CSE P 501 – Compilers

Code Shape I – Basic Constructs

Hal Perkins

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Administrivia

- Semantics/type checking due in two weeks
  - Be sure to (re-)read the MiniJava project overview *carefully* as well as the semantics/type-checking assignment to be sure you catch all the things in MiniJava, especially when you're close to finishing
  - But….
  - We do have enough time in the calendar to allow an extra week for this, and it is the longest part of the project. Good idea? Too bunched up later?
    - What say you?

Agenda

- Mapping source code to x86-64
  - Mapping for other common architectures is similar
- This lecture: basic statements and expressions
  - We'll go quickly since this is review for many, fast orientation for others, and pretty straightforward
- Next: Object representation, method calls, and dynamic dispatch
- Later: specific details for project

Note: These slides include more than is specifically needed for the course project

Review: Variables

- For us, all data will be either:
  - In a stack frame (method local variables)
  - In an object (instance variables)
- Local variables accessed via %rbp

```
movq  -16(%rbp),%rax
```

- Object instance variables accessed via an offset from an object address in a register
  - Details later

Conventions for Examples

- Examples show code snippets in isolation
  - Much the way we'll generate code for different parts of the AST in a compiler visitor pass
  - Different perspective from the 351 holistic view
- Register %rax used here as a generic example
  - Rename as needed for more complex code using multiple registers
- 64-bit data used everywhere
- A few peephole optimizations shown to suggest what's possible
  - Some might be fairly easy to do in our compiler project

What we're skipping for now

- Real code generator needs to deal with many other things like:
  - Which registers are busy at which point in the program
  - Which registers to spill into memory when a new register is needed and no free ones are available
  - Dealing with different sizes of data
  - Exploiting the full instruction set

Code Generation for Constants

- Source

```
17
```

- x86-64

```
movq   $17,%rax
```

  – Idea: realize constant value in a register

- Optimization: if constant is 0

```
xorq     %rax,%rax
```

  (but some processors do better with movq $0,%rax – and this has changed over time, too; also can be considerations about whether condition codes are set or not)

Assignment Statement

- Source

    var = exp;

- x86-64

    <code to evaluate exp into, say, %rax>

    movq   %rax,$\text{offset}_{\text{var}}$(%rbp)

Unary Minus

- Source

  -exp
- x86-64

```
<code evaluating exp into %rax>
negq    %rax
```

- Optimization
  - Collapse -(-exp) to exp
- Unary plus is a no-op

Binary +

- Source

  $exp_1 + exp_2$

- x86-64

  <code evaluating exp_1 into %rax>

  <code evaluating exp_2 into %rdx>

  addq   %rdx,%rax

Binary +

- Some optimizations
  - If exp_2 is a simple variable or constant, don't need to load it into another register first. Instead:

    addq exp_2,%rax
  - Change $exp_1 + (-exp_2)$ into $exp_1 - exp_2$
  - If exp_2 is 1

    incq   %rax
    - Somewhat surprising: whether this is better than addq $1,%rax depends on processor implementation and has changed over time

Binary -, *

- Same as +
  - Use subq for – (but *not* commutative!)
  - Use imulq for *
- Some optimizations
  - Use left shift to multiply by powers of 2
  - If your multiplier is slow or you've got free scalar units and the multiplier is busy or you don't want to power up the multiplier circuit, you can do 10*x = (8*x)+(2*x)
    - But might be slower depending on microarchitecture
  - Use x+x or shift instead of 2*x, etc. (often faster)
  - Can use leaq (%rax,%rax,4),%rax to compute 5*x, then addq %rax,%rax to get 10*x, etc. etc.
  - Use decq for x-1 (but check: subq $1 might be faster)

Signed Integer Division

- Ghastly on x86-64
  - Only works for 128-bit int divided by 64-bit int
    - (similar instructions for 64-bit divided by 32-bit in 32-bit x86)
  - Requires use of specific registers
  - Very slow
- Source

  exp_1 / exp_2

- x86-64

  <code evaluating exp_1 into %rax **ONLY**>

  <code evaluating exp_2 into %rbx>

  cqto   # extend to %rdx:%rax, clobbers %rdx

  idivq %rbx   # quotient in %rax, remainder in %rdx

Control Flow

- Basic idea: decompose higher level operation into conditional and unconditional gotos
- In the following, j_{false} is used to mean jump when a condition is false
  - No such instruction on x86-64
  - Will have to realize with appropriate sequence of instructions to set condition codes followed by conditional jumps
  - Normally don't need to actually generate the value "true" or "false" in a register
    - But this can be a useful ~~shortcut~~ hack for the project

While

- Source

  while (cond) stmt

- x86-64

```
test:   <code evaluating cond>
        j_false done
        <code for stmt>
        jmp  test
done:
```

  – Note: In generated asm code we will need to have unique labels for each loop, conditional statement, etc.

