Lecture 1

Introduction

I What would you get out of this course?
II Structure of a Compiler
III Optimization Example

Reference: Muchnick 1.3-1.5

What Do Compilers Do?

1. Translate one language into another
   - e.g., convert C++ into SPARC object code
   - difficult for “natural” languages, but feasible for computer languages
2. Improve (i.e. “optimize”) the code
   - e.g, make the code run 3 times faster
   - driving force behind modern RISC microprocessors

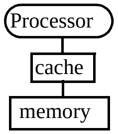
What Do We Mean By “Optimization”?

- **Informal Definition:**
  - transform a computation to an <u>equivalent</u> but “better” form
    - in what way is it equivalent?
    - in what way is it better?
- **“Optimize” is a bit of a misnomer**
  - the result is not actually optimal
  - Full Employment Theorem

How Can the Compiler Improve Performance?

Execution time = Operation count * Machine cycles per operation

- **Minimize the number of operations**
  - arithmetic operations, memory acesses
- **Replace expensive operations with simpler ones**
  - e.g., replace 4-cycle multiplication with 1-cycle shift
- **Minimize cache misses**
  - both data and instruction accesses



- **Related issue: minimize object code size**
  - more important on special-purpose processors (e.g. DSPs)

Why Study Compilers?

- **Crucial for anyone who cares about performance**
  - speed of system = hardware + compilers
- **Key ingredient in modern processor architecture development**
- **Compilation: heart of computing**
  - maps a high-level abstract machine to a lower level one
- **An example of a large software program**
  - Problem solving
    - find common cases, formulate problem mathematically, develop algorithm, implement, evaluate on real data
  - Software engineering
    - build layers of abstraction (based on theory) and support with tools
- **“Silicon Compilers”**
  - CAD tools increasingly rely on optimization
  - optimizing a hardware design is similar to optimizing a program

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What Would You Get Out of This Course?

- Basic knowledge of existing compiler optimizations
- Hands-on experience in constructing optimizations within a fully functional research compiler
- Basic principles and theory for the development of new optimizations
- Understanding of the use of theory and abstraction to solve future problems

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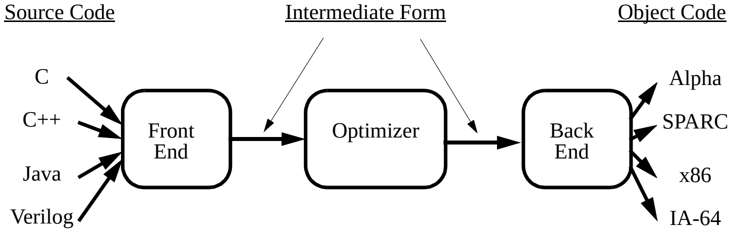
II. Structure of a Compiler



Source Code

Intermediate Form

Object Code

C

C++

Java

Verilog

Front End

Optimizer

Back End

Alpha

SPARC

x86

IA-64

- **Optimizations are performed on an “intermediate form”**
  - similar to a generic RISC instruction set
- **Allows easy portability to multiple source languages, target machines**

Ingredients in a Compiler Optimization

- **Formulate optimization problem**
  - Identify opportunities of optimization
    - applicable across many programs
    - affect key parts of the program (loops/recursions)
    - amenable to “efficient enough” algorithm
- **Representation**
  - Must abstract essential details relevant to optimization
- **Analysis**
  - Detect when it is *legal* and *desirable* to apply transformation
- **Code Transformation**
- **Experimental Evaluation (and repeat process)**

Representation: Instructions

- **Three-address code**

```
A := B op C
```

  - LHS: name of variable e.g. x, A[t] (address of A + contents of t)
  - RHS: value

- **Typical instructions**

```
A := B op C
A := unaryop B
A := B
GOTO s
IF A relop B GOTO s
CALL f
RETURN
```

