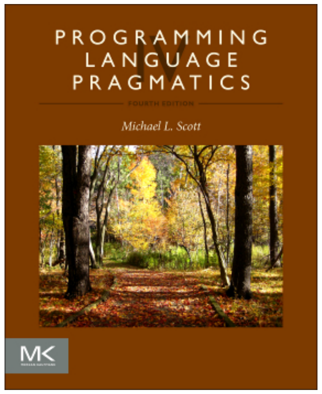
Code Optimization

17-363/17-663: Programming Language Pragmatics



Reading: PLP chapter 17

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Introduction

- We discussed target code generation
  - Typically produces correct but highly suboptimal code
    - redundant computations
    - inefficient use of the registers, multiple functional units, and cache
- This chapter takes a look at *code optimization*: the phases of compilation devoted to generating *good* code
  - we interpret "good" to mean *fast*
  - occasionally we also consider program transformations to decrease memory requirements
  - we say "optimization," but the code produced is rarely truly optimal; "improvement" is more apt, but "optimization" is ubiquitous

Introduction

- In a very simple compiler, we can use a *peephole optimizer* to peruse already-generated target code for obviously suboptimal sequences of adjacent instructions
- At a slightly higher level, we can generate near-optimal code for *basic blocks*
  - a basic block is a maximal-length sequence of instructions that will always execute in its entirety (assuming it executes at all)
  - in the absence of hardware exceptions, control never enters a basic block except at the beginning, and never exits except at the end

Introduction

- Code optimization at the level of basic blocks is known as *local* optimization
  - elimination of redundant operations (unnecessary loads, common sub-expression calculations)
  - effective instruction scheduling and register allocation
- At higher levels of aggressiveness, compilers employ techniques that analyze entire subroutines for further speed improvements
- These techniques are known as *global* optimization
  - multi-basic-block versions of redundancy elimination
  - instruction scheduling, and register allocation
  - code modifications designed to improve the performance of loops

Introduction

- Both global redundancy elimination and loop optimization typically employ a *control flow graph* representation of the program
  - Use a family of algorithms known as *data flow analysis* (flow of information between basic blocks)
- Recent compilers perform various forms of *interprocedural* code optimization
- Interprocedural optimization is difficult
  - subroutines may be called from many different places
    - hard to identify available registers, common subexpressions, etc.
  - subroutines are separately compiled

