Lecture 15: x86-64 assembly language, low-level codegen

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Today

- x86-64 assembly language
- x86-64 tips
- Code generation

x64-64 assembly language

x86-64 assembly language

- Your compiler (in Assignments 3–6) will generate x86-64 assembly language
- x86-64 is the dominant instruction set architecture for general purpose computing (laptops, desktop PCs, servers, etc.)
  - ARM and RISC-V are making inroads, though
- It's a 64-bit architecture
  - Registers are 64 bits wide
  - Memory addresses are 64 bits

x86-64 registers

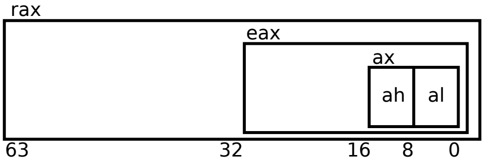
Register(s)	Note
%rip	Instruction pointer
%rax	Function return value
%rdi, %rsi	
%rbx, %rcx, %rdx	
%rsp, %rbp	Stack pointer, frame pointer
%r8, %r9, ..., %r15	

All of these registers are 64 bits (8 bytes)

Aside from %rip and %rsp, all of these are *general-purpose* registers

"Sub"-registers

- For historical reasons (evolution of x86 architecture from 16 to 64 bits), each data register is divided into
  - Low byte
  - Second lowest byte
  - Lowest 2 bytes (16 bits)
  - Lowest 4 bytes (32 bits)
- E.g., `%rax` register has `%al`, `%ah`, `%ax`, `%eax`:



Naming of sub-registers

Register	Sub-register 32 bit	Sub-register 16 bit	Sub-register Lowest 8 bit
%rax	%eax	%ax	%al
%rbx	%ebx	%bx	%bl
%rcx	%ecx	%cx	%cl
%rdx	%edx	%dx	%dl
%rdi	%edi	%di	%dil
%rsi	%esi	%si	%sil
%rsp	%esp	%sp	%spl
%rbp	%ebp	%bp	%bpl
%r8[1]	%r8d	%r8w	%r8b

[1] Same pattern for %r9–%r15

Stack

- The `%rsp` register is the *stack pointer*
  - Contains address of "top" of stack
  - Stack grows down (from high to low addresses), so `%rsp` decreases as stack grows

Assembly language syntax

- Each instruction has a mnemonic (`mov`, `push`, `add`, etc.)
- Most instructions will have one or two *operands* that specify data values (input and/or output)
  - At most **one** operand can be a memory reference
- On Linux, the standard tools use "AT&T" assembly syntax
  - Source is first operand, destination is second
- For instructions that do computations, destination operand is also a source value!
  - I.e., they are destructive
  - This makes code generation a bit interesting

Labels

- A *label* gives a name to the address of a location in memory (code or data)
  - Eventual runtime address generally not known ahead of time, linker and/or dynamic linker will resolve prior to execution
- Used to refer to procedures
- Used to refer to intermediate locations within procedure (local labels)
- Used to refer to global data and constants

Operand size suffixes

- You will notice that instruction mnemonics sometimes use suffixes to indicate the operand size:

Suffix	Bytes	Bits	Note
`b`	1	8	"Byte"
`w`	2	16	"Word"
`l`	4	32	"Long" word
`q`	8	64	"Quad" word

  (Use of `w` to mean 16 bits shows 16-bit origins of x86)
- E.g., `movq` means move a 64 bit value
- You can often omit the operand size suffix, but it's helpful for readability, and can even catch bugs

Assembly operands

Assume `count` and `arr` are global variables, R is a register, N is an immediate, S is 1, 2, 4, or 8

Type	Syntax	Example	Note
Memory ref	*Addr*	`count`	Absolute memory address
Immediate	$\$N$	`$8`, `$arr`	`$arr` is address of `arr`
Register	R	`%rax`	
Memory ref	(R)	`(%rax)`	Address = `%rax`
Memory ref	$N(R)$	`8(%rax)`	Address = `%rax`+8
Memory ref	(R,R)	`(%rax,%rsi)`	Address = `%rax`+`%rsi`
Memory ref	$N(R,R)$	`8(%rax,%rsi)`	Address = `%rax`+`%rsi`+8
Memory ref	$(,R,S)$	`(,%rsi,4)`	Address = `%rsi`×4
Memory ref	(R,R,S)	`(%rax,%rsi,4)`	Address = `%rax`+(`%rsi`×4)
Memory ref	$N(,R,S)$	`8(,%rsi,4)`	Address = (`%rsi`×4)+8
Memory ref	$N(R,R,S)$	`8(%rax,%rsi,4)`	Address = `%rax`+(`%rsi`×4)+8

