Intermediate Code & Local Optimizations

Lecture Outline

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

Code Generation Summary

- We have discussed
  - Simple stack machine code generation
- Compiler maps AST to assembly language directly
  - 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
  - Most real compilers use an intermediate language (IL), which they later convert to assembly or machine language.

Why Intermediate Languages ?

- Slightly higher-level target simplifies translation of AST → Code
- IL can be sufficiently machine-independent to allow multiple backends (translators from IL to machine code) for different machines, which cuts down on labor of porting a compiler.

Intermediate Languages and Optimization

- When to perform optimizations
  - On AST
    - Pro: Machine independent
    - Cons: Too high level
  - On assembly language
    - Pro: Exposes optimization opportunities
    - Cons: Machine dependent
    - Cons: Must reimplement optimizations when retargetting
  - On an intermediate language
    - Pro: Machine independent
    - Pro: Exposes optimization opportunities
    - Cons: One more language to worry about

Intermediate Languages

- Each compiler uses its own intermediate language
- Intermediate language = high-level assembly language
  - 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

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

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

  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
- Major difference: Use any number of IL registers to hold intermediate results
- Problem of mapping these IL registers to real ones is for later parts of the compiler.

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, t_2 are fresh registers)

  igen(e_2, t_2)

  t := t_1 + t_2 (means "Emit code '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

$P \to S\ P \mid \varepsilon$
$S \to$ id := id op id
| id := op id
| id := id
| id := *id
| *id := id
| param id
| call id
| return [id]
| if id relop id goto L
| L:
| goto L

- id's are register names
- Constants can replace id's on right-hand sides
- Typical operators: +, -, *
- param, call, return are high-level; refer to calling conventions on given machine.

Code Optimization: Basic Concepts

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 in a basic block (except at beginning)
  - Cannot jump out of a basic block (except at end)
  - Each instruction in a basic block is executed after all the preceding instructions have been executed
  - A basic block is a single-entry, single-exit, straight-line code segment

Basic Block Example

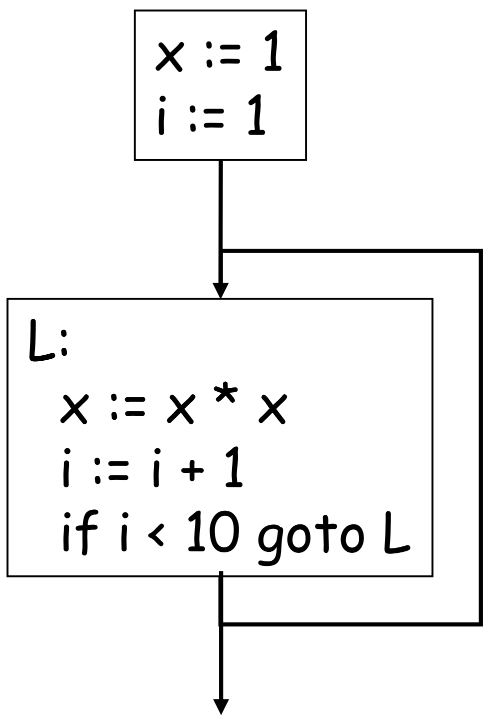
- Consider the basic block
  1. L:
  2. t := 2 * x
  3. w := t + x
  4. if w > 0 goto L'
- No way for (3) to be executed without (2) having been executed right before
  - We can change (3) to w := 3 * x
  - Can we eliminate (2) as well?

Definition. Control-Flow Graphs

- 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 flow 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., the execution can fall-through from block A to block B

- Frequently abbreviated as CFG

Control-Flow Graphs. Example.



- 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 utilization of some resource
  - 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) and very few do (3)

Cost of Optimizations

- In practice, a conscious decision is made <u>not</u> 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
- In general, 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

- Eliminating unreachable basic blocks:
  - Code that is unreachable from the initial block
  - Basic blocks that are not the target of any jump or "fall through" from a conditional
  - Such basic blocks can be eliminated
- 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 assignment is to a temporary that has not appeared already in the basic block
- Rewrite intermediate code in single assignment form
  - More complicated in general, due to loops

$x := a + y$		$x := a + y$
$a := x$	$\Rightarrow$	$a_1 := x$
$x := a * x$		$x_1 := a_1 * x$
$b := x + a$		$b := x_1 + a_1$

(x_1 and a_1 are fresh temporaries)

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
- 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, all subsequent uses of w can be replaced 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	$\Rightarrow$	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
  - <u>Dead</u> = 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	$\Rightarrow$	a := b	$\Rightarrow$	x := 2 * b
x := 2 * a		x := 2 * b		

Applying Local Optimizations

- Each local optimization does little by itself
- Typically optimizations interact
  - Performing one optimizations enables another
- Optimizing compilers repeat optimizations until no improvement is possible
  - The optimizer can also be stopped at any time 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 + b
f := a + d
g := e * f
```

An Example

- Copy propagation:

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

An Example

- Copy propagation:

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

An Example

- Constant folding:

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

- The optimizations presented before 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 (but faster) one

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

- Examples:

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 $\rightarrow$ 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 grossly misnamed
  - Code produced by "optimizers" is not optimal in any reasonable sense
  - "Program improvement" is a more appropriate term
- Next: global optimizations