

Lecture 6: Machine-level program representation

David Hovemeyer

February 2, 2024

601.229 Computer Systems Fundamentals



Compiling and executing a C program

Compilation

- ▶ There are many high-level programming languages (Java, Python, C, C++, ...)

Compilation

- ▶ There are many high-level programming languages (Java, Python, C, C++, ...)
- ▶ A computer can only directly execute *machine code*

Compilation

- ▶ There are many high-level programming languages (Java, Python, C, C++, ...)
- ▶ A computer can only directly execute *machine code*
- ▶ So, translation from high-level language code to machine code is necessary
- ▶ Strategies:

Compilation

- ▶ There are many high-level programming languages (Java, Python, C, C++, ...)
- ▶ A computer can only directly execute *machine code*
- ▶ So, translation from high-level language code to machine code is necessary
- ▶ Strategies:
 - ▶ Interpretation: a program “interprets” the high-level code and carries out the specified computation

Compilation

- ▶ There are many high-level programming languages (Java, Python, C, C++, ...)
- ▶ A computer can only directly execute *machine code*
- ▶ So, translation from high-level language code to machine code is necessary
- ▶ Strategies:
 - ▶ Interpretation: a program “interprets” the high-level code and carries out the specified computation
 - ▶ Compilation: a *compiler* program translates the high-level code into machine code

Compilation

- ▶ There are many high-level programming languages (Java, Python, C, C++, ...)
- ▶ A computer can only directly execute *machine code*
- ▶ So, translation from high-level language code to machine code is necessary
- ▶ Strategies:
 - ▶ Interpretation: a program “interprets” the high-level code and carries out the specified computation
 - ▶ Compilation: a *compiler* program translates the high-level code into machine code
 - ▶ Hybrid strategies are possible (e.g., Java Virtual Machine)

Compiling C code

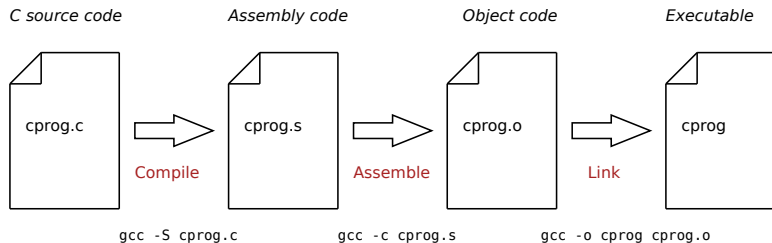
Example C program:

```
#include <stdio.h>
#include <stdlib.h>

long times10(long x) {
    long result = (x << 3) + (x << 1);
    return result;
}

int main(void) {
    printf("Enter value: ");
    long x;
    scanf("%ld", &x);
    long y = times10(x);
    printf("Result=%ld\n", y);
    return 0;
}
```

Compiling a C program



Compile and assemble steps are often combined (convert `.c` to `.o`), but they are still separate steps

C vs. assembly code

C code:

```
long times10(long x) {  
    long result =  
        (x << 3) + (x << 1);  
    return result;  
}
```

Assembly code:

```
times10:  
    leaq (%rdi,%rdi), %rax  
    leaq (%rax,%rdi,8), %rax  
    ret
```

Assembly vs. machine code

Assembly code must be *assembled into machine code*:

Assembly code:

```
times10:
```

```
    leaq (%rdi,%rdi), %rax
```

```
    leaq (%rax,%rdi,8), %rax
```

```
    ret
```

Machine code:

```
48 8d 04 3f
```

```
48 8d 04 f8
```

```
c3
```

The CPU can directly decode and execute machine instructions

x86-64 assembly programming

Why learn assembly language?

- ▶ Since compilers exist, why learn how to write assembly code?

Why learn assembly language?

- ▶ Since compilers exist, why learn how to write assembly code?
 - ▶ Have complete control over hardware

Why learn assembly language?

- ▶ Since compilers exist, why learn how to write assembly code?
 - ▶ Have complete control over hardware
 - ▶ Understand hardware-level program execution
 - ▶ Important for understanding security vulnerabilities, and how to avoid introducing them

Why learn assembly language?

