Today

- *Linking* is the process of
  collecting and *combining* various pieces of code (modules) that make up a *program* (code and data)
  into a single file that be *loaded* (copied) into memory and *executed*

- Linkers are programs that do the linking

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Why Linkers? (programs that do the linking)

- **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: Separate Compilation**
  - Change one source file, compile, and then relink
  - No need to recompile other source files

- **Efficiency! 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

Example C Program

main.c

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

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

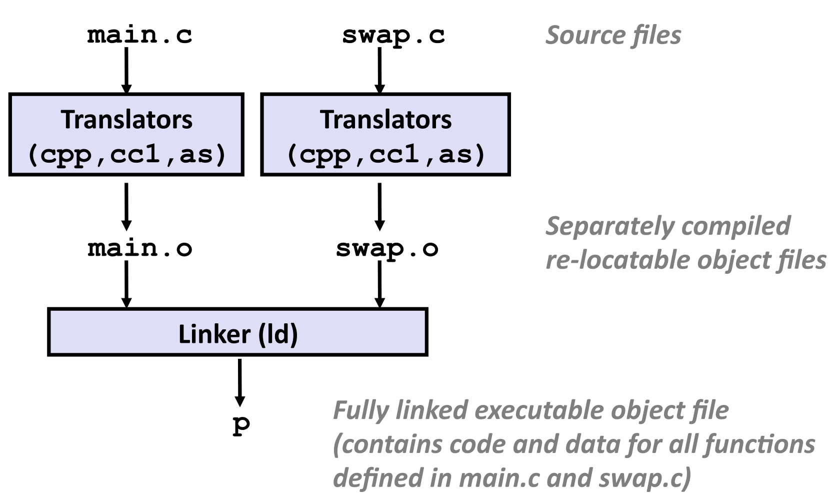
swap.c

```
extern int buf[];

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

void swap()
{
  int temp;

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


Static Linking

- **Programs are translated and linked using a *compiler driver*:**

```
unix> gcc -O2 -g -o p main.c swap.c
unix> ./p
```



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 the compiler) in a *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)

- **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 (static linking)
  - Each .o file is produced from *exactly one source (.c) file*

- **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

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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**
  - Word size, byte ordering, file type (.o, exec, .so), machine type, etc.
- **Segment header table**
  - Page size, virtual addresses, memory segments (sections), segment sizes
- **`.text` section**
  - Code
- **`.rodata` section**
  - Read only data: jump tables, ...
- **`.data` section**
  - Initialized global variables
- **`.bss` section**
  - Uninitialized global variables
  - "Block Started by Symbol", "Better Save Space"
  - Has section header but occupies no space

0
ELF header
Segment header table (required for executables)
`.text` section
`.rodata` section
`.data` section
`.bss` section
`.symtab` section
`.rel.txt` section
`.rel.data` section
`.debug` section
Section header table

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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 them
- **`.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

0
ELF header
Segment header table (required for executables)
`.text` section
`.rodata` section
`.data` section
`.bss` section
`.symtab` section
`.rel.txt` section
`.rel.data` section
`.debug` section
Section header table

Linker Symbols

- **Global symbols**
  - Symbols defined by module *m* that can be referenced by other modules
  - E.g., 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*
  - E.g., C functions and variables defined with the `static` attribute
  - **Local linker symbols are *not* local program variables**

Resolving Symbols

Global

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

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

main.c

External

External   Local

```
extern int buf[];

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

void swap()
{
  int temp;

