INF333 - Operating Systems

Lecture IX

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Lecture IX
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Course website

burakarslan.com/inf333

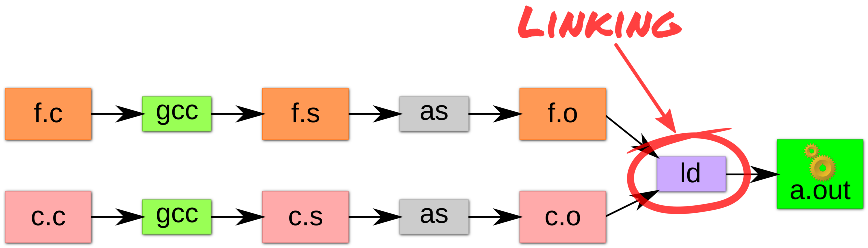
Based On

cs111.stanford.edu

cs212.stanford.edu

OSC-10 Slides

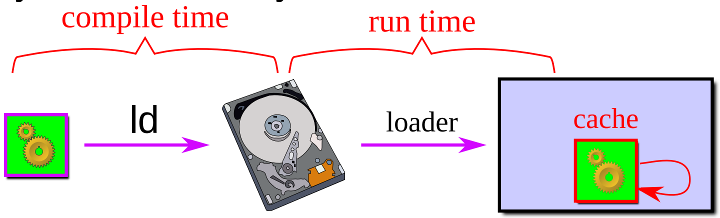
Today's Big Adventure



- How to name and refer to things that don't exist yet
- How to merge separate name spaces into a cohesive whole
- More information:
  - How to write shared libraries
  - Run "`nm`," "`objdump`," and "`readelf`" on a few .o and a.out files.
  - The ELF standard
  - Examine `/usr/include/elf.h`

How is a program executed?

On Unix systems, read by "loader"



- Reads all code/data segments into buffer cache; Maps code (read only) and initialized data (r/w) into addr space
- Or...fakes process state to look like paged out

How is a program executed?

Lots of optimizations happen in practice:

- Zero-initialized data does not need to be read in.
- Demand load: wait until code used before get from disk
- Copies of same program running? Share code
- Multiple programs use same routines: share code

x86 Assembly syntax

- Linux uses AT&T assembler syntax – places destination last
- Types of operand available:
  - Registers start with "%" – `movl %edx,%eax`
  - Immediate values (constants) prefixed by "$" – `movl $0xff,%edx`
  - (%*reg*) is value at address in register *reg* – `movl (%edi),%eax`
  - *n*(%*reg*) is value at address in (register *reg*)+*n* – `movl 8(%ebp),%eax`
  - *%*reg* in an indirection through *reg* – `call *%eax`
  - Everything else is an address – `movl var,%eax; call printf`
- Some heavily used instructions
  - `movl` – moves (copies) value from source to destination
  - `pushl`/`popl` – pushes/pops value on stack
  - `call` – pushes next instruction address to stack and jumps to target
  - `ret` – pops address of stack and jumps to it
  - `leave` – equivalent to `movl %ebp,%esp; popl %ebp`

Gcc extended `asm` syntax [gnu]

`asm volatile (`*template-string* `:` *outputs* `:` *inputs* `:` *clobbers*`);`

- Puts *template-string* in assembly language compiler output
  - Expands %0, %1, ... (a bit like printf conversion specifiers)
  - Use "%%" for a literal % (e.g., "%%cr3" to specify %cr3 register)
- *inputs*/*outputs* specify parameters as `"`*constraint*`" (`*value*`)`

```
int outvar, invar = 3;
asm("movl %1, %0" : "=r" (outvar) : "r" (invar));
/* now outvar == 3 */
```

- *clobbers* lists other state that get used/overwritten
  - Special value `"memory"` prevents reordering with loads & stores
  - Serves as *compiler barrier*, as important as hardware barrier
- `volatile` indicates side effects other than result
  - Otherwise, gcc might optimize away if you don't use result

Perspectives on memory contents

- Programming language view: `x += 1;` `add $1, %eax`
  - Instructions: Specify operations to perform
  - Variables: Operands that can change over time
  - Constants: Operands that never change
- Hardware view:
  - executable: code, usually read-only
  - read only: constants (maybe one copy for all processes)
  - read/write: variables (each process needs own copy)
- Need *addresses* to use data:
  - Addresses locate things. Must update them when you move
  - Examples: linkers, garbage collectors, URL
- Binding time: When is a value determined/computed?
  - Early to late: Compile time, Link time, Load time, Runtime

Clobbering

Clobbering a file, processor register or a region of computer memory is the process of overwriting its contents completely, whether intentionally or unintentionally, or to indicate that such an action will likely occur.

