Linking

15-213: Introduction to Computer Systems
13th Lecture, October 10th, 2017

Instructor:

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Today

- **Linking**
  - Motivation
  - What it does
  - How it works
  - Dynamic linking

- **Case study: Library interpositioning**

Example C Program

```c
int sum(int *a, int n);

int array[2] = {1, 2};

int main(int argc, char** argv)
{
    int val = sum(array, 2);
    return val;
}
```
main.c
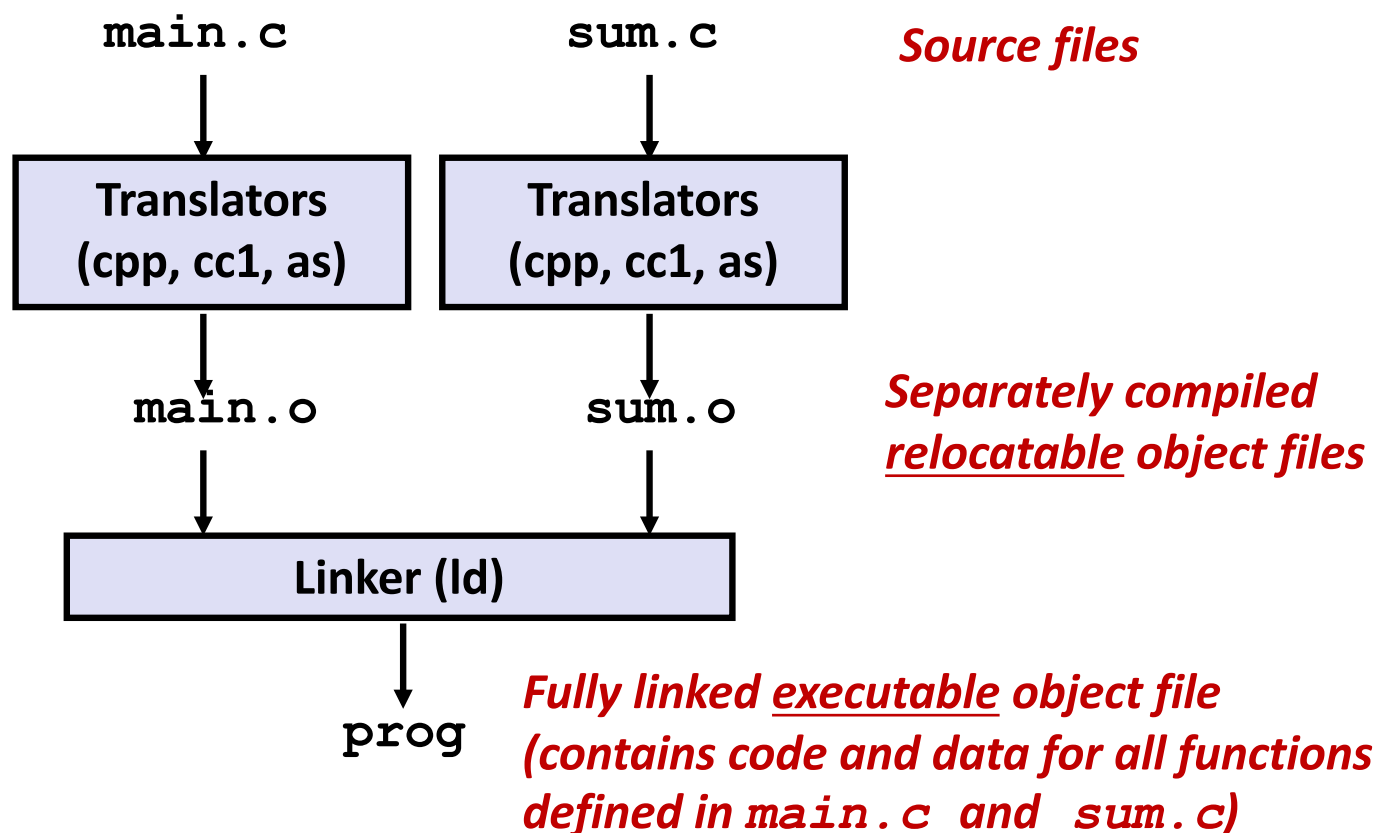
```c
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```
sum.c

Linking

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

   ▪ `linux> gcc -Og -o prog main.c sum.c`

   ▪ `linux> ./prog`

main.c   **sum.c**   *Source files*

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

main.o   **sum.o**   *Separately compiled*
relocatable object files

Linker (ld)

prog   *Fully linked executable object file*
(contains code and data for all functions
defined in `main.c` *and* `sum.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.
    - Can compile multiple files concurrently.
  - Space: Libraries
    - Common functions can be aggregated into a single file...
