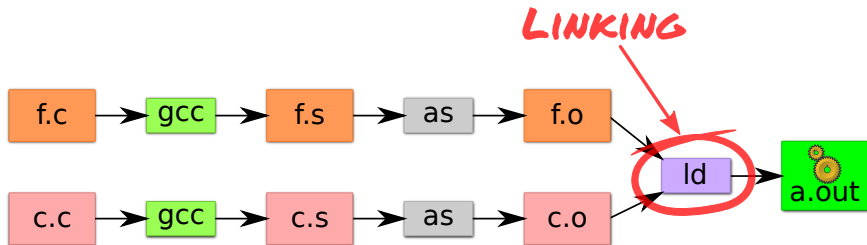


Administrivia

- **Lab 2 due Friday**
- **Midterm review section Friday**
- **Extra (weekend) office hours coming with an additional CA**
- **Midterm exam in class next Monday Feb. 7**
 - Open note, but no textbook or electronic devices
 - Bring lecture note printouts
 - Option D is evolving—prefer one of the others if possible
- **I will hold office hours this Friday 3pm-4:30pm instead of Monday**

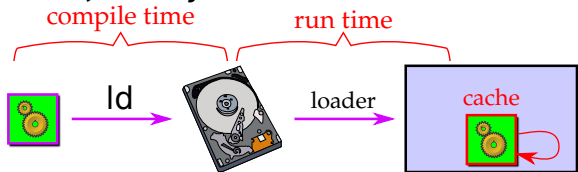
Today's Big Adventure



- 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
- **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
 - Be aware that *intel syntax* (used in manual) places destination first
- **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`

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

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 if you took 106B:**

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

- **Today's lecture: 90 minutes on hello world**

Hello world - CS212-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 /afs/ir.stanford.edu/class/cs212/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
- 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:** `0xffffffff93 = -109`, `0xffffffffaa = -86`
 - Binary encoding takes offset relative to next instruction

How is a process specified?

```
$ readelf -h hello1
```

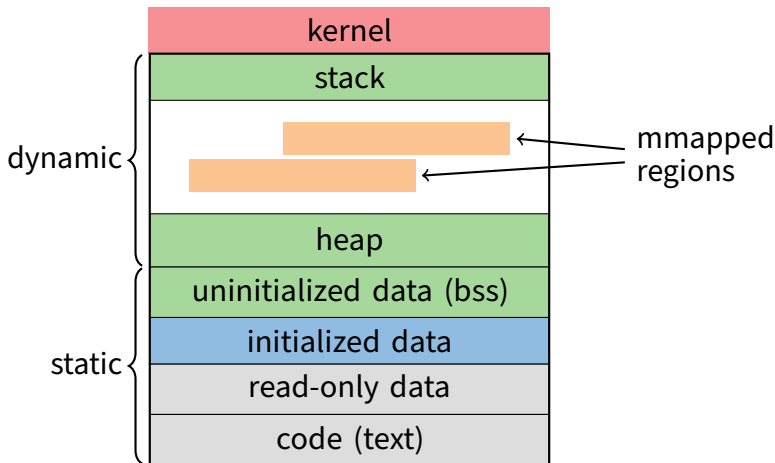
ELF Header:

...

```
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
```

- **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 assembler 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...
01text ...
02	.rodata ...
03data .bss

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

- **Unix: ld**
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 - 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?**
 - 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 char array
- Data is in another big char 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?**

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?**
 - 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

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

- **At link time the linker patches every reference**

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 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

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

```
VA $ nm a.out symbol type  
...  
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 shared objects)**
 - Handy -o flag prints file, useful with grep
- **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 mmappping

```
$ 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
..14 .rodata         00000008   004005b8     004005b8     000005b8     2**2
          CONTENTS, ALLOC, LOAD, READONLY, DATA
..17 .ctors          00000010   00600e18     00600e18     00000e18     2**3
          CONTENTS, ALLOC, LOAD, DATA
..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;
}
```

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

Mangling not compatible across compiler versions

Demangle names

```
% 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):
...
        call    foo_t::foo_t()
```

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

- **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 (continued)

- **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
```

