EffectiveAdvice: Disciplined Advice with Explicit Effects

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ABSTRACT

Advice is a mechanism, widely used in aspect-oriented languages, that allows one program component to augment or modify the behavior of other components. When advice and other components are composed together they become tightly coupled, sharing both control and data flows. However this creates important problems: *modular reasoning* about a component becomes very difficult; and two tightly coupled components may *interfere* with each other's control and data flows.

This paper presents *EffectiveAdvice*, a disciplined model of advice, inspired by Aldrich's *Open Modules*, that has full support for effects. With EffectiveAdvice, equivalence of advice, as well as base components, can be checked by *equational reasoning*. The paper describes EffectiveAdvice as a Haskell library in which advice is modeled by mixin inheritance and effects are modeled by monads. Interference patterns previously identified in the literature are expressed as combinators. *Parametricity*, together with the combinators, is used to prove two *harmless advice* theorems. The result is an effective semantic model of advice that supports effects, and allows these effects to be separated with strong non-interference guarantees, or merged as needed.

Categories and Subject Descriptors

D.3.2 [**Programming Languages**]: Language Classifications—*Functional Languages*; F.3.3 [**Logics and Meanings of Programs**]: Studies of Program Constructs

General Terms

Languages

Keywords

Mixins, monads, AOP, parametricity, interference

1. INTRODUCTION

In many specialized forms of modularity, including *aspect-oriented programming* (AOP) [17], *feature-oriented programming* (FOP) [30], and *object-oriented programming* (OOP) inheritance [7], the control flow and data dependencies between components are quite complex. In all these systems, *open recursion* allows control to flow back and forth between modular components during composition, making these components semantically tightly coupled despite being textually separated. This makes reasoning a significant challenge: it is hard to understand a component in isolation, and it is hard to understand the interaction between components. The former problem is known as *modular reasoning* and it has been intensely studied in both the OOP and AOP literature [33, 16, 1]. The latter problem, usually referred to as *interference*, has also received much attention in the AOP literature [32, 11, 8, 6]. The essence of both problems lies in the hidden *control* and *data* flows, required by the tight coupling of components, but not visible from the interfaces of these same components.

Advice is a mechanism for one program component to augment or modify the behavior of other components, which is widely used in AOP. It is useful to capture so-called *crosscutting* concerns such as logging, error handling or some optimizations. Advice provides a good example of the problems of combining open recursion and effects, since the mechanism creates tight couplings between advice and the advised programs.

Kiczales and Mezini [16] argue that modular reasoning about AOP, and *similar mechanisms* that capture crosscutting concerns is hard, and that a degree of global analysis may always be needed. In contrast, Aldrich [1] presents a pure functional kernel language for advice that does support modular reasoning. A key contribution of Aldrich's work is the idea that a component should control the points where it can be advised and declare these points in a public contract. Aldrich's solution for reasoning about tightly coupled components is simple: he proposes a purely functional core language, which does not allow any effects, removing the biggest obstacle to reasoning. Unfortunately, this solution is not effective in practice, as almost all practical uses of advice involve effects, and many programs subject to advice also use effects.

This paper presents *EffectiveAdvice*, a *semantic* model of advice that is inspired by Aldrich's Open Modules and retains similar reasoning properties. However, unlike Open Modules, effects are fully supported through the use of monads [37]. Our model has close similarities with the monadic model of FOP proposed by Prehofer [31]. However an impor-

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tant difference is the use of open recursion to model tightly coupled components, which are not considered in the basic model by Prehofer. Like Ligatti et al. [21], and even Aldrich [1] to some extent, we propose a non-oblivious core language with *explicit advice points* and *explicit advice composition*. Consequently, our core language cannot be viewed as an AOP language in the traditional sense [13], although it can be viewed, more generally, as a different approach to modularizing crosscutting concerns. Nonetheless, as we shall see, languages like Scala provide linguistic support for our model of advice and enjoy limited obliviousness.

EffectiveAdvice promotes the idea that effects should be an integral part of the interfaces of components, and that no implicit effects should occur. The programming model is based on open recursion, explicit advice points, and a requirement for every component to state the effects that it uses. Unlike Ligatti et al. [21], we do not devise a novel core language, but reuse the well-studied *polymorphic λ-calculus*, System F, extended with recursion and benefit from the many established technical results. Like other authors [36, 35], we use Haskell as a convenient source language for System F and elaborate EffectiveAdvice as a Haskell library[1]. *Mixin composition* is used to weave advice into a base program [7]. Monads [37] model effects and, for compositionality, non-monadic functions must be lifted into a monad.

In the purely functional model for EffectiveAdvice, equivalence of advice, as well as base programs, is determined by *equational reasoning*. Different interference patterns [32] between advice and base programs, constraining possible data and control flow interactions, can be enforced through the use of combinators. *Higher-rank types* [28] are used to ensure non-interference of effects. A key novelty introduced by EffectiveAdvice is the use of *parametricity* [36, 35], a powerful modular reasoning technique based on types only, to prove theorems for combinators providing strong guarantees of non-interference. Parametricity is used to prove two *harmless advice* [8] theorems, allowing a *precise* formulation of non-interference results without looking at the implementation of programs and which can be easily extended to cover new kinds of effects.

In summary, the contributions of this paper are:

- EffectiveAdvice: A disciplined model of advice with full support for effects in both base programs and advice. In EffectiveAdvice effects are an integral part of the interfaces of components. In the idealized programming model, familiar reasoning techniques such as *equational reasoning* and *parametricity* can be used, yet interesting programs can be expressed.

- Strong non-interference guarantees for control and data flow through the use of *combinators* and the type system. This is in contrast to other approaches, which usually achieve similar results by imposing syntactic constraints [31, 5, 29] or using type and effect systems that ensure such non-interference properties [8, 6].

- A novel use of *parametricity* to reason about non-interference of effects between components, which is used to prove theorems for *harmless advice* and *harmless observation advice*. In Section 7 a detailed comparison between different existing harmless advice results and our approach using parametricity is presented.

- An implementation of the EffectiveAdvice model as a Haskell library using open recursion to model advice and monads to model effects. The model is *statically typed* and *purely functional*.

The proofs of the theorems and background information are available in a technical report [26].

[1] www.cs.kuleuven.be/~toms/EffectiveAdvice.tgz

$\textbf{type}\ \mathit{Open}\ s = s \to s$

$\mathit{weave} :: \mathit{Open}\ s \to s$
$\mathit{weave}\ a = a\ (\mathit{weave}\ a)$

$\mathit{zero} :: \mathit{Open}\ s$
$\mathit{zero} = \mathit{id}$

$(\oplus) :: \mathit{Open}\ s \to \mathit{Open}\ s \to \mathit{Open}\ s$
$a_1 \oplus a_2 = \lambda \mathit{proceed} \to a_1\ (a_2\ \mathit{proceed})$

Figure 1: Basic mixin combinators.

2. EFFECTIVEADVICE

This section introduces the Haskell implementation of EffectiveAdvice using open recursion and monads.

2.1 Open Recursion

Open recursion is a property of a component in which recursive references are left open, so that the recursive behavior can be extended later. Open recursion is the basis for inheritance and mixin composition in object-oriented languages [7]. The connection between mixins and aspects is known [22]. Open recursion is easily implemented in Haskell or Scala by introducing an explicit parameter for self-reference, rather than relying on the built-in recursive naming in the language. An explicit fixpoint operation is required to convert an open recursive component into an ordinary, closed component that can be invoked.

