e_{23} \}^1 v
$$

$$
\langle T_1 \rangle^1 \Rightarrow \{x : \text{Int} \mid e_{23} \}^1 v
$$

where

$$
c = \text{join}(\{x : \text{Int} \mid e_{12} \}, \{x : \text{Int} \mid e_{13} \})
$$

$$
= \{x : \text{Int} \mid e_{12} \} \vee \{x : \text{Int} \mid e_{13} \} \Rightarrow \{x : \text{Int} \mid e_{22} \}
$$

Following the outside-in rule for negative positions, we keep the blame label $l_i$ from the newer, outermost cast.

### 4.1 Metatheory

The proof of type soundness is a standard syntactic proof, relying on a few small lemmas concerning refinement list well formedness and the generic metatheory described in Section 3.3. The full proofs are in Appendix A.3.
Lemma [Eidetic canonical forms (A.15)]: If $\emptyset \vdash_{\text{E}} e : T$ and $\text{val}_{\text{E}} e$ then:

- If $T = \{x:B \mid e\}$, then $e = k$ and $\text{ty}(k) = B$ and $e'[e/x] \Rightarrow_{\text{E}} e'$ true.
- If $T = T_{21} \rightarrow T_{22}$, then either $e = \lambda x:T. e'$ or $e = (T_{11} \rightarrow T_{12})^{\ast} T_{21} \rightarrow T_{22}^{\ast} \lambda x:T_{11}. e'$.

Lemma [Eidetic progress (A.16)]: If $\emptyset \vdash_{\text{E}} e : T$, then either:

1. $\text{result}_{\text{E}} e$, i.e., $e = \emptyset l$ or $\text{val}_{\text{E}} e$; or
2. there exists an $e'$ such that $e \Rightarrow_{\text{E}} e'$.

Lemma [Eidetic preservation (A.20)]: If $\emptyset \vdash_{\text{E}} e : T$ and $e \Rightarrow_{\text{E}} e'$ then $\emptyset \vdash_{\text{E}} e' : T$.

Eidetic $\lambda H$ shares source programs (Definition 3.1) with classic $\lambda H$. We can therefore say that classic and eidetic $\lambda H$ are really just modes of a single language.

Lemma [Source program typing for eidetic $\lambda H$ (A.21)]:
Source programs are well typed in $C$ iff they are well typed in $E$, i.e.:

- If $\Gamma \vdash_{\text{C}} e : T$ as a source program iff $\Gamma \vdash_{\text{E}} e : T$ as a source program.
- $\Gamma \vdash_{\text{C}} T$ as a source program iff $\vdash_{\text{E}} T$ as a source program.
- $\Gamma \vdash_{\text{C}} \Gamma$ as a source program iff $\Gamma \vdash_{\text{E}} \Gamma$ as a source program.

5. Soundness for space efficiency

We want space efficiency to be sound: it would be space efficient to never check anything. Classic $\lambda H$ is normative: the more a mode behaves like classic $\lambda H$, the “sounder” it is.

A single property summarizes how a space-efficient calculus behaves with respect to classic $\lambda H$: cast congruence. In classic $\lambda H$, if $e_1 \Rightarrow_{\text{C}} e_2$ then $(T_1 \Rightarrow T_2)^{\ast} e_1 \Rightarrow_{\text{C}} (T_1 \Rightarrow T_2)^{\ast} e_2$ be-have identically. This cast congruence principle is easy to see, because $\text{ECASTINNERC}$ applies freely. In eidetic $\lambda H$, however, $\text{ECASTINNERC}$ can only apply when $\text{ECASTMERGEE}$ doesn’t. Merged casts may not behave the same as running the two casts separately. Eidetic $\lambda H$ recovers a complete cast congruence, just like classic $\lambda H$ has. Diagrammatically:

$\vdash_{\text{E}} e_1 \Rightarrow_{\text{E}} e_2$

The proof is in Appendix B, but it is worth observing here that eidetic $\lambda H$ needs a proof of idempotency to justify the way it uses reflexivity to eliminate redundant coercions: checking a property once is as good as checking it twice. Naturally, this property only holds without state.

Our proofs relating classic $\lambda H$ and eidetic $\lambda H$ are by logical relations, found in Figure 6. In the extended version, the soundness proofs for all three different space-efficient modes use a single mode-indexed logical relation. Here we give its restriction to eidetic $\lambda H$. As far as alternative techniques go, an induction over evaluation derivations wouldn’t give us enough information about evaluations that return lambda abstractions. Other contextual equivalence techniques (e.g., bisimulation) would probably work, too.

