Linking

CSci 2021: Machine Architecture and Organization
Lecture #34-35, April 20th-22nd, 2015

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These Slides

- **Static Linking**
- Dynamic Linking
- Case study: Library interposition

Example C Program

main.c

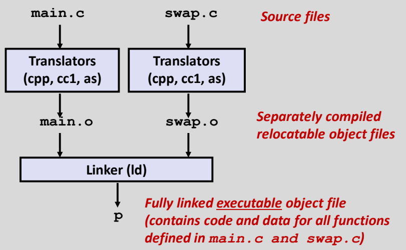
```
int buf[2] = {1, 2};

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

swap.c

```
extern int buf[];

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`



`main.c` `swap.c` *Source files*

Translators (cpp, cc1, as)

Translators (cpp, cc1, as)

`main.o` `swap.o` *Separately compiled relocatable object files*

Linker (ld)

`p` *Fully linked executable object file (contains code and data for all functions defined in `main.c` and `swap.c`)*

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 a */`
    - `int *xp = &x;      /* define symbol xp, reference x */`
  - Symbol definitions are stored (by compiler) in a *symbol table*.
    - Symbol table is an array of structs
    - Each entry includes name, 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)

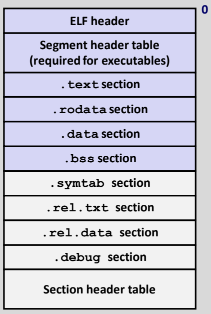
- **Relocatable object file (`.o` file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
    - Each `.o` file is produced from exactly one source (`.c`) file
- **Executable object file (`a.out` file)**
  - Contains code and data in a form that can be copied directly into memory and then executed.
- **Dynamic 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 Linux and then BSD Unix variants
- **One unified format for**
  - Relocatable object files (`.o`),
  - Executable object files (`a.out`)
  - 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 table (AKA program header)**
  - Page size, virtual addresses memory segments (sections), segment sizes.
- **`.text` section**
  - Code
- **`.rodata` section**
  - Read only data: jump tables, string consts, ...
- **`.data` section**
  - Initialized global variables
- **`.bss` section**
  - Uninitialized global variables
  - "Block Started by Symbol"
  - "Better Save Space"
  - Has section header but occupies no space



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ELF header

Segment header table (required for executables)

`.text` section

`.rodata` section

`.data` section

`.bss` section

`.symtab` section

`.rel.txt` section

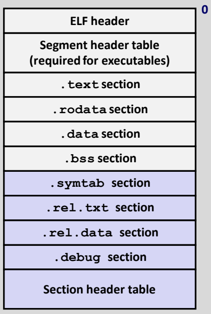
`.rel.data` section

`.debug` section

Section header table

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



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ELF header

Segment header table (required for executables)

