15-213

"The course that gives CMU its Zip!"

Linking
October 14, 2004

Topics

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

Example C Program

main.c

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

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

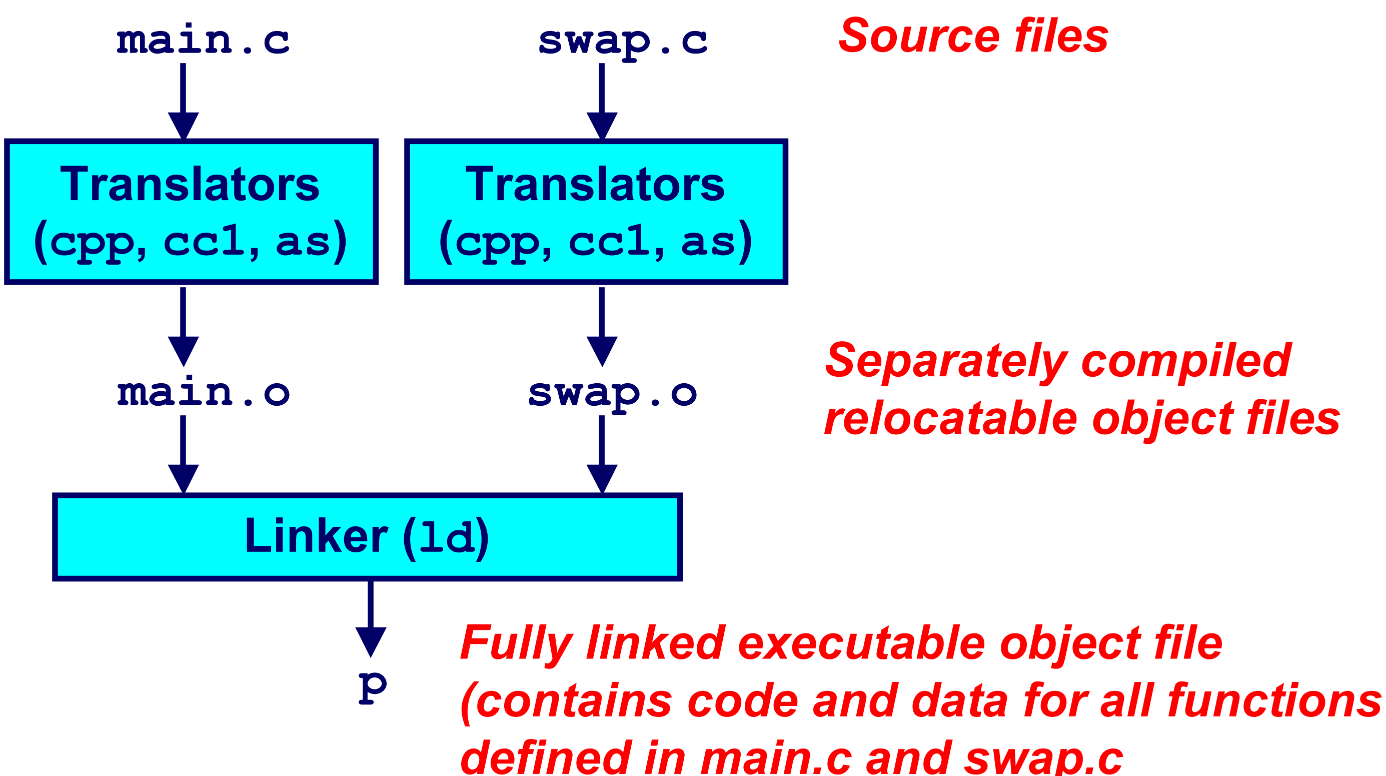
swap.c

```
extern int buf[];

int *bufp0 = &buf[0];
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?

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

Efficiency

- Time:
  - Change one source file, compile, and then relink.
  - No need to recompile other source files.
- Space:
  - Libraries of 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 Does a Linker Do?

Symbol resolution

- Programs define and reference *symbols* (variables and functions):
  - code: `a();             /* reference to symbol a */`