Value rules

$$e_1 \sim_{\text{E}} e_2 : T$$

$$k \sim_{\text{E}} k : \{x:B \mid e\} \iff \text{ty}(k) = B \land e$$

$$e_1 \sim_{\text{E}} e_2 : T \quad \text{or} \quad \forall_{\text{E}} e_2 : T_2 \quad e_1 \sim_{\text{E}} e_2$$

Term rules

$$e_1 \Rightarrow_{\text{E}} e_2 : T$$

$$e_1 \Rightarrow_{\text{E}} e_2 : T$$

$$\forall_{\text{E}} e_2 : T_2$$

Type rules

$$T_1 \Rightarrow_{\text{E}} T_2$$

Closings substitutions and open terms

$$\Gamma \models e_1 \Rightarrow_{\text{E}} e_2 : T$$

$$\Gamma \models e_1 \Rightarrow_{\text{E}} e_2 : T$$

$$\forall \Gamma \models e_1 \Rightarrow_{\text{E}} e_2 : T$$

$$\forall \Gamma \models e_1 \Rightarrow_{\text{E}} e_2 : T$$

Figure 6. Blame-exact, symmetric logical relation between classic $\lambda H$ and eidetic $\lambda H$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cast size</th>
<th>Pending casts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classic ($m = C$)</td>
<td>$2W_b + L$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Eidetic ($m = E$)</td>
<td>$\nu 2^{L+W_b}$</td>
<td>$[e]$</td>
</tr>
</tbody>
</table>

Table 1. Space efficiency of $\lambda H$

Lemma [Similar casts are logically related (B.3)]: If $T_1 \sim_{\text{E}} T_1'$ and $T_2 \sim_{\text{E}} T_2'$ and $e_1 \sim_{\text{E}} e_2 : T_1$, then $(T_1 \Rightarrow T_2)^{\ast} e_1 \sim_{\text{E}} (T_1 \Rightarrow T_2)^{\ast} e_2 : T_2$.

Lemma [Relating classic and eidetic source programs (B.4)]:

1. If $\Gamma \vdash_{\text{C}} e : T$ as a source program then $\Gamma \vdash_{\text{E}} e \Rightarrow_{\text{E}} e : T$.
2. If $\vdash_{\text{C}} e$ as a source program then $T \Rightarrow_{\text{E}} T$.

6. Bounds for space efficiency

We have claimed that eidetic $\lambda H$ is space efficient: what do we mean? What sort of space efficiency have we achieved? We summarize the results in Table 1; proofs are in Appendix C. From a high level, there are only a finite number of types that appear in our programs, and this set of types can only reduce as the program runs. We can effectively code each type in the program as an integer, allowing us to efficiently run the $\Rightarrow$ predicate.

Suppose that a type of height $h$ can be represented in $W_b$ bits and a label in $L$ bits. (Type heights are defined in Figure 7 in Appendix C.) Casts in classic $\lambda H$ each take up $2W_b + L$ bits: two types and a blame label. Coercions in eidetic $\lambda H$ have a different form: the only types recorded are those of height 1, i.e., refinements of base types. Pessimistically, each of these may appear at every position in a function coercion $c_1 \Rightarrow c_2$. We use $s$ to indicate the “size” of a function type, i.e., the number of positions it has. As a first pass, a set of refinements and blame labels take up $2^{L+W_b}$ space. But in fact these coercions must all be between refinements.
of the same base type, leading to $2^{L+W_B}$ space per coercion, where $W_B$ is the highest number of refinements of any single base type. We now have our worst-case space complexity: $s 2^{L+W_B}$. A more precise bound might track which refinements appear in which parts of a function type, but in the worst case—each refinement appears in every position—if degenerates to the bound we give here. Classic $\lambda_0$ can have an infinite number of “pending casts”—casts and function proxies—in a program. Eidetic $\lambda_H$ has no more than one pending cast per term node. Abstractions are limited to a single function proxy, and $E_{\text{CastMergeE}}$ merges adjacent pending casts.

The text of a program $e$ is finite, so the set of types appearing in the program, types$(e)$, is also finite. Since reduction doesn’t introduce types, we can bound the number of types in a program (and therefore the size of casts). We can therefore fix a numerical types in casts.

