

Interoperation for Incompatible Evaluation Strategies

William Faight

October 4, 2010

Abstract

Software components written in different programming languages can co-operate through interoperation. Differences between languages — incompatibilities — complicate interoperation. This paper explores and resolves incompatible type systems, support for parametricity, and evaluation strategies with a model of computation, gives a thorough proof of its type soundness, and describes an implementation of it. The model uses contracts for higher-order functions and lump types to resolve incompatible type systems, label types to resolve incompatible support for parametricity, and delayed conversions for list constructions to resolve incompatible evaluation strategies. These mechanisms enable the interoperation of Haskell, ML, and Scheme without compromising their semantics.

1 Introduction

The complexities of software interoperation in part engender the proverbial reinvention of the wheel. Programmers forgo preexisting solutions to problems where interoperation proves too cumbersome; they reimplement software components, rather than reuse them. Disparate programming language features complicate the conversion of values exchanged between components of different languages. Resolving language incompatibilities transparently at boundaries between component languages facilitates interoperation by unburdening programmers. This paper explores and resolves two such incompatibilities with a model of computation and then proves its type soundness and describes its implementation.

The first incompatibility is type systems. Static type systems calculate and validate the types of expressions before run time, thereby ensuring that well-typed programs do not encounter type errors during run time. Dynamic type systems detect invalid operations on values using value predicates during run time and do not calculate or validate the types of expressions at compile time. Statically-typed languages — languages that use static type systems — that use values from dynamically-typed languages must verify that the values match their expected types. Languages are assumed to exchange a common set of values that can be checked straightforwardly without coercion. Mismatched values and expected types could cause type errors during run time and violate type soundness. Ad-hoc polymorphism in dynamically-typed languages enables argument types to determine polymorphic function behavior. Since determining function behavior is undecidable [1], actual types for these functions cannot be reliably calculated at language boundaries and compared to expected types. Instead, they are wrapped in contracts [2] that defer the checking of their parameter and result types until they are used during run time. If they are never used, their types cannot be checked, but neither can they cause type errors.

The second incompatibility is parametricity. Parametric polymorphism in statically-typed languages enables function types to be abstracted with type variables and then instantiated into concrete types. Parametricity constrains the behavior of parametric polymorphic functions by ensuring that they behave the same regardless of the types and values of their arguments, and that functions with instantiated result types produce as their results the arguments associated with the same instantiated types. Functions from dynamically-typed languages that use value predicates or conditions on arguments and are used as parametric polymorphic functions by languages that have parametricity can violate their parametricity. Arguments for these functions must be obscured such that value predicates and conditions cannot examine them and annotated to ensure the correct ones are produced as results.

The third incompatibility is evaluation strategies. Evaluation strategies determine the order in which languages evaluate expressions. Eager evaluation evaluates expressions regardless of necessity, and lazy evaluation evaluates expressions only where necessary. Lazy languages — languages that use lazy evaluation — can construct infinite streams as lists because they do not evaluate list elements when lists are constructed, but eager languages cannot because they do. Since there exist lazy lists — lists in lazy languages — for which no naturally equivalent eager lists exist, lazy lists crossing to eager languages are not converted to eager lists. Instead, elements of lazy lists are converted when accessed by eager languages if they are not lazy lists too.

The languages in the model must be able to express programs in which the

aforementioned three incompatibilities arise. Haskell, ML, and Scheme each possess a unique combination of properties that together are sufficient for this purpose: Haskell and ML use static type systems and have parametricity, Scheme uses a dynamic type system, ML and Scheme use eager evaluation, and Haskell uses lazy evaluation.

The rest of the paper is organized as follows: Chapter 2 defines the model of computation, Chapter 3 proves the type soundness of the model, Chapter 4 describes an implementation of the model, Chapter 5 discusses related work, Chapter 6 discusses future work, and Chapter 7 discusses the conclusions.

2 Model of Computation

The model of computation comprises three dependent models of computation, based on that of Matthews and Findler ???. The Haskell and ML models are based on System F, extended with a fixed-point operation. The Scheme model is based on lambda calculus, having a simple type system to ensure no free variables, and extended with type predicates. All models have natural numbers, arithmetic, conditions, lists, and errors. The Haskell model has a call-by-name evaluation strategy, and ML and Scheme have call-by-value evaluation strategies. The models are presented with grammars and operational semantics in the style of (((CITATION))) and typing rules.

The Haskell model has a (((STRICT?))) subset of the strictness points of the ML and Scheme models, and hence forces the reduction of fewer expressions where those expressions are not used. When a function from the Haskell model is converted to a function in the ML or Scheme models, this same subset must be preserved or the meaning of the function will change and parametricity will not hold. Concretely, this means that function arguments and list construction operands must not be reduced. Thus evaluation contexts for the ML and Scheme models are made aware of whether Haskell language boundary guards are in these places, and if so, to make them irreducible.

Since Haskell language boundary guards are forced in some places but not others, they must be considered a value sometimes, but not others. Thus there are two kinds of values: all values, called unforced values, which include imported Haskell expressions, and forced values, which exclude imported Haskell expressions. Unforced values occur in the evaluation contexts and reduction rules where Haskell importations should not be forced, namely function arguments and list construction operands, and forced values occur everywhere else a value is required.

Evaluation contexts are split into two: forced, E , and unforced, U . Only forced evaluation contexts can reduce anything, including Haskell importations, and un-

$$\begin{aligned}
& zeroes = \mathbf{fix} (\lambda x_H : \{N\}. \mathbf{cons} \bar{0} x_H) \\
& (\mathbf{hs} (\{N\} \rightarrow \{N\}) (\lambda x_S. x_S)) zeroes \quad \rightarrow \\
& (\lambda x'_H : \{N\}. \mathbf{hs} \{N\} ((\lambda x_S. x_S) (\mathbf{sh} \{N\} x'_H))) zeroes \quad \rightarrow \\
& \mathbf{hs} \{N\} ((\lambda x_S. x_S) (\mathbf{sh} \{N\} zeroes)) \quad \rightarrow \\
& \mathbf{hs} \{N\} (\mathbf{sh} \{N\} zeroes) \quad \rightarrow \\
& \mathbf{hs} \{N\} (\mathbf{sh} \{N\} (\mathbf{cons} \bar{0} zeroes)) \quad \rightarrow \\
& \mathbf{hs} \{N\} (\mathbf{cons} (\mathbf{sh} N \bar{0}) (\mathbf{sh} \{N\} zeroes)) \quad \rightarrow \\
& \mathbf{hs} \{N\} (\mathbf{cons} \bar{0} (\mathbf{sh} \{N\} zeroes)) \quad \rightarrow \\
& \mathbf{cons} (\mathbf{hs} N \bar{0}) (\mathbf{hs} \{N\} (\mathbf{sh} \{N\} zeroes))
\end{aligned}$$

Figure 1: Function and list conversions with unforced points.

forced evaluation contexts restrict where expressions are forced. Where U appears in an evaluation context, any Haskell importation matching that expression is not forced because only E can reduce it.