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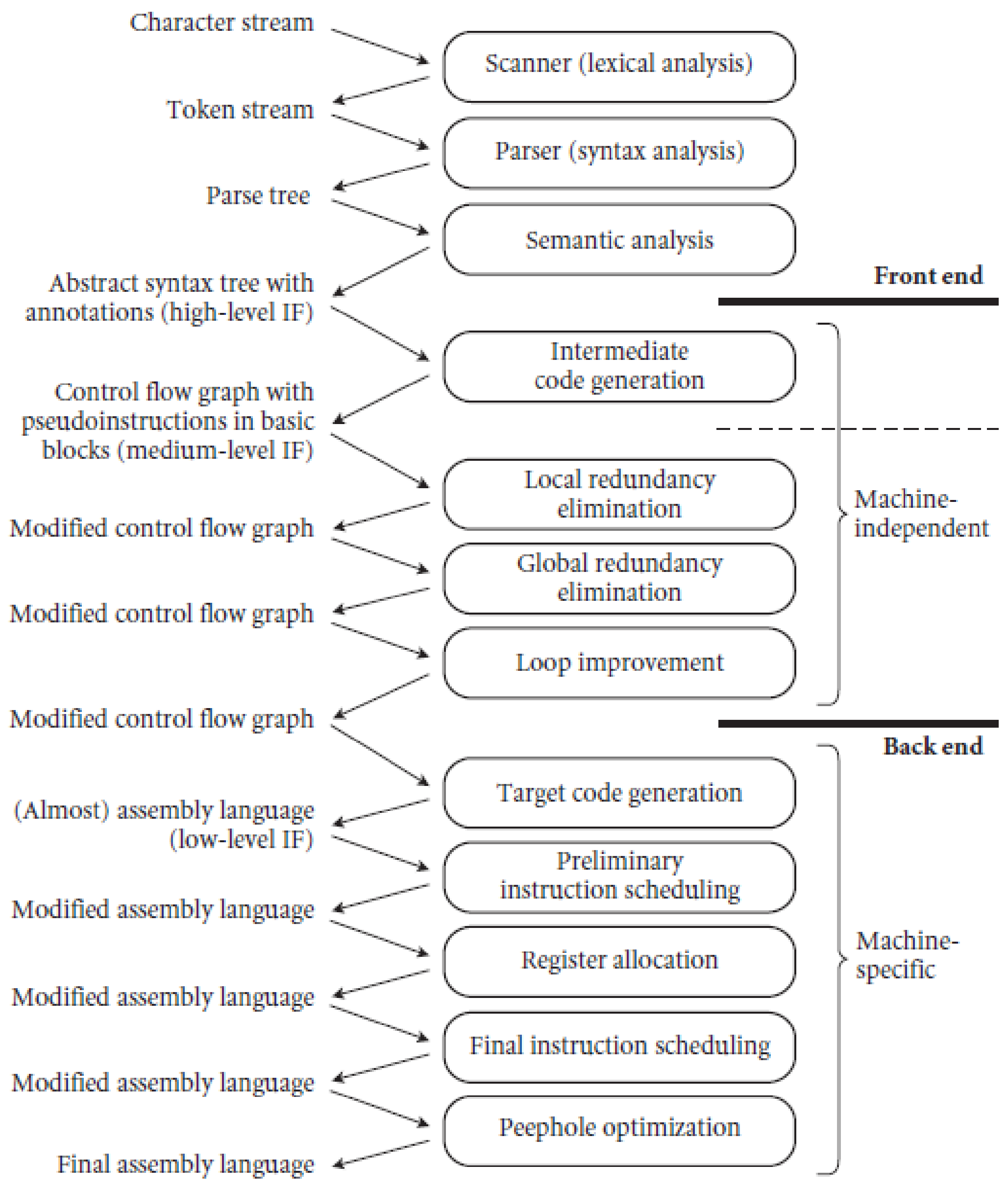
Phases of Code Optimization

- We will concentrate in our discussion on the forms of code optimization that tend to achieve the largest increases in execution speed, and are most widely used
  - Compiler phases to implement these optimizations is shown in Figure 17.1

Phases of Code Optimization



Character stream
Scanner (lexical analysis)
Token stream
Parser (syntax analysis)
Parse tree
Semantic analysis
Abstract syntax tree with annotations (high-level IF)
Front end
Intermediate code generation
Control flow graph with pseudoinstructions in basic blocks (medium-level IF)
Local redundancy elimination
Modified control flow graph
Global redundancy elimination
Modified control flow graph
Loop improvement
Modified control flow graph
Machine-independent
Back end
Target code generation
(Almost) assembly language (low-level IF)
Preliminary instruction scheduling
Modified assembly language
Register allocation
Modified assembly language
Final instruction scheduling
Modified assembly language
Peephole optimization
Final assembly language
Machine-specific

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Phases of Code Optimization

- The *machine-independent* part of the back end begins with intermediate code generation
  - identifies fragments of the syntax tree that correspond to basic blocks
  - creates a control flow graph in which each node contains a sequence of three-address instructions for an idealized machine (unlimited supply of *virtual registers*)
- The *machine-specific* part of the back end begins with target code generation
  - strings the basic blocks together into a linear program
    - translates each block into the instruction set of the target machine and generating branch instructions that correspond to the arcs of the control flow graph

Phases of Code Optimization

- Machine-independent code optimization has three separate phases
  1. Local redundancy elimination: identifies and eliminates redundant loads, stores, and computations within each basic block
  2. Global redundancy elimination: identifies similar redundancies across the boundaries between basic blocks (but within the bounds of a single subroutine)
  3. Loop optimization: effects several optimizations specific to loops
     - these are particularly important, since most programs spend most of their time in loops.
     - Global redundancy elimination and loop optimization may actually be subdivided into several separate phases

Phases of Code Optimization

- Machine-specific code optimization has four separate phases
  - Preliminary and final instruction scheduling are essentially identical (Phases 1 & 3)
  - Register allocation (Phase 2) and instruction scheduling tend to interfere with one another
    - the instruction schedules minimize pipeline stalls which tend to increase the demand for architectural registers (*register pressure*)
    - we schedule instructions first, then allocate architectural registers, then schedule instructions again
      - If it turns out that there aren't enough architectural registers, the register allocator will generate additional load and store instructions to *spill* registers temporarily to memory
      - the second round of instruction scheduling attempts to fill any delays induced by the extra loads

