Linking and Loading - Part I

Godmar Back

Virginia Tech

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Introduction – Learning Goals

- Understanding the overall processes by which most major systems and infrastructure software is built and executed today
  - how symbols in high-level languages are resolved to addresses and constants in machine code
  - the coordination of linker and loader, particularly in systems exploiting virtual address spaces
  - how linkers allocate space for variables and functions, including the role of symbol tables
- Become proficient as a software engineer at the intermediate level in the C language when separate compilation is used for medium and large programs
  - separate compilation and the role of header files in creating modular code
  - common mistakes
  - best practices when declaring and defining functions and variables
  - the role and purpose of static libraries
  - the role and purpose of dynamic libraries
  - the purpose of whole program link-time optimization
  - the implications of virtual address space layout for debugging program faults
  - how to use common tools such as `nm`, `objdump`, etc.

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Big Picture

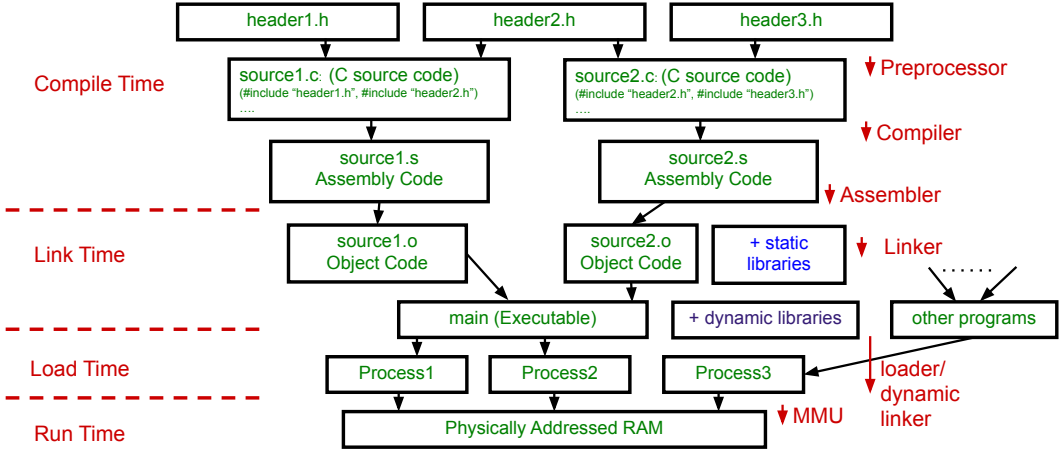

Figure 1: Compilation, Linking, and Loading in a typical System

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Compiler and Assembler

- Preprocessor performs textual insertion of include files
- Compiler resolves the following symbolic names:
  - Local automatic variables, function parameters
  - Field names in structures
- Assembler resolves certain labels for relative branches
- The resulting relocatable .o file still retains symbolic names for all functions and variables that are global in extent

```
extern long longabs(long j);
struct Point {
    long x, y;
};

long manhattan(struct Point * p0,
               struct Point * p1)
{
    long dx = p0->x - p1->x;
    long dy = p0->y - p1->y;
    return longabs(dx)
         + longabs(dy);
}
// symbol table
                 U longabs
0000000000000000 T manhattan
```

```
manhattan:
    pushq    %rbp
    pushq    %rbx
    subq     $8, %rsp
    movq     8(%rdi), %rbp
    movq     (%rdi), %rdi
    subq     8(%rsi), %rbp
    subq     (%rsi), %rdi
    call     longabs
    movq     %rbp, %rdi
    movq     %rax, %rbx
    call     longabs
    addq     $8, %rsp
    addq     %rbx, %rax
    popq     %rbx
    popq     %rbp
    ret
```

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Relocatable Object Files – Text Section

```
0000000000000000 <manhattan>:
   0:   55                      push   %rbp
   1:   53                      push   %rbx
   2:   48 83 ec 08             sub    $0x8,%rsp
   6:   48 8b 6f 08             mov    0x8(%rdi),%rbp
   a:   48 8b 3f                mov    (%rdi),%rdi
   d:   48 2b 6e 08             sub    0x8(%rsi),%rbp
  11:   48 2b 3e                sub    (%rsi),%rdi
  14:   e8 00 00 00 00          callq  19 <manhattan+0x19>
  19:   48 89 ef                mov    %rbp,%rdi
  1c:   48 89 c3                mov    %rax,%rbx
  1f:   e8 00 00 00 00          callq  24 <manhattan+0x24>
  24:   48 83 c4 08             add    $0x8,%rsp
  28:   48 01 d8                add    %rbx,%rax
  2b:   5b                      pop    %rbx
  2c:   5d                      pop    %rbp
  2d:   c3                      retq
```

```
OFFSET           TYPE              VALUE
0000000000000015 R_X86_64_PC32     longabs-0x0000000000000004
0000000000000020 R_X86_64_PC32     longabs-0x0000000000000004
```