- ▶ Since compilers exist, why learn how to write assembly code?
 - ▶ Have complete control over hardware
 - ▶ Understand hardware-level program execution
 - ▶ Important for understanding security vulnerabilities, and how to avoid introducing them
 - ▶ Optimize performance-critical code

Why learn assembly language?

- ▶ Since compilers exist, why learn how to write assembly code?
 - ▶ Have complete control over hardware
 - ▶ Understand hardware-level program execution
 - ▶ Important for understanding security vulnerabilities, and how to avoid introducing them
 - ▶ Optimize performance-critical code
 - ▶ Implement code generators (compilers, JIT compilers)

x86-64 architecture

Selected “x86” processors

CPU	Vendor	Year	Bits	Note
8086	Intel	1978	16	
80386	Intel	1985	32	32-bit, virtual memory
Pentium	Intel	1993	32	
Pentium Pro	Intel	1995	32	
Pentium III	Intel	1999	32	
Pentium 4	Intel	2004	32	
Opteron	AMD	2003	64	First 64-bit x86 (“AMD64”)

Subsequent Intel CPUs adopted the AMD64 architecture (calling it “EM64T”)

Often called “x86-64” or just “x64”

x86-64 registers

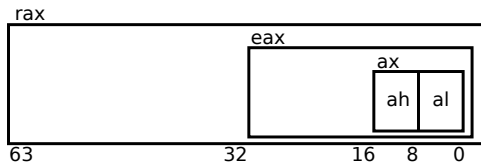
Register(s)	Note
<code>%rip</code>	Instruction pointer
<code>%rax</code>	Function return value
<code>%rdi, %rsi</code>	
<code>%rbx, %rcx, %rdx</code>	
<code>%rsp, %rbp</code>	Stack pointer, frame pointer
<code>%r8, %r9, ..., %r15</code>	

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 %a1, %ah, %ax, %eax:



Memory

- ▶ Conceptually, memory is a big array of byte-sized storage locations
- ▶ Each location has an address
- ▶ In x86-64, addresses are 64 bit, so 2^{64} addresses
- ▶ In reality, there are additional details:
 - ▶ Actual x86-64 processors don't use all of the address bits
 - ▶ *Virtual memory* creates an arbitrary mapping of address to physical memory
 - ▶ Virtual memory is mapped “sparsely”: only some ranges of addresses are mapped to actual memory

A C program

```
#include <stdio.h>

char buf[1000];
int arr[21];

int main(void) {
    int i, j;
    fgets(buf, 1000, stdin);
    for (i = 0; i < 21; i++)
        sscanf(buf + i*2, "%2x", &arr[i]);
    for (i = 0; i < 21; i++)
        printf("%c%s", arr[i], (i+1)%7 == 0 ? "\n" : "");
    return 0;
}
```

Running the C program

```
$ gcc -o art art.c
```

```
$ ./art
```

```
7C5C2D2D2D2F7C7C206F5F6F207C205C5F5E5F2F20
```

```
| \---/ |
```

```
| o_o |
```

```
\_^_/
```

:~)

Memory layout of C program

Using the `pmap` command to inspect the memory map of the running program:

```
29208: ./art
0000562d71c36000      4K r-x-- art
0000562d71e36000      4K r---- art
0000562d71e37000      4K rw--- art
0000562d735fc000    132K rw--- [ anon ]
00007f7b5b9a5000   1948K r-x-- libc-2.27.so
00007f7b5bb8c000   2048K ----- libc-2.27.so
00007f7b5bd8c000     16K r---- libc-2.27.so
00007f7b5bd90000      8K rw--- libc-2.27.so
00007f7b5bd92000     16K rw--- [ anon ]
00007f7b5bd96000    156K r-x-- ld-2.27.so
00007f7b5bfa0000      8K rw--- [ anon ]
00007f7b5bfd0000      4K r---- ld-2.27.so
00007f7b5bfbe000      4K rw--- ld-2.27.so
00007f7b5bfbf000      4K rw--- [ anon ]
00007fff84484000    132K rw--- [ stack ]
00007fff845d4000     12K r---- [ anon ]
00007fff845d7000      8K r-x-- [ anon ]
fffffffff6000000      4K r-x-- [ anon ]
total                4512K
```

Stack

- ▶ The *stack* is an extremely important runtime data structure
- ▶ Is a stack of *activation records*, a.k.a. “stack frames”
- ▶ A stack frame represents an in-progress function call, and contains
 - ▶ Return address (address of instruction where control should return when function returns)
 - ▶ Local variables
 - ▶ Temporary data
- ▶ 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

Clicker quiz!

