Liberating Effects with Rows and Handlers

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Abstract
Algebraic effects and effect handlers provide a modular abstraction for effectful programming. They support user-defined effects, as in Haskell, in conjunction with direct-style effectful programming, as in ML. They also present a structured interface to programming with delimited continuations.

In order to be modular, it is natural for an effect system to support extensible effects. Row polymorphism is a natural abstraction for modelling extensibility at the level of types. In this paper we argue that the abstraction required to implement extensible effects and their handlers is exactly row polymorphism.

We use the Links functional web programming language as a platform to substantiate this claim. Links is a natural starting point as it uses row polymorphism for polymorphic variants, records, and its built-in effect types. It also has infrastructure for manipulating continuations. Through a small extension to Links we smoothly add support for effect handlers, making essential use of rows in the frontend and first-class continuations in the backend.

We evaluate the usability of our implementation by modelling the mathematical game of Nim as an abstract computation. We interpret this abstract computation in a variety of ways, illustrating how rows and handlers support modularity and smooth composition of effectful computations.

We present a core calculus of row-polymorphic effects and handlers based on a variant of A-normal form used in the intermediate representation of Links. We give an operational semantics for the calculus and a novel generalisation of the CEK machine that implements the operational semantics, and prove that the two coincide.

1. Introduction
Algebraic effects and effect handlers are a more modular alternative to monads for managing user-defined computational effects. Effect handlers generalise exception handlers, providing a mechanism for interpreting arbitrary algebraic effects, and they present a structured interface to programming with delimited continuations.

As a simple example consider a choice effect given by a single effectful operation:

```plaintext
choose : Bool
```

We can write an abstract computation \( M \) that invokes `choose`, independently of specifying the meaning of `choose`. We can then handle \( M \) in multiple ways. For instance, we can define a handler that interprets `choose` as nondeterministic choice, returning a list of all possible choices made in \( M \). We can also define a different handler that interprets `choose` as random choice, returning a single value that depends on all of the random choices made in \( M \). Where effect handlers really come into their own as a programming abstraction is when we start composing them: we can handle some effects while forwarding all others, using row types to statically track the forwarded effects. We make extensive use of handler composition in Section 2.

Many existing implementations of effect handlers are Haskell libraries. Notable examples include the effect handlers library of Kammar et al. [13], the extensible effects library of Kiselyov et al. [15] and Kiselyov and Ishii [14], and implementations based on variants of Swierstra’s data types a la carte technique [31], such as the work of Wu et al. [33] on scoped effect handlers. Another notable effect handlers library is the Idris effects library [3]. Each of these libraries uses its own sophisticated encoding of an abstraction which amounts to a restricted form of row polymorphism. In this work we present the first, to our knowledge, implementation of effect handlers using genuine Remy-style row polymorphism [30].

Links is a functional programming language for building web applications. The defining feature of Links is that it provides a single source language that targets all three tiers of a web application: client, server, and database. Links source code is translated into an intermediate representation (IR) based on A-normal form [11]. For the client, the IR is compiled to JavaScript. For the server, the IR is interpreted using a variant of the CEK machine [10]. For the database, the IR is translated into an SQL query, taking advantage of the effect type system and the subscript property to guarantee query generation [20].

Links is a strict language with Hindley-Milner type inference. Links has a row type system for polymorphic variants, records, and its built-in effect types (for concurrency and database integration [8, 20]). It also has support for manipulating first-class continuations, a feature which is helpful in implementing effect handlers.

The row-polymorphic effect type system and continuation support make Links a natural choice for experimenting with row-based algebraic effects and effect handlers. We have implemented an effect handlers extension to Links. Currently, it is supported only on the server-side. The frontend to our implementation makes essential use of row polymorphism, while backend is implemented as a novel generalisation of the CEK machine.

Our main contributions are as follows:

- An implementation of effect handlers using Remy-style row polymorphism [30].
- An evaluation of the usability of our implementation illustrating how rows and handler support modularity and smooth composition of effectful computations.
• A formalisation of our implementation including a small-step call-by-value operational semantics and an abstract machine semantics, based on a novel generalisation of the CEK machine to account for effect handlers.

• A strong correspondence proof between the small-step and abstract machine semantics: every reduction in the operational semantics corresponds to a sequence of administrative steps followed by a λ-step in the abstract machine.

The rest of the paper is structured as follows: Section 2 gives a tutorial introduction to programming with handlers in Links. In Section 3 we present a core calculus Lambda along with a type-and-effect system and a small-step operational semantics. In Section 4 we relate the operational semantics to an abstract machine semantics, that captures the essence of our implementation. In Section 5 we discuss implementation details. Related work is discussed in Section 6. Finally, in Section 7 we conclude and discuss future work.

2. Programming with Handlers in Links

To demonstrate that handlers and rows provide an elegant and modular abstraction for effectful programming, we use a simplified version of the mathematical game Nim [5] as a running example. Starting from an abstract representation of the game, we iteratively extend it with cheat detection and high score tracking capabilities through smooth composition of handlers, without needing to change the initial representation.

2.1 The Game of Nim and Effect Rows

The game of Nim is played between two players: Alice and Bob. The game is played with a heap of n sticks. The players take it in turns to take one, two, or three sticks from the heap. Alice makes the first move. The player who takes the last stick wins the game.

We abstract over the notion of making a move by defining it as an abstract effectful operation \( \text{Move} : (\text{Player}, \text{Int}) \rightarrow \text{Int} \), where a value of Player is either Alice or Bob. The first parameter to Move is the active player, the second parameter is the current number of sticks on the heap. We refer to the pair (Player, Int) as a game configuration. We discuss the meaning of the braces (\{\}) prefix on the arrow shortly. In Links, abstract operations like Move, are invoked using the do primitive, for instance

\[
\text{do Move}(\text{Alice}, 3)
\]

invokes the Move operation with values Alice and 3. Operation names, data constructors, and type aliases all begin with a capital letter. Records, variants, and effect signatures all have row types. All typing is structural in Links, thus it is unnecessary to declare a row occupant, such as an operation, before use. However, we consider it good practice to wrap the invocation of operations as functions, and we wrap Move as follows:

\[
\begin{align*}
\text{sig \quad Move} & : (\text{Player}, \text{Int}) \rightarrow \text{Int} \\
\text{fun \quad move} (p, n) & \quad \text{do Move}(p, n)
\end{align*}
\]

The syntax of Links is loosely based on that of JavaScript. The fun keyword begins a function definition (like function in JavaScript). Just as in JavaScript functions are n-ary, they can also be curried. Unlike in JavaScript, functions are statically typed and the sig keyword begins a type signature. The function move invokes the operation Move with the parameters p and n.

In the type signature, the function arrow (\( \rightarrow \)) is prefixed by a row enclosed in curly braces. This row is the effect signature, or effect row, of the function. The presence of Move in the effect row indicates that the function may perform the Move operation. Furthermore, the effect row is equipped with an effect variable e, which can be instantiated with additional operations. This means that move may be invoked in the scope of additional effects. We say an effect row is closed if it has no effect variable, and open if it does. In general an effect row consists of an unordered collection of operation specifications and an optional effect variable. An operation specification either specifies that an operation is admissible (or present) and has a particular type signature, or that it is absent, or that it is polymorphic in its presence. We discuss the use of absence in Section 4.5.

The effect row on the type signature of the Move operation itself is empty, denoted by a pair of braces (\{\}). This is always the case for abstract operations as any effects they ultimately have are conferred by their handlers.

The Nim game is modelled as two mutually recursive functions aliceTurn and bobTurn. Here we show aliceTurn:

\[
\begin{align*}
\text{sig \quad aliceTurn} & : (\text{Int}) \rightarrow (\text{Player}, \text{Int}) \\
\text{fun \quad aliceTurn} (n) & \quad \begin{cases}
\text{if } (n <= 0) & \text{Bob} \\
\text{else} & \text{bobTurn}(n - \text{move}(\text{Alice}, n))
\end{cases}
\end{align*}
\]

The parameter n is the number of sticks currently on the heap. If n is zero then Bob wins. Otherwise, Alice makes a move and it is now Bob’s turn. The definition of bobTurn is completely symmetric, so we omit it here for brevity.

