**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"?

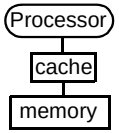
- **Informal Definition:**
  - transform a computation to an equivalent but "better" form
    - in what way is it equivalent?
    - in what way is it better?
- **"Optimize" is a bit of a misnomer**
  - the result is not actually optimal
  - Full Employment Theorem



## 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

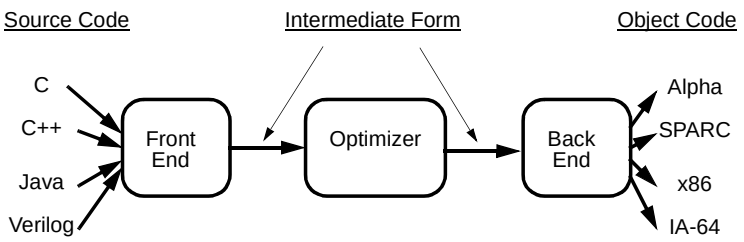


## What Would You Get Out of This Course?

- 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



## II. Structure of a Compiler




- **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                  t8 :=j-1
S5:  if i<1 goto s1            t9 := 4*t8
     j := 1                    temp := A[t9] ;A[j]
s4:  if j>i goto s2            t10 := j+1
     t1 := j-1                 t11:= t10-1
     t2 := 4*t1                t12:= 4*t11
     t3 := A[t2]   ;A[j]       t13 := A[t12] ;A[j+1]
     t4 := j+1                 t14 := j-1
     t5 := t4-1                t15 := 4*t14
     t6 := 4*t5                A[t15] := t13 ;A[j]:=A[j+1]
     t7 := A[t6]   ;A[j+1]     t16 := j+1
     if t3<=t7 goto s3         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

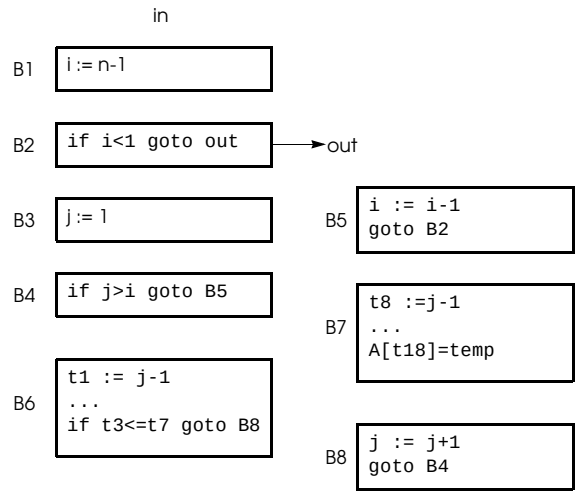
- **Optimizations within a basic block are *local* optimizations**

## 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






## 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                 B7:t8 :=j-1
B2:  if i<1 goto out             t9 := 4*t8
B3:  j := 1                      temp := A[t9] ;temp:=A[j]
B4:  if j>i goto B5              t12:= 4*j
B6:  t1 := j-1                   t13 := A[t12] ;A[j+1]
     t2 := 4*t1                  A[t9]:= t13  ;A[j]:=A[j+1]
     t3 := A[t2]   ;A[j]         t18 := 4*j
     t6 := 4*j                   A[t18]:=temp ;A[j+1]:=temp
     t7 := A[t6]   ;A[j+1]    B8:j := j+1
     if t3<=t7 goto B8           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                 B7:  t8 :=j-1
B2:  if i<1 goto out               t9 := 4*t8
B3:  j := 1                        temp:= A[t9]  ;temp:=A[j]
B4:  if j>i goto B5                t12:= 4*j
B6:  t1 := j-1                     t13 := A[t12] ;A[j+1]
     t2 := 4*t1                    A[t9] := t13
     t3 := A[t2]   ;A[j]           A[t12]:=temp
     t6 := 4*j                B8:  j := j+1
     t7 := A[t6]   ;A[j+1]         goto B4
     if t3<=t7 goto B8        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                B7:  A[t2] := t7
B2:  if i<1 goto out              A[t6] := t3
B3:  j := 1                  B8:  j := j+1
B4:  if j>i goto B5               goto B4
B6:  t1 := j-1               B5:  i := i-1
     t2 := 4*t1                   goto B2
     t3 := A[t2]   ;A[j]     out:
     t6 := 4*j
     t7 := A[t6]   ;A[j+1]
     if t3<=t7 goto B8
```



## Example (after iv)

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



## 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.