Peephole Optimization

- A relatively simple way to significantly improve the quality of naive code is to run a *peephole optimizer* over the target code
  - works by sliding a several instruction window (a peephole) over the target code, looking for suboptimal patterns of instructions
  - the patterns to look for are heuristic
    - patterns to match common suboptimal idioms produced by a particular front end
    - patterns to exploit special instructions available on a given machine
- A few examples are presented in what follows

Peephole Optimization

- ***Elimination of redundant loads and stores***
  - The peephole optimizer can often recognize that the value produced by a load instruction is already available in a register

```
r2 := r1 + 5
i := r2
r3 := i
r3 := r3 × 3
```

becomes

```
r2 := r1 + 5
i := r2
r3 := r2 × 3
```

Peephole Optimization

- ***Constant folding***
- A naive code generator may produce code that performs calculations at run time that could actually be performed at compile time
  - A peephole optimizer can often recognize such code

```
r2 := 3 × 2
```

becomes

```
r2 := 6
```

Peephole Optimization

- ***Constant propagation***
  - Sometimes we can tell that a variable will have a constant value at a particular point in a program
  - We can then replace occurrences of the variable with occurrences of the constant

```
r2 := 4
r3 := r1 + r2
r2 := . . .
```

becomes

```
r2 := 4
r3 := r1 + 4
r2 := . . .
```

and then

```
r3 := r1 + 4
r2 := . . .
```

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Peephole Optimization

- ***Common subexpression elimination***
  - When the same calculation occurs twice within the peephole of the optimizer, we can often eliminate the second calculation:

```
r2 := r1 × 5
r2 := r2 + r3
r3 := r1 × 5
```

becomes

```
r4 := r1 × 5
r2 := r4 + r3
r3 := r4
```

  - Often, as shown here, an extra register will be needed to hold the common value

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Peephole Optimization

- It is natural to think of common subexpressions as something that could be eliminated at the source code level, and programmers are sometimes tempted to do so
- The following, for example,

```
x = a + b + c;
y = a + b + d;
```

could be replaced with

```
t = a + b;
x = t + c;
y = t + d;
```

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Peephole Optimization

- ***Copy propagation***
  - Even when we cannot tell that the contents of register *b* will be constant, we may sometimes be able to tell that register *b* will contain the same value as register *a*
    - replace uses of *b* with uses of *a*, so long as neither *a* nor *b* is modified

```
r2 := r1
r3 := r1 + r2
r2 := 5
```

becomes

```
r2 := r1
r3 := r1 + r1
r2 := 5
```

and then

```
r3 := r1 + r1
r2 := 5
```

Peephole Optimization

- ***Strength reduction***
  - Numeric identities can sometimes be used to replace a comparatively expensive instruction with a cheaper one
    - In particular, multiplication or division by powers of two can be replaced with adds or shifts:

```
r1 := r2 × 2
```

becomes

r1 := **r2 + r2** or r1 := **r2 << 1**

```
r1 := r2 / 2
```

becomes

r1 := **r2 >> 1**

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Peephole Optimization

- ***Filling of load and branch delays***
  - For example, a value that is loaded may not be usable for several cycles

```
r2 := r1 + r2
r3 := A          — load
r3 := r3 + r2    — pipeline stall before r3 can be used
```

  - Since different registers are used, we can schedule the load earlier, avoiding the pipeline stall

```
r3 := A          — load
r2 := r1 + r2
r3 := r3 + r2    — use is late enough to avoid stall
```

  - This optimization is unnecessary on machines with out of order execution
    - Most computers and smartphones, but not necessarily embedded devices

Peephole Optimization

- ***Elimination of useless instructions***
  - Instructions like the following can be dropped entirely:

```
r1 := r1 + 0
r1 := r1 × 1
```

- ***Exploitation of the instruction set***
  - Particularly on CISC machines, sequences of simple instructions can often be replaced by a smaller number of more complex instructions

Optimization Correctness

- Criterion: does the optimized program compute the same result as the original program, for all inputs?

