CSE 401 – Compilers

Lecture 16: x86 Lite for Compiler Writers (a quick review)

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Winter 2013

Reminders

- Project Part 2 due 11:59pm tonight
  - In theory – but the closest the dropbox will enforce is 12:01am tomorrow morning. Hopefully you won't need those extra two minutes, though. ☺
- Midterm on Friday.
  - Review session tomorrow in Sections.
- Homework 1 and 2 solutions are available – pick them up on your way out of class.
  - Please dispose of these after the final.

Quick Shift-Reduce Conflict Example

```
S ::= AList B
AList ::= A AList | ε
A ::= x x
B ::= x y
```

Stack	Rest of input
$	x ? ? …

A lookahead 1 parser only sees the very next character

Quick Shift-Reduce Conflict Example

```
S ::= AList B
AList ::= A AList | ε
A ::= x x
B ::= x y
```

Problem: We are forced to decide which path to take before we have enough information, because one path requires a shift and the other a reduce.

Stack	Rest of input
$	x ? ? …

If second symbol is x, we want to: shift x, shift x, reduce x x → A

If second symbol is y, we want to: reduce ε → AList, shift x, shift y, reduce x y → B, reduce AList B → S

What If We Used Left Recursion?

S ::= AList B
AList ::= AList A | ε
A ::= x x
B ::= x y

Stack
$

Rest of input
x ? ? …

If second symbol is x, we want to: reduce ε → AList (we need build our initial Alist that we append additional A's on to.

If second symbol is y, we want to: reduce ε → AList (we have an empty AList)

What If We Used Left Recursion?

This works better: We don't have to reduce until we know which path we're on.

Note: This type of problem can also sometimes occur without empty productions – try walking through an example with AList ::= A AList | A

S ::= AList B
AList ::= AList A | ε
A ::= x x
B ::= x y

Stack
$AList

Rest of input
x ? ? …

If second symbol is x, we want to: shift x, shift x, reduce x x → A, reduce AList A → A

If second symbol is y, we want to: shift x, shift y, reduce x y → B, reduce AList B → S

Agenda for the next couple weeks

- Overview of x86 architecture
  - Core 32-bit part only to start, not old cruft
  - 64-bit x86-64 later for the project
- Then…
  - Mapping source language constructs to x86
  - Code generation for MiniJava project
- Rest of the quarter…
  - Survey of compiler optimizations, more sophisticated code generation techniques

x86 Selected History

- 40 Years of x86
  - Early 70s: 8008 and 8080 – 8 bit processors
  - 1978: 8086 – 16-bit processor, segmentation – first to use x86 instruction set (designed to be easily translatable from 8008 and 8080 assembly)
  - 1982: 80286 – memory protection
  - 1985: 80386 – 32-bit architecture, "general-purpose" register set, better virtual memory support, IA-32 ISA ← Today's class
  - 1993: Pentium – SIMD support
  - Late 90's, early 00's: Improved SIMD support, many other improvements
  - 2006: Core & Core 2 – Multicore, x86-64 64-bit ISA ←A future class

And It's Backward-Compatible!

- 32-bit mode on current processors will run code written for the 8086
  - And 8008/8080 ISAs can be mechanically translated to run on 8086…
- The Intel descriptions are bloated with modes and flags that obscure the modern, fairly simple 32-bit processor model
- Modern x86 processors have a RISC-like core
  - Simple register-register and register-memory operations
  - Simple x86 instructions preferred; complex CISC instructions supported for compatibility

x86 Assembler

- Two main assembler languages for x86
  - Intel/Microsoft version – what's in the documentation
  - AT&T/GNU assembler – what we're generating
    - Use gcc –S to generate examples from C/C++ code
- These slides use Intel descriptions
  - But slides for x86-64 (the target of your project) will use GNU
- Information later on differences
  - Main changes: dst,src reversed, data types in gnu opcodes, various syntactic changes

Intel ASM Statements

- Format is

  optLabel: opcode operands ; comment

  – optLabel is an optional label
  – opcode and operands make up the assembly language instruction
  – Anything following a ';' is a comment
- Language is very free-form
  – Comments and labels may appear on separate lines by themselves

x86 Memory Model

- 8-bit bytes, byte addressable
- 16-bit words, 32-bit doublewords, and 64-bit quadwords
  – Data should almost always be aligned on "natural" boundaries; huge performance penalty on modern processors if it isn't
- Little-endian – address of a 4-byte integer is address of low-order byte