Clicker quiz omitted from public slides

Assembly language!

- ▶ Assembly code = sequence of instructions
 - ▶ Executed sequentially

Assembly language!

- ▶ Assembly code = sequence of instructions
 - ▶ Executed sequentially (kind of, see Chapter 5)

Assembly language!

- ▶ Assembly code = sequence of instructions
 - ▶ Executed sequentially (kind of, see Chapter 5)
- ▶ Each instruction has a mnemonic (`mov`, `push`, `add`, etc.)

Assembly language!

- ▶ Assembly code = sequence of instructions
 - ▶ Executed sequentially (kind of, see Chapter 5)
- ▶ 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)

Assembly language!

- ▶ Assembly code = sequence of instructions
 - ▶ Executed sequentially (kind of, see Chapter 5)
- ▶ 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)
- ▶ On Linux, the standard tools use “AT&T” assembly syntax
 - ▶ Source is first operand, destination is second

Assembly code structure, labels

- ▶ Assembly code generally specifies both code and data
 - ▶ Much like code written in a high level language
 - ▶ A *label* marks the location of a chunk of code and/or data
 - ▶ Syntax:

```
nameOfLabel:  
    labeled code or data
```

- ▶ When the assembly code eventually runs, its code and data are loaded into memory
- ▶ So, labels are synonymous with *memory addresses*
- ▶ In general, you can use labels as memory addresses in your assembly code

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 labels indicating the addresses of global variables, *R* is a register, *N* is an immediate, *S* is 1, 2, 4, or 8

Type	Syntax	Example	Note
Memory ref	<i>Addr</i>	<i>count</i>	Content of memory location specified by absolute memory address
Immediate	$\$N$	$\$8, \arr	$\$arr$ is address of <i>arr</i>
Register	<i>R</i>	<i>%rax</i>	
Memory ref	(<i>R</i>)	(<i>%rax</i>)	Address = <i>%rax</i>
Memory ref	<i>N</i> (<i>R</i>)	8(<i>%rax</i>)	Address = <i>%rax</i> +8
Memory ref	(<i>R</i> , <i>R</i>)	(<i>%rax,%rsi</i>)	Address = <i>%rax</i> + <i>%rsi</i>
Memory ref	<i>N</i> (<i>R</i> , <i>R</i>)	8(<i>%rax,%rsi</i>)	Address = <i>%rax</i> + <i>%rsi</i> +8
Memory ref	(, <i>R</i> , <i>S</i>)	(, <i>%rsi</i> ,4)	Address = <i>%rsi</i> ×4
Memory ref	(<i>R</i> , <i>R</i> , <i>S</i>)	(<i>%rax,%rsi</i> ,4)	Address = <i>%rax</i> +(<i>%rsi</i> ×4)
Memory ref	<i>N</i> (, <i>R</i> , <i>S</i>)	8(, <i>%rsi</i> ,4)	Address = (<i>%rsi</i> ×4)+8
Memory ref	<i>N</i> (<i>R</i> , <i>R</i> , <i>S</i>)	8(<i>%rax,%rsi</i> ,4)	Address = <i>%rax</i> +(<i>%rsi</i> ×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
<code>movq \$42, %rax</code>	Store the constant value 42 in <code>%rax</code>
<code>movq %rax, %rdi</code>	Copy 8 byte value from <code>%rax</code> to <code>%rdi</code>
<code>movl %eax, 4(%rdx)</code>	Copy 4 byte value from <code>%eax</code> to memory at address <code>%rdx+4</code>
<code>pushq %rbp</code>	Decrement <code>%rsp</code> by 8, store contents of <code>%rbp</code> in memory location <code>%rsp</code>
<code>popq %rbp</code>	Load contents of memory location <code>%rsp</code> into <code>%rbp</code> , increment <code>%rsp</code> by 8

Clicker quiz!

