

Enabling Optimizations through Demodularization

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ABSTRACT

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Programmers want to write modular programs to increase maintainability and create abstractions, but modularity hampers optimizations, especially when modules are compiled separately or written in different languages. In languages with syntactic extension capabilities, each module in a program can be written in a separate language, and the module system must ensure that the modules interoperate correctly. In Racket, the module system ensures this by separating module code into phases for runtime and compile-time and allowing phased imports and exports inside modules. We present an algorithm, called demodularization, that combines all executable code from a phased modular program into a single module that can then be optimized as a whole program. The demodularized programs have the same behavior as their modular counterparts but are easier to optimize. We show that programs maintain their meaning through an operational semantics of the demodularization process and verify that performance increases by comparing modular Racket programs to the equivalent demodularized and optimized programs. We use the existing Racket optimizer to optimize the demodularized programs by decompiling them into an intermediate form that the optimizer uses. We also demonstrate a dead code elimination optimization that dramatically reduces the file size of demodularized Racket programs.

Keywords: macros, Racket, modules, optimization

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Chapter 1

Introduction

Programmers should not have to sacrifice the software engineering goals of modular design and good abstractions for performance. Instead, their tools should make running a well-designed program as efficient as possible.

Many languages provide features for creating modular programs which enable separate compilation and module reuse. Some languages provide expressive macro systems, which enable programmers to extend the compiler in arbitrary ways. Combining module systems with expressive macro systems allow programmers to write modular programs with each module written in its own domain-specific language. A compiler for such a language must ensure that modular programs have the same meaning independent of the order in which the modules are compiled. A phased module system, like the one described by Flatt for Racket [7], is a way to allow both separately compiled modules and expressive macros in a language.

Modular programs are difficult to optimize because the compiler has little to no information about values that come from other modules when compiling a single module. Existing optimizations have even less information when modules can extend the compiler. Good abstractions are meant to obscure internal implementations so that it is easier for programmers to reason about their programs, but this obscurity also limits information available for optimizations. In contrast, non-modular programs are simpler to optimize because the compiler has information about every value in the program. For example, inlining a function in a non-modular program is trivial because every use of the function is known at compile-time.

Some languages avoid the problem of optimizing modular programs by not allowing modules, while others do optimizations at link time, and others use inlining. Not allowing modules defeats the benefits of modular design. Languages such as C and Scheme that do not have well developed module systems make it difficult to manage large programs written in them. Link time optimizations can be too low level to do useful optimizations. Linking is usually performed on already compiled modules, so any optimizations are performed on machine code and are missing source-level information. Inlining must be heuristic-based, and good heuristics are hard to develop. Some work has been done on these heuristics for the ML programming language [2].

Our solution for optimizing modular programs, called demodularization, is to transform a modular program into a non-modular program by combining all runtime code and data in the program into a single module. In a phased module system, finding all of the runtime values is not trivial. Phased module systems allow programmers to refer to the same module while writing compiler extensions and while writing normal programs. A demodularized program does not need to include modules that are only needed during compile-time, but whether or not the module is needed only at compile-time is not obvious from just examining the module in isolation.

A program with a single module is effectively a non-modular program. After demodularization, a program becomes a single module, so existing optimizers have more information. Also, demodularization enables new optimizations that need whole program information. Demodularizing programs in a language with an expressive macro system is feasible and useful.

We explain the Racket module system in Chapter 2. In Chapter 3, we explain demodularization at a high level with a detailed example. Next, we use the operational semantics model of the demodularization process to explain why demodularization is correct (Chapter 4), and we then describe an actual implementation for Racket (Chapter 5), followed by experimental results of demodularizing and optimizing real-world Racket programs (Chap-

ter 6). The operational semantics model removes the unnecessary details of the full implementation so the demodularization process is easier to understand and verify. The actual implementation presents interesting difficulties that the model does not. The experimental results show that demodularization improves performance, especially when a program is highly modular.

Chapter 2

The Racket Module System

2.1 The Racket Programming Language

The Racket Programming Language is a platform for creating powerful abstractions. These abstractions are created through the use of Racket’s macro and module systems. The macro system, a heritage from LISP [12] and Scheme [11], allows programmers to add new features to their programs in an integrated way. The module system allows programmers to separate their programs into logical parts and hide implementation details. Together, they allow programmers to create Languages as Libraries [14] that are suitable for specific tasks.

2.2 Macros

Macros are the main way programmers add new features to Racket. Essentially, macros are functions (known as transformers) whose domain and range are syntax objects. Syntax objects are data structures that contain the raw syntax of a program, along with lexical information and other properties associated with the syntax. If a programmer needs the power, they can write transformers using all of the features of Racket, as long as the function takes in and produces syntax objects. Racket provides pattern-matching for syntax objects that makes writing macros simpler when that is all that a programmer needs.

The **define-syntax** form is used to identify a macro definition that is a function from syntax to syntax. The helper function, **syntax-case** matches syntax patterns so that it is easy to use them in the output of the macro.

Listing 1 shows how to use one of these macros to write a **while** loop. The macro

```

(define-syntax (while stx)
  (syntax-case stx ()
    [(while test body ...)
     #'(begin
         (define (while-loop)
           (when test
             body ...
             (while-loop)))
         (while-loop))]))

```

Listing 1: a macro implementation of a `while` loop

turns a `while` loop into a recursive function and a call to that recursive function. Whatever syntax used by the programmer for the `test` and `body ...` forms will be substituted into the output of the macro. Listing 2 shows a use of the `while` macro and what it expands into after running the macro. Racket’s macros are hygienic [9], which means that identifiers created

```

(while (< x 10)
  (printf "x is ~a\n" x)
  (set! x (add1 x)))

=>

(begin
  (define (while-loop)
    (when (< x 10)
      (printf "x is ~a\n" x)
      (set! x (add1 x))
      (while-loop))))
(while-loop))

```

Listing 2: use and expansion of a `while` loop

from programs will not clash with identifiers created from macros. In this example that means that the Racket program using a `while` loop will not be able to call the `while-loop` function that the macro creates, and that if the program has another definition for `while-loop`, it will be independent from the definition introduced by the macro. Also, each use of the macro will have distinct definitions for `while-loop` so that the macro can be nested and used multiple times.