- Soundness theorem: If p ~> p' then ∀input I, p(I) = p'(I)
  – You'll prove a version of this for a simple constant propagation analysis in Homework 8

Analysis Correctness

- Optimizations often rely on analysis information
  - Value numbering: correspondences between expressions and values in registers

- Rough guide to correctness: when you replace symbolic information in the analysis with concrete information from particular executions, does the result hold?
  - Becomes a lemma in the proof of soundness for the “client” optimization

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Redundancy Elimination in Basic Blocks

- Throughout the remainder of this chapter we will trace the optimization of code for a specific subroutine: calculates into an array the binomial coefficients

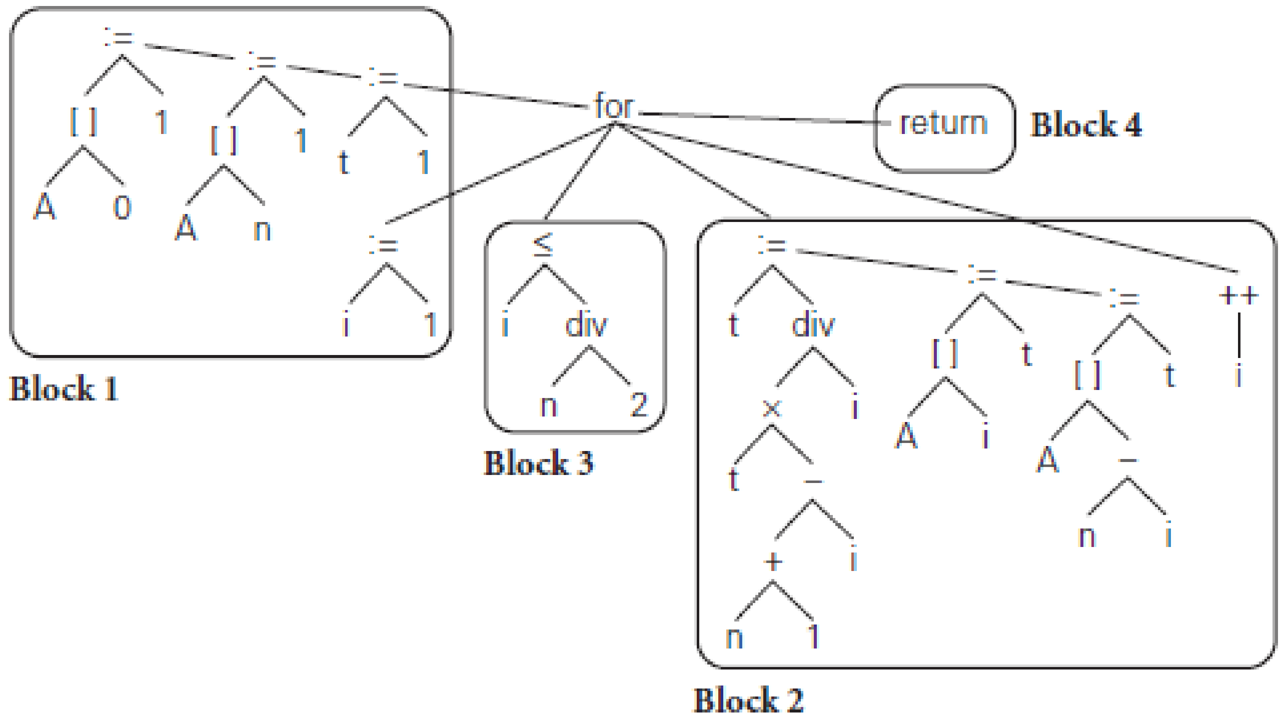


Figure 17.2 **Syntax tree for the `combinations` subroutine.** Portions of the tree corresponding to basic blocks have been circled.

