Implementing UNIX with Effects Handlers

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Abstract

Research Ethics Approval

This project was planned in accordance with the Informatics Research Ethics policy. It did not involve any aspects that required approval from the Informatics Research Ethics committee.

Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

(*Ramsay Carslaw*)

Acknowledgements

Any acknowledgements go here.

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Chapter 1

Introduction

Chapter 2

Background

2.1 Algebraic Effects and Effect Handlers

Algebraic effects [1] and their corresponding handlers [2] [3] are a programming paradigm that when paired together offers a novel way to compose programs. It starts with the definition of the effect or the *effect signature* that gives the effect a name in scope and specifies any input and the return type otherwise known as the *effect operation*. For example, we might define the effect signature *State* that stores state for some type `a`. In order to make use of our *State* effect we can define the effect operations *put* and *get* where put will update the value of type `a` stored in state and get will return the current value. At this stage the effect operation has no implementation and is more an acknowledgement to the compiler that it should expect an implementation. For this reason any function that references these effect operations is known as an *effectful function* or a function whose definition is not complete without an effect handler. In the put and get example, any function that uses put and get to store values would be an effectful function. The *effect handler* provides one implementation of the given effect operation. We could define a simple handler for state that simply updates a variable of the given type or we could define a more complex one that uses hash maps. In this way, we can change the semantics of an effectful function by handling it with a different handler that provides an alternative implementation to the effect. Crucially, we can have multiple handlers defined in the same program for one effect allowing for much more modular programming or *effect-oreinted programming*.

When are programs rely on input from the real world like connecting to a server on the internet or getting input from a user, it is no longer safe to assume this input will be passed as we expect. For example, the server could time out or not be at the address the program is expecting it to be at or the user could enter a string that is too long for the input. These real world uncertainties are known as *Side Effects*. Effect handlers can be used to provide alternate implementations of functions that may have side effects and allow for control flow with these effects.

2.1.1 Example in Unison

Unison [1] is a functional language implemented in Haskell that offers built in support for effect handlers through it's abilities system.

Unison provides the *ability* keyword which allows users to define their own effects. It also provides the *handle ... with ...* pattern to attach handlers to effectful functions.

```
structural ability Store a where
  put: a -> {Store a} ()
  get: {Store a} a
```

Listing 2.1: The *put* and *store* example in Unison. Note that the *structural* keyword refers to the fact that Unison stores type definitions as a hash. Even if we changed all the variable names it would still view it as the same type. To avoid that behaviour you can swap the *structural* keyword for *unique*

This defines the two effect operations `put` and `get` that have the effect signature `Store a`. Put takes a value of type `a` and returns the unit type `()`. The prefix of {`Store a`} to the `()`, refers to the fact that in order to allow for `put` to return, it must be run from an effectful function that is handled with an appropriate handler for `Store a`. Similarly, `put` takes an argument of type `a` and must be handled.

```
addStore : a -> {Store a} ()
addStore x =
  y = get
  put (x + y)
```

Listing 2.2: An example of an effectful function that uses the `Store` effect

The code in listing 2.1.1 is an example of how you would use the effects in Unison. It takes an argument of type `a` and 'adds' it to the current value by using `get`. Note that in order for this to work the infix operation '+' must be implemented for type `a`. Now we only need to define the handler.

```
    storeHandler : a -> Request (Store a) a -> a
    storeHandler value = cases
        {Store.get -> resume} -> handle resume value with storeHandler value
        {Store.put v -> resume} handle resume () with storeHandler v
        {result} -> result
```

Listing 2.3: The handler for the `Store` effect

The handlers in Unison use tail recursion to reduce to the case where just the value is left `result -> result`. For both store and put we use the resumption and the handler to reach the final value. The special type `Request` allows us to perform pattern matching on the possible types of the computation.

```
handle !(addStore 10) with storeHandler 10
```

Finally, we can put it all together by calling the function `addStore` with the handler `storeHandler`. The `addStore 10` is a delayed function due to it using effects. This

[1] https://github.com/unisonweb/unison

means it will not run until we tell it to avoid errors with the handlers. Given we are handling it we force it to run with '!'.