Since the Haskell and ML models have their own types, type abstractions from one imported into the other cannot be easily converted, because any type the conversion is applied to cannot be substituted into the other language. Instead, and like the importation of parametric polymorphic types into the Scheme model, the lump type is substituted into the imported type abstraction, and a lump equality relation, $((\text{LUMP EQUALITY REL}))$ asserts that corresponding parts of the inner and outer types of the importation must be equal, or one of them must be a lump.

2.1 Notation

Symbols that represent grammar non-terminals or relations typically have letter subscripts that specify a model.

The Haskell and ML models have static type systems that use typing environments, written Γ , and typing relations, written \vdash . Typing judgements for expressions are written $\Gamma \vdash e : t$, where e is bound in Γ and has the type t . Typing judgements for types are written $\Gamma \vdash t$ and mean t is bound in Γ . Extended typing environments are written $\Gamma, x : t$ for variables and Γ, u for type variables. Typing environments are omitted where empty. The Scheme model uses a simple type system to ensure no free variables. Every well-typed Scheme model expression has the type **TST**. Type substitution within types is written $x[y/z]$, where the type y is substituted for free occurrences of the type variable z in the type x .

Expression and type substitutions within expressions are written like type substitutions within types.

$$\begin{aligned}
e_H &= x_H \mid v_H \mid e_H e_H \mid e_H \langle t_H \rangle \mid \mathbf{fix} \, e_H \mid o \, e_H e_H \mid \mathbf{if0} \, e_H e_H e_H \mid f \, e_H \\
&\quad \mathbf{null?} \, e_H \mid \mathbf{wrong} \, t_H \, string \mid \mathbf{hm} \, t_H \, t_M \, e_M \mid \mathbf{hs} \, k_H \, e_S \\
v_H &= \lambda x_H : t_H . e_H \mid \Lambda u_H . e_H \mid \bar{n} \mid \mathbf{nil} \, t_H \mid \mathbf{cons} \, e_H e_H \mid \mathbf{hm} \, L \, t_M \, w_M \\
&\quad \mathbf{hs} \, L \, w_S \\
t_H &= L \mid N \mid u_H \mid \{t_H\} \mid t_H \rightarrow t_H \mid \forall u_H . t_H \\
k_H &= L \mid N \mid u_H \mid \{k_H\} \mid k_H \rightarrow k_H \mid \forall u_H . k_H \mid b \diamond t_H \\
o &= + \mid - \\
f &= \mathbf{hd} \mid \mathbf{tl} \\
E_H &= []_H \mid E_H e_H \mid E_H \langle t_H \rangle \mid \mathbf{fix} \, E_H \mid o \, E_H e_H \mid o \, v_H \, E_H \\
&\quad \mathbf{if0} \, E_H e_H e_H \mid f \, E_H \mid \mathbf{null?} \, E_H \mid \mathbf{hm} \, t_H \, t_M \, E_M \mid \mathbf{hs} \, k_H \, E_S
\end{aligned}$$

Figure 2: Haskell syntax and evaluation contexts

$$\begin{array}{c}
\overline{\vdash_H \mathbf{L}} \quad \overline{\vdash_H \mathbf{N}} \quad \overline{\Gamma, u_H \vdash_H u_H} \\
\frac{\Gamma \vdash_H t_H}{\Gamma \vdash_H \{t_H\}} \quad \frac{\Gamma \vdash_H t_H \quad \Gamma \vdash_H t'_H}{\Gamma \vdash_H t_H \rightarrow t'_H} \quad \frac{\Gamma, u_H \vdash_H t_H}{\Gamma \vdash_H \forall u_H. t_H} \\
\\
\frac{\Gamma \vdash_H t_H \quad \Gamma, x_H : t_H \vdash_H e_H : t'_H}{\Gamma \vdash_H (\lambda x_H : t_H. e_H) : t_H \rightarrow t'_H} \quad \frac{\Gamma, u_H \vdash_H e_H : t_H}{\Gamma \vdash_H \Lambda u_H. e_H : \forall u_H. t_H} \quad \overline{\vdash_H \overline{n} : \mathbf{N}} \\
\frac{\Gamma \vdash_H t_H : \quad \Gamma \vdash_H e_H : t_H \quad \Gamma \vdash_H e'_H : \{t_H\}}{\Gamma \vdash_H \mathbf{nil} \ t_H : \{t_H\}} \quad \frac{\Gamma \vdash_H e_H : t_H \quad \Gamma \vdash_H e'_H : \{t_H\}}{\Gamma \vdash_H \mathbf{cons} \ e_H \ e'_H : \{t_H\}} \quad \frac{\Gamma, x_H : t_H \vdash_H x_H : t_H}{\Gamma \vdash_H \mathbf{cons} \ e_H \ e'_H : \{t_H\}} \\
\frac{\Gamma \vdash_H e_H : t_H \rightarrow t'_H \quad \Gamma \vdash_H e'_H : t_H}{\Gamma \vdash_H e_H \ e'_H : t'_H} \quad \frac{\Gamma \vdash_H e_H : t_H \rightarrow t_H}{\Gamma \vdash_H \mathbf{fix} \ e_H : t_H} \\
\frac{\Gamma \vdash_H t_H \quad \Gamma \vdash_H e_H : \forall u_H. t'_H}{\Gamma \vdash_H e_H \langle t_H \rangle : t'_H[t_H/u_H]} \quad \frac{\Gamma \vdash_H e_H : \{t_H\}}{\Gamma \vdash_H \mathbf{hd} \ e_H : t_H} \quad \frac{\Gamma \vdash_H e_H : \{t_H\}}{\Gamma \vdash_H \mathbf{tl} \ e_H : \{t_H\}} \\
\frac{\Gamma \vdash_H e_H : \mathbf{N} \quad \Gamma \vdash_H e'_H : \mathbf{N}}{\Gamma \vdash_H o \ e_H \ e'_H : \mathbf{N}} \quad \frac{\Gamma \vdash_H e_H : \{t_H\}}{\Gamma \vdash_H \mathbf{null?} \ e_H : \mathbf{N}} \quad \frac{\Gamma \vdash_H [k_H] \quad \Gamma \vdash_S e_S : \mathbf{TST}}{\Gamma \vdash_H \mathbf{hs} \ k_H \ e_S : [k_H]} \\
\frac{\Gamma \vdash_H e_H : \mathbf{N} \quad \Gamma \vdash_H e'_H : t_H \quad \Gamma \vdash_H e''_H : t_H}{\Gamma \vdash_H \mathbf{if0} \ e_H \ e'_H \ e''_H : t_H} \quad \frac{\Gamma \vdash_H t_H}{\Gamma \vdash_H \mathbf{wrong} \ t_H \ string : t_H} \\
\frac{\Gamma \vdash_H t_H \quad \Gamma \vdash_M t_M \quad \Gamma \vdash_M e_M : t'_M \quad t_H \doteq t_M \quad t_M = t'_M}{\Gamma \vdash_H \mathbf{hm} \ t_H \ t_M \ e_M : t_H}
\end{array}$$