Running example: hello program

- Hello program
  - Write friendly greeting to terminal
  - Exit cleanly
- Every programming language addresses this problem

[demo]

Running example: hello program

- Hello program
  - Write friendly greeting to terminal
  - Exit cleanly
- Every programming language addresses this problem
- Concept should be familiar:

```
int main(int argc, char **argv) {
    cout << "Hello, world!" << endl;
}
```

- Today's lecture: 2 hours on Hello World 😅

Hello world – INF333-style

```
#include <sys/syscall.h>
int my_errno;
const char greeting[] = "hello world\n";

int my_write(int fd, const void *buf, size_t len) {
  int ret;
  asm volatile ("int $0x80" : "=a" (ret)
                : "0" (SYS_write),
                  "b" (fd), "c" (buf), "d" (len)
                : "memory");
  if (ret < 0) { my_errno = -ret; return -1; }
  return ret;
}

int main() { my_write (1, greeting, my_strlen(greeting)); }
```

Examining `hello1.s`

- Grab the source and try it yourself
    - `tar xzf hello.tar.gz`
- `gcc -S hello1.c` produces assembly output in `hello1.s`
- Check the definitions of `my_errno`, `greeting`, `main`, `my_write`
- `.globl` symbol makes *symbol* global

Examining `hello1.s`

- Sections of `hello1.s` are directed to various segments
  - `.text` says put following contents into text segment
  - `.data`, `.rodata` says to put into data or read-only data
  - `.comm` *symbol,size,align* declares *symbol* and allows multiple definitions (like C but not C++, now requires `-fcommon` flag)
- See how function calls push arguments to stack, then pop

```
pushl   $greeting # Argument to my_strlen is greeting
call    my_strlen # Make the call (length now in %eax)
addl    $4, %esp  # Must pop greeting back off stack
```

Disassembling `hello1`

```
 my_write (1, greeting, my_strlen(greeting));
8049208:   68 08 a0 04 08        push   $0x804a008
804920d:   e8 93 ff ff ff        call   80491a5 <my_strlen>
8049212:   83 c4 04              add    $0x4,%esp
8049215:   50                    push   %eax
8049216:   68 08 a0 04 08        push   $0x804a008
804921b:   6a 01                 push   $0x1
804921d:   e8 aa ff ff ff        call   80491cc <my_write>
8049222:   83 c4 0c              add    $0xc,%esp
```

- Disassemble from shell with `objdump -Sr hello1`
- Note `push` encodes address of greeting (0x804a008)
- Offsets in `call` instructions: 0xffffff93 = -109, 0xffffffaa = -86
  - Binary encoding takes offset relative to next instruction

How is a process specified?

```
$ readelf -h hello1
ELF Header:
...
Entry point address:              0x8049030
Start of program headers:         52 (bytes into file)
Start of section headers:         14968 (bytes into file)
Number of program headers:             8
Number of section headers:             23
Section header string table index: 22
```

How is a process specified?

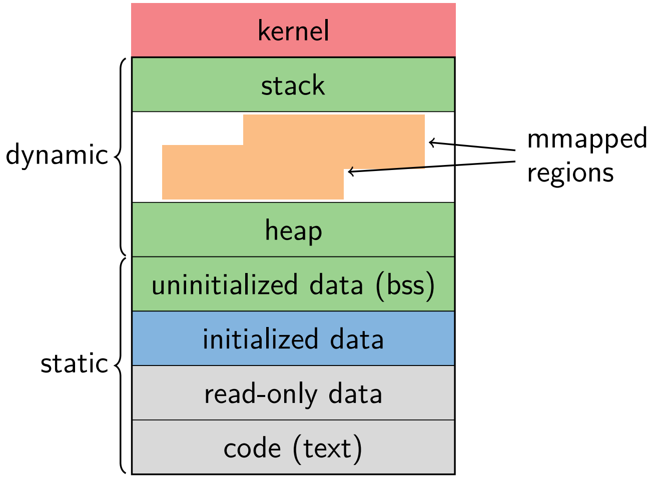
Executable files are the linker/loader interface. Must tell OS:

- What is code? What is data? Where should they live?
- This is part of the purpose of the ELF standard

Every ELF file starts with ELF an *header*

- Specifies *entry point* virtual address at which to start executing
- But how should the loader set up memory?

Recall what process memory looks like



Address space divided into "segments"

- Text, read-only data, data, bss, heap (dynamic data), and stack
- Recall gcc told in which segments to put what contents

Who builds what?

- Heap: allocated and laid out at runtime by malloc
  - Namespace constructed dynamically, managed by *programmer* (names stored in pointers, and organized using data structures)
  - Compiler, linker not involved other than saying where it can start
- Stack: allocated at runtime (func. calls), layout by compiler
  - Names are relative off of stack (or frame) pointer
  - Managed by compiler (alloc on procedure entry, free on exit)
  - Linker not involved because namespace entirely local: Compiler has enough information to build it.
- Global data/code: allocated by compiler, layout by *linker*
  - Compiler emits them and names with symbolic references
  - Linker lays them out and translates references
- Mmapped regions: Managed by programmer or linker
  - Some programs directly call `mmap`; dynamic linker uses it, too