2.2 Affine and 'Multi-Shot' Handlers

If remaining computation or continuation of an effect can be resumed once from a handler then the effect system implements *one-shot* or *affine* effect handlers. If it is able to resume the computation multiple times then it is a *multi-shot* handler.

2.3 The State of Effect-Oriented Programming

2.3.1 Library Based Effects

- libhandler [5] is a portable c99 library that implements algebraic effect handlers for C. It implements high performance multi-shot effects using standard C functions. It is limited by the assumptions it makes about the stack such as it being contiguous and not moving. In practice this could lead to memory leaks if it copies pointers.
- libmprompt [2] is a C/C++ library that adds effect handlers. It uses virtual memory to solve the problem mentioned with libhandler. By keeping the stack in a fixed location in virtual memory it restores safety. It also provides the higher level libmpeff interface. A downside is they recommend at least 2GiB of virtual memory to allow for 16000 stacks which may be challenging on some systems.
- cpp-effects [6] is a C++ implementation of effect handlers. It uses C++ template classes and types to create modular effects and handlers. It's performance has been shown to be comparable to C++20 coroutines. It's limitations are it only supports one-shot resumptions.
- There are several Haskell libraries that implement effect handlers [7, 8, 9]. Some are discussed in more detail below.
  - EvEff uses lambda calculus based evidence translation to implement it's effects system. It provides deep effects.
  - fused-effects [3] fuses the effect handlers it provides with computation by applying *fusion laws* that avoid intermediate representation. The handlers in fused-effects are one-shot however.

2.3.2 First-Class Effects

- Unison is shown in more detail in section 2.1.1
- Koka [10] is a statically typed functional language with effect types and handlers. It can also compile straight to C code without needing a garbage collector. Koka

[2]https://github.com/koka-lang/libmprompt
[3]https://hackage.haskell.org/package/fused-effects

is developed by a small team and as such is still missing much of its standard library.

- Frank [11] is a strict functional language that is *effectful* in that it has first class support for bi-directional effects and effect handlers.
- Links [12] is a functional programming language designed for the web. Out of the box it does not support true algebraic effects, however through an extension [13] it gains first class support for continuations.

2.4 Shallow vs. Deep Effect Handlers

There are two types of effect handler implementation, *deep handlers*, as originally defined by Plotkin and Pretnar [2] and *shallow handlers* [4]. Deep handlers pass a copy of the full handler along with the computation which allows for the handler to be invoked again as the handlers receive themselves as an argument. Shallow handlers do not pass the handler with the computation. There are also *sheep handlers*, which while being shallow implement some of the behaviour of deep handlers leading to the name sheep or shallow + deep. In practice, the type of handler is more of an implementation detail although it can have an effect on how code is structured.

2.5 UNIX

UNIX [14] is an operating system designed and implemented by Dennis M. Ritchie and Ken Thompson at AT&T's Bell Labs in 1974. It provides a file system (directories, file protection etc.), a shell, processes (pipe, fork etc) and a userspace. Since it's first release it has been reimplemented for a variety of systems.

2.5.1 The UNIX Philosophy

A phrase often associated with UNIX is the *Unix philosophy*. The UNIX philosophy refers to some of the core principles with which it was developed. The core principles involve composing many small simple programs that accomplish one task well to solve more complex tasks [15]. The idea of many small modular components has spread to many areas of computer science including effect oriented programming.

2.6 Effect Handlers and UNIX

In chapter 2 of his 2022 thesis, Daniel Hillerström [16] outlines a theoretical implementation of UNIX using the effects syntax outlined by Kammar et. al. [17]. In this he provides an implementation of the original UNIX paper [14] that includes a filesystem and timesharing. Hillerström makes several assumptions about the effect system that would need to be taken into account in order to implement this with a real language. The main assumption is multi-shot handlers. For example the implementation of `fork` uses multi-shot handlers to copy the full stack on both branches. There are also some partial implementations such as `sed` [4] from which he only implements string replacement.