III. Optimization Example

- **Bubblesort program that sorts an array A that is allocated in static storage:**
  - an element of A requires four bytes of a byte-addressed machine
  - elements of A are numbered 1 through n (n is a variable)
  - A[j] is in location &A+4*(j-1)

```
FOR i := n-1 DOWNTO 1 DO
   FOR j := 1 TO i DO
      IF A[j]> A[j+1] THEN BEGIN
         temp := A[j];
         A[j] := A[j+1];
         A[j+1] := temp
      END
```

Translated Code

```
     i := n-1
S5:  if i<1 goto s1
     j := 1
s4:  if j>i goto s2
     t1 := j-1
     t2 := 4*t1
     t3 := A[t2]   ;A[j]
     t4 := j+1
     t5 := t4-1
     t6 := 4*t5
     t7 := A[t6]   ;A[j+1]
     if t3<=t7 goto s3
```

```
   t8 :=j-1
   t9 := 4*t8
   temp := A[t9] ;A[j]
   t10 := j+1
   t11:= t10-1
   t12:= 4*t11
   t13 := A[t12] ;A[j+1]
   t14 := j-1
   t15 := 4*t14
   A[t15] := t13 ;A[j]:=A[j+1]
   t16 := j+1
   t17 := t16-1
   t18 := 4*t17
   A[t18]:=temp  ;A[j+1]:=temp
s3:j := j+1
   goto S4
S2:i := i-1
   goto s5
s1:
```

Representation: a Basic Block

- **Basic block = a sequence of 3-address statements**
  - only the first statement can be reached from outside the block (no branches into middle of block)
  - all the statements are executed consecutively if the first one is (no branches out or halts except perhaps at end of block)

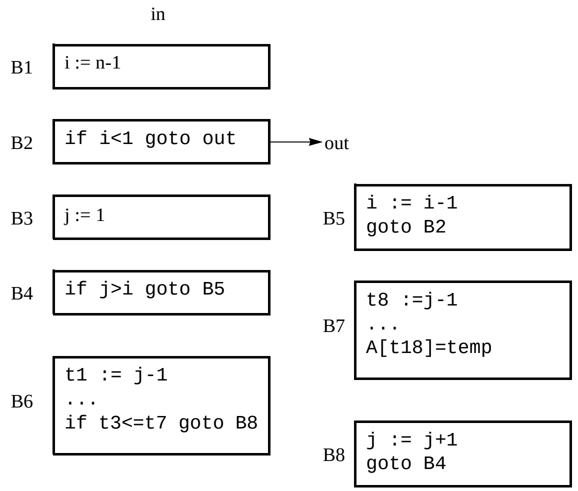
- **We require basic blocks to be *maximal***
  - they cannot be made larger without violating the conditions

- **Optimizations within a basic block are *local* optimizations**

Flow Graphs

- **Nodes: basic blocks**
- **Edges: B_i -> B_j, iff B_j can follow B_i immediately in *some* execution**
  - Either first instruction of B_j is target of a goto at end of B_i
  - Or, B_j physically follows B_i, which does not end in an unconditional goto.
- **The block led by first statement of the program is the *start*, or *entry* node.**

Example



in

B1
```
i := n-1
```

B2
```
if i<1 goto out
```
→ out

B3
```
j := 1
```

B4
```
if j>i goto B5
```

B6
```
t1 := j-1
...
if t3<=t7 goto B8
```

B5
```
i := i-1
goto B2
```

B7
```
t8 :=j-1
...
A[t18]=temp
```

B8
```
j := j+1
goto B4
```

Sources of Optimization

- **Algorithm optimization**
- **Algebraic optimization**

  `A := B+0    =>      A := B`

- **Local optimizations**
  - within a basic block -- across instructions
- **Global optimizations**
  - within a flow graph -- across basic blocks
- **Interprocedural analysis**
  - within a program -- across procedures (flow graphs)