Clicker quiz omitted from public slides

Assigning 32 bit value to 64 bit register

- ▶ Each 64 bit register has an alias for the lower 32 bits
 - ▶ `%rax, %eax`
 - ▶ `%rdi, %edi`
 - ▶ `%r10, %r10d`
 - ▶ etc.
- ▶ Storing a value in the low 32 bits *clears the upper 32 bits*
- ▶ E.g.:

```
movq $0xffffffffffffffff, %rax /* %rax initially contains ffffffffffffffff */
movl $1, %eax                 /* %rax now contains 1 */
```

Zero-extension, sign-extension

- ▶ When moving a smaller source value to a larger destination, sign-extension (copying sign bit to high bits of result) is necessary to preserve the value of a signed value
- ▶ E.g., representation of -16381 as 16 bit and 32 bit values:

Bits	Representation
16	1100000000000011
32	11111111111111111100000000000011

- ▶ Data movement with sign-extension: `movsbw`, `movsbl`, `movswl`, etc.
 - ▶ E.g., `movswl %ax, %edi`
- ▶ For unsigned values, data movement with zero-extension (copying 0 into high bits of result): `movzbw`, `movzbl`, `movzwl`, etc.

Example C program

```
#include <stdio.h>

void addLongs(long x, long y, long *p) {
    *p = x + y;
}

int main(void) {
    long a, b, result;
    scanf("%ld", &a);
    scanf("%ld", &b);
    addLongs(a, b, &result);
    printf("Result is %ld\n", result);
    return 0;
}
```

Example assembly program

```
.section .rodata
longIntFmt:
    .string "%ld"
resultFmt:
    .string "Result is %ld\n"

.section .text

    .globl addLongs
addLongs:
    addq %rdi, %rsi
    movq %rsi, (%rdx)
    ret

    .globl main
main:
    pushq %rbp
    subq $32, %rsp
    movq %rsp, %rbp

    movq $longIntFmt, %rdi
    leaq 0(%rbp), %rsi
    call scanf

    movq $longIntFmt, %rdi
    leaq 8(%rbp), %rsi
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    leaq 16(%rbp), %rdx
    call addLongs

    movq $resultFmt, %rdi
    movq 16(%rbp), %rsi
    call printf

    addq $32, %rsp
    popq %rbp
    ret
```

Example assembly program

```
.section .rodata
longIntFmt:
    .string "%ld"
resultFmt:
    .string "Result is %ld\n"

.section .text

    .globl addLongs
addLongs:
    addq %rdi, %rsi
    movq %rsi, (%rdx)
    ret

    .globl main
main:
    pushq %rbp
    subq $32, %rsp
    movq %rsp, %rbp

    movq $longIntFmt, %rdi
    leaq 0(%rbp), %rsi
    call scanf

    movq $longIntFmt, %rdi
    leaq 8(%rbp), %rsi
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    leaq 16(%rbp), %rdx
    call addLongs

    movq $resultFmt, %rdi
    movq 16(%rbp), %rsi
    call printf

    addq $32, %rsp
    popq %rbp
    ret
```

Things to note:

Example assembly program

```
.section .rodata

longIntFmt:
    .string "%ld"
resultFmt:
    .string "Result is %ld\n"

.section .text

    .globl addLongs
addLongs:
    addq %rdi, %rsi
    movq %rsi, (%rdx)
    ret

    .globl main
main:
    pushq %rbp
    subq $32, %rsp
    movq %rsp, %rbp

    movq $longIntFmt, %rdi
    leaq 0(%rbp), %rsi
    call scanf

    movq $longIntFmt, %rdi
    leaq 8(%rbp), %rsi
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    leaq 16(%rbp), %rdx
    call addLongs

    movq $resultFmt, %rdi
    movq 16(%rbp), %rsi
    call printf

    addq $32, %rsp
    popq %rbp
    ret
```

Things to note:

- ▶ The first three function parameters are passed in `%rdi`, `%rsi`, and `%rdx`

Example assembly program

```
.section .rodata

longIntFmt:
    .string "%ld"
resultFmt:
    .string "Result is %ld\n"

.section .text

    .globl addLongs
addLongs:
    addq %rdi, %rsi
    movq %rsi, (%rdx)
    ret

    .globl main
main:
    pushq %rbp
    subq $32, %rsp
    movq %rsp, %rbp

    movq $longIntFmt, %rdi
    leaq 0(%rbp), %rsi
    call scanf

    movq $longIntFmt, %rdi
    leaq 8(%rbp), %rsi
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    leaq 16(%rbp), %rdx
    call addLongs

    movq $resultFmt, %rdi
    movq 16(%rbp), %rsi
    call printf

    addq $32, %rsp
    popq %rbp
    ret
```