`.text` section

`.rodata` section

`.data` section

`.bss` section

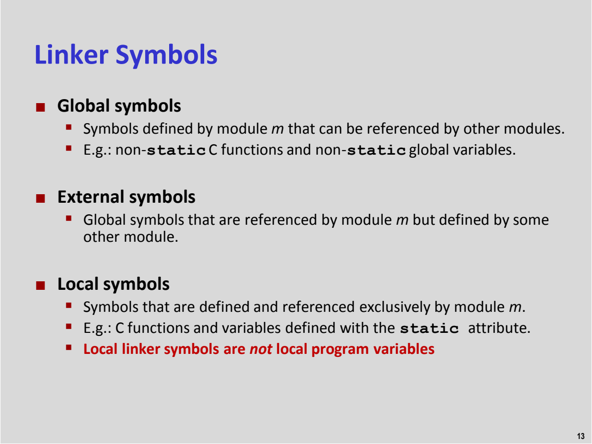
`.symtab` section

`.rel.txt` section

`.rel.data` section

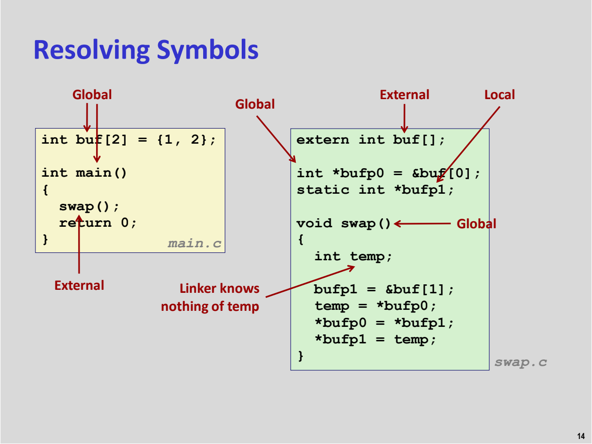
`.debug` section

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



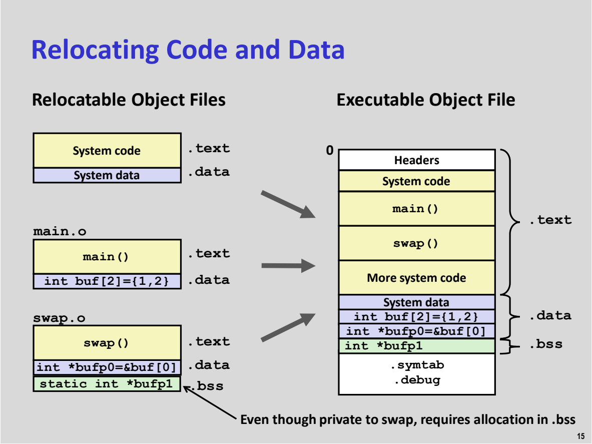
Resolving Symbols

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

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

`main.c`

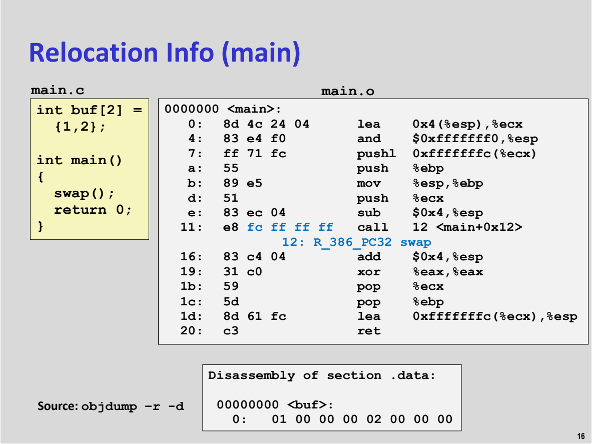
```
extern int buf[];

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

void swap()
{
  int temp;

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

`swap.c`



Relocating Code and Data

Even though private to swap, requires allocation in .bss



Relocation Info (main)

`main.c`

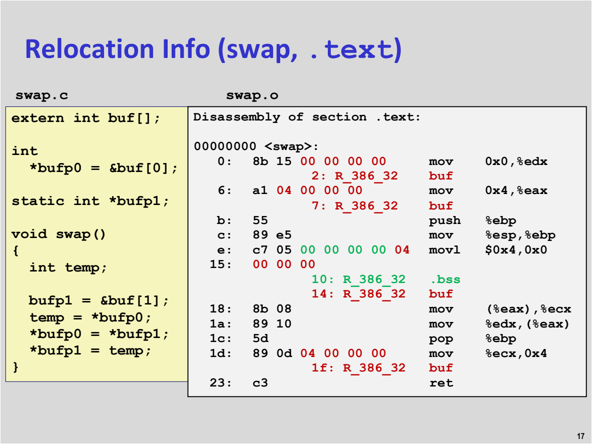
```
int buf[2] =
  {1,2};

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

`main.o`

```
0000000 <main>:
   0:   8d 4c 24 04       lea    0x4(%esp),%ecx
   4:   83 e4 f0          and    $0xfffffff0,%esp
   7:   ff 71 fc          pushl  0xfffffffc(%ecx)
   a:   55                push   %ebp
   b:   89 e5             mov    %esp,%ebp
   d:   51                push   %ecx
   e:   83 ec 04          sub    $0x4,%esp
  11:   e8 fc ff ff ff    call   12 <main+0x12>
              12: R_386_PC32 swap
  16:   83 c4 04          add    $0x4,%esp
  19:   31 c0             xor    %eax,%eax
  1b:   59                pop    %ecx
  1c:   5d                pop    %ebp
  1d:   8d 61 fc          lea    0xfffffffc(%ecx),%esp
  20:   c3                ret
```