The basis of the implementation is shown in Figure 1. The type *Open s* is a synonym for a function with type $s \to s$ representing open recursion. The parameter of that function is called a *join point*, that is, the point in the component in which advice is added. The operation $\oplus$ defines component (or advice) composition. Composition is associative, and it has the *zero* component as left and right units of $\oplus$, forming a monoid. Note that this is just the monoid of endofunctions with identity and function composition.

$f \oplus \mathit{zero} \equiv f \equiv \mathit{zero} \oplus f$
$(f \oplus g) \oplus h \equiv f \oplus (g \oplus h)$

The function *weave* is a fixpoint combinator used for closing, or sealing, an open and potentially advised component.

Consider the following open functions:

$\mathit{fib}_1 :: \mathit{Open}\ (\mathit{Int} \to \mathit{Int})$
$\mathit{fib}_1\ \mathit{proceed}\ n = \textbf{case}\ n\ \textbf{of}$
$\quad 0 \to 0$
$\quad 1 \to 1$
$\quad \_ \to \mathit{proceed}\ (n-1) + \mathit{proceed}\ (n-2)$

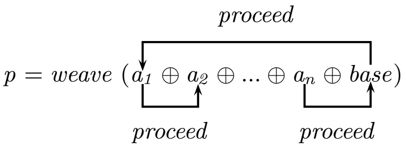
$\mathit{advfib} :: \mathit{Open}\ (\mathit{Int} \to \mathit{Int})$
$\mathit{advfib}\ \mathit{proceed}\ n = \textbf{case}\ n\ \textbf{of}$
$\quad 10 \to 55$
$\quad 30 \to 832040$
$\quad \_ \to \mathit{proceed}\ n$

The open function fib_1 defines the standard fibonacci function, except that recursive calls are replaced by *proceed*. The open function *advfib* optimizes two calls of the fibonacci function by returning the appropriate values immediately. Note that *advfib* is not meant to be used standalone. It assumes that it is used in combination with an open function like fib_1 that takes care of the uncovered cases.

Different combinations of open functions are closed through weaving:

```
slowfib1, optfib :: Int → Int
slowfib1 = weave fib1
optfib   = weave (advfib ⊕ fib1)
```

The functions $slowfib_1$ and *optfib* illustrate that EffectiveAdvice unifies the concept of advice and base programs under a single type. There is still a conceptual difference between them, because in a base program *proceed* is understood as a recursive call, while in advice *proceed* refers to the original computation being wrapped. Weaving advice alone will typically result in a useless program, as it has no base case. This distinction becomes clearer when we visualize what happens with *proceed* calls in a chain of advice being composed.



In the advice a_1 the *proceed* reference is pointing to a_2 (the next advice in the chain); in the a_2 advice *proceed* points to the next advice in the chain and so on for the other advice. When the base program is reached, *proceed* just points back to the beginning of the advice chain. The behavior of *proceed* for advice and base programs are, respectively, akin to *super* and *this* in an OO language.

In the Haskell approach presented in this section, the *proceed* argument to advice or base programs is always explicitly passed. However, it is possible to make *proceed* implicit using *implicit parameters* [19].

EffectiveAdvice captures the essence of Aldrich's Open Modules. As in Open Modules, a programmer must anticipate the points at which advice can be applied by declaring a component *Open*. This is different from most aspect-oriented languages, which allow advice to be applied anywhere, at the cost of potentially breaking any advice when any part of a program changes.

2.2 Monads as Explicit Effects

For practical applications pure advice is of limited use. Most well-known examples of advice are effectful, including logging, tracing, backups, and memoization. A setting without effects is severely limited. Take the example in Section 2.1. Ideally it should be possible to construct a dynamic lookup table for the calls of the fibonacci function. However, without effects, the best we can do is to build in a static lookup table for some of the calls. Effectful advice is useful to provide a better solution for this problem, allowing the creation of a dynamic memo table where previously computed calls can be looked up.

EffectiveAdvice models effects using monads and monad transformers. For reasons of space, an introduction to these concepts is not presented in this paper. However, one such introduction can be found in the technical report [26] and there are several other, more complete, resorces available [37, 38, 20]. We summarize the essential monad definitions used throughout the paper in Figure 2.

```
runId       :: Id a → a
runIdT      :: IdT m a → m a
runState    :: State s a → s → (a, s)
runStateT   :: StateT s m a → s → m (a, s)
runWriter   :: Writer w a → (a, w)
runWriterT  :: WriterT w m a → m (a, w)
runErrorT   :: ErrorT e m a → m (Either e a)
class Monad m where
    return :: a → m a
    (>>=)  :: m a → (a → m b) → m b
class Monad m ⇒ MonadState s m | m → s where
    get :: m s
    put :: s → m ()
class Monad m ⇒ MonadError e m | m → e where
  throwError :: e → m a
  catchError :: m a → (e → m a) → m a
class (Monoid w, Monad m) ⇒
  MonadWriter w m | m → w where
    tell :: w → m ()
class MonadTrans t where
    lift :: Monad m ⇒ m a → t m a
```

Figure 2: Monads and monad transformer types.

```
memo :: MonadState (Map Int Int) m ⇒ Open (Int → m Int)
memo proceed x =
  do m ← get
     if member x m then return (m ! x)
                   else do y ← proceed x
                           m′ ← get
                           put (insert x y m′)
                           return y
fib2 :: Monad m ⇒ Open (Int → m Int)
fib2 proceed n = case n of
  0 → return 0
  1 → return 1
  _ → do y ← proceed (n − 1)
         x ← proceed (n − 2)
         return (x + y)
```

Figure 3: Memoization

A simple effectful memoization advice is presented in Figure 3. The *MonadState* class, which models state, is used by the *memo* aspect to read and update the cached values in the memo table. The memo table is implemented using a map from integers to integers.[2] If the input value to the function exists in the memo table, then the associated value is returned. Otherwise, the call proceeds and the memo table is updated with the input value and the result of the call.

The introduction of effects requires a change to the fibonacci component: it too must be written in a monadic manner, though it is fully parametric in the monad type. We can instantiate different monads, using the corresponding run functions in Figure 2, to recover variations of the

[2] *empty* denotes an empty map, *insert* inserts a key-value pair, and (!) looks up the value for a given key.

fibonacci function. For example, the identity monad recovers the effect-free function

$slowfib_2 :: Int \to Int$
$slowfib_2 = runId \circ weave\ fib_2$

while a fast fibonacci function is obtained by adding the memo advice and suitably instantiating the state monad:

$evalState :: State\ s\ a \to s \to a$
$evalState\ (State\ f)\ s = fst\ (f\ s)$

$fastfib :: Int \to Int$
$fastfib\ n = evalState\ (weave\ (memo \oplus fib_2)\ n)\ empty$

Equational Reasoning Reasoning about the equivalence of EffectiveAdvice components does not require special-purpose mechanisms such as Aldrich's logical equivalence laws. Instead, Haskell's equational reasoning directly applies to effects modeled as monads. Consider the following two variants of fib_2

```
fib3 proceed n = case n of
  0 → return 0
  1 → return 1
  _ → do y ← proceed (n − 2)
         x ← proceed (n − 1)
         return (x + y)
fib4 proceed n = case n of
  0 → return 0
  1 → return 1
  _ → do m ← return (n − 1)
         x ← proceed m
         y ← proceed (m − 1)
         return (x + y)
```

Are these two variants indistinguishable with respect to fib_2 for any client? Obviously it is not possible to show this for fib_3, which has switched the recursive calls, because it is possible, for example, to use tracing advice to notice that recursive calls are in a different order. However, straightforward equational reasoning shows that $fib_2 \equiv fib_4$:

```
  do m ← return (n − 1)
     x ← proceed m
     y ← proceed (m − 1)
     return (x + y)
≡ {-Monad left unit: return x >>= f = f x -}
  do x ← proceed (n − 1)
     y ← proceed (n − 1 − 1)
     return (x + y)
≡ {-n − 1 − 1 ≡ n − 2 -}
  do x ← proceed (n − 1)
     y ← proceed (n − 2)
     return (x + y)
```

The same approach shows that the two pure functions $slowfib_2$ and *fastfib*, or alternative implementations of the *memo* advice, are equivalent.

