Intermediate Code and Optimizations

- We have discussed
  - Runtime organization
  - Simple stack machine code generation
  - Improvements to stack machine code generation
- Our compiler goes directly from AST to assembly language
  - And does not perform optimizations
- Most real compilers use intermediate languages

Why Intermediate Languages ?

- When to perform optimizations
  - On AST
    - Pro: Machine independent
    - Con: Too high level
  - On assembly language
    - Pro: Exposes optimization opportunities
    - Con: Machine dependent
    - Con: Must re-implement optimizations when re-targetting
  - On an intermediate language
    - Pro: Machine independent
    - Pro: Exposes optimization opportunities

Intermediate Languages

- Each compiler uses its own intermediate language
  - IL design is still an active area of research
- Intermediate language = high-level assembly language
  - Uses register names, but has an unlimited number
  - Uses control structures like assembly language
  - Uses op-codes but some are higher level
    - E.g., push translates to several assembly instructions
    - Most op-codes correspond directly to assembly op-codes

Three-Address Intermediate Code

- Each instruction is of the form

  x := y op z

  - y and z can be only registers or constants
  - Just like assembly
- Common form of intermediate code
- The AST expression x + y * z is translated as

  t_1 := y * z

Generating Intermediate Code

- Similar to assembly code generation
- Major difference
  - Use any number of IL registers to hold intermediate results

Generating Int. 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

An Intermediate Language

$P \rightarrow S\ P \mid \varepsilon$

$S \rightarrow$ 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 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)
  - Each instruction in a basic block is executed after all the preceding instructions have been executed

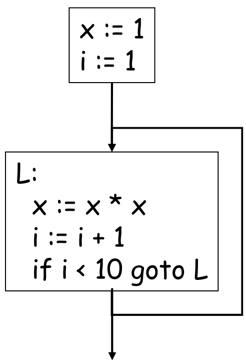
Basic Block Example

- 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 know 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 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

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 Java 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 not to implement the fanciest optimization known
- Why?
  - Some optimizations are hard to implement
  - Some optimizations are costly in terms of compilation time
  - The fancy optimizations are both hard and costly
- The goal: maximum improvement with minimum of 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 code:
  - Code that is unreachable in the control-flow graph
  - 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 register occurs only once on the left-hand side of an assignment
- Intermediate code can be rewritten to be 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 Sub-expression Elimination

- Assume
  - Basic block is in single assignment form
  - A definition x := is the first use of x in a block
- If any assignment 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, all subsequent uses of w can be replaced with uses of x
- Example:

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

- This does not make the program smaller or faster but might enable 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 := x + y
a := x	⇒	a := b	⇒	x := 2 * b
x := 2 * x		x := 2 * b		

Applying Local Optimizations

- Each local optimization does very little by itself
- Typically optimizations interact
  - Performing one optimizations enables other optimizations
- Typical optimizing compilers repeatedly perform optimizations until no improvement is possible
  - The optimizer can also be stopped at any time to limit the 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
```

Note: assume b, c, d, e are temporaries (introduced by the compiler) and hence are not used outside this basic block

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
  - They are target independent
  - But they can be applied on assembly language also
- Peephole optimization is an effective technique 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
- Just like for local optimizations, peephole optimizations need to be applied repeatedly to get 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