    - **Option 1: *Static Linking***
      - Executable files and running memory images contain only the library code they actually use
    - **Option 2: *Dynamic linking***
      - Executable files contain no library code
      - During execution, single copy of library code can be shared across all executing processes
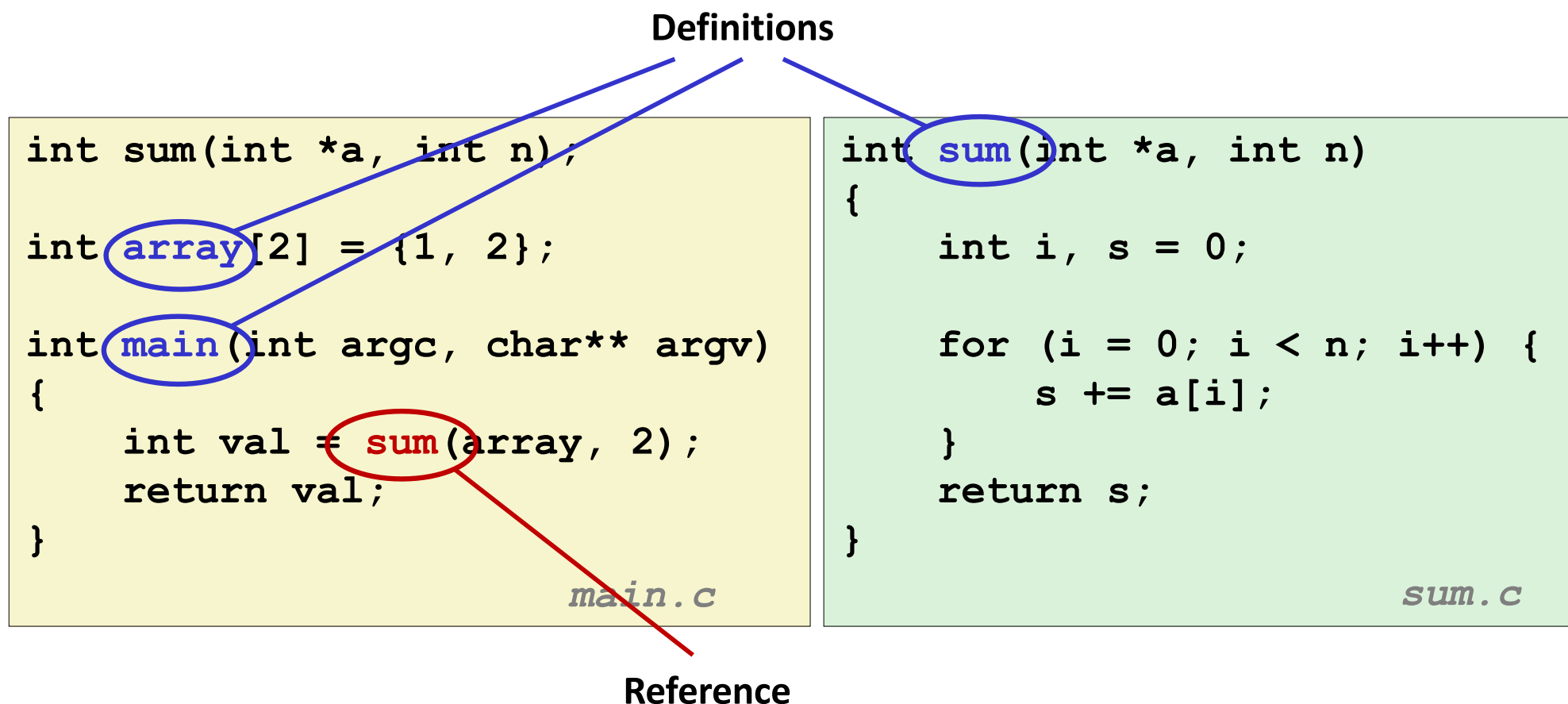
What Do Linkers Do?

- **Step 1: Symbol resolution**

  - Programs define and reference *symbols* (global variables and functions):
    - `void swap() {…}    /* define symbol swap */`
    - `swap();            /* reference symbol swap */`
    - `int *xp = &x;      /* define symbol xp, reference x */`

  - Symbol definitions are stored in object file (by assembler) in *symbol table*.
    - Symbol table is an array of entries
    - Each entry includes name, size, and location of symbol.

  - **During symbol resolution step, the linker associates each symbol reference with exactly one symbol definition.**

Symbols in Example C Program

Definitions

```
int sum(int *a, int n);

int array[2] = {1, 2};

int main(int argc, char** argv)
{
    int val = sum(array, 2);
    return val;
}
                              main.c
```

