Intermediate Code & Local Optimizations

Lecture 14

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 languages

Why Intermediate Languages?

- 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 language
    - Pro: Machine independent
    - Pro: Exposes optimization opportunities

Intermediate Languages

- Intermediate language = 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

Three-Address Intermediate Code

- Each instruction is of the form
  x := y op z
  x := 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 IL 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
  ⇒ 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 Language

P → S P | ε
S → 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 basic block 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

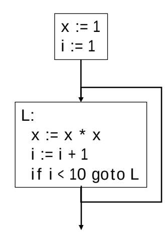
Basic Block Example

- 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

- A <u>control-flow graph</u> 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 ⇒ x := 0

  y := y ** 2 ⇒ y := y * y

  x := x * 8 ⇒ x := x << 3

  x := x * 15 ⇒ 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 ⇒ 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)

Single Assignment 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       ⇒      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     ⇒      x := 10
y := x + 6            y := 16
t := x * y            t := x << 4
```


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

– Dead = does not contribute to the program's result

Example: (a is not used anywhere else)

```
x := z + y        b := z + y        b := z + y
a := x      ⇒     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
- <u>Peephole optimization</u> 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 → 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 → 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 → move $a $b
  - Example: move $a $a →
  - 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 grossly misnamed
  - Code produced by “optimizers” is not optimal in any reasonable sense
  - “Program improvement” is a more appropriate term

- Next time: global optimizations