Two observations are worth making about the effect signature of aliceTurn. First, the effect variable is anonymous (_), type (or effect) variables need not be named when only appear once. Second, the function arrow is squiggily (\( \rightarrow \)), which is syntactic sugar for denoting that the computation has the wild effect. This is a built-in effect in Links used for language integrated query support [20], where a computation that cannot be translated into SQL is said to be wild. The wild effect is unimportant here, but will appear from time to time in our examples, as we build on top of the existing system.

Links employs a strict evaluation strategy, so we thunk computations we wish to handle and define the following type alias:

\[
\text{typename Comp}(\epsilon :: \text{Row}, a) = () \{ |\epsilon| \rightarrow a; \}
\]

The keyword typename is used to define type aliases. The Comp type captures our notion of abstract computation, it is an alias for a thunk with an empty, open effect row and return type a.

The game function begins a game with a given number of sticks. Alice starts:

\[
\begin{align*}
\text{sig \quad game} & : (\text{Int}) \rightarrow \text{Comp}((\text{Move} : (\text{Player}, \text{Int}) \rightarrow \text{Int}|\_\_), \text{Player}) \\
\text{fun \quad game} (n) & \quad \{ \text{aliceTurn}(n) \}
\end{align*}
\]

2.2 Strategies and Handlers

In general, algebraic effects come with equations [26], but as with most other implementations of effect handlers, we do not consider equations. Thus, on their own, abstract operations have no meaning; handlers give them a semantics. We can use handlers to encode particular strategies for Alice and Bob by interpreting the operation Move. We start by considering the perfect strategy, defined by \( ps(n) = \max \{1, n \mod 4\} \), where n is the number of sticks left in the game. If player p adopts the perfect strategy, then p is guaranteed to win if on p’s turn n is not divisible by 4. We define a handler perfect

\[
\begin{align*}
\text{sig \quad perfect} & : (\text{Comp}((\text{Move} : (\text{Player}, \text{Int}) \rightarrow \text{Int}|\_\_), a)) \rightarrow a \\
\text{fun \quad perfect} (m) & \quad \begin{cases}
\text{handle} (m) & \quad \text{\{} \\
\text{case} \text{Return} (x) & \quad \rightarrow x \\
\text{case} \text{Move}(p, n, k) & \quad \rightarrow k(\text{maximum}(1, n \mod 4)) \text{\}}
\end{cases}
\end{align*}
\]

which implements the perfect strategy for both players. We describe the handler line by line.
Line 1 gives the type of perfect: it takes a computation that may invoke the Move operation and returns a value of type a.

Lines 2 and 3 begin the definition. The function perfect wraps the actual handler, which is applied to the argument m using the handle construct, which specifies how to interpret abstract operations through a sequence of clauses.

Line 4 is a return clause. It defines how to handle the final return value of the input computation. In this case, this value is simply returned as is.

Line 5 is an operation clause. It expresses how to handle Move. In general, an operation clause takes the form \( Op(p_1, \ldots, p_n, k) \rightarrow M \), where \( p_1, \ldots, p_n \) are patterns that bind the operation parameters and \( k \) is a pattern that binds the continuation of the computation in \( M \). In this case \( p \) and \( n \) are bound to the active player and number of sticks in the heap, respectively. The continuation is invoked with the perfect strategy, irrespective of the player.

We can now compute the winner of a game in which both players play the perfect strategy:

```plaintext
links> perfect(game(7));
Alice : Player
Alice wins
```

In our restricted Nim game the perfect strategy is a winning strategy for Alice iff the number of sticks \( n \) is not divisible by four.

### Syntactic Sugar

The input computation in perfect is immediately supplied to handle. This abstract-over-handle idiom arises frequently, so Links provides syntactic sugar for it. We can give a more succinct definition of perfect using the handler keyword:

```plaintext
handler perfect {
  case Return(x) -> x
  case Move(_,n,k) -> k(maximum(1,n mod 4))
}
```

The simplest possible handler, we can define is

```plaintext
sig run : (Comp({}, a)) {} -> a
handler run { case Return(x) -> x }
```

which simply runs a given computation. Although, it may seem useless, but it proves to be useful in Section 2.4.

#### 2.3 Game Trees and Multi-shot Continuations

The handler `perfect` computes the winner of a particular game. It only considers one scenario in which both players play the same strategy, but we can use Link handlers to compute other data about a game. For instance, we can give an interpretation that computes the strategy, but we can use handlers to compute other data about a game tree. Each node represents the active player and a list of possible moves, where each move is paired with the subsequent game tree. A `Winner` leaf denotes the winner of a game.

We define a handler `gametree` that generates game trees:

```plaintext
sig gametree :
  (Comp({Move:(Player,Int)}{}-> Int), Player) {}-> GTree
handler gametree {
  case Return(x) -> Winner(x)
  case Move(p,n,k) ->
    var subgames = map(k, validMoves(n));
    var subtrees = zip([1,2,3], subgames);
    Take(p, subtrees)
}
```

The effect signatures of `gametree` and `perfect` are identical, though their interpretations of `Move` differ. The return clause wraps the winning player \( x \) in a leaf node. The operation clause for `Move` reifies the move as a node in the game tree. The `var` keyword denotes a let binding. The crucial part is the invocation of `map` which applies the continuation multiple times, once each for valid move, enumerating every possible subgame. The function `validMoves` is a simple filter:

```plaintext
fun validMoves(n) {
  filter(fun(m) {m <= n}, [1,2,3])
}
```

Figure 1 shows the game tree generated by the handler when \( n = 3 \).

#### 2.4 Cheating and Forwarding

The handlers of Sections 2.2 and 2.3 are closed — closed handlers are not composable. Open handlers, on the other hand, compose. Open handlers cooperate to interpret an abstract computation, each handler operates on a particular subset of the abstract operations, leaving the remainder abstract for other handlers. Thus, open handlers are flexible as we may write a collection of fine-grained handlers which we can combine to fully interpret a computation. In particular, this flexibility makes it possible to reinterpret computations by changing individual handlers.

In Links open handlers are defined using the open keyword. For example, we can refine `perfect` as an open handler:

```plaintext
open handler pp {
  case Return(x) -> x
  case Move(_,n,k) -> k(maximum(1, n mod 4))
}
```

We may omit type signatures altogether as the type system infers the appropriate effect rows. The extensibility of rows is absolutely key to make this viable. We defer further discussion of type signatures for open handlers until Section 2.5.

[Fig. 1] shows an example game tree. Each node represents the active player, and each edge corresponds to a possible move for that player. We define a game tree inductively:

```plaintext
typename GTree = [ |Take:(Player,[(Int,GTree)]) |
  |Winner:(Player)| ];
```

The syntax \([\ldots]\) denotes a (polymorphic) variant type in Links in which components of the variant type are delimited by the pipe symbol (|). A `Take` node includes the active player and a list of possible moves, where each move is paired with the subsequent game tree. A `Winner` leaf denotes the winner of a game.

We demonstrate the flexibility of open handlers by augmenting the game model with a cheat detection mechanism. A cheating strategy might remove all remaining sticks from the heap, thus winning in a single move. We introduce an additional operation `Cheat` to signal that a cheater has been detected. The operation is parameterised by the player, who was caught cheating:

```plaintext
fun cheat(p) {
  switch (do Cheat(p)) { } }
```

We may omit type signatures altogether as the type system infers the appropriate effect rows. The extensibility of rows is absolutely key to make this viable. We defer further discussion of type signatures for open handlers until Section 2.5.

