15-213

"The course that gives CMU its Zip!"

Linking
February 28, 2008

Topics
- Static linking
- Dynamic linking
- Case study: Library interpositioning

Meta-Announcements

Look for announcements on
- Gentler grading formula for Performance Lab
- Upgrade in correctness checking for same

Exams
- Target: Monday recitation

I have somebody's hat

Example C Program

main.c

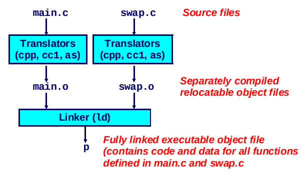
```c
int buf[2] = {1, 2};

int main()
{
  swap();
  return 0;
}
```

swap.c

```c
extern int buf[];

static int *bufp0 = &buf[0];
static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```


Static Linking

Programs are translated and linked using a *compiler driver*:
- `unix> gcc -O2 -g -o p main.c swap.c`
- `unix> ./p`



Why Linkers?

Reason 1: Modularity

- Program can be written as a collection of smaller source files, rather than one monolithic mass.
- Can build libraries of common functions (more on this later)
  - e.g., Math library, standard C library

Why Linkers? (cont)

Reason 2: Efficiency

- Time: Separate Compilation
  - Change one source file, compile, and then relink.
  - No need to recompile other source files.
- Space: Libraries
  - Common functions can be aggregated into a single file...
  - Yet executable files and running memory images contain only code for the functions they actually use.

What Do Linkers Do?

Step 1. Symbol resolution

- Programs define and reference *symbols* (variables and functions):
  - `void swap() {…}   /* define symbol swap */`
  - `swap();           /* reference symbol swap */`
  - `int *xp = &x;     /* define xp, reference x */`
- Symbol definitions are stored (by compiler) in *symbol table*.
  - Symbol table is an array of structs
  - Each entry includes name, type, size, and location of symbol.
- Linker associates each symbol reference with exactly one symbol definition.

What Do Linkers Do? (cont)

Step 2. Relocation

- Merges separate code and data sections into single sections
- Relocates symbols from their relative locations in the `.o` files to their final absolute memory locations in the executable.
- Updates all references to these symbols to reflect their new positions.

Three Kinds of Object Files (Modules)

1. Relocatable object file (`.o` file)
- Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
  - Each .o file is produced from exactly one source (.c) file

2. Executable object file
- Contains code and data in a form that can be copied directly into memory and then executed.

3. Shared object file (`.so` file)
- Special type of relocatable object file that can be loaded into memory and linked dynamically, at either load time or run-time.
- Called *Dynamic Link Libraries* (DLLs) by Windows

Executable and Linkable Format (ELF)

Standard binary format for object files

Originally proposed by AT&T System V Unix
- Later adopted by BSD Unix variants and Linux

One unified format for
- Relocatable object files (`.o`),
- Executable object files
- Shared object files (.so)

Generic name: ELF binaries

ELF Object File Format

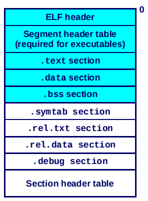
Elf header
- Magic number, type (.o, exec, .so), machine, byte ordering, etc.

Segment header table
- Page size, virtual addresses memory segments (sections), segment sizes.

`.text` section
- Code

`.data` section
- Initialized global variables

.bss section
- Uninitialized global variables
- "Block Started by Symbol"
- "Better Save Space"
- Has section header but occupies no space



ELF Object File Format (cont)

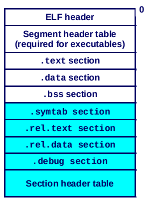
`.symtab` section
- Symbol table
- Procedure and static variable names
- Section names and locations

`.rel.text` section
- Relocation info for `.text` section
- Addresses of instructions that will need to be modified in the executable
- Instructions for modifying.

`.rel.data` section
- Relocation info for `.data` section
- Addresses of pointer data that will need to be modified in the merged executable

.debug section
- Info for symbolic debugging (`gcc -g`)

Section header table
- Offsets and sizes of each section



Linker Symbols

Global symbols

- Symbols defined by module *m* that can be referenced by other modules.
- Ex: non-`static` C functions and non-`static` global variables.

External symbols

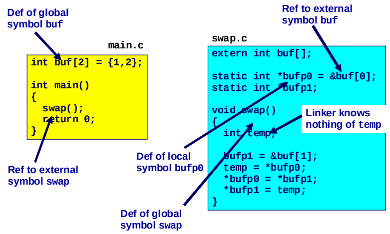
- Global symbols that are referenced by module *m* but defined by some other module.

Local symbols

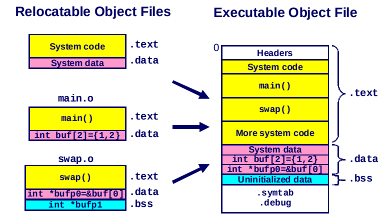
- Symbols that are defined and referenced exclusively by module *m*.
- Ex: C functions and variables defined with the `static` attribute.

Key Point: Local linker symbols are *not* local program variables

Resolving Symbols



Relocating Code and Data



`main.o` Relocation Info