Processor Registers

- 8 32-bit, mostly general purpose registers (in theory)
  - In reality, 6 or 7 are usable, depending on whether you use ebp
  - eax, ebx, ecx, edx, esi, edi, ebp (base pointer), esp (stack pointer)
- Other registers, not directly addressable
  - 32-bit eflags register
    - Holds condition codes, processor state, etc.
  - 32-bit "instruction pointer" eip
    - Holds address of first byte of next instruction to execute

Processor Fetch-Execute Cycle

- Basic conceptual cycle (same as most other processors you've seen)

```
while (running) {
  fetch instruction beginning at eip address
  eip <- eip + instruction length
  execute instruction
}
```

- Sequential execution unless a jump stores a new "next instruction" address in eip

Instruction Format

- Typical data manipulation instruction
  - opcode dst,src
- Meaning is
  - dst <- dst op src
- Normally, one operand is a register, the other is a register, memory location, or integer constant
  - Can't have both operands in memory – can't encode two memory addresses in 1 instruction

x86 Memory Stack

- Register esp points to the "top" of stack
  - Dedicated for this use; don't use otherwise – some instructions expect this usage
  - Stack grows down (push decrements esp, pop increments)
  - Points to the last 32-bit doubleword pushed onto the stack (not next "free" doubleword)
  - Should always be doubleword aligned
    - Can assume it will start out this way, and will stay aligned unless your code does something bad

Stack Instructions

push src

- esp <- esp – 4; memory[esp] <- src
  (e.g., push src onto the stack)

pop dst

- dst <- memory[esp]; esp <- esp + 4
  (e.g., pop top of stack into dst and logically remove it from the stack)

- These are highly optimized and heavily used
  - The x86 doesn't have enough registers, so the stack is frequently used for temporary space

Stack Frames

- When a method is called, a *stack frame* is traditionally allocated on the top of the stack to hold its local variables
- Frame is popped on method return
- By convention, ebp (base pointer) points to a known offset into the stack frame
  - Local variables referenced relative to ebp
  - (This is often optimized to use esp-relative addresses instead. Frees up ebp, which can be helpful on a register-starved machine; needs additional bookkeeping at compile time, not too hard)

Operand Address Modes (1)

- These should cover most of what we'll need

```
mov  eax,17          ; store 17 in eax
mov  eax,ecx         ; copy ecx to eax
mov  eax,[ebp+8]     ; copy memory to eax
mov  [ebp-12],eax    ; copy eax to memory
```

- References to object fields work similarly – put the object's memory address in a register and use that address plus an offset
- Remember: can't have two memory addresses in a single instruction

Operand Address Modes (2)

- In full generality, a memory address can combine the contents of two registers (with one being scaled) plus a constant displacement:

  [basereg + indexreg*scale + constant]

  – Scale can be 2, 4, 8
- Main use for general form is for array subscripting
- Example: suppose:
  – Array of 4-byte ints; address of the array A is in ecx; subscript i is in eax
  – Code to store ebx in A[i]

```
mov   [ecx+eax*4],ebx
```

Basic Data Movement and Arithmetic Instructions

mov dst,src
- dst <- src

add dst,src
- dst <- dst + src

sub dst,src
- dst <- dst – src

inc dst
- dst <- dst + 1

dec dst
- dst <- dst - 1

neg dst
- dst <- - dst
  (2's complement arithmetic negation)

Integer Multiply and Divide

imul dst,src
- dst <- dst * src
- 32-bit product
- dst *must* be a register

imul dst,src,imm8
- dst <- dst*src*imm8
- imm8 – 8 bit constant
- Can be useful for some subscript computations

idiv src
- Divide edx:eax by src (edx:eax holds sign-extended 64-bit value; cannot use other registers for division)
- eax <- quotient
- edx <- remainder

cdq
- edx:eax <- 64-bit sign extended copy of eax

Bitwise Operations

and dst,src
- dst <- dst & src

or dst,src
- dst <- dst | src

xor dst,src
- dst <- dst ^ src

not dst
- dst <- ~ dst (logical or 1's complement)