```
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
                              sum.c
```

Reference

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.

Let's look at these two steps in more detail….

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.

- **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**

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

- **`.text` section**
  - Code

- **`.rodata section`**
  - Read only data: jump tables, string constants, …

- **`.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 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

0

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

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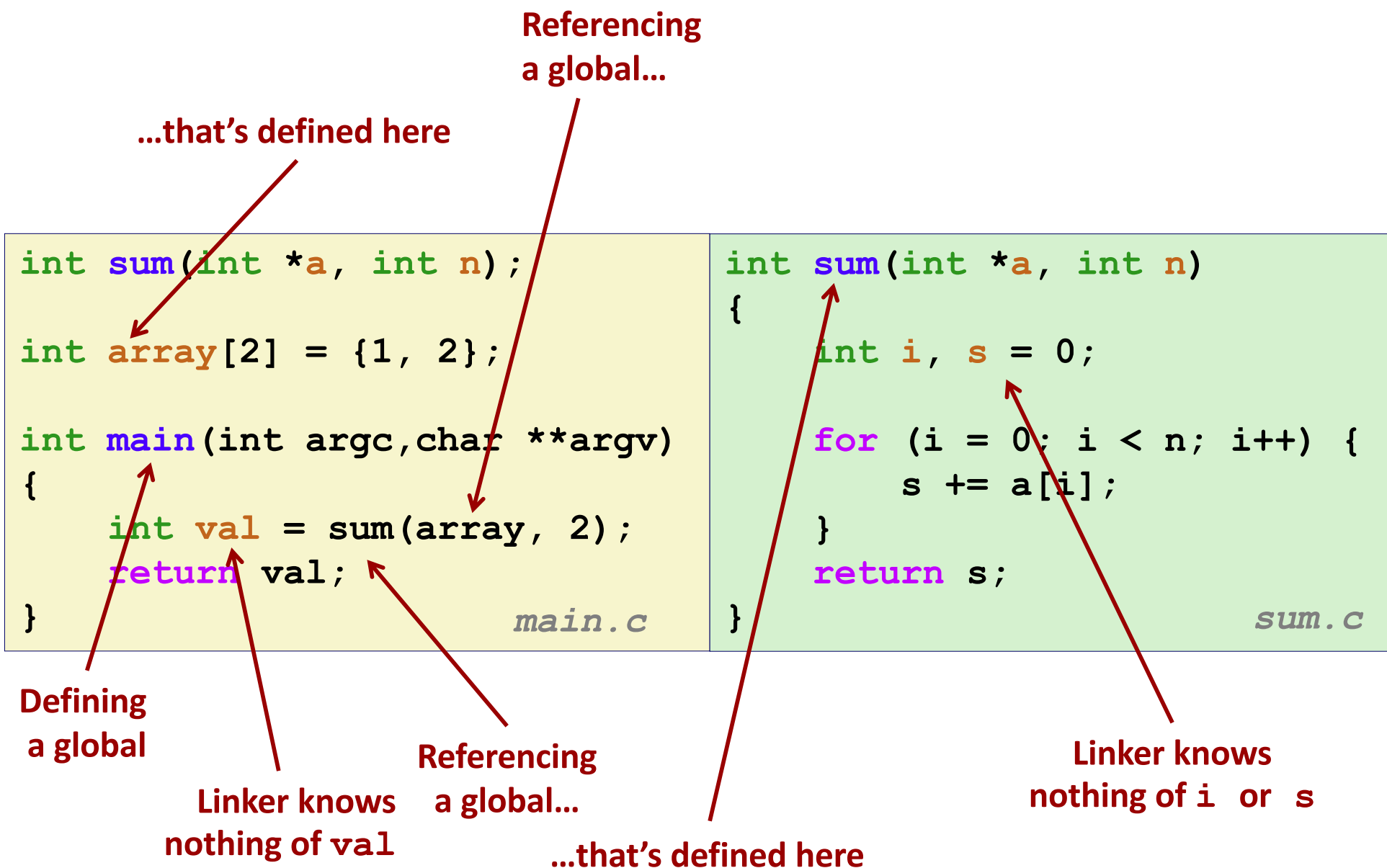
- **External symbols**
  - Global symbols that are referenced by module *m* but defined by some other module.

- **Local symbols**
  - Symbols that are defined and referenced exclusively by module *m*.
  - E.g.: C functions and global variables defined with the `static` attribute.
  - **Local linker symbols are *not* local program variables**

Step 1: Symbol Resolution

Referencing a global…

…that's defined here

```c
int sum(int *a, int n);

int array[2] = {1, 2};

int main(int argc,char **argv)
{
    int val = sum(array, 2);
    return val;
}
                          main.c
```