Figure 3: Haskell typing rules

$$\begin{aligned}
& \mathcal{E}[(\lambda x_H : t_H.e_H) e'_H]_H \rightarrow \mathcal{E}[e_H[e'_H/x_H]] \\
& \mathcal{E}[(\Lambda u_H.e_H)(t_H)]_H \rightarrow \mathcal{E}[e_H[b \diamond t_H/u_H]] \\
& \mathcal{E}[\mathbf{fix} (\lambda x_H : t_H.e_H)]_H \rightarrow \mathcal{E}[e_H[\mathbf{fix} (\lambda x_H : t_H.e_H)/x_H]] \\
& \mathcal{E}[+ \bar{n} \bar{n'}]_H \rightarrow \mathcal{E}[\overline{n + n'}] \\
& \mathcal{E}[- \bar{n} \bar{n'}]_H \rightarrow \mathcal{E}[\overline{\max(n - n', 0)}] \\
& \mathcal{E}[\mathbf{if0} \bar{0} e_H e'_H]_H \rightarrow \mathcal{E}[e_H] \\
& \mathcal{E}[\mathbf{if0} \bar{n} e_H e'_H]_H \rightarrow \mathcal{E}[e'_H] \ (n \neq 0) \\
& \mathcal{E}[\mathbf{hd} (\mathbf{nil} t_H)]_H \rightarrow \mathcal{E}[\mathbf{wrong} t_H \text{ “Empty list”}] \\
& \mathcal{E}[\mathbf{tl} (\mathbf{nil} t_H)]_H \rightarrow \mathcal{E}[\mathbf{wrong} \{t_H\} \text{ “Empty list”}] \\
& \mathcal{E}[\mathbf{hd} (\mathbf{cons} e_H e'_H)]_H \rightarrow \mathcal{E}[e_H] \\
& \mathcal{E}[\mathbf{tl} (\mathbf{cons} e_H e'_H)]_H \rightarrow \mathcal{E}[e'_H] \\
& \mathcal{E}[\mathbf{null?} (\mathbf{nil} t_H)]_H \rightarrow \mathcal{E}[\bar{0}] \\
& \mathcal{E}[\mathbf{null?} (\mathbf{cons} e_H e'_H)]_H \rightarrow \mathcal{E}[\bar{1}] \\
& \mathcal{E}[\mathbf{wrong} t_H \text{ string}]_H \rightarrow \mathbf{Error: string}
\end{aligned}$$

Figure 4: Haskell operational semantics

$$\begin{aligned}
& \mathcal{E}[\mathbf{hm} \ t_H \ \mathbf{L} \ (\mathbf{mh} \ \mathbf{L} \ t'_H \ e_H)]_H \rightarrow \mathcal{E}[e_H] \quad (t_H = t'_H \text{ and } t_H \neq \mathbf{L}) \\
& \mathcal{E}[\mathbf{hm} \ t_H \ \mathbf{L} \ (\mathbf{mh} \ \mathbf{L} \ t'_H \ e_H)]_H \rightarrow \mathcal{E}[\mathbf{wrong} \ t_H \ \text{“Type mismatch”}] \\
& \quad (t_H \neq t'_H \text{ and } t_H \neq \mathbf{L}) \\
& \mathcal{E}[\mathbf{hm} \ t_H \ \mathbf{L} \ (\mathbf{ms} \ \mathbf{L} \ w_S)]_H \rightarrow \mathcal{E}[\mathbf{wrong} \ t_H \ \text{“Bad value”}] \quad (t_H \neq \mathbf{L}) \\
& \mathcal{E}[\mathbf{hm} \ \mathbf{N} \ \mathbf{N} \ \bar{n}]_H \rightarrow \mathcal{E}[\bar{n}] \\
& \mathcal{E}[\mathbf{hm} \ \{t_H\} \ \{t_M\} \ (\mathbf{nil} \ t'_M)]_H \rightarrow \mathcal{E}[\mathbf{nil} \ t_H] \\
& \mathcal{E}[\mathbf{hm} \ \{t_H\} \ \{t_M\} \ (\mathbf{cons} \ v_M \ v'_M)]_H \rightarrow \\
& \quad \mathcal{E}[\mathbf{cons} \ (\mathbf{hm} \ t_H \ t_M \ v_M) \ (\mathbf{hm} \ \{t_H\} \ \{t_M\} \ v'_M)] \\
& \mathcal{E}[\mathbf{hm} \ (t_H \rightarrow t'_H) \ (t_M \rightarrow t'_M) \ (\lambda x_M : t''_M . e_M)]_H \rightarrow \\
& \quad \mathcal{E}[\lambda x_H : t_H . \mathbf{hm} \ t'_H \ t'_M \ ((\lambda x_M : t''_M . e_M) \ (\mathbf{mh} \ t_M \ t_H \ x_H))] \\
& \mathcal{E}[\mathbf{hm} \ (\forall u_H . t_H) \ (\forall u_M . t_M) \ (\Lambda u'_M . e_M)]_H \rightarrow \mathcal{E}[\Lambda u_H . \mathbf{hm} \ t_H \ t_M [\mathbf{L}/u_M] \ e_M [\mathbf{L}/u'_M]]
\end{aligned}$$

