

# Profile-Guided Meta-Program Optimizations

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## Abstract

Modern compilers such as GCC, .NET, and LLVM incorporate profile-guided optimizations (PGOs) on low-level intermediate code and basic blocks, with impressive results over purely static heuristics. Recent work shows that profile information is also useful for optimizing source programs via meta-programming (writing programs that perform source-to-source transformations). For example, using profiling information to inform decisions about data structures and algorithms can potentially lead to asymptotic improvements in performance. Meta-programming systems should make profile information available to enable meta-programmers to write their own, potentially domain-specific optimizations. Currently, each existing profile-guided meta-program comes with its own special-purpose toolkit, specific to a single optimization, creating barriers to use and development of new profile-guided meta-programs.

We propose an approach for supporting profile-guided meta-programs in a single general-purpose system. Our approach is parametric over particular profiling technique and meta-programming systems.

We demonstrate our approach by implementing it in two different (albeit similar) meta-programming systems: Chez Scheme's macro system and Racket's syntactic extension system.

## 1. Introduction

Profile-guided optimization (PGO) is a compiler technique in which the compiler uses profile information, e.g., execution counts, gathered from test runs on representative sets of inputs to generate more efficient code. The profile information acts as an oracle for runtime behavior, and is used to inform low-level optimization decisions about, e.g., reordering basic blocks, inlining, reordering conditional branches, and function layout (Gupta et al. 2002). The resulting code

usually exhibits improved performance, at least on the represented class of inputs, than code generated with static optimization heuristics. For example, using profiling information to inform inlining decisions in Java resulted in up to 59% improvement over static heuristics (Arnold et al. 2000). Modern compilers that support PGO include .NET (Profile-Guided Optimizations 2013), GCC (Optimize Options - Using the GNU Compiler Collection 2013), and LLVM (Latner 2002).

Profile information has also proven useful to implement optimizing meta-programs. Meta-programs, i.e., programs that operate on programs, are used to implement high-level abstractions such as abstract libraries such as Boost (Dawes and Abrahams 2009), compiler generators (W. Keep and Kent Dybvig 2013),

domain specific languages (Flatt et al. 2009; K. Sujeeth et al. 2013), and even whole general purpose languages (Barzilay and Clements 2005; Rafkind and Flatt 2012; Tobin-Hochstadt and Felleisen 2008; Tobin-Hochstadt et al. 2011). Scala Languages with existing meta-programming systems include C, C++, Haskell (Sheard and Peyton Jones 2002), Java (Erdweg et al. 2011), ML (Sheard and Jones 2002; Taha and Sheard 2000), Racket (Flatt and PLT 2010), Scheme (Dybvig et al. 1993), and Scala. (Burmako 2013). Chen et. al. implement a profile-guided meta-program for performing process placement for SMP clusters (Chen et al. 2006). Liu and Rus provide a tools that uses profile information to identify suboptimal usage of the C++ STL (Liu and Rus 2009). Hawkins et. al. implement a compiler for a language that generates C++ implementations of data structures based on high-level specifications (Hawkins et al. 2011; Hawkins et al. 2012).

Existing general-purpose meta-programming systems do not provide profile information about the input programs on which the meta-program is operating. Therefore, existing profile-guided meta-programs introduce new special-purpose toolkits for profiling and meta-programming. Instead, meta-programmers need an approach that gives existing general-purpose meta-programming systems access to profile information. Meta-programmers could then implement the profile-guided meta-programs in a single system, reusing the meta-programming and profiling tools of an existing, familiar, system. Programmers could then take advantage of all the optimizations implemented in that system.

TODO:  
Ensure we make point about efficient, standard instrumentation techniques in implementation section.

TODO:  
Should add some references to Delite, Scala work. Maybe in the related work

TODO:  
Say  
something  
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profiling  
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available  
for  
run-time  
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We propose an approach for supporting multiple profile-guided meta-programs in a single general-purpose system. The approach provides a simple API through which meta-programs can access fine-grain source-level profile information, and does not interfere with traditional, i.e., “low-level” PGOs.

We implement this approach in Chez Scheme using standard and efficient block-level profiling techniques (Ball and R. Larus 1994) (Burger and Dybvig 1998). We also implement this approach in Racket (Flatt and PLT 2010) purely as a library, using preexisting meta-programming facilities and profiling libraries.

The remainder of the paper is organized as follows. In section 2 we present a running example and introduce meta-programming in Scheme. In section 3 we present the design of our system at a high level, and the implementation details for both Chez Scheme and Racket. In section 4 we demonstrate that our approach is general enough to easily implement and improve upon existing profile-guided optimizations and profile-guided meta-programs. In section 5 we give a more detailed discussion of existing work on PGOs and profile-guided meta-programming, and how our approach supports this work. We conclude in section 6 a discussion of how our approach could be implemented in other meta-programming systems.

The main contributions of our work are:

- A proposed approach for general-purpose profile-guided meta-programming.
- An open-source implementation of this approach in Racket, using existing profiling and meta-programming tools.
- Open-source implementations of case studies demonstrating how past work can be implemented and improved using our approach.