```c
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
                          sum.c
```

Defining a global

Linker knows nothing of val

Referencing a global…

…that's defined here

Linker knows nothing of i or s

Symbol Identification

Which of the following names will be in the symbol table of `symbols.o`?

symbols.c:

```
int time;

int foo(int a) {
  int b = a + 1;
  return b;
}

int main(int argc,
         char* argv[]) {
  printf("%d\n", foo(5));
  return 0;
}
```

Names:

- `time`
- `foo`
- `a`
- `argc`
- `argv`
- `b`
- `main`
- `printf`
- `"%d\n"`

Local Symbols

- **Local non-static C variables vs. local static C variables**
  - local non-static C variables: stored on the stack
  - local static C variables: stored in either `.bss,` or `.data`

```
static int x = 15;

int f() {
    static int x = 17;
    return x++;
}


int g() {
    static int x = 19;
    return x += 14;
}


int h() {
    return x += 27;
}
                        static-local.c
```
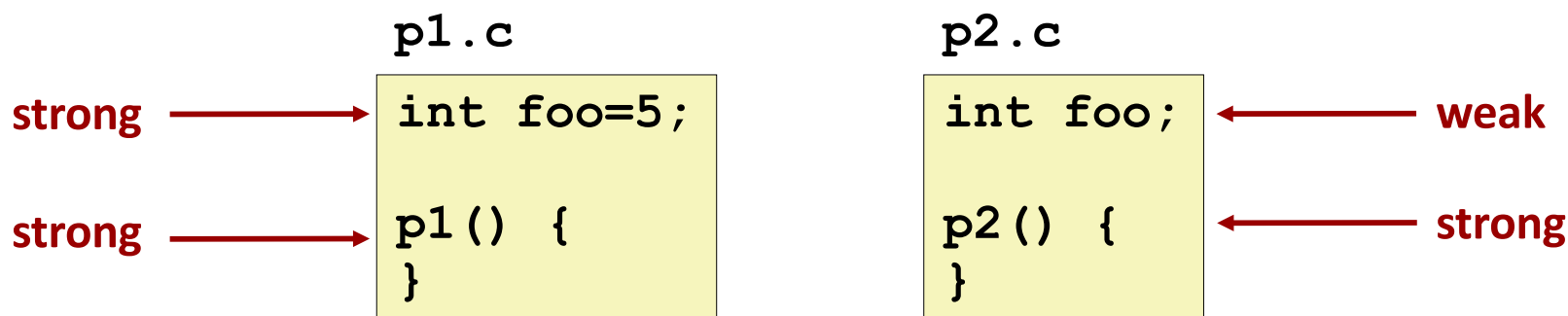
Compiler allocates space in `.data` for each definition of `x`

Creates local symbols in the symbol table with unique names, e.g., `x`, `x.1721` and `x.1724`.

How Linker Resolves Duplicate Symbol Definitions

- **Program symbols are either *strong* or *weak***
  - *Strong*: procedures and initialized globals
  - *Weak*: uninitialized globals
    - Or ones declared with specifier `extern`

```
p1.c                          p2.c
```

strong ──────→ `int foo=5;`   `int foo;` ←────── weak

strong ──────→ `p1() {`   `p2() {` ←────── strong
               `}`   `}`

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 symbols, 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`

- **Puzzles on the next slide**

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.

Important: Linker does not do type checking.

Type Mismatch Example

```
long int x;   /* Weak symbol */

int main(int argc,
         char *argv[]) {
   printf("%ld\n", x);
   return 0;
}
                    mismatch-main.c
```

```
/* Global strong symbol */
double x = 3.14;



                mismatch-variable.c
```

- **Compiles without any errors or warnings**
- **What gets printed?**

Global Variables

- **Avoid if you can**

- **Otherwise**
  - Use `static` if you can
  - Initialize if you define a global variable
  - Use `extern` if you reference an external global variable
    - Treated as weak symbol
    - But also causes linker error if not defined in some file

Use of `extern` in .h Files (#1)

c1.c

```
#include "global.h"

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

global.h

```
extern int g;
int f();
```

c2.c

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

int g = 0;

int main(int argc, char argv[]) {
   int t = f();
   printf("Calling f yields %d\n", t);
   return 0;
}
```

Use of .h Files (#2)

global.h

c1.c

```
#include "global.h"

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

```
extern int g;
static int init = 0;
```

```
#else
  extern int g;
  static int init = 0;
#endif
```
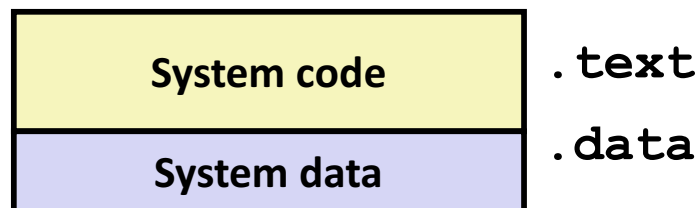
c2.c