Figure 5: Haskell-ML operational semantics

$$\begin{aligned}
& \mathcal{E}[\mathbf{hs} \ N \ \bar{n}]_H \rightarrow \mathcal{E}[\bar{n}] \\
& \mathcal{E}[\mathbf{hs} \ N \ w_S]_H \rightarrow \mathcal{E}[\mathbf{wrong} \ N \ \text{“Not a number”}] \ (w_S \neq \bar{n}) \\
& \mathcal{E}[\mathbf{hs} \ \{k_H\} \ \mathbf{nil}]_H \rightarrow \mathcal{E}[\mathbf{nil} \ [k_H]] \\
& \mathcal{E}[\mathbf{hs} \ \{k_H\} \ (\mathbf{cons} \ v_S \ v'_S)]_H \rightarrow \mathcal{E}[\mathbf{cons} \ (\mathbf{hs} \ k_H \ v_S) \ (\mathbf{hs} \ \{k_H\} \ v'_S)] \\
& \mathcal{E}[\mathbf{hs} \ \{k_H\} \ w_S]_H \rightarrow \mathcal{E}[\mathbf{wrong} \ [\{k_H\}] \ \text{“Not a list”}] \\
& \quad (w_S \neq \mathbf{nil} \text{ and } w_S \neq \mathbf{cons} \ v_S \ v'_S) \\
& \mathcal{E}[\mathbf{hs} \ (b \diamond t_H) \ (\mathbf{sh} \ (b \diamond t_H) \ e_H)]_H \rightarrow \mathcal{E}[e_H] \\
& \mathcal{E}[\mathbf{hs} \ (b \diamond t_H) \ w_S]_H \rightarrow \mathcal{E}[\mathbf{wrong} \ t_H \ \text{“Brand mismatch”}] \ (w_S \neq \mathbf{sh} \ (b \diamond t_H) \ e_H) \\
& \mathcal{E}[\mathbf{hs} \ (k_H \rightarrow k'_H) \ (\lambda x_S. e_S)]_H \rightarrow \mathcal{E}[\lambda x_H : [k_H]. \mathbf{hs} \ k'_H \ ((\lambda x_S. e_S) \ (\mathbf{sh} \ k_H \ x_H))] \\
& \mathcal{E}[\mathbf{hs} \ (k_H \rightarrow k'_H) \ w_S]_H \rightarrow \mathcal{E}[\mathbf{wrong} \ [k_H \rightarrow k'_H] \ \text{“Not a function”}] \\
& \quad (w_S \neq \lambda x_S. e_S) \\
& \mathcal{E}[\mathbf{hs} \ (\forall u_H. k_H) \ w_S]_H \rightarrow \mathcal{E}[\Lambda u_H. \mathbf{hs} \ k_H \ w_S]
\end{aligned}$$

Figure 6: Haskell-Scheme operational semantics

$$\begin{aligned}
e_M &= x_M \mid v_M \mid e_M e_M \mid e_M \langle t_M \rangle \mid \mathbf{fix} \ e_M \mid o \ e_M \ e_M \mid \mathbf{if0} \ e_M \ e_M \ e_M \\
&\quad \mathbf{cons} \ e_M \ e_M \mid f \ e_M \mid \mathbf{null?} \ e_M \mid \mathbf{wrong} \ t_M \ string \mid \mathbf{ms} \ k_M \ e_S \\
v_M &= w_M \mid \mathbf{mh} \ t_M \ t_H \ e_H \\
w_M &= \lambda x_M : t_M . e_M \mid \Lambda u_M . e_M \mid \bar{n} \mid \mathbf{nil} \ t_M \mid \mathbf{cons} \ v_M \ v_M \mid \mathbf{mh} \ L \ t_H \ e_H \\
&\quad \mathbf{ms} \ L \ w_S \\
t_M &= L \mid N \mid u_M \mid \{t_M\} \mid t_M \rightarrow t_M \mid \forall u_M . t_M \\
k_M &= L \mid N \mid u_M \mid \{k_M\} \mid k_M \rightarrow k_M \mid \forall u_M . k_M \mid b \diamond t_M \\
o &= + \mid - \\
f &= \mathbf{hd} \mid \mathbf{tl} \\
E_M &= U_M \mid \mathbf{mh} \ t_M \ t_H \ E_H \\
U_M &= []_M \mid E_M \ e_M \mid w_M \ U_M \mid E_M \langle t_M \rangle \mid \mathbf{fix} \ E_M \mid o \ E_M \ e_M \mid o \ w_M \ E_M \\
&\quad \mathbf{if0} \ E_M \ e_M \ e_M \mid \mathbf{cons} \ U_M \ e_M \mid \mathbf{cons} \ v_M \ U_M \mid f \ E_M \mid \mathbf{null?} \ E_M \\
&\quad \mathbf{ms} \ k_M \ E_S
\end{aligned}$$