```
int buf[2] = {1,2};

int main()
{
  swap();
  return 0;
}
```

```
0000000 <main>:
  0:   55                push   %ebp
  1:   89 e5             mov    %esp,%ebp
  3:   83 ec 08          sub    $0x8,%esp
  6:   e8 fc ff ff ff    call   7 <main+0x7>
                         7: R_386_PC32 swap
  b:   31 c0             xor    %eax,%eax
  d:   89 ec             mov    %ebp,%esp
  f:   5d                pop    %ebp
 10:   c3                ret
```

```
Disassembly of section .data:

 00000000 <buf>:
   0:   01 00 00 00 02 00 00 00
```

Source: `objdump`

`swap.o` Relocation Info (`.text`)

```
extern int buf[];

static int *bufp0 =
             &buf[0];
static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

```
Disassembly of section .text:

00000000 <swap>:
 0: 55                         push   %ebp
 1: 8b 15 00 00 00 00          mov    0x0,%edx
                               3: R_386_32 bufp0
 7: a1 0 00 00 00              mov    0x4,%eax
                               8: R_386_32 buf
 c: 89 e5                      mov    %esp,%ebp
 e: c7 05 00 00 00 00 04       movl   $0x4,0x0
15: 00 00 00
                               10: R_386_32 bufp1
                               14: R_386_32 buf
18: 89 ec                      mov    %ebp,%esp
1a: 8b 0a                      mov    (%edx),%ecx
1c: 89 02                      mov    %eax,(%edx)
1e: a1 00 00 00 00             mov    0x0,%eax
                               1f: R_386_32 bufp1
23: 89 08                      mov    %ecx,(%eax)
25: 5d                         pop    %ebp
26: c3                         ret
```


`swap.o` Relocation Info (`.data`)

```
extern int buf[];

static int *bufp0 =
             &buf[0];
static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

```
Disassembly of section .data:

00000000 <bufp0>:
   0:   00 00 00 00

        0: R_386_32 buf
```

Executable After Relocation (.text)

```
080483b4 <main>:
 80483b4:       55                          push   %ebp
 80483b5:       89 e5                       mov    %esp,%ebp
 80483b7:       83 ec 08                    sub    $0x8,%esp
 80483ba:       e8 09 00 00 00              call   80483c8 <swap>
 80483bf:       31 c0                       xor    %eax,%eax
 80483c1:       89 ec                       mov    %ebp,%esp
 80483c3:       5d                          pop    %ebp
 80483c4:       c3                          ret
080483c8 <swap>:
 80483c8:       55                          push   %ebp
 80483c9:       8b 15 5c 94 04 08           mov    0x804945c,%edx
 80483cf:       a1 58 94 04 08              mov    0x8049458,%eax
 80483d4:       89 e5                       mov    %esp,%ebp
 80483d6:       c7 05 48 95 04 08 58        movl   $0x8049458,0x8049548
 80483dd:       94 04 08
 80483e0:       89 ec                       mov    %ebp,%esp
 80483e2:       8b 0a                       mov    (%edx),%ecx
 80483e4:       89 02                       mov    %eax,(%edx)
 80483e6:       a1 48 95 04 08              mov    0x8049548,%eax
 80483eb:       89 08                       mov    %ecx,(%eax)
 80483ed:       5d                          pop    %ebp
 80483ee:       c3                          ret
```


Executable After Relocation (.data)

