Intermediate Code & Local Optimizations

CS143

Lecture 14

Instructor: Fredrik Kjolstad

Slide design by Prof. Alex Aiken, with modifications

Lecture Outline

- Intermediate code
- Local optimizations
- Next time: global optimizations

Code Generation Summary

- We have discussed
  - Runtime organization
  - Simple stack machine code generation
  - Improvements to stack machine code generation
- Our compiler maps AST to assembly language
  - And does not perform optimizations

Optimization

- Optimization is our last compiler phase
- Most complexity in modern compilers is in the optimizer
  - Also by far the largest phase
- First, we need to discuss intermediate representations

Why Intermediate Representations?

- When should we perform optimizations?
  - On AST
    - Pro: Machine independent
    - Con: Too high level
  - On assembly language
    - Pro: Exposes optimization opportunities
    - Con: Machine dependent
    - Con: Must reimplement optimizations when retargetting
  - On an intermediate representation (language)
    - Pro: Machine independent
    - Pro: Exposes optimization opportunities

Intermediate Representations (IR)

- Intermediate representation = high-level assembly
  - Uses register names, but has an unlimited number
  - Uses control structures like assembly language
  - Uses opcodes but some are higher level
    - E.g., push translates to several assembly instructions
    - Most opcodes correspond directly to assembly opcodes

Definition: Three-Address Intermediate Code

- Each instruction is of the form

$$x := y \text{ op } z$$

$$x := \text{op } y$$

  – y and z are registers or constants
  – Common form of intermediate code

- The expression $x + y * z$ is translated

$$t_1 := y * z$$

$$t_2 := x + t_1$$

  – Each subexpression has a “name”

Generating Intermediate Code

- Similar to assembly code generation
- But use any number of IR registers to hold intermediate results

Generating Intermediate Code (Cont.)

- igen(e, t) function generates code to compute the value of e in register t
- Example:

  igen($e_1 + e_2$, t) =

  igen(e_1, t_1) (t_1 is a fresh register)

  igen(e_2, t_2) (t_2 is a fresh register)

  $t := t_1 + t_2$
- Unlimited number of registers

  $\Rightarrow$ simple code generation

Intermediate Code Notes

- You should be able to use intermediate code
  - At the level discussed in lecture

- You are not expected to know how to generate intermediate code
  - Because we won't discuss it
  - But really just a variation on code generation . . .

An Intermediate Representation

$P \rightarrow S\ P \mid \varepsilon$
$S \rightarrow$ id := id op id
| id := op id
| id := id
| push id
| id := pop
| if id relop id goto L
| L:
| jump L

- id's are register names
- Constants can replace id's
- Typical operators: +, -, *

Definition: Basic Blocks

- A <u>basic block</u> is a maximal sequence of instructions with:
  - no labels (except at the first instruction), and
  - no jumps (except in the last instruction)

- Idea:
  - Cannot jump into a basic block (except at beginning)
  - Cannot jump out of a basic block (except at end)
  - A basic block is a single-entry, single-exit, straight-line code segment

Basic Block Example

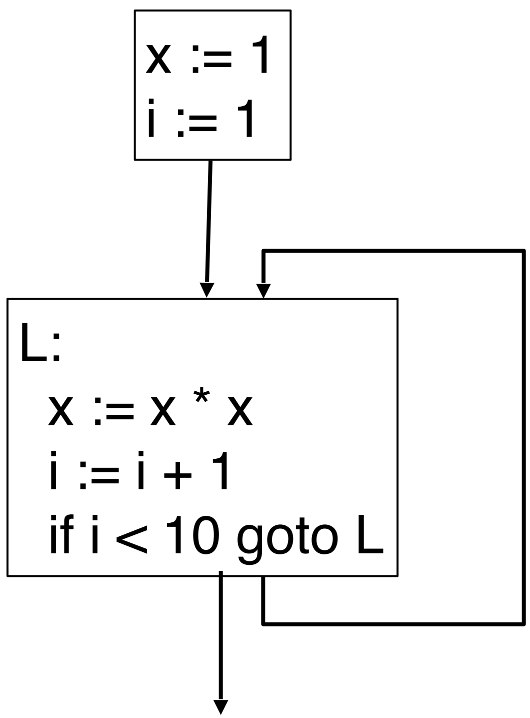
- Consider the basic block
  1. L:
  2. t := 2 * x
  3. w := t + x
  4. if w > 0 goto L’

- (3) executes only after (2)
  - We can change (3) to w := 3 * x
  - Can we eliminate (2) as well?