Figure 7: ML syntax and evaluation contexts

$$\begin{array}{c}
\overline{\vdash_M \mathbf{L}} \quad \overline{\vdash_M \mathbf{N}} \quad \overline{\Gamma, u_M \vdash_M u_M} \\
\frac{\Gamma \vdash_M t_M}{\Gamma \vdash_M \{t_M\}} \quad \frac{\Gamma \vdash_M t_M \quad \Gamma \vdash_M t'_M}{\Gamma \vdash_M t_M \rightarrow t'_M} \quad \frac{\Gamma, u_M \vdash_M t_M}{\Gamma \vdash_M \forall u_M. t_M} \\
\\
\frac{\Gamma \vdash_M t_M \quad \Gamma, x_M : t_M \vdash_M e_M : t'_M}{\Gamma \vdash_M (\lambda x_M : t_M. e_M) : t_M \rightarrow t'_M} \quad \frac{\Gamma, u_M \vdash_M e_M : t_M}{\Gamma \vdash_M \Lambda u_M. e_M : \forall u_M. t_M} \quad \overline{\vdash_M \bar{n} : \mathbf{N}} \\
\\
\frac{\Gamma \vdash_M t_M}{\Gamma \vdash_M \mathbf{nil} \ t_M : \{t_M\}} \quad \frac{\Gamma \vdash_M e_M : t_M \quad \Gamma \vdash_M e'_M : \{t_M\}}{\Gamma \vdash_M \mathbf{cons} \ e_M \ e'_M : \{t_M\}} \quad \frac{}{\Gamma, x_M : t_M \vdash_M x_M : t_M} \\
\\
\frac{\Gamma \vdash_M e_M : t_M \rightarrow t'_M \quad \Gamma \vdash_M e'_M : t_M}{\Gamma \vdash_H e_M \ e'_M : t'_M} \quad \frac{\Gamma \vdash_M e_M : t_M \rightarrow t_M}{\Gamma \vdash_M \mathbf{fix} \ e_M : t_M} \\
\\
\frac{\Gamma \vdash_M t_M \quad \Gamma \vdash_M e_M : \forall u_M. t'_M}{\Gamma \vdash_M e_M \langle t_M \rangle : t'_M[t_M/u_M]} \quad \frac{\Gamma \vdash_M e_M : \{t_M\}}{\Gamma \vdash_M \mathbf{hd} \ e_M : t_M} \quad \frac{\Gamma \vdash_M e_M : \{t_M\}}{\Gamma \vdash_M \mathbf{tl} \ e_M : \{t_M\}} \\
\\
\frac{\Gamma \vdash_M e_M : \mathbf{N} \quad \Gamma \vdash_M e'_M : \mathbf{N}}{\Gamma \vdash_M o \ e_M \ e'_M : \mathbf{N}} \quad \frac{\Gamma \vdash_M e_M : \{t_M\}}{\Gamma \vdash_M \mathbf{null?} \ e_M : \mathbf{N}} \quad \frac{\Gamma \vdash_M \lfloor k_M \rfloor \quad \Gamma \vdash_S e_S : \mathbf{TST}}{\Gamma \vdash_M \mathbf{ms} \ k_M \ e_S : \lfloor k_M \rfloor} \\
\\
\frac{\Gamma \vdash_M e_M : \mathbf{N} \quad \Gamma \vdash_M e'_M : t_M \quad \Gamma \vdash_M e''_M : t_M}{\Gamma \vdash_M \mathbf{if0} \ e_M \ e'_M \ e''_M : t_M} \quad \frac{\Gamma \vdash_M t_M}{\Gamma \vdash_M \mathbf{wrong} \ t_M \ string : t_M} \\
\\
\frac{\Gamma \vdash_M t_M \quad \Gamma \vdash_H t_H \quad \Gamma \vdash_H e_H : t'_H \quad t_M \doteq t_H \quad t_H = t'_H}{\Gamma \vdash_M \mathbf{mh} \ t_M \ t_H \ e_H : t_M}
\end{array}$$

Figure 8: ML typing rules

$$\begin{aligned}
& \mathcal{E}[(\lambda x_M : t_M.e_M) v_M]_M \rightarrow \mathcal{E}[e_M[v_M/x_M]] \\
& \mathcal{E}[(\Lambda u_M.e_M)\langle t_M \rangle]_M \rightarrow \mathcal{E}[e_M[b \diamond t_M/u_M]] \\
& \mathcal{E}[\mathbf{fix} (\lambda x_M : t_M.e_M)]_M \rightarrow \mathcal{E}[e_M[\mathbf{fix} (\lambda x_M : t_M.e_M)/x_M]] \\
& \mathcal{E}[+ \bar{n} \bar{n}']_M \rightarrow \mathcal{E}[\overline{n + n'}] \\
& \mathcal{E}[- \bar{n} \bar{n}']_M \rightarrow \mathcal{E}[\overline{\max(n - n', 0)}] \\
& \mathcal{E}[\mathbf{if0} \bar{0} e_M e'_M]_M \rightarrow \mathcal{E}[e_M] \\
& \mathcal{E}[\mathbf{if0} \bar{n} e_M e'_M]_M \rightarrow \mathcal{E}[e'_M] \ (n \neq 0) \\
& \mathcal{E}[\mathbf{hd} (\mathbf{nil} t_M)]_M \rightarrow \mathcal{E}[\mathbf{wrong} t_M \text{ “Empty list”}] \\
& \mathcal{E}[\mathbf{tl} (\mathbf{nil} t_M)]_M \rightarrow \mathcal{E}[\mathbf{wrong} \{t_M\} \text{ “Empty list”}] \\
& \mathcal{E}[\mathbf{hd} (\mathbf{cons} v_M v'_M)]_M \rightarrow \mathcal{E}[v_M] \\
& \mathcal{E}[\mathbf{tl} (\mathbf{cons} v_M v'_M)]_M \rightarrow \mathcal{E}[v'_M] \\
& \mathcal{E}[\mathbf{null?} (\mathbf{nil} t_M)]_M \rightarrow \mathcal{E}[\bar{0}] \\
& \mathcal{E}[\mathbf{null?} (\mathbf{cons} v_M v'_M)]_M \rightarrow \mathcal{E}[\bar{1}] \\
& \mathcal{E}[\mathbf{wrong} t_M \text{ string}]_H \rightarrow \mathbf{Error: string}
\end{aligned}$$

Figure 9: ML operational semantics

$$\begin{aligned}
& \mathcal{E}[\mathbf{mh} \ t_M \ \mathbf{L} \ (\mathbf{hm} \ \mathbf{L} \ t'_M \ w_M)]_M \rightarrow \mathcal{E}[w_M] \ (t_M = t'_M \text{ and } t_M \neq \mathbf{L}) \\
& \mathcal{E}[\mathbf{mh} \ t_M \ \mathbf{L} \ (\mathbf{hm} \ \mathbf{L} \ t'_M \ w_M)]_M \rightarrow \mathcal{E}[\mathbf{wrong} \ t_M \ \text{“Type mismatch”}] \ (t_M \neq t'_M \text{ and } t_M \neq \mathbf{L}) \\
& \mathcal{E}[\mathbf{mh} \ t_M \ \mathbf{L} \ (\mathbf{hs} \ \mathbf{L} \ w_S)]_H \rightarrow \mathcal{E}[\mathbf{wrong} \ t_M \ \text{“Bad value”}] \ (t_M \neq \mathbf{L}) \\
& \mathcal{E}[\mathbf{mh} \ \mathbf{N} \ \mathbf{N} \ \bar{n}]_M \rightarrow \mathcal{E}[\bar{n}] \\
& \mathcal{E}[\mathbf{mh} \ \{t_M\} \ \{t_H\} \ (\mathbf{nil} \ t'_H)]_M \rightarrow \mathcal{E}[\mathbf{nil} \ t_M] \\
& \mathcal{E}[\mathbf{mh} \ \{t_M\} \ \{t_H\} \ (\mathbf{cons} \ e_H \ e'_H)]_M \rightarrow \mathcal{E}[\mathbf{cons} \ (\mathbf{mh} \ t_M \ t_H \ e_H) \ (\mathbf{mh} \ \{t_M\} \ \{t_H\} \ e'_H)] \\
& \mathcal{E}[\mathbf{mh} \ (t_M \rightarrow t'_M) \ (t_H \rightarrow t'_H) \ (\lambda x_H : t''_H . e_H)]_M \rightarrow \\
& \quad \mathcal{E}[\lambda x_M : t_M . \mathbf{mh} \ t'_M \ t'_H \ ((\lambda x_H : t''_H . e_H) \ (\mathbf{hm} \ t_H \ t_M \ x_M))] \\
& \mathcal{E}[\mathbf{mh} \ (\forall u_M . t_M) \ (\forall u_H . t_H) \ (\Lambda u'_H . e_H)]_M \rightarrow \mathcal{E}[\Lambda u_M . \mathbf{mh} \ t_M \ t_H [\mathbf{L}/u_H] \ e_H [\mathbf{L}/u'_H]]
\end{aligned}$$