Data movement

90% of assembly code is data movement (made-up statistic)

- `mov`: copy source operand to destination operand
  - Register
  - Memory location (only one operand can be memory location)
  - Immediate value (source operand only)
- Stack manipulation: `push` and `pop` instructions
  - Generally used for saving and restoring register values
  - `push`: decrement `%rsp` by operand size, copy operand to `(%rsp)`
  - `pop`: copy `(%rsp)` to operand, increment `%rsp` by operand size

Data movement examples

Instruction	Note
`movq $42, %rax`	Store the constant value 42 in `%rax`
`movq %rax, %rdi`	Copy 8 byte value from `%rax` to `%rdi`
`movl %eax, 4(%rdx)`	Move 4 byte value from `%eax` to memory at address `%rdx`+4
`pushq %rbp`	Decrement `%rsp` by 8,
	store contents of `%rbp` in memory location `%rsp`
`popq %rbp`	Load contents of memory location `%rsp` into `%rbp`,
	increment `%rsp` by 8

ALU operations

- ALU = "Arithmetic Logic Unit"
- An ALU is a hardware component within the CPU that does computations (of various kinds) on data values
  - Addition/subtraction
  - Logical operations (shifts, bitwise and/or/negation), etc.
- So, ALU instructions are the ones that do computations on values
  - Typically, ALU operates only on integer values
  - CPU will typically have floating-point unit(s) for operations on FP values

lea instruction

- `lea` stands for "Load Effective Address"
- Instructions that allow a memory reference as an operand generally do an *address computation*
  - E.g., `movl 12(%rdx,%rsi,4), %eax`
  - Computed address (for source memory location) is `%rdx`+(`%rsi`×4)+12
- The `lea` instruction computes a memory address, but does *not* access a memory location
  - E.g., `leaq 12(%rdx,%rsi,4), %rdi`
  - Quite similar to the address-of (&) operator in C and C++

Addition, subtraction

- `add` and `sub` instructions add and subtract integer values
- Two operands, second operand modified to store the result
  - Note that either operand (but not both) could be a memory reference
- E.g.,

```
movq $1, %r9
movq $2, %r10
addq %r9, %r10
/* %r10 now contains the value 3 */
```

- Overflow is possible!
  - Can detect using condition codes

Other ALU operations

There are lots of other ALU instructions!

- `inc`, `dec` (increment and decrement)
- Multiplication and division
- Logical/bitwise operations

Consult your favorite x86-64 reference for details

Control flow, condition codes

- Intra-procedural control flow: unconditional jump, conditional jump
- Target is the address of an instruction (in the same procedure)
  - Usually specified by a label
- Conditional jump check a *condition code*
  - E.g., "jump if equal", "jump if less than", etc.
- Most ALU instructions set condition codes
- Most useful one is the `cmp` instruction

Comparing values

- `cmp` instruction: essentially the same as `sub`, except that it doesn't modify the "result" operand
  - Useful for comparing integer values
- Annoying quirk: AT&T syntax puts the operands in the opposite of the order you might expect
  - E.g., `cmpl %eax, %ebx` computes `%ebx - %eax` and sets condition codes appropriately

Conditional jump

Most often, we want to use the result of a comparison in order to influence a *conditional jump* instruction (used for implementing `if`/`else` logic and eventually-terminating loops)

Examples (^ means XOR, ~ means NOT, & means AND, | means OR):

Instruction	Condition for jump	Meaning
`je`, `jz`	ZF	jump if equal
`jl`	SF ^ OF	jump if less
`jle`	(SF ^ OF) | ZF	jump if less than or equal
`jg`	~(SF ^ OF) & ~ZF	jump if greater
`jge`	~(SF ^ OF)	jump if greater than or equal
`ja`	~CF & ~ZF	jump if above (unsigned)
`jae`	~CF	jump if above or equal (unsigned)
`jb`	CF	jump if below (unsigned)
`jbe`	CF | ZF	jump if below or equal (unsigned)

call and ret

- `call` instruction: calls procedure
  - `%rip` contains address of instruction following `call` instruction
  - Push `%rip` onto stack (as though `pushq %rip` was executed): this is the *return address*
  - Change `%rip` to address of first instruction of called procedure
  - Called procedure starts executing
- `ret` instruction: return from procedure
  - Pop saved return address from stack into `%rip` (as though `popq %rip` was executed)
  - Execution continues at return address

Stack alignment

- The Linux x86-64 calling conventions require `%rsp` to be a multiple of 16 at the point of a procedure call (to ensure that 16 byte values can be accessed on the stack if necessary)
- **Issue:** on entry to a procedure, `%rsp` $\bmod 16 = 8$ because the `call` instruction (which called the procedure) pushed `%rip` (the program counter) onto the stack