ELF program header

```
$ readelf -l hello1
Program Headers:
  Type      Offset   VirtAddr   PhysAddr   FileSiz MemSiz  Flg Align
  LOAD      0x001000 0x08049000 0x08049000 0x00304 0x00304 R E 0x1000
  LOAD      0x002000 0x0804a000 0x0804a000 0x00158 0x00158 R   0x1000
  LOAD      0x002ff8 0x0804bff8 0x0804bff8 0x0001c 0x0003c RW  0x1000
  ...
 Section to Segment mapping:
  Segment Sections...
   01     ... .text ...
   02     .rodata ...
   03     ... .data .bss
```

- For executables, the ELF header points to a *program header*
  - Says what segments of file to map where, with what permissions

ELF program header

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  LOAD     0x002000 0x0804a000 0x0804a000 0x00158 0x00158 R   0x1000
  LOAD     0x002ff8 0x0804bff8 0x0804bff8 0x0001c 0x0003c RW  0x1000
  ...
 Section to Segment mapping:
  Segment Sections...
   01      ... .text ...
   02      .rodata ...
   03      ... .data .bss
```

- Segment 03 has shorter file size then memory size
  - Only 0x1c bytes must be read into memory from file
  - Remaining 0x20 bytes constitute the .bss
- Who creates the program header? The linker

Linkers (Linkage editors)

- Unix: ld
  - Usually hidden behind compiler
  - Run `gcc -v hello.c` to see ld or invoked (may see collect2)
- Three functions:
  - Collect together all pieces of a program
  - Coalesce like segments
  - Fix addresses of code and data so the program can run
- Result: runnable program stored in new object file
- Why can't compiler do this?

- Usually linkers don't rearrange segments, but can
  - E.g., re-order instructions for fewer cache misses;
    remove routines that are never called from `a.out`

Linkers (Linkage editors)

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- Three functions:
  - Collect together all pieces of a program
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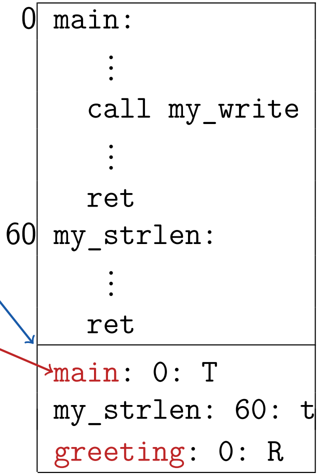
- Result: runnable program stored in new object file
- Why can't compiler do this?
  - Limited world view: sees one file, rather than all files
- Usually linkers don't rearrange segments, but can
  - E.g., re-order instructions for fewer cache misses; remove routines that are never called from `a.out`

Simple linker: two passes needed

- Pass 1:
  - Coalesce like segments; arrange in non-overlapping memory
  - Read files' symbol tables, construct global symbol table with entry for every symbol used or defined
  - Compute virtual address of each segment (at start+offset)
- Pass 2:
  - Patch references using file and global symbol table
  - Emit result
- Symbol table: information about program kept while linker running
  - Segments: name, size, old location, new location
  - Symbols: name, input segment, offset within segment

Where to put emitted objects?

- Assembler:
  - Doesn't know where data/code should be placed in the process's address space
  - Assumes each segment starts at zero
  - Emits symbol table that holds the name and offset of each created object
  - Routines/variables exported by file are recorded as global definitions
- Simpler perspective:
  - Code is in a big byte array
  - Data is in another big byte array
  - Assembler creates (object name, index) tuple for each interesting thing
  - Linker then merges all of these arrays


```
0  main:
      ⋮
     call my_write
      ⋮
     ret
60 my_strlen:
      ⋮
     ret
   -------------------
   main: 0: T
   my_strlen: 60: t
   greeting: 0: R
```

Object files

```
$ objdump -Sr hello2.o
 ...
 48:   50                       push   %eax
 49:   68 00 00 00 00           push   $0x0
                      4a:   R_386_32     greeting
 4e:   6a 01                    push   $0x1
 50:   e8 fc ff ff ff           call   51 <main+0x2a>
                      51:   R_386_PC32   my_write
 55:   83 c4 10                 add    $0x10,%esp
```

- Let's create two-file program `hello2` with `my_write` in separate file
  - Compiler and assembler can't possibly know final addresses
- Notice `push` uses 0 as address of `greeting`
- And `call` uses -4 as address of `my_write`—why?

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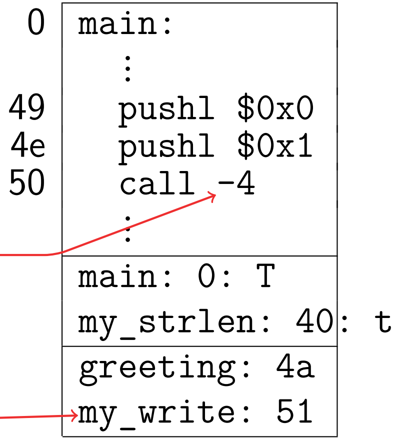
- Let's create two-file program `hello2` with `my_write` in separate file
  - Compiler and assembler can't possibly know final addresses
- Notice `push` uses 0 as address of `greeting`
- And `call` uses -4 as address of `my_write`—why?
  - Target (sitting at offset 51 in text) encoded relative to next instruction (add at offset 55)

Where is everything?

- How to call procedures or reference variables?
  - E.g., call to `my_write` needs a target addr
  - Assembler uses 0 or PC (`%eip`) for address
  - Emits an external reference telling the linker the instruction's offset and the symbol it needs to be patched with
- At link time the linker patches every reference