  - data: `int *xp=&x;  /* reference to symbol x */`
- Symbol definitions are stored (by compiler) in *symbol table*.
  - Each entry includes name, size, and location of object.
- Linker associates each symbol reference with exactly one symbol definition.

Relocation

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

Object Files (Modules)

Relocatable object file (`.o` file)

- Contains code and data in a form that can be combined with other relocatable object files at compile time to form an executable.

Executable object file

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

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

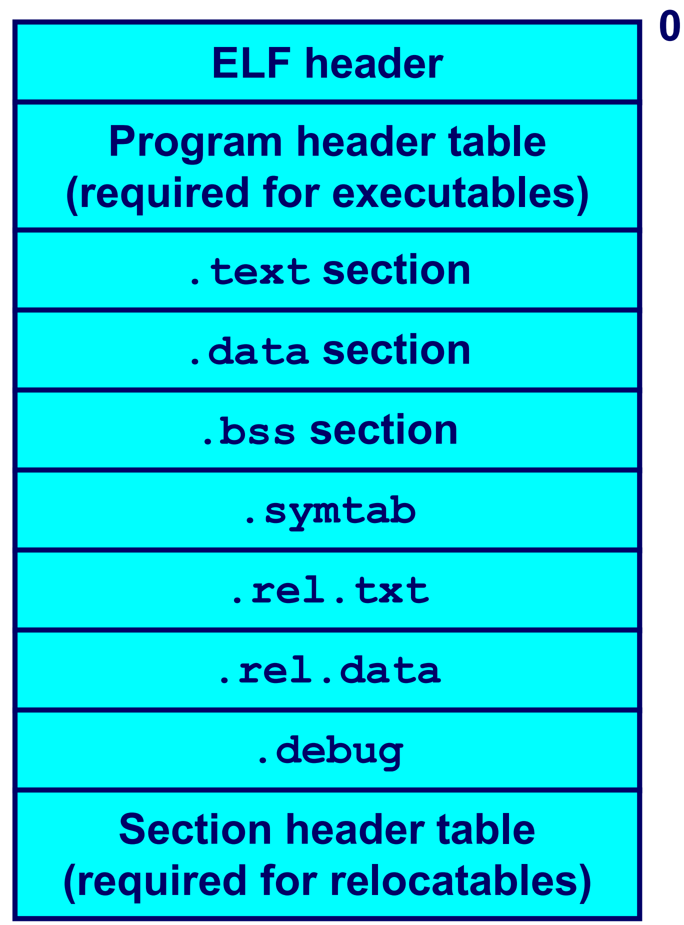
- Later adopted by BSD Unix variants and Linux

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.

Program header table