Shifts and Rotates

shl dst,count
- dst shifted left count bits

shr dst,count
- dst <- dst shifted right count bits (0 fill)

sar dst,count
- dst <- dst shifted right count bits (sign bit fill)

rol dst,count
- dst <- dst rotated left count bits

ror dst,count
- dst <- dst rotated right count bits

Uses for Shifts and Rotates

- Can often be used to optimize multiplication and division by small constants
  - If you're interested, look at "Hacker's Delight" by Henry Warren, A-W, 2003
    - Lots of very cool bit fiddling and other algorithms
  - But be careful – be sure semantics are OK
- There are additional instructions that shift and rotate double words, use a calculated shift amount instead of a constant, etc.

Load Effective Address

- The unary & operator in C/C++

```
lea  dst,src ; dst <- address of src
```

  - dst must be a register, src should be memory address computation
  - Computes any address arithmetic or indexing in src, stores resulting address in dst
  - Useful to capture addresses for pointers, reference parameters, etc.
  - Also useful for computing arithmetic expressions that match r1+scale*r2+const

Unconditional Jumps

jmp dst

- eip <- address of dst (label)
- Processor will execute that instruction at dst next

Conditional Jumps

- Most arithmetic instructions set "condition code" bits in eflags to record information about the result (zero, non-zero, >0, etc.)
  - True of add, sub, and, or; but *not* imul, idiv, lea
- Other instructions that set eflags

```
cmp dst,src     ; compare dst to src
test dst,src    ; calculate dst & src (logical
                ; and); doesn't change either
```

Conditional Jumps Following Arithmetic Operations

```
jz    label     ; jump if result == 0
jnz   label     ; jump if result != 0
jg    label     ; jump if result > 0
jng   label     ; jump if result <= 0
jge   label     ; jump if result >= 0
jnge  label     ; jump if result < 0
jl    label     ; jump if result < 0
jnl   label     ; jump if result >= 0
jle   label     ; jump if result <= 0
jnle  label     ; jump if result > 0
```

- Obviously, the assembler is providing multiple opcode mnemonics for several of the actual instructions

Compare and Jump Conditionally

- Want: compare two operands and jump if a relationship holds between them
- Would like to do this

  jmp_{cond} op1,op2,label

  but can't, because 3-operand instructions can't be encoded in x86

  (also true of most other machines for that matter)

cmp and jcc

- Instead, use a 2-instruction sequence

```
cmp  op1,op2
jcc  label
```

where jcc is a conditional jump that is taken if the result of the comparison matches the condition cc

Conditional Jumps Following cmp

```
je    label     ; jump if op1 == op2
jne   label     ; jump if op1 != op2
jg    label     ; jump if op1 > op2
jng   label     ; jump if op1 <= op2
jge   label     ; jump if op1 >= op2
jnge  label     ; jump if op1 < op2
jl    label     ; jump if op1 < op2
jnl   label     ; jump if op1 >= op2
jle   label     ; jump if op1 <= op2
jnle  label     ; jump if op1 > op2
```

- Again, the assembler is mapping more than one mnemonic to some machine instructions

Function Call and Return

- The x86 instruction set itself only provides for transfer of control (jump) and return
- Stack is used to capture return address and recover it
- Everything else – parameter passing, stack frame organization, register usage – is a matter of convention and not defined by the hardware

call and ret Instructions

call label

- Push address of next instruction and jump
- esp <- esp – 4; memory[esp] <- eip
  eip <- address of label

ret

- Pop address from top of stack and jump
- eip <- memory[esp]; esp <- esp + 4
- **WARNING!** The word on the top of the stack had better be an address, not some leftover data – i.e., make sure you've popped off everything you pushed since the call

enter and leave

- Complex instructions for languages with nested procedures
  - enter can be slow on current CPUs – best avoided
    - i.e., don't use it in your project
  - leave is equivalent to

```
mov esp,ebp
pop ebp
```

and is generated by many compilers. Fits in 1 byte, saves space. Not clear if it's any faster.