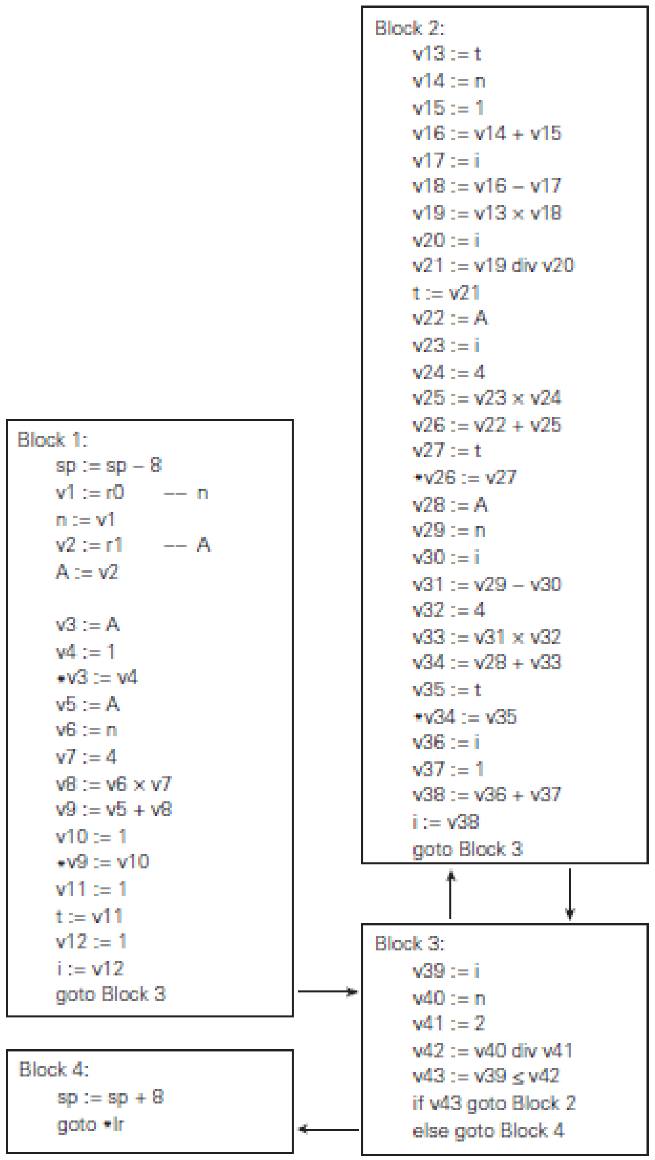
Redundancy Elimination in Basic Blocks

- Let's look at improving intermediate code generated from this C program for binomial coefficients:

```
combinations(int n, int *A) {
    int i, t;
    A[0] = 1;
    A[n] = 1;
    t = 1;
    for (i = 1; i <= n/2; i++) {
        t = (t * (n+1-i)) / i;
        A[i] = t;
        A[n-i] = t;
    }
}
```

Redundancy Elimination in Basic Blocks

- We employ a medium level intermediate form (IF) for control flow
  - Every calculated value is placed in a separate register
  - To emphasize virtual registers (of which there is an unlimited supply), we name them v1, v2, . . .
  - We use r1, r2, . . . to represent architectural registers in Section 17.8.



```
Block 1:
    sp := sp − 8
    v1 := r0       –– n
    n := v1
    v2 := r1       –– A
    A := v2

    v3 := A
    v4 := 1
    *v3 := v4
    v5 := A
    v6 := n
    v7 := 4
    v8 := v6 × v7
    v9 := v5 + v8
    v10 := 1
    *v9 := v10
    v11 := 1
    t := v11
    v12 := 1
    i := v12
    goto Block 3

Block 2:
    v13 := t
    v14 := n
    v15 := 1
    v16 := v14 + v15
    v17 := i
    v18 := v16 − v17
    v19 := v13 × v18
    v20 := i
    v21 := v19 div v20
    t := v21
    v22 := A
    v23 := i
    v24 := 4
    v25 := v23 × v24
    v26 := v22 + v25
    v27 := t
    *v26 := v27
    v28 := A
    v29 := n
    v30 := i
    v31 := v29 − v30
    v32 := 4
    v33 := v31 × v32
    v34 := v28 + v33
    v35 := t
    *v34 := v35
    v36 := i
    v37 := 1
    v38 := v36 + v37
    i := v38
    goto Block 3

Block 3:
    v39 := i
    v40 := n
    v41 := 2
    v42 := v40 div v41
    v43 := v39 ≤ v42
    if v43 goto Block 2
    else goto Block 4

Block 4:
    sp := sp + 8
    goto *lr
```

Figure 17.3 Naive control flow graph for the `combinations` subroutine. Note that reference parameter A contains the address of the array into which to write results; hence we write v3 := A instead of v3 := &A.