- Contain multiple sections (only `text` shown here)
- Each section is laid out starting as if starting at 0
- Contains *relocation records*: placeholders and meta information about how to patch them up once actual addresses are known

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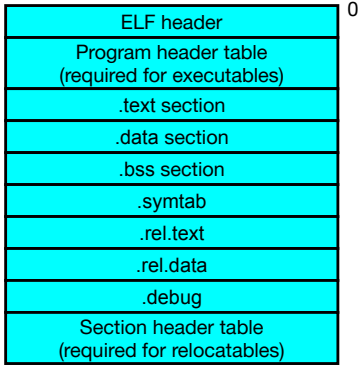
Executable and Linkable Format (ELF)

- ELF is a standard format for relocatable object files, executables, and shared objects (dynamic libraries) used in System V and derived systems, including Linux [URL]
- Other formats include Mach-O (OSX), PE (Windows), a.out
- Provides the link between compiler → linker → loader
- Carries all information needed by the next tool; also debugging and exception handling information
- Extensive tool support



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Treatment of Global Variables

```
extern long elong;

char *name = "CS3214";
long *ptr = &elong;
long s_long = 42;
long w_long;

long adder()
{
  return *ptr + s_long + w_long;
}
// symbol table
0000000000000000 T adder
                 U elong
0000000000000010 D name
0000000000000008 D ptr
0000000000000000 D s_long
0000000000000008 C w_long
```

```
adder:
    movq    ptr(%rip), %rdx
    movq    s_long(%rip), %rax
    addq    (%rdx), %rax
    addq    w_long(%rip), %rax
    ret

    .comm   w_long,8,8
    .data
s_long:
    .quad   42
ptr:
    .quad   elong

    .section    .rodata
.LC0:
    .string "CS3214"

    .data
name:
    .quad   .LC0
```

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Relocatable Object Files – Data, BSS, Read-only Section

```
0000000000000000 <adder>:
   0:        48 8b 15 00 00 00 00          mov    0x0(%rip),%rdx
   7:        48 8b 05 00 00 00 00          mov    0x0(%rip),%rax
   e:        48 03 02                      add    (%rdx),%rax
  11:        48 03 05 00 00 00 00          add    0x0(%rip),%rax
  18:        c3                            retq

OFFSET           TYPE              VALUE
0000000000000003 R_X86_64_PC32     ptr-0x0000000000000004
000000000000000a R_X86_64_PC32     s_long-0x0000000000000004
0000000000000014 R_X86_64_PC32     w_long-0x0000000000000004

OFFSET           TYPE              VALUE
0000000000000008 R_X86_64_64       elong
0000000000000010 R_X86_64_64       .rodata.str1.1

Contents of section .rodata.str1.1:
 0000 43533332 313400                      CS3214.
```

- Global variables that have programmer-defined initial values are stored in the `data` section (`readonly` if constant)
- Global variables without programmer-defined initial values are listed in so-called BSS section ("better save space")

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Linking Multiple Objects Files

- Multiple .o object files are merged into an executable by the linker
- This merging process creates an in-memory layout of the process's code and data
- The linker resolves references (by matching them to definitions) and relocates symbols to their computed address and fills in any placeholders referring to them

```
long elong = 13;
long longabs(long j) {
    return j >= 0 ? j : -j;
}

int
main()
{
    extern long adder();
    return adder();
}

// symbol table
                 U adder
0000000000000000 D elong
0000000000000000 T longabs
0000000000000000 T main
```