Win 32 C Function Call Conventions

- Wintel code obeys the following conventions for C programs
  - Note: calling conventions normally designed very early in the instruction set/ basic software design. Hard (e.g., basically impossible) to change later.
  - Note: Mac x86 has more restrictive stack frame alignment requirements
- C++ augments these conventions to handle the "this" pointer

Win32 C Register Calling Conventions

- These registers must be restored to their original values before a function returns, if they are altered during execution: esp, ebp, ebx, esi, edi
  - Sometimes called *callee-saved* registers
  - Traditional: push/pop from stack to save/restore (aka *spill/reload*)
- A function may use the other registers (eax, ecx, edx) however it wants, without having to save/restore them
  - Sometimes called *caller-saved*, because the caller must save their values if it wants them later.
- A 32-bit function result is expected to be in eax when the function returns
- Generated code can get away with bending the rules, but watch it when you call external C code (and you will need to do this for your project).
  - i.e., follow the rules when you do make these calls…

Call Site

- Caller is responsible for
  - Pushing arguments on the stack from right to left (allows implementation of varargs)
  - Execute call instruction
  - Pop arguments from stack after return
    - For basic MiniJava, this means add 4*(# arguments) to esp after the return, since everything is either a 32-bit variable (int, bool), or a reference (pointer), and there are no varargs to keep track of

Call Example

n = sumOf(17,42)

```
        push   42                  ; push args
        push   17
        call   sumOf               ; jump & push addr
        add    esp,8               ; pop args
        mov    [ebp+offset_n],eax  ; store result
```


Callee

- Called function must do the following
  - Save (*spill*) registers if necessary
  - Allocate stack frame for local variables
  - Execute function body
  - Ensure result of non-void function is in eax
  - Restore (*reload*) any required registers if necessary
  - Pop the stack frame
  - Return to caller

Function Prologue

- The code that needs to be executed before the statements in the body of the function are executed is referred to as the *prologue*
- For a Win32 function *f*, it looks like this:

```
f:  push    ebp             ; save old frame pointer
    mov     ebp,esp         ; new frame ptr is top of
                            ;  stack after arguments and
                            ;  return address are pushed
    sub     esp,"# bytes needed for stack frame"
                            ; allocate stack frame
```


Win32 Function Epilogue

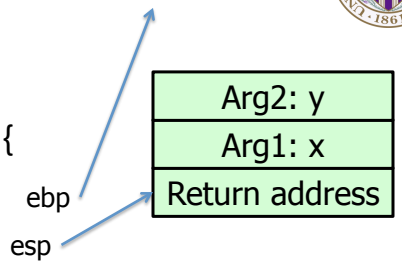
- The *epilogue* is the code that is executed to obey a return statement (or if execution "falls off" the bottom of a void function)
- For a Win32 function, it looks like this:

```
    mov     eax,"function result"
                            ; put result in eax if not already
                            ; there (if non-void function)
    mov     esp,ebp         ; restore esp to old value
                            ; before stack frame allocated
    pop     ebp             ; restore ebp to caller's value
    ret                     ; return to caller
```

Example Function

- Source code

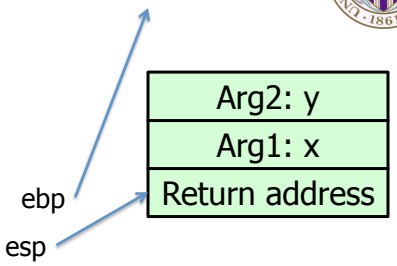
```
int sumOf(int x, int y) {
    int a, int b;
    a = x;
    b = a + y;
    return b;
}
```



Example Function

```
;; int sumOf(int x, int y) {
;;   int a, int b;
sumOf:
    push  ebp       ; prologue
    mov   ebp,esp
    sub   esp, 8

;;  a = x;
    mov  eax,[ebp+8]
    mov  [ebp-4],eax
```



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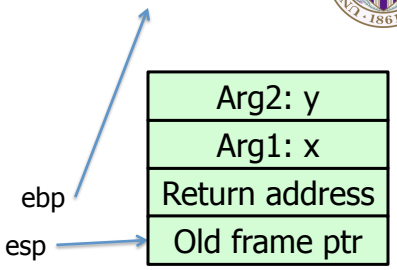

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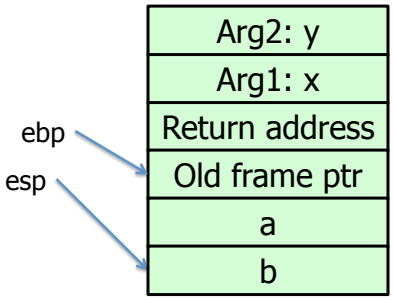

