• Lab 2 due Friday
• Midterm review section this Friday
• Midterm exam in class next Wednesday Feb. 12
  - Open note, but no textbook or electronic devices
  - Bring lecture note printouts
• I’ll hold extra office hours Tuesday, check web site
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
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]
• **Hello program**
  - Write friendly greeting to terminal
  - Exit cleanly

• **Every programming language addresses this problem**

• **Concept should be familiar if you took 106B:**
  ```c
  int main() {
    cout << "Hello, world!" << endl;
    return 0;
  }
  ```

• **Today’s lecture: 80 minutes on hello world**
#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

- Watching video? Grab the source and try it yourself
- 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++)
- See how function calls push arguments to stack, then pop
  
  ```assembly
  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));
```

```asm
80491f9: 68 08 a0 04 08 push $0x804a008
80491fe: e8 92 ff ff ff call 8049195 <my_strlen>
8049203: 83 c4 04 add $0x4,%esp
8049206: 50 push %eax
8049207: 68 08 a0 04 08 push $0x804a008
804920c: 6a 01 push $0x1
804920e: e8 a9 ff ff ff call 80491bc <my_write>
8049213: 83 c4 0c add $0xc,%esp
```

- **Disassemble from shell with** `objdump -Sr hello1`
- **Note** `push` encodes address of greeting (0x80483c0)
- **Offsets in call instructions:** 0xffffffff92 = -110, 0xfffffffffa9 = -87
  - Binary encoding takes offset relative to next instruction
How is a process specified?

$ readelf -h hello1
ELF Header:

...  
**Entry point address:** 0x8049020  
Start of program headers: 52 (bytes into file)  
Start of section headers: 15196 (bytes into file)  
Number of program headers: 7  
Number of section headers: 22  
Section header string table index: 21

- **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
$ readelf -l hello1

Program Headers:
<table>
<thead>
<tr>
<th>Type</th>
<th>Offset</th>
<th>VirtAddr</th>
<th>PhysAddr</th>
<th>FileSiz</th>
<th>MemSiz</th>
<th>Flg</th>
<th>Align</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOAD</td>
<td>0x001000</td>
<td>0x08049000</td>
<td>0x08049000</td>
<td>0x002d8</td>
<td>0x002d8</td>
<td>R E</td>
<td>0x1000</td>
</tr>
<tr>
<td>LOAD</td>
<td>0x002000</td>
<td>0x0804a000</td>
<td>0x0804a000</td>
<td>0x0015c</td>
<td>0x0015c</td>
<td>R</td>
<td>0x1000</td>
</tr>
<tr>
<td>LOAD</td>
<td>0x002ff8</td>
<td>0x0804bff8</td>
<td>0x0804bff8</td>
<td>0x0001c</td>
<td>0x0003c</td>
<td>RW</td>
<td>0x1000</td>
</tr>
</tbody>
</table>

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
- **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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- **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
$ 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 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?
$ objdump -Sr hello2.o

... 
50 50 push %eax
49 68 68 00 00 00 push $0x0
4a R_386_32 greeting
4e 6a 01 push $0x1
50 e8 fc ff 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

```
  main:
    ...
  49  pushl $0x0
  4e  pushl $0x1
  50  call -4
    ...
```

• At link time the linker patches every reference
Relocations

$ readelf -r hello2.o

<table>
<thead>
<tr>
<th>Offset</th>
<th>Info</th>
<th>Type</th>
<th>Sym.Value</th>
<th>Sym. Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000039</td>
<td>00000f01</td>
<td>R_386_32</td>
<td>00000000</td>
<td>greeting</td>
</tr>
<tr>
<td>0000004a</td>
<td>00000f01</td>
<td>R_386_32</td>
<td>00000000</td>
<td>greeting</td>
</tr>
<tr>
<td>00000051</td>
<td>00001102</td>
<td>R_386_PC32</td>
<td>00000000</td>
<td>my_write</td>
</tr>
</tbody>
</table>

- **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
$ readelf -S hello2.o

<table>
<thead>
<tr>
<th>Nr</th>
<th>Name</th>
<th>Type</th>
<th>Addr</th>
<th>Off</th>
<th>Size</th>
<th>ES</th>
<th>Flg</th>
<th>Lk</th>
<th>Inf</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>NULL</td>
<td>00000000</td>
<td>000000</td>
<td>000000</td>
<td>00</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>.text</td>
<td>PROGBITS</td>
<td>00000000</td>
<td>000034</td>
<td>0000a4</td>
<td>00</td>
<td>AX</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>.rel.text</td>
<td>REL</td>
<td>00000000</td>
<td>0005b8</td>
<td>000018</td>
<td>08</td>
<td>I</td>
<td>18</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>.data</td>
<td>PROGBITS</td>
<td>00000000</td>
<td>0000d8</td>
<td>000000</td>
<td>00</td>
<td>WA</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>.bss</td>
<td>NOBITS</td>
<td>00000000</td>
<td>0000d8</td>
<td>000000</td>
<td>00</td>
<td>WA</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>.rodata</td>
<td>PROGBITS</td>
<td>00000000</td>
<td>0000d8</td>
<td>00000d</td>
<td>00</td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