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Resulting Symbol Table

source1.o

```
                 U longabs
0000000000000000 T manhattan
```

source2.o

```
0000000000000000 T adder
                 U elong
0000000000000010 D name
0000000000000008 D ptr
0000000000000000 D s_long
0000000000000008 C w_long
```

source3.o

```
                 U adder
0000000000000000 D elong
0000000000000000 T longabs
000000000000001a T main
```

exe

```
// .text.startup
0000000000400450 T main

// .text
0000000000400550 T manhattan
0000000000400580 T adder
00000000004005a0 T longabs

// .data
0000000000601020 D s_long
0000000000601028 D ptr
0000000000601030 D name
0000000000601038 D elong

// .bss
0000000000601048 B w_long
```

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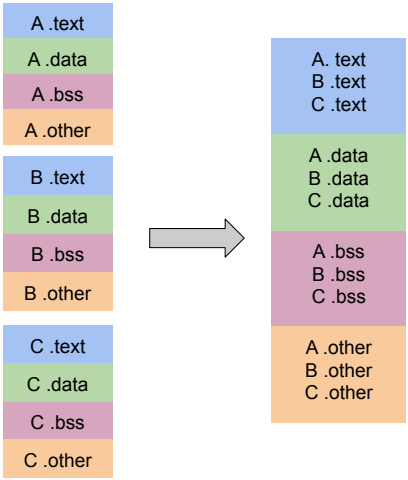
Conceptual Depiction of Merging

- The linker merges like-sections in sequential order (usually as provided on the command line)
- Guided by linker script (`ld --verbose`)
- Resulting executable is designed to be efficiently loaded (or mapped) at load time into the process's virtual address space



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Content of Final Executable

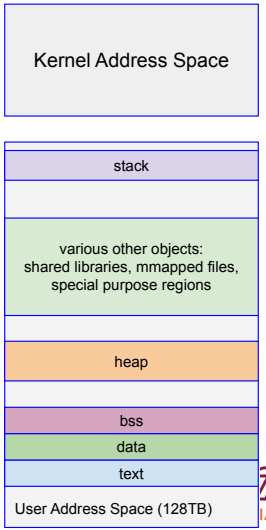
(showing excerpts from .text and .data sections)

```
0000000000400450 <main>:
  400450:       48 83 ec 08          sub    $0x8,%rsp
  400454:       31 c0                xor    %eax,%eax
  400456:       e8 25 01 00 00       callq  400580 <adder>
  40045b:       48 83 c4 08          add    $0x8,%rsp
  40045f:       c3                   retq

0000000000400550 <manhattan>:
  400550:       55                   push   %rbp
  400551:       53                   push   %rbx
  400552:       48 83 ec 08          sub    $0x8,%rsp
  400556:       48 8b 6f 08          mov    0x8(%rdi),%rbp
  40055a:       48 8b 3f             mov    (%rdi),%rdi
  40055d:       48 2b 6e 08          sub    0x8(%rsi),%rbp
  400561:       48 2b 3e             sub    (%rsi),%rdi
  400564:       e8 37 00 00 00       callq  4005a0 <longabs>
  400569:       48 89 ef             mov    %rbp,%rdi
  40056c:       48 89 c3             mov    %rax,%rbx
  40056f:       e8 2c 00 00 00       callq  4005a0 <longabs>
  400574:       48 83 c4 08          add    $0x8,%rsp
  400578:       48 01 d8             add    %rbx,%rax
  40057b:       5b                   pop    %rbx
  40057c:       5d                   pop    %rbp
  40057d:       c3                   retq
  40057e:       66 90                xchg   %ax,%ax
```

```
0000000000400580 <adder>:
  400580:   48 8b 15 a1 0a 20 00    mov    0x200aa1(%rip),%rdx  # 601028 <ptr>
  400587:   48 8b 05 92 0a 20 00    mov    0x200a92(%rip),%rax  # 601020 <s_long>
  40058e:   48 03 02                add    (%rdx),%rax
  400591:   48 03 05 b0 0a 20 00    add    0x200ab0(%rip),%rax  # 601048 <w_long>
  400598:   c3                      retq
  400599:   0f 1f 80 00 00 00 00    nopl   0x0(%rax)

00000000004005a0 <longabs>:
  4005a0:   48 89 fa                mov    %rdi,%rdx
  4005a3:   48 89 f8                mov    %rdi,%rax
  4005a6:   48 c1 fa 3f             sar    $0x3f,%rdx
  4005aa:   48 31 d0                xor    %rdx,%rax
  4005ad:   48 29 d0                sub    %rdx,%rax
  4005b0:   c3                      retq

0000000000601020 <s_long>:
  601020:       2a 00 00 00 00 00 00 00                           *.......

0000000000601028 <ptr>:
  601028:       38 10 60 00 00 00 00 00                           8.`.....

0000000000601030 <name>:
  601030:       58 06 40 00 00 00 00 00                           X.@.....

0000000000601038 <elong>:
  601038:       0d 00 00 00 00 00 00 00
```