```
Disassembly of section .data:

08049454 <buf>:
 8049454:       01 00 00 00 02 00 00 00

0804945c <bufp0>:
 804945c:       54 94 04 08
```


Strong and Weak Symbols

Program symbols are either strong or weak
- ***strong***: procedures and initialized globals
- ***weak***: uninitialized globals

p1.c

```
int foo=5;      <- strong

p1() {          <- strong
}
```

p2.c

```
int foo;        <- weak

p2() {          <- strong
}
```


Linker's Symbol Rules

Rule 1. A strong symbol can only appear once.
- (Each item can be defined only once)

Rule 2. A weak symbol can be overridden by a strong symbol of the same name.
- references to the weak symbol resolve to the strong symbol.

Rule 3. If there are multiple weak symbols, the linker will pick an arbitrary one.
- Can override this with gcc `-fno-common`

Linker Puzzles

`int x;` `p1() {}`	`p1() {}`	Link time error: two strong symbols (p1)
`int x;` `p1() {}`	`int x;` `p2() {}`	References to x will refer to the same uninitialized int. Is this what you really want?
`int x;` `int y;` `p1() {}`	`double x;` `p2() {}`	Writes to x in p2 might overwrite y! Evil!
`int x=7;` `int y=5;` `p1() {}`	`double x;` `p2() {}`	Writes to x in p2 will overwrite y! Nasty!
`int x=7;` `p1() {}`	`int x;` `p2() {}`	References to x will refer to the same initialized variable.

Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.

Packaging Commonly Used Functions

How to package functions commonly used by programmers?
- Math, I/O, memory management, string manipulation, etc.

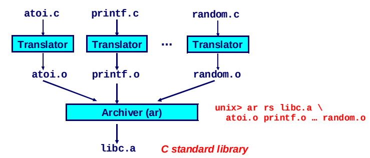
Awkward, given the linker framework so far:
- Option 1: Put all functions in a single source file
  - Programmers link big object file into their programs
  - Space and time inefficient
- Option 2: Put each function in a separate source file
  - Programmers explicitly link appropriate binaries into their programs
  - More efficient, but burdensome on the programmer

Static Libraries

Solution: *static libraries* (.a archive files)

- Concatenate related relocatable object files into a single file with an index (called an *archive*).
- Enhance linker so that it tries to resolve unresolved external references by looking for the symbols in one or more archives.
- If an archive member file resolves reference, link into executable.

Creating Static Libraries



Archiver allows incremental updates:
- Recompile function that changes and replace .o file in archive.

Commonly Used Libraries

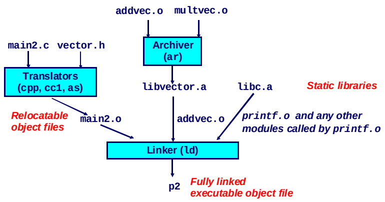
`libc.a` (the C standard library)
- 8 MB archive of 900 object files.
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

`libm.a` (the C math library)
- 1 MB archive of 226 object files.
- floating point math (sin, cos, tan, log, exp, sqrt, ...)

```
% ar -t /usr/lib/libc.a | sort
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
…
```

```
% ar -t /usr/lib/libm.a | sort
…
e_acos.o
e_acosf.o
e_acosh.o
e_acoshf.o
e_acoshl.o
e_acosl.o
e_asin.o
e_asinf.o
e_asinl.o
…
```


Linking with Static Libraries



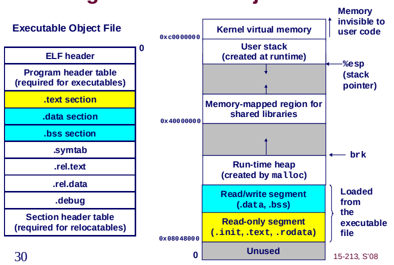
Using Static Libraries

Linker's algorithm for resolving external references:
- Scan `.o` files and `.a` files in the command line order.
- During the scan, keep a list of the current unresolved references.
- As each new `.o` or `.a` file, *obj*, is encountered, try to resolve each unresolved reference in the list against the symbols defined in *obj*.
- If any entries in the unresolved list at end of scan, then error.

Problem:
- Command line order matters!
- Moral: put libraries at the end of the command line.