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```plaintext
fun cheat(p) {
  switch (do Cheat(p)) { } }
```

The `Cheat` operation can never return a value as its return type is the empty type `Zero`. Thus invoking `Cheat` amounts to raising an exception. Concretely an operation clause for `Cheat` can never invoke the continuation. The `switch(e){...}` construct pattern matches on the expression \( e \), through a possibly empty list of clauses. We
define an open (exception) handler that interprets Cheat by outputting an error message and exiting the program:

```haskell
open handler cheatReport {
  case Return(x) -> x
  case Cheat(Alice,_) -> error("Alice cheated!")
  case Cheat(Bob,_) -> error("Bob cheated!")
}
```

We implement the heart of the cheat detection machinery as an open handler:

```haskell
open handler check {
  case Return(x) -> x
  case Move(p,n,k) -> var m = move(p,n);
      if (m 'elem' validMoves(n)) k(m)
      else cheat(p)
}
```

To detect cheating the handler analyses the active player’s move. If it is legal, then the game continues. Otherwise, the Cheat operation is invoked to signal that cheating has occurred. We may compose pp with cheatReport and check to give an interpretation of a game in which no player may cheat. To make handler composition syntactically lightweight we define a pipeline operator (\(-<\)) for composing handlers and another operator (\(<-\)) for applying a computation to a pipeline of handlers:

```haskell
op f <- g {f(g(m))}
```

The keyword **op** is used to define infix binary operators. The operators are meant to indicate that unhandled operations are forwarded from right to left in a pipeline. In order to run a pipeline of handlers, we may apply the closed handler run:

```haskell
links> run <- pp -> cheatReport <- check <- game(7);
```

**Alice : Player**

The Cheat operation is never invoked as both players play the same legal strategy. Let us define another handler that assigns the perfect strategy to Alice and a cheating strategy to Bob

```haskell
open handler pc {
  case Return(x) -> x
  case Move(Alice,n,k) -> k(maximum(1, n 'mod' 4))
  case Move(Bob,n,k) -> var m = move(Bob,n);
      if (m 'elem' validMoves(n)) k(m)
      else cheat(Bob)
}
```

Now, the cheat detection handler catches Bob:

```haskell
links> run <- pc <- cheatReport <- check <- game(7);
*** Fatal error : Bob cheated!
```

The order of composition is important and pc and check both handle moves. Bob gets away with cheating if we swap the two handlers:

```haskell
links> run <- pp <- cheatReport <- check <- pc <- game(7);
```

**Bob : Player**

Here we also use pp, because the type system does not know that check is not performing any Move operations.

### 2.5 Composition and Row Polymorphism

In this section we will discuss the typing of open handlers. For example, the handler cheatReport has the following type:

```haskell
sig cheatReport :
  (Comp({Move: (Player,Int) {}-> Int|e},a)) ->
  Comp({Move (Player) {}-> Int|e},a)
```

In general, an open handler accepts a computation as input and produces another computation as output. Moreover, open handlers have open input and output effect rows, which both share the same effect variable, as a consequence both rows mention the same operation names. However, some of these operation names may be marked as absent or polymorphic in their presence. In the output effect row of cheatReport, the syntax Cheat(\(p\)) denotes that the operation is presence polymorphic. The type variable \(p\) can be instantiated to either present with a particular type (\(\cdot\)) or absent (\(\overline{\cdot}\)). Presence polymorphism is useful for seamless composition of handlers. We illustrate why by type checking the composition:

```haskell
var f = run <- (pp <- cheatReport);
```

The inferred type for pp is:

```haskell
(Comp({Move: (Player,Int) {}-> Int|e},a)) ~> Comp({Move (Player) {}-> Int|e},a)
```

The output effect row of cheatReport must be compatible with the input effect row of pp, therefore the composition gives rise to the following unification constraint:

```haskell
{Move: (Player,Int) {}-> Int |r} ~ {Cheat(\(p\)) |e}
```

The output effect row of cheatReport is to instantiate e with Move and r as Cheat to obtain:

```haskell
{Move: (Player,Int) {}-> Int, Cheat: (Player) {}-> Zero} ~ a
```

Note that with rows the order of operations is unimportant. The new field propagates to the output effect row of pp which must be compatible with the input row of run:

```haskell
{} ~ {Cheat (\(p\)), Move (\(q\)) |r}
```

The solution is to instantiate both \(p\) and \(q\) as \(\cdot\). Thus \(f\) has type:

```haskell
Comp({Move : (Player,Int) {}-> Int, Cheat : (Player) {}-> Zero}, a) {}-> a
```

The composite handler’s input effect row is the union of the respective input effects of pp, cheatReport and run.

The handler check has identical input and output effects:

```haskell
sig check :
  (Comp({Cheat: (Player) {}-> Zero, Move: (Player,Int) {}-> Int|e},a)) ~> Comp({Cheat: (Player) {}-> Zero, Move: (Player,Int) {}-> Int|e},a)
```

The reason Cheat appears in the input effect is that the shared row variable dictates that it must at least be mentioned. To be sound, if it is present it must have the same type as in the output effect. We could alternatively have asserted that it be absent, which would specify that the input computation must not have the Cheat effect. What we actually require for soundness is that if the Cheat effect is present then it must have type (Player) {}-> Zero, as that is the type it has in the output. In a more refined system along the lines of Remy’s HML [30], we could specify this as follows:

```haskell
sig check :
  (Comp({Cheat, : (Player) {}-> Zero, Move: (Player,Int) {}-> Int|e},a)) ~> Comp({Cheat, : (Player) {}-> Zero, Move: (Player,Int) {}-> Int|e},a)
```

The (\(\_\)) indicates that Cheat is polymorphic in its presence. But now the type is independent of whether or not Cheat is present.

### 2.6 Choice and Built-in Effects

In this section we implement the choice effect described in the introduction. We let Bob to choose which strategy he will adopt. First, we define a wrapper for the choice operation.

```haskell
sig choose : Comp({Choose:Bool|\(_\)\(_\), Bool
fun choose() {do Choose}
```

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Using this operation we define a strategy selecting function in which Bob decides between playing the perfect or cheating strategy

```plaintext
fun bobChooses(m) ()
  { if (choose()) pc(m)() else pp(m)() }
```

We can give a nondeterministic interpretation of `Choose` that infuses Bob with oracular powers that enable him to explore both alternatives. We define it as an open handler `allResults`

```plaintext
open handler allResults {
  case Return(x) -> [x]
  case Choose(k) -> k(true) ++ k(false)
}
```

The handler wraps the result of the input computation into a singleton list. In the `Choose` clause the handler accumulates the results of either alternative by invoking the continuation twice.

Now, we can put everything together:

```plaintext
links> run <- allResults <- bobChooses <- game(7);
[Alice,Bob] : [Player]
```

Thus Bob only wins when he cheats.

Alternatively, we can replace Bob’s oracular powers with a fair coin and let him perform a coin flip to decide which strategy to pick. We use Links’ built-in random number generator, which returns a float from the interval $[0.0:1.0]$:

```plaintext
open handler coin {
  sig coin : (Comp({Choose:Boolean|e},a)) ->
  Comp({Choose_{|}e},a)
  open handler coin {
    case Return(x) -> x
    case Choose(k) -> if (random() > 0.5) k(true)
      else k(false)
  }
}
```

The handler uniformly interprets `Choose` as `true` or `false`. Thus, using this handler Bob will be equally likely to either play the perfect strategy or fall victim to cheating. The computation

```plaintext
links> run <- coin <- bobChooses <- game(7);
returns either `Alice` or `Bob`. Built-in effects interact smoothly with the rest of the system.