2.3 Modules

Racket modules are a way of grouping definitions, expressions, and macros into groups. Modules also allow control over imports and exports, using the Racket forms **require** and **provide** respectively. Listing 3 shows a simple Racket module and some of the features of the Racket module system. The `counter` module contains a variable definition and functions

```
#lang racket/base
(provide get-counter-val count-up)

(define x 0)
(define (get-counter-val) x)
(define (count-up . v) (set! x (add1 x)))
```

Listing 3: `counter.rkt`: A simple Racket module implementing a counter

for getting and incrementing that variable. The module only exports the functions, so the module encapsulates the variable. If a programmer wanted to use this module, they would import it using **require** as shown in Listing 4.

```
#lang racket/base
(require "while-lang.rkt")
(require "counter.rkt")

(while (< (get-counter-val) 4)
  (printf "loop runtime val is ~a\n" (get-counter-val))
  (count-up))
```

Listing 4: `while-test.rkt`: A Racket module that uses other modules

It is also possible to use modules to help write macros. For example, if a programmer wanted to change the `while` macro so that it reported how many expressions were in each while loop, they could use the `counter` module inside the `while` definition as seen in Listing 5. It is possible to add code to the `while` macro because it is just a function from syntax to syntax that runs at compile-time. Also, the **require** form includes a **for-syntax** form to indicate that the `counter` module is needed at compile-time (along with the `racket/base`

```

#lang racket/base
(require (for-syntax racket/base
                    "counter.rkt"))

(provide while)

(define-syntax (while stx)
  (syntax-case stx ()
    [(while test body ...)
     (begin
       (for-each count-up
                  (syntax->list #'(body ...)))
       (printf "while loop contains ~a expressions\n"
               (get-counter-val))
       #'(begin
            (define (while-loop)
              (when test
                body ...
                (while-loop)))
            (while-loop)))))]))

```

Listing 5: `while-lang.rkt`: A Racket module implementing a language with `while` loops

module for `printf`). Now this module can be used to extend the language of other programs by adding a `while` loop, although it is just a library that is included like any other library.

2.4 Languages

The ability to use modules as languages allows programmers to write specialized domain-specific languages (DSLs) to better express solutions to domain problems. Using this ability, programmers have added languages for Typed Racket [13], Object-Oriented Racket [6], Logic Programming [10], and more. Also, because they are modules, it is possible to use them all in the same program and use the right language for each specific problem. The language creating facilities of Racket extend to more than just collections of functions and macros; they also allow changing the parser and changing the meaning of things like function application syntax.

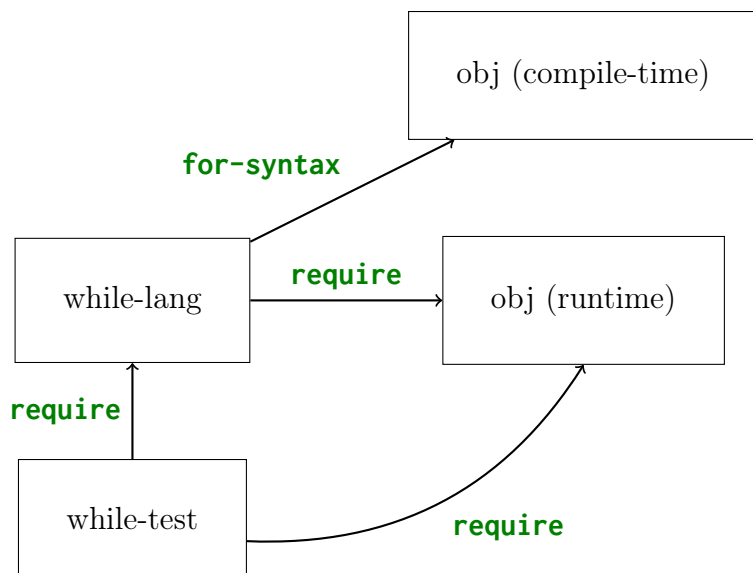


Figure 2.1: Module dependencies for the `while-test` program

2.5 Separate Compilation

In the presence of macros that can run arbitrary code, compilation of a single module becomes complicated. Compilation and execution of code has to be interleaved in order to produce the correct compiled program. All of the listings in the previous section form a program with the `while-test` module as the main module. Figure 2.1 shows the relationship between the different modules in the program. To compile the program, both the `while-lang` and `counter` need to be compiled before `while-test`, but also the `counter` module needs to be compiled and ready to use while compiling `while-test` because the counter functions are used inside the `while` macro. While compiling `while-test`, the `while` macro will be expanded and code from the `counter` module will run. The value of the counter is not shared between compiling `while-test` and running it.

2.6 Phases

The way the Racket module system allows for reliable separate compilation is by separating compilation and execution into phases. Phase 0 is the execution phase of the main module of a program, what could be considered running the program. Phase 1 is the compilation

phase of the main module, which could include execution of code inside macros. Phase 2 is the compilation phase of any modules that need to execute during phase 1, and higher phases are used as needed to compile and run code used in lower phases. It is possible for a single module to be used in multiple phases. Each phase will have a separate instantiation of the module. It is possible for modules to reference modules at higher phases by using the **for-syntax** form as seen above, and it is also possible to reference modules at lower phases by using the **for-template** form. The **for-template** form is used when a programmer wants to include code from an imported module in the output of a macro.

In the example above, the **while-test** module is compiled at phase 1, which triggers compilation of the **counter** module at phase 2, so that the **counter** module can be instantiated at phase 1 to count how many expressions are in the **while** loop. The phase 1 instantiation of the **counter** module is separate from the phase 0 instantiation of the module. The separate compilation guarantee of the Racket module system is that “Any effects of the instantiation of the module’s phase 1 due to compilation on the Racket runtime system are discarded” [1].

2.7 Program Evaluation

Running a separately compiled Racket program involves following all of the **require** forms and running all phase 0 code in the order in which the code is imported. It is possible that phase 0 code will come through a module that is required by using **for-syntax** if somewhere along the line code is then required using **for-template**.

By understanding how Racket programs are compiled and evaluated, it is apparent that only phase 0 code is necessary to run the program. This is the basis for how demodularization can recover whole programs from separately compiled Racket modules.

Chapter 3

Intuition

Demodularization is the process of collecting all phase 0 code required by a program into a single module. This is done by tracing through the **require** graph starting at a program's main module. The following example program illustrates the need for demodularization and how it is done.

3.1 Example Program

A programmer wants to use a queue library where the library uses different backing structures depending on the length of the queue. Listing 6 shows an example of using such a library. The library is implemented as a macro, shown in Listing 7, that switches between two

```
#lang racket/base
(require "queue.rkt")

(with-queue (1 2 3 4 5 6)
  (enqueue 4)
  (displayln (dequeue))
  (displayln (dequeue)))
```

Listing 6: `main.rkt` module with queue usage

implementations depending on the length of the initial queue. Listing 8 and Listing 9 show the two queue implementations, with the `long-queue` using vectors and the `short-queue` using lists. The `...` notation has meaning in Racket, so `....` is used to indicate elided code.

```

#lang racket/base
(require (for-syntax racket/base
                    racket/syntax)
         "short-queue.rkt"
         "long-queue.rkt")

(define-syntax (with-queue stx)
  (syntax-case stx ()
    [(with-queue (v ...) e ...)
     (begin
      (define type
        (if (> (length (syntax->list #'(v ...))) 5)
            'long
            'short))
      (define make-queue
        (format-id #'stx "make-~a-queue" type))
      (define enqueue (format-id #'stx "~a-enqueue" type))
      (define dequeue (format-id #'stx "~a-dequeue" type))
      #`(let ([q (#,make-queue v ...)])
          (define (#,(datum->syntax stx 'dequeue))
            (#,dequeue q))
          (define (#,(datum->syntax stx 'enqueue) x)
            (#,enqueue q x))
          e ...)))]))

(provide with-queue)

```

Listing 7: queue.rkt module

3.2 Compilation

Compiling this program involves expanding the `with-queue` macro, which will turn the program into Listing 10.