Mutual Recursion In EffectiveAdvice, mutual recursive functions can also be defined. In Haskell this is achieved using records, as shown in Figure 4. The record type *EvenOdd* is the signature for a pair of two functions *even* and *odd* and the component *evenodd* provides an implementation. The advice *logEO* adds logging to those definitions (the implementation of *log* is shown in Figure 7). Logged versions of *even* and *odd* are recovered through weaving as follows:

```
leven = runWriter ∘ even (weave (logEO ⊕ evenodd))
lodd  = runWriter ∘ odd (weave (logEO ⊕ evenodd))
```

Mutual recursion can also be used to introduce additional functions that can be advised. The designer of a component must anticipate where extensions maybe useful, although the designer need not predict what kind of extensions are made. All of advice, open and closed components fit in the same purely functional framework and abide by the same reasoning principles.

```
data EvenOdd m = EO{
  even :: Int → m Bool,
  odd  :: Int → m Bool
}
evenodd :: Monad m ⇒ Open (EvenOdd m)
evenodd proceed = EO ev od where
  ev x | x ≡ 0     = return True
       | otherwise = odd proceed (x − 1)
  od x | x ≡ 0     = return False
       | otherwise = even proceed (x − 1)
logEO :: MonadWriter String m ⇒ Open (EvenOdd m)
logEO proceed = EO (log "even" (even proceed))
                   (log "odd" (odd proceed))
```

Figure 4: Mutually recursive definitions.

```
data Expr where
  Lit      :: Int → Expr
  Var      :: String → Expr
  Plus     :: Expr → Expr → Expr
  Assign   :: String → Expr → Expr
  Sequence :: [Expr] → Expr
  While    :: Expr → Expr → Expr
type Env = [(String, Int)]
```

Figure 5: Types for a simple imperative language.

3. ADVISING EFFECTFUL PROGRAMS

There is a significant gap between the pure core language presented by Aldrich and realistic AOP systems like AspectJ. Kiczales and Mezini [16] noted this gap and concluded that the restrictions in terms of expressiveness in such an approach may just be too limiting. Indeed, the lack of effects is extremelly limiting for practical applications. In this section, we show how EffectiveAdvice scales to a much more realistic setting that: 1) allows effects on both base programs and advice, and 2) handles multiple kinds of effects, such as state or exceptions.

In the remainder of this section we elaborate on these two points and illustrate them by implementing a modular monadic interpreter.

3.1 Effects for Base Programs

With EffectiveAdvice's monadic approach, both advice and base program may be effectful using monads. An example of an effectful base program is the monadic interpreter in Figure 6 for the simple imperative language of Figure 5. The interpreter's type *Open* (*Expr* → *m Int*) can be understood in the by now familiar way: it exports a function of type *Expr* → *m Int* and a join point of the same type. The type variable *m* means that advice may introduce effects. However, the constraint on *m* is now not *Monad m* for an unknown type of effect. Instead it is *MonadState Env m*: the effect must involve an updateable state of type *Env*, the environment used by the interpreter. In other words, the interpreter itself is effectful. In dealing with the *Var* and

```
beval :: MonadState Env m ⇒ Open (Expr → m Int)
beval proceed exp = case exp of
  Lit x          → return x
  Var s          → do e ← get
                      case lookup s e of
                        Just x → return x
                        _      → error msg
  Plus l r       → do x ← proceed l
                      y ← proceed r
                      return (x + y)
  Assign x r     → do y ← proceed r
                      e ← get
                      put ((x, y) : e)
                      return y
  Sequence []    → return 0
  Sequence [x]   → proceed x
  Sequence (x : xs) → proceed x ≫ proceed (Sequence xs)
  While c b      → do x ← proceed c
                      if (x ≡ 0) then return 0
                        else (proceed b ≫ proceed exp)
  where msg = "Variable not found!"
```

Figure 6: A monadic evaluator using advice.

```
log :: (MonadWriter String m, Show a, Show b)
  ⇒ String → Open (a → m b)
log name proceed x = do
  tell ("Entering " ++ name ++ "with" ++ show x ++ "\n")
  y ← proceed x
  tell ("Exiting " ++ name ++ "with" ++ show y ++ "\n")
  return y
```

Figure 7: The logging aspect.

Assign cases it reads and writes the environment with the *get* and *put* functions.

A basic unadvised monadic evaluator is recovered as follows:

```
eval :: Expr → State Env Int
eval = weave beval
```

The exported join point is sealed and m is instantiated to the state monad.

3.2 Effects Beyond State

State, due to its role in imperative languages, is the most widely used and well-known type of effect. However, there are many other useful types of effect. EffectiveAdvice allows any effect expressible as a monad, including output streams, exceptions, I/O, non-determinism, and combinations thereof. This point is illustrated next with three interesting uses of effect in advice.

Logging aspect Figure 7 shows how to define a logging aspect modularly. The advice writes a log message when entering the function call, delegates to *proceed* and finally writes another log message when exiting. It uses the writer monad transformer in Figure 2 for writing logging messages.

Dumping aspect Figure 8 shows how to define modular advice for dumping the environment at each evaluation step. The aspect intercepts the evaluation of every expression, retrieves the current environment, writes it out using a writer monad transformer and delegates the actual evaluation to *proceed*. This example is interesting because it shows that the advice not only introduces its own writer effect, but also relies on the presence of the state effect.

```
dump :: (MonadState s m, MonadWriter String m, Show s)
  ⇒ Open (a → m b)
dump proceed arg =
  do s ← get
     tell (show s ++ "\n")
     proceed arg
```

Figure 8: The environment dumping aspect.

```
type Exc = (String, Expr, Env)
eeval :: (MonadState Env m, MonadError Exc m) ⇒
      Open (Expr → m Int)
eeval proceed exp = case exp of
  Var s → do e ← get
             case lookup s e of
               Just x → return x
               _      → throwError (msg, exp, e)
  _     → proceed exp
  where msg = "Variable not found!"
```

Figure 9: The exception handling aspect.

Exception handling aspect A last example of a useful aspect is given in Figure 9, to provide a better error handling facility for the interpreter. In the interpreter, an error can occur when a variable is looked up in the environment. The exception handling aspect overrides the case for variables and replaces the *error* primitive by *throwError* (see Figure 2). There are two advantages of using *throwError* instead of *error*. The first advantage is that additional useful information can be returned together with the exception (with *error* it is only possible to provide a string error message). For example, it may be useful to return the current environment, or the expression where the error has occurred so that the user can more easily identify the locale in the program that is to blame. The second advantage is that the exception is now explicit on the type of the evaluator and the client code must handle the exception, which ensures that the main program remains in a usable state. Like with the dumping aspect, two different types of monads are involved: a state and an error monad.