Redundancy Elimination in Basic Blocks

- To improve the code within basic blocks, we need to
  - minimize loads and stores
  - identify redundant calculations
- There are two techniques usually employed
  1. translate the syntax tree for a basic block into an *expression DAG* (directed acyclic graph) in which redundant loads and computations are merged into individual nodes with multiple parents
  2. similar functionality can also be obtained without an explicitly graphical program representation, through a technique known as local *value numbering*
- We describe the last technique below

Redundancy Elimination in Basic Blocks

- Value numbering assigns the same name (a “number”) to any two or more symbolically equivalent computations (“values”), so that redundant instances will be recognizable by their common name
- Our names are virtual registers, which we merge whenever they are guaranteed to hold a common value
- While performing local value numbering, we will also implement
  - local constant folding
  - constant propagation, copy propagation
  - common subexpression elimination
  - strength reduction
  - useless instruction elimination

Value Numbering

- Keep track of a table: replace *e* with *reg*/*imm*
  - Replacements are *virtual registers* or *immediates*
    - Virtual registers are numbered v_1, v_2, v_3, …
      - Origin of the term "value numbering" – we give each virtual register a number
    - Immediate values
      - i.e. value small enough to fit in the immediate operand of an instruction
      - MIPS architecture: ≤ 16 bits (unsigned value smaller than 65536)
  - Expressions *e* to replace include:
    - Program variables that are already in a register ($x \rightarrow v_1$)
    - An operand applied to small constants or register ($v_1 + 3 \rightarrow v_2$)
    - A register that duplicates another register ($v_3 \rightarrow v_2$) or holds a small constant value ($v_4 \rightarrow 1$)
    - "large" constants ($100000 \rightarrow v_5$)
      - i.e. too big to fit in the immediate operand of an instruction

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Value Numbering

- Keep track of a table: replace *e* with *reg*/*imm*
  - Invariants:
    - Large (non-immediate) values appear alone only on the left
    - Small (immediate) values appear in an expression on the left, or alone on the right
- Procedure
  - Replace expressions with reg/imm according to the table
  - Add what we learn to the table
  - Perform simple optimizations along the way
    - constant folding, strength reduction, useless instruction removal
  - Delay stores (mark variable dirty in table)
    - At end of basic block, store dirty variables
    - Rationale: avoid double-stores

Redundancy Elimination in Basic Blocks

- Let’s do value numbering for the basic block for the main loop:

```
v13 := t
v14 := n
v15 := 1
v16 := v14 + v15
v17 := i
v18 := v16 - v17
v19 := v13 * v18
v20 := i
v21 := v19 / v20
t := v21
v22 := A
v23 := i
v24 := 4
v25 := v23 * v24
v26 := v22 + v25
v27 := t
*v26 := v27
v28 := A
v29 := n
v30 := i
v31 := v29 – v30
v32 := 4
v33 := v31 * v32
v34 := v28 + v33
v35 := t
*v34 := v35
v36 := i
v37 := 1
v38 := v36 + v37
i := v38
```

Redundancy Elimination in Basic Blocks

- Let’s do value numbering for a simple example:

```
v1 := x
v2 := 1
v3 := v1 + v2
y := v3
v4 := x
v5 := 1
v6 := v4 + v5
v7 := 3
v8 := 1
v9 := v7 + v8
v10 := v6 * v9
v11 := 1
v12 := v11 * v10
v13 := 100000
v14 := v12 + v13
y := v14
```

What the source might look like:

```
y := x + 1;
y := (x+1) * (3+1) * 1 + 100000;
```

Your Turn: Value Numbering

- Perform value numbering optimization on the following:

```
v1 := x
v2 := 3
v3 := v1 + v2
y := v3
v4 := 1
v5 := x
v6 := 2
v7 := v4 + v6
v8 := v5 + v7
v9 := v8 - v3
y := v9
```

Value Numbering & Aliasing

- Aliasing: x and y might refer to the same location
  - Distinguish x and y ***must*** alias from x and y ***may*** alias

- Concerns
  - If x may alias y:
    - store to x → remove knowledge of y
      → can't move below a load of y
  - If x must alias y:
    - store to x → update knowledge of y in table
    - load of x → can replace with existing load of y