The expanded program contains references to `long-queue` operations because the length of the initial queue is over 5. Although the expanded program is not fully compiled to bytecode, it can stand in for a fully compiled program with regard to optimization and demodularization.

With the expanded program, it is possible to see how cross-module optimizations would be difficult. The program has calls to functions in the `long-queue` module, so the op-

```

#lang racket/base
(define (make-long-queue . vs)
  .... make-vector ....)

(define (long-enqueue q v)
  .... vector-set! ....)

(define (long-dequeue q)
  .... vector-ref ....)

(provide (all-defined-out))

```

Listing 8: long-queue.rkt module

```

#lang racket/base
(define (make-short-queue . vs)
  .... list ....)

(define (short-enqueue q v)
  .... cons ....)

(define (short-dequeue q)
  .... list-ref ....)

(provide (all-defined-out))

```

Listing 9: short-queue.rkt module

timizer does not have access to the definitions of the functions while finishing the compilation of the main module.

3.3 Demodularization

Demodularization of the program proceeds by following the **require** graph and including all phase 0 code from the required modules into the main module of the program. The main module requires the **queue** module, but the **queue** module only has phase 1 code, so it is not included in the final module. The **queue** module requires the **long-queue** and **short-queue** modules, which have various phase 0 definitions that get included in the order they appear in their original modules. Listing 11 shows what the demodularized example program would

```

(module main racket/base
  (%module-begin
    (require "queue.rkt")
    (let ((q (make-long-queue 1 2 3 4 5 6)))
      (define (dequeue) (long-dequeue q))
      (define (enqueue x) (long-enqueue q x))
      (enqueue 4)
      (displayln (dequeue))
      (displayln (dequeue))))))

```

Listing 10: main.rkt module after macro expansion

look like.

The demodularized program should have the exact same behavior at runtime as the modular program. At this point, the only thing that changes is that the Racket runtime does not need to follow the **require** graph because all phase 0 definitions and expressions are in a single module. Also, both queue implementations appear in the demodularized program even though only one of them is used.

3.4 Optimization

After a program has been demodularized, the optimizer now has all the information it needs to do optimizations on the whole program. Listing 12 shows what the example program would look like after optimization.

The existing optimizer is able to inline the various functions because it has access to all of the definitions within the module. The optimizer also removes the extra queue implementation because it is dead code. Therefore, demodularization enables optimization by providing the optimizer access to the whole program in one place.


```

(module main racket/base
  (%module-begin
    (define (make-short-queue . vs)
      .... list ....)

    (define (short-enqueue q v)
      .... cons ....)

    (define (short-dequeue q)
      .... list-ref ....)

    (define (make-long-queue . vs)
      .... make-vector ....)

    (define (long-enqueue q v)
      .... vector-set! ....)

    (define (long-dequeue q)
      .... vector-ref ....)

    (let ((q (make-long-queue 1 2 3 4 5 6)))
      (define (dequeue) (long-dequeue q))
      (define (enqueue x) (long-enqueue q x))
      (enqueue 4)
      (displayln (dequeue))
      (displayln (dequeue))))))

```

Listing 11: main.rkt module after demodularization

```

(module main racket/base
  (%module-begin
    (let ((q (.... make-vector .... 1 2 3 4 5 6 ....)))
      (.... vector-set! .... 4 ....)
      (displayln (.... vector-ref ....))
      (displayln (.... vector-ref ....)))))

```

Listing 12: main.rkt module after optimization

Chapter 4

Model

We can understand the specifics of demodularization by describing it as an algorithm for a simple language with a well defined semantics. The simple language models the existing Racket module system. We describe a small-step operational semantics (a series of syntactic rules) that define how the language works. We also define a compiled version of the language that mirrors the compiled version of Racket. Next, we describe how the demodularization algorithm works as a metafunction over the language. Finally, we show that programs before and after demodularization produce the same results.

4.1 A Module Language

The *mod* language (Figure 4.1) contains only the features necessary to write modular programs where it is possible to observe the effects of module evaluation order.

A program in *mod* consists of a list of modules that can refer to each other. Each module has a name, any number of imports, any number of definitions, and a body of code. All definitions in a module are exposed as exports to other modules, but to use definitions from another module, the program must import it through a **require** expression. Both **require** and **define** expressions have phase annotations; this simulates the interactions between modules in a language with macros without requiring a model of macro expansion. The language includes variable references, numbers, addition, and mutation. Mutation makes module evaluation order observable, and addition represents the work that a module does. In addition to numbers and variables, there are two special forms of values and references

```

program ::= (mod ...)
mod ::= (module id (req ...) (def ...) expr)
req ::= (require id @ phase)
expr ::= var
      | val
      | (+ expr expr)
      | (set! var expr)
      | (begin expr expr)
val ::= number
      | (quote id @ phase)
var ::= id
      | (ref id @ phase)
id ::= variable-not-otherwise-mentioned
phase ::= number
def ::= (define id @ phase as expr)

```

Figure 4.1: *mod* language grammar

that model the interaction of macros with the module system. A **quote** expression is like a reference to syntax at runtime. A **ref** expression is like a macro that can only do one thing: refer to a variable at a phase.

4.2 Compilation

We have to compile *mod* programs before demodularizing them, just like in the Racket implementation. In Racket, compiling expands all macros in a program and changes definitions and variable references to refer to memory locations. In *mod*, compiling eliminates **ref** expressions, turns definitions into **set!** expressions, changes variable references to include module information, and sorts code into phases. Compilation in both cases still leaves behind a relatively high-level language, but the language is free of syntactic extensions. This is important for demodularization because otherwise macro expansion would have to be part of the algorithm, which would complicate it and possibly duplicate work. The grammar in Figure 4.2 specifies the compiled language for *mod*.