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

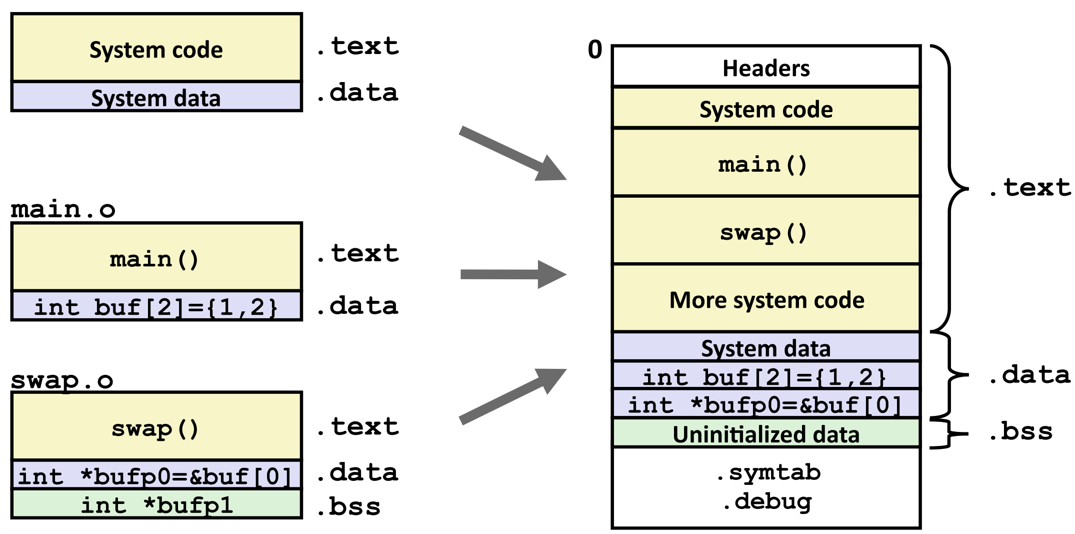
swap.c

Global

Linker knows nothing of temp

Relocating Code and Data

Relocatable Object Files | **Executable Object File**



Relocation Info (main) – before

main.c

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

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

main.o Source: objdump

```
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
```

relocatable object
r.offset = 0x7
r.symbol = swap
r.type = R_386_PC32

ADDR(.text) = 0x804883b4
ADDR(r.symbol) = ADDR(swap) = 0x80483c8

refaddr = ADDR(s) + r.offset = 0x804883b4 + 0x7 = 0x80483bb
*refptr = ADDR(r.symbol) + *refptr – refaddr = 0x80483c8 + (–4) – 0x80483bb = 0x9

Relocation Info (main) – after

main.c

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

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

main.o

Source: objdump

```
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
```

```
Disassembly of section .data:

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

ADDR(.text) = 0x804883b4
ADDR(r.symbol) = ADDR(swap) = 0x80483c8

refaddr = ADDR(s) + r.offset = 0x804883b4 + 0x7 = 0x80483bb
*refptr = ADDR(r.symbol) + *refptr – refaddr = 0x80483c8 + (–4) – 0x80483bb = 0x9

Relocation Info (swap, .text)

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;
}
```

swap.o

```
Disassembly of section .text:

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

Relocation Info (swap, .data)

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;
}
```

```
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       movl   $0x8049458,0x8049548
 80483dc:       58 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
```

In another file, where bufp1 resides:

```
08049548 <bufp1>:
 8049548:        00 00 00 00
```

Note that it is not initialized….

Strong and Weak Symbols

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

`p1.c`

strong → `int foo=5;`

strong → `p1() { }`

```
p1() {
}
```

`p2.c`

`int foo;` ← weak

`p2() { }` ← strong

```
p2() {
}
```

Linker's Symbol Rules

- **Rule 1: Multiple strong symbols are not allowed**
  - Each item can be defined only once
  - Otherwise: Linker error
- **Rule 2: Given a strong symbol and multiple weak symbol, choose the strong symbol**
  - References to the weak symbol resolve to the strong symbol
- **Rule 3: If there are multiple weak symbols, 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

Global Variables

- **Avoid if you can**

- **Otherwise**
  - Use **`static`** if you can
  - Initialize if you define a global variable
  - Use **`extern`** if you use external global variable