Definition: Control-Flow Graphs (CFG)

- A control-flow graph is a directed graph with
  - Basic blocks as nodes
  - An edge from block A to block B if the execution can pass from the last instruction in A to the first instruction in B
    - E.g., the last instruction in A is jump L_B
    - E.g., execution can fall-through from block A to block B

Example of Control-Flow Graphs



- The body of a method (or procedure) can be represented as a control-flow graph

- There is one initial node

- All “return” nodes are terminal

Optimization Overview

- Optimization seeks to improve a program's resource utilization
  - Execution time (most often)
  - Code size
  - Network messages sent, etc.

- Optimization should not alter what the program computes
  - The answer must still be the same

A Classification of Optimizations

- For languages like C and Cool there are three granularities of optimizations
  1. Local optimizations
     - Apply to a basic block in isolation
  2. Global optimizations
     - Apply to a control-flow graph (method body) in isolation
  3. Inter-procedural optimizations
     - Apply across method boundaries

- Most compilers do (1), many do (2), few do (3)

Cost of Optimizations

- In practice, a conscious decision is made not to implement the fanciest optimization known

- Why?
  - Some optimizations are hard to implement
  - Some optimizations are costly in compilation time
  - Some optimizations have low benefit
  - Many fancy optimizations are all three!

- Goal: Maximum benefit for minimum cost

Local Optimizations

- The simplest form of optimizations
- No need to analyze the whole procedure body
  - Just the basic block in question
- Example: algebraic simplification

Algebraic Simplification

- Some statements can be deleted

  x := x + 0

  x := x * 1

- Some statements can be simplified

  x := x * 0 $\Rightarrow$ x := 0

  y := y ** 2 $\Rightarrow$ y := y * y

  x := x * 8 $\Rightarrow$ x := x << 3

  x := x * 15 $\Rightarrow$ t := x << 4; x := t - x

  (on some machines << is faster than *; but not on all!)

Constant Folding

- Operations on constants can be computed at compile time
  - If there is a statement x := y op z
  - And y and z are constants
  - Then y op z can be computed at compile time

- Example: x := 2 + 2 $\Rightarrow$ x := 4
- Example: if 2 < 0 jump L can be deleted
- When might constant folding be dangerous?

Flow of Control Optimizations

- Eliminate unreachable basic blocks:
  - Code that is unreachable from the initial block
    - E.g., basic blocks that are not the target of any jump or “fall through” from a conditional
- Why would such basic blocks occur?
- Removing unreachable code makes the program smaller
  - And sometimes also faster
    - Due to memory cache effects (increased spatial locality)

Definition: Static Single Assignment (SSA) Form

- Some optimizations are simplified if each register occurs only once on the left-hand side of an assignment

- Rewrite intermediate code in single assignment form

x := z + y		b := z + y
a := x	⇒	a := b
x := 2 * x		x := 2 * b

(b is a fresh register)

  – More complicated in general, due to loops

Common Subexpression Elimination

- If
  - Basic block is in single assignment form
  - A definition x := is the first use of x in a block
- Then
  - When two assignments have the same rhs, they compute the same value
- Example:

x := y + z		x := y + z
…	⇒	…
w := y + z		w := x

(the values of x, y, and z do not change in the … code)

Copy Propagation

- If w := x appears in a block, replace subsequent uses of w with uses of x
  - Assumes single assignment form

- Example:

b := z + y		b := z + y
a := b	$\Rightarrow$	a := b
x := 2 * a		x := 2 * b

- Only useful for enabling other optimizations
  - Constant folding
  - Dead code elimination

