Code Generation for Data Processing

Lecture 9: Object Files, Linker, and Loader

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Winter 2024/25

Overview: Post-compilation

- Compiler emits object file
  - Somehow? Some format?
- Linker merges object files and determines required shared libraries
  - Somehow resolves missing symbols?
- Linker creates executable file
  - Somehow? Some format the OS understands?
- Kernel loads executable file into memory
- Someone loads shared libraries

Code Model and Position Independent Code

- Code Model = address constraints
- Allows for better code
  - Long addrs/offsets = more instrs.
- Exact constraints arch/ABI-specific

- x86-64 SysV ABI:
  - Small: code and data max. 2 GiB
  - Medium: code max. 2 GiB
  - Large: no restrictions

- non-PIC: absolute addresses fixed at link-time
  - Addrs can be encoded directly
  - Sometimes slightly faster
  - Not possible for shared libs

- PIC: address random at load time
  - Offsets need be PC-relative
  - Addresses need fixup at load time (e.g., in jump tables)

Compiler needs to know code model

Section 1

Object Files

Executable and Linkable Format (ELF)

- Widely used format for code
  - `REL`: relocatable/object file
  - `EXEC`: executable (non-PIE)
  - `DYN`: shared library/PIE
  - `CORE`: coredump
- ELF header: general information
- Program headers: used for execution
- Section headers: used for linking

ELF Header
Program Headers (not for `REL`)
`.text`
`.rodata`
`.data`
... e.g., symtab, debug
Section Headers (primarily for `REL`)

ELF Header

```
// from glibc's elf.h
typedef struct {
  unsigned char e_ident[EI_NIDENT]; /* Magic number and other info */
  Elf64_Half e_type; /* Object file type */
  Elf64_Half e_machine; /* Architecture */
  Elf64_Word e_version; /* Object file version */
  Elf64_Addr e_entry; /* Entry point virtual address */
  Elf64_Off e_phoff; /* Program header table file offset */
  Elf64_Off e_shoff; /* Section header table file offset */
  Elf64_Word e_flags; /* Processor-specific flags */
  Elf64_Half e_ehsize; /* ELF header size in bytes */
  Elf64_Half e_phentsize; /* Program header table entry size */
  Elf64_Half e_phnum; /* Program header table entry count */
  Elf64_Half e_shentsize; /* Section header table entry size */
  Elf64_Half e_shnum; /* Section header table entry count */
  Elf64_Half e_shstrndx; /* Section header string table index */
} Elf64_Ehdr;
```

ELF Sections

- Structures content of object files for linker
  - Linker later merges content sections of same "type"
- Some sections have "meta" information (e.g., symbols)

- `.text` – program text/code, executable
- `.rodata` – read-only data
- `.data` – initialized data, writable
- `.bss` – zero-initialized data, no storage, writable
  - Name history: block started by symbol
- `.strtab` – string table for symbol names
- `.symtab` – symbol table, references string table for names
- `.shstrtab` – string table for section header names

ELF String Table

- Sequence of NUL-terminated character sequences
- String identified by byte offset
- Must start with a NUL byte: string 0 always empty string
- Must end with a NUL byte: all strings are terminated

Example `.strtab`:

```
\0  v  a  r  n  a  m  e  \0  f  o  o  \0
```

String 0	String 1	String 4	String 9
`""`	`"varname"`	`"name"`	`"foo"`

ELF Section Header

```
typedef struct {
  Elf64_Word sh_name; /* Section name (string tbl index) */
  Elf64_Word sh_type; /* Section type */
  // SHT_{NULL,PROGBITS,SYMTAB,STRTAB,RELA,HASH,NOBITS,...}
  Elf64_Xword sh_flags; /* Section flags */
  // SHF_{WRITE,ALLOC,EXECINSTR,MERGE,STRINGS,...}
  Elf64_Addr sh_addr; /* Section virtual addr at execution */
  Elf64_Off sh_offset; /* Section file offset */
  Elf64_Xword sh_size; /* Section size in bytes */
  Elf64_Word sh_link; /* Link to another section */
  Elf64_Word sh_info; /* Additional section information */
  Elf64_Xword sh_addralign; /* Section alignment */
  Elf64_Xword sh_entsize; /* Entry size if section holds table */
} Elf64_Shdr;
// first section is always undefined/SHT_NULL
```