The grammar no longer has definitions, all variables now include module references, and code is sorted into phases. The actual compilation function is not relevant to demodularization.

```

program ::= (mod ...)
mod ::= (module id (req ...) (code ...))
code ::= (phase expr)
req ::= (require id @ phase)
expr ::= var
        | val
        | (+ expr expr)
        | (set! var expr)
        | (begin expr expr)
val ::= number
        | (quote id @ phase)
var ::= (id id)
id ::= variable-not-otherwise-mentioned
phase ::= number

```

Figure 4.2: Compiled language grammar

4.3 Evaluation

We evaluate the compiled language using a small-step reduction semantics. Because the reduction rules are syntactic, we extend the compiled language further with evaluation contexts, a heap representation, and a stack representation to keep track of the order to instantiate modules. These extensions are in Figure 4.3. An expression of the form:

$$(\sigma / (program / ((id\ phase) \dots) / ((id\ phase) \dots)))$$

represents the state of the machine during evaluation. σ represents the heap of the program, and when evaluation finishes represents the output of the program. The list of modules is the code of program in the compiled language. The first list of $(id\ phase)$ pairs is the list of modules to evaluate, and the second list is the modules that have already been evaluated.

```

E ::= []
      | (+ E expr)
      | (+ val E)
      | (set! var E)
      | (begin E expr)
σ ::= ([var val] ...)
state ::= (program / (inst ...) / (inst ...))
inst ::= (id phase)
st ::= (σ / state)

```

Figure 4.3: Extensions to compiled language grammar

The reduction rules in Equations 4.1–4.7 evaluate a compiled program that starts with an empty heap, the program code, a stack that contains the identifier of the main module at phase 0, and an empty completed module list. Evaluation proceeds by adding required modules to the evaluation stack and executing code of modules in the order they appear on the evaluation stack when there are no more requires left.

$$\begin{aligned}
&(\sigma / ((mod_0 \dots (\text{module } id_0 ((\text{require } id_{new} @ phase_{new}) req \dots) (code \dots)) mod_n \dots) / ((id_0 phase_0) inst_n \dots) / (inst_d \dots))) \longrightarrow \\
&(\sigma / ((mod_0 \dots (\text{module } id_0 (req \dots) (code \dots)) mod_n \dots) / ((id_{new} (\ominus phase_0 phase_{new})) (id_0 phase_0) inst_n \dots) / (inst_d \dots))) \quad (4.1)
\end{aligned}$$

The rule in Equation 4.1 matches a program with a **require** expression in the module at the top of the evaluation stack and evaluates it by removing the **require** expression from the module and pushing the required module onto the evaluation stack with the phase shifted by the difference between the current module’s relative phase and the required phase. The \ominus is not part of the language and represents the prefix version of the math function minus. The current module is still on the stack and will continue evaluating after the required module is done evaluating. The subsequent rules all apply only when the phase relative to the main module is zero.

$$\begin{aligned}
&(\sigma / ((mod_0 \dots (\text{module } id_0 () (code_0 \dots (phase_0 E) code_n \dots)) mod_n \dots) / ((id_0 phase_0) inst_n \dots) / (inst_d \dots))[var]) \longrightarrow \\
&(\sigma / ((mod_0 \dots (\text{module } id_0 () (code_0 \dots (phase_0 E) code_n \dots)) mod_n \dots) / ((id_0 phase_0) inst_n \dots) / (inst_d \dots))[val]) \\
&\quad \text{where } val = \text{lookup } \llbracket \sigma, var \rrbracket \quad (4.2)
\end{aligned}$$

The rule in Equation 4.2 looks up a variable in the heap and replaces the variable with its current value. The lookup function is a simple list lookup function that matches the variable name with its occurrence in the heap.

$$\begin{aligned}
&(\sigma / ((mod_0 \dots (\text{module } id_0 () (code_0 \dots (phase_0 E) code_n \dots)) mod_n \dots) / ((id_0 phase_0) inst_n \dots) / (inst_d \dots))[(+ number_0 number_i)]) \longrightarrow \\
&(\sigma / ((mod_0 \dots (\text{module } id_0 () (code_0 \dots (phase_0 E) code_n \dots)) mod_n \dots) / ((id_0 phase_0) inst_n \dots) / (inst_d \dots))[(\oplus number_0 number_i)]) \quad (4.3)
\end{aligned}$$

The rule in Equation 4.3 replaces an addition expression of numbers with the result of computing their sum. The \oplus represents the prefix version of the math function plus.

$$\begin{aligned}
& (\sigma_0 / ((mod_0 \dots (\text{module } id_0 () (code_0 \dots (phase_0 E) code_n \dots)) mod_n \dots) / ((id_0 phase_0) inst_n \dots) / (inst_d \dots)) [(\text{set! } var \ val)]) \longrightarrow \\
& (\sigma_1 / ((mod_0 \dots (\text{module } id_0 () (code_0 \dots (phase_0 E) code_n \dots)) mod_n \dots) / ((id_0 phase_0) inst_n \dots) / (inst_d \dots)) [val]) \\
& \quad \text{where } \sigma_1 = \text{assign } [\sigma_0, var, val] \quad (4.4)
\end{aligned}$$

The rule in Equation 4.4 installs a value for a variable into the heap and reduces to the value. The assign function either replaces the existing value for a variable in the heap or installs a new entry in the heap if it does not exist already.

$$\begin{aligned}
& (\sigma / ((mod_0 \dots (\text{module } id_0 () (code_0 \dots (phase_0 E) code_n \dots)) mod_n \dots) / ((id_0 phase_0) inst_n \dots) / (inst_d \dots)) [(\text{begin } val \ expr)]) \longrightarrow \\
& (\sigma / ((mod_0 \dots (\text{module } id_0 () (code_0 \dots (phase_0 E) code_n \dots)) mod_n \dots) / ((id_0 phase_0) inst_n \dots) / (inst_d \dots)) [expr]) \quad (4.5)
\end{aligned}$$

When an expression is a **begin** with a value in the first position, the rule in Equation 4.5 removes the value and replaces the **begin** expression with the expression in the second position.

$$\begin{aligned}
& (\sigma / ((mod_0 \dots (\text{module } id_0 () (code_0 \dots (phase_0 val) code_n \dots)) mod_n \dots) / ((id_0 phase_0) inst_n \dots) / (inst_d \dots))) \longrightarrow \\
& (\sigma / ((mod_0 \dots mod_n \dots) / (inst_n \dots) / ((id_0 phase_0) inst_d \dots))) \quad (4.6)
\end{aligned}$$

When there are no more expressions left in a module, the rule in Equation 4.6 applies by removing the module from the program and placing a reference to it in the list of finished modules.

$$\begin{aligned}
& (\sigma / ((mod \dots) / (inst_0 inst_n \dots) / (inst_{d0} \dots inst_0 inst_{dn} \dots))) \longrightarrow \\
& (\sigma / ((mod \dots) / (inst_n \dots) / (inst_{d0} \dots inst_0 inst_{dn} \dots))) \quad (4.7)
\end{aligned}$$

The rule in Equation 4.7 applies when the current module on the stack is in the finished list, so that modules are not evaluated multiple times.

The combination of all of these rules forms a definition for how modular programs in the compiled *mod* language are evaluated.

4.4 Demodularization

Figures 4.4–4.7 show the demodularization algorithm for the compiled language. The algorithm takes as input an *id* specifying the main module of the program, a working list of phased requires, and a list of modules that make up the program.