## 2. A running example

We first introduce a Scheme macro which we will use as a running example and to familiarize readers with Scheme’s meta-programming system. This example is not to be taken as a useful optimization.

```
(define-syntax (if-r stx)
  (syntax-case stx ()
    [(if-r test t-exp f-exp)
     (let ([t-prof (profile-query #'t-exp)]
           [f-prof (profile-query #'f-exp)])
       (if (< t-prof f-prof)
           #'(if (not test) f-prof t-prof)
           #'(if test t-prof f-prof)))]))
```

Figure 1: Sample macro

In figure 1, we create a new macro with `define-syntax`. A macro takes a single piece of syntax as its argument. For

example, the function in figure 2 uses the new macro `if-r`. The implementation of macro `if-r` will receive the argument `#'(if-r (subject-contains-ci email "PLDI") (flag email 'important) (flag email 'spam))`, which is a data representation of syntax called a syntax object. The forms `#'`, `#\`, and `#`, implement Lisp’s quote, quasiquote, and unquote but on syntax instead of lists. The form `syntax-case` performs pattern matching on syntax objects.

```
(define (classify email)
  (if-r (subject-contains-ci email "PLDI")
        (flag email 'important)
        (flag email 'spam)))
```

Figure 2: Using `if-r`

The definition of `if-r` defines a new syntactic form similar to `if`. At compile time, it looks up the profile information attached to each expressions, and reorders the branches based on which is more likely to be executed. This macro is run at compile-time, while the resulting `if` will be run at run-time. Figure 3 shows the resulting code after `if-r` is run.

```
(define (classify email)
  (if (not (subject-contains-ci email "PLDI"))
      (flag email 'spam)
      (flag email 'important)))
```

Figure 3: Result of `if-r` meta-program

## 3. Design and Implementation

This section presents the essential pieces of our approach, design decisions, and implementation details. We first discuss what profile information we use and how we handle multiple data sets. We then discuss source objects, which are used to identify expressions and track profile information. We discuss how we efficiently instrument code, and finally we discuss how we ensure source-level and block-level profile-guided optimizations work together in our approach.

### 3.1 Profile Information

In our implementations, we use counter-based profiling. We associate unique counters with each profile point identified by the meta-program. Our approach is not specific to counter-based profiling and should work with other profiling techniques, such as timing-based profiling.

While we track exact counts, exact counts are not comparable across different data sets. Multiple data sets are important to ensure PGOs can optimize for multiple classes of inputs expected in production. Instead, our API provides profile *weights*. The profile weight of a source point in a given data set is the ratio of the exact count for the source point

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...

to the maximum count for any source point, represented as a number in the range [0,1]. That is, the profile weight for a given source object is profile count for that source object divided by the the profile count for the most frequently executed source object in the database. This provides a single value identifying the relative importance of an expression and simplifies the combination of multiple profile data sets.

To understand how we compute profile weights, consider our running example from figure 2. Suppose in our first benchmark, `(flag email 'important)` is executed 5 times and `(flag email 'spam)` is executed 10 times. In a second benchmark, `(flag email 'important)` is executed 100 times and `(flag email 'spam)` is executed 10 times. Figure 4 shows the profile weights computed after each benchmark.

```
;; After loading data from benchmark 1
(flag email 'important) → 5/10          ;; 0.5
(flag email 'spam)      → 10/10         ;; 1

;; After loading data from benchmarks 1 and 2
(flag email 'important) → (.5 + 100/100)/2 ;; 0.75
(flag email 'spam)      → (1 + 10/100)/2  ;; 0.55
```

Figure 4: Sample profile weight computations

### 3.2 Source objects

We use *source objects* (Dybvig et al. 1993) to uniquely identify points in a program to profile. Source objects are typically introduced by the lexer and parser for a source language and maintained throughout the compiler to correlate source expressions with intermediate or object code. This enables both error messages and debuggers to refer to source expressions instead of target or intermediate representations.

We reuse source objects in our approach to uniquely identify profile counters. If two expressions are associated with the same source object, then they both increment the same profile counter when executed. Conversely, if two expressions are associated with different source objects, then they increment different profile counters when executed.

While source objects are typically introduced by the lexer and parser, we also require the ability to create new source objects in meta-programs. This is useful, for instance, when implementing a DSL. You may want to profile generated expressions separately from any other expression in the source language.