Example: Section Headers

```c
void external(void);
static void bar(void) {}
void foo(void) { bar(); }
void func(void) {
  foo(); external(); }
```

```
Section Headers:
 [Nr] Name              Type     ES Flg Lk Inf Al
 [ 0]                   NULL     00      0   0  0
 [ 1] .text             PROGBITS 00  AX  0   0  1
 [ 2] .rela.text        RELA     18   I 10   1  8
 [ 3] .data             PROGBITS 00  WA  0   0  1
 [ 4] .bss              NOBITS   00  WA  0   0  1
 [ 5] .comment          PROGBITS 01  MS  0   0  1
 [ 6] .note.GNU-stack   PROGBITS 00      0   0  1
 [ 7] .note.gnu.property NOTE    00   A  0   0  8
 [ 8] .eh_frame         PROGBITS 00   A  0   0  8
 [ 9] .rela.eh_frame    RELA     18   I 10   8  8
 [10] .symtab           SYMTAB   18     11   4  8
 [11] .strtab           STRTAB   00      0   0  1
 [12] .shstrtab         STRTAB   00      0   0  1
```

Symbol Table

- Describes symbolic reference to object/function
- Names in associated string table, referenced by byte offset
- Binding: local (`static`), weak, or global

```
typedef struct {
  Elf64_Word st_name; /* Symbol name (string tbl index) */
  unsigned char st_info; /* Symbol type and binding */
  unsigned char st_other; /* Symbol visibility */
  Elf64_Section st_shndx; /* Section index */
  Elf64_Addr st_value; /* Symbol value */
  Elf64_Xword st_size; /* Symbol size */
} Elf64_Sym;
```

Example: Symbol Table

```
void external(void);
static void bar(void) {}
void foo(void) { bar(); }
void func(void) {
  foo(); external(); }
```

- Ndx=UND: undefined
  - value is zero
- Ndx=ABS: no section base
  - value is absolute
- Ndx=num: section idx.
  - value is offset into sec.
  - later refers to address

```
Section Headers:
  [Nr] Name      Type     Size   ES Flg Lk Inf Al
  [ 0]           NULL     000000 00      0   0  0
  [ 1] .text     PROGBITS 00001a 00  AX  0   0  1
  // ...
  [10] .symtab   SYMTAB   0000a8 18     11   4  8
             sizeof(Elf64_Sym) --/       |   |
                link to strtab ---------/    |
           first non-local sym -------------/
  [11] .strtab   STRTAB   00001f 00      0   0  1
  [12] .shstrtab STRTAB   00006c 00      0   0  1
```

```
Symbol table '.symtab' contains 7 entries:
 Num: Val  Size Type    Bind   Vis     Ndx Name
   0: 000     0 NOTYPE  LOCAL  DEFAULT UND
   1: 000     0 FILE    LOCAL  DEFAULT ABS <stdin>
   2: 000     0 SECTION LOCAL  DEFAULT   1 .text
   3: 000     1 FUNC    LOCAL  DEFAULT   1 bar
   4: 001     6 FUNC    GLOBAL DEFAULT   1 foo
   5: 007    19 FUNC    GLOBAL DEFAULT   1 func
   6: 000     0 NOTYPE  GLOBAL DEFAULT UND external
```

Example: Writing Code to .text

```c
void external(void);
static void bar(void) {}
void foo(void) { bar(); }
void func(void) {
  foo(); external(); }
```