```
 0  main:
      :
49    pushl $0x0
4e    pushl $0x1
50    call -4
      :
    main: 0: T
    my_strlen: 40: t
    greeting: 4a
    my_write: 51
```

Relocations

```
$ readelf -r hello2.o
    ⋮
 Offset     Info    Type               Sym.Value  Sym. Name
00000039  00000801 R_386_32           00000000   greeting
0000004a  00000801 R_386_32           00000000   greeting
00000051  00000a02 R_386_PC32         00000000   my_write
    ⋮
```

- Object file stores list of required relocations
  - `R_386_32` says add symbol value to value already in file (often 0)
  - `R_386_PC32` says add difference between symbol value and patch location to value already in file (often -4 for `call`)
  - Info encodes type and index of symbol value to use for patch

ELF sections

```
$ readelf -S hello2.o
  [Nr] Name          Type         Addr     Off    Size   ES Flg Lk Inf Al
  [ 0]               NULL         00000000 000000 000000 00      0   0  0
  [ 1] .text         PROGBITS     00000000 000034 0000a4 00  AX  0   0  1
  [ 2] .rel.text     REL          00000000 0005f8 000018 08   I 20   1  4
  [ 3] .data         PROGBITS     00000000 0000d8 000000 00  WA  0   0  1
  [ 4] .bss          NOBITS       00000000 0000d8 000000 00  WA  0   0  1
  [ 5] .rodata       PROGBITS     00000000 0000d8 00000d 00   A  0   0  4
   ⋮
  [20] .symtab       SYMTAB       00000000 0004f0 0000d0 10     21   9  4
  [21] .strtab       STRTAB       00000000 0005c0 000038 00      0   0  1
```

- Memory segments have corresponding PROGBITS file segments
- But relocations and symbol tables reside in segments, too
- Segments can be arrays of fixed-size data structures
    - So strings referenced as offsets into special string segments
- Remember ELF header had section header string table index
    - That's so you can interpret names in section header

Symbol table

```
$ readelf -s hello2.o
   Num:    Value Size Type    Bind   Vis      Ndx Name
               ⋮
     3: 00000000   39 FUNC    LOCAL  DEFAULT    1 my_strlen
               ⋮
     9: 00000000   13 OBJECT  GLOBAL DEFAULT    5 greeting
    10: 00000027   62 FUNC    GLOBAL DEFAULT    1 main
    11: 00000000    0 NOTYPE  GLOBAL DEFAULT  UND my_write
               ⋮
```

- Lists all global, exported symbols
  - Sometimes local ones, too, for debugging (e.g., `my_strlen`)
- Each symbol has an offset in a particular section number
  - On previous slide, 1 = `.text`, 5 = `.rodata`
  - Special undefined section 0 means need symbol from other file

How to lay out emitted objects?

- At link time, linker first:
  - Coalesces all like segments (e.g., all `.text`, `.rodata`) from all files
  - Determines the size of each segment and the resulting address to place each object at
  - Stores all global definitions in a global symbol table that maps the definition to its final virtual address
- Then in a second phase:
  - Ensure each symbol has exactly 1 definition (except weak symbols, when compiling with `-fcommon`)
  - For each relocation:
    - Look up referenced symbol's virtual address in symbol table
    - Fix reference to reflect address of referenced symbol

What is a (static) library?

- A static library is just a collection of `.o` files
- Bind them together with `ar` program, much like `tar`
  - E.g., `ar cr libmylib.a obj1.o obj2.o obj3.o`
  - On many OSes, run `ranlib libmylib.a` (to build index)
- You can also list (`t`) and extract (`x`) files
  - E.g., try: `ar tv /usr/lib/libc.a`
- When linking a `.a` (archive) file, linker only pulls in needed files
  - Ensures resulting executable can be smaller than big library
- `readelf` will operate on every archive member (unweildy)
  - But often convenient to disassemble with `objdump -d /usr/lib/libc.a`

Examining programs with nm

```c
int uninitialized;
int initialized = 1;
const int constant = 2;
int main ()
{
  return 0;
}
```

VA

symbol type

```
$ nm a.out
…
0400400 T _start
04005bc R constant
0601008 W data_start
0601020 D initialized
04004b8 T main
0601028 B uninitialized
```

- If don't need full `readelf`, can use `nm` (`nm -D` on .so)
- R means read-only data (`.rodata` in elf)
  - Note `constant` VA on same page as `main`
  - Share pages of read-only data just like text
- B means uninitialized data in "BSS"
- Lower-case letters correspond to local symbols (`static` in C)

Examining sections with `objdump`

Note Load mem addr. and File off have same page alignment for easy mmapping