Copy Propagation and Constant Folding

- Example:

a := 5		a := 5
x := 2 * a	$\Longrightarrow$	x := 10
y := x + 6		y := 16
t := x * y		t := 160

Copy Propagation and Dead Code Elimination

If

w := rhs appears in a basic block

w does not appear anywhere else in the program

Then

the statement w := rhs is dead and can be eliminated

– <u>Dead</u> = does not contribute to the program's result

Example: (a is not used anywhere else)

b := z + y		b := z + y		b := z + y
a := b	⇒	a := b	⇒	x := 2 * b
x := 2 * a		x := 2 * b		

Applying Local Optimizations

- Each local optimization does little by itself
- Typically optimizations interact
  - Performing one optimization enables another
- Optimizing compilers repeat optimizations until no improvement is possible
  - The optimizer can also be stopped at any point to limit compilation time

An Example

- Initial code:

```
a := x ** 2
b := 3
c := x
d := c * c
e := b * 2
f := a + d
g := e * f
```

An Example

- Algebraic optimization:

```
a := x ** 2
b := 3
c := x
d := c * c
e := b * 2
f := a + d
g := e * f
```

An Example

- Algebraic optimization:

```
a := x * x
b := 3
c := x
d := c * c
e := b << 1
f := a + d
g := e * f
```

An Example

- Copy propagation:

```
a := x * x
b := 3
c := x
d := c * c
e := b << 1
f := a + d
g := e * f
```

An Example

- Copy propagation:

```
a := x * x
b := 3
c := x
d := x * x
e := 3 << 1
f := a + d
g := e * f
```

An Example

- Constant folding:

```
a := x * x
b := 3
c := x
d := x * x
e := 3 << 1
f := a + d
g := e * f
```

An Example

- Constant folding:

```
a := x * x
b := 3
c := x
d := x * x
e := 6
f := a + d
g := e * f
```

An Example

- Common subexpression elimination:

```
a := x * x
b := 3
c := x
d := x * x
e := 6
f := a + d
g := e * f
```

An Example

- Common subexpression elimination:

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + d
g := e * f
```

An Example

- Copy propagation:

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + d
g := e * f
```

An Example

- Copy propagation:

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + a
g := 6 * f
```

An Example

- Dead code elimination:

```
a := x * x
b := 3
c := x
d := a
e := 6
f := a + a
g := 6 * f
```

An Example

- Dead code elimination:

```
a := x * x



f := a + a
g := 6 * f
```

- This is the final form

Peephole Optimizations on Assembly Code

- These optimizations work on intermediate code
  - Target independent
  - But they can be applied on assembly language also
- Peephole optimization is effective for improving assembly code
  - The "peephole" is a short sequence of (usually contiguous) instructions
  - The optimizer replaces the sequence with another equivalent one (but faster)

Peephole Optimizations (Cont.)

- Write peephole optimizations as replacement rules

  $i_1, \ldots, i_n \rightarrow j_1, \ldots, j_m$

  where the rhs is the improved version of the lhs

- Example:

  move \$a \$b, move \$b \$a $\rightarrow$ move \$a \$b

  – Works if move \$b \$a is not the target of a jump

- Another example

  addiu \$a \$a i, addiu \$a \$a j $\rightarrow$ addiu \$a \$a i+j

Peephole Optimizations (Cont.)

- Many (but not all) of the basic block optimizations can be cast as peephole optimizations
  - Example: addiu \$a \$b 0 $\rightarrow$ move \$a \$b
  - Example: move \$a \$a $\rightarrow$
  - These two together eliminate addiu \$a \$a 0

- As for local optimizations, peephole optimizations must be applied repeatedly for maximum effect

Local Optimizations: Notes

- Intermediate code is helpful for many optimizations

- Many simple optimizations can still be applied on assembly language

- “Program optimization” is somewhat misnamed
  - Code produced by “optimizers” is not optimal in any reasonable sense
  - “Program improvement” is a more appropriate term

- Next time: global optimizations