CSE P 501 – Compilers

x86-64, Running MiniJava,
Basic Code Generation and Bootstrapping

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Administrivia

- Codegen part of project posted now
  - Final push deadline Sun. 3/13, 11pm – no extensions
  - Project report due next night (will post info later)
  - Project meetings Tue. & Wed. 3/15-16 – scheduling later
  - Grading of previous parts – long story…
- HW4 out (~~now~~ | soon) [pick one]
  - Review problems on analysis/opt/IRs/SSA
  - Due Monday night, 2/29 – no extensions; solutions posted next day
- Exam next Thur. 3/3 @UW and @Microsoft, 6:30-8:00
  - Topic list & old exams on web now
  - OK to use textbook + slides + topic list + 2 handouts (x86-64, MiniJava grammar) during exam; laptops ok if only used to access items linked from exam resources or topics pages

Codegen/Execution for MiniJava

- Build on Codeshape lectures
- More specifics here about execution environment and compiler code gen routines

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

- Compiler output is an assembly-language source file (.s)
- GNU syntax is roughly this (asm samples included in starter src/runtime directory, links to gcc/as refs. on project page)

```
    # comments start with # and go to end of the line
    .text                   # code segment
    .globl asm_main         # start of compiled static main
    <generated code>        # repeat .text/.data as needed
asm_main:                   # start of compiled "main"
    ...
    .data
    <generated method tables>
    # repeat .text/.data as needed
    ...
    end
```

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
  - but what you turn in should run on CSE linux using the Linux conventions
  - Exceptions? Check with course staff first

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 in visitor methods
  - Visitor may traverse the tree in ad-hoc ways depending on the sequence in which parts need to be written to the code assembler file
- Treat the x86 as a 1-register machine with a stack for additional intermediate values
  - Ugly code, but will work – better later if there's time

(The?) Simplifying Assumption

- Store all values (reference, int, boolean) in 64-bit quadwords
  - Natural size for 64-bit pointers, e.g., object references (variables of class types)
  - C's "long" size for integers
    - Better to use int64_t or uint64_t in C code to guarantee size (declared in <stdint.c>)

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 more details about code generation

Example: Generate Code for Constants and Identifiers

Integer constants, say 17

gen(movq $17,%rax)

- leaves value in %rax

Local variables (any type – int, bool, reference)

gen(movq varoffset(%rbp),%rax)

Example: Generate Code for exp1 + exp1

Visit exp1
- generate code to evaluate exp1 with result in %rax

gen(pushq %rax)
- push exp1 onto stack

Visit exp2
- generate code for exp2; result in %rax

gen(popq %rdx)
- pop left argument into %rdx; clean up stack

gen(addq %rdx,%rax)
- perform the addition; result in %rax

Example: var = exp; (1)

Assuming that var is a local variable:

Visit node for exp

- Generates code to eval exp and leave result in %rax

gen(movq %rax,offset_of_variable(%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 (i.e., address of) 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 some register, probably %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 feel free to do something better
- Other one: what if a method has too many parameters?
  – OK for P 501 to assume that all methods have ≤ 5 parameters plus “this” – do better if you want

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
- But….

Stack Alignment (1)

0xnnnn - in 0

- 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 while evaluating an expression
  - (We might get away with it if it only involves calls to our own generated, not library, code, but it would be wrong* to do that)
    - *i.e., might "work", but not the right way to solve the problem

Stack Alignment (2)

- Workable solution: keep a counter in the code generator of how much has been pushed on the stack. If needed, emit extra gen(pushq %rax) to align stack before generating a call instruction
  - Be sure to pop it after!!
- Another solution: make stack frame big enough and use movq instead of pushq to store arguments and temporaries
  - Will need some extra bookkeeping to keep track of how much to allocate and how temps are used

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
- Feel free to do better than this simple push/pop scheme – but remember, simple and works wins over fancy and broken

class C

Code Gen for Method Definitions

int f( )

lbl:

return

- Generate label for method
  - ✓ Classname$methodname:
- Generate method prologue
  - Push %rbp, copy %rsp to %rbp, subtract frame size from %rsp
- 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

Registers again…

- Method parameters are in registers
- But code generated for methods also will be using registers, even if there are no calls to other methods
- So how do we avoid clobbering parameters?
- Suggestion: Allocate space in the stack frame and save copies of all parameter registers on method entry. Use those copies as local variables when you need to reference a parameter.

Example: return exp;

- Visit exp; this leaves result in %rax where it should be
- Generate method epilogue (copy %rbp to %rsp, pop %rbp) to unwind the stack frame; follow with ret instruction

Control Flow: Unique Labels

- Needed in code generator: a String-valued method that returns a different label each time it is called (e.g., L1, L2, L3, …)
  - Improvement: 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

while (a<b) {

}

endw3 →

- So the visitor for a boolean expression should receive this information from the parent node

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: exp1 < exp2

- Similar to other binary operators
- Difference: context is a target label and whether to jump if true or false
- Code

```
visit exp1
gen(pushq %rax)
visit exp2
gen(popq %rdx)
gen(cmpq %rdx,%rax)
gen(condjump targetLabel)
```

  - appropriate conditional jump depending on sense of test if (a<b) if(!(a<b))

Boolean Operators

Else: Else.

&& (and || if you add it)

- Create label(s) needed to skip around parts of the expression
- Generate subexpressions with appropriate target labels and conditions

!exp

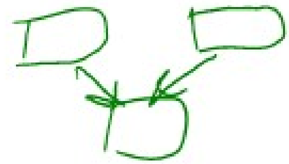
- Generate exp with same target label, but reverse the sense of the condition

Reality check

$b = x < y$

- Lots of projects in the past have evaluated all booleans to get 1 or 0, then tested that value for control flow
- Would be nice to do better (as above), but "simple and works…"

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 get there
  – 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 usually be true without needing extra work; with better use of registers it becomes a bigger 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 hand-written library routine instead of generating in-line code – implementer tradeoff

Bootstrap Program Sketch

```
#include <stdio.h>
extern void asm_main( );  /* compiled code */
/* execute compiled program */
void main( ) { asm_main(); }
/* write x to standard output */
void put(int64_t x) { … }
/* return a pointer to a zeroed  block of memory at least
   nBytes large (or null on failure) */
char* mjcalloc(size_t nBytes) { return calloc(1,nBytes); }
```

Main Program Label

- Compiler needs special handling for the publicstaticvoid `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: where is the real `main`?)

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 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 can cause a runtime error (*will* cause error halt on OS X)

And That's It…

- We've now got enough on the table to complete the compiler project
- Coming Attractions
  - Back end (instruction selection and scheduling, register allocation)
  - and more…

    (including an exam)