Virtual Address Space Layout (Linux x86_64, 48-bit)

```
$ tac /proc/88988/maps
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0      [vsyscall]
7fffffffd000-7ffffffff000 rw-p 00000000 00:00 0              [stack]
7ffff7ffe000-7ffff7fff000 rw-p 00000000 00:00 0
7ffff7ffd000-7ffff7ffe000 rw-p 00029000 fd:00 1714           /usr/lib64/ld-2.28.so
7ffff7ffc000-7ffff7ffd000 r--p 00028000 fd:00 1714           /usr/lib64/ld-2.28.so
7ffff7ffa000-7ffff7ffc000 r-xp 00000000 00:00 0              [vdso]
7ffff7ff7000-7ffff7ffa000 r--p 00000000 00:00 0              [vvar]
7ffff7ff4000-7ffff7ff6000 rw-p 00000000 00:00 0
7ffff7fdc000-7ffff7fdf000 rw-p 00000000 00:00 0
7ffff7dd4000-7ffff7dfd000 r-xp 00000000 fd:00 1714           /usr/lib64/ld-2.28.so
7ffff7dd3000-7ffff7dd4000 rw-p 00002000 fd:00 852474         /usr/local/lib/libph.so
7ffff7dd2000-7ffff7dd3000 r--p 00001000 fd:00 852474         /usr/local/lib/libph.so
7ffff7bd2000-7ffff7dd2000 ---p 00001000 fd:00 852474         /usr/local/lib/libph.so
7ffff7bd1000-7ffff7bd2000 r-xp 00000000 fd:00 852474         /usr/local/lib/libph.so
7ffff7bcd000-7ffff7bd1000 rw-p 00000000 00:00 0
7ffff7bcb000-7ffff7bcd000 rw-p 001bc000 fd:00 1721           /usr/lib64/libc-2.28.so
7ffff7bc7000-7ffff7bcb000 r--p 001b8000 fd:00 1721           /usr/lib64/libc-2.28.so
7ffff79c8000-7ffff7bc7000 ---p 001b9000 fd:00 1721           /usr/lib64/libc-2.28.so
7ffff780f000-7ffff79c8000 r-xp 00000000 fd:00 1721           /usr/lib64/libc-2.28.so
7ffff780e000-7ffff780f000 rw-p 00003000 fd:00 1723           /usr/lib64/libdl-2.28.so
7ffff780d000-7ffff780e000 r--p 00002000 fd:00 1723           /usr/lib64/libdl-2.28.so
7ffff760e000-7ffff780d000 ---p 00003000 fd:00 1723           /usr/lib64/libdl-2.28.so
7ffff760b000-7ffff760e000 r-xp 00000000 fd:00 1723           /usr/lib64/libdl-2.28.so
00601000-00602000 rw-p 00001000 00:2f 120565397402           /home/staff/gback/tmp/m
00600000-00601000 r--p 00000000 00:2f 120565397402           /home/staff/gback/tmp/m
00400000-00401000 r-xp 00000000 00:2f 120565397402           /home/staff/gback/tmp/m
```



Address Space Layout Randomization (ASLR)

- To increase defenses against remote execution vulnerabilities modern systems try to randomize as much of their address space as possible
- E.g., stack, heap locations, but to an increasing extent also code + data
- This impacts the linking process: in general, linker-assigned addresses are "baked" into the machine code, which can be loaded directly
- Loaders can also perform load time relocation (at a cost)
- Position-Independent Code (PIC) can be loaded at any address in the address space without further relocation
- In general, PIC requires indirection. The x86_64's IP-relative addressing mode `disp(%rip)` was introduced to assist in this.

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Summary

- Compiler resolves certain symbolic names, but passes any that are global in extent onto the linker as references in relocatable object files
- Linker merges object files to produce an executable, computing a virtual address space layout in the process
- The executable contains the text and data needed to load a program into memory
- We have ignored so far:
  - Lexical scoping rules (global vs. local to a compilation unit)
  - Rules the linker applies when deciding how to resolve an external reference
  - Static and dynamic libraries

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