Global Value Numbering in Factor

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To Lindsay—he is my rock

Abstract

Compilers translate code in one programming language into semantically equivalent code in another language—canonically from a high-level language to low-level machine primitives. Generally, the further removed a language's abstractions get from those of a computer, the harder it gets to compile code into an efficient representation. What isn't redundant in the source language may map to repetitive target instructions that waste time recomputing results. To combat this, compilers try to optimize away redundancies by looking for values that are provably equivalent when the program is run.

This thesis explores the theory and implementation of a particularly aggressive analysis called global value numbering in a particularly high-level language called Factor. Factor is a stack-based, dynamically-typed, object-oriented language born in late 2003. A baby among languages (now at version 0.94), its compiler craves all the optimizations it can get. By altering the existing local value numbering pass, redundancies can be identified and eliminated across entire programs, rather than isolated regions of code. This induces speedups as high as 45% across the majority of benchmarks. The results from these comparatively simple changes hold much promise for future improvements in making Factor programs more efficient.

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1 Introduction

Compilers translate programs written in a source language (e.g., Java) into semantically equivalent programs in some target language (e.g., assembly code). They let us make our source language arbitrarily abstract so we can write programs in ways that humans understand while letting the computer execute programs in ways that machines understand. In a perfect world, such translation would be straightforward. Reality, however, is unforgiving. Straightforward compilation results in clunky target code that performs a lot of redundant computations. To produce efficient code, we must rely on less-than-straightforward methods. Typical compilers go through a stage of *optimization*, whereby a number of semantics-preserving transformations are applied to an *intermediate representation* of the source code. These then (hopefully) produce a more efficient version of said representation. Optimizers tend to work in *phases*, applying specific transformations during any given phase.

Global value numbering (GVN) is such a phase performed by many highly-optimizing compilers. Its roots run deep through both the theoretical and the practical. Using the results of this analysis, the compiler can identify expressions in the source code that produce the same value—not just by lexical comparison (i.e., comparing variable names), but by proving equivalences between what's actually computed at runtime. These expressions can then be simplified by further algorithms for redundancy elimination. This is the very essence of most compiler optimizations: avoid redundant computation, giving us code that runs as quickly as possible while still following what the programmer originally wrote.

High-level, dynamic languages tend to suffer from efficiency issues. They're often interpreted rather than compiled, and perform no heavy optimization of the source code. However, the Factor language (`http://factorcode.org`) fills an intriguing design niche, as it's very high-level yet still fully compiled. It's still young, though, so its compiler craves all the improvements it can get. In particular, while the current Factor version (as of this writing, 0.94) has a *local* value numbering analysis, it is inferior to GVN in several significant ways.

In this thesis, we explore the implementation and use of GVN in improving the strength

of optimizations in Factor. Because Factor is a young and relatively unknown language, Chapter 2 provides a short tutorial, laying a foundation for understanding the changes. **??** describes the overall architecture of the Factor compiler, highlighting where the exact contributions of this thesis fit in. Finally, **??** goes into detail about the existing and new value numbering passes, closing with a look at the results achieved and directions for future work.

In the unlikely event that you want to cite this thesis, you may use the following BibTeX entry:

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  month  = sep,
  year   = {2011},
}
```

2 Language Primer

Factor is a rather young language created by Slava Pestov in September 2003 [*Factor* 2010]. Its first incarnation was an embedded scripting language for a game that targeted the Java Virtual Machine (JVM). As such, its feature set was minimal. Factor has since evolved into a general-purpose programming language, gaining new features and redesigning old ones as necessary for larger programs. Today's implementation sports an extensive standard library and has moved away from the JVM in favor of native code generation. In this chapter, we cover the basic syntax and semantics of Factor for those unfamiliar with the language. This should be just enough to understand the later material in this thesis. More thorough documentation can be found via Factor's website, `http://factorcode.org`.

2.1 Stack-Based Languages

Like Reverse Polish Notation (RPN) calculators, Factor's evaluation model uses a global stack upon which operands are pushed before operators are called. This naturally facilitates postfix notation, in which operators are written after their operands. For example, instead of `1 + 2`, we write `1 2 +`. Figure 1 on the following page shows how `1 2 +` works conceptually:

- `1` is pushed onto the stack
- `2` is pushed onto the stack
- `+` is called, so two values are popped from the stack, added, and the result (`3`) is pushed back onto the stack

Other stack-based programming languages include Forth [American National Standards Institute and Computer and Business Equipment Manufacturers Association 1994], Cat [Diggins 2007], and PostScript [Adobe Systems Incorporated 1999].

The strength of this model is its simplicity. Evaluation essentially goes left to right: literals (like `1` and `2`) are pushed onto the stack, and operators (like `+`) perform some computation using values currently on the stack. This "flatness" makes parsing easier,

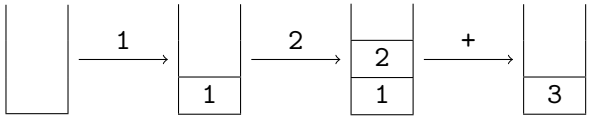

Figure 1: Visualizing stack-based calculation

since we don't need complex grammars with subtle ambiguities and precedence issues. Rather, we basically just scan left-to-right for tokens separated by whitespace. In the Forth tradition, functions are called *words* since they're made up of any contiguous non-whitespace characters. This also lends to the term *vocabulary* instead of "module" or "library". In Factor, the parser works as follows:

- If the current character is a double-quote (`"`), try to parse ahead for a string literal.
- Otherwise, scan ahead for a single token.
  - If the token is the name of a *parsing word*, that word is invoked with the parser's current state.
  - If the token is the name of an ordinary (i.e., non-parsing) word, that word is added to the parse tree.
  - Otherwise, try to parse the token as a numeric literal.

Parsing words serve as hooks into the parser, letting Factor users extend the syntax dynamically. For instance, instead of having special knowledge of comments built into the parser, the parsing word `!` scans forward for a newline and discards any characters read (adding nothing to the parse tree).

Similarly, there are parsing words for what might otherwise be hard-coded syntax for data structure literals. Many act as sided delimeters: the parsing word for the left-delimiter will parse ahead until it reaches the right-delimiter, using whatever was read in between to add objects to the data structure. For example, `{ 1 2 3 }` denotes an array of three numbers. Note the deliberate spaces in between the tokens, so that the delimeters are themselves distinct words. In `{␣1␣2␣3␣}` (with spaces as marked), the parsing word `{` parses objects until it reaches `}`, collecting the results into an array. The `{` word would not