Aside – Instruction execution

- Actual execution of an instruction has multiple steps/phases inside a processor. Fairly typical steps for a simple processor:
  - IF: instruction fetch. Load instruction from memory/cache into internal processor register(s)
  - ID: instruction decode / read operand registers
  - EX: execute or calculate memory addresses
  - MEM: access memory (not all instructions)
  - WB: write back – store result
- (x86-64 is waaaaay more complex, but basic ideas are the same)
- See 351 textbook, sec. 4.4, 4.5, etc. for more details

Pipelining (on 1 slide, oversimplified)

- If instructions are independent, we can execute them on an assembly line – start processing the next one while previous one is in some later stage. Ideally we could overlap like this:

1.	IF	ID	EX	MEM	WB			
2.		IF	ID	EX	MEM	WB		
3.			IF	ID	EX	MEM	WB	
4.				IF	ID	EX	MEM	WB
5.					IF	ID	…	

- Modern processors have multiple function units and buffers to support this

Pipelining bottlenecks

- This strategy works great – *if* the instructions are independent. Things that cause problems:
  - Output of one instruction needed for next one: next one can't proceed until data is available from earlier one
  - Jumps: If there's a conditional jump, the processor has to either stall the pipeline until we decide whether to jump, or make a guess and be prepared to "undo" if it guesses wrong
- Processors have lots of hardware to try to "guess right" and avoid delays caused by these dependencies, but …
- Compilers can help the processor by generating code to minimize these issues

Optimization for While

- Put the test at the end:

```
        jmp     test
loop:   <code for stmt>
test:   <code evaluating cond>
        jtrue   loop
```

- Why bother?
  - Pulls one instruction (jmp) out of the loop
  - Avoids a pipeline stall on jmp on each iteration
    - Although modern processors will often predict control flow and avoid the stall – x86-64 does this particularly well
- Easy to do from AST or other IR; not so easy if generating code on the fly (e.g., recursive descent 1-pass compiler)

Do-While

- Source

  do stmt while(cond)

- x86-64

  loop: <code for stmt>

  <code evaluating cond>

  j_{true} loop

If

- Source

  if (cond) stmt

- x86-64

  <code evaluating cond>

  j_{false} skip

  <code for stmt>

  skip:

If-Else

- Source

  if (cond) $stmt_1$ else $stmt_2$

- x86-64

```
        <code evaluating cond>
        j_false else
        <code for stmt_1>
        jmp  done
else:   <code for stmt_2>
done:
```

Jump Chaining

- Observation: naïve implementation can produce jumps to jumps (if … elseif … else; or nested loops and conditionals, …)
- Optimization: if a jump has as its target an unconditional jump, change the target of the first jump to the target of the second
  - Repeat until no further changes
  - Often done in peephole optimization pass after initial code generation

Boolean Expressions

- What do we do with this?

  x > y

- It is an expression that evaluates to true or false
  - Could generate the value (1|0 or whatever the local convention is)
  - But normally we don't want/need the value – we're only trying to decide whether to jump
    - (Although for our project we might simplify and always produce the value)

Code for exp1 > exp2

- Basic idea: Generated code depends on context:
  - What is the jump target?
  - Jump if the condition is true or if false?
- Example: evaluate exp1 > exp2, jump on false, target if jump taken is L123

```
<evaluate exp1 into %rax>
<evaluate exp2 into %rdx>
cmpq   %rdx,%rax        # dst-src = exp1-exp2
jng    L123
```

Boolean Operators: !