Weaving in functionality The different aspects can be combined in various ways, bringing together different effects or shared uses of the same effect:

```
debug1, debug2 :: (MonadWriter String m,
  MonadState Env m) ⇒ Expr → m Int
debug1 = weave (log "eval" ⊕ beval)
debug2 = weave (log "eval" ⊕ dump ⊕ beval)
exc :: (MonadError Exc m, MonadWriter String m,
        MonadState Env m) ⇒ Expr → m Int
exc = weave (eeval ⊕ log "eval" ⊕ beval)
```

The $debug_1$ program adds logging of function calls to the evaluator, while $debug_2$ is more verbose and also dumps the environment at each call. Finally, the third program logs calls, and may throw an exception if a variable that does not exist in the environment is used.

These programs can be run by picking suitable monads and extracting the relevant information. For example, in the programs shown next, the log string is returned (except if an error occurs).

```
getLog = snd ∘ fst
```

```
test1 e = getLog
  (runState (runWriterT (debug1 e)) [ ])
test2 e = getLog
  (runState (runWriterT (debug2 e)) [ ])
test3 e = extract
  (runStateT (runWriterT (exc e)) [ ]) where
  extract (Left (msg, exp, _)) =
    "Error: " ++ msg ++
    "\nIn Expression: " ++ show exp
  extract (Right t) = getLog t
```

While the first two programs may silently give an error if a variable is not in the environment, the last program has to handle the exception explicitly and it can report an error message with the faulty expression.

4. INTERFERENCE COMBINATORS

Rinard et al. [32] propose a classification system for interference patterns that can occur between advice and advised programs: *direct interference* consists of control flow manipulations, whereas *indirect interference* consist of state manipulations. They use program analysis to *identify* those patterns automatically.

EffectiveAdvice takes a different approach by providing combinators to *enforce* the different interference patterns at aspect composition time. Each combinator associates a particular type shape with an interference pattern. Thus, a composition that does not meet the type shape required by the combinator fails to type-check. Note that no special purpose extension of the type system is needed for this approach.

4.1 Enforcing Control Flow Properties

Direct interference is related to control flow and how the use of *proceed* calls can guarantee that a program satisfies certain properties. According to Rinard et al., advice can be classified as:

Combination: An advice can call *proceed* any number of times.

Replacement: There are no calls to *proceed* in advice.

Augmentation: An advice that calls *proceed* exactly once, and does not modify the arguments to *proceed* or the value returned by *proceed*.

Narrowing: An advice that calls *proceed* at most once, and does not modify the arguments to *proceed* or the value returned by *proceed*.

Consider the logging advice *log* of the previous section. This advice calls *proceed* exactly once. Therefore *log* is an example of augmentation advice. In EffectiveAdvice, the different forms of direct interference are enforced, rather than identified, using combinators. These interference combinators are discussed below.

Combination There is no new combinator since no interference properties are enforced. The ⊕ operator already composes advice of the general form *Open s*.

Replacement The informal requirement for replacement is that no calls are made to *proceed*. This requirement can be captured by the following combinator:

```
type Replace s = s

replace :: Replace s → Open s
replace radv = λproceed → radv
```

Replacement advice has type *Replace s*, which is the same type as the whole program. This reflects the fact that replacement advice is a proper program by itself. In other words the base program's behavior is replaced (or overridden) entirely, which has the effect of destroying the usual control flow of the base program.

Augmentation The informal requirement for augmentation advice is that *proceed* is called exactly once. This behavior is enforced with the *augment* combinator

```
type Augment a b c m = (a → m c, a → b → c → m ())

augment :: Monad m
        ⇒ Augment a b c m → Open (a → m b)
augment (bef, aft) proceed a =
  do { c ← bef a; b ← proceed a; aft a b c; return b }
```

This combinator is responsible for calling *proceed* itself, rather than delegating this responsibility to the advice. The augmentation advice has type *Augment a b c m*, and it consists of two components: the first component is called *before proceed* and the second is called *afterwards*. Both parts can use the input *a*, but only the *after* argument has access to the result *b* of *proceed*. Moreover, the *before* part can communicate an auxiliary value *c* to the *after* part. For instance, log_1 is logging advice

```
log1 :: (MonadWriter String m, Show a, Show b)
    ⇒ String → Augment a b () m
log1 name = (bef, aft) where
  bef x     = write "Entering " x
  aft _ y _ = write "Exiting " y
  write a b = tell (a ++ name ++ show b ++ "\n")
```

such that $log \equiv augment \circ log_1$.

Combinators similar to the well-known AOP notions of *before* and *after* advice, can be implemented on top of *augment*:

```
before :: Monad m ⇒ (a → m ()) → Open (a → m b)
after  :: Monad m ⇒ (a → b → m ()) → Open (a → m b)

before bef =
  augment (λa → bef a ≫ return (), λa b c → return ())
after aft =
  augment (λ_ → return (), λa b c → aft a b)
```

Our earlier dumping advice can be written as *before* advice:

```
dump1 :: (MonadState s m, MonadWriter String m, Show s)
  ⇒ a → m ()
dump1 arg =
  do s ← get
     tell (show s ++ "\n")
```

Note that $dump \equiv before\ dump_1$.

Narrowing This form of advice calls *proceed* at most once. Hence, a runtime choice can be made between replacement or augmentation advice:

```
type Narrow a b c m =
  (a → m Bool, Augment a b c m, Replace (a → m b))
narrow :: Monad m ⇒
  Narrow a b c m → Open (a → m b)
narrow (p, aug, rep) proceed x =
  do b ← p x
     if b then augment aug proceed x
          else replace rep proceed x
```

The runtime choice is made by the predicate of type $a \to m\ Bool$, i.e. based on the input *a* and monad *m*.

A typical example of narrowing is *memoization*. In the case of a repeated call, normal evaluation is *replaced* by a table lookup. In case of a new call, normal evaluation is *augmented* with tabulation.

$memo_1 :: (MonadState\ (Map\ a\ b)\ m, Ord\ a)$
$\quad \Rightarrow Narrow\ a\ b\ ()\ m$
$memo_1 = (p, (bef, aft), rep)$ **where**
$\quad p\ x \quad = \mathbf{do}\ \{m \leftarrow get; return\ (member\ x\ m)\}$
$\quad bef\ \_ \quad = return\ ()$
$\quad aft\ x\ r\ \_ = \mathbf{do}\ \{m \leftarrow get; put\ (insert\ x\ r\ m)\}$
$\quad rep\ x \quad = \mathbf{do}\ \{m \leftarrow get; return\ (m\ !\ x)\}$

This version of memoization makes it clear that proceed is called at most once.

4.2 Enforcing Data Flow Properties

Indirect interference is related to data flow through the possible interaction of shared effects (or data) between advice and base programs. The most common form of shared effects is that of shared state. Another conventional form of effectful interaction is the throwing and catching of exceptions. Rinard et al. [32] consider five different forms of interference between advice and method (of the base program), specific to state:

Orthogonal: The advice and method access disjoint fields. In this case we say that the scopes are orthogonal.

Independent: Neither the advice nor the method may write a field that the other may read or write. In this case we say that the scopes are independent.