Figure 10: ML-Haskell operational semantics

$$\begin{aligned}
& \mathcal{E}[\mathbf{ms} \ \mathbf{N} \ \bar{n}]_M \rightarrow \mathcal{E}[\bar{n}] \\
& \mathcal{E}[\mathbf{ms} \ \mathbf{N} \ w_S]_M \rightarrow \mathcal{E}[\mathbf{wrong} \ \mathbf{N} \ \text{“Not a number”}] \ (w_S \neq \bar{n}) \\
& \mathcal{E}[\mathbf{ms} \ \{k_M\} \ \mathbf{nil}]_M \rightarrow \mathcal{E}[\mathbf{nil} \ [k_M]] \\
& \mathcal{E}[\mathbf{ms} \ \{k_M\} \ (\mathbf{cons} \ v_S \ v'_S)]_M \rightarrow \mathcal{E}[\mathbf{cons} \ (\mathbf{ms} \ k_M \ v_S) \ (\mathbf{ms} \ \{k_M\} \ v'_S)] \\
& \mathcal{E}[\mathbf{ms} \ \{k_M\} \ w_S]_M \rightarrow \mathcal{E}[\mathbf{wrong} \ [\{k_M\}] \ \text{“Not a list”}] \\
& \quad (w_S \neq \mathbf{nil} \text{ and } w_S \neq \mathbf{cons} \ v_S \ v'_S) \\
& \mathcal{E}[\mathbf{ms} \ (b \diamond t_M) \ (\mathbf{sm} \ (b \diamond t_M) \ v_M)]_M \rightarrow \mathcal{E}[v_M] \\
& \mathcal{E}[\mathbf{ms} \ (b \diamond t_M) \ w_S]_M \rightarrow \mathcal{E}[\mathbf{wrong} \ [b \diamond t_M] \ \text{“Brand mismatch”}] \\
& \quad (w_S \neq \mathbf{sm} \ (b \diamond t_M) \ e_M) \\
& \mathcal{E}[\mathbf{ms} \ (k_M \rightarrow k'_M) \ (\lambda x_S. e_S)]_M \rightarrow \\
& \quad \mathcal{E}[\lambda x_M : [k_M]. \mathbf{ms} \ k'_M \ ((\lambda x_S. e_S) \ (\mathbf{sm} \ k_M \ x_M))] \\
& \mathcal{E}[\mathbf{ms} \ (k_M \rightarrow k'_M) \ w_S]_M \rightarrow \mathcal{E}[\mathbf{wrong} \ [k_M \rightarrow k'_M] \ \text{“Not a function”}] \\
& \quad (w_S \neq \lambda x_S. e_S) \\
& \mathcal{E}[\mathbf{ms} \ (\forall u_M. k_M) \ w_S]_M \rightarrow \mathcal{E}[\Lambda u_M. \mathbf{ms} \ k_M \ w_S]
\end{aligned}$$

Figure 11: ML-Scheme operational semantics

$$\begin{aligned}
e_S &= x_S \mid v_S \mid e_S e_S \mid o e_S e_S \mid p e_S \mid \text{if0 } e_S e_S e_S \mid \text{cons } e_S e_S \mid f e_S \\
&\quad \text{wrong } string \mid \text{sm } k_M e_M \\
v_S &= w_S \mid \text{sh } k_H e_H \\
w_S &= \lambda x_S. e_S \mid \bar{n} \mid \text{nil} \mid \text{cons } v_S v_S \mid \text{sh } (b \diamond t_H) e_H \mid \text{sm } (b \diamond t_M) w_M \\
o &= + \mid - \\
f &= \text{hd} \mid \text{tl} \\
p &= \text{fun?} \mid \text{list?} \mid \text{null?} \mid \text{num?} \\
E_S &= U_S \mid \text{sh } k_H E_H \\
U_S &= []_S \mid E_S e_S \mid w_S U_S \mid o E_S e_S \mid o w_S E_S \mid p E_S \mid \text{if0 } E_S e_S e_S \\
&\quad \text{cons } U_S e_S \mid \text{cons } v_S U_S \mid f E_S \mid \text{sm } k_M E_M
\end{aligned}$$