Packaging Commonly Used Functions

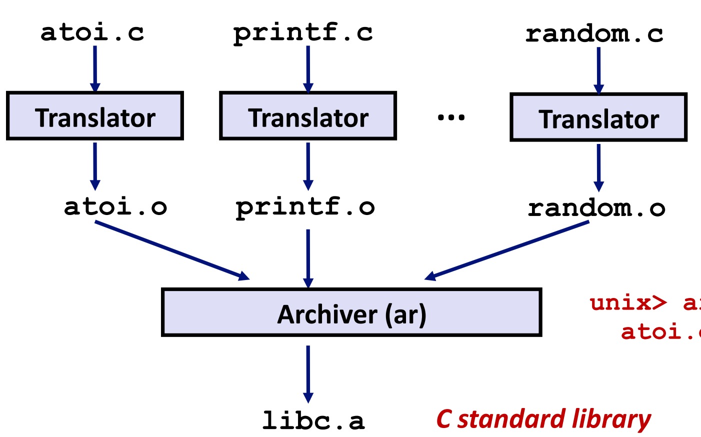
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **Awkward, given the linker framework so far:**
  - **Option 1:** Put all functions into 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

- **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 replaces .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

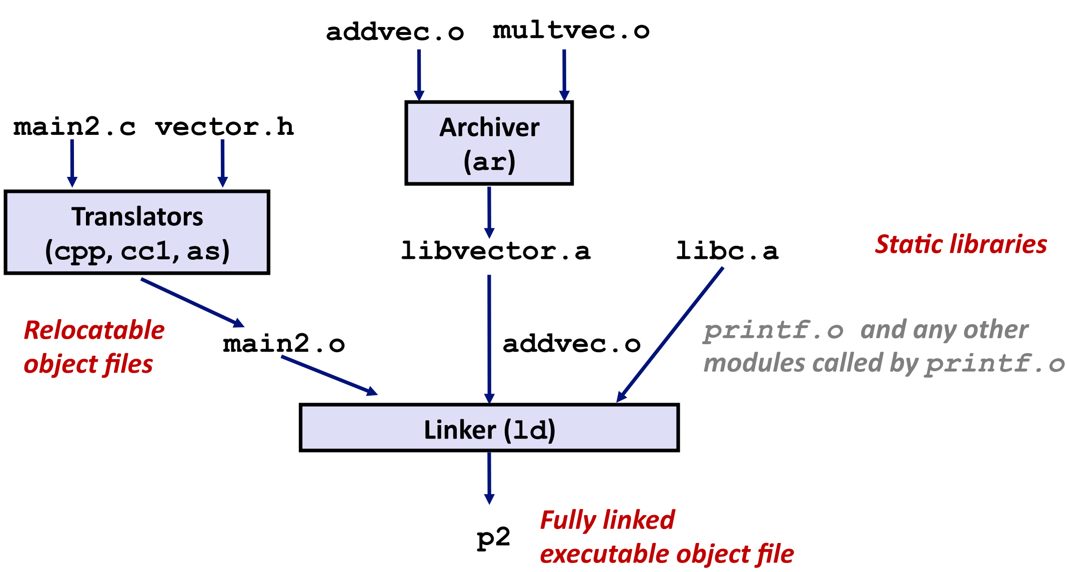
`libm.a` (the C math library)

