Towards Modular Compilation using Higher-order Effects

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Abstract

Compilers transform a human readable source language into machine readable target language. Nanopass compilers simplify this approach by breaking up this transformation into small steps that are more understandable, maintainable, and extensible. We propose a semantics-driven variant of the nanopass compiler architecture exploring the use a effects and handlers to model the intermediate languages and the transformation passes, respectively. Our approach is fully typed and ensures that all cases in the compiler are covered. Additionally, by using an effect system we abstract over the control flow of the intermediate language making the compiler even more flexible. We apply this approach to a minimal compiler from a language with arithmetic and let-bound variables to a string of pretty printed X86 instructions. In the future, we hope to extend this work to compile a larger and more complicated language and we envision a formal verification framework from compilers written in this style.

2012 ACM Subject Classification Theory of computation → Program semantics; Software and its engineering → Compilers

Keywords and phrases algebraic effects and handlers, higher-order effects, monadic semantics, modularity, compilation, nanopass

Digital Object Identifier 10.4230/OASIcs.CVIT.2016.23

1 Introduction

The essence of a compiler is a function from a source language, suitable for humans, to a machine language, suitable for computers. As our computers have become more powerful we have seen increasingly complex compilers providing extensive safety guarantees and powerful optimizations. To manage this complexity, modern compilers are designed as a composition of multiple passes. However, the total number of passes has traditionally been kept low for the sake of performance, because each pass adds extra overhead. Thus, compiler passes are more complicated than necessary and therefore harder to *understand*, *maintain*, and *extend*.

To address this problem, Sarkar, Waddell, and Dybvig [7] introduce the nanopass compiler architecture. In the nanopass architecture, each pass is designed to be as simple as possible. It is not a problem to use many more passes than are used in traditional compilers. To address concerns about the performance of this architecture, Keep and Dybvig [4] show that it is possible to write a competitive commercial compiler using this architecture.

While the development of the nanopass architecture and the development of a commercial compiler is a great engineering achievement, we believe the theoretical foundation is underexplored. In this paper, we present our ongoing work on developing a semantics-driven nanopass compiler architecture. The foundation of our approach is a higher-order effect system [1] which is a state of the art technique for modeling the semantics of programming languages with side effects. Our approach has the practical advantage of preventing type errors in the compiler and ensuring all cases are covered. Additionally, our approach abstracts over the control flow giving many of the benefits of continuation-passing-style while retaining a simple monadic interface. While developing our approach, we are anticipating the possibility of verifying the correctness of compilers written in this style. We discuss that possibility briefly in our future work (Section 4).

42nd Conference on Very Important Topics (CVIT 2016).
Editors: John Q. Open and Joan R. Access; Article No. 23; pp. 23:1–23:7
OpenAccess Series in Informatics
Schloss Dagstuhl – Leibniz-Zentrum für Informatik, Dagstuhl Publishing, Germany

Concretely, we make the following contributions:

- We introduce a novel approach to designing and implementing practical compilers while staying close to formal denotational semantics specifications (Section 2).
- We demonstrate our approach on a simple language with arithmetic and let-bound variables by compiling it to a subset of X86 (Section 2).

2 Compiling with Higher-order Effects

In this section, we present our approach by applying it to a very simple language with arithmetic and let-bound variables. The target language of our compiler is X86 machine code. We explain the required concepts as we develop our compiler for this language. The specifications and compiler passes are presented in a simplified notation, but we have implemented all the work we present here in the Agda programming language [2]. Our code can be found on GitHub[1].

We start off by assuming our parser and possibly type checker has finished and produced an abstract syntax tree which follows the grammar described in Figure 1. Our language has integers, addition, subtraction, negation, a read operation to read an input integer, and a let to bind variables and a var to refer to bound variables. The abstract syntax is unusual because we reuse the variable binding facilities from our host language in the form of the $\lambda x.$ binding in the let constructor. This style of abstract syntax is called parametric higher-order abstract syntax (PHOAS) [3]. It allows us to avoid the complexities of variable binding and thus simplify our presentation.

$$
\begin{aligned}
\mathit{expr} ::=\ & \mathrm{int}(n) \\
\mid\ & \mathrm{add}(\mathit{expr}, \mathit{expr}) \\
\mid\ & \mathrm{sub}(\mathit{expr}, \mathit{expr}) \\
\mid\ & \mathrm{neg}(\mathit{expr}) \\
\mid\ & \mathrm{read} \\
\mid\ & \mathrm{let}(\mathit{expr}, \lambda x.\, \mathit{expr}) \\
\mid\ & \mathrm{var}(x)
\end{aligned}
$$

Figure 1 Abstract syntax of our simple language with arithmetic and let-bound variables.