```
bass> gcc -L. libtest.o -lmine
bass> gcc -L. -lmine libtest.o
libtest.o: In function `main':
libtest.o(.text+0x4): undefined reference to `libfun'
```


Loading Executable Object Files



Shared Libraries

Static libraries have the following disadvantages:

- Potential for duplicating lots of common code in the executable files on a filesystem.
  - e.g., every C program needs the standard C library
- Potential for duplicating lots of code in the virtual memory space of many processes.
- Minor bug fixes of system libraries require each application to explicitly relink

Modern Solution: Shared Libraries

- Object files that contain code and data that are loaded and linked into an application *dynamically*, at either *load-time* or *run-time*
- Also called: dynamic link libraries, DLLs, .so files

Shared Libraries (cont)

Dynamic linking can occur when executable is first loaded and run (load-time linking).

- Common case for Linux, handled automatically by the dynamic linker (`ld-linux.so`).
- Standard C library (`libc.so`) usually dynamically linked.

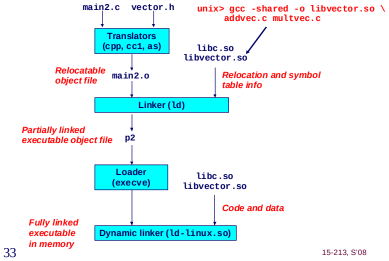
Dynamic linking can also occur after program has begun (run-time linking).

- In Unix, this is done by calls to the `dlopen()` interface.
  - High-performance web servers.
  - Runtime library interpositioning

Shared library routines can be shared by multiple processes.

- More on this when we learn about virtual memory.

Dynamic Linking at Load-time



Dynamic Linking at Run-time

```
#include <stdio.h>
#include <dlfcn.h>

int x[2] = {1, 2};
int y[2] = {3, 4};
int z[2];

int main()
{
    void *handle;
    void (*addvec)(int *, int *, int *, int);
    char *error;

    /* dynamically load the shared lib that contains addvec() */
    handle = dlopen("./libvector.so", RTLD_LAZY);
    if (!handle) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
```


Dynamic Linking at Run-time

```
    ...

    /* get a pointer to the addvec() function we just loaded */
    addvec = dlsym(handle, "addvec");
    if ((error = dlerror()) != NULL) {
        fprintf(stderr, "%s\n", error);
        exit(1);
    }

    /* Now we can call addvec() it just like any other function */
    addvec(x, y, z, 2);
    printf("z = [%d %d]\n", z[0], z[1]);

    /* unload the shared library */
    if (dlclose(handle) < 0) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
    return 0;
}
```


Case Study: Library Interpositioning

Library interpositioning is a powerful linking technique that allows programmers to intercept calls to arbitrary functions

Interpositioning can occur at:

- compile time
  - When the source code is compiled
- link time
  - When the relocatable object files are linked to form an executable object file
- load/run time
  - When an executable object file is loaded into memory, dynamically linked, and then executed.

See Lectures page for real examples of using all three interpositioning techniques to generate malloc traces.

Some Interpositioning Applications

Security

- Confinement (sandboxing)
  - Interpose calls to libc functions.
- Behind the scenes encryption
  - Automatically encrypt otherwise unencrypted network connections.

Monitoring and Profiling

- Count number of calls to functions
- Characterize call sites and arguments to functions
- Malloc tracing
  - Detecting memory leaks
  - Generating malloc traces

Example: `malloc()` Statistics

Count how much memory is allocated by a function

```
void *malloc(size_t size){
    static void *(*fp)(size_t) = 0;
    void *mp;
    char *errorstr;

    /* Get a pointer to the real malloc() */
    if (!fp) {
        fp = dlsym(RTLD_NEXT, "malloc");
        if ((errorstr = dlerror()) != NULL) {
            fprintf(stderr, "%s(): %s\n", fname, errorstr);
            exit(1);
        }
    }

    /* Call the real malloc function */
    mp = fp(size);

    mem_used += size;

    return mp;
}
```