- 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
$ readelf -s hello2.o

<table>
<thead>
<tr>
<th>Num</th>
<th>Value</th>
<th>Size</th>
<th>Type</th>
<th>Bind</th>
<th>Vis</th>
<th>Ndx</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>00000000</td>
<td>39</td>
<td>FUNC</td>
<td>LOCAL</td>
<td>DEFAULT</td>
<td>1</td>
<td>my_strlen</td>
</tr>
<tr>
<td>15</td>
<td>00000000</td>
<td>13</td>
<td>OBJECT</td>
<td>GLOBAL</td>
<td>DEFAULT</td>
<td>5</td>
<td>greeting</td>
</tr>
<tr>
<td>16</td>
<td>00000027</td>
<td>62</td>
<td>FUNC</td>
<td>GLOBAL</td>
<td>DEFAULT</td>
<td>1</td>
<td>main</td>
</tr>
<tr>
<td>17</td>
<td>00000000</td>
<td>0</td>
<td>NOTYPE</td>
<td>GLOBAL</td>
<td>DEFAULT</td>
<td>UND</td>
<td>my_write</td>
</tr>
</tbody>
</table>

- 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 syms.)
  - 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

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

$ 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 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
### Examining sections with objdump

$ objdump -h a.out

a.out:  file format elf64-x86-64

<table>
<thead>
<tr>
<th>Idx</th>
<th>Name</th>
<th>Size</th>
<th>VMA</th>
<th>LMA</th>
<th>File off</th>
<th>Algn</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>.text</td>
<td>000001a8</td>
<td>00400400</td>
<td>00400400</td>
<td>00000000</td>
<td>2**4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CONTENTS, ALLOC, LOAD, READONLY, CODE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>.rodata</td>
<td>00000008</td>
<td>004005b8</td>
<td>004005b8</td>
<td>00000008</td>
<td>2**2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CONTENTS, ALLOC, LOAD, READONLY, DATA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>.ctors</td>
<td>00000010</td>
<td>00600e18</td>
<td>00600e18</td>
<td>00000e18</td>
<td>2**3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CONTENTS, ALLOC, LOAD, DATA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>.data</td>
<td>0000001c</td>
<td>00601008</td>
<td>00601008</td>
<td>00001008</td>
<td>2**3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CONTENTS, ALLOC, LOAD, DATA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>.bss</td>
<td>0000000c</td>
<td>00601024</td>
<td>00601024</td>
<td>00001024</td>
<td>2**2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ALLOC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

No contents in file

- Another portable alternative to readelf
// C++
int foo (int a)
{
    return 0;
}

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

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

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?
#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?
  - dl_sym 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

  - dl_open, 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.
  
  ![Diagram showing space consumption]
  
  - 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...
• Code must be able to run anywhere in virtual mem
• Runtime linking would prevent code sharing, so...
• Add a level of indirection!

Static Libraries

0x080480
00
program

main:
... call printf

printf:
... ret

0x080480
00
program

main:
...
call printf

PLT
(r/o code)

GOT
(r/w data)

[5]: &printf
...

Printf: call GOT[5]

Dynamic Shared Libraries

0x400012
34
libc

printf:
...
ret

0x400012
34
libc

printf:
...
ret
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

```
0x08048000
program

PLT (r/o code)

GOT (r/w data)

main:
  ...
call printf

printf:
call GOT[5]

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

```
0x40001234
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>

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:

<table>
<thead>
<tr>
<th>Offset</th>
<th>Info</th>
<th>Type</th>
<th>Sym. Value</th>
<th>Sym. Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0804c00c</td>
<td>00000107</td>
<td>R_386_JUMP SLOT</td>
<td>000000000</td>
<td>my_write</td>
</tr>
<tr>
<td>0804c010</td>
<td>00000507</td>
<td>R_386_JUMP SLOT</td>
<td>000000000</td>
<td>my_strlen</td>
</tr>
</tbody>
</table>

- **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

```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

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

mywrite-pic.s

```assembly
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
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
- 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, rsrcl, rsrcl2”

  ![32bit diagram]

  binary =  
  
  bit pos: 31 30 25 19 14 0

• 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;
  
  ...

• Jump to the address of the buffer:
  
  ((int (*)(()))code)();