2.7 A Scoreboard and Parameterised Handlers

As a final extension we add a scoreboard that accumulates the number of wins for each player. The scoreboard is updated after each game. We represent state as an effect with operations for reading (`Get`) and updating (`Put`) state of type `s`. We wrap them in the usual way:

```plaintext
sig get : () {Get:s|e} -> s
fun get() {do Get}

sig put : (s) {Put:(s) {}-> ()|e} -> ()
fun put(s) {do Put(s)}
```

We use an open, parameterised handler to give an interpretation of state. In addition, to supplying a computation to a parameterised handler, we also supply one or more parameters. In this instance we pass the state as an additional parameter `s`

```plaintext
sig state : (s) -> (Comp({Get:s,Put:(s) {}-> ()|e},a) ->
  Comp({Get_{|},Put_{|}} e,a))
open handler state(s) {
  case Return(x) -> x
  case Get(k) -> k(s)
  case Put(p,k) -> k(p)
}
```

The main difference compared to an unparameterised handler is that the continuation `k` is a curried function which takes a return value followed by the handler parameters. In the `Get` clause we return the state and also pass it unmodified to any subsequent invocations of the handler. Similarly, in the `Put` clause we return unit, and update the state.

We represent high scores as an association list and refer to a value of this type as the game state:

```plaintext
typename Gstate = [(Player,Int)];
```

We define an initial state $s_0 = [(\langle Alice,0 \rangle, \langle Bob,0 \rangle)]$. We now need a mechanism to update the game state when a game finishes. Recall that `game(n)` returns a computation whose type is:

```plaintext
Comp({Move:(Player,Int) {}-> Int|_}, Player).
```

The computation returns the winner of the game. We may exploit the fact that the return clauses of handlers are invoked in the order of composition, therefore we define a simple post-processing handler, that contains only a `Return` case, to update the scoreboard:

```plaintext
open handler scoreUpdater {
  sig scoreUpdater : (Comp({Get:Gstate,Put:(Gstate) {}-> (), Player}) ->
    Comp({Get:Gstate,Put:(Gstate) {}-> ()|e}, Player)
  open handler scoreUpdater {
    case Return(x) -> var s = updateScore(x, get());
      put(s); x
  }
}
```

The function `updateScore` is pure, it simply returns a copy of the given game state, in which the number of wins for the given player `p` has been incremented by one. The handler the reads and updates the game state. Accordingly, the composition `scoreUpdater(game(n))` causes the effect row to grow:

```plaintext
Comp({Move:(Player,Int) {}-> Int, Get:Gstate,Put:(Gstate) {}-> ()|_}, Player).
```

In a similar fashion, we define a handler that prints the scoreboard:

```plaintext
open handler printer {
  sig printer : (Comp({Get:Gstate|e}, a)) ->
    Comp({Choose_{|}e}, a)
  open handler printer {
    case Return(x) -> printBoard(get()); x
  }
}
```

The function `printBoard` is impure as it prints an ASCII representation of the given game state to standard out. To make matters more interesting we add replay functionality, which we implement by invoking a handler recursively on its input computation:

```plaintext
open handler [m] replay(n)
  { case Return(x) -> if (n <= 1) x else replay(n-1)(m())
  }
```

Here, we used an additional bit of syntactic sugar to name the input computation `m`. The `replay` handler reevaluates the computation `m` precisely `n` times. Note, that the handler’s effect signature is an empty, open row. This means the handler forwards every operation that might occur to subsequent handlers. Now, we can wire everything together:

```plaintext
links> run <- state(s0) <- printer <- replay(10) <-
coin <- bobChooses <- scoreUpdater <- game(7);
```

Figure 2 shows a possible output. In the same manner, we can effortlessly merge the cheating infrastructure into the pipeline, without changing the underlying computation.

3. A Calculus of Handlers and Rows

In this section, we present a type and effect system and a small-step operational semantics for $\lambda^\text{eff}$ (pronounced “lambda-eff-row”), a Church-style row-polymorphic call-by-value calculus for effect handlers. We prove that the operational semantics is sound with respect to the type and effect system.
and where Alice played the perfect strategy and Bob chose between the perfect and cheating strategies.

### 3.1 Types

| Value types | \(A, B ::= A \rightarrow C \mid \forall \alpha^k.C\) |
| Computation types | \(C, D ::= \lambda E\) |
| Effect types | \(E ::= \{R\}\) |
| Row types | \(R ::= \ell : P; R \mid \rho\) |
| Presence types | \(P ::= \text{Pre}(A) \mid \text{Abs}\) |
| Kinds | \(K ::= \text{Type} \mid \text{Row}_C \mid \text{Presence}\) |
| Label sets | \(L ::= \emptyset \mid (\ell \oplus L)\) |
| Type environments | \(\Gamma ::= \emptyset \mid \Gamma, x : A\) |
| Kind environments | \(\Delta ::= \emptyset \mid \Delta, \alpha : K\) |

A key advantage of row polymorphism is that it integrates rather smoothly with Hindley-Milner type inference. We concern ourselves only with the explicitly-typed core language, as the treatment of type inference is quite standard.

The design of \(\lambda_{cl}\) is inspired by the \(\lambda\)-calculi of Kammar et al. [13], Pretnar [29], and Lindley and Cheney [20]. As in the work of Kammar et al. [13], each handler can have its own effect signature. As in the work of Pretnar [29], the underlying formalism is fine-grained call-by-value [13], which names each intermediate computation like in A-normal form [11], but unlike A-normal form is closed under \(\beta\)-reduction. As in the work of Lindley and Cheney [20], the effect system is based on row polymorphism.

### 3.2 Terms

The terms are given in Figure 4. We let \(x, y, z, k\) range over term variables. By convention, we use \(k\) to denote names of continuations.

The syntax partitions terms into values, computations and handlers. Value terms comprise variables (\(x\)), lambda abstraction (\(\lambda x^A.M\)), type abstraction (\(\lambda \alpha^k.M\)), and the introduction forms for records and variants. Records are introduced using the empty record \(\langle\rangle\) and record extension \((\ell \mapsto V)\), whilst variants are introduced using injection \((\ell V)^k\) which injects a field with label \(\ell\) and value \(V\) into a row whose type is \(R\). We include the row type annotation in order to support bottom-up type reconstruction.

All elimination forms are computation terms. Abstraction and type abstraction are eliminated using application \((V W)\) and type application \((V A)\) respectively. The record eliminator \((\ell \mapsto V)\) splits a record \(V\) into \(x\), the value associated with \(\ell\), and \(y\), the rest of the record. Non-empty variants are eliminated using the case construct \((\text{case } V \{\ell x \mapsto M; y \mapsto N\})\), which evaluates the computation \(M\) if the tag of \(V\) matches \(\ell\), otherwise it falls through to \(y\) and evaluates \(N\). The elimination form for empty variants is \((\text{absurd}^k V)\). A trivial computation \((\text{return } V)\) returns value \(V\). The expression \((\text{let } x \leftarrow M \text{ in } N)\) evaluates \(M\) and binds the result value to \(x\) in \(N\).
The construct \((\text{do } \ell \text{ V})E\) invokes an operation \(\ell\) with value argument \(V\). The handle construct \((\text{handle } M \text{ with } H)\) runs a computation \(M\) with handler definition \(H\). A handler definition \(H\) consists of a return clause \text{return } x \mapsto M\) and a possibly empty set of operation clauses \(\{l_i, x_i, k_i \mapsto M_i\}\). The return clause defines how to handle the final return value of the handled computation, which is bound to \(x\) in \(M\). The \(i\)-th operation clause binds the operation parameter to \(x_i\) and the a continuation \(k_i\) in \(M_i\).

We write \(H(\text{return})\) for the return clause of \(H\) and \(H(\ell)\) for the set of either zero or one operation clauses in \(H\) that handle the operation \(\ell\). We write \(\text{dom}(H)\) for the set of operations handled by \(H\). We annotate various subterms with their types in order to aid type reconstruction (injection, operations, empty cases, and handlers); we sometimes omit these annotations.

### 3.3 Static Semantics

The kinding rules are given in Figure 5 and the typing rules are given in Figure 6.