Things to note:

- ▶ The first three function parameters are passed in `%rdi`, `%rsi`, and `%rdx`
- ▶ (`%rdx`) means the memory location pointed-to by `%rdx` (like pointer dereference)

Example assembly program

```
.section .rodata

longIntFmt:
    .string "%ld"
resultFmt:
    .string "Result is %ld\n"

.section .text

    .globl addLongs
addLongs:
    addq %rdi, %rsi
    movq %rsi, (%rdx)
    ret

    .globl main
main:
    pushq %rbp
    subq $32, %rsp
    movq %rsp, %rbp

    movq $longIntFmt, %rdi
    leaq 0(%rbp), %rsi
    call scanf

    movq $longIntFmt, %rdi
    leaq 8(%rbp), %rsi
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    leaq 16(%rbp), %rdx
    call addLongs

    movq $resultFmt, %rdi
    movq 16(%rbp), %rsi
    call printf

    addq $32, %rsp
    popq %rbp
    ret
```

Things to note:

- ▶ The first three function parameters are passed in `%rdi`, `%rsi`, and `%rdx`
- ▶ `(%rdx)` means the memory location pointed-to by `%rdx` (like pointer dereference)
- ▶ `8(%rbp)` means the memory location at address `%rbp+8`

Example assembly program

```
.section .rodata

longIntFmt:
    .string "%ld"
resultFmt:
    .string "Result is %ld\n"

.section .text

    .globl addLongs
addLongs:
    addq %rdi, %rsi
    movq %rsi, (%rdx)
    ret

    .globl main
main:
    pushq %rbp
    subq $32, %rsp
    movq %rsp, %rbp

    movq $longIntFmt, %rdi
    leaq 0(%rbp), %rsi
    call scanf

    movq $longIntFmt, %rdi
    leaq 8(%rbp), %rsi
    call scanf

    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    leaq 16(%rbp), %rdx
    call addLongs

    movq $resultFmt, %rdi
    movq 16(%rbp), %rsi
    call printf

    addq $32, %rsp
    popq %rbp
    ret
```

Things to note:

- ▶ The first three function parameters are passed in `%rdi`, `%rsi`, and `%rdx`
- ▶ `(%rdx)` means the memory location pointed-to by `%rdx` (like pointer dereference)
- ▶ `8(%rbp)` means the memory location at address `%rbp+8`
- ▶ `leaq 16(%rbp), %rdx` means compute the address `%rbp+16` and store it in `%rdx` (like address-of)

Example assembly program (continued)

```
.section .rodata

longIntFmt:
    .string "%ld"
resultFmt:
    .string "Result is %ld\n"

.section .text

    .globl addLongs
addLongs:
    addq %rdi, %rsi
    movq %rsi, (%rdx)
    ret

    .globl main
main:
    pushq %rbp
    subq $32, %rsp
    movq %rsp, %rbp

    movq $longIntFmt, %rdi
    leaq 0(%rbp), %rsi
    call scanf

    movq $longIntFmt, %rdi
    leaq 8(%rbp), %rsi
    call scanf

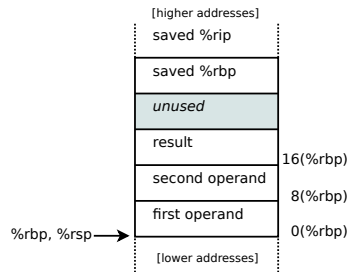
    movq 0(%rbp), %rdi
    movq 8(%rbp), %rsi
    leaq 16(%rbp), %rdx
    call addLongs

    movq $resultFmt, %rdi
    movq 16(%rbp), %rsi
    call printf

    addq $32, %rsp
    popq %rbp
    ret
```

Things to note:

- ▶ 40 bytes are allocated within `main`'s stack frame, including 24 bytes for local variables:



`%rbp` is used to access the local variables