- Symbol may be unknown
- Linker needs to resolve offset later

⇝ Relocations

```
0000000000000000 <bar>:
   0:   c3                  ret
0000000000000001 <foo>:
   1:   e8 fa ff ff ff call    0 <bar>
   6:   c3                  ret
0000000000000007 <func>:
   7:   48 83 ec 08         sub    rsp,0x8
   b:   e8 00 00 00 00 call    10 <func+0x9>
        c: R_X86_64_PC32^a         foo-0x4
  10:   e8 00 00 00 00 call    15 <func+0xe>
        11: R_X86_64_PLT32         external-0x4
  15:   48 83 c4 08         add    rsp,0x8
  19:   c3                  ret
```

[a] Recent GAS emits R_X86_64_PLT32, which is equivalent for local symbols.

Relocations

- Problem: symbol values unknown before linking
  - External symbols: unavailable; other section: distance unknown
- Idea: store *relocations* ⇒ linker patches code/data

- Relocation: quadruple of (offset in sec., type, symbol idx, addend)
- Contained in `REL`/`RELA`/`RELR` sections

Static Relocation `ET_REL`

- For static linker (`ld`)
- Either: resolve or emit dyn. reloc

Dynamic Relocation `ET_EXEC`/`ET_DYN`

- For dynamic linker/loader
- Shall be fast, outside code

Relocation Types

- Types and meaning defined by psABI[47]

P: address of place being relocated; **S**: symbol address; **L**: PLT addr. for symbol; **Z**: sym. size;
A: addend; **B**: dynamic base address of shared obj.; **G**: GOT offset; **GOT**: GOT address

Name	Field	Calculation
R_X86_64_64	64	$S + A$
R_X86_64_PC32	32	$S + A - P$
R_X86_64_GOT32	32	$G + A$
R_X86_64_PLT32	32	$L + A - P$
R_X86_64_GLOB_DAT	addr	S
R_X86_64_JUMP_SLOT	addr	S
R_X86_64_RELATIVE	addr	$B + A$
R_X86_64_GOTPCREL	32	$G + GOT + A - P$
R_X86_64_GOTPCRELX		
R_X86_64_REX_GOTPCRELX		

Name	Field	Calculation
R_X86_64_32	32	$S + A$ (zext)
R_X86_64_32S	32	$S + A$ (sext)
R_X86_64_GOTOFF64	64	$S + A - GOT$
R_X86_64_GOTPC32	32	$GOT + A - P$
R_X86_64_GOT64	64	$G + A$
R_X86_64_GOTPCREL64	64	$G + GOT + A - P$
R_X86_64_GOTPC64	64	$GOT + A - P$
R_X86_64_PLTOFF64	64	$L - GOT + A$
R_X86_64_SIZE32	32	$Z + A$
R_X86_64_SIZE64	64	$Z + A$

[47] x86-64: HJ Lu et al. *System V Application Binary Interface: AMD64 Architecture Processor Supplement*. 2022. 🌐.

Relocation Section

```
Section Headers:
  [Nr] Name        Type     Size   ES Flg Lk Inf Al
  [ 1] .text       PROGBITS 00001a 00  AX  0   0  1
  [ 2] .rela.text  RELA     000030 18   I 10   1  8
             sizeof(Elf64_Rela) --/    |  |    |
          I: info is section link ------/  |    |
                 link to symtab ---------/    |
      target sec. for relocations -------------/
  [10] .symtab     SYMTAB   0000a8 18     11   4  8

Relocation section '.rela.text' at offset 0x1e0 contains 2 entries:
    Offset             Info             Type           Symbol's Name + Addend
00000000000000c  0000000400000002 R_X86_64_PC32    foo - 4
000000000000011  0000000600000004 R_X86_64_PLT32   external - 4
```