```
V{ 1 2 3 }                          ! vector
B{ 1 2 3 }                          ! byte array
BV{ 1 2 3 }                         ! byte vector
HS{ 1 2 3 }                         ! hash set
H{ { key1 val1 } { key2 val2 } }    ! hash table
```

Figure 2: Data structure literals in Factor

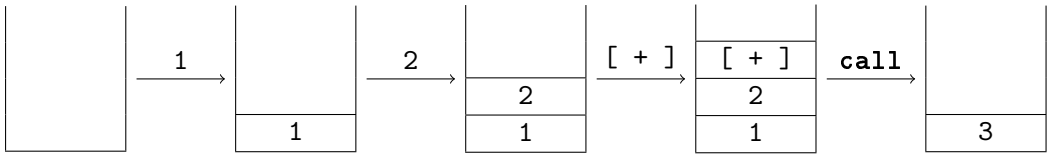

Figure 3: Quotations

be called if not for that space, whereas `{1␣2␣3}` parses as the word `{1`, the number `2`, and the word `3}`—not an array. Further, since the left-delimeter words parse recursively, such literals can be nested, contain comments, etc. Other literals include those in Figure 2.

A particularly important set of parsing words in Factor are the square brackets, `[` and `]`. Any code in between such brackets is collected up into a special sequence called a *quotation*. Essentially, it's a snippet of code whose execution is suppressed. The code inside a quotation can then be run with the **`call`** word. Quotations are like anonymous functions in other languages, but the stack model makes them conceptually simpler, since we don't have to worry about variable binding and the like. Consider a small example like

```
1 2 [ + ] call
```

You can think of **`call`** working by "erasing" the brackets around a quotation, so this example behaves just like `1 2 +`. Figure 3 shows its evaluation: instead of adding the numbers immediately, `+` is placed in a quotation, which is pushed to the stack. The quotation is then invoked by **`call`**, so `+` pops and adds the two numbers and pushes the result onto the stack. We'll show how quotations are used in **??** on page ??.

2.2 Stack Effects

Everything else about Factor follows from the stack-based structure outlined in Section 2.1. Consecutive words transform the stack in discrete steps, thereby shaping a result. In a way, words are functions from stacks to stacks—from "before" to "after"—and whitespace is effectively function composition. Even literals (numbers, strings, arrays, quotations, etc.) can be thought of as functions that take in a stack and return that stack with an extra element pushed onto it.

With this in mind, Factor requires that the number of elements on the stack (the *stack height*) is known at each point of the program in order to ensure consistency. To this end, every word is associated with a *stack effect* declaration using a notation implemented by parsing words. In general, a stack effect declaration has the form