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

`.text` section

- Code

`.data` section

- Initialized (static) data

`.bss` section

- Uninitialized (static) data
- "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`)

0

ELF header
Program header table (required for executables)
`.text` section
`.data` section
`.bss` section
`.symtab`
`.rel.text`
`.rel.data`
`.debug`
Section header table (required for relocatables)

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 that are defined with the `static` attribute.**

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

Resolving Symbols

Def of global symbol `buf`

main.c

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

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

Ref to external symbol `swap`

Ref to external symbol `buf`

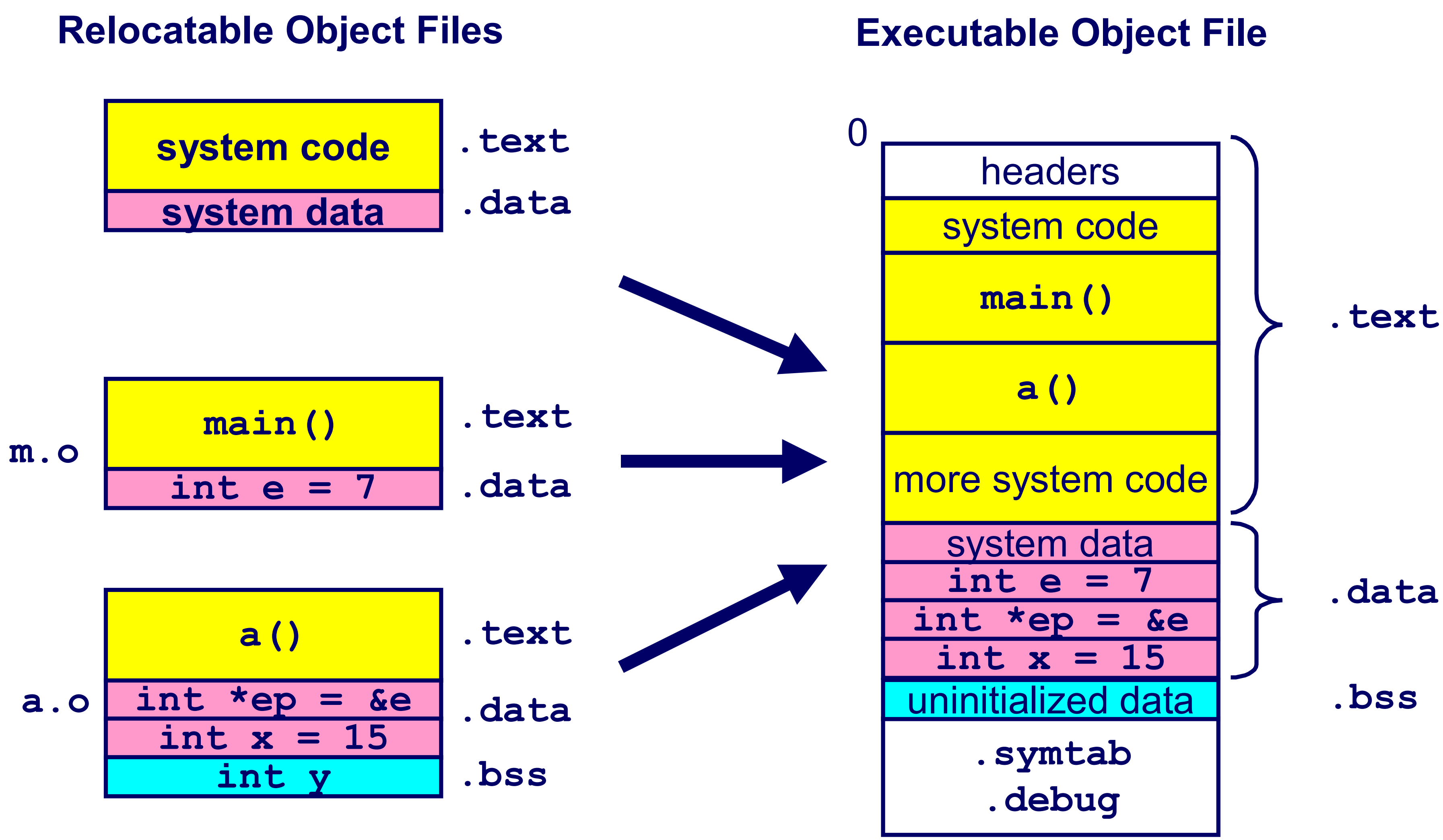
swap.c

