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The semantic marriage of monads and effects
Extended abstract

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Abstract
Wadler and Thiemann unified type-and-effect systems with monadic semantics via a syntactic correspondence and soundness results with respect to an operational semantics. They conjecture that a general, “coherent” denotational semantics can be given to unify effect systems with a monadic-style semantics. We provide such a semantics based on the novel structure of an indexed monad, which we introduce. We redefine the semantics of Moggi’s computational λ-calculus in terms of (strong) indexed monads which gives a one-to-one correspondence between indices of the denotations and the effect annotations of traditional effect systems. Dually, this approach yields indexed comonads which gives a unified semantics and effect system to contextual notions of effect (called coeffects), which we have previously described.

Previously, Wadler and Thiemann established a syntactic correspondence between type-and-effect systems and the monadic semantics approach by annotating monadic type constructors with the effect sets of the type-and-effect system [10]. They established soundness results between the effect system and an operational semantics, and conjectured a “coherent semantics” of effects and monads in a denotational style. One suggestion was to associate to each effect set σ a different monad Tσ.

We take a different approach to a coherent semantics, unifying effect systems with a monadic-style semantics in terms of the novel notion of indexed monads, which generalises monads [1].

Indexed monads
Indexed monads comprise a functor

\[ T : I \to [C, C] \]

(i.e., an indexed family of endofunctors) where I is a strict monoidal category (I, ⊗, 1) and T is a lax monoidal functor, mapping the strict monoidal structure on I to the strict monoid of endofunctor composition ([C, C], ⊗, 1C).

The operations of the lax monoidal structure are thus:

\[ \eta_I : I_C \to T1 \quad \mu_{F,G} : TF \circ TG \to T(F \otimes G) \]

These lax monoidal operations of T match the shape of the regular monad operations. Furthermore, the standard associativity and unitality conditions of the lax monoidal functor give coherence conditions to \( \eta_I \) and \( \mu_{F,G} \), which are analogous to the regular monad laws, but with added indices, e.g., \( \mu_{I,G} \circ (\eta_I)_{TG} = id_{TG} \).

Example (Indexed exponent/reader monad) Given the monoid \((P(X), \cup, \emptyset)\) (for some set X), the indexed family of Set endofunctors where \( TX = X \Rightarrow A \) (with \( \Rightarrow \) denoting exponents) and \( TXf = \lambda k.f \circ k \), is an indexed monad with:

\[ \eta_0a = \lambda x.a \quad \mu_{F,G} = \lambda x.(k(x - (G - F)))(x - (F - G)) \]

where \( x : F \cup G \) and \( k : F \Rightarrow (G \Rightarrow A) \) thus k takes two arguments, the F-only subset of x (written \( x - (G - F) \)) and the G-only subset of x (written \( x - (F - G) \)) where \( (\_)-(\_) \) is set difference.

The indexed reader monad models the composition of computations with implicit parameters, where the required implicit parameters of subcomputations are combined in their composition. This provides a more refined model to the notion of implicitly parameterised computations than the traditional reader monad, where implicit parameters are uniform throughout a computation and its subcomputations.

Relating indexed monads and monads
Indexed monads collapse to regular monads when I is a single-object monoidal category. Thus, indexed monads generalise monads.

Note that indexed monads are not indexed families of monads. That is, for all indices \( F \in obj(I) \) then \( TF \) may not be a monad.

An indexed monadic semantics for \( \lambda \)
We extend indexed monads to strong indexed monads, with an indexed strength operation (and analogous laws to usual monadic strength):

\[ (\tau_F)_{A,B} : (A \times TF B) \to TF(A \times B) \]

We replay Moggi’s categorical semantics for the computational λ-calculus (λc) [5], replacing the regular strong monad operations with the analogous operations of an indexed strong monad. This provides an indexed semantics. For example, the semantics of λ-abstraction becomes the following (where we write the parameter to T as a subscript for notational clarity below):

\[ \Gamma, x : \sigma \vdash e : \tau \quad \Gamma \vdash \lambda x : \sigma.e : \tau = \eta_\sigma \circ (\Lambda g : \Gamma) [\Gamma \vdash T_F \tau] \]

(where for \( g : A \times B \to C, \Lambda g : A \to (B \Rightarrow C) \).