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

int main(int argc, char** argv) {
  if (init)
    // do something, e.g., g=31;
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```
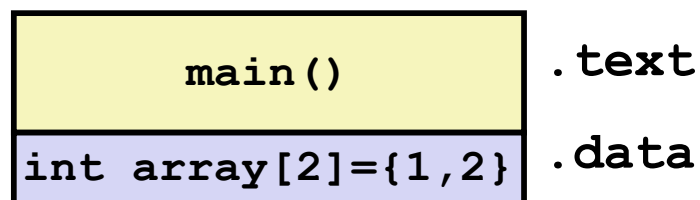
```
int g = 23;
static int init = 1;
```

Step 2: Relocation

Relocatable Object Files

| System code | .text |
| System data | .data |

main.o

| main() | .text |
| int array[2]={1,2} | .data |

sum.o

| sum() | .text |

Executable Object File

0

| Headers |
| System code |
| main() |
| sum() |
| More system code |
| System data |
| int array[2]={1,2} |
| .symtab .debug |

.text

.data
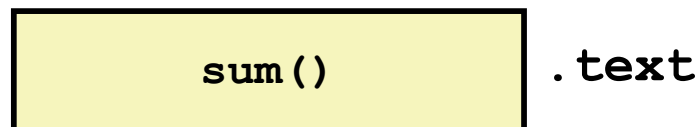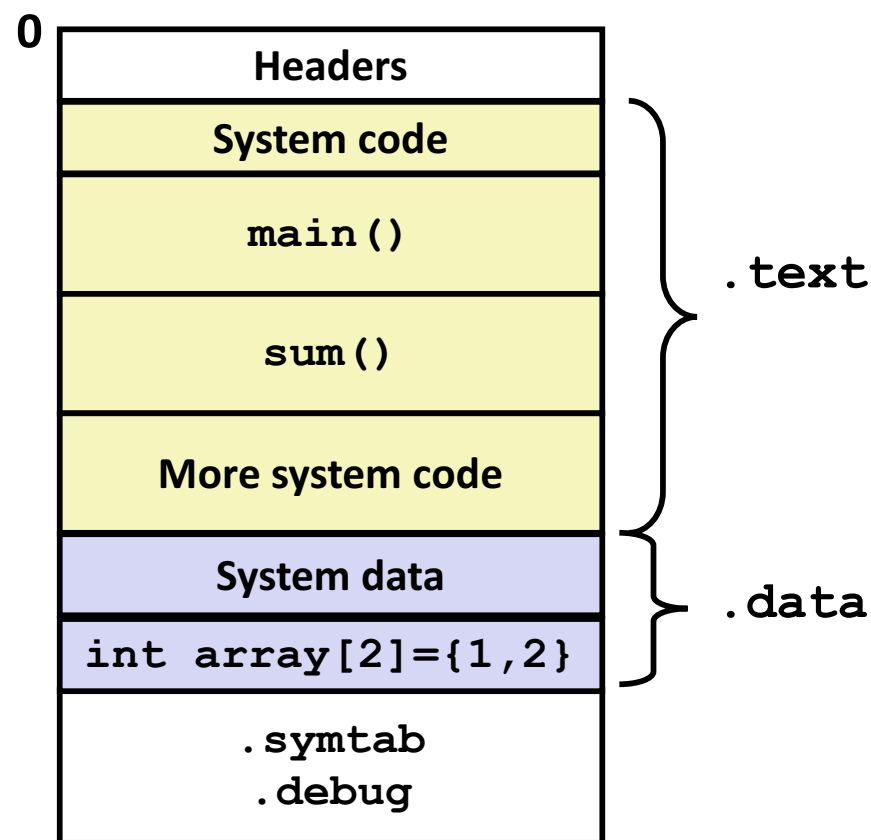
Relocation Entries

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

int main(int argc, char**
argv)
{
    int val = sum(array, 2);
    return val;

}                           main.c
```

```
0000000000000000 <main>:
  0:    48 83 ec 08              sub     $0x8,%rsp
  4:    be 02 00 00 00           mov     $0x2,%esi
  9:    bf 00 00 00 00           mov     $0x0,%edi    # %edi = &array
                       a: R_X86_64_32 array           # Relocation entry

  e:    e8 00 00 00 00           callq   13 <main+0x13> # sum()
                       f: R_X86_64_PC32 sum-0x4        # Relocation entry
 13:    48 83 c4 08              add     $0x8,%rsp
 17:    c3                       retq