The first step of our compilation pipeline will be to denote these syntactic constructs onto a set of semantic algebraic operations in the sense of algebraic effects [5]. As is customary when using algebraic effects in functional programming languages, we group these operations under units we call effects. We could group every operation under a single effect, however with the benefit of hindsight we decide to distribute the operations over four effects: Int, Arith, Read, and Let.

Figure 2 shows the operations that correspond directly to our source language. However, there are some particularities we address individually:

- To keep our example simple, we have chosen to use this single type for all values, but we keep the type abstract and simply call it 'val'. It is crucial to keep this type abstract for

[1] `https://github.com/heft-lang/hefty-compilation`

effect Int **where**
  $int : \mathbb{Z} \to m\ val$

effect Read **where**
  $read : m\ val$

effect Arith **where**
  $add : val \to val \to m\ val$
  $sub : val \to val \to m\ val$
  $neg : val \to m\ val$

effect Let **where**
  $let : m\ val \to (val \to m\ val) \to m\ val$

Figure 2 The effects of our source language and their operations with type signatures.

reasons we explain at the end of this section. Also note that we now need a special *int* operation to inject integers into this abstract value type.

- We write the surrounding monadic context as m, which provides the standard $\gg\!=$, $\gg$, and *return* operations. The monadic context of each operation always includes at least the effect that the operation belongs to, but it can accomodate other effects too. For example, the monadic context of $int\ 1 \gg\!= \lambda x.\ add\ x\ x$ contains at least the Int and Arith effects.
- Readers knowledgeable about effect systems might notice that the *let* operation has arguments that are themselves monadic computations. In standard algebraic effects and handlers this is not allowed, however our approach uses a novel higher-order effect formalism that does support such effectful subcomputations [1].

The first pass of our compiler pipeline is to map our abstract syntax from Figure 1 onto the operations we have defined for our source language from Figure 2. This mapping, called a denotation and written using the $[\![\cdot]\!]$ notation, is a recursive traversal of the abstract syntax tree shown in Figure 3. The result of this mapping is a monadic computation involving the Int, Arith, Read, and Let effects.

$$
\begin{aligned}
[\![\mathrm{int}(n)]\!] &= int\ n \\
[\![\mathrm{add}(e_1, e_2)]\!] &= [\![e_1]\!] \gg\!= \lambda x.\ [\![e_2]\!] \gg\!= \lambda y.\ add\ x\ y \\
[\![\mathrm{sub}(e_1, e_2)]\!] &= [\![e_1]\!] \gg\!= \lambda x.\ [\![e_2]\!] \gg\!= \lambda y.\ sub\ x\ y \\
[\![\mathrm{neg}(e)]\!] &= [\![e]\!] \gg\!= \lambda x.\ neg\ x \\
[\![\mathrm{read}]\!] &= read \\
[\![\mathrm{let}(e, f)]\!] &= let\ [\![e]\!]\ (\lambda x.\ [\![f\ x]\!]) \\
[\![\mathrm{var}(x)]\!] &= return\ x
\end{aligned}
$$

Figure 3 A denotational mapping from our abstract syntax onto our initial set of effectful operations.

Now that we have denoted our syntactic elements into our semantic domain as operations, we can start refining these operations to get closer to the desired target language which is X86 in our case. In the practice of algebraic effects, this refinement is facillitated by handlers as introduced by Plotkin and Pretnar [6]. These handlers give us access to the operations that occur in the program and the continuation of the program which we will simply call k. We only have to provide the rules that map the operation and continuation onto our semantic domain consisting of primitives, existing operations, or newly introduced operations.