In the case of our running example, the lexer and parser introduce source objects for each expression (and sub-expression). That is, separate source objects are created for `#'(if ...)`, `#'(subject-contains-ci email "PLDI")`, `#'subject-contains-ci`, `#'email`, `#'"PLDI"`, `#'(flag email 'spam)`, and so on. Note that `#'flag` and `#'email` appear multiple times, and will have a unique source object for each occurrence.

```
(define (make-fresh-source-obj-factory! prefix)
  (let ([n 0])
    (lambda (syn)
      (let* ([sfd (make-source-file-descriptor
                  (format "~a:~a:~a"
                    (syntax->filename syn)
                    prefix n)
                  #f)])
        [src (make-source-object n n sfd)])
        (set! n (add1 n))
        src))))
```

Figure 5: Chez implementation for generating source objects

```
(define (make-fresh-source-obj-factory! prefix)
  (let ([n 0])
    (lambda (syn)
      (let ([src (struct-copy srcloc
                            (syntax->srcloc syn)
                            [source (format "~a:~a:~a"
                              (syntax-source syn)
                              prefix n)])])
        (set! n (add1 n))
        src))))
```

Figure 6: Racket implementation for generating source objects

#### 3.2.1 Chez Scheme Source Objects

In Chez Scheme, a source object contains a file name and starting and ending character positions. The Chez Scheme reader automatically creates and attaches these to each piece of syntax read from a file.

Chez Scheme also provides an API to programmatically manipulate source objects and attach them to syntax (Dybvig 2011 Chapter 11). We use the function defined in figure 5 to generate new source objects. This function takes a string prefix and creates a new source object generator. The generator uses the prefix, a counter, and some given piece of syntax to generate a fake file name and fake character positions. The generated file name is partly based on the input syntax to make them more useful if when they show up in error messages.

#### 3.2.2 Racket Source Objects

Racket does not attach separate source objects to syntax. Instead, the file name, line number, column number, position, and span are all attached directly to the syntax object. We provide wrappers to extract these into separate source objects, called `srclocs`, and to merge these source objects into Racket syntax objects. Figure 6 shows the Racket implementation of the previous function. Again we generate a fake file names, but simply copy the line number, column number, etc. from the given syntax object.

### 3.3 Instrumenting code

In this section we discuss how we instrument code to collect profiling information.

#### 3.3.1 Chez Scheme Instrumentation

The naïve method for instrumenting code to collect source profile information would be to add a counter for each source expression. However this method can easily distort the profile counts. As expressions are duplicated or thrown out during optimizations, the source information is also duplicated or lost.

Instead we create a separate profile form that is created after macro expansion. Each expression `e` that has a source object attached is expanded internally to `(begin (profile src) e)`, where `src` is the source object attached to `e`. The profile form is considered an effectful expression and should never be thrown out or duplicated, even if `e` is. While the separate profile form has benefits, it can interfere with optimizations based on pattern-matching on the structure of expressions, such as those implemented in a nanopass framework (W. Keep and Kent Dybvig 2013).

We keep profile forms until generating basic blocks. While generating basic blocks, all the source objects from the profile forms are attached to the basic block in which they appear. When a basic block is entered, every instruction in that block will be executed, so it is safe to increment the counters for all the instructions in the block at the top of the block.

In our implementation, we minimize the number of counters incremented at runtime. After generating basic blocks and attaching the counters to blocks, we analyze the blocks to determine which counters can be calculated in terms of other counters. If possible, a counter is computed as the sum of a list of other counters. This complicates the internal representation of counters and the generation of counters, but decreases the overhead of profiling. These techniques are based on the work of Burger and Dybvig (Burger and Dybvig 1998). We generate at most one increment per block, and fewer in practice.

To instrument block-level profiling, we reuse the above infrastructure by creating fake source objects. Before compiling a file, we reset global initial block number to 0, and create a fake source file based on the file name. We give each block a source object using the fake file name and using the blocks number as the starting and ending file position.

When loading profile information from a previous run, we compute profile weights and store them in a two-level hash table. The first level hash table maps source file names to hash tables. Each second level hash table maps the starting character position to a profile weight. These tables are not updated in real time, only when a new data set is manually loaded by an API call in a program or meta-program.

After the hash tables are populated, the information can be accessed via the function `profile-query-weight`. The

function `profile-query-weight` takes a source object or syntax object. When given a syntax object, it extract the source object first. The result of `profile-query-weight` is either the profile weight associated with the given source object, or `#f` (the Scheme value for false) if no profile information exists. In our running example, we called this `profile-query`, and ignored the possibility of get `#f`, to simplify the example.

#### 3.3.2 Racket Instrumentation

We use one of the pre-existing Racket profiling systems. The `errortrace` library provides exact profile counters, like the Chez Scheme profiler. We implement several wrappers to provide an API similar to the API provided by Chez Scheme. All these wrappers are implemented simply as Racket functions that can be called at compile time, requiring no change to either the Racket implementation or the `errortrace` library.

The current Racket implementation does not use hash tables the way the Chez Scheme implementation does. Profile information is simply stored as an association list mapping source objects to profile counts. Profile weights are computed on each call to `profile-query-weight`.

TODO: It really ought to use hash tables. Current implementation is kinda dumb.

### 3.4 Source and block PGO

In this section we describe how our approach works with both source and block-level PGO. This section is only relevant to our Chez Scheme implementation. While the Chez Scheme compiler produces machine code and offers block-level PGOs, Racket uses a JIT compiler and does not take profile information as input.