The kinding judgement \(\Delta \vdash \alpha : K\) asserts that the type variable \(\alpha\) has kind \(K\) in kind environment \(\Delta\). The value typing judgement \(\Delta; \Gamma \vdash V : A\) states that value term \(V\) has type \(A\) under kind environment \(\Delta\) and type environment \(\Gamma\). The computation typing judgement \(\Delta; \Gamma \vdash M : A; E\) states that the term \(M\) has type \(A\) and effects \(E\) under kind environment \(\Delta\) and type environment \(\Gamma\). In typing judgements, we implicitly assume that \(\Gamma, E\) and \(A\) are well-kindred with respect to \(\Delta\). We define the functions \(\text{FTV}(\Gamma)\) and \(\text{FTV}(E)\) to be the set of free type variables in \(\Gamma\) and \(E\), respectively.

The kind and typing rules are mostly straightforward. The interesting typing rules are \(\text{T-HANDLE}\) and the two handler rules. The \(\text{T-HANDLE}\) rule states that \((\text{handle } M \text{ with } H)\) produces a computation of type \(B\) given that the computation \(M\) is typeable under effect context \(E\), and that \(H\) is a handler which transforms a computation of type \(A\) with effect signature \(E\) into another computation of type \(B\) with effect signature \(E'\).

The \(\text{T-HANDLER}\) rule is crucial. The input effect \(E\) and the output effect \(E'\) must share the same suffix \(R\). This means that \(E'\) must explicitly mention each of the operations \(\ell_i\), whether that be to say that an \(\ell_i\) is present with a given type signature, absent, or polymorphic in its presence. The row \(R\) describes the operations that are forwarded. It may include a row-variable, in which case an arbitrary number of effects may be forwarded by the handler. The typing of the return clause is straightforward. In the typing of each operation clause, the continuation returns the output computation type \(D\). Thus, we are here defining deep handlers in which the handler is implicitly wrapped around the continuation, such that any subsequent operations are handled uniformly by the same handler. The Links implementation also supports shallow handlers in which the continuation is instead annotated with the input effect and one has to explicitly reinvoke the handler after applying the continuation inside an operation clause.

### 3.4 Operational Semantics

We give a small-step operational semantics for \(\lambda^e_{\text{eff}}\). Figure 7 displays the operational rules. The reduction relation \(\rightsquigarrow\) is defined on computation terms. The statement \(M \rightsquigarrow M'\) reads: term \(M\) reduces to term \(M'\) in a single step. Most of the rules are standard. We use evaluation contexts to simplify the evaluation rules, by allowing us to focus on an active expression. The interesting rules are the handler rules.

We write \(BL(E)\) for the set of operation labels bound by \(E\).

\[
\begin{align*}
BL([]) &= \emptyset \\
BL(\text{let } x \leftarrow E \text{ in } N) &= BL(E) \\
BL(\text{handle } E \text{ with } H) &= BL(E) \cup \text{dom}(H)
\end{align*}
\]

The rule \(S\)-\(\text{HANDLE-RET}\) invokes the return clause of a handler. The rule \(S\)-\(\text{HANDLE-OP}\) handles an operation by invoking the appropriate operation clause. The constraint \(\ell \notin BL(E)\) ensures that no inner handler inside the evaluation context is able to handle the operation: thus a handler is able to reach past any other inner handlers that do not handle \(\ell\). In our abstract machine semantics we realise this behaviour using explicit forwarding operations, but more efficient implementations are perfectly feasible.

We write \(R^+\) for the transitive closure of relation \(R\). Subject reduction and type soundness for \(\lambda^e_{\text{eff}}\) are standard.

#### Theorem 3.1 (Subject Reduction). If \(\Delta; \Gamma \vdash M : A; E\) and \(M \rightsquigarrow M'\), then \(\Delta; \Gamma \vdash M' : A; E\).

There are two ways in which a computation can terminate. It can either successfully return a value, or it can get stuck on an unhandled operation.

#### Definition 3.2. We say that computation term \(N\) is normal with respect to effect \(E\), if \(N\) is either of the form return \(V\), or \(E[\text{do } \ell \text{ W}]\), where \(\ell \in E\) and \(\ell \notin BL(E)\).

If \(N\) is normal with respect to the empty effect \(\{\}\), then \(N\) has the form return \(V\).

#### Theorem 3.3 (Type Soundness). If \(\vdash M : A; E\), then there exists \(\vdash N : A; E\), such that \(M \rightsquigarrow^+ N \not\in E\), and \(N\) is normal with respect to effect \(E\).

### 4. Abstract Machine Semantics

In this section we present an abstract machine semantics for \(\lambda^e_{\text{eff}}\), which is closely related to the actual implementation of effect handlers in Links. We prove that the abstract machine simulates the operational semantics in the sense that each reduction in the small operational semantics corresponds exactly to a finite sequence of one or more steps of the abstract machine.

The Links interpreter is based on a CEK-style abstract machine and operates directly on ANF terms. The standard CEK machine operates on configurations which are triples of the form \((C \mid E \mid K)\).
Values

\[ \begin{align*}
T-\text{VAR} & : x : A \in \Gamma \quad \Delta; \Gamma \vdash x : A \\
T-\text{LAM} & : \Delta; \Gamma \vdash \lambda x : A : M : C \\
T-\text{POLY} & : \Delta; \alpha : K; \Gamma \vdash M : A|E \quad \alpha \notin FTV(\Gamma) \\
T-\text{POLYLAM} & : \Delta; \Gamma \vdash \lambda^{\alpha} : M : \forall \alpha^{\alpha}.A|E \\
\end{align*} \]

Computations

\[ \begin{align*}
T-\text{APP} & : \Delta; \Gamma \vdash V : A \rightarrow C \quad \Delta; \Gamma \vdash W : B \\
& \quad \Delta; \Gamma \vdash V \ W : C \\
T-\text{EXTEND} & : \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
& \quad \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
T-\text{INJECT} & : \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
& \quad \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
T-\text{SPLIT} & : \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
& \quad \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
T-\text{UNDEL} & : \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
& \quad \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
T-\text{SET} & : \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
& \quad \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
T-\text{CASE} & : \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
& \quad \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
T-\text{LET} & : \Delta; \Gamma \vdash M : A|E \\
& \quad \Delta; \Gamma \vdash \ell \rightarrow \text{let } x \rightarrow M \text{ in } N : B|E \\
T-\text{DO} & : \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
& \quad \Delta; \Gamma \vdash \ell : \ell \rightarrow \langle \rangle \\
T-\text{HANDLER} & : \Delta; \Gamma \vdash H : C \Rightarrow D \\
\end{align*} \]

Handlers

\[ \begin{align*}
T-\text{HANDLER} & : C = A|\{\ell : A_i \rightarrow B_i \} : R \\
& \quad D = B|\{\ell : P_i \} : R \\
& \quad H = \{\text{return } x \rightarrow M \} \cup \{\ell, y k \rightarrow N_i \} \\
& \quad \Delta; \Gamma \vdash H : C \Rightarrow D \\
\end{align*} \]

Figure 6: Typing Rules

S-\text{APP} : (\lambda x^{\alpha}.M)V \rightarrow M[V/x] \\
S-\text{TYAPP} : (\lambda x^{\alpha}.M)A \rightarrow M[A/x] \\
S-\text{SPLIT} : \text{let } (\ell = x, y) \leftarrow (\ell = V; W) \text{ in } N \rightarrow N[V/x, W/y] \\
S-\text{CASE} : \text{case } (\ell V) \{\ell x \rightarrow M ; y \rightarrow N \} \rightarrow M[V/x] \\
S-\text{CASE} : \text{case } (\ell V) \{\ell x \rightarrow M ; y \rightarrow N \} \rightarrow N[(\ell V)\{\ell x \rightarrow M \}] \\
S-\text{LET} : \text{let } x \leftarrow \text{return } V \text{ in } N \rightarrow N[V/x] \\
S-\text{HANDLER-RET} : \text{handle (return } V \text{) with } H \rightarrow M[V/x], \text{ where } \{\text{return } x \rightarrow M \} \in H \\
S-\text{HANDLER-OP} : \text{handle } E[\text{do } \ell V] \text{ with } H \rightarrow M[V/x, \lambda y. \text{handle } E[\text{return } y] \text{ with } H[k], \text{ where } \ell \notin BL(E) \text{ and } \{\ell x k \rightarrow M \} \in H \\
\]
The rule \( (M-O) \) is a handler. The rule \( (M-R) \) is no pure continuation in the current continuation frame, but there is a pure continuation in the current continuation frame. The rule \( (M-\text{HANDLE}) \) extends the current continuation with let bindings and handlers respectively.

