CSE 401 – Compilers

Lecture 20: x86-64, GNU Assembler, and Project Code Generation, Part II

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Reminders/ Announcements

- Midterms are graded
  - If you haven't picked yours up yet, you can stop by during my office hours today (2:30-3:30)
- Project part 3 due this Friday
- Part 4 will be due on Friday, March 15 (last day of class). I will put the assignment out this afternoon.
- Laure out of town next week – no office hours.

Review: boot.c

- We will provide a small bootstrap named boot.c with the part 4 assignment.
  - A tiny C program that calls your compiled code as if it were an ordinary C function (assumes your main label is asm_main).
- It also contains some functions that compiled code can call as needed
  - This is a mini "runtime library"
    - Leverages gcc's C runtime for program startup/initialization, I/O, memory management, etc.
    - A tiny MiniJava interface layer on top for access to input, output, memory allocation
  - Add to this if you like
    - Sometimes simpler to generate a call to a newly written library routine instead of generating in-line code

Bootstrap Program Sketch

```
#include <stdio.h>
extern void asm_main();  /* label for your 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* mjmalloc(long nBytes) { return malloc(nBytes); }
```

Review: Library Calls

- To call these library functions (get, put, mjmalloc, and anything you might add), just follow x86-64 calling conventions. On Linux, call target label is just the function name (Windows and OS X add a preceding _).
- E.g., a code template for System.out.println(exp) (MiniJava's "print" statement) might be:

```
<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

Assembler File Format

- GNU .s file syntax is roughly this (sample code will be provided with part 4 of the project)

```
    .text                  # code segment
    .globl asm_main        # label for main program

asm_main:                  # start of compiled "main"
    …

class1$method1:            # code for additional methods
    …

    .data                  # generated method tables
    …                      # generated method tables
    …                      # generated method tables
    # repeat .text/.data as needed
```

Let's Take A Look at the Bootstrap, and a sample .s file

Generating .asm Code

- Suggestion: isolate the actual assmebly 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 (based on code recipes/templates we studied for particular syntax constructs/AST nodes).
- Treat the x86 as a 1-register machine with a stack for additional intermediate values
  - Except for function calls (due to register-based calling convention on x86-64)
  - Don't have to worry about register allocation

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
  - Means you won't necessarily get the right overflow behavior for ints (supposed to be 32-bit in Java), but that is okay (you'll still get full credit).
    - MiniJava was originally designed for 32-bit machines.

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

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 offset(%rbp),%rax")

  – Recall simplifying assumption that everything is 64-bit in MiniJava

Example: Generate Code for exp1 + exp2

- Visit exp1
  - generate code to evaluate exp1 with result in %rax
- gen("pushq %rax")
  - push exp1 result onto stack
- Visit exp2
  - generate code for exp2; result in %rax
- gen("popq %rdx")
  - pops exp1 result into %rdx (also cleans up stack)
- gen("addq %rdx,%rax")
  - perform the addition; result in %rax

Example: var = exp; (1)

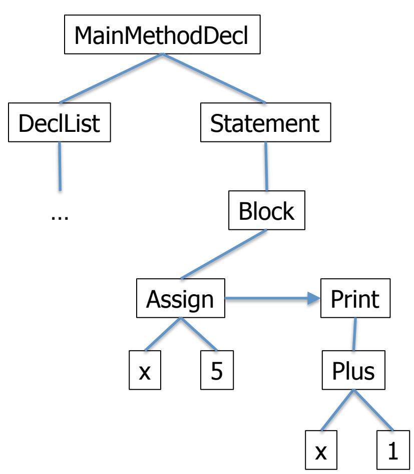
- Assuming that var is a local variable
  - Visit node for exp
    - Generates code that leaves the result of evaluating exp in %rax
  - gen("movq %rax,offset_of_variable(%rbp)")

Example: Simple main()

- With this, we can now generate code for a simple main method:

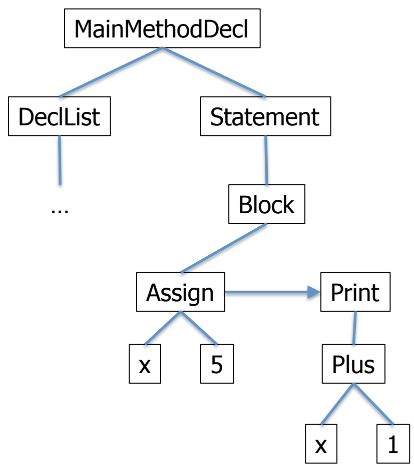
```
public static void main() {
    int x;
    {
        x = 5;
        System.out.println(x + 1);
    }
}
```


Possible AST