```
extern int buf[];

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

void swap()
{
   int temp;

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

Def of local symbol `bufp0`

Linker knows nothing of `temp`

Relocating Symbol Definitions and References



`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
```

a.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;

p1() {
}
```

p2.c

```
int foo;

p2() {
}
```

strong → `int foo=5;`

strong → `p1() {`

weak → `int foo;`

strong → `p2() {`

Linker's Symbol Rules

Rule 1. A strong symbol can only appear 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 can pick an arbitrary one.

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 Functions

How to package functions commonly used by programmers?

- Math, I/O, memory management, string manipulation, etc.

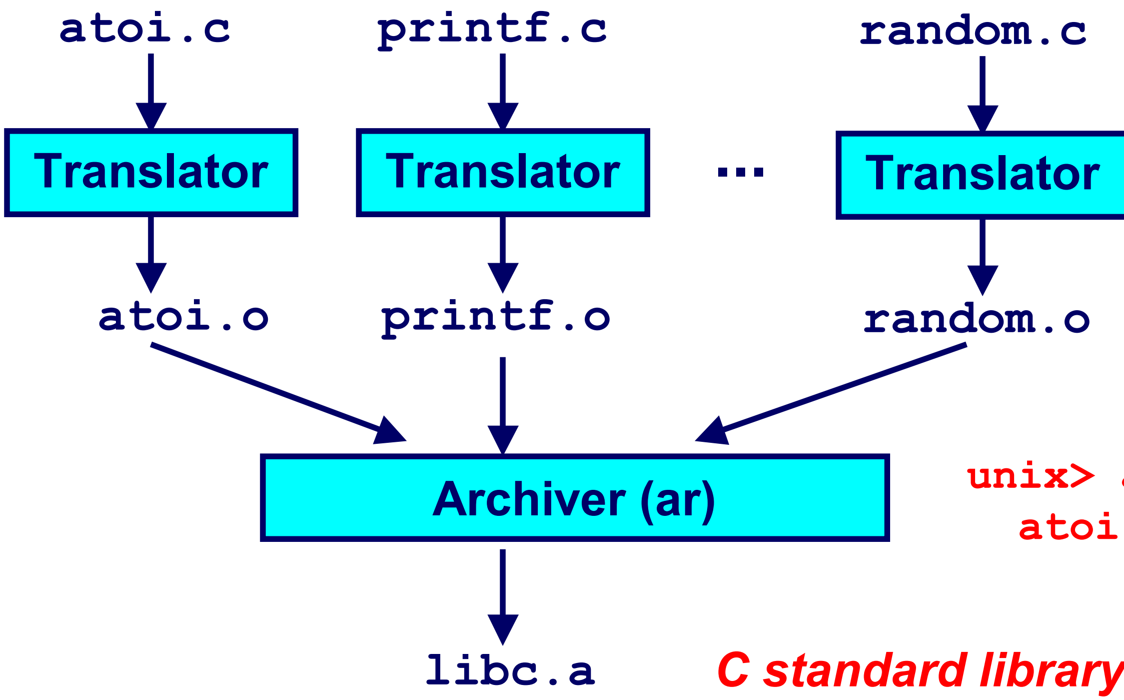
Awkward, given the linker framework so far:

- 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

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




```
unix> ar rs libc.a \
  atoi.o printf.o … random.o
```