```
$ objdump -h a.out
a.out:     file format elf64-x86-64
Sections:
Idx Name     Size      VMA       LMA       File off  Algn
  …
 12 .text    000001a8  00400400  00400400  00000400  2**4
             CONTENTS, ALLOC, LOAD, READONLY, CODE
  …
 23 .data    0000001c  00601008  00601008  00001008  2**3
             CONTENTS, ALLOC, LOAD, DATA
  …
 24 .bss     0000000c  00601024  00601024  00001024  2**2
             ALLOC
  …
```

No contents in file

- Another portable alternative to `readelf`

Name mangling

```
// C++
int foo (int a) {
  return 0;
}

int foo (int a, int
b) {
  return 0;
}
```

Mangling not compatible across compiler versions

```
% nm overload.o
0000000 T _Z3fooi
000000e T _Z3fooii
        U __gxx_personality_v0
```

Name demangler

```
% nm overload.o | c++filt
0000000 T foo(int)
000000e T foo(int, int)
        U __gxx_personality_v0
```

- C++ can have many functions with the same name
- Compiler therefore *mangles* symbols
  - Makes a unique name for each function
  - Also used for methods/namespaces (`obj::fn`), template instantiations, & special functions such as `operator new`

Initialization and destruction

```
// C++
int a_foo_exists;
struct foo_t {
  foo_t () {
    a_foo_exists = 1;
  }
};
foo_t foo;
```

- Initializers run before main
  - Mechanism is platform-specific
- Example implementation:
  - Compiler emits static function in each file running initializers
  - Wrap linker with `collect2` program that generates `___main` function calling all such functions
  - Compiler inserts call to `___main` when compiling real `main`

```
% cc -S -o- ctor.C | c++filt
…
.text
.align 2
__static_initialization_and_destruction_0(int, int):
```

Other information in executables

```
// C++
struct foo_t {
  ~foo_t() {/*...*/}
  except() { throw 0; }
};
void fn () {
  foo_t foo;
  foo.except();
  /* ... */
}
```

- Throwing exceptions destroys automatic variables
- During exception, must find
  - All such variables with non-trivial destructors
  - In all procedures' call frames until exception caught
- Record info in special sections

- Executables can include debug info (compile w. -g)
  - What source line does each binary instruction correspond to?

Dynamic (runtime) linking (`hello3.c`)

```
#include <dlfcn.h>
int main(int argc, char **argv, char **envp) {
  size_t (*my_strlen)(const char *p);
  int (*my_write)(int, const void *, size_t);
  void *handle = dlopen("dest/libmy.so", RTLD_LAZY);
  if (!handle || !(my_strlen = dlsym(handle, "my_strlen"))
              || !(my_write = dlsym(handle, "my_write")))
    return 1;
  return my_write (1, greeting, my_strlen(greeting)) < 0;
}
```

- Link time isn't special, can link at runtime too
  - Get code (e.g., plugins) not available when program compiled

Dynamic (runtime) linking (`hello3.c`)

```
#include <dlfcn.h>
int main(int argc, char **argv, char **envp) {
  size_t (*my_strlen)(const char *p);
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  if (!handle || !(my_strlen = dlsym(handle, "my_strlen"))
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    return 1;
  return my_write (1, greeting, my_strlen(greeting)) < 0;
}
```

- Issues:
  - How can behavior differ compared to static linking?
  - Where to get unresolved symbols (e.g., `my_write`) from?
  - How does `my_write` know its own addresses (e.g., for `my_errno`)?

Dynamic linking

- How can behavior differ compared to static linking?
  - Runtime failure (can't find file, doesn't contain symbols)
  - No type checking of functions, variables
- Where to get unresolved symbols (e.g., `my_write`) from?
  - `dlsym` must parse ELF file to find symbols
- How does `my_write` know its own addresses?

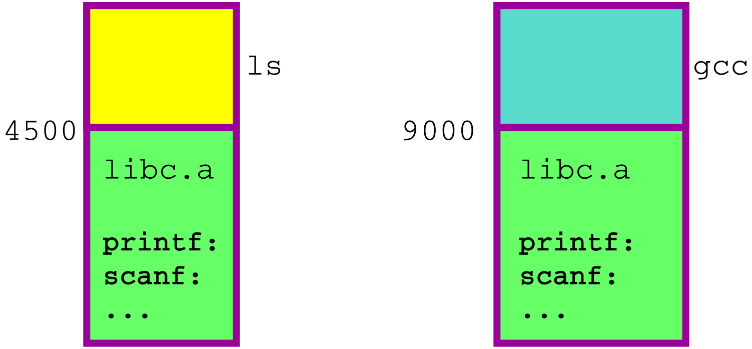
```
$ readelf -r dest/libmy.so