$\text{demod} \llbracket id, (), (mod_0 \dots (module \ id \ () \ (code_0 \dots (0 \ expr) \ code_n \dots)) \ mod_n \dots) \rrbracket = ((module \ id \ () \ ((0 \ expr))))$

Figure 4.4: Demodularization algorithm

The rule in Figure 4.4 applies when the main module has no requires left and there are no requires in the working list, meaning the algorithm can terminate with just the phase 0 code of the main module remaining.

$$\begin{aligned} \text{demod} \llbracket id, (), ((module \ id \ ((require \ id_r \ @ \ phase_r) \ req_m \dots) \ (code_{m0} \dots (0 \ expr_m) \ code_{mm} \dots)) \ (module \ id_r \ (req_r \dots) \ (code_{r0} \dots (phase_{nr} \ expr_r) \ code_{rm} \dots)) \ mod_n \dots) \rrbracket &= \text{demod} \llbracket id, ((id, (\neg phase_r))), \\ &\quad ((module \ id \ (req_m \dots) \ (code_{m0} \dots (0 \ (begin \ expr_r \ expr_m)) \ code_{mm} \dots)) \ (module \ id_r \ (req_r \dots) \ (code_{r0} \dots (phase_{nr} \ expr_r) \ code_{rm} \dots)) \ mod_n \dots) \rrbracket \\ \text{where } phase_{nr} &= (\neg phase_r) \\ \text{demod} \llbracket id, (), ((module \ id \ ((require \ id_r \ @ \ phase_r) \ req_m \dots) \ (code_m \dots)) \ (module \ id_r \ (req_r \dots) \ (code_r \dots)) \ mod_n \dots) \rrbracket &= \text{demod} \llbracket id, ((id, (\neg phase_r))), \\ &\quad ((module \ id \ (req_m \dots) \ (code_m \dots)) \ (module \ id_r \ (req_r \dots) \ (code_r \dots)) \ mod_n \dots) \rrbracket \end{aligned}$$

Figure 4.5: Demodularization algorithm

The rules in Figure 4.5 apply when the main module requires the next module in the module list. Both rules add the required module’s *id* to the working list of required modules so that the algorithm will follow the complete require graph. The first rule handles the case where the required module has code that will be at phase 0 for the main module and puts that code before the existing phase 0 code of the main module. The rules in Figure 4.6 apply when handling the working list of required modules. The first rule is similar to the first rule of Figure 4.5 because it extracts code that will be in phase 0 of the main module and inserts it into the main module. The second rule handles the case where there is no matching code for phase 0. The third rule removes an entry from the working list when the module has no more requires.

$\text{demod } \llbracket id, ((id_c \text{ phase}_c) (id_n \text{ phase}_n) \dots),$ $((\text{module } id (req_m \dots) (code_{m0} \dots (0 \text{ expr}_m) code_{mn} \dots))$ $(\text{module } id_c ((\text{require } id_c @ \text{phase}_c) req_c \dots) (code_c \dots))$ $(\text{module } id_r (req_r \dots) (code_{r0} \dots (\text{phase}_c \text{ expr}_r) code_{rn} \dots))$ $mod_n \dots \rrbracket$	$= \text{demod } \llbracket id, ((id_c (\neg \text{phase}_c \text{ phase}_c)) (id_c \text{ phase}_c) (id_n \text{ phase}_n) \dots),$ $((\text{module } id (req_m \dots) (code_{m0} \dots (0 (\text{begin } \text{expr}_r \text{ expr}_m)) code_{mn} \dots))$ $(\text{module } id_c (req_c \dots) (code_c \dots))$ $(\text{module } id_r (req_r \dots) (code_{r0} \dots (\text{phase}_c \text{ expr}_r) code_{rn} \dots))$ $mod_n \dots \rrbracket$
$\text{demod } \llbracket id, ((id_c \text{ phase}_c) (id_n \text{ phase}_n) \dots),$ $((\text{module } id (req_m \dots) (code_m \dots))$ $(\text{module } id_c ((\text{require } id_c @ \text{phase}_c) req_c \dots) (code_c \dots))$ $(\text{module } id_r (req_r \dots) (code_r \dots))$ $mod_n \dots \rrbracket$	$= \text{demod } \llbracket id, ((id_c (\neg \text{phase}_c \text{ phase}_c)) (id_c \text{ phase}_c) (id_n \text{ phase}_n) \dots),$ $((\text{module } id (req_m \dots) (code_m \dots))$ $(\text{module } id_c (req_c \dots) (code_c \dots))$ $(\text{module } id_r (req_r \dots) (code_r \dots))$ $mod_n \dots \rrbracket$
$\text{demod } \llbracket id, ((id_c \text{ phase}_c) (id_n \text{ phase}_n) \dots),$ $((\text{module } id (req_m \dots) (code_m \dots))$ $(\text{module } id_c () (code_c \dots))$ $mod_n \dots \rrbracket$	$= \text{demod } \llbracket id, ((id_n \text{ phase}_n) \dots),$ $((\text{module } id (req_m \dots) (code_m \dots))$ $(\text{module } id_c () (code_c \dots))$ $mod_n \dots \rrbracket$

Figure 4.6: Demodularization algorithm

$\text{demod } \llbracket id, (), (mod_0 \dots (\text{module } id (req \dots) (code \dots)) mod_n \dots) \rrbracket$	$= \text{demod } \llbracket id, (), ((\text{module } id (req \dots) (code \dots)) mod_0 \dots mod_n \dots) \rrbracket$
$\text{demod } \llbracket id, (), ((\text{module } id ((\text{require } id_r @ \text{phase}_r) req_m \dots) (code_m \dots))$ $mod_i \dots (\text{module } id_r (req_r \dots) (code_r \dots)) mod_n \dots) \rrbracket$	$= \text{demod } \llbracket id, (), ((\text{module } id ((\text{require } id_r @ \text{phase}_r) req_m \dots) (code_m \dots))$ $(\text{module } id_r (req_r \dots) (code_r \dots)) mod_i \dots mod_n \dots) \rrbracket$
$\text{demod } \llbracket id, ((id_c \text{ phase}_c) (id_n \text{ phase}_n) \dots),$ $((\text{module } id (req_m \dots) (code_m \dots))$ $mod_i \dots$ $(\text{module } id_c (req_c \dots) (code_c \dots))$ $mod_n \dots \rrbracket$	$= \text{demod } \llbracket id, ((id_c \text{ phase}_c) (id_n \text{ phase}_n) \dots),$ $((\text{module } id (req_m \dots) (code_m \dots))$ $(\text{module } id_c (req_c \dots) (code_c \dots))$ $mod_i \dots$ $mod_n \dots \rrbracket$
$\text{demod } \llbracket id, ((id_c \text{ phase}_c) (id_n \text{ phase}_n) \dots),$ $((\text{module } id (req_m \dots) (code_m \dots))$ $(\text{module } id_c ((\text{require } id_r @ \text{phase}_r) req_c \dots) (code_c \dots))$ $mod_i \dots$ $(\text{module } id_r (req_r \dots) (code_r \dots))$ $mod_n \dots \rrbracket$	$= \text{demod } \llbracket id, ((id_c \text{ phase}_c) (id_n \text{ phase}_n) \dots),$ $((\text{module } id (req_m \dots) (code_m \dots))$ $(\text{module } id_c ((\text{require } id_r @ \text{phase}_r) req_c \dots) (code_c \dots))$ $(\text{module } id_r (req_r \dots) (code_r \dots))$ $mod_i \dots$ $mod_n \dots \rrbracket$

Figure 4.7: Demodularization algorithm

The final four rules in Figure 4.7 rearrange the program's module list so that modules that require each other are adjacent in the list and the other rules can apply.

