CSE P 501 – Compilers

x86-64, Running MiniJava,
Basic Code Generation and Bootstrapping
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Some x86-64 References
(Links on course web)

- x86-64 Machine-Level Programming
  - Earlier version of sec. 3.13 of *Computer Systems: A Programmer’s Perspective* 2nd ed. by Bryant & O’Hallaron (CSE351 textbook)

- From www.x86-64.org:
  - System V Application Binary Interface AMD64 Architecture Processor Supplement
  - Gentle Introduction to x86-64 Assembly

- x86-64 Instructions and ABI
  - Handout for University of Chicago CMSC 22620, Spring 2009, by John Reppy
Compiler Target

- Compiler output is an assembly-language file that is linked to the “real” main program written in C
  - Lets the C library set up the stack, heap; handle I/O, etc.
- Default target is Linux x86-64
  - Should not need big changes for Microsoft MASM, but not tried yet
    - Help each other out – discussion board, etc.
  - Examples below use gnu/linux asm notation
### Intel vs. GNU Assembler

The GNU assembler uses AT&T syntax. Main differences:

<table>
<thead>
<tr>
<th></th>
<th>Intel/Microsoft</th>
<th>AT&amp;T/GNU as</th>
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</thead>
<tbody>
<tr>
<td><strong>Operand order:</strong></td>
<td>op a,b</td>
<td>b = a op b (dst last)</td>
</tr>
<tr>
<td><strong>Memory address</strong></td>
<td>[baseregister + offset]</td>
<td>offset(baseregister)</td>
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<tr>
<td><strong>Instruction mnemonics</strong></td>
<td>mov, add, push, ...</td>
<td>movl, addl, pushl [operand size is added to end]</td>
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<tr>
<td><strong>Register names</strong></td>
<td>eax, ebx, ebp, esp, ...</td>
<td>%eax, %ebx, %ebp, %esp, ...</td>
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<tr>
<td><strong>Constants</strong></td>
<td>17, 42</td>
<td>$17, $42</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>; to end of line</td>
<td># to end of line or /* ... */</td>
</tr>
</tbody>
</table>
x86-64 Main features

- 16 64-bit general registers; 64-bit integers (but int typically defaults to 32 bits; long is 64 bits)
- 64-bit address space; pointers are 8 bytes
- 8 additional SSE registers (total 16); used instead of x87 floating point by default
- Register-based function call conventions
- Additional addressing modes (pc relative)
- 32-bit legacy mode
- Some pruning of old features
x86-64 registers

- 16 64-bit general registers
  - %rax, %rbx, %rcx, %rdx, %rsi, %rdi,
    %rbp, %rsp, %r8-%r15

- Registers can be used as 64-bit ints or pointers, or 32-bit ints (upper half set to 0 automatically)
  - Also possible to reference low-order 16- and 8-bit chunks
x86-64 Function Calls

- First 6 arguments in registers, rest on the stack
- Int/pointer result returned in %rax
- Stack frame should be 16-byte aligned when call instruction is executed (i.e., %rsp value is 0xdddddddddddddddddd0; pushed return address has that address minus 8)
- We’ll use %rbp as frame pointer, but compilers often adjust %rsp once on function entry and reference locals relative to %rsp using a fixed-size stack frame
x86-Register Usage

- `%rax` – function result
- Arguments 1-6 passed in these registers:
  - `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9
    - "this" pointer is first argument, in `%rdi`
- `%rsp` – stack pointer; value must be 8-byte aligned always and 16-byte aligned when calling a function
- `%rfp` – frame pointer (optional use)
x86-64 Register Save Conventions

- A called function must preserve these registers (or save/restore them if it wants to use them)
  - %rbx, %rbp, %r12-%r15
- %rsp isn’t on the “callee save list”, but needs to be properly restored for return
- All other registers can change across a function call
gcc -S foo.c => foo.s

x86-64 Function Call

- Caller places up to 6 arguments in registers, rest on stack, then executes call instruction (which pushes 8-byte return address)

- On entry, called function prologue is like the 32-bit version:
  - pushq  %rbp
  - movq  %rbp,%rsp
  - subq  $framesize,%rsp
x86-64 Function Return

- Called function puts result in `%rax` (if any) and restores any callee-save registers if needed
- Called function returns with:
  
  ```
  movq  %rbp, %rsp  # or leave instead of
  popq  %rbp  # movq/popq
  ret
  ```

- Same logic as 32-bit

- If caller allocated space for arguments it deallocates as needed
The Nice Thing About Standards...