Source: `objdump -r -d`

```
Disassembly of section .data:

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



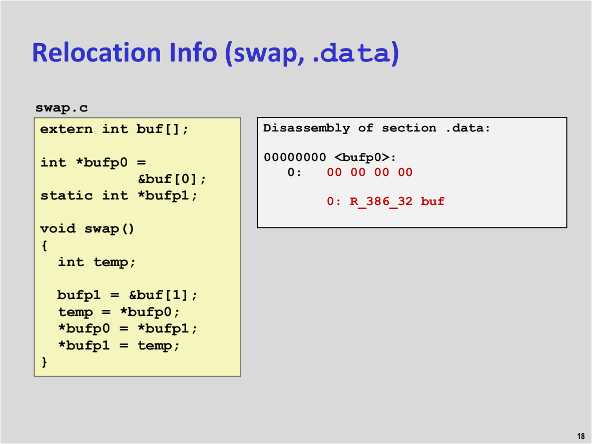
Relocation Info (swap, `.text`)

`swap.c`

```
extern int buf[];

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:   8b 15 00 00 00 00       mov    0x0,%edx
              2: R_386_32       buf
   6:   a1 04 00 00 00          mov    0x4,%eax
              7: R_386_32       buf
   b:   55                      push   %ebp
   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      .bss
              14: R_386_32      buf
  18:   8b 08                   mov    (%eax),%ecx
  1a:   89 10                   mov    %edx,(%eax)
  1c:   5d                      pop    %ebp
  1d:   89 0d 04 00 00 00       mov    %ecx,0x4
              1f: R_386_32      buf
  23:   c3                      ret
```



Relocation Info (swap, `.data`)

`swap.c`

```
extern int buf[];

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 Before/After Relocation (`.text`)

```
0000000 <main>:
  . . .
  e:   83 ec 04          sub    $0x4,%esp
 11:   e8 fc ff ff ff    call   12 <main+0x12>
               12: R_386_PC32 swap
 16:   83 c4 04          add    $0x4,%esp
 . . .
```

```
0x8048396 + 0x1a
= 0x80483b0
```

```
08048380 <main>:
 8048380:       8d 4c 24 04             lea    0x4(%esp),%ecx
 8048384:       83 e4 f0                and    $0xfffffff0,%esp
 8048387:       ff 71 fc                pushl  0xfffffffc(%ecx)
 804838a:       55                      push   %ebp
 804838b:       89 e5                   mov    %esp,%ebp
 804838d:       51                      push   %ecx
 804838e:       83 ec 04                sub    $0x4,%esp
 8048391:       e8 1a 00 00 00          call   80483b0 <swap>
 8048396:       83 c4 04                add    $0x4,%esp
 8048399:       31 c0                   xor    %eax,%eax
 804839b:       59                      pop    %ecx
 804839c:       5d                      pop    %ebp
 804839d:       8d 61 fc                lea    0xfffffffc(%ecx),%esp
 80483a0:       c3                      ret
```

```
  0:   8b 15 00 00 00 00       mov    0x0,%edx
               2: R_386_32     buf
  6:   a1 04 00 00 00          mov    0x4,%eax
               7: R_386_32     buf
  ...
  e:   c7 05 00 00 00 00 04    movl   $0x4,0x0
 15:   00 00 00
               10: R_386_32    .bss
               14: R_386_32    buf
  . . .
 1d:   89 0d 04 00 00 00       mov    %ecx,0x4
               1f: R_386_32    buf
 23:   c3                      ret
```

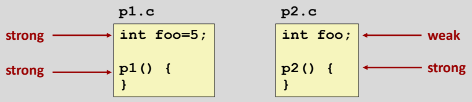
```
080483b0 <swap>:
 80483b0:       8b 15 20 96 04 08       mov    0x8049620,%edx
 80483b6:       a1 24 96 04 08          mov    0x8049624,%eax
 80483bb:       55                      push   %ebp
 80483bc:       89 e5                   mov    %esp,%ebp
 80483be:       c7 05 30 96 04 08 24    movl   $0x8049624,0x8049630
 80483c5:       96 04 08
 80483c8:       8b 08                   mov    (%eax),%ecx
 80483ca:       89 10                   mov    %edx,(%eax)
 80483cc:       5d                      pop    %ebp
 80483cd:       89 0d 24 96 04 08       mov    %ecx,0x8049624
 80483d3:       c3                      ret
```

Executable After Relocation (`.data`)

```
Disassembly of section .data:

08049620 <buf>:
 8049620:        01 00 00 00 02 00 00 00

08049628 <bufp0>:
 8049628:        20 96 04 08
```