Finally, what is the right representation for a function? When calling a function, do we need to run coercions or not? Jeremy Siek suggested a “smart closure” which holds the logic for branching inside its own code; this may support better branch prediction than an indirect jump or branching at call sites.

### 7. Related work

Some earlier work uses first-class casts, whereas our casts are always applied to a term [1, 17]. It is of course possible to re-expand a cast with an abstraction, so no expressiveness is lost. Leaving casts fully applied saves us from the puzzling rules managing how casts work on other casts in space-efficient semantics, like: $(T_1 \rightarrow T_{12} \rightarrow T_{21}) \rightarrow (T_1 \rightarrow T_{12}) \rightarrow (T_{21} \rightarrow T_{22})$.

Previous approaches to space-efficiency have focused on gradual typing [27]. This work uses coercions [14], casts, casts annotated with intermediate types $a/k/a$ threeesomes, or some combination of all three [8, 16, 24, 26, 28]. Recent work relates all three frameworks, making particular use of coercions [25]. Our type structure differs from that of gradual types, so our space bounds come in a somewhat novel form. Gradual types, without the more complicated checking that comes with predicate contracts, allow for simpler designs. Siek and Wadler [28] can define a simple recursive operator on labeled types with a strong relationship to subtyping, the fundamental property of casts. We haven’t been able to discover a connection in our setting. Instead, we ignore the type structure of functions and focus our attention on managing labels in lists of first-order predicate contracts. In the gradual world, only Rastogi et al. [23] take a similar approach, “recursively deconstruct[ing] higher-order types down to their first-order parts” when they compute the closure of flows into and out of type variables. Gradual types occasionally have simpler proofs, too, e.g., by induction on evaluation [24]; even when strong reasoning principles are needed, the presence of dynamic types leads them to use bisimulation [8, 25, 28]. We use logical relations because $\lambda_H$‘s type structure is readily available, and because they allow us to easily reason about how checks evaluate.

Our coercions are inspired by Henglein’s coercions for modeling injection to and projection from the dynamic type [14], Henglein’s primitive coercions tag and untag values, while ours represent checks to be performed on base types; both our formulation and Henglein’s use structural function coercions.

Greenberg [9], the most closely related work, offers a coercion language combining the dynamic types of Henglein’s original work with predicate contracts; his EFFICIENT language does not quite achieve “sound” space efficiency. Rather, it is forgetful, occasionally dropping casts. He omits blame, though he conjectures that blame for coercions reads left to right (as it does in Siek and Garcia [26]); our eidetic $\lambda_H$ verifies this conjecture. While Greenberg’s languages offer dynamic, simple, and refined types, our types here are entirely refined. His coercions use Henglein’s ! and ? syntax for injection and projection, while our coercions lack such a distinction. In our refinement lists, each coercion simultaneously projects from one refinement type and injects into another (possibly producing blame). We reduce notation by omitting the interrobang ’?’. Dimoulas et al. [3] introduce option contracts, which offer a programmatic way of turning off contract checking, as well as a controlled way to “pass the buck”, handing off contracts from component to component. Option contracts address less time efficiency, not space efficiency. Findler et al. [6] studied space and time efficiency for datatype contracts, as did Koukoutsos and Kuncak [19]. Racket contracts have a mild form of space efficiency: the tail-marks-match? predicate? checks for exact duplicate contracts and blame at tail positions. The redundancy it detects seems

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1From racket/collects/racket/contract/private/arrov.rkt.
to rely on pointer equality. Since Racket contracts are (a) module-oriented "macro" contracts and (b) first class, this optimization is somewhat unpredictable—and limited compared with our eidetic calculus, which can handle differing contracts and blame labels.

8. Conclusion and future work

Semantics-preserving space efficiency for manifest contracts is possible—leaving the admissibility of state as the final barrier to practical utility. We established that eidetic $\lambda_{\idt{H}}$ behaves exactly like its classic counterpart without compromising space usage.