When designing our source level profiling system, we wanted to continue using prior work on low level profile-guided optimizations (Gupta et al. 2002; Hwu and Chang 1989; Pettis and C. Hansen 1990). However, optimizations based on source-level profile information may result in a different set of blocks. If we use the same profile information gathered when profiling the source, the block-level profile information will be stale. Therefore optimization using source profile information and those using block profile information cannot be done after a single profiled run of a program. We need a new workflow.

TODO: Have a Racketeer double check that last sentence. And may rephrase it

To use both source and block-level PGO, first we compile and instrument a program to collect source-level information. We run this program and collect only source-level information. Next we recompile and optimize the program using the source-level information only, and instrument the program to collect block-level information. From this point on, source-level optimizations should run and the blocks should remain stable. We run this program and collect only the block-level information. Finally, we recompile the program with both source-level and block-level information. Since the source information has not changed, the meta-programs generate the same source code, and thus the compiler gen-

TODO:  
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only use  
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nation  
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to the  
example.

erates the same blocks. The blocks are then optimized with the correct profile information.

For example, to get both source-level and block-level optimizations on our running example, we would first instrument the program in figure 2 for source profiling. After running it on representative inputs, we get the profile weights such as in figure 4. Next we recompile using that source profile information, and instrument block profiling. The resulting source program is the code from figure 3. Since we will continue to use the same source profile information, `if-r` continues to expand to the same source code, regardless of the block profile information, so the blocks remain stable. Now we pass the optimized source program and block profile information to the compiler to perform block-level optimizations.

## 4. Case Studies

In this section we evaluate our approach. We show it is general enough to implement and improve upon existing profile-guided meta-programs. We first demonstrate optimizing Scheme’s `case` construct, a multi-way branching construct similar to C’s `switch`. Then we then demonstrates profile-guided receiver class prediction (Grove et al. 1995) for an object-oriented DSL. Finally we demonstrate that our approach is powerful enough to reimplement and improve upon Perflint (Liu and Rus 2009) by providing a list and vector libraries that warn programmers when they may be using a less than optimal data structure, based on profile information. We provide implementations of all case studies in both Chez Scheme and Racket.

### 4.1 Profile-guided conditional branch optimization

The .NET compiler features value probes, which enable profile-guided reordering of `if/else` and `switch` statements. As our first case study, we optimize Scheme’s `cond` and `case` constructs, which are similar to `if/else` and `switch` in other languages. This demonstrates that our approach can be used to easily implement this optimization without the specialized support of value probes. It also demonstrates that our approach allows programmers to use meta-programming to encode their knowledge of the program, enabling optimizations that may have been otherwise impossible.

The Scheme `cond` construct is analogous to a series of `if/else-if` statements. To execute a `cond`, we run the left-hand side of each clause until some left-hand side evaluates to true. When we find the first true clause, we run the right-hand side of that clause, and ignore further clauses. If there is an `else` clause, we run the right-hand side of the `else` clause only if no other clause’s left-hand side is true. Figure 7 shows an example program using `cond`.

We introduce the `exclusive-cond` construct, figure 8, as a condition branch construct similar to `cond`, but one that expects all branches to be mutually exclusive. When the branches are mutually exclusive we can safely reorder the

```
(define (lex char)
  (cond
    [(is-whitespace? char) e1]
    [(is-open-parn? char) e1]
    [else (* n (fact (sub1 n)))]))
```

Figure 7: An example using `cond`

clauses to execute the most likely clauses first. While the compiler cannot prove such a property in general, meta-programming allows the programmer to encode this knowledge in their program and take advantage of optimizations that would have otherwise been impossible.

The `exclusive-cond` macro rearranges clauses based on the profiling information of the right-hand sides. Since the left-hand sides are executed depending on the order, profiling information from the left-hand side cannot be used to determine which clause is executed most often. The `clause` structure stores the original syntax for `exclusive-cond` clause and the weighted profile count for that clause. Recall that `profile-query-weight` may return `#f`. We do not care to distinguish between 0 and `#f`, so we use 0 when if we there is no profile information. Since a valid `exclusive-cond` clause is also a valid `cond` clause, we copy the syntax and generate a new `cond` in which the clauses are sorted according to profile weights. The `#,@` splices a list of syntax objects into a syntax object. Of course the `else` clause is always last and is not included when sorting the other clauses.