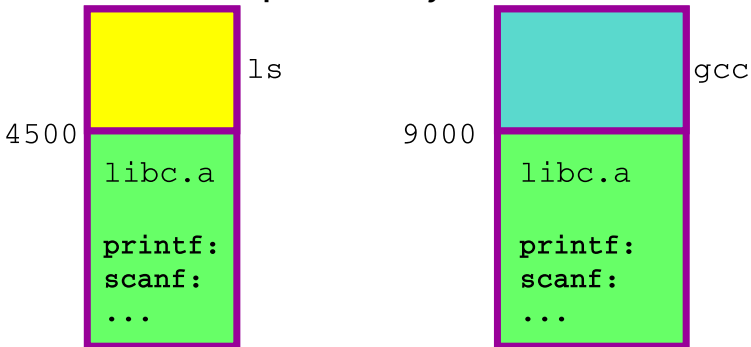
```
Relocation section '.rel.dyn' at offset 0x20c contains 1 entry:
```

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

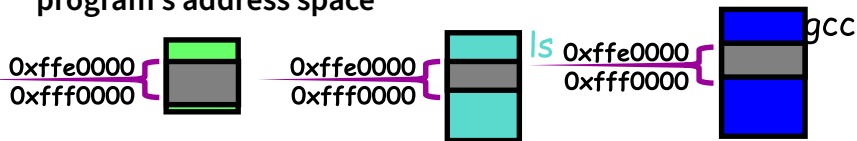
- **Observation:** everyone links in standard libraries (libc.a.), these libs consume space in every executable.



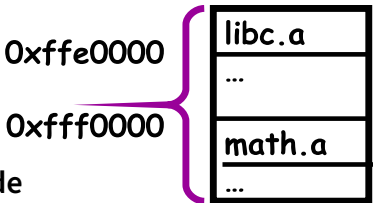
- **Insight:** we can have a single copy on disk if we don't actually include libc code in executable

Static shared libraries

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



- Every shared lib is allocated a unique range in this seg, and computes where its external defs reside
- 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, seg faults: embedded linker brings in lib code from known place & maps it in.
- Now different running programs can share code!

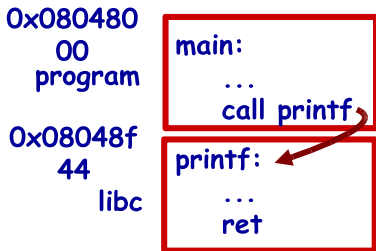


Dynamic shared libraries

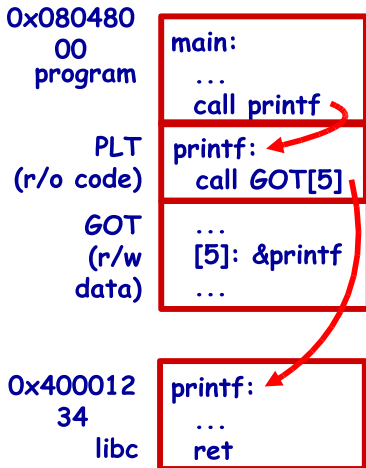
- **Static shared libraries require system-wide pre-allocation of address space**
 - Clumsy, inconvenient
 - What if a library gets too big for its space? (fragmentation)
 - Can't upgrade libraries w/o relinking applications
 - Can space ever be reused?
- **Solution: Dynamic shared libraries**
 - Combine shared library and dynamic linking ideas
 - Any library can be loaded at any VA, chosen at runtime
- **New problem: Linker won't know what names are valid**
 - Solution: stub library
- **New problem: How to call functions whose position varies?**
 - Solution: next page...

Position-independent code

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



Static Libraries



Dynamic Shared Libraries

Lazy dynamic linking

0x080480
00
program

```
main:  
...  
call printf
```

PLT
(r/o code)

```
printf:  
call GOT[5]
```

GOT
(r/w
data)

```
...  
[5]: dlfixup  
...
```

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

0x400012
34
libc

```
printf:  
...  
ret
```

```
dlfixup:  
GOT[5] = &printf  
call printf
```

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 OpenOffice 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. Now fashionable to use:
 - ▷ `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**
 - Calls `dlfixup` with relocation index
 - `dlfixup` needs no relocation because `jmp` takes relative address

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)***
 - 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

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 command 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

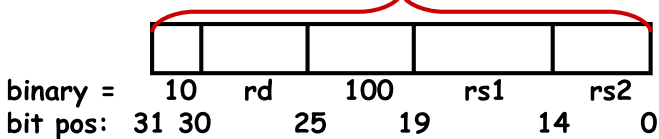
How?

- Determine binary encoding of desired instructions

SPARC: sub instruction

symbolic = "sub rdst, rsrc1, rsrc2"

32bits



- 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)();`