The continuation \( \text{κ} \) consists of a pure continuation \( \text{δ} \) and continuations \( \text{σ} \) and \( \text{χ} \) for an empty stack, \( | \text{κ} \). A handler value \( \text{φ} \) closes a handler definition \( \text{H} \). A continuation frame \( \text{ℓ} \) consists of a pure continuation \( \text{κ} \) and a handler value \( \text{χ} \). A pure continuation frame \( (\gamma, x, \text{N}) \) closes a let-binding \( x = [ ] \) in \( \text{N} \) over environment \( \gamma \). A handler value \( (\gamma, \text{H}) \) closes a handler definition \( \text{H} \) over environment \( \gamma \).

We write \([ ]\) for an empty stack, \( x :: x \) for the result of pushing \( x \) on top of stack \( s \), and \( s ++ s' \) for the concatenation of stack \( s \) on top of \( s' \). We use pattern matching to deconstruct stacks. We write \( \text{χ}(\ell) \) for \( H(\ell) \), where \( \text{χ} = (\text{κ}, \text{H}) \).

The abstract machine semantics is given in Figure 8. The transition function is given by \( \Rightarrow \). This depends on an interpretation function \( [ ] \) for values.

The machine is initialised \( (M-\text{INIT}) \) by placing a term in a configuration alongside the empty environment and identity continuation \( \kappa_0 \). The rules \( (M-\text{APP}), (M-\text{TYAPP}), (M-\text{SPLIT}), \) and \( (M-\text{CASE}) \) enact the elimination of values. Note that \( (M-\text{APP}) \) handles application of both closures and of captured continuations. The rules \( (M-\text{LET}) \) and \( (M-\text{HANDLE}) \) extend the current continuation with let bindings and handlers respectively. The rule \( (M-\text{RETCONT}) \) binds a returned value if there is a pure continuation in the current continuation frame. The rule \( (M-\text{RETHANDLER}) \) invokes the return clause of a handler if there is no pure continuation in the current continuation frame, but there is a handler. The rule \( (M-\text{RETTOP}) \) returns a final value if the continuation is empty. The rule \( (M-\text{OP}) \) switches to a special four place configuration in order to handle an operation. The fourth component of the configuration is an auxiliary forwarding continuation, which keeps track of the continuation frames through which the operation has been forwarded. It is initialised to be empty. The rule \( (M-\text{OP-HANDLE}) \) uses the current handler to handle an operation if the label matches one of the operation clauses of the current handler. The captured continuation is assigned the forwarding continuation with the current continuation frame appended to the bottom of it. The rule \( (M-\text{OP-FORWARD}) \) appends the current continuation frame onto the bottom of the forwarding continuation. Notice that if the main continuation is empty then the machine gets stuck. This occurs when an operation is unhandled, and the forwarding continuation describes the succession of handlers that have failed to handle the operation along with any pure continuations that were encountered along the way.

Assuming the input is a well-typed closed computation term \( \vdash M : A \text{E} \), the machine will either return a value of type \( A \), or it will get stuck failing to handle an operation appearing in \( E \). We now make the correspondence between the operational semantics and the abstract machine more precise.

### 4.1 Correctness

The \( (M-\text{INIT}) \) rule immediately gives us a canonical way to map a computation term onto the abstract machine. A more interesting question is how to map an arbitrary configuration to a computation term. Figure 10 describes such a mapping \( [ ] \) from configurations to terms via a collection of mutually recursive functions defined on configurations, continuations, computation terms, handler definitions, value terms, and values. We write \( \text{dom}(\gamma) \) for the domain of \( \gamma \), and \( \gamma \{ x_1, \ldots, x_n \} \) for the restriction of environment \( \gamma \) to \( \text{dom}(\gamma) \{ x_1, \ldots, x_n \} \).

The \( [ ] \) function enables us to classify the abstract machine reduction rules in according to how they relate to the operational semantics.

The rules \( (M-\text{INIT}) \) and \( (M-\text{RETTOP}) \) just concern initial input and final output, neither of which is a feature of the operational semantics, so we can ignore them. The rules \( (M-\text{APP}), (M-\text{TYAPP}), (M-\text{SPLIT}), (M-\text{CASE}), (M-\text{RETCONT}), (M-\text{RETHANDLER}), \) and \( (M-\text{OP-HANDLE}) \) are administrative in the sense that \( [ ] \) is invariant under these rules. This leaves the \( \text{β}-\)rules \( (M-\text{APP}), (M-\text{TYAPP}), (M-\text{SPLIT}), (M-\text{CASE}) \) and \( (M-\text{RETCONT}), (M-\text{RETHANDLER}), (M-\text{OP-HANDLE}) \). Each of these corresponds directly with performing a reduction in the operational semantics.

We write \( \Rightarrow_a \) for administrative steps, \( \Rightarrow_\beta \) for \( \beta \)-steps, and \( \Rightarrow \) for a sequence of steps of the form \( \Rightarrow_a \Rightarrow_\beta \Rightarrow_\beta \Rightarrow_\beta \). The following lemma describes how we can simulate each reduction in the operational semantics by a sequence of administrative steps followed by one \( \beta \)-step in the abstract machine. The idea is to represent a computation term \( M \) by the equivalence class of configurations \( C \) such that \( [C] = M \).

**Lemma 4.1.** If \( M \Rightarrow N \), then for any \( C \), such that \( [C] = M \), there exists \( C' \), such that \( C \Rightarrow C' \) and \( [C'] = N \).

**Proof.** By induction on the derivation of \( M \Rightarrow N \). If \( [C] = M \), then the underlying structure of the term in the configuration \( C \) must be the same as \( M \), as \( [ ] \) is homomorphic on computation terms. Some other subterms of \( M \) may appear in the environment, and part of the evaluation context of \( M \) may appear in the continuation. Administrative reductions update \( C \) by growing the continuation, whilst maintaining the invariant that \( [C] = M \). This process corresponds directly to traversing an evaluation context. It is straightforward to see that only a finite number of administrative reductions can occur consecutively as they either reduce the size of \( M \) or leave it unchanged and reduce the size of \( C \) in the case of forwarding. Eventually the control part of the continuation will contain a redex.
Identity continuation

\[ \kappa_0 = ([[\lambda, (\emptyset, \{\text{return } x \mapsto x\})]]) \]

Transition function

### M-INIT

\[ M \mapsto (M \mid \emptyset \mid \kappa_0) \]

### M-APP

\[ (V W \mid \gamma \mid \kappa) \mapsto (M \mid \gamma' \mapsto [W]_\gamma \mid \kappa), \quad \text{if } [V]_\gamma = \lambda^\gamma x^4.M \]

### M-APPCont

\[ (V W \mid \gamma \mid \kappa) \mapsto (\text{return } W \mid \gamma \mid \kappa', \ldots \kappa), \quad \text{if } [V]_\gamma = (\kappa')^4 \]

### M-TYAPP

\[ (M A \mid \gamma \mid \kappa) \mapsto (M/A/\alpha) \mid \gamma' \mid \kappa), \quad \text{if } [V]_\gamma = \Lambda^\gamma \alpha^E.M \]