```
public static void main() {
  int x;
  {
    x = 5;
    System.out.println(x + 1);
  }
}
```

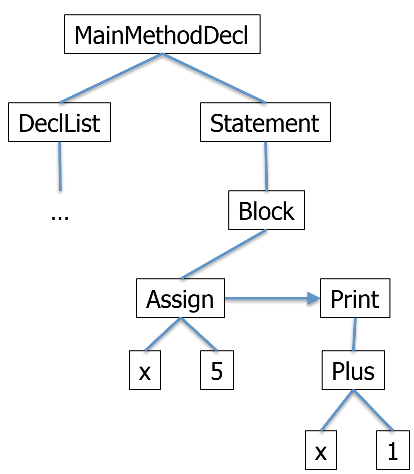
Possible AST




```
#prologue
push    %rbp
movq    %rsp,%rbp
subq    $16,%rsp
```

You'll likely have a method to generate prologues, e.g., genPrologue(int numLocals). Call it before generating the method's statement list. Also, recall suggestion to round up frame size to multiples of 16.

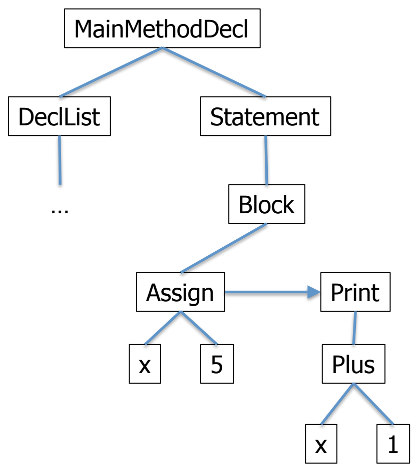
Possible AST




```
#prologue
push    %rbp
movq    %rsp,%rbp
subq    $16,%rsp

#Assign right: 5
movq $5,%rax
```

Possible AST

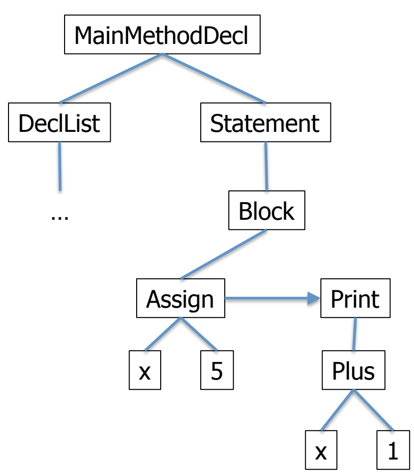



```
#prologue
push      %rbp
movq      %rsp,%rbp
subq      $16,%rsp

#Assign right: 5
movq $5,%rax

#Assign
movq %rax,-8(%rbp)
```


Possible AST



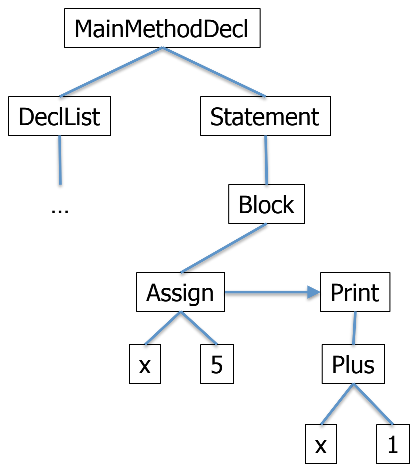

```
#prologue
push      %rbp
movq      %rsp,%rbp
subq      $16,%rsp

#Assign right: 5
movq $5,%rax

#Assign
movq %rax,-8(%rbp)

#Print exp
#Plus exp1
movq -8(%rbp),%rax
pushq %rax
```

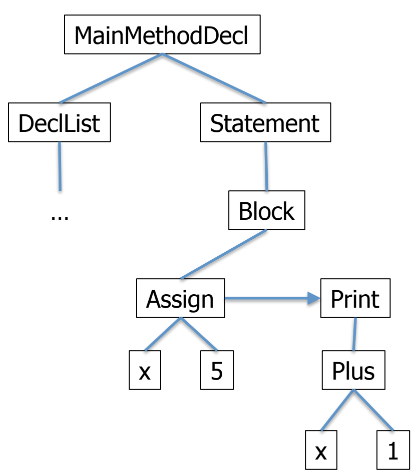
Possible AST




```
…
#Plus exp1
movq -8(%rbp),%rax
pushq %rax

#Plus exp2
movq $1,%rax
```


Possible AST

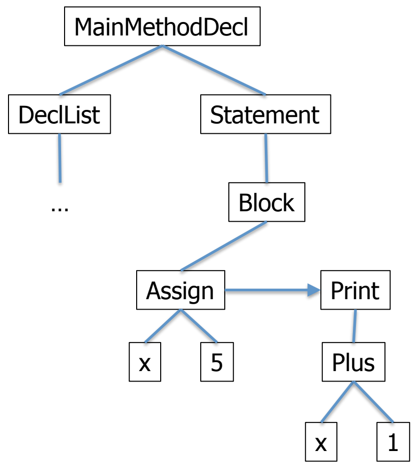