- Source

    ! exp

- Context: evaluate exp and jump to L123 if false (or true)
- To compile !, just reverse the sense of the test: evaluate exp and jump to L123 if true (or false)

Boolean Operators: && and ||

- In C/C++/Java/C#/many others, these are short-circuit operators
  - Right operand is evaluated only if needed
- Basically, generate the if statements that jump appropriately and only evaluate operands when needed

Example: Code for &&

- Source

    if (exp_1 && exp_2) stmt

- x86-64

        <code for exp_1>

        j_{false} skip

        <code for exp_2>

        j_{false} skip

        <code for stmt>

    skip:

Example: Code for ||

- Source

  if (exp_1 || exp_2) stmt

- x86-64

```
       <code for exp1>
       jtrue doit
       <code for exp2>
       jfalse skip
doit:  <code for stmt>
skip:
```

Realizing Boolean Values

- If a boolean value needs to be stored in a variable or method call parameter, generate code needed to actually produce it
- Typical representations: 0 for false, +1 or -1 for true
  - C specifies 0 and 1 if stored; we'll use that
  - Best choice can depend on machine instructions & language; normally some convention is picked during the primeval history of the architecture

Boolean Values: Example

- Source

  var = bexp;

- x86-64

```
        <code for bexp>
        j_false   genFalse
        movq      $1,%rax
        jmp       store
genFalse:
        movq      $0,%rax                # or xorq
store:
        movq      %rax,offset_var(%rbp)  # generated by asg stmt
```

Better, If Enough Registers

- Source

```
var = bexp;
```

- x86-64

```
        xorq    %rax,%rax             # or movq $0,%rax
        <code for bexp>
        j_false store
        incq    %rax                  # or movq $1,%rax
store:
        movq    %rax,offset_var(%rbp) # generated by asg
```

  - Better: use movecc instruction to avoid conditional jump
  - Can also use conditional move instruction for sequences like x = y<z ? y : z

Better yet: setcc

- Source

  var = x < y;

- x86-64

```
movq     offset_x(%rbp),%rax      # load x
cmpq     offset_y(%rbp),%rax      # compare to y
setl     %al                      # set low byte %rax to 0/1
movzbq   %al,%rax                 # zero-extend to 64 bits
movq     %rax,offset_var(%rbp)    # gen. by asg stmt
```

Other Control Flow: switch

- Naïve: generate a chain of nested if-else if statements
- Better: switch statement is intended to allow *O*(1) selection, provided the set of switch values is reasonably compact
- Idea: create a 1-D array of jumps or labels and use the switch expression to select the right one
  - Need to generate the equivalent of an if statement to ensure that expression value is within bounds

Switch

- Source

```
switch (exp) {
    case 0: stmts0;
    case 1: stmts1;
    case 2: stmts2;
}
```

"break" is an unconditional jump to the end of switch

- x86-64:

```
  <put exp in %rax>
  "if (%rax < 0 || %rax > 2)
      jmp defaultLabel"
  movq    swtab(,%rax,8),%rax
  jmp     *%rax
      .data
swtab:
      .quad L0
      .quad L1
      .quad L2
      .text
L0:   <stmts0>
L1:   <stmts1>
L2:   <stmts2>
```

Arrays

- Several variations
- C/C++/Java
  - 0-origin: an array with n elements contains variables a[0]…a[n-1]
  - 1 dimension (Java); 1 or more dimensions using row major order (C/C++)
- Key step is evaluate subscript expression, then calculate the location of the corresponding array element

0-Origin 1-D Integer Arrays

- Source

  $exp_1[exp_2]$

- x86-64

  <evaluate exp_1 (array address) into %rax>

  <evaluate exp_2 into %rdx>

  address is (%rax,%rdx,8)   # if 8 byte elements

  - For our project, we'll likely add exp_1+8*exp_2 to get the address of (ptr to) the array element in a register. Maybe simpler that way….

2-D Arrays

- Subscripts start with 0 (default)
- C/C++, etc. use row-major order
  - E.g., an array with 3 rows and 2 columns is stored in sequence: a(0,0), a(0,1), a(1,0), a(1,1), a(2,0), a(2,1)
- Fortran uses column-major order
  - Exercises: What is the layout? How do you calculate location of a[i][j]? What happens when you pass array references between Fortran and C/C++ code?
- Java does not have "real" 2-D arrays. A Java 2-D array is a pointer to a list of pointers to the rows
  - And rows may have different lengths (ragged arrays)

a[i][j] in C/C++/etc.

- If a is a "real" 0-origin, 2-D array, to find a[i][j], we need to know:
  - Values of i and j
  - How many columns (but not rows!) the array has
- Location of a[i][j] is:
  - Location of a + ((i*(#of columns) + j) * sizeof(elt))
- Can factor to pull out allocation-time constant part and evaluate that once – no recalculating at runtime; only calculate part depending on i, j
  - Details in most compiler books

Coming Attractions

- Code Generation for Objects
  - Representation
  - Method calls
  - Inheritance and overriding
- Strategies for implementing code generators
- Code improvement – "optimization"