Figure 12: Scheme syntax and evaluation contexts

$$\begin{array}{c}
\overline{\vdash_S \text{TST}} \\
\\
\frac{\Gamma, x_S : \text{TST} \vdash_S e_S : \text{TST}}{\Gamma \vdash_S \lambda x_S. e_S : \text{TST}} \quad \overline{\vdash_S \bar{n} : \text{TST}} \quad \overline{\vdash_S \text{nil} : \text{TST}} \\
\frac{\Gamma \vdash_S e_S : \text{TST} \quad \Gamma \vdash_S e'_S : \text{TST}}{\Gamma \vdash_S \text{cons } e_S e'_S : \text{TST}} \quad \overline{\Gamma, x_S : \text{TST} \vdash_S x_S : \text{TST}} \\
\frac{\Gamma \vdash_S e_S : \text{TST} \quad \Gamma \vdash_S e'_S : \text{TST}}{\Gamma \vdash_H e_S e'_S : \text{TST}} \quad \frac{\Gamma \vdash_S e_S : \text{TST}}{\Gamma \vdash_S f e_S : \text{TST}} \\
\frac{\Gamma \vdash_S e_S : \text{TST} \quad \Gamma \vdash_S e'_S : \text{TST}}{\Gamma \vdash_S o e_S e'_S : \text{TST}} \quad \frac{\Gamma \vdash_S e_S : \text{TST}}{\Gamma \vdash_S p e_S : \text{TST}} \\
\frac{\Gamma \vdash_S e_S : \text{TST} \quad \Gamma \vdash_S e'_S : \text{TST} \quad \Gamma \vdash_S e''_S : \text{TST}}{\Gamma \vdash_S \text{if0 } e_S e'_S e''_S : \text{TST}} \quad \overline{\vdash_S \text{wrong string} : \text{TST}} \\
\frac{\Gamma \vdash_H [k_H] \quad \Gamma \vdash_H e_H : t_H \quad [k_H] = t_H}{\Gamma \vdash_S \text{sh } k_H e_H : \text{TST}} \quad \frac{\Gamma \vdash_M [k_M] \quad \Gamma \vdash_M e_M : t_M \quad [k_M] = t_M}{\Gamma \vdash_S \text{sm } k_M e_M : \text{TST}}
\end{array}$$

Figure 13: Scheme typing rules

$$\begin{aligned}
& \mathcal{E}[(\lambda x_S. e_S) v_S]_S \rightarrow \mathcal{E}[e_S[v_S/x_S]] \\
& \mathcal{E}[w_S v_S]_S \rightarrow \mathcal{E}[\mathbf{wrong} \text{ “Not a function”}] \ (w_S \neq \lambda x_S. e_S) \\
& \mathcal{E}[+ \bar{n} \bar{n}']_S \rightarrow \mathcal{E}[\overline{n + n'}] \\
& \mathcal{E}[- \bar{n} \bar{n}']_S \rightarrow \mathcal{E}[\overline{\max(n - n', 0)}] \\
& \mathcal{E}[o w_S w'_S]_S \rightarrow \mathcal{E}[\mathbf{wrong} \text{ “Not a number”}] \ (w_S \neq \bar{n} \text{ or } w'_S \neq \bar{n}) \\
& \mathcal{E}[\mathbf{if0} \bar{0} e_S e'_S]_S \rightarrow \mathcal{E}[e_S] \\
& \mathcal{E}[\mathbf{if0} \bar{n} e_S e'_S]_S \rightarrow \mathcal{E}[e'_S] \ (n \neq 0) \\
& \mathcal{E}[\mathbf{if0} w_S e_S e'_S]_S \rightarrow \mathcal{E}[\mathbf{wrong} \text{ “Not a number”}] \ (w_S \neq \bar{n}) \\
& \mathcal{E}[f \mathbf{nil}]_S \rightarrow \mathcal{E}[\mathbf{wrong} \text{ “Empty list”}] \\
& \mathcal{E}[\mathbf{hd} (\mathbf{cons} v_S v'_S)]_S \rightarrow \mathcal{E}[v_S] \\
& \mathcal{E}[\mathbf{tl} (\mathbf{cons} v_S v'_S)]_S \rightarrow \mathcal{E}[v'_S] \\
& \mathcal{E}[f w_S]_S \rightarrow \mathcal{E}[\mathbf{wrong} \text{ “Not a list”}] \ (w_S \neq \mathbf{nil} \text{ and } w_S \neq \mathbf{cons} v_S v'_S) \\
& \mathcal{E}[\mathbf{fun?} (\lambda x_S. e_S)]_S \rightarrow \mathcal{E}[\bar{0}] \\
& \mathcal{E}[\mathbf{fun?} w_S]_S \rightarrow \mathcal{E}[\bar{1}] \ (w_S \neq \lambda x_S. e_S) \\
& \mathcal{E}[\mathbf{list?} \mathbf{nil}]_S \rightarrow \mathcal{E}[\bar{0}] \\
& \mathcal{E}[\mathbf{list?} (\mathbf{cons} v_S v'_S)]_S \rightarrow \mathcal{E}[\bar{0}] \\
& \mathcal{E}[\mathbf{list?} w_S]_S \rightarrow \mathcal{E}[\bar{1}] \ (w_S \neq \mathbf{nil} \text{ and } w_S \neq \mathbf{cons} v_S v'_S) \\
& \mathcal{E}[\mathbf{null?} \mathbf{nil}]_S \rightarrow \mathcal{E}[\bar{0}] \\
& \mathcal{E}[\mathbf{null?} w_S]_S \rightarrow \mathcal{E}[\bar{1}] \ (w_S \neq \mathbf{nil}) \\
& \mathcal{E}[\mathbf{num?} \bar{n}]_S \rightarrow \mathcal{E}[\bar{0}] \\
& \mathcal{E}[\mathbf{num?} w_S]_S \rightarrow \mathcal{E}[\bar{1}] \ (w_S \neq \bar{n}) \\
& \mathcal{E}[\mathbf{wrong} \text{ string}]_S \rightarrow \mathbf{Error: string}
\end{aligned}$$

Figure 14: Scheme operational semantics

$$\begin{aligned}
& \mathcal{E}[\mathbf{sh\ L\ (hm\ L\ } k_M\ w_M)]_S \rightarrow \mathcal{E}[\mathbf{wrong\ “Bad\ value”}] \\
& \mathcal{E}[\mathbf{sh\ L\ (hs\ L\ } w_S)]_S \rightarrow \mathcal{E}[w_S] \\
& \mathcal{E}[\mathbf{sh\ N\ } \bar{n}]_S \rightarrow \mathcal{E}[\bar{n}] \\
& \mathcal{E}[\mathbf{sh\ } \{k_H\}\ (\mathbf{nil\ } t_H)]_S \rightarrow \mathcal{E}[\mathbf{nil}] \\
& \mathcal{E}[\mathbf{sh\ } \{k_H\}\ (\mathbf{cons\ } e_H\ e'_H)]_S \rightarrow \mathcal{E}[\mathbf{cons\ (sh\ } k_H\ e_H)\ (\mathbf{sh\ } \{k_H\}\ e'_H)] \\
& \mathcal{E}[\mathbf{sh\ (} k_H \rightarrow k'_H \mathbf{)\ (} \lambda x_H : t_H.e_H \mathbf{)]}_S \rightarrow \\
& \quad \mathcal{E}[\lambda x_S.\mathbf{sh\ } k'_H\ ((\lambda x_H : t_H.e_H)\ (\mathbf{hs\ } k_H\ x_S))] \\
& \mathcal{E}[\mathbf{sh\ (} \forall u_H.k_H \mathbf{)\ (} \Lambda u'_H.e_H \mathbf{)]}_S \rightarrow \mathcal{E}[\mathbf{sh\ } k_H[\mathbf{L}/u_H]\ e_H[\mathbf{L}/u'_H]]
\end{aligned}$$