The `case` construct takes an expression `key-expr` and an arbitrary number of clauses, followed by an optional `else` clause. The left-hand side of each clause is a list of constants. `case` executes the right-hand side of the first clause in which `key-expr` is `eqv?` to some element of the left-hand. If `key-expr` is not `eqv?` to any element of any left-hand side and an `else` clause exists then the right-hand side of the `else` clause is executed. Figure 9 shows an example `case` expression. In this example, the programmer has a spurious 0 in the second clause which should never be matched against, since the first clause will always match 0.

```
(define (fact n)
  (case n
    [(0) 1]
    [(0 5) 120]
    [else (* n (fact (sub1 n)))]))
```

Figure 9: An example using `case`

Figure 10 shows the full profile-guided implementation of `case` that sorts clauses by which is executed most often. The majority of the work is in `trim-keys!`, which removes duplicate keys to ensure mutually exclusive clauses. We omit its definition for brevity. Since `case` permits clauses



```

(define-syntax (exclusive-cond x)
  (define-record-type clause (fields syn weight))
  (define (parse-clause clause)
    (syntax-case clause ()
      [(e0 e1 e2 ...) (make-clause clause (or (profile-query-weight #'e1) 0))]
      [_ (syntax-error clause "invalid clause")]))
  (define (sort-clauses clause*)
    (sort (lambda (c11 c12) (> (clause-weight c11) (clause-weight c12)))
          (map parse-clause clause*)))
  (define (reorder-cond clause* els?)
    #'(cond #,@(map clause-syn (sort-clauses clause*)) . #,els?))
  (syntax-case x (else)
    [( _ m1 ... (else e1 e2 ...) ) (reorder-cond #'(m1 ...) #'([else e1 e2 ...]))]
    [( _ m1 ... ) (reorder-cond #'(m1 ...) #'())])

```

Figure 8: Implementation of `exclusive-cond`

to have overlapping elements and uses order to determine which branch to take, we must remove overlapping elements before reordering clauses. We parse each clause into the set of left-hand side keys and right-hand side bodies. We remove overlapping keys by keeping only the first instance of each key when processing the clauses in the original order. After removing overlapping keys, we generate an `exclusive-cond` expression.

Figure 11 shows how the example `case` expression from figure 9 expands into `exclusive-cond`. Note the duplicate `0` in the second clause is dropped to preserve ordering constraints from `case`.

```

(define (fact n)
  (let ([x n])
    (exclusive-cond x
      [(memv x '(0)) 1]
      [(memv x '(5)) 120]
      [else (* n (fact (sub1 n)))])))

```

Figure 11: The expansion of figure 9

Finally, figure 12 show the result of expanding `exclusive-cond` in figure 11. In the final generated program, the most common case is checked first.

```

(define (fact n)
  (let ([x n])
    (cond x
      [(memv x '(5)) 120]
      [(memv x '(0)) 1]
      [else (* n (fact (sub1 n)))])))

```

Figure 12: The expansion of figure 11

## 4.2 Profile-guided receiver class prediction

We provide a meta-program that implements profile-guided receiver class prediction (Grove et al. 1995; Hölzle and Ungar 1994) for a simplified object-oriented DSL implemented as a syntax extension. This case study demonstrates that our mechanism is both general enough to implement well-known profile-guided optimizations, and powerful enough to provide DSL writers with standard PGOs.

Figure 13 shows the key parts of our implementation of receiver class prediction. A method call such as `(method shape area)` will generate code as follows. First, we generate a new source object for each class in the system. Then we instrument a call to the dynamic dispatch routine for each of the newly generated source objects. When there is no profile data, we expand into a `cond`<sup>1</sup> that calls the instrumented version of the dynamic dispatch depending on the class of the object `shape`. When there is profiling information, we expand into a `cond` that tests for the most frequently used classes at this method call site, and inlines those methods. Otherwise we fall back to dynamic dispatch.

TODO:  
Maybe  
implement  
the instru-  
mented  
hash table  
later

The entire implementation of profile-guided receiver class prediction is 44 lines of code. The rest of the OO DSL implementation requires an additional 82 lines.

Figure 14 shows an example method call, the resulting code after instrumentation, and the resulting code after optimization. Note that the each occurrences of `(instrumented-dispatch x area)` has a different source objects, so they are each profiled separately.

We have demonstrated that our approach can easily implement a well known profile-guided optimization as a meta-program, but our approach provides one additional advantage. We can reuse `exclusive-cond` to test for the most likely class first.

<sup>1</sup> A production implementation would create a table of instrumented dynamic dispatch calls and dynamically dispatch through this table, instead of instrumenting code with `cond`.

```

(define-syntax (case x)
  (define (helper key-expr clause* els?)
    (define-record-type clause (fields (mutable keys) body))
    (define (parse-clause clause)
      (syntax-case clause ()
        [((k ...) e1 e2 ...) (make-clause #'(k ...) #'(e1 e2 ...))]
        [_ (syntax-error "invalid case clause" clause)]))
    (define (emit clause*)
      #'(let ([t #,key-expr])
          (exclusive-cond
            #,@(map (λ (cl) #'[(memv t '#, (clause-keys cl)) #,@(clause-body cl)]) clause*)
            . #,els?)))
    (let ([clause* (map parse-clause clause*)])
      (for-each trim-keys! clause*) (emit clause*)))
    (syntax-case x (else)
      [(_ e clause ... [else e1 e2 ...]) (helper #'e #'(clause ...) #'([else e1 e2 ...]))]
      [_ e clause ...] (helper #'e #'(clause ...) #'()))))