- The above is the System V/AMD64 ABI convention (used by Linux, OS X)
- Microsoft’s x64 calling conventions are slightly different (sigh...)
  - First four parameters in registers %rcx, %rdx, %r8, %r9; rest on the stack
  - Stack frame needs to include empty space for called function to save values passed in parameter registers if desired
Running MiniJava Programs

- To run a MiniJava program
  - Space needs to be allocated for a stack and a heap
  - %rsp and other registers need to have sensible initial values
  - We need some way to allocate storage (new) and communicate with the outside world
Bootstraping from C

- Idea: take advantage of the existing C runtime library
- Use a small C main program to call the MiniJava main method as if it were a C function
- C’s standard library provides the execution environment and we can call C functions from compiled code for I/O, malloc, etc.
Assembler File Format

- GNU syntax is roughly this (sample code will be provided with codegen phase of the project)

```
.text
.globl asm_main
;; generated code
asm_main:
... # code segment
.data
;; generated method tables
... end # start of compiled static main
# repeat .code/.data as needed
# start of compiled "main"
```

```
# repeat .text/.data as needed
```

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External Names

- In a Linux environment, an external symbol is used as-is (xyzzy)
- In Windows and OS X, an external symbol xyzzy is written in asm code as _xyzzy (leading underscore)
- Adapt to whatever environment you’re using
Generating .asm Code

- Suggestion: isolate the actual compiler output operations in a handful of routines
  - Modularity & saves some typing
  - Possibilities
    - // write code string s to .asm output
      void gen(String s) { ... }
    - // write "op src,dst" to .asm output
      void genbin(String op, String src, String dst) { ... }
    - // write label L to .asm output as "L:"
      void genLabel(String L) { ... }
  - A handful of these methods should do it
A Simple Code Generation Strategy

- Goal: quick 'n dirty correct code, optimize later if time
- Traverse AST primarily in execution order and emit code during the traversal
  - Visitor may traverse the tree in ad-hoc ways depending on sequence that parts need to appear in the code
- Treat the x86 as a 1-register machine with a stack for additional intermediate values
(The?) Simplifying Assumption

- Store all values (reference, int, boolean) in 64-bit quadwords
  - Natural size for 64-bit pointers, i.e., object references (variables of class types)
  - C’s “long” size for integers
x86 as a Stack Machine

- Idea: Use x86-64 stack for expression evaluation with %rax as the "top" of the stack
- Invariant: Whenever an expression (or part of one) is evaluated at runtime, the generated code leaves the result in %rax
- If a value needs to be preserved while another expression is evaluated, push %rax, evaluate, then pop when first value is needed
  - Remember: always pop what you push
  - Will produce lots of redundant, but correct, code
- Examples below follow code shape examples, but with some details about where code generation fits


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Example: Generate Code for Constants and Identifiers

- Integer constants, say 17
  \[ \text{gen(movq } \$17,\%rax) \]
  - leaves value in \%rax

- Local variables (any type – int, bool, reference)
  \[ \text{gen(movq offset(\%rbp),\%rax)} \]
Example: Generate Code for \( \text{exp1 + exp1} \)

- Visit \text{exp1}
  - generate code to evaluate \text{exp1} with result in \%rax
  - \text{gen(pushq \%rax)}
    - push \text{exp1} onto stack
- Visit \text{exp2}
  - generate code for \text{exp2}; result in \%rax
  - \text{gen(popq \%rdx)}
    - pop left argument into \%rdx; clean up stack
  - \text{gen(addq \%rdx,\%rax)}
    - perform the addition; result in \%rax
Example: \( \text{var} = \text{exp}; \) (1)

- Assuming that \( \text{var} \) is a local variable
  - Visit node for \( \text{exp} \)
    - Generates code that leaves the result of evaluating \( \text{exp} \) in \( \%\text{rax} \)
    - \text{gen}(\text{movq} \%\text{rax}, \text{offset\_of\_variable}(\%\text{rbp})) \)
Example: `(var = exp; (2)

- If `var` is a more complex expression (object or array reference, for example)
  - visit `var`
  - gen(`pushq %rax`)
    - push reference to variable or object containing variable onto stack
  - visit `exp` – leaves rhs value in `%rax`
  - gen(`popq %rdx`)
    - gen(`movq %rax,appropriate_offset(%rdx)`)
Example: Generate Code for obj.f(e1,e2,...,en)

- In principal the code should work like this:
  - Visit obj
    - leaves reference to object in %rax
  - gen(movq %rax, rdi)
    - "this" pointer is first argument
  - Visit e1, e2, ..., en. For each argument,
    - gen(movq %rax, correct_argument_register)
  - generate code to load method table pointer located at 0(%rdi) into register like %rax
  - generate call instruction with indirect jump
Method Call Complications

- Big one: code to evaluate any argument might clobber argument registers (i.e., method call in some parameter value)
  - Possible strategy to cope on next slides, but better solutions would be welcome
- Not quite so bad: what if a method has more than 6 (or 4 for Microsoft folks) parameters?
  - Let’s punt that one and restrict the number of parameters to the number of parameter registers
    - Looks like the test programs are all ok here
Method Calls in Parameters

- Suggestion to avoid trouble:
  - Evaluate parameters and push them on the stack
  - Right before the call instruction, pop the parameters into the correct registers
    - Or leave the parameters in storage and copy them into registers, then deallocate after return

- But....
Stack Alignment (1)

- Above idea hack works provided we don’t call a method while an odd number of parameter values are pushed on the stack!
  - (violates 16-byte alignment on method call...)