Observation: The advice may read one or more fields that the method may write but they are otherwise independent. In this case we say that the advice scope observes the method scope.

Actuation: The advice may write one or more fields that the method may read but they are otherwise independent. In this case we say that the advice scope actuates the method scope.

Interference: The advice and method may write the same field. In this case we say that the two scopes interfere.

EffectiveAdvice generalizes these notions from state to arbitrary effects. Just as for control flow interference, it provides a number of combinators that enforce the form of effect interference.

Interference Primitives Interference arises by bringing together two programs, advice and a base program. EffectiveAdvice builds interference combinators from primitive combinators for individual programs. These primitives express whether the advice with effect t knows the type of effect m of the base program. If it does not know the type, then it cannot initiate interference. This absence of knowledge is captured by a higher-ranked type [28] and a corresponding conversion function to plain advice:

type $NIAdvice\ a\ b\ t = \forall m.(Monad\ m, Monad\ (t\ m))$
$\quad \Rightarrow Open\ (a \rightarrow t\ m\ b)$

$niadvice :: (Monad\ m, MonadTrans\ t, Monad\ (t\ m))$
$\quad \Rightarrow NIAdvice\ a\ b\ t \rightarrow Open\ (a \rightarrow t\ m\ b)$
$niadvice\ adv = adv$

The opposite case does not require a new operator, since the plain type $Open\ (a \rightarrow t\ m\ b)$ suggests that interference may be possible.

Similarly, for the base program interference may not be initiated with:

type $NIBase\ a\ b\ m = \forall t.(MonadTrans\ t, Monad\ (t\ m))$
$\quad \Rightarrow Open\ (a \rightarrow t\ m\ b)$

$nibase :: (Monad\ m, MonadTrans\ t, Monad\ (t\ m))$
$\quad \Rightarrow NIBase\ a\ b\ m \rightarrow Open\ (a \rightarrow t\ m\ b)$
$nibase\ bse = bse$

The types *NIAdvice* and *NIBase* allow us to separate the effects that can be manipulated by the advice from the effects that can be manipulated by the base program. The type system guarantees that this is indeed the case.

In their general form the types of log_1 and *beval* are not sufficiently instantiated to establish non-interference. In fact, it is possible to obtain both non-interference and interference, depending on the instantiation of the monad.

Fortunately, the type checker confronts us with this issue by rejecting $niadvice\ (augment\ (log_1\ \texttt{"eval"}))$ and $nibase\ beval$. The solution is to instantiate the types such that the overall effect monad is cleanly split into two independent parts, one for the advice and one for the base program:

$log_2 :: (Show\ a, Show\ b) \Rightarrow NIAdvice\ a\ b\ (WriterT\ String)$
$log_2 = augment\ (log_1\ \texttt{"eval"})$
$beval_1 :: NIBase\ Expr\ Int\ (State\ Env)$
$beval_1 = beval$

Interference Combinators Using the above primitives, EffectiveAdvice defines four primitive interference combinators:

$adv \ominus bse = niadvice\ adv \oplus nibase\ bse$

$adv \circleddash bse = adv \oplus nibase\ bse$

$adv \oslash bse = niadvice\ adv \oplus bse$

$adv \otimes bse = adv \oplus bse$

Note that, unlike Rinard's categories, these combinators are not specific for state: they are parametric in the type of effect. The combinators $\otimes$ and $\ominus$ closely correspond to Rinard's interference and orthogonal categories. The $\circleddash$ and $\oslash$ combinators indicate which of the two programs is aware of the other's effects, which are thus shared between the two programs.

For instance, the composition $log_2 \ominus beval_1$ expresses that the logging advice and the monadic evaluator do not interfere with each other's effects.

Stateful Effects Rinard et al. [32] consider more refined forms of stateful interaction, based on read-only or read&write access to a shared state. EffectiveAdvice distinguishes between such forms of interaction by imposing appropriate constraints on the monad type variable m.

For this purpose EffectiveAdvice refines *MonadState* to cater for different views:

class $Monad\ m \Rightarrow MGet\ s\ m \mid m \rightarrow s$ **where**
$\quad get :: m\ s$

class $Monad\ m \Rightarrow MPut\ s\ m \mid m \rightarrow s$ **where**
$\quad put :: s \rightarrow m\ ()$

class $(MGet\ s\ m, MPut\ s\ m) \Rightarrow MonadState\ s\ m$

The constraint $MGet\ s\ m$ only allows reading the state s of monad m, while the class *MPut* only allows writing it. The new $MonadState\ s\ m$ allows both reading and writing by subclassing both *MGet* and *MPut*. Four laws govern the semantics of the *get* and *put* methods:

$$\begin{aligned} get \gg m &\equiv m \\ get \ggg \lambda s_1 \rightarrow get \ggg f\ s &\equiv get \ggg \lambda s_1 \rightarrow f\ s\ s \\ put\ x \gg put\ y &\equiv put\ y \\ put\ x \gg get &\equiv put\ x \gg return\ x \end{aligned}$$

The new classes allow more accurate types, for instance dumping advice only requires reading the state:

$dump_2 :: (MGet\ s\ m, MonadWriter\ String\ m, Show\ s)$
$\quad \Rightarrow a \rightarrow m\ ()$
$dump_2\ \_ = \mathbf{do}\ \{s \leftarrow get; tell\ (show\ s +\!\!+ \texttt{"\textbackslash n"})\}$
With the two new constraints, EffectiveAdvice also defines relaxed versions of *NIAdvice*:
type $ROAdvice\ a\ b\ t\ s\ = \forall m.(MGet\ s\ m, MGet\ s\ (t\ m)) \Rightarrow$
$\quad Open\ (a \rightarrow t\ m\ b)$

type $WOAdvice\ a\ b\ t\ s = \forall m.(MPut\ s\ m, MPut\ s\ (t\ m)) \Rightarrow$
$\quad Open\ (a \rightarrow t\ m\ b)$
The $dump_3$ advice instantiates $dump_2$ as a *ROAdvice*:
$dump_3 :: Show\ s \Rightarrow ROAdvice\ a\ b\ (WriterT\ String)\ s$
$dump_3 = before\ dump_2$
The new interference primitives in turn allow Rinard's state-specific interference classes to be expressed as combinators:
$observation :: (MGet\ s\ m, MGet\ s\ (t\ m), MonadTrans\ t) \Rightarrow$
$\quad ROAdvice\ a\ b\ t\ s \rightarrow NIBase\ a\ b\ m \rightarrow Open\ (a \rightarrow t\ m\ b)$
$observation\ adv\ bse = adv \oplus bse$

$actuation :: (MPut\ s\ m, MPut\ s\ (t\ m), MonadTrans\ t) \Rightarrow$
$\quad WOAdvice\ a\ b\ t\ s \rightarrow NIBase\ a\ b\ m \rightarrow Open\ (a \rightarrow t\ m\ b)$
$actuation\ adv\ bse = adv \oplus bse$
EffectiveAdvice puts similar constraints on the base program and distinguishes nine different forms of interference. The following table connects these nine forms to the corresponding four terms used by Rinard et al.:

	MGet	*MPut*	*MonadState*
MGet	Independent	Observation	Observation
MPut	Actuation	Interference	Interference
MonadState	Actuation	Interference	Interference

Note that, by distinguishing between *MonadState* and *MPut*, EffectiveAdvice has a more fine-grained classification. $MPut \times MPut$, for instance, is only a weak form of interference. While both programs write to the same state, neither's computations are affected; only the resulting state is.