Relocations on RISC Architectures

- RISC architectures typically have *more* relocation types
  - Example: AArch64[48] has >50 relocations
- Building a 64-bit address requires several instructions (AArch64: one for bits 0–15, 16–31, ...)
  - Each instruction needs a different relocation to patch in the bits!

```
movz x0, #:abs_g0_nc:globalVariable
movk x0, #:abs_g1_nc:globalVariable
movk x0, #:abs_g2_nc:globalVariable
movk x0, #:abs_g3:globalVariable
```

- Often: page-granular address with added offset for low bits
  - `adrp` for ±4 GiB range, `add` or load offset for low bits
  - Scaled load offsets require different relocations for each scale

[48] Arm Ltd. *ELF for the Arm 64-bit Architecture (AArch64).* (visited on 11/21/2022).

Branch Relocations

- Branches (often) have limited range; compiler must assume max. distance
- x86-64: $\pm$2 GiB range, if larger use `mov` and indirect jump
- AArch64: $\pm$128 MiB range $\rightsquigarrow$ executable sections must be $<$127 MiB
  linker will insert veneer between different `.text` sections
  - Veneer allowed to clobber inter-procedural scratch registers `x16`/`x17`
- *badly designed ISA*: $\pm$1 MiB range $\rightsquigarrow$ needs ind. jump *often*

Branch Relocations on RISC-V

1. Compile the code with:
   `clang -target=riscv64 -c -o rv.o rv.c -falign-functions=16`

   ```
   int f() { return 0; }
   int g() { return f(); }
   int h() { return g(); }
   ```

2. Look at the relocations and disassembly: `llvm-objdump -dr rv.o`
   How are the function calls lowered? What types of relocations are there?
3. Link the file: `ld.lld -shared -o rv.so rv.o` and disassemble `rv.so`.
   What is different now?

Section 2

Executable Files

Linker[49]

- Goal: combine multiple input files (.o/.so/.a) into executable or shared lib.

1. Find and load all input files
2. Scan input, store symbols, resolve symbols on-the-fly
3. Create synthetic section (GOT, PLT, relocations for output file)
4. Process relocations: create PLT/GOT entry and dynamic reloc.
5. Optimize and deduplicate sections
6. Write section to output file
   - Apply relocations which are now known; compress sections; etc.

[49] Interesting blog on LLD: F Song. *Personal Blog*. (visited on 11/21/2022).

ELF Executable File

- Entry in ELF header: entry address of the program
  - Typically provided by libc to call `__libc_start_main`
- Program headers: instructions for loading the program

- `PT_PHDR`: described program headers
- `PT_LOAD`: loadable segment
  - Specifies virtual address, file offset, file size/memory size, permission
  - `vaddr&(pgsize-1)==offset&(pgsize-1)` – kernel will just `mmap` the file
  - memory size > file size ⇒ filled up with zeros (for `.bss`)
- `PT_INTERP`/`PT_DYNAMIC`: when PIE or with shared libraries
- `PT_GNU_STACK`: permissions indicate whether stack is non-executable

Example: Program Headers

```
Program Headers:
  Type           Offset   VirtAddr   FileSiz  MemSiz   Flg Align
  LOAD           0x000000 0x00400000 0x0a0d5e 0x0a0d5e R E 0x1000
  LOAD           0x0a17d8 0x004a27d8 0x005ab8 0x00b2e8 RW  0x1000
        offset in file -/          |          |        |   |
       virtual address -----------/           |        |   |
bytes provided in file ----------------------/         |   |
    segment size in mem ------------------------------/    |
  (memsz > filesz = zero-filled)                           |
       mmap protection -----------------------------------/
  // ...
  GNU_STACK      0x000000 0x00000000 0x000000 0x000000 RW  0x10
```

- Note: the kernel always maps full pages from the file cache
- Note: first segment includes ELF header and program headers