Strong and Weak Symbols

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



```
int foo=5;

p1() {
}
```

```
int foo;

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.

Role of .h Files

c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

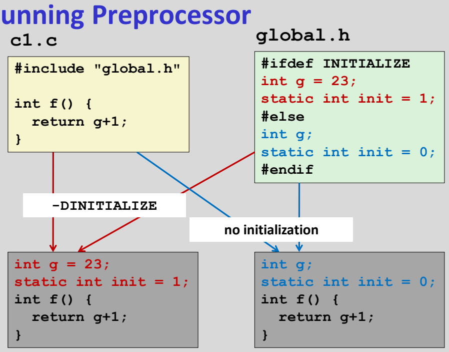
global.h

```
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

c2.c

```
#include <stdio.h>
#include "global.h"

int main() {
  if (!init)
    g = 37;
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

Running Preprocessor



c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

```
int g = 23;
static int init = 1;
int f() {
  return g+1;
}
```

```
int g;
static int init = 0;
int f() {
  return g+1;
}
```

#include causes C preprocessor to insert file verbatim

Role of .h Files (cont.)

c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```
#ifdef INITIALIZE
int g = 23;
static int init = 1;
#else
int g;
static int init = 0;
#endif
```

c2.c

```
#include <stdio.h>
#include "global.h"

int main() {
  if (!init)
    g = 37;
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

What happens:

```
gcc -o p c1.c c2.c
   ??
gcc -o p c1.c c2.c \
  -DINITIALIZE
   ??
```

Global Variables

- **Avoid if you can**
  - They make large programs hard to understand
  - They make it difficult to run multiple copies of the same code (including in threads)
  - They can't grow larger at runtime and so can cause arbitrary limits

- **Otherwise**
  - Use `static` if you can: low-tech module system
  - Initialize if you define a global variable
  - Use `extern` if you use external global variable

Packaging Commonly Used Functions

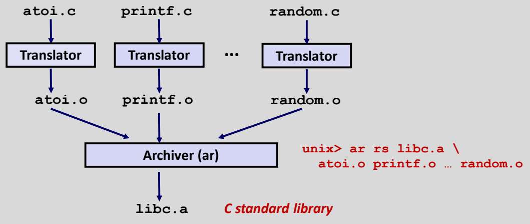
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **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 it into the executable.

Creating Static Libraries



`atoi.c` `printf.c` `random.c`

Translator Translator … Translator

`atoi.o` `printf.o` `random.o`

Archiver (ar)

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

`libc.a` *C standard library*

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

Commonly Used Libraries

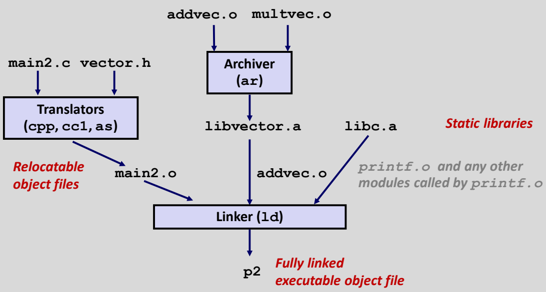
`libc.a` (the C standard library, included by default)
  - 4.6 MB archive of 1496 object files.
  - I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

`libm.a` (the C math library)
  - 2 MB archive of 444 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



`addvec.o` `multvec.o`

`main2.c` `vector.h`

Archiver (`ar`)

Translators (`cpp`, `cc1`, `as`)

`libvector.a` `libc.a` *Static libraries*

Relocatable object files `main2.o` `addvec.o` *`printf.o` and any other modules called by `printf.o`*

Linker (`ld`)

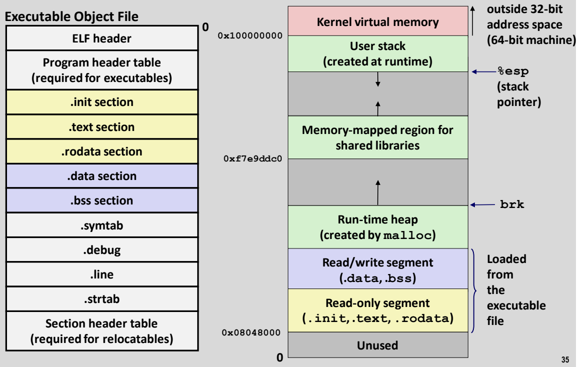
`p2` *Fully linked executable object file*

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.
- **Common pitfall:**
  - 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



Executable Object File

0

ELF header

Program header table (required for executables)

.init section

.text section

.rodata section

.data section

.bss section

.symtab

.debug

.line

.strtab

Section header table (required for relocatables)

Kernel virtual memory

Memory outside 32-bit address space (64-bit machine)

`0x100000000`

User stack (created at runtime)

`%esp` (stack pointer)

Memory-mapped region for shared libraries

`0xf7e9ddc0`

`brk`

Run-time heap (created by `malloc`)

Read/write segment (`.data`, `.bss`)

Read-only segment (`.init`, `.text`, `.rodata`)

Loaded from the executable file

`0x08048000`

Unused

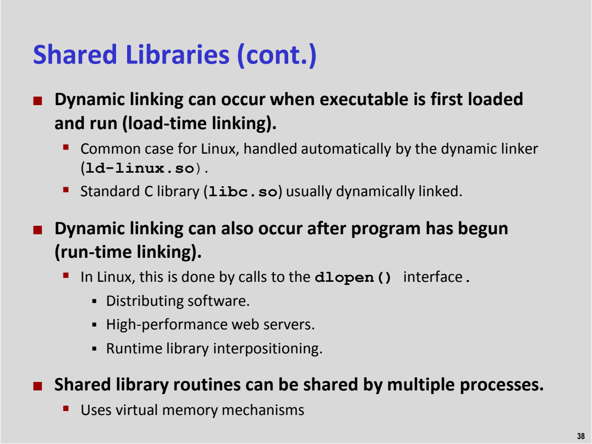
0

These Slides

- Static Linking
- **Dynamic Linking**
- Case study: Library interposition

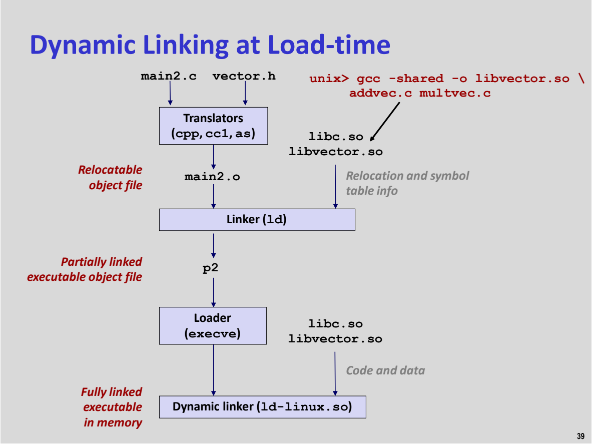
Shared Libraries

- **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: (Dynamic) 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



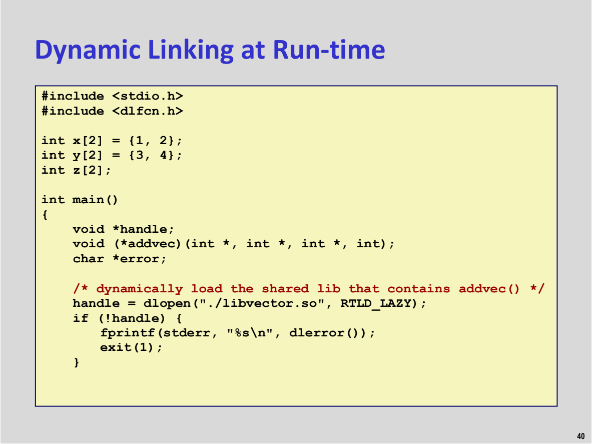
Shared Libraries (cont.)

- **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 Linux, this is done by calls to the `dlopen()` interface.
    - Distributing software.
    - High-performance web servers.
    - Runtime library interpositioning.
- **Shared library routines can be shared by multiple processes.**
  - Uses virtual memory mechanisms



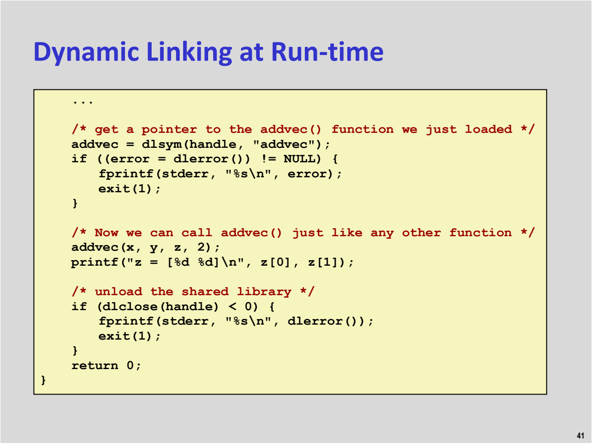
Dynamic Linking at Load-time