The effect that we choose to handle first is the Let effect, which only has the *let* operation. We handle this operation by running the right hand side of the binding, passing the resulting value to the body, and finally passing the result of that to the continuation. In code that looks as follows:

$$\text{handle}\ (\mathit{let}\ e\ f)\ k = e \ggg\!= \lambda x.\, f\ x \ggg\!= \lambda z.\, k\ z$$

Note that this defines a strict semantics for our let bindings. By using a different handler we could give different semantics to our language. This is an example of the flexiblility of algebraic effects and handlers.

$$\begin{array}{ll}
\textbf{effect}\ \text{X86}\ \textbf{where} & \qquad \textbf{effect}\ \text{X86Var}\ \textbf{where} \\
\quad \begin{array}{lll}
\mathit{addq} & : \mathit{val} \to \mathit{val} & \to m\ () \\
\mathit{subq} & : \mathit{val} \to \mathit{val} & \to m\ () \\
\mathit{negq} & : \mathit{val} & \to m\ () \\
\mathit{movq} & : \mathit{val} \to \mathit{val} & \to m\ () \\
\mathit{callq} & : \mathit{lab} & \to m\ () \\
\mathit{reg} & : \text{Register} & \to m\ \mathit{val} \\
\mathit{deref} & : \text{Register} \to \mathbb{Z} & \to m\ \mathit{val}
\end{array} & \qquad \quad \mathit{x86var} : m\ \mathit{val}
\end{array}$$

Figure 4 The effects related to X86 and their operations with type signatures.

At this point, since our language is so simple we can already begin translating into our target language. In Figure 4 we show the a minimal subset of X86 that we need to compile our Arith and Read effects. This subset contains in-place arithmetic instructions, the ubiquitous move instruction, the call instruction, and an operation to inject concrete registers into our abstract value type. Additionally, we add an operation to generate fresh variables and inject them into our abstract value type.

We can trasnlate our Arith effect operations into X86 operations by creating a fresh X86 variable, populating it, and then applying the in-place arithmetic operation to the variable. So, we write handler as follows:

$$\begin{aligned}
&\text{handle}\ (\mathit{add}\ x\ y)\ k = \mathit{x86var} \ggg\!= \lambda z.\, \mathit{movq}\ x\ z \gg \mathit{addq}\ y\ z \gg k\ z \\
&\text{handle}\ (\mathit{sub}\ x\ y)\ \ k = \mathit{x86var} \ggg\!= \lambda z.\, \mathit{movq}\ x\ z \gg \mathit{subq}\ y\ z \gg k\ z \\
&\text{handle}\ (\mathit{neg}\ x)\quad\ k = \mathit{x86var} \ggg\!= \lambda z.\, \mathit{movq}\ x\ z \gg \mathit{negq}\ z \gg k\ z
\end{aligned}$$

The *read* operation requires us to call a function that we will assume is defined in a standard library called _read_int. This function places its output in the %rax register, so we have to move it to avoid it being overwritten by other parts of our program. The full definition of our handler for the Read effect is as follows:

$$\text{handle}\ \mathit{read}\ k = \mathit{x86var} \ggg\!= \lambda z.\, \mathit{callq}\ \_\text{read\_int} \gg \mathit{reg}\ \%\text{rax} \ggg\!= \lambda x.\, \mathit{movq}\ x\ z \gg k\ z$$

The final challenge to complete this minimal compiler pipeline is to allocate the X86 variables on the stack. Conceptually, this requires us to give each *x86var* operation and give each its own location of the stack. Keeping track of such information in our handler, however, is something we have not yet needed to do for the passes up to this point. Until now, we have handled each effect by translating into other effects direclty. Instead, we can parameterize our handlers which means we pass along an extra parameter while handling our operations. Parameterized handlers take one extra parameter and need to pass one extra argument to the continuation[2]. Now we can write the parameterized handler for the X86Var effect which assigns each variable to its own stack location as follows:

$$\text{handle } \mathit{x86var}\ k\ n = \mathit{deref}\ \%\text{rbp}\ (-8 \cdot n) \ggg\!= \lambda z.\, k\ z\ (n+1)$$

Note that we assume sufficient space is allocated on the stack. Additionally, when applying this handler we need to provide the starting value of the parameter n, which we will choose to be 1.