4.5 Equivalence

We claim that the programs will evaluate to the same answers before and after demodularization.

Theorem. *Evaluating a program P a number of steps n and the demodularized program P' a number of steps m will be bisimilar with respect to the stores of the programs as shown in Figure 4.8.*

Proof Sketch. The proof is by induction on the DAG of required modules in a program. For each shape of possible requires in a program, we would show the evaluation before and

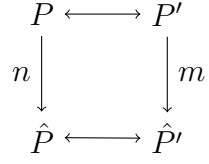


Figure 4.8: Bisimulation of a program before and after demodularization

after demodularization run the same module code in the same order and result in the same stores. □

The full proof of the theorem would not be instructive because of the complexities of the implementation of the model and the demodularization algorithm.

Chapter 5

Implementation

The implementation of demodularization for the Racket module system integrates with the existing compilation process. The goal of the implementation was to write the actual algorithm in Racket, but to use as much of the existing infrastructure as possible. We did not want to duplicate work done by the compiler, so the demodularization algorithm operates on Racket bytecode. We also did not want to duplicate work done by the optimizer, so we pass the demodularized program through the existing optimizer. All of the pieces of the demodularization process are contained within a command line tool.

5.1 Racket Compilation Process

Figure 5.1 shows the compilation process that a Racket module undergoes and the various intermediate forms the code takes. In principle it would be possible to write the demodularization algorithm for modules at any point in this process, but we chose to write it at the bytecode level because it is a well defined file type and phases are clearly delineated.

The compilation process for Racket is all written in C. The first step of compiling a Racket module is to expand all of the macros it uses into what is known as the Racket kernel language or fully expanded code. The next step is compilation to an Intermediate Representation (IR) made up of C data structures. The optimizer works on this IR to produce an optimized version of it. Then, the compiler finishes turning the IR into bytecode.

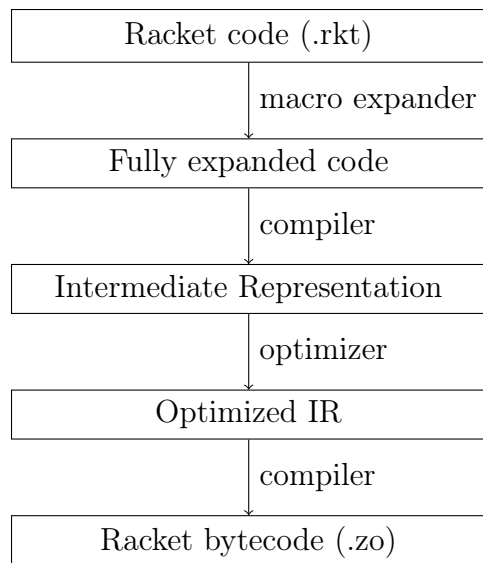


Figure 5.1: Racket compilation process

5.2 Racket bytecode

Racket bytecode is different from most other forms of bytecode in that it mostly maintains the structure of the abstract syntax tree from the original program. The main aspect that changes between fully-expanded Racket programs and Racket bytecode is the use of stack positions instead of variables and the addition of stack-manipulating instructions. A full explanation of Racket bytecode and what it means can be found in [8].

A table is created in the bytecode for the top level bindings in a module, which is known as the prefix. All top level bindings have an entry in the prefix, including bindings that come from other modules, and any use of a top level binding in a program is replaced with a numeric reference to the entry. Listing 13 shows a simple program written in the most basic language that Racket supports: the `kernel` language. When this code is compiled, it turns into the bytecode in Listing 14.

In the bytecode, all references to the variable `y` have been replaced with references to the prefix in the form of `(toplevel 0)`. All references to `displayln` have also been replaced with `(toplevel 1)` references, which in turn references element 7 of the prefix of the `racket/private/misc` module. The references to `x` are now all different because the

```

(module hello '%kernel
  (%require racket/private/misc)
  (define-values (y) (random))
  (let-values ([ (x) #f ])
    (set! x 5)
    (displayln x)
    (displayln (+ x y))))

```

Listing 13: Example program written in kernel language

```

(module hello
  (prefix (y (module-variable racket/private/misc displayln 7)))
  (requires '%kernel racket/private/misc)
  (def-values (toplevel 0)
    (app (primval 273)))
  (let-one
    (box-env
      (install-value 0 5
        (seq
          (app (toplevel 1) (local 1))
          (app (toplevel 1)
            (app (primval 247) (local 3) (toplevel 0))))))))

```

Listing 14: Bytecode representation of program from Listing 13

stack changes between each usage of `x`. The references to `random` and `+` are replaced with references to primitive implementations in the Racket runtime.

5.3 Demodularization

The implementation of demodularization for the Racket module system is written in Racket and consumes and produces Racket bytecode. Figure 5.3 shows the demodularization process and how it interacts with existing racket components. The library for reading and writing Racket bytecode in Racket was mainly used for debugging purposes and was incomplete, so the first task was to fully implement the Racket bytecode library.

The actual algorithm for demodularization is similar to the model in the previous chapter in that it traces `requires` and includes all phase 0 code in the final module, but it

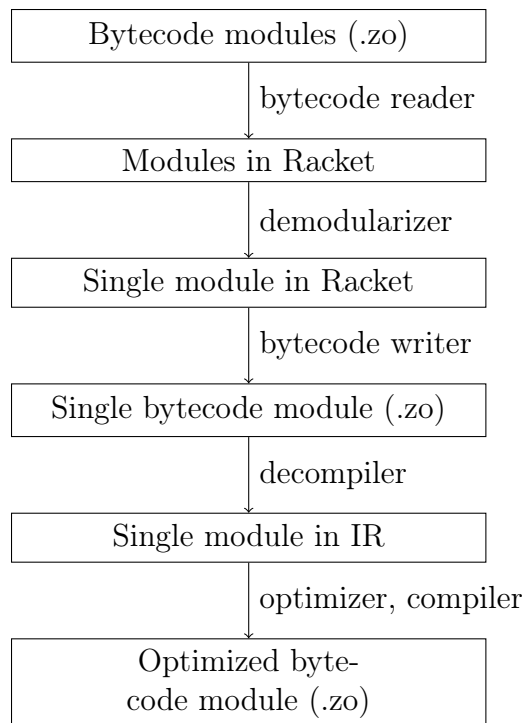


Figure 5.2: Demodularization process

also has to deal with the module prefix and references to the prefix. When the algorithm includes a required module, it also includes that module’s prefix appended to the end of the main module’s prefix. Then, it must adjust all references in that module’s code to point at the new combined prefix. Also, the algorithm tracks cross-module references and rewrites them to point to the new prefix as well. In the example in Listing 14, when the algorithm includes the module `racket/private/misc` it must rewrite the reference to `(toplevel 1)` to whatever the new position for `displayln` is in the combined prefix.