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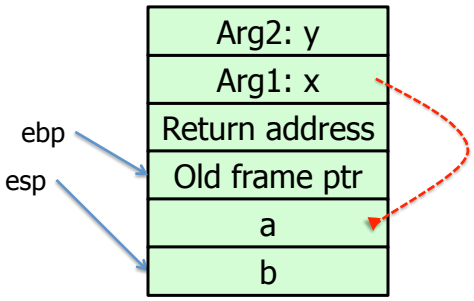
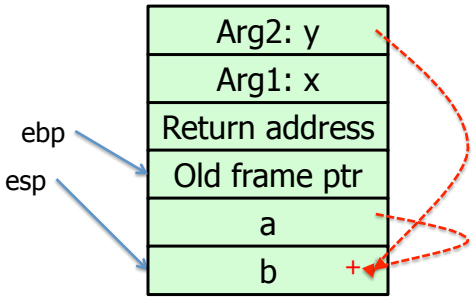


Example Function

```
;; b = a + y;
    mov  eax,[ebp-4]
    add   eax,[ebp+12]
    mov  [ebp-8],eax

;; return b;
    mov  eax,[ebp-8]
    mov  esp,ebp
    pop   ebp
    ret
;; }
```



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    pop   ebp
    ret
;; }
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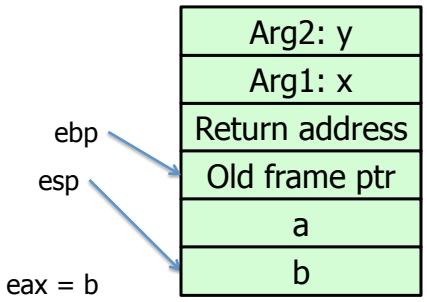

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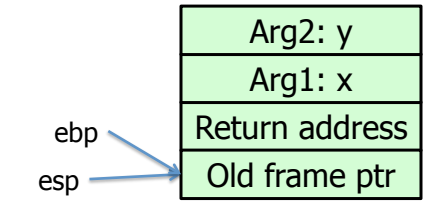

Example Function

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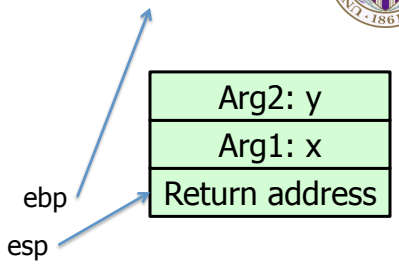
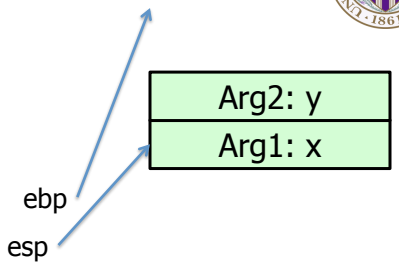


eax = b

Example Function

```
;; b = a + y;
    mov  eax,[ebp-4]
    add  eax,[ebp+12]
    mov  [ebp-8],eax

;; return b;
    mov  eax,[ebp-8]
    mov  esp,ebp
    pop  ebp
    ret
;; }
```



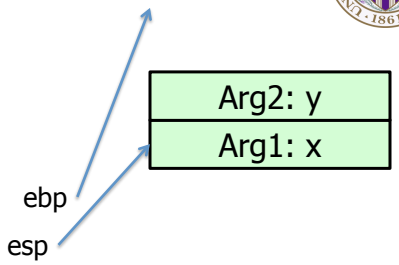
eax = b

eip = Return address

Example Function

```
;; b = a + y;
    mov  eax,[ebp-4]
    add   eax,[ebp+12]
    mov  [ebp-8],eax

;; return b;
    mov  eax,[ebp-8]
    mov  esp,ebp
    pop   ebp
    ret
;; }
```



eax = b

eip = Return address

Caller then pops arguments and stores return value from eax.

Coming Attractions

- Now that we've got a basic idea of the x86 instruction set, we need to map language constructs to x86
  - Code Shape
- Then x86-64, gnu assembler, and MiniJava code generation and execution

Midterm Questions?