Ensuring correct stack alignment

- To ensure correct stack alignment:
  - On procedure entry: `subq $8, %rsp`
  - Prior to procedure return: `addq $8, %rsp`
- The Linux `printf` function will segfault if the stack is misaligned

Register use conventions

- Very important issue:
  - There is only one set of registers
  - Procedures must share them
  - *Register use conventions* are rules that all procedures use to avoid conflicts
- Another important issue:
  - How are argument values passed to called procedures?
  - Calling conventions typically designate that some argument values are passed in specific registers
  - Procedure return value is typically returned in a specific register

x86-64 Linux register use conventions

- Arguments 1–6 passed in `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`
  - Argument 7 and beyond, and "large" arguments such as pass-by-value struct data, passed on stack
- Integer or pointer return value returned in `%rax`
- Caller-saved registers: `%r10`, `%r11` (and also the argument registers)
- Callee-saved registers: `%rbx`, `%rbp`, `%r12`, `%r13`, `%14`, `%r15`

Caller-saved vs. callee-saved

- What happens to register contents when a procedure is called?
- *Callee-saved* registers: caller may assume that the procedure call will preserve their value
  - In general, all procedures must save their values to memory before modifying them, and restore them before returning
- *Caller-saved* registers: caller must *not* assume that the procedure call will preserve their value
  - In general any procedure can freely modify them
  - A caller might need to save their contents to memory prior to calling a procedure and restore the value afterwards

Using registers

- Using registers correctly and effectively is one of the main challenges of assembly language programming
- Some advice:
  - Use caller-saved registers (`%r10`, `%r11`, etc.) for very short-term temporary values or computations
  - You can use the argument registers as (caller-saved) temporary registers
    - Understand that called procedures could modify them!
  - Use callee-saved registers for longer term values that need to persist across procedure calls
    - Use `pushq`/`popq` to save and restore their values on procedure entry and exit

x86-64 tips

Know where to put things

- The `.section` directive specifies which "section" of the executable program assembled code or data will be placed in
- Put things in the right place!
- Code goes in `.text`
- Read-only data such as string constants go in `.rodata`
- Uninitialized (zero-filled) variables and buffers go in `.bss`
  - Use the `.space` directive to indicate how large these are
- Initialized (non-zero-filled) variables and buffers go in `.data`
  - There are various directives such as `.byte`, `.2byte`, `.4byte`, etc. to specify initialized data values

Labels

- Labels are names representing addresses of code or data in memory
- For functions and global variables, use appropriate names
  - Functions and data exported to other modules must be marked with `.globl`
- For control-flow targets within a function, use *local labels*
  - These are labels which start with `.L` (dot, followed by upper case L)
  - The assembler will not add these to the module's symbol table
  - Using "normal" labels for control flow makes debugging difficult because `gdb` thinks they are functions!

Using gdb

- You can debug assembly programs using gdb!
- "Debugging by adding print statements" is less practical for assembly programs than programs in a high level language
  - Which isn't to say it's not possible or (occasionally) useful
- Being able to use gdb confidently will greatly enhance your ability to develop working assembly language programs

gdb tips

- Set breakpoints (`break main`, `break myProg.S:123`)
- `where`: see current call stack
- `disassemble` (or just `disas`): display assembly code of current function (not necessary if code has debug symbols)
- `step`: step to next instruction
- `next`: step to next instruction (stepping over `call` instructions)
- Use $ prefix to refer to registers (e.g., `$rax`, `$edi`, etc.)
- Use `print` and casts to C data types when inspecting data:
  - Print 64 bit value %rsp points to: `print *(unsigned long *)$rsp`
  - Print character string %rdi points to: `print (char *)$rdi`
  - Print fourth element of array of `int` elements that %r12 points to: `print ((int *)$r12)[3]`

Low-level codegen

Generating x86-64 code

In Assignment 4, you will implement generation of high-level code and low-level (x86-64) code for input C programs.

The low-level code generator will translate each high-level instruction into one or more low-level instructions.

There are three key issues to think about:

1. Storage for local variables requiring storage in memory
2. Storage for virtual registers
3. Semantics of high-level instructions vs. x86-64 instructions

Keep in mind the goal of Assignment 4 is *working* code, not *efficient* code

Storage for local variables

Any local integral or pointer local variable whose address is not taken should be assigned a virtual register as its storage (`vr10` or higher).

Arrays, instances of struct types, and any variable whose address is taken will require storage in memory within the stack frame.

`LocalStorageAllocation` is an AST visitor class whose job is to determine storage locations for all local variables in function definitions. Storage allocation decisions should be recorded in symbol table entries (`Symbol` objects)

- Variable references point to these, code generator will be able to access them easily

`StorageCalculator` may be useful for determining storage requirements for local variables requiring storage in memory (but feel free to use your own strategy.)