We believe it would be easy to design a latent version of eidetic $\lambda_{\idt{H}}$, following the translations in Greenberg et al. [11]. In our simple (i.e., not dependent) case, our refinement types close over a single variable of base type. Space efficiency for a dependent calculus remains open. The first step towards dependent types would be extending $\supset$ with a context (and a source of closing substitutions, a serious issue [1]). In a dependent setting the definition of what it means to compare closures isn’t at all clear. Closures’ environments may contain functions, and closures over extensionally equivalent functions may not be intensionally equal. A more nominal approach to contract comparison may resolve some of the issues here. Comparisons might be more straightforward when contracts are explicitly declared and referenced by name. Similarly, a dependent $\supset$ predicate might be more easily defined over some explicit structured family of types, like a lattice. Findler et al. [6] has made some progress in this direction.

Finally, a host of practical issues remain. Beyond representation choices, having expensive checks makes it important to predict when checks happen. The $\supset$ predicate compares closures and will surely have delicate interactions with optimizations.

Acknowledgments

Comments from Rajeev Alur, Ron Garcia, Fritz Henglein, Greg Morrisett, Stephanie Weirich, Phil Wadler, and Steve Zdancewic improved a previous version of this work done at the University of Pennsylvania. Some comments from Benjamin Pierce led me to realize that a cast formulation was straightforward. Discussions with Atsushi Igarashi, Robby Findler, and Sam Tobin-Hochstadt greatly improved the quality of the exposition. Phil Wadler encouraged me to return to coercions to understand the eidetic formulation. The POPL reviewers had many excellent suggestions, and Robby Findler helped once more with angelic guidance. Hannah de Keijzer helped once more with angelic guidance. Hannah de Keijzer improved the quality of the exposition. Phil Wadler encouraged me.

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References


A. Proofs of type soundness

This appendix includes the proofs of type soundness for all four modes of $\lambda_t$; we first prove some universally applicable metatheoretical properties.

A.1 Generic metatheory

A.1 Lemma [Weakening]: If $\Gamma_1, \Gamma_2 \vdash_m e : T$ and $\vdash_m e' : T'$ and $x$ is fresh, then $\vdash_m \Gamma_1, x : T', \Gamma_2$ and $\Gamma_1, x : T', \Gamma_2 \vdash_m e : T$.

A.2 Lemma [Substitution]: If $\Gamma_1, x : T' \vdash_m e : T$ and $\not\vdash_m e' : T'$, then $\Gamma_1, \Gamma_2 \vdash_m e[e'/x] : T$ and $\vdash_m \Gamma_1, \Gamma_2$.

A.3 Lemma [Regularity]: If $\Gamma \vdash_m e : T$, then $\vdash_m \Gamma$ and $\vdash_m T$.

A.4 Lemma [Symmetry of similarity (Lemma A.5)]: $\vdash_m$ is fresh, then $\vdash_m T$.

Proof: By induction on $T$.

\[(T = \{x : B \mid e\}) \text{ By S\_REFINE,} \]
\[(T = T_1 \rightarrow T_2) \text{ By S\_FUN and the IHs.}\]

A.5 Lemma [Symmetry is symmetric]: If $\vdash T_1 \parallel T_2$, then $\vdash T_2 \parallel T_1$.

Proof: By induction on the similarity derivation.

(S\_REFINE) \text{ By S\_REFINE,} \]
(S\_FUN) \text{ By S\_FUN and the IHs.}

A.6 Lemma [Symmetry is transitive]: If $\vdash T_1 \parallel T_2$ and $\vdash T_2 \parallel T_3$, then $\vdash T_1 \parallel T_3$.

Proof: By induction on the derivation of $\vdash T_1 \parallel T_2$.

(S\_REFINE) The other derivation must also be by S\_REFINE; \]
(S\_FUN) The other derivation must also be by S\_FUN; \]
\text{by S\_FUN and the IHs.}

A.7 Lemma [Well formed type sets have similar indices]:

If $\vdash_m S \parallel T_1 \Rightarrow T_2$ then $\vdash_m T_1 \parallel T_2$.

Proof: Immediate by inversion.

A.8 Lemma [Type set well formedness is symmetric]: $\vdash_m a \parallel T_1 \Rightarrow T_2$ iff $\vdash_m a \parallel T_2 \Rightarrow T_1$ for all $m \neq E$.

Proof: We immediately have $\vdash_m T_1$ and $\vdash_m T_2$, and $\vdash T_1 \parallel T_2$ iff $\vdash T_2 \parallel T_1$ by Lemma A.5.

If $m = C$ or $m = E$, then by A\_NONE and symmetry of similarity (Lemma A.5).