```

Figure 10: Implementation of `case` using `exclusive-cond`

```

(begin-for-syntax
  (define make-fresh-source-obj! (make-fresh-source-obj-factory! "method-call"))
  (define-syntax (method syn)
    (define source-objs (map (λ (x) (make-fresh-source-obj! syn)) class-list))
    ...
    (syntax-case syn ()
      [(_ obj m val* ...)
        (let ([instrumented-dispatches (for/list ([source-obj source-objs])
            (instrument-dispatch source-obj #'m #'(val* ...)))]
              [sorted-classes (drop-zero-weight (sort-by-weight source-objs class-list))])
          ...
          #'(let* ([x obj])
              (cond
                #,@(if no-profile-data?
                  (for/list ([d instrumented-dispatches] [class class-list])
                    #'((class-equal? x #,class) (#,d x)))
                  (for/list ([class (take sorted-classes inline-limit)])
                    #'((class-equal? x #,class)
                      #,(inline-method class #'x #'m #'(val* ...))))
                [else (dynamic-dispatch obj m val* ...)])
              )
          )

```

Figure 13: Implementation of profile-guided receiver class prediction

### 4.3 Data Structure Specialization

While profile-guided optimizations can provide important speeds up by optimizing code paths, programmers can use profile information to identify much higher level performance issues. For instance, profile information can be used to figure out that a different algorithms or data structures might be cause an asymptotic speed up. (Liu and Rus 2009) In this case study we show our mechanism is general enough to implement this kind of profiling tool, and even go beyond it by automating the recommendations.

We provide implementations of lists and vectors (array) that warn the programmer when they may be using a less optimal data structure. The implementations provide wrappers around the standard list and vector functions that introduce

new source objects to profile the uses of each new list and vector separately. Finally, we provide an implementation of a sequence datatype that will automatically specialize to a list or vector based on profiling information. Complete versions of both Chez Scheme and Racket implementations of this code are freely available at (??? ???).

Figure 16 shows the implementation of the profiled list constructor. This constructor has the same interface as the standard Scheme list constructor—it takes an arbitrary number of elements and returns a representation of a linked list. We represent a list as a pair of the underlying linked list and a hash table of profiled list operations. We generate these profiled operations by simply wrapping calls to underlying, ‘real’, list operations with freshly generated source objects. We generate two source objects for each list. One is used

```

(class Square
  ((length 0))
  (define-method (area this)
    (sqr (field this length))))
(class Circle
  ((radius 0))
  (define-method (area this)
    (* pi (sqr (field this radius)))))
(class Triangle
  ((base 0) (height 0))
  (define-method (area this)
    (* 1/2 base height)))
...
(for/list ([s (circle-and-squares)])
  (method s area))

; -----
; After instrumentation
...
(let* ([x c])
  (cond
    [(class-equal? x 'Square) (instrumented-dispatch x area)]
    [(class-equal? x 'Circle) (instrumented-dispatch x area)]
    [(class-equal? x 'Triangle) (instrumented-dispatch x area)]))

; -----
; After optimization
...
(let* ([x c])
  (cond
    [(class-equal? x 'Square) (let ([this x]) (sqr (field x length)))]
    [(class-equal? x 'Circle) (let ([this x]) (* pi (sqr (field x radius)))]
    [else (dynamic-dispatch x area)]))

```

---

Figure 14: Example of profile-guided receiver class prediction

```

; -----
; After optimization
...
(let* ([x c])
  (exclusive-cond
    [(class-equal? x 'Square) (let ([this x]) (sqr (field x length)))]
    [(class-equal? x 'Circle) (let ([this x]) (* pi (sqr (field x radius)))]
    [else (dynamic-dispatch x area)]))

; -----
; After more optimization
...
(let* ([x c])
  (cond
    [(class-equal? x 'Circle) (let ([this x]) (* pi (sqr (field x radius)))]
    [(class-equal? x 'Square) (let ([this x]) (sqr (field x length)))]
    [else (dynamic-dispatch x area)]))

```

---

Figure 15: Profile-guided receiver class prediction, sorted.



```

(define-record list-rep (op-table ls))
(define (car ls)
  (make-list-rep (list-rep-op-table ls)
    ((hashtable-ref (list-rep-op-table ls) 'car #f)
     (list-rep-ls ls))))
...
(meta define make-fresh-source-obj! (make-fresh-source-obj-factory! "profiled-list"))
(define-syntax (list x)
  ; Create fresh source object. list-src profiles operations that are
  ; fast on lists, and vector-src profiles operations that are fast on
  ; vectors.
  (define list-src (make-fresh-source-obj! x))
  (define vector-src (make-fresh-source-obj! x))
  ; Defines all the sequences operations, giving profiled implementations
  (define op-name* '(list? map car cdr cons list-ref length))
  (define op*
    (real:map
     (lambda (v src)
       (datum->annotated-syntax x '(lambda args (apply ,v args)) src))
     ' (real:list? real:map real:car real:cdr real:cons real:list-ref real:length)
     (real:list #f #f #f list-src list-src vector-src vector-src)))
  (syntax-case x ()
    [(_ init* ...)]
    (unless (>= (or (profile-query-weight list-src) 0)
                (or (profile-query-weight vector-src) 0))
      (printf "WARNING: You should probably reimplement this list as a vector: ~a\n" x))
    #'(let ()
        (make-list-rep
         (let ([ht (make-eq-hashtable)])
           #,@(real:map (lambda (op op-name) #'(hashtable-set! ht #,op-name #,op))
                        (syntax->list op*) (syntax->list op-name*))
          ht)
         (real:list init* ...))))))