5.4 Optimization

For demodularization to be useful, the program needs to be optimized after demodularizing it. To optimize the demodularized bytecode, we wanted the existing Racket optimizer built into the Racket compiler so that we get all existing optimizations “for free” and any new optimizations in the future will work on both regularly compiled and demodularized programs. The existing optimizer works on an intermediate form between fully-expanded

Racket code and Racket bytecode. This intermediate form only exists as C data structures in the implementation of Racket. Therefore, to use the existing optimizer, Racket bytecode needed to be decompiled into this intermediate form.

5.5 Decompilation

The decompiler was written in C, so that it could interoperate with the optimizer. There are three main differences between Racket bytecode and the intermediate form: stack positions, cyclic closures, and reference arguments. In Racket bytecode and in the intermediate form, all references to bindings are numeric, but in bytecode the references are stack positions and in the intermediate form the references are lexical. For example, the bytecode in Listing 14 has three references to `x`, in the form of `(install-value 0 5)`, `(local 1)`, and `(local 3)`. In the intermediate form, all of these references to `x` should be `0` because lexically they all refer to the same variable that is the closest binding.

Racket bytecode allows for cyclic closures, or closures which contain a reference to themselves. Nothing like this exists in the intermediate form, so to decompile cyclic closures, the decompiler creates a new top level definition for the closure and replaces references to the closure (including the self-references) with references to the top level definition.

Finally, Racket bytecode allows reference arguments (like C++ reference arguments) in functions, but the intermediate form doesn't allow them. The decompiler turns reference arguments into `case-lambda` closures over the reference arguments with one case for getting the argument value and one case for setting the argument value.

The decompilation algorithm is not the identity function when composed with compilation because of the transformations performed on cyclic closures and reference arguments. Sometimes the optimizer will remove the `case-lambda` arguments and turn them back into reference arguments, but this is not guaranteed. Racket has robust bytecode verification built in to the module loading system, so errors that were introduced by the decompiler were mostly caught by bytecode verification.

5.6 Limitations

Racket provides features that treat modules as first-class objects during runtime. For example, programs can load and evaluate modules at runtime through `dynamic-require`. Because the demodularizer cannot know ahead of time what modules might be loaded at runtime, it disallows programs that use `dynamic-require`. If the modules loaded through `dynamic-require` were completely separate (meaning they do not share any required modules) from the main program, it would be possible to demodularize the program, but in practice most modules required at runtime will share with the main program.

The restriction of not allowing `dynamic-require` means that programs that need to load modules on the fly, such as REPLs, sandboxed evaluation environments, and scripting environments cannot be demodularized. This is okay because it is unclear what whole program compilation means for such programs.

5.7 Usage

The implementation of demodularization is included in the Racket distribution as part of the build tool `raco`. Users can pass in a module they would like to demodularize and optimize to the tool and it will compile all the necessary modules, run the demodularization algorithm on them, decompile the resulting module, and run optimizations on it to produce the final module. For example, to demodularize a program whose main module was `while-test.rkt`, a user would type the following command:

```
raco demod -O while-test.rkt
```


Chapter 6

Evaluation

For demodularization to be useful, it should improve performance of modular programs. To test whether or not this is the case, we created benchmarks to test the speed of demodularized programs versus their modular counterparts. We also compare the results with the cross-module inliner included in Racket. We show improvements in the size of programs through the use of a dead-code elimination algorithm. Finally, we discuss further improvements that demodularization can enable.

6.1 Racket Optimizer

The Racket optimizer included a cross-module inliner in version 5.2. This inliner accomplishes many of the same improvements that the demodularizer does. The inliner does have limitations on the size of functions that it will inline, so with large functions demodularization is still preferable. We compare the results with the inliner turned off, with the inliner turned on, and with demodularization. The demodularized programs are also run through the existing Racket optimizer.

6.2 Testing Setup

The tests were run on a MacBook Pro (2GHz Intel i7 processor, 8GB Memory) in OS X Yosemite, using Racket v6.2. Each test was run 5 times and an average of the results was taken.

