Lecture 6: Machine-level program representation

September 11, 2019

601.229 Computer System Fundamentals

Compiling and executing a C program

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- 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

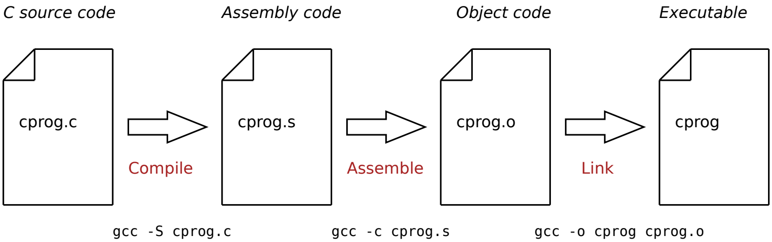
Example C program:

```
#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:	Machine code:
`times10:`	
`    leaq (%rdi,%rdi), %rax`	`48 8d 04 3f`
`    leaq (%rax,%rdi,8), %rax`	`48 8d 04 f8`
`    ret`	`c3`

The CPU can directly decode and execute machine instructions

x86-64 assembly programming

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  - Have complete control over hardware
  - Understand hardware-level program execution
    - Very 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

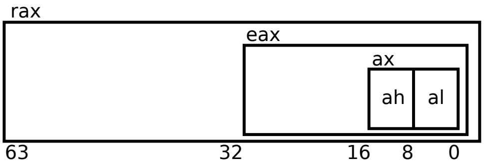
Register(s)	Note
`%rip`	Instruction pointer
`%rax`	Function return value
`%rdi`, `%rsi`	
`%rbx`, `%rcx`, `%rdx`	
`%rsp`, `%rbp`	Stack pointer, frame pointer
`%r8`, `%r9`, ..., `%r15`	

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`:



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 ]
00007f7b5bfbd000      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 ]
ffffffffff600000      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

Assembly operands

TODO: table showing operand types and syntax

Data movement

- General data movement instruction `mov`: an operand can be
  - 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, store operand in memory location pointed-to by `%rsp`
  - `pop`: load value from memory location pointed-to by `%rsp`, store in operand, increment `%rsp` by operand size

Data movement examples

Example C program

```c
#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

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Things to note:

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

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- `(%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)

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

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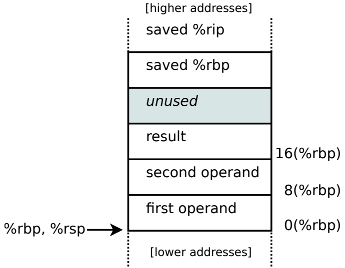

Things to note:

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



`%rbp` is used to access the local variables