                                                       main.o
```

Bryant and O'Hallaron, Computer Systems: A Programmer's Perspective, Third Edition

Source: `objdump –r –d main.o`

Relocated .text section

```
00000000004004d0 <main>:
  4004d0:       48 83 ec 08          sub      $0x8,%rsp
  4004d4:       be 02 00 00 00       mov      $0x2,%esi
  4004d9:       bf 18 10 60 00       mov      $0x601018,%edi   # %edi = &array
  4004de:       e8 05 00 00 00       callq    4004e8 <sum>       # sum()
  4004e3:       48 83 c4 08          add      $0x8,%rsp
  4004e7:       c3                   retq

00000000004004e8 <sum>:
  4004e8:       b8 00 00 00 00                mov      $0x0,%eax
  4004ed:       ba 00 00 00 00                mov      $0x0,%edx
  4004f2:       eb 09                         jmp      4004fd <sum+0x15>
  4004f4:       48 63 ca                      movslq %edx,%rcx
  4004f7:       03 04 8f                      add      (%rdi,%rcx,4),%eax
  4004fa:       83 c2 01                      add      $0x1,%edx
  4004fd:       39 f2                         cmp      %esi,%edx
  4004ff:       7c f3                         jl       4004f4 <sum+0xc>
  400501:       f3 c3                         repz retq