```
…
#Plus exp1
movq -8(%rbp),%rax
pushq %rax

#Plus exp2
movq $1,%rax

#Plus
popq %rdx
addq %rdx,%rax
```

Possible AST



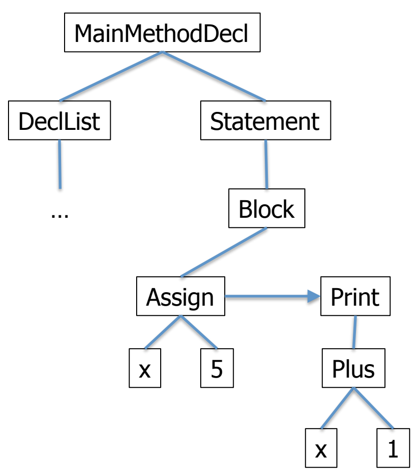

```
…
#Plus exp1
movq -8(%rbp),%rax
pushq %rax

#Plus exp2
movq $1,%rax

#Plus
popq %rdx
addq %rdx,%rax

#Print
movq %rax,%rdi
call put
```


Possible AST




```
…
#Print
movq %rax,%rdi
call put

#Epilogue
leave
ret
```

Generate epilogue after statements.

Suggestion

- Build your code generator incrementally.
  - Start with enough functionality to compile very simple programs.
  - Then, add functionality to compile slightly more complex programs.
  - ~~Rinse~~ Test (thoroughly) and repeat.
- The last step is *key*.
  - Debugging code generators is hard (basically, it comes down to debugging assembly code).
  - By doing small pieces, and testing thoroughly after each one, you make your life much easier.
- The assignment will have a (time-tested) approach to incrementally building your code generator.

Example: var = exp; (2)

- If var is a more complex expression (object or array reference, for example)
  - visit var
    - Since it's going to be used as a store target, you want to evaluate the address, not the value. For objects this may be default, but probably not fields/array elements.
    - MiniJava has a limited set of "var" possibilities, so you could possibly special case them if you wanted.
  - gen(pushq %rax)
    - push address of object/field/array element/etc
  - 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
    - gen("movq (%rdi),%rax")
  - generate call instruction with indirect jump
    - gen("call *M(%rax)"), where M is offset of f in method table

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, other solutions may be possible
- Not quite so bad: what if a method has more than 6 parameters?
  - Traditionally, supporting extra parameters hasn't been required in this course, so I won't either.
  - Not hard, and a reasonable extension to attempt for some extra credit.
  - Requires extra bookkeeping in caller and callee (especially when combined with our strategy for dealing with the above issue, due to evaluation order rules).

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
    - Works if we are dealing with at most 6 parameters.
    - If attempting extension: later parameters should be evaluated after earlier parameters, so parameters 7+ will normally be in the way of popping first 6.
    - Could use free registers to hold them temporarily, and repush (but requires a register allocator to track free regs).
    - Or could leave all the parameters in storage and copy the first 6 into registers, then deallocate everything after return
    - But….

Stack Alignment (1)

- Above strategy 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/temporary values are pushed on the stack when we call a function in the middle of evaluating an expression

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
  - Be sure to generate a popq afterwards, iff you pushed
- Another solution: make stack frame big enough and use movq instead of pushq to store arguments and temporaries
  - What most real compilers do – also frees up %rbp
  - Will need some extra bookkeeping to allocate space for arguments and temporaries

In Summary …

- 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
- For project, you are only required to handle up to 6 parameters.
  - But you may try to do more as an extension, if you wish.

Code Gen for Method Definitions

- Generate label for method
    - Classname$methodname:
- Walk list of declarations
    - Assign offsets from %rbp for each local: -8, -16, -24, etc. Store in variable's symbol table entry.
- 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 (or return statements branch to epilogue)
    - In MiniJava the return is generated after visiting the method body to generate its code
        - MiniJava only allows a single return at the end of the method.
        - Main special case: Generate epilogue without return

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, …)
  - Allows us to create *unique* labels for control flow.
  - 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
  - There's a few ways you can do this
    - Visitor object can store state: parent can store for child. Make sure visit method remembers the state when it was called (may make nested calls with different state, e.g. x < y && x < z, or !exp).
    - Or, can augment the accept/visit methods for expressions to pass additional parameters – and pass null state (or whatever) for non-boolean expressions, since it shouldn't be used.
    - Or, have parent visitor store context in child's AST 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 (jl, jnl) depending on sense of test

Boolean Operators

- && (and || if you include it)
  - Follow the same recipes as the IA-32 examples from last week, except in Gnu x86-64
  - 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
  - Stack of temporary values should be empty after each statement

And That's It…

- We've now got enough on the table to complete the compiler project

- Coming Attractions
  - Survey of optimization: analysis and transformations
  - More sophisticated code generation
  - Two guest lectures:
    - Real-world parsing (it's not just for compilers!)
    - Real register allocators
    - Yes, they will be on the final ☺