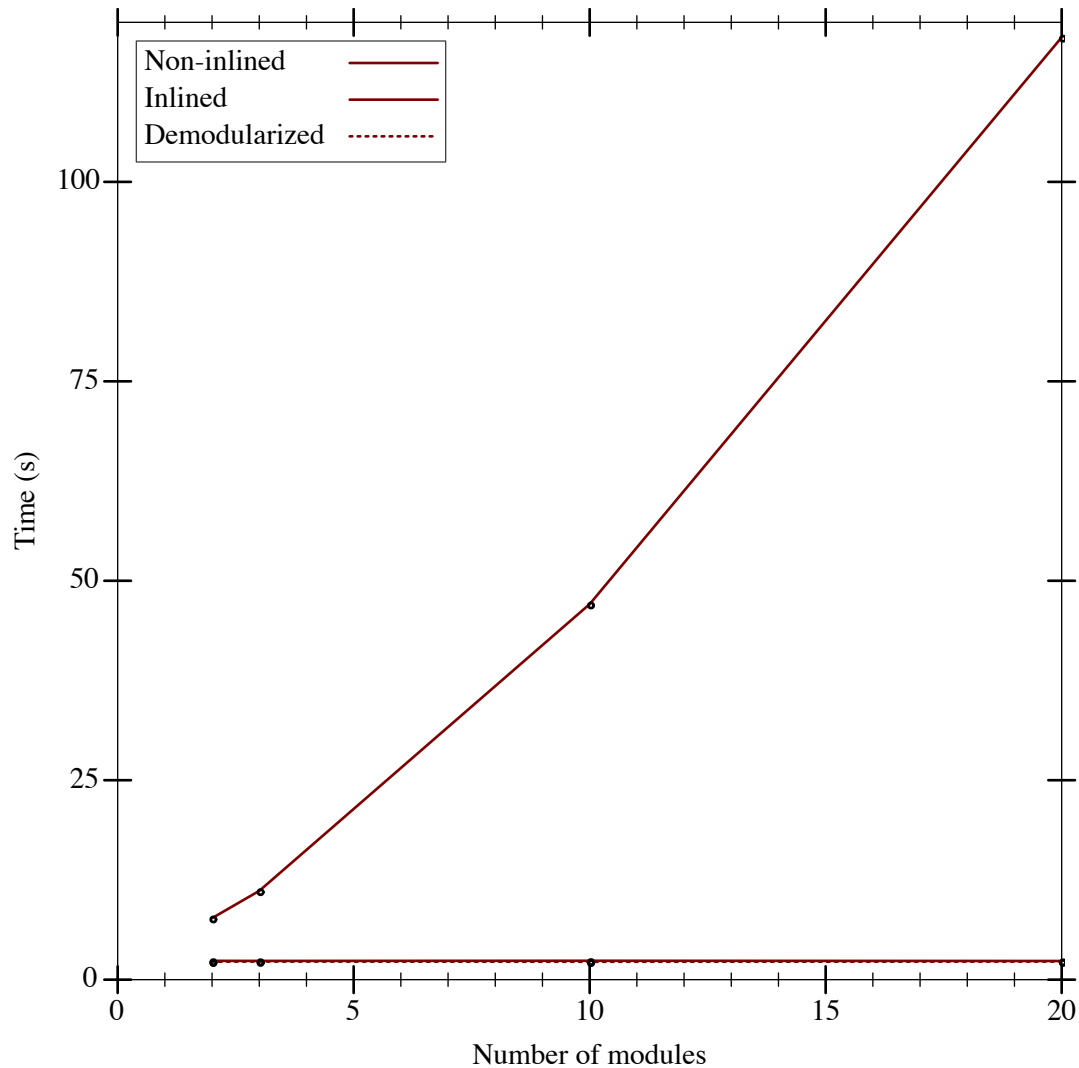


Figure 6.1: Results from micro-benchmarks

6.3 Micro-benchmarks

The micro-benchmarks for demodularization involve a module that calls a function from another module, which calls a function from another module, and so on for the number of modules in the test. The function call happens in a loop to get times that are significant. The full test generation code can be found in Appendix A. Figure 6.1 shows the results of running these benchmarks with different numbers of modules. Without inlining, the micro-benchmarks increase in a linear fashion with an increase in the number of modules. With inlining, the micro-benchmarks stay at a constant speed. It would be possible to trick the

Figure 6.2: Results from real world benchmarks

Figure 6.3: Dead code elimination results

inliner by creating large function bodies of unused code, but that is not the goal of the micro-benchmarks. With demodularization, the micro-benchmarks also stay at a constant speed, with a slightly better speed than inlining.

6.4 Real World Benchmarks

For real world benchmarks we selected programs that would terminate deterministically and that used multiple modules. One of the programs we tested was a program that uses the Racket xml library to read large xml files. The program can be found in Appendix A. For test data, we used astronomical data from NASA [?]. The second program we tested is a benchmark for the Redex tool. Redex is a library that allows users to build and test semantic models. The benchmark is also included in Appendix A. Figure 6.2 shows the results of running demodularization on larger programs.

6.5 Dead Code Elimination

As an experiment, we implemented an unsound dead code elimination algorithm for demodularized programs. It identifies all uses of toplevel definitions in the body of the demodularized program and eliminates all other toplevels. The reason it is unsound is because although some toplevels may not be referenced directly in the program, they may be needed for side-effects that they have. These side-effects may include setting up global objects or tables that will be referenced by the program, or I/O operations. In order to make the dead code elimination algorithm sound, we would need to identify primitives that can have side-effects and include any toplevels that use those primitives. Figure 6.3 shows how much smaller programs become after running the dead code elimination algorithm on them.

6.6 Further Optimizations

Having access to the whole-program at once enables optimizations that currently are not implemented by the Racket optimizer. For example, any optimizations that rely on Control-Flow Analysis (CFA) require access to the whole program. Demodularization enables these sorts of optimizations to be performed on modular programs.

Chapter 7

Related Work

Prior work on whole-program optimization has come in two flavors, depending on how much access to the source code the optimizer has. The first approach assumes full access to the source code and is based on inlining. The second approach only has access to compiled modules and is based on combining modules.

The first approach is based on selectively inlining code across module boundaries because it has full access to the source code of the program [2, 3]. Most of the focus of this approach is finding appropriate heuristics to inline certain functions without ballooning the size of the program and making sure the program still produces the same results. Resulting programs are not completely demodularized; they still have some calls to other modules. Specifically, Chambers et al. [3] show how this approach applies to object-oriented languages like C++ and Java, where they are able to exploit properties of the class systems to choose what to inline. Blume and Appel [2] showed how to deal with inlining in the presence of higher order functions, to make sure the semantics of the program didn't change due to inlining. Their approach led to performance increases of around 8%.

The second approach is taking already compiled modules, combining them into a single module, and optimizing the single module at link time [4, 5]. Most of the work done with this approach optimized at the assembly code level, but because they were able to view the whole program, the performance increases were still valuable. The link-time optimization system by Sutter et al. [4] achieves a 19% speedup on C programs. One of the reasons for starting with compiled modules is so that programs using multiple languages

can be optimized in a common language, like the work done by Debray et al. [5] to combine a program written in both Scheme and Fortran. The main problem with this approach is that the common language has less information for optimization than the source code had. These approaches are similar to demodularization, but they operate at a lower level and work on languages without phased module systems.

Chapter 8

Conclusion

Demodularization is a useful optimization for deploying modular programs. A programmer can write a modular program and get the benefits of separate compilation while developing the program, and then get additional speedups by running the demodularizer on the completed program. Demodularization also enables new optimizations that are not feasible to implement for modular programs. Without module boundaries, inter-procedural analysis is much easier and worthwhile. Also, dead code elimination works much better because the whole program is visible, while in a modular program, only dead code that is private to the module can be eliminated. We would like to see implementations of Control-Flow Analysis for Racket programs now that whole programs are accessible through demodularization.

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Appendix A

Benchmarks

A.1 Micro-benchmark generator

#lang racket

```
(define (compile-without-optimizations filename)
  (parameterize ([current-namespace (make-base-namespace)]
                 [compile-context-preservation-enabled #t])
    (with-output-to-file (format "compiled/~a" (path-add-suffix filename ".zo"))
      #:exists 'truncate
      (lambda ()
        (write (compile (read (open-input-file filename))))))))

(define (write-module n)
  (with-output-to-file (format "m~a.rkt" n)
    #:exists 'truncate
    (lambda ()
      (printf
        "(module m~a '##kernel
          (%require \"m~a.rkt\")
          (%provide f~a)
          (define-values (f~a) (lambda (x)
                                (f~a x))))
        "
        n (add1 n) n n (add1 n))))))

(define (write-first-module)
  (with-output-to-file "m0.rkt"
    #:exists 'truncate
```

```

    (lambda ()
      (printf
" (module m0 '##kernel
  (%require \"m1.rkt\")
  (letrec-values ([ (loop)
                    (values (lambda (x)
                              (if (= x 0)
                                  'done
                                  (begin
                                    (f1 x)
                                    (loop (sub1 x)))))))]])
    (loop 1000000000)))
" ))))

(define (write-last-module n)
  (with-output-to-file (format "m~a.rkt" n)
    #:exists 'truncate
    (lambda ()
      (printf
" (module m~a '##kernel
  (%provide f~a)
  (define-values (f~a) (lambda (x)
                        (add1 x))))
"
n n n ))))

(define num-modules
  (sub1 (string->number (vector-ref (current-command-line-arguments) 0))))
(write-first-module)
(for ([i (in-range 1 num-modules)])
  (write-module i))
(write-last-module num-modules)

(for ([i (in-range (add1 num-modules))])
  (compile-without-optimizations (format "m~a.rkt" i)))

```

A.2 XML benchmark

```
#lang racket/base
(require xml)
(time (void (read-xml)))
```