```

Figure 16: Implementation of profiled list

to profile operations that are fast for lists and the other is used to profile operations that are fast for vectors. Finally, we export new versions of all the list operations that work on our new list representation. For instance, `car` takes our profiled list representations, and calls the profiled version of `car` from the hash table of the profiled list on the underlying list. When profiling information already exists, for instance, after a profiled run, this list constructor emits a warning (at compile time) if the list fast vector operations are more common than fast list operations.

We also provide an analogous implementation of vectors. While we implement only two data structures here, this technique should scale to the many other data structures analyzed by Perflint. However, we can do one step better. Since our meta programs are integrated into the language, rather than existing as a separate tool in front of the compiler, we can provide libraries to the programmer that automatically follow these recommendations rather than asking the programmer to change their code. To demonstrate this, we implement a profiled sequence data type that will automatically specialize to a list or vector, at compile time, based on profile information.

Figure 17 shows the implementation of the profiled sequence constructor. The code follows exactly the same pattern as the profiled list. The key difference is we conditionally generate wrapped versions of the list *or* vector operations, and represent the underlying data using a list *or* vector, depending on the profile information.

This implementation of an automatically specializing data structure is not ideal. The extra indirects through a hashtable and wrapped operations introduce constant overhead to constructing a sequence, and to every operation on the sequence. This case study does, however, demonstrate that our mechanism is general and powerful enough to implement novel profile directed optimizations.

## 5. Related and Future Work

### 5.1 Low-level PGO

Modern systems such as GCC, .NET, and LLVM use profile directed optimizations (Lattner 2002; Optimize Options - Using the GNU Compiler Collection 2013). These systems use profile information to guide decisions about code po-

TODO:  
Add links  
for all  
references.

```

(define-record seq-rep (op-table s))
...
(meta define make-fresh-source-obj! (make-fresh-source-obj-factory! "profiled-seq"))
(define-syntax (seq x)
  (define list-src (make-fresh-source-obj! x))
  (define vector-src (make-fresh-source-obj! x))
  (define previous-list-usage (or (profile-query-weight list-src) 0))
  (define previous-vector-usage (or (profile-query-weight vector-src) 0))
  (define list>=vector (>= previous-list-usage previous-vector-usage))
  (define op-name* '(seq? seq-map seq-first seq-rest seq-cons seq-append
    seq-copy seq-ref seq-set! seq-length))
  (define op*
    (map
      (lambda (v src)
        (datum->annotated-syntax x `(lambda args (apply ,v args)) src))
      (if list>=vector
        '(list? map first rest cons append list-copy list-ref
          list-set! length)
        '(vector? vector-map vector-first vector-rest vector-cons
          vector-append vector-copy vector-ref vector-set!
          vector-length)))
      (list #f #f #f list-src list-src list-src #f vector-src vector-src
        vector-src)))
  (syntax-case x ()
    [(_ init* ...)
     #'(let ()
        (make-seq-rep
          (let ([ht (make-eq-hashtable)])
            #,@(map (lambda (op op-name) #'(hashtable-set! ht #,op-name #,op))
              (syntax->list op*) (syntax->list op-name*))
            ht)
          (#, (if list>=vector #'list #'vector) init* ...)))]))

```

Figure 17: Implementation of profiled sequence

sitioning, register allocation, inlining, and branch optimizations.

GCC profiles an internal control-flow graph (CFG). To maintain a consistent CFGs across instrumented and optimization builds, GCC requires similar optimization decisions across builds (Chen et al. 2010). In addition to the common optimizations noted previously, .NET extends their profiling system to probe values in `switch` statements. They can use this value information to optimize `switch` branches, similar to the implementation of `case` we presented in section 4.1.

Our system supports all these optimizations and has several advantages. While .NET extends their profiling system to get additional optimizations, we can support all the above optimizations in a single general-purpose system. By using profile information associated with source expressions, we reduce reliance specific internal compiler decisions and make profile information more reusable. When there is no substitute for block-level information, such as when reordering basic blocks, we support both source and block profiling in the same system.

## 5.2 Dynamic Recompilation

The standard model for PGO requires the instrument-profile-optimize workflow. LLVM has a different model for PGO. LLVM uses a runtime reoptimizer that monitors the running program. The runtime can profile the program as it runs “in the field” and perform simple optimizations to the machine code, or call to an offline optimizer for more complex optimizations on the LLVM bytecode.