Storage for virtual registers

For Assignment 4, we recommend allocating storage for all virtual registers in memory in the function's stack frame. Just allocate 8 bytes per virtual register requiring memory storage (`vr10` and above.) The memory block for virtual register storage can be placed alongside the storage for variables requiring memory storage (if any.)

The low-level code generator should be able to easily translate a virtual register into a memory operand accessing memory in the stack frame.

High-level vs. low-level instructions

The high-level IR is "RISC-like": most instructions have one destination operand and two source operands.

The low-level (x86-64) instructions differ in important ways:

- The last operand is the destination (not the first)
- The destination operand is also a source operand (e.g., `subl %edi, %eax` means `%eax ← %eax − %edi`)

The low-level code generator can reserve one or two CPU registers to use as temporary storage locations when a single high-level instruction needs to be translated into multiple low-level instructions. (Suggestion: use `%r10` and `%r11` for this purpose.)

ABI-compliant stack frames

Suggestion: the low-level code for each function should have the form

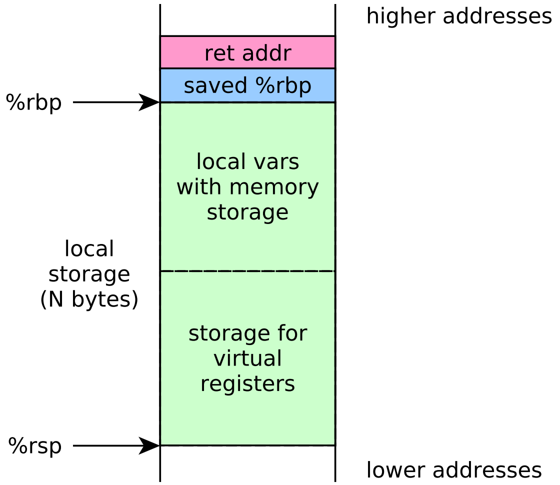
```
        .globl funcname
funcname:
        pushq %rbp
        movq %rsp, %rbp
        subq $N, %rsp

        ...code...

        addq $N, %rsp
        popq %rbp
        ret
```

This will reserve an area of size N to use for local variables requiring storage in memory and virtual registers requiring storage in memory. Locations in this area can be accessed at negative offsets from `%rbp`.

Example stack frame



Example program (example10.c)

```
int main(void) {
  int a, *p;
  p = &a;
  *p = 42;
  return a; // should return 42
}
```

High-level translation

```
/* variable 'a' allocated 4 bytes of storage at offset 0 */
/* variable 'p' allocated vreg 10 */
/* Function 'main' uses 4 bytes of memory and 11 virtual registers */
        .globl main
main:
        enter     $4
        localaddr vr11, $0
        mov_q     vr10, vr11
        mov_l     vr11, $42
        mov_l     (vr10), vr11
        localaddr vr11, $0
        mov_l     vr0, (vr11)
        jmp       .Lmain_return
.Lmain_return:
        leave     $4
        ret
```

Low-level translation

```
/* Function 'main': placing memory variables at offset -8 from %rbp */
/* Function 'main' uses 16 total bytes of memory storage for vregs */
/* Function 'main': placing vreg storage at offset -24 from %rbp */
/* Function 'main': 32 bytes of local storage allocated in stack frame */
        .globl main
main:
        pushq   %rbp                /* enter    $4 */
        movq    %rsp, %rbp
        subq    $32, %rsp
        leaq    -8(%rbp), %r10      /* localaddr vr11, $0 */
        movq    %r10, -16(%rbp)
        movq    -16(%rbp), %r10     /* mov_q    vr10, vr11 */
        movq    %r10, -24(%rbp)
        movl    $42, -16(%rbp)      /* mov_l    vr11, $42 */
        movq    -24(%rbp), %r11     /* mov_l    (vr10), vr11 */
        movl    -16(%rbp), %r10d
        movl    %r10d, (%r11)
        leaq    -8(%rbp), %r10      /* localaddr vr11, $0 */
        movq    %r10, -16(%rbp)
        movq    -16(%rbp), %r11     /* mov_l    vr0, (vr11) */
        movl    (%r11), %eax
        jmp     .Lmain_return       /* jmp      .Lmain_return */
.Lmain_return:
        addq    $32, %rsp           /* leave    $4 */
        popq    %rbp
        ret                         /* ret       */
```

Observations

The generated low-level code has obvious inefficiencies:

- Frequent use of memory operands
- Frequent use of `%r10` and `%r11` as temporary locations

We will cover techniques to fix these inefficiencies later on.