While Rinard's classification is specific for state, EffectiveAdvice allows similar classifications for other kinds of effects. For example, with exceptions the rights to throw and catch exceptions are separated into different monad subclasses: $MonadThrow\ e\ m$ for throwing an exception e, $MonadCatch\ e\ m$ for catching, and $MonadException\ e\ m$ for both. By considering the permitted operations of the advice and base program, the possible interference patterns between them are established.

5. HARMLESS ADVICE: STRONG GUARANTEES OF NON-INTERFERENCE

This section uses direct and indirect non-interference combinators to enforce strong guarantees of non-interference.

5.1 Harmless Advice

The *harmless composition* combinator $\circledast$ ensures both control and data flow properties.
type $NIAugment\ a\ b\ c\ t = \forall m.(Monad\ m, Monad\ (t\ m)) \Rightarrow$
$\quad Augment\ a\ b\ c\ (t\ m)$
$(\circledast) :: (Monad\ m, MonadTrans\ t, Monad\ (t\ m)) \Rightarrow$
$\quad NIAugment\ a\ b\ c\ t \rightarrow NIBase\ a\ b\ m \rightarrow Open\ (a \rightarrow t\ m\ b)$
$adv \circledast bse = augment\ adv \ominus bse$
Harmless composition requires a special type of non-interfering augmentation advice, which is defined by *NIAugment*. It is important that the advice used by $\circledast$ is augmentation since, for instance, if an effectful base program could be called by advice twice, it could give different results than if called only once. This is because the result may depend on the effects of the base program. The $\ominus$ combinator used by $\circledast$ ensures that the advice and the base program have non-interfering effects.

Dantas and Walker [8] introduced the notion of *harmless advice* for advice that guarantees full non-interference with the base program:

> *A piece of harmless advice is a computation that, like ordinary aspect-oriented advice, executes when control reaches a designated control-flow point. However, unlike ordinary advice, harmless advice is designed to obey a weak non-interference property. Harmless advice may change the termination behavior of computations and use I/O, but it does not otherwise influence the final result of the mainline code.*

The full non-interference provided by the $\circledast$ combinator enforces that the advice is harmless. Let us cast the informal notion of harmlessness in a formal theorem:

Theorem 1 (Harmless Advice) *Consider any base program bse and any advice adv with the types:*
$bse :: \forall t.(MonadTrans\ t, Monad\ (t\ \kappa)) \Rightarrow Open\ (\alpha \rightarrow t\ \kappa\ \beta)$
$adv :: \forall m.(Monad\ m, Monad\ (\tau\ m)) \Rightarrow Augment\ \alpha\ \beta\ \gamma\ (\tau\ m)$
where κ is a monad and τ a monad transformer. If a function $proj :: \forall m, a.Monad\ m \Rightarrow \tau\ m\ a \rightarrow m\ a$ exists that satisfies the property:

$$proj \circ lift \equiv id$$

, then advice adv is harmless with respect to bse:

$$proj \circ (weave\ (adv \circledast bse)) \equiv runIdT \circ (weave\ bse)$$

Informally, the theorem states that, if we ignore the effects introduced by the advice, the advised program is equivalent to the unadvised program. The role of the projection function $proj$ is to ignore the effects introduced by the advice. The required property $proj \circ lift \equiv id$ expresses the intuition that projection has no impact if there are no effects.

This theorem is proved in the companion technical report [26]. Rather than looking into the details of the proof itself, it is more interesting to look into the techniques used by the proof: equational reasoning and parametricity.

Equational reasoning is the basic mechanism used in purely functional languages to reason about programs. Equational reasoning allows replacing a program for an equivalent one in any context, which leads to a simple algebraic style of proofs about programs like the one in Section 2.2. In impure languages equational reasoning does not generally hold, because a program may implicitly depend on the context of that program.

Parametricity [36] allows the derivation of theorems for a whole class of programs, only knowing their type. Voigtländer [35] has recently shown how to extend the parametricity approach to type constructor classes such as *Monad*. This way we can derive theorems about effectful programs without knowing the particular effects used.

Parametricity in its simplest form only holds for total, i.e. fully defined and terminating, programs. If partial and non-terminating programs are also allowed, the advice may introduce non-termination and partiality. This is our counterpart of "may change the termination behavior" in Dantas's and Walker's definition.

5.2 Harmless Effects

In order to suit the Harmless Advice theorem, advice cannot introduce arbitrary effects. There must be a suitable projection function for ignoring the effects. Such projection functions do indeed exist for several state-related monad transformers.

WriterT For the *WriterT* monad transformer we define the following projection function:

$projW :: \forall w\ m\ a.(Monad\ m, Monoid\ w)$
$\quad \Rightarrow WriterT\ w\ m\ a \rightarrow m\ a$
$projW\ m = runWriterT\ m \gg\!= return \circ fst$

It is indeed suitable:

Lemma 1 *The function projW is a suitable function for the Harmless Advice theorem:*

$$projW \circ lift \equiv id$$

With the help of *projW*, the Harmless Advice theorem establishes that the logging advice is harmless:

$$proj \circ weave\ (log_2\ \texttt{"eval"} \circledast beval_1) \equiv runIdT \circ weave\ beval_1$$

StateT We can also define a suitable projection function for the *StateT* monad transformer:

$projS :: \forall s\ m\ a.Monad\ m \Rightarrow s \rightarrow StateT\ s\ m\ a \rightarrow m\ a$
$projS\ s0\ m = runStateT\ m\ s0 \gg\!= return \circ fst$

Indeed, the required property holds:

Lemma 2 *The function projS s0 is a suitable function for the Harmless Advice theorem:*

$$projS\ s0 \circ lift \equiv id$$

for any s0.

The proofs for both lemmas are presented in the companion technical report [26].

Other Harmless Effects There are several other harmless effects, such as *IdT* with trivial projection function *runIdT*, *ReaderT* and variations on these.

5.3 Harmful effects

An interesting aspect of our theorem is that harmless advice may not introduce arbitrary effects. Only those effects for which a suitable projection function *proj* exists, may be used in harmless advice.

Consider again the *ErrorT e* monad transformer of Figure 2. We can only partially define the projection function:

$projE :: \forall e\ m\ a.Monad\ m \Rightarrow ErrorT\ e\ m\ a \rightarrow m\ a$
$projE\ m = runErrorT\ m \gg\!= \lambda x \rightarrow \textbf{case}\ x\ \textbf{of}$
$\qquad Left\ e \rightarrow ???$
$\qquad Right\ x \rightarrow return\ x$

In the case of an error, we cannot produce a value. We could attempt to fix this issue by parametrizing *projE* with a default value d:

$projE' :: \forall e\ m\ a.Monad\ m \Rightarrow a \rightarrow ErrorT\ e\ m\ a \rightarrow m\ a$
$projE'\ d\ m = runErrorT\ m \gg\!= \lambda x \rightarrow \textbf{case}\ x\ \textbf{of}$
$\quad Left\ e \rightarrow return\ d$
$\quad Right\ x \rightarrow return\ x$

but now $projE'\ d :: \forall e\ m.Monad\ m \Rightarrow ErrorT\ e\ m\ a \rightarrow m\ a$ fixes the type parameter a to the type of d, which is inappropriate.

