15-745: Optimizing Compilers for Modern Architectures

Lecture 1: Introduction

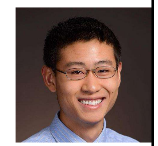
What would you get out of this course?

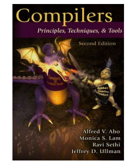
Structure of a Compiler

Optimization Example

Course Logistics

- Want to get off the waitlist?
  - See me in my office (GHC 7221) after class to discuss
  - This course is not intended to be your first compiler course
- Let Dominic know if can't get on Piazza or Blackboard for this course
- Need to get the book





- Let's run through the course webpage at http://www.cs.cmu.edu/~15745/

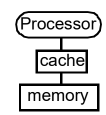
What Do Compilers Do?

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
     - or more energy efficient, more robust, etc.
   - driving force behind modern processor design

How Can the Compiler Improve Performance?

Execution time = **Operation count** * **Machine cycles per operation**

- **Minimize the number of operations**
  - arithmetic operations, memory accesses
- **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

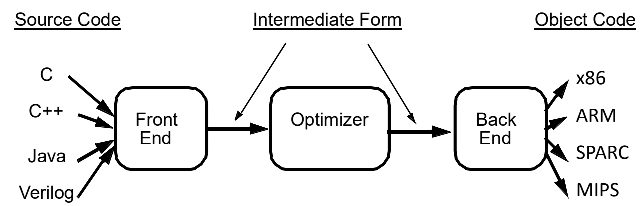


More accurately, machine cycles per operation must account for instruction overlap

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

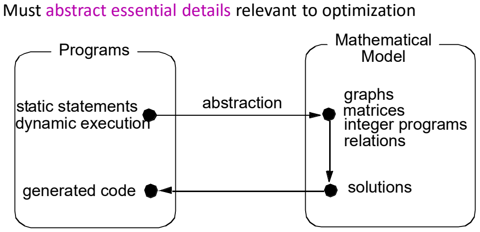
II. Structure of a Compiler



- **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



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 desirable and safe 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:
```

```
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
```


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

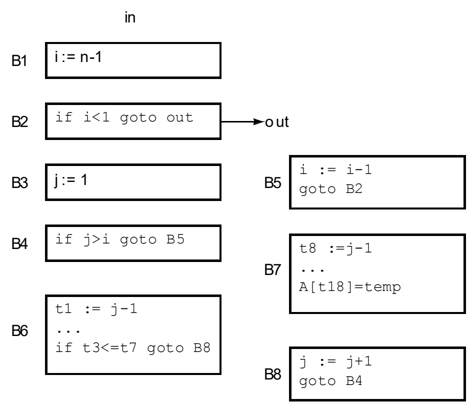
- **Nodes: basic blocks**
- **Edges: B_i -> B_j, iff B_j can follow B_i immediately in *some* execution**
  - Either first instruction of B_j is target of a goto at end of B_i
  - Or, B_j physically follows B_i, which does not end in an unconditional goto.
- **The block led by first statement of the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


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]
    A[t12]:=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.

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]
    A[t12]:=temp  ;A[j+1]:=temp
B8: j := j+1
    goto B4
B5: i := i-1
    goto B2
out:
```


Example (After Global 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:
```


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

```
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 Induction Variable 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

```
B4: t19 := 4*i                        t19 := 4*i
    if t6>t19 goto B5         B4: if t6>t19 goto B5
```


Machine Dependent Optimizations

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

Wednesday's Class

- Dominic will present "LLVM Compiler: Getting Started"
  - part 1 of 2 on LLVM
- Assignment 1 will be handed out