If $m = H$, then let $T \in S$ be given. The $\vdash_H T$ premises hold immediately; we are then done by transitivity (Lemma A.6) and symmetry (Lemma A.5) of similarity ($\vdash T \parallel T_1$ iff $\vdash T \parallel T_2$ when $\vdash T \parallel T_1$).

A.9 Lemma [Type set well formedness is transitive]: If $\vdash T_1 \parallel T_2$ and $\vdash_m a \parallel T_2 \Rightarrow T_3$ and $\vdash_m T_1$ and $m \neq E$ then $\vdash_m a \parallel T_1 \Rightarrow T_3$.

Proof: We immediately have $\vdash_m T_1$ and $\vdash_m T_2$; we have $\vdash T_1 \parallel T_3$ by transitivity of similarity (Lemma A.6).

If $m = C$ or $m = E$, we are done immediately by A\_NONE.

If, on the other hand, $m = H$, let $T \in S$ be given. We know that $\vdash_H T$ and $\vdash T \parallel T_2$; by symmetry (Lemma A.5) and transitivity (Lemma A.6) of similarity, we are done by A\_TYPESET.

A.2 Classic type soundness

A.10 Lemma [Classic determinism]: If $e \rightarrow_c e_1$ and $e \rightarrow_c e_2$ then $e_1 = e_2$.

Proof: By induction on the first evaluation derivation.

A.11 Lemma [Classic canonical forms]: If $\emptyset \vdash_c e : T$ and $\val e$ then:

- If $T = \{x : B \mid e'\}$, then $e = k$ and $\ty(k) = B$ and $\epsilon'[e/x] \rightarrow^* \text{true.}$
- If $T = T_1 \rightarrow T_2$, then $e = \lambda x : T. e'$ or $e = (T_{11} \rightarrow T_{12}) \Rightarrow (T_{21} \rightarrow T_{22})^* \lambda x : T_{11}. e'$.

A.12 Lemma [Classic progress]: If $\emptyset \vdash_c e : T$, then either:

1. $\result e$, i.e., $e = \uparrow l$ or $\val e$; or
2. there exists an $e'$ such that $e \rightarrow_c e'$.

Proof: By induction on the typing derivation.

A.3 Eidetic type soundness

A.13 Lemma [Eidetic type soundness]: $\vdash e$.

Proof: By induction on the typing derivation.

A.14 Lemma [Determinism of eidetic $\lambda_H$]: $\vdash e$.

Proof: By induction on the first evaluation derivation. In every case, only a single step can be taken.

A.15 Lemma [Eidetic canonical forms]: $\emptyset \vdash e : T$ and $\val e$ then:

- If $T = \{x : B \mid e'\}$, then $e = k$ and $\ty(k) = B$ and $\epsilon'[e/x] \rightarrow^* \text{true.}$
- If $T = T_1 \rightarrow T_2$, then $e = \lambda x : T. e'$ or $e = (T_{11} \rightarrow T_{12}) \Rightarrow (T_{21} \rightarrow T_{22})^* \lambda x : T_{11}. e'$.

A.16 Lemma [Eidetic progress]: $\emptyset \vdash e : T$, then either:

1. $\result e$, i.e., $e = \uparrow l$ or $\val e$; or
2. there exists an $e'$ such that $e \rightarrow_e e'$.

Proof: By induction on the typing derivation.

A.17 Lemma [Extended refinement lists are well formed]:

If $\vdash e$ then $\{x : B \mid e\}$ and $\vdash e' \rightarrow e' \Rightarrow e' \Rightarrow e' \Rightarrow e' \Rightarrow e' \Rightarrow e' \Rightarrow e' \Rightarrow e'$.

Proof: By cases on the rule used.

(A\_REFINE) All of the premises are immediately restored except in one tricky case. When $\{x : B \mid e\} \supseteq \{x : B \mid e'\}$ where $\{x : B \mid e'\}$ is the only type implying $\{x : B \mid e_2\}$. Then drop ($r, \{x : B \mid e\}$) isn’t well formed on its own, but adding $\{x : B \mid e\}$ makes it so by transitivity. If not, then we know that drop ($r, \{x : B \mid e\}$) is well formed, and so is its extensions by assumption.

We know that there are no duplicates by reflexivity of $\supseteq$.

(A\_FUN) Contradictory.

A.18 Lemma [Merged coercions are well formed]: $\vdash c_1 \parallel T_1 \Rightarrow T_2$ and $\vdash c_2 \parallel T_3$ then $\vdash \join(c_1, c_2) \parallel T_1 \Rightarrow T_3$.