Dantas and Walker mention that "Harmless advice may ... use I/O." However, undiscriminated use of I/O may definitely interfere with I/O in the base program. In Haskell, this manifests itself in the fact that there is no safe way to project from the *IO* monad. Only more disciplined effects, such as *WriterT*, *ReaderT* and *StateT* are possible.

```
class A {val x : Int; ... def get = x}
class B {val y : Char; ... def get = y}
trait IGet[T] {def get : T}
trait LoggedGet[T] extends IGet[T] {
  abstract override def get : T = {
    val r = super.get; //super used as proceed
    System.out.println("Extracted the value: " + r);
    return r;
  }
}
object loggedA extends A with LoggedGet[Int]
object loggedB extends B with LoggedGet[Char]
```

Figure 10: Oblivious advice in Scala with mixins.

5.4 Harmless Observation Advice

In the main Harmless Advice theorem, we have used the $\circledast$ operator which enforces that advice and base program are orthogonal. While orthogonality is a sufficient condition, it is certainly not a necessary one. For instance, observation advice may be harmless too. A combinator that forces harmless observation advice is:

$\textbf{type}\ NIOAugment\ a\ b\ c\ s\ t = \forall m.$
$\quad (MGet\ s\ m, Monad\ (t\ m)) \Rightarrow Augment\ a\ b\ c\ (t\ m)$
$(\odot) :: (MGet\ s\ m, MonadTrans\ t, MGet\ s\ (t\ m)) \Rightarrow$
$\quad NIOAugment\ a\ b\ c\ s\ t \rightarrow NIBase\ a\ b\ m$
$\qquad \rightarrow Open\ (a \rightarrow t\ m\ b)$
$adv \odot bse = augment\ adv\ `observation`\ bse$

Now we can adapt the theorem accordingly:

Theorem 2 (Harmless Observation Advice) *Consider any base program and any advice with the types:*
$bse :: \forall t.MonadTrans\ t \Rightarrow Open\ (\alpha \rightarrow t\ \kappa\ \beta)$
$adv :: \forall m.MGet\ \sigma\ m \Rightarrow Augment\ \alpha\ \beta\ \gamma\ (\tau\ m)$
with κ a MonadState σ and τ a MonadTrans. If a function $proj :: \forall m\ a.Monad\ m \Rightarrow \tau\ m\ a \rightarrow m\ a$ *exists that satisfies the property:*

$$proj \circ lift \equiv id$$

, then advice adv is harmless with respect to bse:

$$proj \circ (weave\ (adv \odot bse)) \equiv runIdT \circ (weave\ bse)$$

We refer to the technical report again for the proof [26]. It is similar in style to that of the Harmless Advice theorem. The main difference lies in the fact that the advice knows more about the m type parameter. As a consequence, weaker parametricity results are obtained. The loss in parametricity is made up for by exploiting the two *get* laws.

Theorem 2 establishes that dumping advice is harmless:

$$projW \circ weave\ (dump_3 \odot beval_1) \equiv runIdT \circ weave\ beval_1$$

6. LANGUAGE SUPPORT

This section discusses language support for EffectiveAdvice, including how to solve some of the current limitations.

Object-Oriented Languages The EffectiveAdvice model is easily implemented in Haskell, which is directly based on a variant of System F. However, while Haskell provides a great setting for reasoning, it has practical drawbacks. For instance, components are not oblivious, but need to be marked *Open* to allow for advice.

As it turns out, some object-oriented languages like Scala, provide good linguistic support for implicit advice points[3], directly based on our semantic model of advice:

- Scala supports mixins natively. Hence, Scala classes are open to mixins by default, and the native support for inheritance avoids explicit arguments like *proceed*. So, unlike Haskell, programs are *oblivious* of advice.
- Grouping multiple functions in a class is directly supported by the language through objects, which can ultimately be viewed as groups of possibly mutually recursive functions. Hence, extending an open module from a single to multiple functions does not incur any notational overhead.

Also, subtyping poses an interesting alternative to type classes for expressing restricted rights to explicit effects. Furthermore, Scala has some support for monads [25].

Figure 10 illustrates the native support for mixins on a simple logging example for methods named *get*. Two unrelated classes A and B define a *get* method that retrieves a value stored in the corresponding objects. Note that the classes are written in the usual OO way and have not received any explicit preparation for advice. The $IGet\,[T]$ trait is an interface for classes that contain a *get* method. The $LoggedGet\,[T]$ trait implements $IGet\,[T]$ by adding logging information. Mixin inheritance is used by marking the definition with **abstract override**, which allows the call of **super**.*get* even though *get* is abstract in the supertype. Note that with conventional inheritance (as in Java), this is not possible and a compile-time error is reported; the **super** reference corresponds to the *proceed* argument used in the Haskell model. Finally, the objects *loggedA* and *loggedB* provide logged implementations of the methods *get* for the classes A and B in an oblivious way, that is, without requiring any modifications on the original classes.

To summarize, languages that support mixin inheritance natively already provide linguistic support to the model of advice proposed in EffectiveAdvice. This support is closer to traditional AOP advice in the sense that obliviousness is preserved. A drawback of using Scala is that the theoretical developments presented in Section 5 regarding interference are not enforceable by the language. In the future we would like to combine the advantages of Haskell in terms of reasoning with the advantages of Scala for practical programming.

Pointcuts Pointcut declarations allow the definition of sets of join points. This is useful to advise multiple join points with a single declaration, which allows easy deployment of *massively cross-cutting concerns* such as logging. Typically advice and pointcut declarations are combined together, allowing statements such as "advise all the methods called *get* in the system", which are highly syntax-oriented. Our approach avoids such syntactic quantification and relies on explicit composition of aspects and programs. However, for massively cross-cutting concerns, a lot of compositions are required. For example, in a big program with lots of classes like A and B in Figure 10, defining every single advice composition explicitly would be extremely tedious and difficult to maintain. We view this as the biggest limitation of EffectiveAdvice from a practical point of view. Finding a more semantic alternative to syntactic quantification, while avoiding the caveats of that mechanism is something that we hope to investigate in the future.

Obliviousness and Explicit Effects EffectiveAdvice promotes the idea that effects should be an integral part of the interfaces of components. Adding information about effects causes some loss of obliviousness because the component needs to be written with potential effects in mind. Yet, we argue that 1) this loss is not too severe, and that 2) the benefits are quite substantial. Firstly, while it is true that we need to be conscious of effects, programs can still be written without anticipating the *specific* effects added by potential advice. In other words, a form of *effect obliviousness* exists in our approach. Secondly, the big advantage of being more conscious about effects is that modular reasoning and reasoning about interference becomes possible, using well established reasoning techniques such as equational reasoning and parametricity. Therefore we gain quite a bit in terms of program understanding and reasoning at a relatively small cost of being more explicit about effects.

Explicit effects in practice A related question concerns the practical use of explicit effects. In purely functional languages like Haskell, explicit effects are the only kinds of effects, but most programmers (not using purely functional programming) are used to implicit effects. For example, the Scala advice in Figure 10 makes use of implicit side-effects, which is inline with what a typical programmer would write, but goes against our premise of making effects explicit. It is possible to program in Scala with explicit effects. The technical report [26] shows one alternative way to program advice in Scala using monads. However, the question remains whether programmers accept monads. Peyton Jones and Wadler [27] show that the monadic programming style is quite close to imperative programming. Yet, we acknowledge that the monadic style can be hard to grasp at times, and more work is needed to make particular situations more manageable. For instance, using different instances of the same monad transformer within different components is very awkward. This may arise when combining different advices on the same base components, or when using multiple advised components within the same application.