```

callq instruction uses PC-relative addressing for sum():
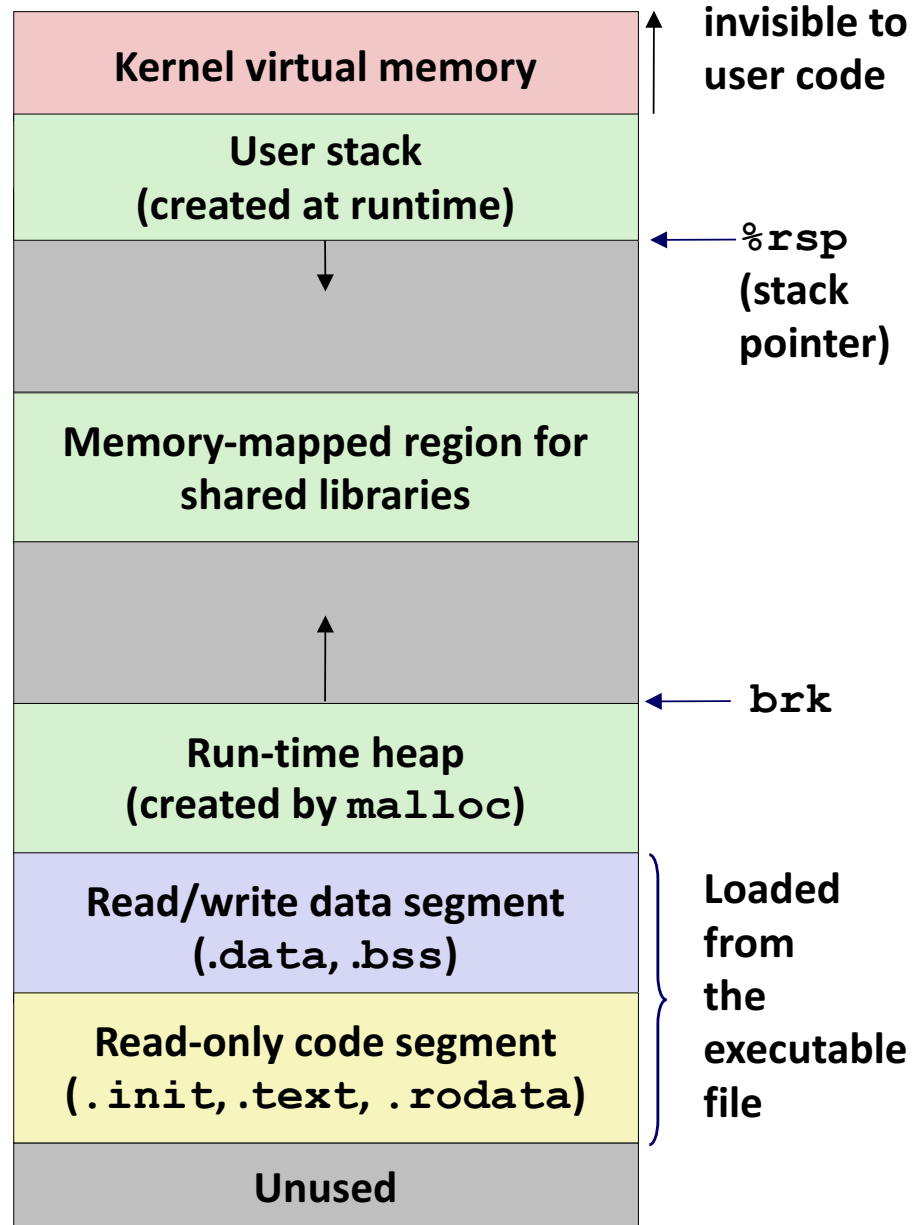
0x4004e8 = 0x4004e3 + 0x5

Loading Executable Object Files

Executable Object File

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)

0

Memory invisible to user code ↑

Kernel virtual memory
User stack (created at runtime)

← `%rsp` (stack pointer)

↓

Memory-mapped region for shared libraries

↑

← `brk`

Run-time heap (created by `malloc`)
Read/write data segment (`.data, .bss`)
Read-only code segment (`.init, .text, .rodata`)

Loaded from the executable file

`0x400000`

Unused

0

Quiz Time!

Check out:

https://canvas.cmu.edu/courses/1221
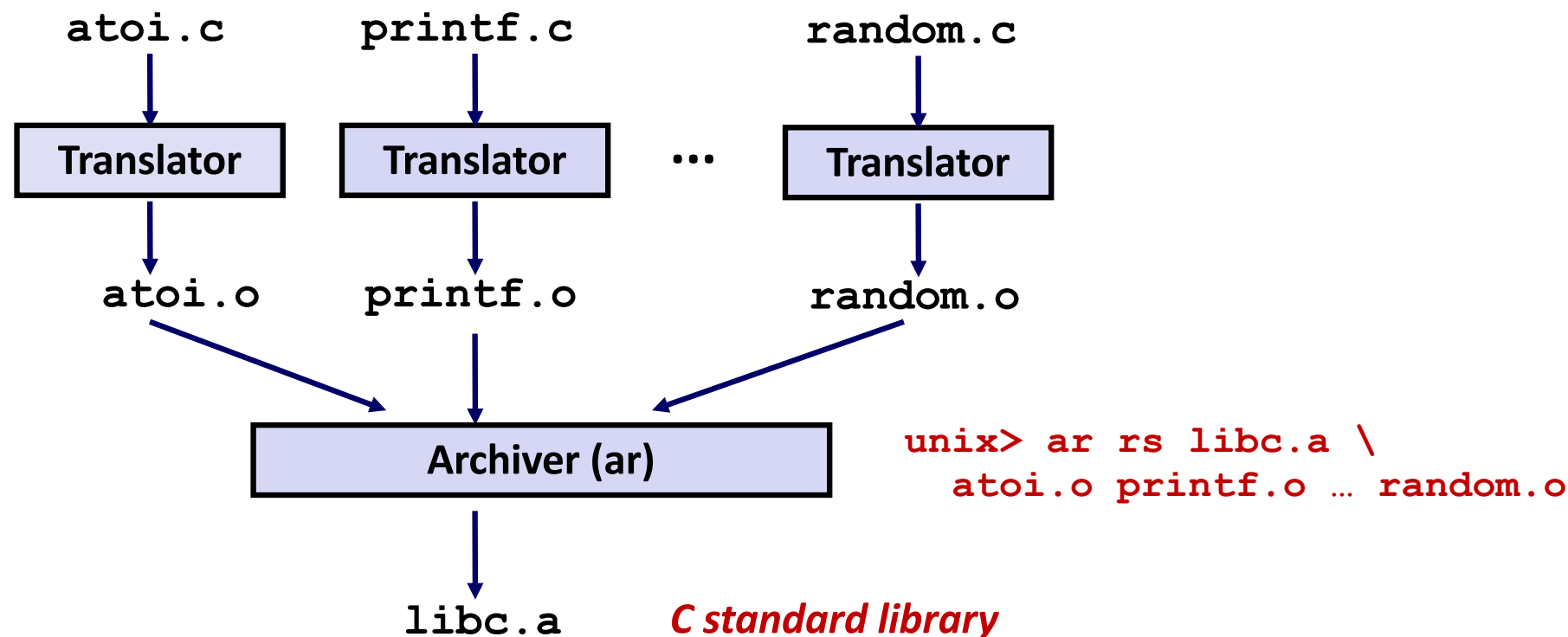
Packaging Commonly Used Functions

- **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

Old-fashioned 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)

- 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

libvector.a

```c
#include <stdio.h>
#include "vector.h"

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

int main(int argc, char**
argv)
{
    addvec(x, y, z, 2);
    printf("z = [%d %d]\n",
           z[0], z[1]);
    return 0;
}                    main2.c
```