Loading a Binary to Memory

- Load ELF header and program header
- If `ET_DYN` ($\rightsquigarrow$ PIE), set random base added to all addresses
- Look if `PT_INTERP` is present
  - If present, load interpreter using same algorithm (but no nested interpreters)
- Iterate over `PT_LOAD` and `mmap` segments
  - May needs zeroing of last page and mapping extra zero pages
- Setup initial stack frame and auxiliary vector (e.g., with phdr address)
- Start execution at (the interpreter's) entry

This is the kernel's job

Section 3

Linker Optimizations

Eliminating Duplicate Strings/Constants

- Sections in different object may contain same data, e.g. strings
  - Critical for debug info (file names, function names, etc.)
- Idea: linker finds and deduplicates strings and other constant data
- Precondition: relative order of entries irrelevant

- `SHF_MERGE` – fixed-size entries, size stored in header
  - Collect all entries in hash map; afterwards emit all keys

- `SHF_MERGE|SHF_STRINGS` – NUL-terminated strings, entsize is char width
  - Precondition: strings must not contain NUL-byte
  - Tail merging: `foobar\0` + `bar\0` $\rightsquigarrow$ `foobar\0`
  - Sort strings from tail (e.g., radix sort), deduplicate neighbors

COMDAT Groups

```
//--- inline1.cpp
inline int x(int n) {
  return n ? x(n-1) + n : 1; }
int f(int n) { return x(n); }
//--- inline2.cpp
inline int x(int n) {
  return n ? x(n-1) + n : 1; }
int g(int n) { return x(n); }
int main() {}

// clang++ -c -o inline1.o inline1.cpp
// clang++ -c -o inline2.o inline2.cpp
// clang++ -o inline.o inline{1,2}.o
```

1. Inspect sections and symbols of the object files with `llvm-readelf -aW`.
   - What sections are there?
   - Which symbol bindings?
2. Likewise, inspect the executable file
   - How many instances of `x(int)` exist?

Linker Garbage Collection

- Problem: objects may contain unused functions
  - Compiler can't know whether function is used
- Idea: put all function into separate sections, drop unused sections

- Sections are considered as inseparable units
- GC roots: exported symbols, init functions, ...
- Iteratively mark all referenced sections, drop unmarked sections

- Downside: may need longer relocations $\rightsquigarrow$ possibly less efficient code
- GCC/Clang `-ffunction-sections`, `ld --gc-sections`

Identical Code Folding

- Problem: objects may contain duplicate code
  - Same function compiled in many objs, e.g. template instantiation
- Idea: deduplicate read-only sections (same flags, contents, relocations(!))

- Hash all sections and their relocations, remove duplicates
- Repeat until convergence
  - Only after folding `foo1` and `foo2`, these become equivalent:

```
int funcA(void) { foo1(); } int funcB(void) { foo2(); }
```

- Caution: function pointers may be guaranteed to be different
- LLD has more aggressive deduplication

Link-Time Optimization

- Problem: no optimizations across object files
  - Inlining, constant propagation+cloning, specialized call conv., ...
  - Optimization across language boundaries
- Idea 1: glue all source code together, compile with `-fwhole-program`
  - Downside: single core, problematic with same-name `static` functions
- Idea 2: Use static binary optimization during linking (severely limited)
- Idea 3: dump IR into object, glue IR together (`-flto`)
  - Done as very first step at link-time
- LTO is widely used and highly effective

Section 4

Static Libraries

Static Libraries

- Archive of relocatable object files
- Header often contains index mapping symbol to object file
- Linker takes only object files that are needed
- Code/data copied into final executable

+ Simple and fast, no ABI problems, no extra library needed at run-time
− Larger executable files, library changes need relinking

Section 5

Shared Libraries

Shared Libraries

- Problem: code duplication, large executables, recompile needed for changes
- Idea: *share* code between different executables

- Executable references functions/objects in shared library
  - Shared libraries can refer to other shared libraries, too
  - Linker needs to retain dynamic relocations and symbols (dynamic symbol = externally visible symbol)
- Run-time loader links executable and libraries program start
  - Find and load libraries from different paths, resolve all relocations