### M-SPLIT

\[ (\text{let } \ell = x; \gamma \leftarrow V \text{ in } N \mid \gamma \mid \kappa) \mapsto \begin{cases} (M \mid \gamma \mapsto V \mid \gamma', \ldots \kappa), & \text{if } [V]_\gamma = \ell \nu \vspace{1em} \\
(N \mid \gamma \mapsto \ell \nu \mid \gamma', \ldots \kappa), & \text{if } [V]_\gamma = \ell \nu \text{ and } \ell \neq \ell' \end{cases} \]

### M-CASE

\[ (\text{case } V \{x \mapsto M; y \mapsto N \mid \gamma \mid \kappa} \mapsto \begin{cases} (M \mid \gamma \mapsto V \mid \gamma', \ldots \kappa), & \text{if } [V]_\gamma = \ell \nu \vspace{1em} \\
(N \mid \gamma \mapsto \ell \nu \mid \gamma', \ldots \kappa), & \text{if } [V]_\gamma = \ell \nu \end{cases} \]

### M-LET

\[ (\text{let } x \leftarrow M \text{ in } N \mid \gamma \mid \kappa \mid \kappa) \mapsto (M \mid \gamma \mid (\gamma, x, N) \mid \sigma, \chi \mid \kappa) \]

### M-RETCont

\[ (\text{return } V \mid \gamma \mid (\gamma', x, N) \mid \sigma, \chi \mid \kappa) \mapsto (N \mid \gamma' \mapsto [V]_\gamma \mid (\gamma, \chi) \mid \kappa) \]

### M-RETHandler

\[ (\text{return } V \mid \gamma \mid ([\ldots, (\gamma', H)] \mid \kappa) \mapsto (M \mid \gamma \mid [\ldots, (\gamma', V)] \mid \kappa), \quad \text{if } H(\text{return}) = \{\text{return } x \mapsto M\} \]

### M-RETTop

\[ (\text{return } V \mid \gamma \mid []) \mapsto [V]_\gamma \]

### M-OP

\[ (\text{do } \ell \nu)^E \mid \gamma \mid \kappa \mapsto (\text{do } \ell \nu)^E \mid \gamma \mid \kappa \mid []_{\text{op}} \]

### M-OP-HANDLE

\[ (\text{do } \ell \nu)^E \mid \gamma \mid \delta :: \kappa \mid \kappa'_{\text{op}} \mapsto (M \mid \gamma' \mapsto [V]_\gamma \mid \kappa \mid \kappa' \mid \delta)^E_{\text{op}}, \quad \text{if } \ell : A \rightarrow B \in \mathcal{E} \text{ and } \delta(\ell) = \{\ell \mid k \mapsto M\} \]

### M-OP-FORWARD

\[ (\text{do } \ell \nu)^E \mid \gamma \mid \delta :: \kappa \mid \kappa'_{\text{op}} \mapsto (\text{do } \ell \nu)^E \mid \gamma \mid \kappa \mid \kappa' \mid \delta)^E_{\text{op}}, \quad \text{if } \delta(\ell) = 0 \]

### Value interpretation

\[ [x]_\gamma = \gamma(x) \]

\[ [\ell]_\gamma = \gamma \]

\[ [\lambda A.M]_\gamma = \lambda^\gamma A^E.M \]

\[ [\Lambda A^E.M] \gamma = \Lambda^\gamma A^E.M \]

**Figure 9:** Abstract Machine Semantics

### Configurations

\[ (\langle M \mid \gamma \mid \kappa \rangle) = \langle \emptyset \rangle (M, \gamma) \]

\[ (\langle M \mid \gamma \mid \kappa \mid \kappa'_{\text{op}} \rangle = \langle \kappa' \mid \kappa \rangle (M, \gamma) = \langle \kappa' \rangle (\langle \emptyset \rangle (M, \gamma), \emptyset) \]

### Continuations

\[ (\langle [] \rangle (M, \gamma) = (M)_\gamma \]

\[ (\langle \gamma' \mid x, N \mid \sigma, \chi \mid \kappa \mid \kappa'_{\text{op}} \rangle (M, \gamma) = (\langle \sigma, \chi \mid \kappa \rangle \langle \text{let } x \leftarrow M \text{ in } \langle N \rangle(\gamma' \setminus \{x\}), \gamma \rangle \]

\[ (\langle [[\ldots, (\gamma', H)] \mid \kappa \rangle (M, \gamma) = \langle \emptyset \rangle (\langle H \rangle \gamma, \gamma) \]

### Computation terms

\[ (V W)\gamma = [V]_\gamma (W)\gamma \]

\[ (V A)\gamma = [V]_\gamma A \]

\[ (\text{let } \ell = x; \gamma \leftarrow V \text{ in } N)\gamma = (\text{let } x = y; \gamma \leftarrow V \text{ in } (N(\gamma \setminus \{x, y\})) \]

\[ (\text{case } V \{x \mapsto M; y \mapsto N\} \mid \gamma \mid \kappa) = (\langle V \rangle_\gamma \{x \mapsto [M]_\gamma(\gamma \setminus \{x\}); y \mapsto [N]_\gamma(\gamma \setminus \{y\}) \}

\[ (\text{return } V)\gamma = \text{return } [V]_\gamma \]

\[ (\text{let } x \leftarrow M \text{ in } N)\gamma = (\text{let } x \leftarrow M) \gamma \]

\[ (\text{do } \ell \nu)^E \gamma = (\text{do } \ell \nu)^E \gamma \]

\[ \langle \text{handle } M \text{ with } \langle H \rangle \gamma, \gamma \rangle \]

### Handler definitions

\[ (\langle \text{return } x \mapsto M \rangle \gamma = \langle \text{return } x \mapsto [M]_\gamma(\gamma \setminus \{x\}) \}

\[ \langle \{x \mid k \mapsto M\} \cup \langle H \rangle \gamma = \{x \mid k \mapsto [M]_\gamma(\gamma \setminus \{x, k\}) \cup \langle H \rangle \gamma \]

### Value terms and values

\[ ([x]_\gamma = \gamma), \quad \text{if } \gamma(x) = v \]

\[ ([x]_{\text{op}} = x), \quad \text{if } x \notin \text{dom}(\gamma) \]

\[ ((\lambda A.M)\gamma = \lambda^E A^E.([M]_\gamma(\gamma \setminus \{x\})) \]

\[ ((\Lambda A^E.M)\gamma = \Lambda^E A^E.([M]_\gamma) \]

\[ ([\emptyset]_\gamma = \emptyset \]

\[ ([\ell]_\gamma = \gamma \]

\[ ([\ell; V; W]_\gamma = [\ell; \langle V \rangle_\gamma; \langle W \rangle_\gamma) \]

\[ ([\ell; V)^E_\gamma = [\ell; \langle V \rangle_\gamma)^E \]

\[ ([\ell; V]_\gamma = \ell; [\langle V \rangle_\gamma \gamma \]

\[ ([\ell; V)^E_\gamma = \ell; [\langle V \rangle_\gamma)^E \]

\[ ([\ell; V]_\gamma = \ell; [\langle V \rangle_\gamma \gamma \]

\[ ([\ell; V)^E_\gamma = \ell; [\langle V \rangle_\gamma)^E \]

\[ ([\ell; V]_\gamma = \ell; [\langle V \rangle_\gamma \gamma \]

**Figure 10:** Mapping from Abstract Machine Configurations to Terms
corresponding to the active redex in $M$ and it will then transition via a $\beta$-rule to a configuration $C'$, such that $\langle C' \rangle = N$. □

The correspondence here is rather strong; there is a one-to-one mapping between $\leadsto$ and $\Rightarrow$. The inverse of the lemma is straightforward as the semantics is deterministic. Notice that Lemma 4.1 does not require that $M$ be well-typed. We have chosen here not to perform type-erase, but it is straightforward to adapt the results to semantics in which all polymorphism is erased and all type annotations are erased.

**Theorem 4.2 (Simulation).** If $\vdash M : A \rightarrow E$, and $M \leadsto^+ N$, such that $N$ is normal with respect to $E$, then $M \rightarrow^{+} C$, such that $\langle C \rangle = N$.