Proof: By induction on $c_1$’s typing derivation.

(A\_REFINE) By the IH, Lemma A.17, and A\_REFINE.

(A\_FUN) By the IHs and A\_FUN.
A.19 Lemma [coerce generates well formed coercions]:
If $\Gamma \vdash T_1 \parallel T_2$ then $\Gamma \vdash \text{coerce}(T_1, T_2, l) \parallel T_1 \Rightarrow T_2$.

Proof: By induction on the similarity derivation.

(S,REFINE) By A.REFINE, with coerce($(x:B \mid e_1), (x:B \mid e_2), l) = (x:B \mid e_2)$.

(S,FUN) By A.FUN and the IHs.

A.20 Lemma [Eidetic preservation]: If $\emptyset \vdash e : T$ and $e \to^{E} e'$ then $\emptyset \vdash e' : T$.

Proof: By induction on the typing derivation.

A.21 Lemma [Source program typing for eidetic $\lambda_H$]: Source programs are well typed in C if they are well typed in E, i.e.:
- $\Gamma \vdash_C e : T$ as a source program iff $\Gamma \vdash_E e : T$ as a source program.
- $\vdash_C T$ as a source program iff $\vdash_E T$ as a source program.
- $\vdash_C \Gamma$ as a source program iff $\vdash_E \Gamma$ as a source program.

Proof: By mutual induction on $e$, $T$, and $\Gamma$.

B. Proofs of space-efficiency soundness

B.1 Lemma [Idempotence of coercions]: If $\emptyset \vdash_E e_1 : \{x:B \mid e_1\}$ and $\vdash_E \text{join}(r_1, r_2) \parallel \{x:B \mid e_1\} \Rightarrow \{x:B \mid e_2\}$, then for all results $e$, we have $(\{x:B \mid e_1\} \text{join}(r_1, r_2)(x:B, e_1)) : \{x:B \mid e_2\} \Rightarrow e$. 

Proof: By induction on their evaluation derivations: the only difference is that the latter derivation performs some extra checks that are implied by $e_1[k/x] \Rightarrow_E e$—which we already know to hold.

As before, cast congruence is the key lemma in our proof—in this case, the strongest property we have: reduction to identical results.

B.2 Lemma [Cast congruence (single step)]: If 
- $\emptyset \vdash_E e_1 : T_1$ and $\vdash_E e \parallel T_1 \Rightarrow T_2$ (and so $\emptyset \vdash_E (T_1 \Rightarrow T_2), e_1 : T_2$).
- $e_1 \Rightarrow_E e_2$ (and so $\emptyset \vdash_E e_2 : T_1$),

then for all results $e$, we have $(T_1 \Rightarrow T_2), e_1 \Rightarrow_E e$ iff $(T_1 \Rightarrow T_2), e_2 \Rightarrow_E e$.

Proof: By cases on the step taken to find $e_1 \Rightarrow_E e_2$.

Our proof strategy is as follows: we show that the casts between related types are applicative, and then we show that well typed source programs in classic $\lambda_H$ are logically related to their translation. Our definitions are in Figure 6. Our logical relation is blame-exact. Like our proofs relating forgetful and heedful $\lambda_H$ to classic $\lambda_H$, we use the space-efficient semantics in the refinement case and use space-efficient type indices.

B.3 Lemma [Similar casts are logically related]: If $T_1 \Rightarrow_E T_1'$ and $T_2 \Rightarrow_E T_2'$ and $e_1 \Rightarrow_E e_2 : T_1$, then $(T_1 \Rightarrow T_2), e_1 \Rightarrow_E (T_1' \Rightarrow T_2'), e_2 : T_2$.

Proof: By induction on the invariant relation, using coercion congruence in the function case when $e_2$ is a function proxy.

B.4 Lemma [Relating classic and eidetic source programs]:
1. If $\Gamma \vdash_C e : T$ as a source program then $\Gamma \vdash e \Rightarrow_E e : T$.