Shared Libraries: Changes in Compiler

None :)
(almost)

- When building a shared library, code must be position-independent

Shared Libraries: Changes in Linker

- Relocations to symbols in shared libraries must be retained
  - Store dynamic relocations and symbols in separate sections (`.dynsym`, `.rela.dyn`)
- Create table (GOT) for pointers to external function/objects
  - Allocate space where loader puts addresses, add relocations
- Create stub functions for external functions (PLT)
  - Compiler still creates near call, which gets redirected to stub
  - Stub jumps to address stored in table
- Emit `PT_DYNAMIC` segment with info for loader
  - Point loader to needed libs, relocations, symtab, strtab, ...

Global Offset Table (GOT) and Procedure Linkage Table (PLT)

- Global Offset Table: pointer table filled by loader
  - Linker emits dynamic relocations for GOT; loader fills addresses
  - Often subject to RELRO: after relocations are applied, GOT becomes read-only
- Procedure Linkage Table: stubs that perform jump using GOT

```
00401030 <func@plt>:
  401030: ff 25 8a 2f 00 00 jmp    QWORD PTR [rip+0x2f8a] # GOT slot
```

- PLT can be disabled (`-fno-plt`): indirect jump is duplicated
  - Compiler emits indirect calls/jumps instead of near calls to PLT
  - Linker cannot convert into near jump if target is in same DSO

PT_DYNAMIC segment

- Loader needs to know needed libraries, flags, locations of relocations, etc.
  - Sections headers might be unavailable and more info is needed
- Info for loader stored in dynamic section

```
Type                    Name/Value
(NEEDED)                Shared library: [libm.so.6]
(NEEDED)                Shared library: [libc.so.6]
(GNU_HASH)              0x4003c0
(STRTAB)                0x4004b8
(SYMTAB)                0x4003e0
(STRSZ)                 259 (bytes)
(SYMENT)                24 (bytes)
// ...
(NULL)                  0x0
```

Symbol Lookup

- Symbol lookup using linear search + `strcmp` is slow
- Idea: linker creates hash table
  - Hash symbol names and store them in hash table
  - Dynamic symbols grouped by hash bucket
  - Additional bloom filter to avoid useless walks for absent symbols
- Lookup:
  - Compute hash of target symbol string
  - Check bloom filter, if absent: abort
  - Iterate through symbols in bucket, compare names (and version)
- Documentation unfortunately sparse[50]

[50] A Roenky. *ELF: better symbol lookup via DT_GNU_HASH.* (visited on 12/14/2022)

Miscellaneous Things

- Purpose of all these dynamic entries
- Symbols: versioning and visibility
- Thread-local storage
- Constructors/destructors: called at load/unload of DSO
- Indirect functions (ifunc)
  - Function to dynamically determine actual address of symbol
  - Used e.g. for determining `memcpy` variant based on CPU features
- Dynamic loading of DSOs (`dlopen`)

Object Files, Linker, and Loader – Summary

- Compiler needs to know code model to emit proper asm code/relocations
- ELF format used for relocatable files, executables and shared libraries
- ELF relocatables structured in sections and have static relocations
- ELF dynamic executables grouped in segments and have dynamic relocations
  - Need dynamic loader to resolve dynamic relocations and shared libraries
- Linker combines relocatable files into executables or shared libraries
- Linker can perform further optimizations

Object Files, Linker, and Loader – Questions

- Which ELF file types exist? What is different?
- What are typical sections found in an ELF relocatable file?
- What information is contained in a symbol table?
- What information is required for a relocation?
- What are typical differences between static and dynamic relocations?
- Which steps and possible optimization does a linker perform?
- How does the OS load a binary into memory?
- What is the difference between static and shared libraries?
- How are symbols from other shared libraries resolved?