While not currently enabled, our mechanism supports this kind of reoptimization. We build on the work of Burger and Dybvig, who present an infrastructure for profile-directed dynamic reoptimization (Burger and Dybvig 1998). Their work shows just 14% run-time overhead for instrumented code, but they express concerns that dynamic recompilation will not overcome this cost. Our internal microbenchmarks show similar overhead. To enable dynamic PGO, we would need to modify our mechanism to automatically reload profile information, such as whenever `profile-query-weight` is called, instead of manually loading information from a file. This is a trivial change to our system, but we have no optimizations in mind that make use of profile-guided at runtime. It may also increase overhead, since we compute pro-

file weights and many counters when loading new profile data.

### 5.3 Meta-program optimizations

Meta-programming has proven successful at providing higher levels of abstraction while still producing efficient code. Meta-programming has been used to implement abstract libraries (Dawes and Abrahams 2009)

, domain specific languages (Flatt et al. 2009; K. Sujeeth et al. 2013), and even whole general purpose languages (Barzilay and Clements 2005; Rafkind and Flatt 2012; Tobin-Hochstadt and Felleisen 2008; Tobin-Hochstadt et al. 2011). The HERMIT toolkit provides an API for performing program transformations on Haskell intermediate code before compiling, even allowing interactive experimentation (Farmer et al. 2012). These meta-programs can lose or obscure information during the translation into target-language code.

We're not the first to realize this. Many meta-program optimizations exist. Tobin-Hochstadt et. al. implement the optimizer for Typed Racket as a meta-program (Tobin-Hochstadt et al. 2011). Sujeeth et. al. provide a framework for generated optimized code from DSLs (K. Sujeeth et al. 2013). Hawkins et. al. implement a compiler for a language that generates C++ implementations of data structures based on high-level specifications (Hawkins et al. 2011; Hawkins et al. 2012).

Even using profile information to perform optimizations in meta-programs is not new. Chen et. al. implement their own profile and meta-program tools to provide a profile-guided meta-program for performing process placement for SMP clusters (Chen et al. 2006). Liu and Rus provide a tools that uses profile information to identify suboptimal usage of the C++ STL (Liu and Rus 2009).

We support these works by providing a single, general-purpose mechanism in which we can implement new languages, DSLs, abstract libraries, and arbitrary meta-programs, all taking advantage of profile-guided optimizations. Further, we our mechanism reuses existing meta-programming and profiling facilities, rather than implementing new tools in front of the compiler.

### 5.4 More PGO

We have referred to past work on both low-level PGOs and profile-guided meta-programs. But the use of profile information is still an active area of research. Furr et. al. present a system for inferring types in dynamic languages to assist in debugging (Furr et al. 2009). Chen et. al. use profile information to reorganize the heap and optimize garbage collection (Chen et al. 2006). Luk et. al. use profile information to guide data prefetching (Luk et al. 2002). Debray and Evans use profile information to compress infrequently executed code on memory constrained systems (Debray and Evans 2002).

With so many profile-guided optimizations, we need a general-purpose mechanism in which to implement them

without reimplementing profiling, compiling, and meta-programming tools.

## 6. Conclusion

We have presented a general mechanism for profile-guided meta-program optimizations implemented in Scheme. While our mechanism should easily extend to other meta-programming facilities, we conclude by discussing precisely how other common meta-programming facilities need to be extended to use our mechanism.

Template Haskell, MetaOcaml, and Scala all feature powerful meta-programming facilities similar to Scheme's (Burmako 2013; Czarnecki et al. 2004; Dybvig et al. 1993; Sheard and Jones 2002; Taha and Sheard 2000). They allow executing arbitrary code at compile-time, provide quoting and unquoting of syntax, and provide direct representations of the source AST. Source objects could be attached to the AST, and `profile-query-weight` could access the source objects given an AST. These languages all appear to lack source profilers, however.

C++ template meta-programming does not support running arbitrary programs at compile time. This might limit the kinds of optimizations that could be implemented using C++ template meta-programming as it exists today. Many source level profilers already exist for C++, so the challenge is in implementing source objects and `profile-query-weight`. C++ templates offers no way to directly access and manipulate syntax, so it is not clear where to attach source objects.

C preprocessor macros do support using syntax as input and output to macros, but are very limited in what can be done at compile time. Adding directives to create, instrument, and read source profile points might be enough to support limited profile-guided meta-programming using C preprocessor macros.

Meta-programming is being used to implement high-level optimizations, generate code from high-level specifications, and create DSLs. Each of these can take advantage of PGO to optimize before information is lost or constraints are imposed. Until now, such optimizations have been implemented via toolchains designed for a specific meta-program or optimization. We have described a general mechanism for implementing arbitrary profile-guided meta-program optimizations, and demonstrated its use by implementing several optimizations previously implemented in separate, specialized toolchains.

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TODO: Rewrite Hermit references for more examples of meta-programming?

TODO: Add two related works sitting on my desk for profile-guided meta-programming.

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