- 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



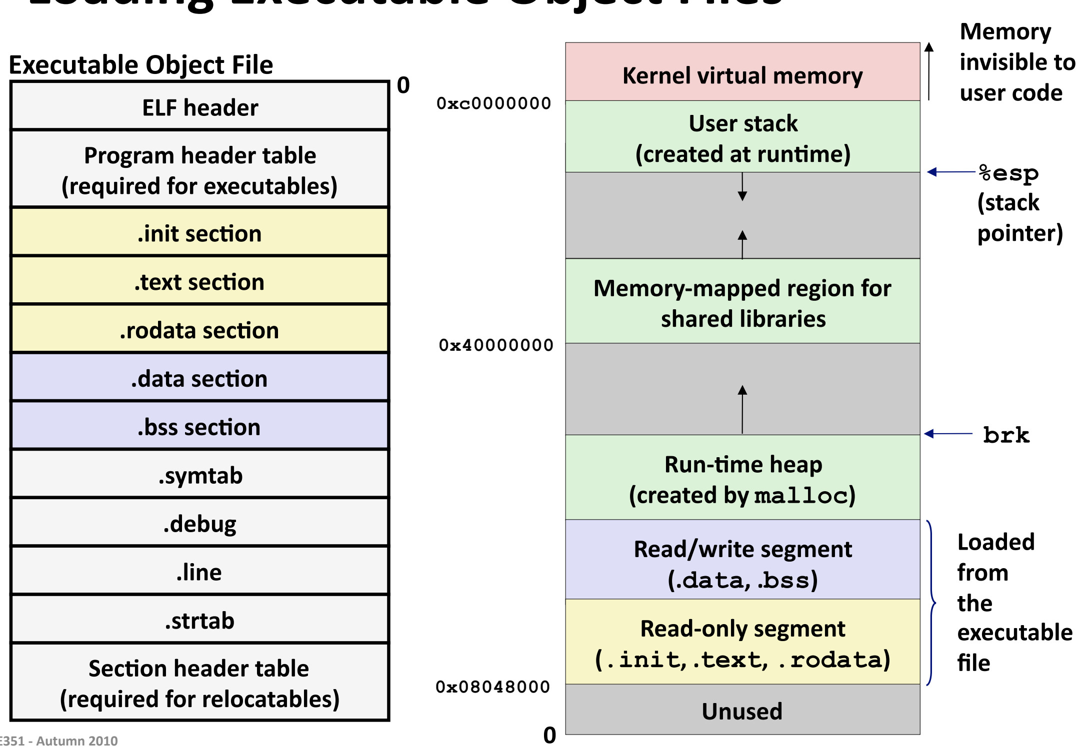
Using Static Libraries

- **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

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


Loading Executable Object Files

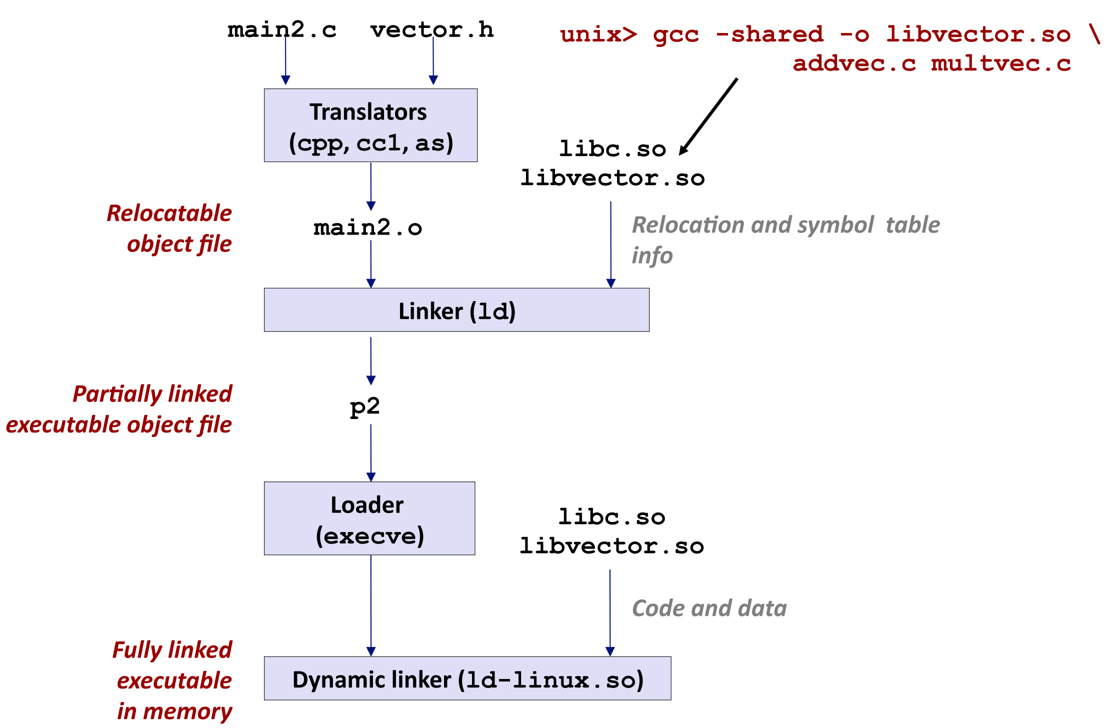


Shared Libraries

- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function need std libc)
  - Duplication in the running executables
  - 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

Dynamic Linking at Load-time



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 – *outside the scope of this course*)**
  - 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