```
unix> gcc -shared -o libvector.so \
        addvec.c multvec.c
```



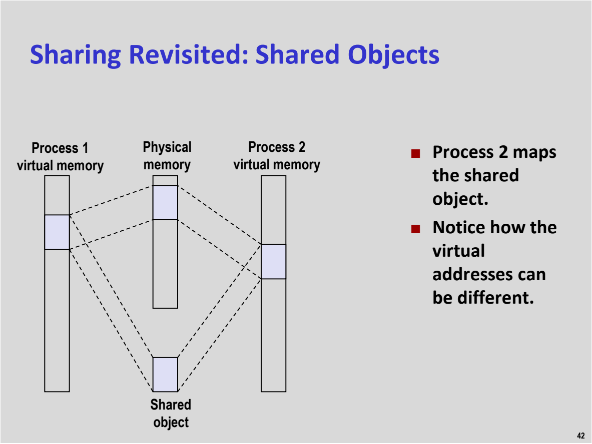
Dynamic Linking at Run-time

```
#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() 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;
}
```



Sharing Revisited: Shared Objects

- **Process 2 maps the shared object.**
- **Notice how the virtual addresses can be different.**

x86 Detail: Position Independent Code

- **Requirement**
  - Shared library code may be loaded at different addresses in different processes, must still run correctly
- **Solution for direct jumps: PC relative**
  - Target of calls and jumps is encoded as a relative offset, so works correctly if source and target move together
- **For other accesses: indirect through Global Offset Table (GOT)**
  - GOT contains absolute addresses of code and data
  - Offset between PC and GOT is known at static linking time
  - Keep GOT offset in a register, usually `%ebx`
  - Losing one register for other uses can decrease performance

GOT Pointer Setup and Use

- **Load GOT pointer in %ebx, based on PC:**

```
      call  L1
      addl  $VAROFF, %ebx
      …
L1:   movl  (%esp), %ebx
      ret
```

- **Translate absolute accesses to GOT accesses**

```
movl   global, %eax
…
movl   $FUNCPTR, %eax
call   *(%eax)
```

```
movl   0x44(%ebx), %eax
movl   (%eax), %eax
…
movl   0x48(%ebx), %eax
call   *(%eax)
```

Procedure Lookup Table

- **Used for calls to functions in a shared library**
  - Address determined lazily at first use
  - Indirection is transparent to the caller

```
08048300 <PLT[0]>:
 8048300:    pushl  0x8049ff8     push &GOT[1]
 8048306:    jmp    *0x8049ffc    jump to *GOT[2] (linker)

08048310 <printf@plt>:
 8048310:    jmp    *0x804a000    jump to *GOT[3]
 8048316:    push   $0x0          ID for printf
 804831b:    jmp    8048300       jmp to PLT[0]

08048320 <addvec@plt>:
 8048320:    jmp    *0x804a004    jump to *GOT[4]
 8048326:    push   $0x8          ID for addvec
 804832b:    jmp    8048300       jmp to PLT[0]
```

Address Space Layout Randomization

- **Recall: defense to make attacks more difficult**
  - Idea: choose random locations for memory areas
  - Attacker has to guess, modify attack, or leak information
- **ASLR for stack and heap is easy**
- **ASLR for code and data depends on PIC**
  - Always done for shared libraries on modern systems
- **ASLR for the main program is optional**
  - Compiling main program PIC = PIE
    - "Position Independent Exectutable"
  - Slows down 32-bit x86 due to register use
  - Done for security-critical programs

These Slides

- **Static Linking**
- **Dynamic Linking**
- **Case study: Library interposition**

Case Study: Library Interposition

- **Library interposition : powerful linking technique that allows programmers to intercept calls to arbitrary functions**
- **Interposition can occur at:**
  - Compile time: When the source code is compiled
  - Link time: When the relocatable object files are statically linked to form an executable object file
  - Load/run time: When an executable object file is loaded into memory, dynamically linked, and then executed.

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 address traces**

Example program