**Proof.** By repeated application of Lemma 4.1. □

5. Implementation

Our implementation of handlers is based on a mild syntactic extension to Links: the syntax is extended with the `do` construct for invoking operations and the `handle(a)` `{...}` for handling abstract computations.

**Syntactic Sugar** We provide syntactic sugar to make it more convenient to program with handlers. The function $\mathcal{D}$ desugars handlers into their functional form. Figure 11 shows the cases for handlers only; $\mathcal{D}$ is a homomorphism on the other syntax constructors. The crucial difference between desugaring of closed and open handlers is that the latter desugars into a curried function, which returns a thunk after the variable $a$ gets bound. This difference is important to ensure that open handlers compose smoothly. For the same reason a parameterised handler desugars into a curried function, where the parameters precede the computation argument $a$. The parameters are passed around by enclosing each operation clause by a function. Thus, the initial parameter values are applied directly to the `handle` expression.

**Backend** The Links interpreter is based on a CEK machine for ANF expressions. We have generalised this machine to support handlers based on the abstract machine of Section 4. The interpreter maintains a stack of handlers with first-in-last-out semantics, which makes it straightforward to implement effect forwarding. The invocation of an operation causes the interpreter to unwind the stack to find a suitable handler for the operation.

**Row Polymorphism** We have extended Links with support for user-defined operations, making use of the existing row type system. The current row type system is based on that of Rémy [30], adapted to support effect typing in a similar manner to the work of Leroy and Pessaux [17] and Blume et al. [4] on typing exceptions. Fields in a record can be absent, present at a particular type, or polymorphic in their presence. An earlier version of Links [20] was based on a slightly more refined variant of Rémy’s system, IMIL’ [30], in which the type of a label is independent of whether or not it is present. This system was abandoned because it seemed somewhat counterintuitive for the purposes of record typing, but (as discussed in Section 2.4) it does seem quite useful for effect typing, so it may be worth reinstating.

**Subtyping and Row Typing**

Subtyping is in fact a poor man’s row polymorphism.

— Andreas Rossberg

Subtyping (or subeffecting) and row typing address similar concerns. However, they are not the same thing. Row polymorphism is more expressive than subtyping and subtyping is more expressive than row polymorphism. Row polymorphism allows part of an effect to be named and reused in several places. This is essential for typing polymorphic functions such as `map`. Row polymorphism can also be used whenever one might otherwise use subtyping in a first order manner. In terms of effects, this amounts to always keeping functions polymorphic in the effect, in order that the effect variable can be instantiated in order to simulate an upcast. On the other hand, subtyping applies at higher-order when row typing does not.

Links does not support subsumption (implicitly inferred subtyping), but it does support subtyping through explicit upcasts. However, such casts seem to be rarely needed in practice and can often be avoided altogether by using first-class polymorphism (another feature of Links) instead.

**Shallow Handlers** We have not covered them in much detail here, but our implementation also supports shallow handlers [13]. These are indicated by using the `shallowhandler` keyword in place of `handler`. Whereas a deep handler performs a fold over a computation, a shallow handler merely performs a case-split. This means that one must explicitly reinvoke the handler each time the continuation is implied inside an operation clause. An advantage is that it makes it easy to switch to a different handler midway through a computation. A disadvantage is that shallow handlers are not much use without an external notion of recursion, and they are less easy to optimise than deep handlers [23]. The changes to the typing rules and operational semantics to accommodate shallow handlers are standard [13]. The modifications to the abstract machine are quite modest. The `M-OP-HANDLE` should drop the current handler and the pure continuation must be appended onto its successor, i.e.

$$\rightarrow (\langle do \ell V \rangle^{k} | \gamma | (\sigma, \chi) :: (\sigma', \chi') :: \kappa | \kappa')_{op}$$

$$\rightarrow (M | \gamma | x \mapsto [V], k \mapsto \kappa' | (\sigma' \mapsto | \sigma'))_{op}$$

6. Related Work

**Faking Row Polymorphism in Haskell** Haskell provides a rather rich type system which allows one to simulate many aspects of row polymorphism. Perhaps the biggest mismatch between row polymorphism and most other typing features is that rows are inherently unordered, whereas other typing features are usually inherently ordered.

One approach is Swierstra’s `data types a la carte` technique [31]. This amounts to encoding a row type as a sum, and then leveraging the type class system to automatically navigate through the sum type as if it was unordered. In practice, this encoding is a little fragile (e.g. sometimes additional type annotations are required), although recent improvements can make it somewhat more robust [24], particularly if one adds support for instance chains [24].

Another approach is to take advantage of the fact that type class constraints genuinely are unordered. Early work on monad transformers [19] uses this idea to write modular abstract computations, as do Kammar et al. [14], Kiselyov et al. [13], and Kiselyov and Ishii [14] in their effect handlers libraries. However, without some form of higher-order constraint solving (not supported by Haskell), one must still materialise ordered lists of effects when composing effect handlers. For many useful examples this is not a problem, but suppose we wish to build a list of handlers, from disparate sources, then we need to carefully ensure that their effects are composed in the same order.

Orchard and Petricek [25] make some progress towards encoding unordered effect rows, by performing a sorting algorithm at the level of types, taking advantage of GHC’s support for dependently-typed programming [34]. However, this approach can fail in practice as the type system cannot always infer that two types are equivalent in the presence of effect polymorphism.

**Implementations** Any signature of abstract operations can be understood as a free algebra and represented as a functor. In particular,
every such functor gives rise to a free monad. Thus, free monads provide a natural basis for implementing effect handlers. Many of the library implementations of effect handlers include implementations based on free monads [6, 13, 15, 33].

Kammar et al. [13] provide an implementation of effect handlers using a continuation monad, which completely avoids materialising any data constructors. Wu and Schrijvers [32] explain how it works, by taking advantage of Haskell’s fusion optimisations. This approach does appear to depend rather critically on the handlers being deep rather than shallow, and in Haskell it relies on them being type classes, and hence not really first class.

The Idris effects library [6] takes advantage of dependent types based on free monads. It includes a novel feature for supporting fresh generalisation of effects in order to support effects such as ML-style continuations. The client backend already produces JavaScript in continuation-passing style in order to support concurrency. We plan to extend our implementation to the client backend of Links.

Shonky does not use an ANF representation, so has more forms of continuation to handle, and where our continuations have a nested structure, Shonky uses a completely flat structure for continuations.

Although OCaml itself has no support for effect handlers, a development branch, Multicore OCaml [9], does. Multicore OCaml does not include an effect type system, and handlers are restricted so that continuations are affine, that is, they can be invoked at most once. This design admits a particularly efficient implementation, as continuations need never be copied, so can simply be stored on the stack.

7. Conclusions and Future Work

We have implemented algebraic effects and handlers using row polymorphism and demonstrated that the extensibility of rows enables us to compose effectful computations seamlessly. We have formalised our system as the core calculus λeff for which we presented and proved a correspondence between two semantics: a small-step operational semantics and an abstract machine semantics, the latter of which is close to the actual implementation. We conclude by discussing some areas of future work.

Effects are pervasive in modern web applications, thus we would like to extend our implementation to the client backend of Links. The client backend already produces JavaScript in continuation-passing style in order to support concurrency. We plan to extend this representation to incorporate handlers.

The overhead incurred by the Links interpreter is significant [12]. Thus, compilation of handlers into efficient, low-level code would be interesting to explore. One performance bottleneck of the handler abstraction is the need to support copying of continuations. But, it is well-known that one-shot continuations can be implemented efficiently [7]. Links now has a linear type system. We envisage taking advantage of this to track the linearity of handlers. Then during code generation we can specialise the run-time representation of handlers according to their linearity.

Furthermore, Links employs a message-passing concurrency model, similar to Erlang, but typed. Taking ideas from Multicore OCaml [9], we would like to investigate whether we can rebuild the Links concurrency implementation directly in terms of handlers.

References