Lecture 1

Introduction

- What would you get out of this course?
- Structure of a Compiler
- Optimization Example

What Do Compilers Do?

1. Translate one language into another
   - e.g., convert C++ into x86 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 processor design

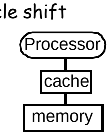
What Do We Mean By "Optimization"?

- **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

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
- **Perform work in parallel**
  - instruction scheduling within a thread
  - parallel execution across multiple threads



- **Related issue: minimize object code size**
  - more important on embedded systems

Other Optimization Goals Besides Performance

- Minimizing power and energy consumption
- Finding (and minimizing the impact of) software bugs
  - security vulnerabilities
  - subtle interactions between parallel threads
- Increasing reliability, fault-tolerance

Reasons for Studying Compilers

- **Compilers are important**
  - An essential programming tool
    - Improves software productivity by hiding low-level details
  - A tool for designing and evaluating computer architectures
    - Inspired RISC, VLIW machines
    - Machines' performance measured on compiled code
  - Techniques for developing other programming tools
    - Examples: error detection tools
  - Little languages and program translations can be used to solve other problems
- **Compilers have impact: affect all programs**

Compiler Study Trains Good Developers

Excellent software engineering case study

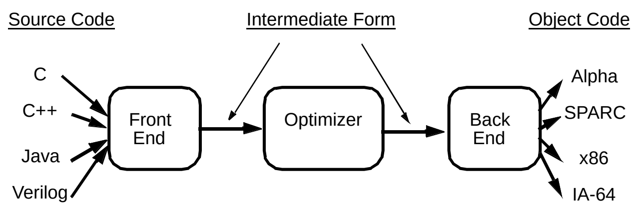
- **Optimizing compilers are hard to build**
  - Input: all programs
  - Objectives:
- **Methodology for solving complex real-life problem s**
  - Key to success: Formulate the right approximation!
    - Desired solutions are often NP-complete / undecidable
  - Where theory meets practice
    - Can't be solved by just pure hacking
      - theory aids generality and correctness
    - Can't be solved by just theory
      - experimentation validates and provides feedback to problem formulation
- **Reasoning about programs, reliability & security makes you a better programmer**

There are programmers, and there are tool builders…

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

II. Structure of a Compiler



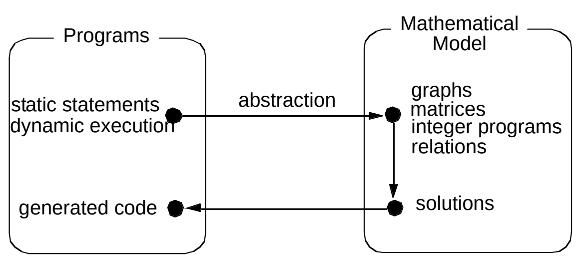
- **Optimizations are performed on an "intermediate form"**
    - similar to a generic RISC instruction set
- **Allows easy portability to multiple source languages, target machines**

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 and to apply transformation
- **Code Transformation**

- **Experimental Evaluation (and repeat process)**

Use of Mathematical Abstraction



- **Design of mathematical model & algorithm**
    - Generality, power, simplicity and efficiency

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

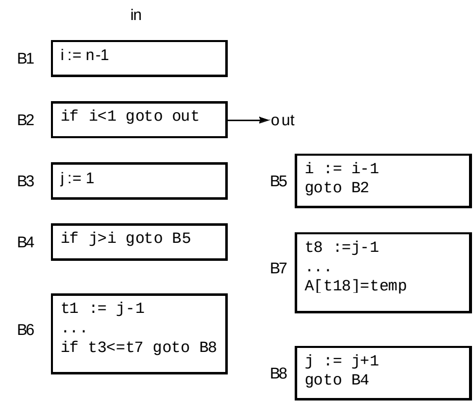
- **Nodes: basic blocks**
- **Edges: B_i -> B_j, iff B_j can follow B_i immediately in *some* execution**
  - Either first instruction of B_j is target of a goto at end of B_i
  - Or, B_j physically follows B_i, which does not end in an unconditional goto.
- **The block led by first statement of the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

Find the Basic Blocks

```
     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:
```


Basic Blocks from Example



Sources of Optimizations

- **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

```
     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:
```


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]         A[t12]:=temp   ;A[j+1]:=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:
```


(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.

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]         A[t12]:=temp  ;A[j+1]:=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:
```

Example (After Global CSE)

```
B1: i := n-1                  B7: A[t2] := t7
B2: if i<1 goto out               A[t6] := t4
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
```


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 IV Elimination)

```
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.