Relocation section '.rel.dyn' at offset 0x20c contains 1 entry:
 Offset     Info    Type            Sym.Value  Sym. Name
00003ffc  00000106 R_386_GLOB_DAT    0000400c   my_errno
```

  - `dlopen`, too, must parse ELF to patch relocations

Static shared libraries

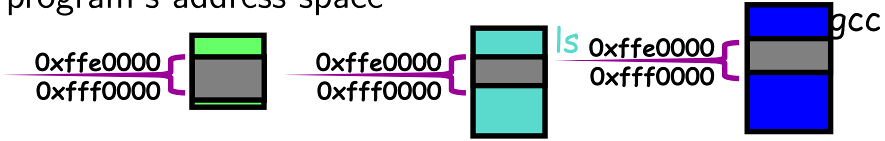
- Observation: everyone links in standard libraries (libc.a.), these libs consume space in every executable.



- Insight: we can have a single copy on disk if we don't actually include libc code in executable

Static shared libraries

- Define a “shared library segment” at same address in every program’s address space



Static shared libraries

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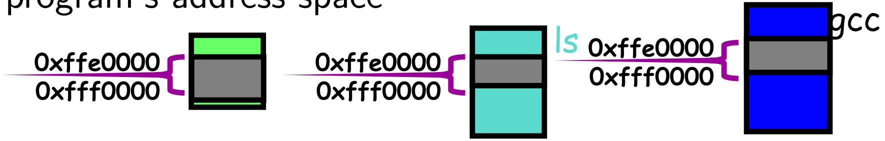
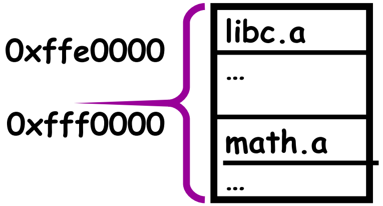
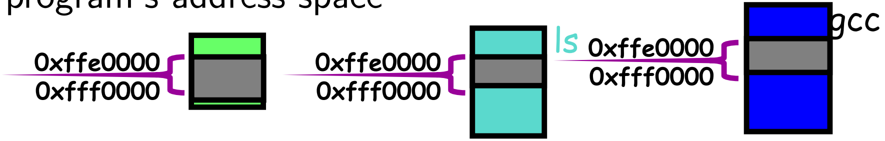


- Every shared lib is allocated a unique range in this seg, and computes where its external defs reside



Static shared libraries

- Define a "shared library segment" at same address in every program's address space



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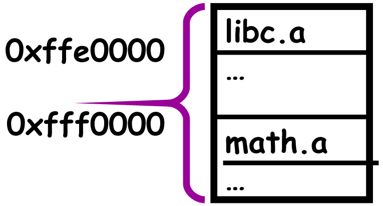
- Linker links program against lib (why?) but does not bring in actual code



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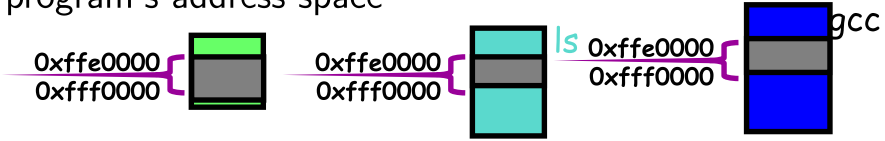

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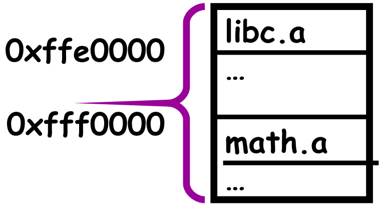

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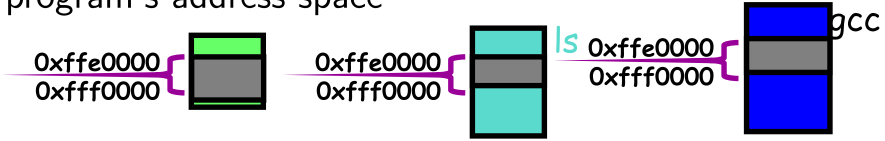

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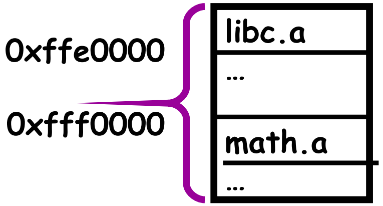


- Linker links program against lib (why?) but does not bring in actual code
- Loader marks shared lib region as unreadable
- When process calls lib code, page faults: embedded linker brings in lib code from known place & maps it in.

Dynamic shared libraries