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

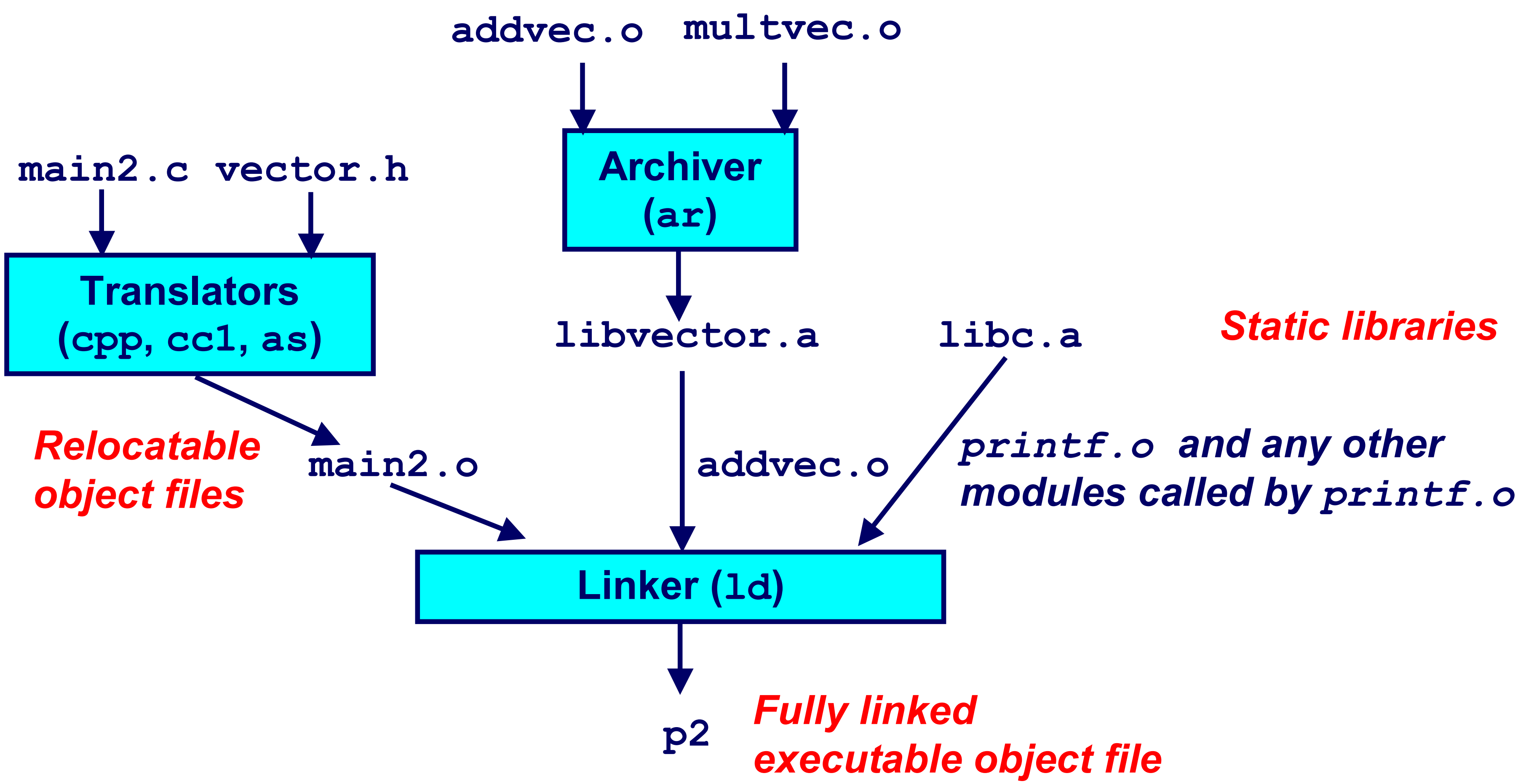
`libm.a` (the C math library)

- 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:

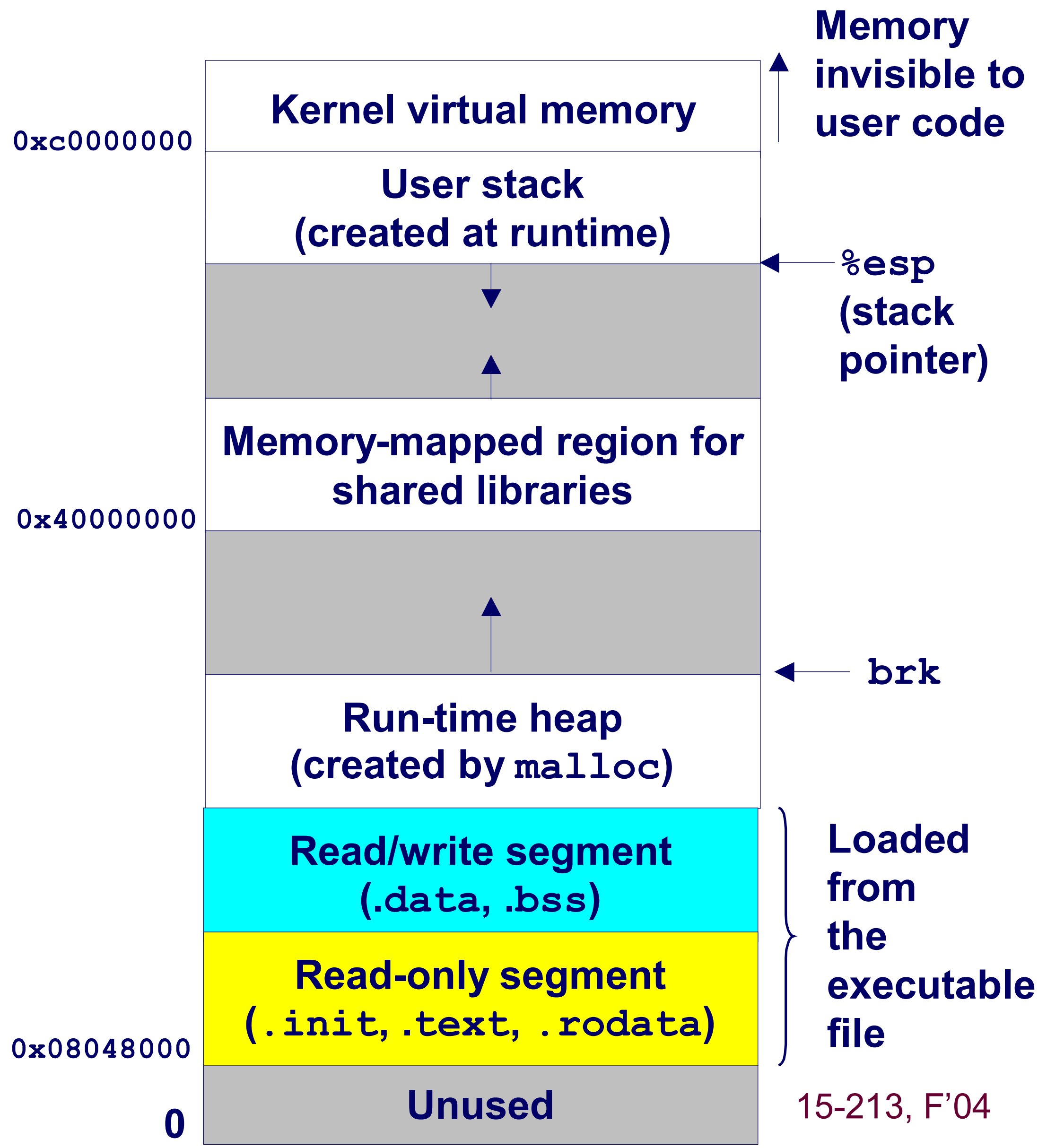
- Command line order matters!
- Moral: put libraries at the end of the command line.

```
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

Executable Object File

ELF header	0
Program header table (required for executables)	
.text section	
.data section	
.bss section	
.symtab	
.rel.text	
.rel.data	
.debug	
Section header table (required for relocatables)	



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*
- 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.

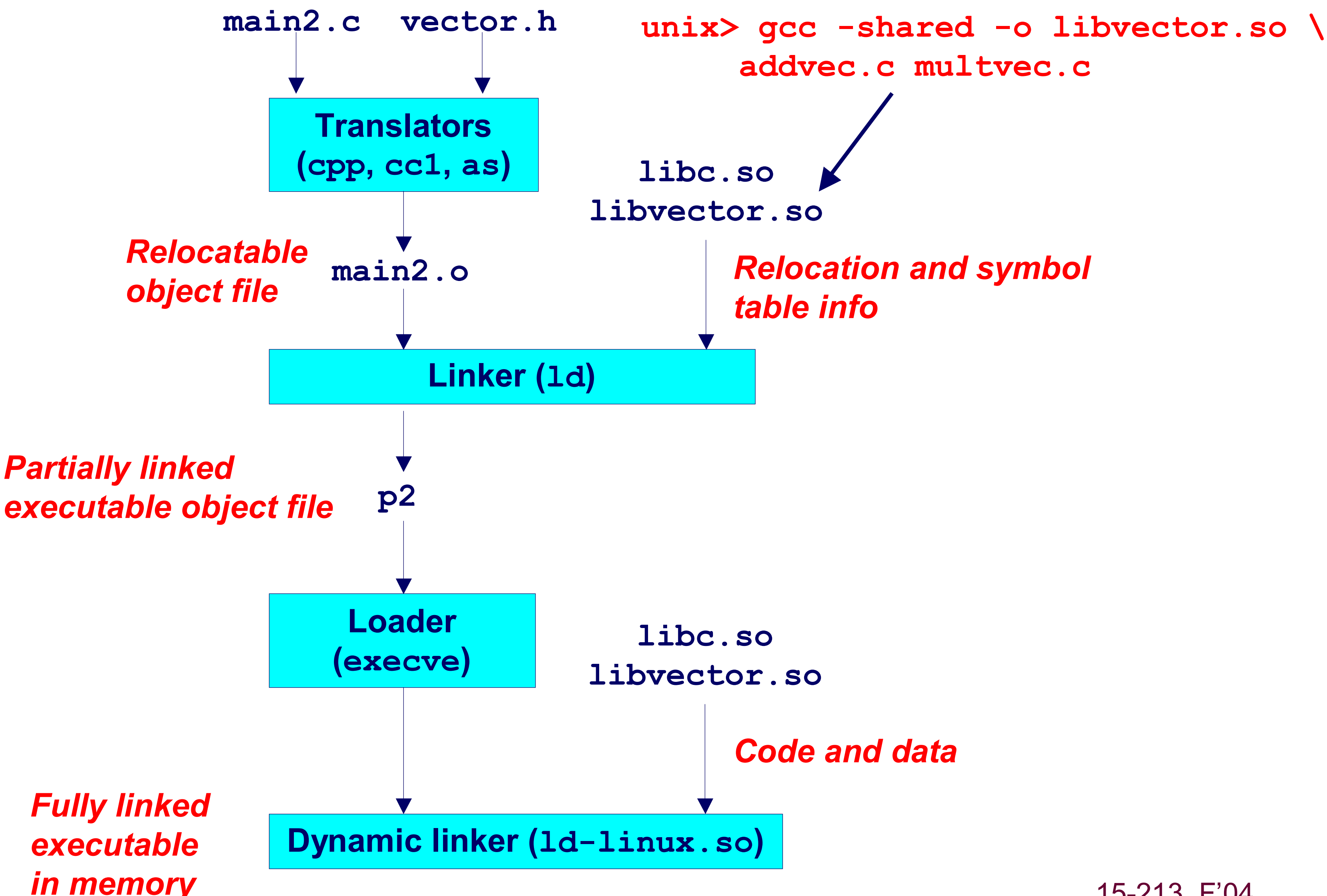
Dynamic linking can also occur after program has begun (run-time linking).

- In Unix, this is done by calls to the `dlopen()` interface.
  - High-performance web wervers.
  - 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;
}
```

Some Interpositioning Applications

Security

- Confinement (sandboxing)
  - Autolab interposes calls to libc functions.
  - Running `/bin/xterm` from student code on server a no-no.
- 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

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.

Example: `malloc()` Statistics

Find out how much memory is allocated by a function

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

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

    mp = fp(size);
    if (!mp) { /* report malloc failure */
    }

    mem_used += size;

    return mp;
}
```