Local Optimizations

- **Analysis & transformation performed within a basic block**
- **No control flow information is considered**
- **Examples of local optimizations:**
  - local common subexpression elimination
    analysis: same expression evaluated more than once in b.
    transformation: replace with single calculation
  - local constant folding or elimination
    analysis: expression can be evaluated at compile time
    transformation: replace by constant, compile-time value
  - dead code elimination

Example

```
B1:  i := n-1
B2:  if i<1 goto out
B3:  j := 1
B4:  if j>i goto B5
B6:  t1 := j-1
     t2 := 4*t1
     t3 := A[t2]   ;A[j]
     t6 := 4*j
     t7 := A[t6]   ;A[j+1]
     if t3<=t7 goto B8
```

```
B7:t8 :=j-1
   t9 := 4*t8
   temp := A[t9] ;temp:=A[j]
   t12:= 4*j
   t13 := A[t12] ;A[j+1]
   A[t9]:= t13  ;A[j]:=A[j+1]
   t18 := 4*j
   A[t18]:=temp ;A[j+1]:=temp
B8:j := j+1
   goto B4
B5:i := i-1
   goto B2
out:
```

(Intraprocedural) Global Optimizations

- **Global versions of local optimizations**
  - global common subexpression elimination
  - global constant propagation
  - dead code elimination
- **Loop optimizations**
  - reduce code to be executed in each iteration
  - code motion
  - induction variable elimination
- **Other control structures**
  - Code hoisting: eliminates copies of identical code on parallel paths in a flow graph to reduce code size.

Global Common Subexpression Elimination

```
B1:  i := n-1
B2:  if i<1 goto out
B3:  j := 1
B4:  if j>i goto B5
B6:  t1 := j-1
     t2 := 4*t1
     t3 := A[t2]   ;A[j]
     t6 := 4*j
     t7 := A[t6]   ;A[j+1]
     if t3<=t7 goto B8
```

```
B7:  t8 :=j-1
     t9 := 4*t8
     temp:= A[t9]  ;temp:=A[j]
     t12:= 4*j
     t13 := A[t12] ;A[j+1]
     A[t9] := t13
     A[t12]:=temp
B8:  j := j+1
     goto B4
B5:  i := i-1
     goto B2
out:
```

Induction Variable Elimination

- **Intuitively**
  - Loop indices are induction variables
    (counting iterations)
  - Linear functions of the loop indices are also induction variables
    (for accessing arrays)
- **Analysis: detection of induction variable**
- **Optimizations**
  - strength reduction: replace multiplication by additions
  - elimination of loop index -- replace termination by tests on other induction variables

Example (after cse)

```
B1:  i := n-1
B2:  if i<1 goto out
B3:  j := 1
B4:  if j>i goto B5
B6:  t1 := j-1
     t2 := 4*t1
     t3 := A[t2]   ;A[j]
     t6 := 4*j
     t7 := A[t6]   ;A[j+1]
     if t3<=t7 goto B8
B7:  A[t2] := t7
     A[t6] := t3
B8:  j := j+1
     goto B4
B5:  i := i-1
     goto B2
out:
```

Example (after iv)

```
B1:  i := n-1
B2:  if i<1 goto out
B3:  t2 := 0
     t6 := 4
B4:  t19 := 4*i
     if t6>t19 goto B5
B6:  t3 := A[t2]
     t7 := A[t6]   ;A[j+1]
     if t3<=t7 goto B8
B7:  A[t2] := t7
     A[t6] := t3
B8:  t2 := t2+4
     t6 := t6+4
     goto B4
B5:  i := i-1
     goto B2
out:
```

Loop Invariant Code Motion

- **Analysis**
    - a computation is done within a loop and
    - result of the computation is the same as long as we keep going around the loop
- **Transformation**
    - move the computation outside the loop

Machine Dependent Optimizations

- Register allocation
- Instruction scheduling
- Memory hierarchy optimizations
- etc.