Static shared libraries require system-wide pre-allocation of address space

- Clumsy, inconvenient
- What if a library gets too big for its space? (fragmentation)
- Can't upgrade libraries w/o relinking applications
- Can space ever be reused?

Solution: Dynamic shared libraries

- Combine shared library and dynamic linking ideas
- Any library can be loaded at any VA, chosen at runtime

Dynamic shared libraries

New problem: Linker won't know what names are valid

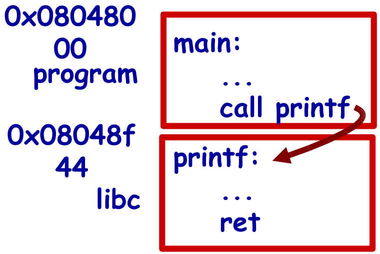
- Solution: stub library

New problem: How to call functions whose position varies?

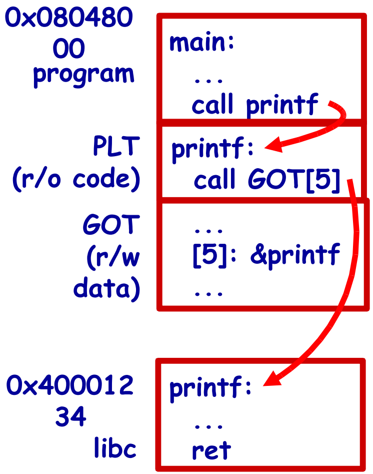
- Solution: Position-independent Code ...

Position-independent code

- Code must be able to run anywhere in virtual memory
- Runtime linking would prevent code sharing, so...
- Add a level of indirection!

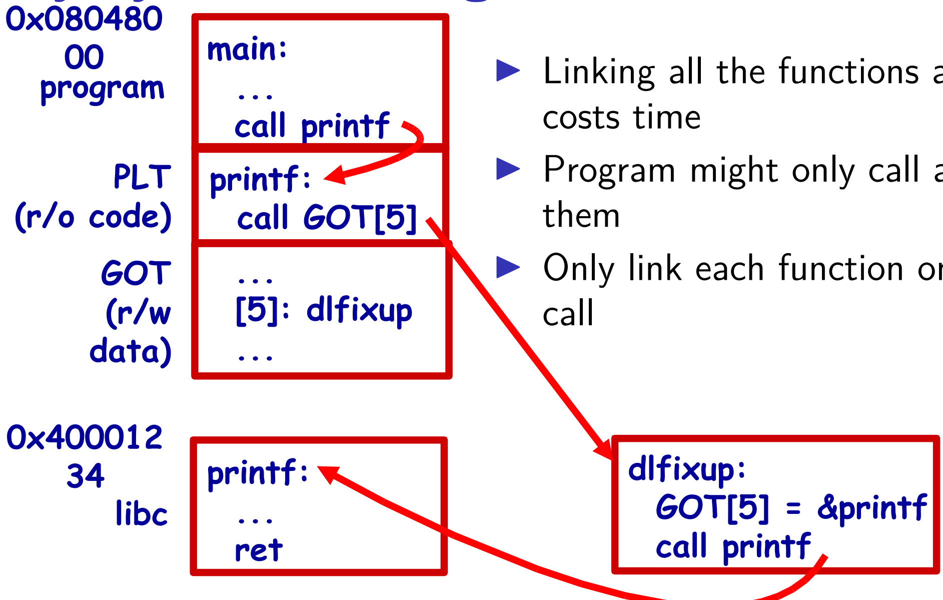


Static Libraries



Dynamic Shared Libraries

Lazy dynamic linking



- Linking all the functions at startup costs time
- Program might only call a few of them
- Only link each function on its first call

Dynamic linking with ELF

- Every dynamically linked executable needs an *interpreter*
  - Embedded as string in special `.interp` section
  - `readelf -p .interp /bin/ls` → `/lib64/ld-linux-x86-64.so.2`
  - So all the kernel has to do is run `ld-linux`
- `dlfixup` uses hash table to find symbols when needed
- Hash table lookups can be quite expensive [Drepper]
  - E.g., big programs like LibreOffice are very slow to start
  - Solution 1: Use a better hash function
    - linux added `.gnu.hash` section, later removed `.hash` sections
  - Solution 2: Export fewer symbols – Imitate Windows:
    - `gcc -fvisibility=hidden` (keep symbols local to DSO)
    - `#pragma GCC visibility push(hidden)`/`visibility pop`
    - `__attribute__(visibility("default"))`, (override for a symbol)

Dynamic shared library example: `hello4`