[4] It is worth mentioning `sed` has $20,000+$ lines of code

Chapter 3

Methods

Chapter 4

Results

Chapter 5

Conclusion

Bibliography

[1] Gordon Plotkin and John Power. Computational effects and operations: An overview. 2002.

[2] Gordon Plotkin and Matija Pretnar. Handlers of algebraic effects. In *European Symposium on Programming*, pages 80–94. Springer, 2009.

[3] Matija Pretnar. An introduction to algebraic effects and handlers. invited tutorial paper. *Electronic notes in theoretical computer science*, 319:19–35, 2015.

[4] Daniel Hillerström and Sam Lindley. Shallow effect handlers. In *Programming Languages and Systems: 16th Asian Symposium, APLAS 2018, Wellington, New Zealand, December 2–6, 2018, Proceedings 16*, pages 415–435. Springer, 2018.

[5] Daan Leijen. Implementing algebraic effects in c. Technical Report MSR-TR-2017-23, June 2017.

[6] Dan R. Ghica, Sam Lindley, Marcos Maroñas Bravo, and Maciej Piróg. High-level effect handlers in C++. *Proc. ACM Program. Lang.*, 6(OOPSLA2):1639–1667, 2022.

[7] Ningning Xie and Daan Leijen. Effect handlers in haskell, evidently. In Tom Schrijvers, editor, *Proceedings of the 13th ACM SIGPLAN International Symposium on Haskell, Haskell@ICFP 2020, Virtual Event, USA, August 7, 2020*, pages 95–108. ACM, 2020.

[8] Oleg Kiselyov and Hiromi Ishii. Freer monads, more extensible effects. In Ben Lippmeier, editor, *Proceedings of the 8th ACM SIGPLAN Symposium on Haskell, Haskell 2015, Vancouver, BC, Canada, September 3-4, 2015*, pages 94–105. ACM, 2015.

[9] Nicolas Wu, Tom Schrijvers, and Ralf Hinze. Effect handlers in scope. In Wouter Swierstra, editor, *Proceedings of the 2014 ACM SIGPLAN symposium on Haskell, Gothenburg, Sweden, September 4-5, 2014*, pages 1–12. ACM, 2014.

[10] Daan Leijen. Koka: Programming with row polymorphic effect types. In Paul Blain Levy and Neel Krishnaswami, editors, *Proceedings 5th Workshop on Mathematically Structured Functional Programming, MSFP@ETAPS 2014, Grenoble, France, 12 April 2014*, volume 153 of *EPTCS*, pages 100–126, 2014.

[11] Sam Lindley, Conor McBride, and Craig McLaughlin. Do be do be do. In Giuseppe Castagna and Andrew D. Gordon, editors, *Proceedings of the 44th ACM*

SIGPLAN Symposium on Principles of Programming Languages, POPL 2017, Paris, France, January 18-20, 2017, pages 500–514. ACM, 2017.

[12] Ezra Cooper, Sam Lindley, Philip Wadler, and Jeremy Yallop. Links: Web programming without tiers. In Frank S. de Boer, Marcello M. Bonsangue, Susanne Graf, and Willem P. de Roever, editors, *Formal Methods for Components and Objects, 5th International Symposium, FMCO 2006, Amsterdam, The Netherlands, November 7-10, 2006, Revised Lectures*, volume 4709 of *Lecture Notes in Computer Science*, pages 266–296. Springer, 2006.

[13] Daniel Hillerström and Sam Lindley. Liberating effects with rows and handlers. In James Chapman and Wouter Swierstra, editors, *Proceedings of the 1st International Workshop on Type-Driven Development, TyDe@ICFP 2016, Nara, Japan, September 18, 2016*, pages 15–27. ACM, 2016.

[14] Dennis M Ritchie and Ken Thompson. The unix time-sharing system. *Bell System Technical Journal*, 57(6):1905–1929, 1978.

[15] Eric S Raymond. *The art of Unix programming*. Addison-Wesley Professional, 2003.

[16] Daniel Hillerström. Foundations for programming and implementing effect handlers. 2022.

[17] Ohad Kammar, Sam Lindley, and Nicolas Oury. Handlers in action. *ACM SIGPLAN Notices*, 48(9):145–158, 2013.