```
#include <stdio.h>
#include <stdlib.h>
#include <malloc.h>

int main()
{
    free(malloc(10));
    printf("hello, world\n");
    exit(0);
}
                                    hello.c
```

- **Goal: trace the addresses and sizes of the allocated and freed blocks, without modifying the source code.**
- **Three solutions: interpose on the `lib` `malloc` and `free` functions at compile time, link time, and load/run time.**

Compile-time Interposition

```
#ifdef COMPILETIME
/* Compile-time interposition of malloc and free using C
 * preprocessor. A local malloc.h file defines malloc (free)
 * as wrappers mymalloc (myfree) respectively.
 */

#include <stdio.h>
#include <malloc.h>

/*
 * mymalloc - malloc wrapper function
 */
void *mymalloc(size_t size, char *file, int line)
{
    void *ptr = malloc(size);
    printf("%s:%d: malloc(%d)=%p\n", file, line, (int)size,
ptr);
    return ptr;
}                                                  mymalloc.c
```

Compile-time Interposition

```
#define malloc(size) mymalloc(size, __FILE__, __LINE__ )
#define free(ptr) myfree(ptr, __FILE__, __LINE__ )

void *mymalloc(size_t size, char *file, int line);
void myfree(void *ptr, char *file, int line);
                                                    malloc.h
```

```
linux> make helloc
gcc -O2 -Wall -DCOMPILETIME -c mymalloc.c
gcc -O2 -Wall -I. -o helloc hello.c mymalloc.o
linux> make runc
./helloc
hello.c:7: malloc(10)=0x501010
hello.c:7: free(0x501010)
hello, world
```

Link-time Interposition

```
#ifdef LINKTIME
/* Link-time interposition of malloc and free using the
static linker's (ld) "--wrap symbol" flag. */

#include <stdio.h>

void *__real_malloc(size_t size);
void __real_free(void *ptr);

/*
 * __wrap_malloc - malloc wrapper function
 */
void *__wrap_malloc(size_t size)
{
    void *ptr = __real_malloc(size);
    printf("malloc(%d) = %p\n", (int)size, ptr);
    return ptr;
}                                                  mymalloc.c
```

Link-time Interposition

```
linux> make hellol
gcc -O2 -Wall -DLINKTIME -c mymalloc.c
gcc -O2 -Wall -Wl,--wrap,malloc -Wl,--wrap,free \
-o hellol hello.c mymalloc.o
linux> make runl
./hellol
malloc(10) = 0x501010
free(0x501010)
hello, world
```

- **The “`-Wl`” flag passes argument to linker**
- **Telling linker “`--wrap,malloc`” tells it to resolve references in a special way:**
  - Refs to `malloc` should be resolved as `__wrap_malloc`
  - Refs to `__real_malloc` should be resolved as `malloc`

Load/Run-time Interposition

```
#ifdef RUNTIME
 /* Run-time interposition of malloc and free based on
 * dynamic linker's (ld-linux.so) LD_PRELOAD mechanism */
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>
#include <dlfcn.h>

void *malloc(size_t size)
{
    static void *(*mallocp)(size_t size);
    char *error;
    void *ptr;

    /* get address of libc malloc */
    if (!mallocp) {
        mallocp = dlsym(RTLD_NEXT, "malloc");
        if ((error = dlerror()) != NULL) {
            fputs(error, stderr);
            exit(1);
        }
    }
    ptr = mallocp(size);
    printf("malloc(%d) = %p\n", (int)size, ptr);
    return ptr;
}
```

mymalloc.c

Load/Run-time Interposition

```
linux> make hellor
gcc -O2 -Wall -DRUNTIME -shared -fPIC -o mymalloc.so mymalloc.c
gcc -O2 -Wall -o hellor hello.c
linux> make runr
(LD_PRELOAD="/usr/lib64/libdl.so ./mymalloc.so" ./hellor)
malloc(10) = 0x501010
free(0x501010)
hello, world
```

- **The `LD_PRELOAD` environment variable tells the dynamic linker to resolve unresolved refs (e.g., to `malloc`) by looking in `libdl.so` and `mymalloc.so` first.**
  - `libdl.so` necessary to resolve references to the `dlopen` functions.

Interposition Recap

- **Compile Time**
  - Apparent calls to malloc/free get macro-expanded into calls to mymalloc/myfree
- **Link Time**
  - Use linker trick to have special name resolutions
    - malloc → __wrap_malloc
    - __real_malloc → malloc
- **Compile Time**
  - Implement custom version of malloc/free that use dynamic linking to load library malloc/free under different names