```
( input1 input2 ... -- output1 output2 ... )
```

where the parsing word `(` scans forward for the special token `--` to separate the two sides of the declaration, and then for the `)` token to end the declaration. The names of the intermediate tokens don't technically matter—only how many of them there are. However, names should be meaningful for clarity's sake. The number of tokens on the left side of the declaration (before the `--`) indicates the minimum stack height expected before executing the word. Given exactly this number of inputs, the number of tokens on the right side is the stack height after executing the word.

For instance, the stack effect of the `+` word is `( x y -- z )`, as it pops two numbers off the stack and pushes one number (their sum) onto the stack. This could be written any number of ways, though. `( x x -- x )`, `( number1 number2 -- sum )`, and `( m n -- m+n )` are all equally valid. Further, while the stack effect `( junk x y -- junk z )` has the same relative height change, this declaration would be wrong, since it requires at least three inputs but `+` might legitimately be called on only two.

For the purposes of documentation, of course, the names in stack effects do matter. They correspond to elements of the stack from bottom-to-top. So, the rightmost value

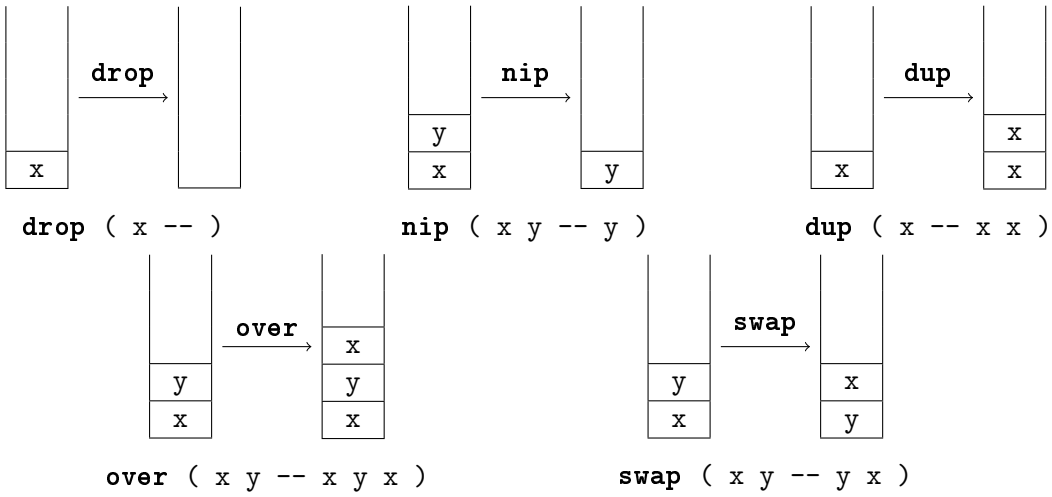

Figure 4: Stack shuffler words and their effects

on either side of the declaration names the top element of the stack. We can see this in Figure 4, which shows the effects of standard *stack shuffler* words. These words are used for basic data flow in Factor programs. For example, to discard the top element of the stack, we use the **drop** word, whose effect is simply `( x -- )`. To discard the element just below the top of the stack, we use **nip**, whose effect is `( x y -- y )`. This stack effect indicates that there are at least two elements on the stack before **nip** is called: the top element is `y`, and the next element is `x`. After calling the word, `x` is removed, leaving the original `y` still on top of the stack. Other shuffler words that remove data from the stack are **2drop** with the effect `( x y -- )`, **3drop** with the effect `( x y z -- )`, and **2nip** with the effect `( x y z -- z )`.

The next stack shufflers duplicate data. **dup** copies the top element of the stack, as indicated by its effect `( x -- x x )`. **over** has the effect `( x y -- x y x )`, which tells us that it expects at least two inputs: the top of the stack is `y`, and the next object is `x`. `x` is copied and pushed on top of the two original elements, sandwiching `y` between two `x`s. Other shuffler words that duplicate data on the stack are **2dup** with the effect `( x y -- x y x y )`, **3dup** with the effect `( x y z -- x y z x y z )`, **2over** with the effect `( x y z -- x y z x y )`, and **pick** with the effect `( x y z -- x y z x )`.

True to the name **swap**, the final shuffler in Figure 4 permutes the top two elements of the stack, reversing their order. The stack effect `( x y -- y x )` indicates as much.

The left side denotes that two inputs are on the stack (the top is `y`, the next is `x`), and the right side shows the outputs are swapped (the top element is `x` and the next is `y`). Factor has other words that permute elements deeper into the stack. However, their use is discouraged because it's harder for the programmer to mentally keep track of more than a couple items on the stack. We'll see how more complex data flow patterns are handled in **??** on page ??.

References

Adobe Systems Incorporated. 1999. *PostScript Language Reference*. Third edition. Addison-Wesley. ISBN: 0-201-37922-8. URL: `http://partners.adobe.com/public/developer/en/ps/PLRM.pdf` (visited on August 15, 2011).

American National Standards Institute and Computer and Business Equipment Manufacturers Association. 1994. *American National Standard for information systems: programming languages: Forth: ANSI/X3.215-1994*. American National Standards Institute.

Diggins, C. 2007. *The Cat Programming Language*. URL: `http://cat-language.com/` (visited on August 15, 2011).

Factor. 2010. From Factor's documentation wiki. URL: `http://concatenative.org/wiki/view/Factor` (visited on August 15, 2011).