Type Discipline Our type-based approach *conservatively* approximates harmless advice. Some advice implementations are harmless, even though they do not have the appropriate declared type or have not written in the right form for our approach. Then program transformations based on equational reasoning may help to expose the appropriate form and type. At other times, the advice is harmless only *conditionally*, when used in particular restricted circumstances. For instance, the memoization advice is harmless when used with effect-free base programs like the finonicci function. In such cases, condititional harmlessness theorems may depend on the actual implementations.

7. RELATED WORK

Kiczales et al. [17] introduced AOP and stated its goal: to modularize concerns that cut across the components of a software system. A more direct definition of AOP is proposed by Filman and Friedman [13]: the distinguishing characteristics of AOP systems are support for *quantification* and *obliviousness*. Quantification is the ability to write sep-

[3]Note that explicit composition is still needed.

arate pieces of code that affect many different (non-local) places in a software system. Obliviousness means that the places affected by quantifications do not need to prepare for the additional behavior. This definition of AOP is broad and general enough to include related technologies, including feature-oriented programming, which might not be included in a narrow definition of AOP.

Functional AOP systems Two main approaches to functional AOP exist, both following the pointcut-advice model: 1) *statically typed language-based* approaches such as Aspectual Caml [23], AspectFun [4] and AspectML [9], and 2) *lightweight dynamically typed* approaches like AspectScheme [12]. While the statically typed approach has obvious benefits, dynamically typed languages usually allow more lightweight library-based solutions. This has benefits in terms of *reusable aspects* [14] and expressing *dynamically deployed* aspects [34]. In some sense, EffectiveAdvice combines the best of both worlds: it is a very lightweight *statically typed library-based* approach. However, it uses a model of explicit composition of advice instead of the pointcut model. In EffectiveAdvice, "features" (such as *first-class*, *polymorphic* and *inferable types for* advice) come for free. In language-based approaches adding support for each of these features is non-trivial, and only AspectML supports all of them.

Mixins Filman and Friedman argue that many systems supporting a form of *mixin inheritance* [7, 2] have *oblivious quantification*, since the derived classes are unaware of the specific super classes that affect them. Thus, for them, mixin inheritance is a *full-blown* form of (black-box) AOP. Mixin inheritance as been widely used in functional programming [7, 24, 18, 3], using techniques similar to that in Section 2. However, only Brown and Cook [3] have used it with explicit effects, to modularize memoization.

Modular Reasoning Kiczales and Mezini [16] argue that modular reasoning about cross-cutting aspects is impossible. Instead they propose a global analysis that infers interfaces of deployed systems. Changing one component may lead to pervasive changes of interfaces. In contrast, Aldrich [1] does define the concept of Open Modules that allows modular reasoning. However, this approach is severely limited: reasoning about equivalence is limited to pure base programs with respect to impure advice. Reasoning about effectful base programs or advice is not covered. Moreover, it is not clear at all what forms of effect are allowed in advice because the advice language is not part of the formal framework.

Interference Many authors have identified interference as an important factor in reasoning about advice.

In the context of FOP Prehofer [31] defines a notion similar to harmless advice, but with two important differences. Firstly in Prehofer's monadic model there is no use of open recursion, which makes it hard to model tightly coupled advice such as memoization. Secondly, the approach used to reason about harmlessness is quite different. Instead of using parametricity, Prehofer requires a certain syntactic pattern for his form of harmless advice. Exploiting this syntactic pattern it is possible to reason by induction on the operation sequences and equational reasoning to prove a harmless advice-like theorem. This also allows for conditional harmlessness, that is not covered by our approach. An advantage of our approach is that any piece of advice of a certain type can be proved harmless once and for all by applying our harmlessness theorems. In contrast, with conservative redefinitions each composition of advice needs to be checked for harmlessness. Nevertheless, we believe that given sufficiently polymorphic advice it should be possible to use parametricity in Prehofer's setting to prove that a piece of advice is conservative regardless of the base program.

Prehofer [29] also considers when the composition of two conservative extensions is conservative: not always, because the form of composition depends in an ad-hoc manner on the involved advices. Using our approach, the uniformity of composition seems to suggest that the composition of two harmless advices is always harmless, but this needs further investigation.

Dantas and Walker [8] propose a type-and-effect system for identifying harmless advice on the MinAML core language [21]: protection domains prevent information flow from advice to base program. Their modular analysis supports a formal result similar to our harmless observation advice theorem. Orthogonal data flow interference cannot be enforced, and it is not clear how non-stateful effects like exceptions fit in their approach. Because MinAML is impure, effects are needed in addition to types.

Clifton and Leavens [5] identify that observers (harmless observation advice) do not change the specification of the advised module. Later, Clifton et al. [6] propose an extension of AspectJ with (optional) annotations for *control* and *heap* effects, which are similar to Rinard et al.'s two forms of interference. A type-and-effect system is used to modularly verify the annotations. *Spectator advice* is their counterpart of harmless observation advice, and they prove that it does not modify the base program's state. No formal statement is made about the lack of control-flow interference.

Douence et al. [11] present a formal approach for determining *strong independence* of stateful aspects: when aspects commute, they do not interfere with each other. Equational reasoning laws are used to determine (non-modularly) whether two given aspect implementations commute; in contrast, EffectiveAdvice only looks at the types. No formal statement is provided. They focus on aspect/aspect interaction and overlapping pointcuts, and do not address aspect/base program interaction. Moreover, the insert language is only partially defined and no equational reasoning laws for effects are provided. While this paper focuses on the advice/base program interference, the same approach applies equally to the interaction of two aspects.

Rinard et al. [32] formulate a classification scheme for different forms of interference, and combine a number of program analyses for automated classification. No formal results are proved.

In summary, existing approaches to non-interference formulate special-purpose program analyses or type systems. A major advantage of EffectiveAdvice over all of these is its extremely light-weight nature. Everything is built on top of existing and familiar language features; no new analysis or type system is required. Moreover, it is possible to reason formally and modularly about programs using familiar techniques such as equational reasoning and parametricity.

Aspects and Effects The connection between AOP and effects is a recurring theme since De Meuter [10] argued for the use of monads as a theoretical foundation for AOP; this view is not widely accepted. Hofer and Ostermann [15] argued recently that "*monads and aspects have to be regarded as quite different mechanisms*". EffectiveAdvice shows that aspects (when understood as advice) and monads have complementary roles when it comes to separation of concerns:

aspects provide textual separation of code, and monads provide conceptual separation of effects used by different aspects. The relationship between aspects and effects is not 1-to-1, since an aspect may produce several types of effects, and the same effect may be manipulated by several aspects.

8. CONCLUSION

EffectiveAdvice promotes the idea that effects should be an integral part of the interface of components, avoiding hidden data flows. This has important benefits:

- Modular reasoning is possible, since only the implementation of a program and the interfaces of the components used by that program are needed to understand that program locally.
- Reasoning about the interference between components is possible by looking at the interfaces only.

EffectiveAdvice provides a simple and lightweight model of advice that can be elaborated as a Haskell library. Some languages like Scala already provide linguistic support for an advice-like mechanism that is based directly in our model of advice, although implicit data flows cannot be ruled out. Our hope is that EffectiveAdvice brings new insights that help designing new languages aimed at addressing the problem of crosscutting concerns while, at the same time, supporting nice modular and interference reasoning properties.

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