At this point, we have a full compiler pipeline from our source language to a subset of X86, but is still in the form of an effectful computation. To get a concrete representation, we implement two handlers for the remaining Int and X86 effects to produce an output string. As part of choosing this concrete representation, we also choose the concrete type for the variables *val* and *lab* to be the string type. We define the handler that turns our effectful computation of Int and X86 effects into a concrete string representation as follows:

$$\begin{array}{ll}
\text{handle } (\mathit{int}\ n) & k = k\ (\text{showInt}\ n) \\
\text{handle } (\mathit{addq}\ x\ y) & k = \texttt{"addq "} + x + \texttt{", "} + y + \texttt{"\textbackslash n"} + k\ () \\
\text{handle } (\mathit{subq}\ x\ y) & k = \texttt{"subq "} + x + \texttt{", "} + y + \texttt{"\textbackslash n"} + k\ () \\
\text{handle } (\mathit{negq}\ x) & k = \texttt{"negq "} + x + \texttt{"\textbackslash n"} + k\ () \\
\text{handle } (\mathit{movq}\ x\ y) & k = \texttt{"movq "} + x + \texttt{", "} + y + \texttt{"\textbackslash n"} + k\ () \\
\text{handle } (\mathit{callq}\ l) & k = \texttt{"callq "} + l + \texttt{"\textbackslash n"} + k\ () \\
\text{handle } (\mathit{reg}\ r) & k = k\ (\text{showReg}\ r) \\
\text{handle } (\mathit{int}\ r\ n) & k = k\ (\text{showInt}\ n + \texttt{"("} + \text{showReg}\ r + \texttt{")"})
\end{array}$$

3 Related Work

The origins of this work can be traced back to Eelco Visser's work on the Spoofax Language Workbench [9]. As part of Spoofax, Eelco is one of the designers of the Stratego [8] program transformation language. While Stratego can be used for developing compilers, Eelco was still looking for a way of specifying compilers that also abstracts over the control flow. We hope that this work can be the start of an answer to that research direction.

As mentioned in the introduction, our approach embraces the nanopass architecture [7, 4]. We improve upon this work by putting it on more formal foundations, making it fully typed to prevent common errors and even check that all cases are covered, and abstracting over the control flow in the compiler.

Our semantics-driven approach using an effect system is inspired by the work on symbolic execution by Wei et al. [10].

For our vision on verification of compilers we have taken inspiration from Interaction Trees [11]. Interaction Trees use algebraic laws of effects to prove the correctness of compilers. We hope to learn from that technique to prove the correctness of compilers written using our approach.

[2] We ignore effectful subcomputations, because they were already removed in an earlier pass.

4 Conclusions and Future Work

We have presented a new semantics-driven approach to writing compilers by using effect operations as an intermediate representation. We use effect handlers to iteratively refine operations in terms of increasingly lower level operations to finally reach a target machine language.

We have shown a concrete example of this approach applied to a very simple language with arithmetic and let-bound variables. We show the implementation of a denotation function and handlers which compile this language is compiled in several passes to X86 machine language with variables. Currently, we are working on a stack allocation pass to complete this minimal compiler.

In the future, we would like to complete the minimal compiler and extend it with more complicated language constructs such as conditionals and anonymous functions. Additionally, we would like to implement more complicated analyses on this effectful representation, such as register allocation. We expect these analyses to consist of two stages: first derive concrete structures such as control-flow graphs and interference graphs from our effectful representation, and then perform a pass over the effectful computation that uses the results of the analysis over these structures to transform the program. The first stage would be similar to our handler that turns the effectful computation into a concrete string and the second stage would employ a parameterized handler similar to our stack allocation handler.

Furthermore, we would like to explore the verification of our compilers using algebraic laws for our effect operations. To be specific, we can define a set of laws that describe the behavior of each of the effects in our compiler pipeline. If these laws are sound and complete, with respect to for example definitional interpreters for the effects, then we can prove compiler correctness by proving that these laws are preserved by each of our handlers.

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