Term type extraction $\text{types}(e) : \mathcal{P}(T)$

- types($x$) = $\emptyset$
- types($k$) = $\emptyset$
- types($\text{dom}(a)) \subseteq \text{types}(a)$
- types($\text{cod}(a)) \subseteq \text{types}(a)$
- types($\text{join}(r_1, r_2) e_1$) = types($T_1$) $\cup$ types($T_2$) $\cup$ types($e_1$) $\cup$ types($e_2$)
- types($\emptyset$) = $\emptyset$
- types($\{x : B \mid e_1\}$) $\cup$ types($r$) $\cup$ types($e$)
- types($\emptyset$) = $\emptyset$

Type, type set, and coercion type extraction $\text{height}(T)$

- types($\{x : B \mid e\}$) = $\{x : B \mid e\} \cup \text{types}(e)$
- types($T_1 \Rightarrow T_2$) = $T_1 \Rightarrow T_2$ $\cup$ types($T_1$) $\cup$ types($T_2$)
- types($\emptyset$) = $\emptyset$

$\text{height}(T)$

- types($\emptyset$) = $\emptyset$
- types($\{x : B \mid e\}$) $\cup$ types($r$) $\cup$ types($e$)
- types($\emptyset$) = $\emptyset$

$\text{height}(T_1 \Rightarrow T_2)$ = $1 + \max_{e \in \{1, 2\}} \text{height}(T_e)$

Figure 7. Type extraction and type height

2. If $\vdash_C T$ as a source program then $T \Rightarrow_E T$.

Proof: By mutual induction on the typing derivations.

C. Proofs of bounds for space-efficiency

This section contains our definitions for collecting types in a program and the corresponding proof of bounded space consumption (for all modes at once).

We define a function collecting all of the distinct types that appear in a program in Figure 7. If the type $T = \{x : \text{Int} \mid x \geq 0\} \to \{y : \text{Int} \mid y \neq 0\}$ appears in the program $e$, then $\text{types}(e)$ includes the type $T$ itself along with its subparts $\{x : \text{Int} \mid x \geq 0\}$ and $\{y : \text{Int} \mid y \neq 0\}$.

C.1 Lemma: $\text{types}(e[e'/x]) \subseteq \text{types}(e) \cup \text{types}(e')$

Proof: By induction on $e$.

C.2 Lemma: $\text{types}(\text{dom}(a)) \subseteq \text{types}(a)$

Proof: This property is trivial when $a = \bullet$.

C.3 Lemma: $\text{types}(\text{cod}(a)) \subseteq \text{types}(a)$

Proof: Similar to Lemma C.2.

C.4 Lemma [Coercing types doesn’t introduce types]:
$\text{types}(\text{coerce}(T_1, T_2, l)) \subseteq \text{types}(T_1) \cup \text{types}(T_2)$
**Proof:** By induction on $T_1$ and $T_2$. When they are refinements, we have the coercion just being $\{x:B \mid e_2\}$. When they are functions, by the IH. □

**C.5 Lemma [Dropping types doesn’t introduce types]:**

$\text{types}(\text{drop }(r, \{x:B \mid e\})) \subseteq \text{types}(r)$

**Proof:** By induction on $r$.

$(r = \text{nil})$ The two sides are immediately equal.

$(r = \{x:B \mid e\}, r')$ If $\{x:B \mid e\} \not\supseteq \{x:B \mid e\}$, then the two are identical. If not, then we have $\text{types}(r') \subseteq \text{types}(r)$ by the IH. □

**C.6 Lemma [Coercion merges don’t introduce types]:**

$\text{types}(\text{join}(r_1, r_2)) \subseteq \text{types}(r_1) \cup \text{types}(r_2)$

**Proof:** By induction on $r_1$.

$(r_1 = \text{nil})$ The two sides are immediately equal.

$(r_1 = \{x:B \mid e\}, r_1')$ Using Lemma C.5, we find:

$\text{types}(\text{join}(r_1, r_2)) = \{\{x:B \mid e\}\} \cup \text{types}(\text{join}(r_1', \text{drop }(r_2, \{x:B \mid e\})))$

$\subseteq \{\{x:B \mid e\}\} \cup \text{types}(r_1') \cup \text{types}(\text{drop }(r_2, \{x:B \mid e\}))$

$\subseteq \{\{x:B \mid e\}\} \cup \text{types}(r_1') \cup \text{types}(r_2)$

$= \text{types}(r_1) \cup \text{types}(r_2)$ □

**C.7 Lemma [Reduction doesn’t introduce types]:** If $e \rightarrow_m e'$ then $\text{types}(e') \subseteq \text{types}(e)$.

**Proof:** By induction on the step taken. □