Figure 15: Scheme-Haskell operational semantics

$$\begin{aligned}
& \mathcal{E}[\mathbf{sm} \ L \ (\mathbf{mh} \ L \ k_H \ e_H)]_S \rightarrow \mathcal{E}[\mathbf{wrong} \ \text{“Bad value”}] \\
& \mathcal{E}[\mathbf{sm} \ L \ (\mathbf{ms} \ L \ w_S)]_S \rightarrow \mathcal{E}[w_S] \\
& \mathcal{E}[\mathbf{sm} \ N \ \bar{n}]_S \rightarrow \mathcal{E}[\bar{n}] \\
& \mathcal{E}[\mathbf{sm} \ \{k_M\} \ (\mathbf{nil} \ t_M)]_S \rightarrow \mathcal{E}[\mathbf{nil}] \\
& \mathcal{E}[\mathbf{sm} \ \{k_M\} \ (\mathbf{cons} \ v_M \ v'_M)]_S \rightarrow \mathcal{E}[\mathbf{cons} \ (\mathbf{sm} \ k_M \ v_M) \ (\mathbf{sm} \ \{k_M\} \ v'_M)] \\
& \mathcal{E}[\mathbf{sm} \ (k_M \rightarrow k'_M) \ (\lambda x_M : t_M. e_M)]_S \rightarrow \\
& \quad \mathcal{E}[\lambda x_S. \mathbf{sm} \ k'_M \ ((\lambda x_M : t_M. e_M) \ (\mathbf{ms} \ k_M \ x_S))] \\
& \mathcal{E}[\mathbf{sm} \ (\forall u_M. k_M) \ (\Lambda u'_M. e_M)]_S \rightarrow \mathcal{E}[\mathbf{sm} \ k_M[L/u_M] \ e_M[L/u'_M]]
\end{aligned}$$

Figure 16: Scheme-ML operational semantics

$$\begin{aligned}
\lfloor \mathbf{L} \rfloor &= \mathbf{L} \\
\lfloor \mathbf{N} \rfloor &= \mathbf{N} \\
\lfloor u_H \rfloor &= u_H \\
\lfloor u_M \rfloor &= u_M \\
\lfloor \{k_H\} \rfloor &= \{\lfloor k_H \rfloor\} \\
\lfloor \{k_M\} \rfloor &= \{\lfloor k_M \rfloor\} \\
\lfloor k_H \rightarrow k_H \rfloor &= \lfloor k_H \rfloor \rightarrow \lfloor k_H \rfloor \\
\lfloor k_M \rightarrow k_M \rfloor &= \lfloor k_M \rfloor \rightarrow \lfloor k_M \rfloor \\
\lfloor \forall u_H. k_H \rfloor &= \forall u_H. \lfloor k_H \rfloor \\
\lfloor \forall u_M. k_M \rfloor &= \forall u_M. \lfloor k_M \rfloor \\
\lfloor b \diamond t_H \rfloor &= t_H \\
\lfloor b \diamond t_M \rfloor &= t_M
\end{aligned}$$

Figure 17: Unbrand function

$$\begin{aligned}
& x \dot{=} x \\
& x \dot{=} y \Rightarrow y \dot{=} x \\
& x \dot{=} y \text{ and } y \dot{=} z \Rightarrow x \dot{=} z \\
& t_H \dot{=} L \\
& t_M \dot{=} L \\
& t_H = t_M \Rightarrow t_H \dot{=} t_M
\end{aligned}$$

Figure 18: Lump equality relation

| Symbol | Name |
|---------------|-----------------------------|
| b | Brand |
| k | Conversion scheme |
| e | Expression |
| E | Forced evaluation context |
| w | Forced value |
| L | Lump |
| \doteq | Lump equality relation |
| \mathcal{E} | Meta evaluation context |
| \bar{n} | Natural number |
| \mathbb{N} | Natural number |
| \rightarrow | Reduction relation |
| t | Type |
| u | Type variable |
| Γ | Typing environment |
| \vdash | Typing relation |
| U | Unforced evaluation context |
| v | Unforced value |
| x | Variable |

Figure 19: Symbol names.

| Syntax | Name |
|--|-----------------------|
| $+ e e$ | Addition |
| $b \diamond t$ | Branded type |
| <code>if0 $e e e$</code> | Condition |
| <code>nil t</code> | Empty list |
| <code>nil</code> | Empty list |
| <code>wrong $t string$</code> | Error |
| <code>wrong $string$</code> | Error |
| <code>fix e</code> | Fixed-point operation |
| $\forall u.t$ | Forall |
| $\forall u.k$ | Forall |
| $\lambda x : t.e$ | Function abstraction |
| $\lambda x_S.e_S$ | Function abstraction |
| $t \rightarrow t$ | Function abstraction |
| $k \rightarrow k$ | Function abstraction |
| $e e$ | Function application |
| $\{t\}$ | List |
| $\{k\}$ | List |
| <code>cons $e e$</code> | List construction |
| <code>hd e</code> | List head |
| <code>tl e</code> | List tail |
| $- e e$ | Subtraction |
| $\Lambda u.e$ | Type abstraction |
| $e\langle t \rangle$ | Type application |
| <code>fun? e_S</code> | Value predicate |
| <code>list? e_S</code> | Value predicate |
| <code>null? e</code> | Value predicate |
| <code>num? e_S</code> | Value predicate |

Figure 20: Syntax names.

3 Conclusion

This work resolved three language incompatibilities in a system of interoperation for three diverse languages. It resolved incompatible type systems with contracts for higher-order functions and lump types. It resolved incompatible support for parametricity with label types. It resolved incompatible evaluation strategies with delayed conversions for list constructions. It defined a model of computation that can express interoperation where the aforementioned incompatibilities arise and resolve them, provided a proof of its type soundness, and described an implementation of it that supported additional language features.

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