- We have a similar problem if an odd number of intermediate values are pushed on the stack when we call a function in the middle of evaluating an expression

- (But we may get away with it if it only involves calls to our generated, not library, code)
Stack Alignment (2)

- Workable solution: keep a counter in the code generator of how much has been pushed on the stack. If needed, `gen(pushq %eax)` to align the stack before generating a call instruction.

- Another solution: make stack frame big enough and use `movq` instead of `pushq` to store arguments and temporaries.
  - Will need some extra bookkeeping to allocate space for arguments and temporaries.
Sigh...

- Multiple registers for method arguments is a big win compared to pushing on the stack, but complicates our life since we do not have a fancy register allocator.
- Better ideas for handling x86-64 function calls in MiniJava are most welcome.
Code Gen for Method Definitions

- Generate label for method
- Generate method prologue
- Visit statements in order
  - Method epilogue is normally generated as part of each return statement (next)
  - In MiniJava the return is generated after visiting the method body to generate its code
Example: return exp;

- Visit exp; leaves result in %rax where it should be
- Generate method epilogue to unwind the stack frame; end with ret instruction
Control Flow: Unique Labels

- Needed: a String-valued method that returns a different label each time it is called (e.g., L1, L2, L3, ...)
- Variation: a set of methods that generate different kinds of labels for different constructs (can really help readability of the generated code)
  - (while1, while2, while3, ...; if1, if2, ...; else1, else2, ...; fi1, fi2, ....)
Control Flow: Tests

- Recall that the context for compiling a boolean expression is
  - Label or address of jump target
  - Whether to jump if true or false
- So the visitor for a boolean expression should receive this information from the parent node

\[ x > y \]
Example: while(exp) body

- Assuming we want the test at the bottom of the generated loop...
  - gen(jmp testLabel)
  - gen(bodyLabel: )
  - visit body
  - gen(testLabel: )
  - visit exp (condition) with target=bodyLabel and sense="jump if true"
Example: $\text{exp1} < \text{exp2}$

- Similar to other binary operators
- Difference: context is a target label and whether to jump if true or false
- Code
  - visit $\text{exp1}$
  - gen($\text{pushq } \%\text{rax}$)
  - visit $\text{exp2}$
  - gen($\text{popq } \%\text{rdx}$)
  - gen($\text{cmpeq } \%\text{rdx}, \%\text{rax}$)
  - gen($\text{condjump targetLabel}$)
    - appropriate conditional jump depending on sense of test
Boolean Operators

- \&\& (and || if you include it)
  - Create label needed to skip around the two parts of the expression
  - Generate subexpressions with appropriate target labels and conditions

- !exp
  - Generate exp with same target label, but reverse the sense of the condition
Join Points

- Loops and conditional statements have join points where execution paths merge.
- Generated code must ensure that machine state will be consistent regardless of which path is taken to reach a join point.
  - i.e., the paths through an if-else statement must not leave a different number of words pushed onto the stack.
  - If we want a particular value in a particular register at a join point, both paths must put it there, or we need to generate additional code to move the value to the correct register.

With a simple 1-accumulator model of code generation, this should generally be true without needing extra work; with better use of registers this becomes an issue.
Bootstrap Program

- The bootstrap is a tiny C program that calls your compiled code as if it were an ordinary C function
- It also contains some functions that compiled code can call as needed
  - Mini “runtime library”
  - Add to this if you like
    - Sometimes simpler to generate a call to a newly written library routine instead of generating in-line code – implementer tradeoff
#include <stdio.h>

extern void asm_main(); /* compiled code */
/* execute compiled program */
void main() { asm_main(); }
/* return next integer from standard input */
long get() { ... }
/* write x to standard output */
void put(long x) { ... }
/* return a pointer to a block of memory at least nBytes large (or null if insufficient memory available) */
char* minijavaalloc(long nBytes) { return malloc(nBytes); }
Main Program Label

- Compiler needs special handling for the static main method label
  - Label must be the same as the one declared extern in the C bootstrap program and declared .globl in the .s asm file
  - asm_main used above
    - Could be changed, but probably no point
    - Why not “main”? (Hint: what is/where is the real main function?)
Interfacing to “Library” code

- Trivial to call “library” functions
- Evaluate parameters using the regular calling conventions
- Generate a call instruction using the function label
  - (External names need a leading _ in Windows, OS X)
  - Linker will hook everything up
System.out.println(exp)

- MiniJava’s “print” statement
  
  ```
  <compile exp; result in %rax>
  movq %rax,%rdi ; load argument register
  call put ; call external put routine
  ```

- If the stack is not kept 16-byte aligned, calls to external C or library code are the most likely place for a runtime error.
And That’s It...

- We’ve now got enough on the table to complete the compiler project
- Coming Attractions
  - Lower-level IR and control-flow graphs
  - Back end (instruction selection and scheduling, register allocation)
  - Middle (optimizations)