Coherent semantics
In this indexed monadic semantics, the indices of denotations have exactly the same structure as the effect annotations of a traditional effect system (with judgments \( \Gamma, e : \tau, F \) for an expression e with effects F).

We unify effect systems with indexed monadic semantics, so that \( \Gamma \vdash e : \tau, F \) : \( [\Gamma] \to T_F [\tau] \), taking \( obj(I) \) as the effect
sets of a traditional effect system, with the strict monoidal structure on \( I \) provided by the effect lattice, with \( \bot = \bot \) and \( \otimes = \otimes \), and morphisms \( f : X \rightarrow Y \) in \( I \) iff \( X \subseteq Y \) in the effect lattice. Pleasingly, the usual equational theory for \( \lambda_\text{e} \) (such as \( \beta \)-equality for values) follows directly from the strict indexed monad axioms.

The morphism mapping of \( T \) defines natural transformations \( \iota_{X,Y} : TX \rightarrow TY \) when \( X \subseteq Y \) which provides a semantics to sub-effecting:

\[
\begin{align*}
\Gamma \vdash e : \tau, F' & \Rightarrow g : \Gamma' \rightarrow TF' \tau \\
\Gamma \vdash e : \tau, F & \Rightarrow \iota_{\rho,\rho} \circ g : \Gamma \rightarrow TF \tau
\end{align*}
\]

For a particular notion of effect, the indexed strong monad can be defined such that the propagation of effect annotations in an effect system maps directly to the semantic propagation of effects. For example, for memory effects the functor can be made more precise with respect to the effect, e.g., \( T(\text{read } \rho : \tau) A = \tau \rightarrow A \) and \( T(\text{write } \rho : \tau) A = A \times \tau \) (note: the latter is not itself a monad).

Therefore strong indexed monads neatly unify a (categorical) semantics of effects with traditional effect systems. The indexed monad structure arises simply from the standard category theory construction of lax monoidal functors, where \( T \) preserves the strict monoidal structure of \( I \) in \([C,C]\). Crucially, indexed monads are not an indexed family of monads (contrasting with Wadler and Thiemann’s original conjecture).

In context We argue our approach provides an intermediate solution between the traditional monadic approach (which does not couple annotations of an effect system to semantics) and algebraic effect theories (see, e.g., Kammar and Plotkin [3]).

Our approach differs somewhat to Atkey’s parameterised monads, defined for \( T : S \times S^{\text{op}} \rightarrow [C,C] \). Our indexed monad structure has a more systematic derivation, arising from the strict monoidal preservation of the lax monoidal functor. This technique can be applied to derive coherent semantic structures/effect system pairs for other notions of computation.

Effect systems traditionally define effect annotations in terms of sets with composition via set union [2]. This has the additional structure of an indexed (semi-)monoidal comonad (written \( \otimes \)). Thus, with respect to contextual requirements, \( \lambda \)-abstraction is not “pure” as it is for effects.

In an indexed semantics unifying a coeffect system with an indexed comonad, the semantics of \( \lambda \)-abstraction requires the additional structure of an indexed (semi-)monoidal comonad with the operation:

\[
(m_{\rho,G})_{A,B} : DP_A \times DC_B \rightarrow DC\left(\lambda x.e : A \rightarrow \tau\right)
\]

where \( \otimes \) is an associative binary operation over \( I \).

2. Nielsen and Nielson defined a more general effect system with a richer algebraic effect structure, separating the traditional approach of an effect lattice into operations for sequential composition, alternation, and fixed-points [6]. Relatedly on the semantic side, the structure of a joinad has been proposed to give the semantics of sequencing, alternation and parallelism in an effectful language [8], adding additional monoidal structures to a monad. Similarly to indexed monads, joinads can be generalised to indexed joinads, giving a correspondence between the richer effect systems of Nielsen and Nielson and a joinad-based semantics. This is future work.

References