```
$ objdump -Sr hello4
    ⋮
08049030 <my_write@plt>:
 8049030:       ff 25 0c c0 04 08       jmp    *0x804c00c
 8049036:       68 00 00 00 00          push   $0x0
 804903b:       e9 e0 ff ff ff          jmp    8049020 <.plt>
08049040 <my_strlen@plt>:
 8049040:       ff 25 10 c0 04 08       jmp    *0x804c010
 8049046:       68 08 00 00 00          push   $0x8
 804904b:       e9 d0 ff ff ff          jmp    8049020 <.plt>
    ⋮
 804917a:       68 08 a0 04 08          push   $0x804a008
 804917f:       e8 bc fe ff ff          call   8049040 <my_strlen@plt>
```

- 0x804c00c and 0x804c010 initially point to next instruction

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```

- Calls `dlfixup` with relocation index

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```

- Note the second `jmp` of each entry goes to 0th PLT entry, which jumps to `dlfixup`

hello4 relocations

```
$ readelf -r hello4
Relocation section '.rel.plt' at offset 0x314 contains 2 entries:
 Offset     Info    Type            Sym.Value  Sym. Name
0804c00c  00000107 R_386_JUMP_SLOT   00000000   my_write
0804c010  00000507 R_386_JUMP_SLOT   00000000   my_strlen
```

- PLT = *procedure linkage table* on last slide
  - Small 16 byte snippets, read-only executable code
- `dlfixup` Knows how to parse relocations, symbol table
  - Looks for symbols by name in hash tables of shared libraries
- `my_write` & `my_strlen` are pointers in *global offset table*
  - GOT non-executable, read-write (so `dlfixup` can fix up)
- Note `hello4` knows address of `greeting`, PLT, and GOT
  - How does a shared object (`libmy.so`) find these?
  - PLT is okay because calls are relative
  - In PIC, compiler reserves one register `%ebx` for GOT address

hello4 shared object contents

mywrite.c

```
int my_errno;
int my_write(int fd, const void *buf, size_t len) {
    int ret;
    asm volatile (/* ... */);
    if (ret < 0) {
        my_errno = -ret;
        return -1;
      }
    return ret;
  }
```

mywrite.s

```
        negl %eax
        movl %eax, my_errno
```

mywrite-pic.s

```
        negl %eax
        movl %eax, %edx
        movl my_errno@GOT(%ebx), %eax
        movl %edx, (%eax)
```

How does %ebx get set?

mywrite-pic.s

```
my_write:
       pushl  %ebp
       movl   %esp, %ebp
       pushl  %ebx
       subl   $16, %esp
       call   __x86.get_pc_thunk.bx
       addl   $_GLOBAL_OFFSET_TABLE_, %ebx
        ⋮
__x86.get_pc_thunk.bx:
       movl   (%esp), %ebx
       ret
```

```
$ readelf -r .libs/mywrite.o
 Offset     Info    Type            Sym.Value  Sym. Name
00000008  00000a02 R_386_PC32        00000000   __x86.get_pc_thunk.bx
0000000e  00000b0a R_386_GOTPC       00000000   _GLOBAL_OFFSET_TABLE_
00000036  0000082b R_386_GOT32X      00000000   my_errno
```

Linking and security

```
void fn () {
    char buf[80];
    gets (buf);
    /* ... */
}
```

1. Attacker puts code in buf
   - Overwrites return address to jump to code
2. Attacker puts shell cmd above buf
   - Overwrites return address so function "returns" to `system` function in libc

- People try to address problem with linker
- W^X: No memory both writable and executable
  - Prevents 1 but not 2, must be disabled for jits
- Address space randomization
  - Makes attack #2 a little harder, not impossible
  - Leads to position-independent executable, compiled `-fpie` and linked `-pie`—like PIC for executables
- Also address with compiler (stack protector, CFI)

Linking Summary

- Compiler/Assembler: 1 object file for each source file
  - Problem: incomplete world view
  - Where to put variables and code? How to refer to them?
  - Names definitions symbolically ("`printf`"), refers to routines/variable by symbolic name
- Linker: combines all object files into 1 executable file
  - Big lever: global view of everything. Decides where everything lives, finds all references and updates them
  - Important interface with OS: what is code, what is data, where is start point?
- OS loader reads object files into memory:
  - Allows optimizations across trust boundaries (share code)
  - Provides interface for process to allocate memory (`sbrk`)

Code = data, data = code

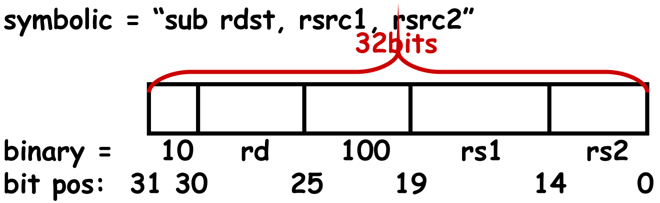
- No inherent difference between code and data
  - Code is just something that can be run through a CPU without causing an "illegal instruction fault"
  - Can be written/read at runtime just like data "dynamically generated code"
- Why? Speed (usually)
  - Big use: eliminate interpretation overhead. Gives 10-100x performance improvement
  - Example: Just-in-time Javascript compiler, or qemu vs. bochs
  - In general: optimizations thrive on information. More information at runtime.
- The big tradeoff:
  - Total runtime = code gen cost + cost of running code

How?

- Determine binary encoding of desired instructions

SPARC: sub instruction

symbolic = "sub rdst, rsrc1, rsrc2"



- Write these integer values into a memory buffer

```
unsigned code[1024], *cp = &code[0];
/* sub %g5, %g4, %g3 */
*cp++ = (2<<30) | (5<<25) | (4<<19) |(4<<14) | 3;
...
```

- Use `mprotect` to disable W^X
- Jump to the address of the buffer: `((int (*)())code)();`