```c
void addvec(int *x, int *y,
            int *z, int n) {
    int i;

    for (i = 0; i < n; i++)
        z[i] = x[i] + y[i];
}                    addvec.c
```
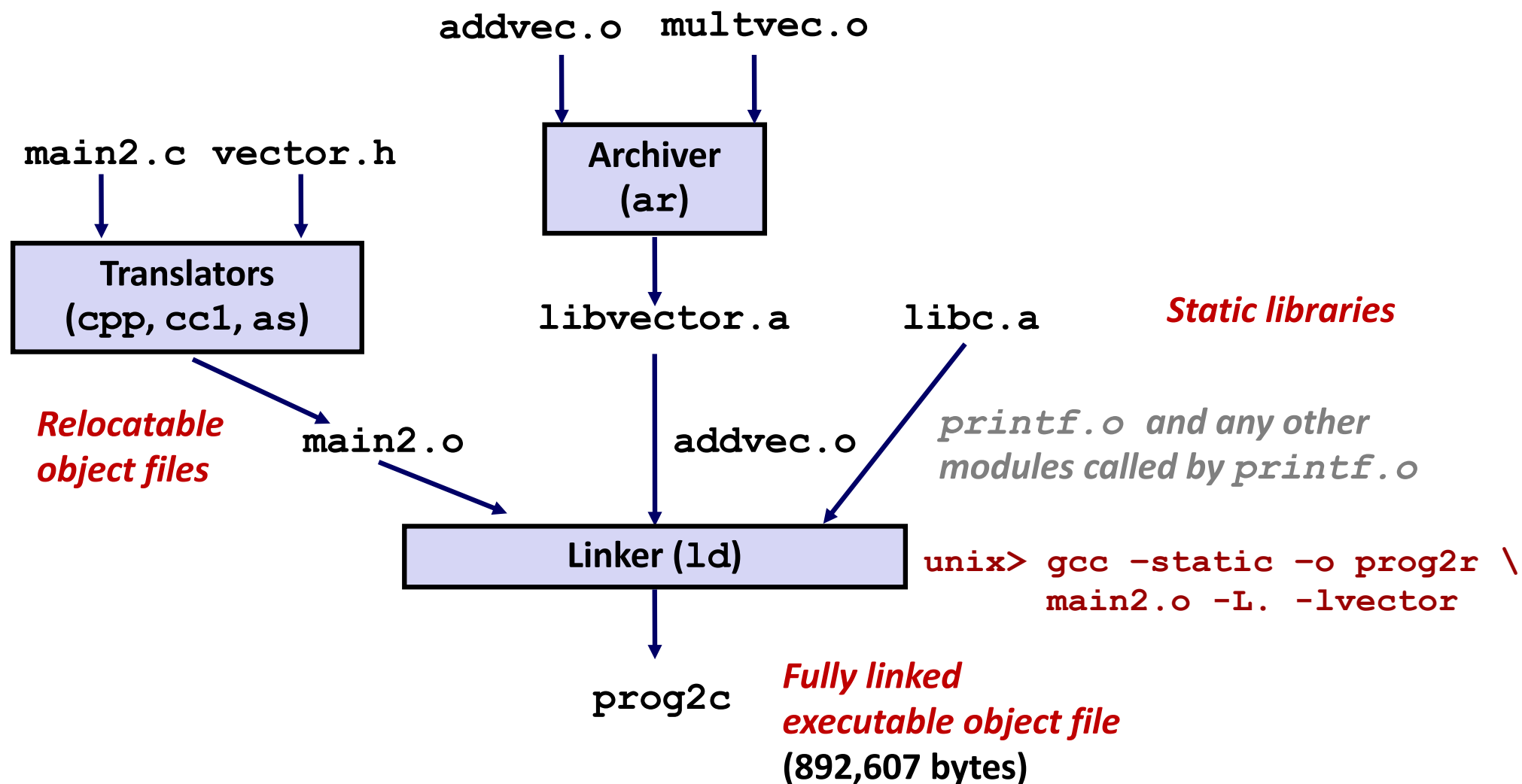
```c
void multvec(int *x, int *y,
             int *z, int n)
{
    int i;

    for (i = 0; i < n; i++)
        z[i] = x[i] * y[i];
}                    multvec.c
```

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)   unix> gcc –static –o prog2r \
                            main2.o -L. -lvector

prog2c   **Fully linked executable object file**
           (892,607 bytes)

"c" for "compile-time"

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'
```

Modern Solution: Shared Libraries

- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function needs libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink
    - Rebuild everything with glibc?
    - https://security.googleblog.com/2016/02/cve-2015-7547-glibc-getaddrinfo-stack.html

- **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 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.**
  - More on this when we learn about virtual memory

What dynamic libraries are required?

- **.interp section**
  - Specifies the dynamic linker to use (i.e., `ld-linux.so`)

- **.dynamic section**
  - Specifies the names, etc of the dynamic libraries to use
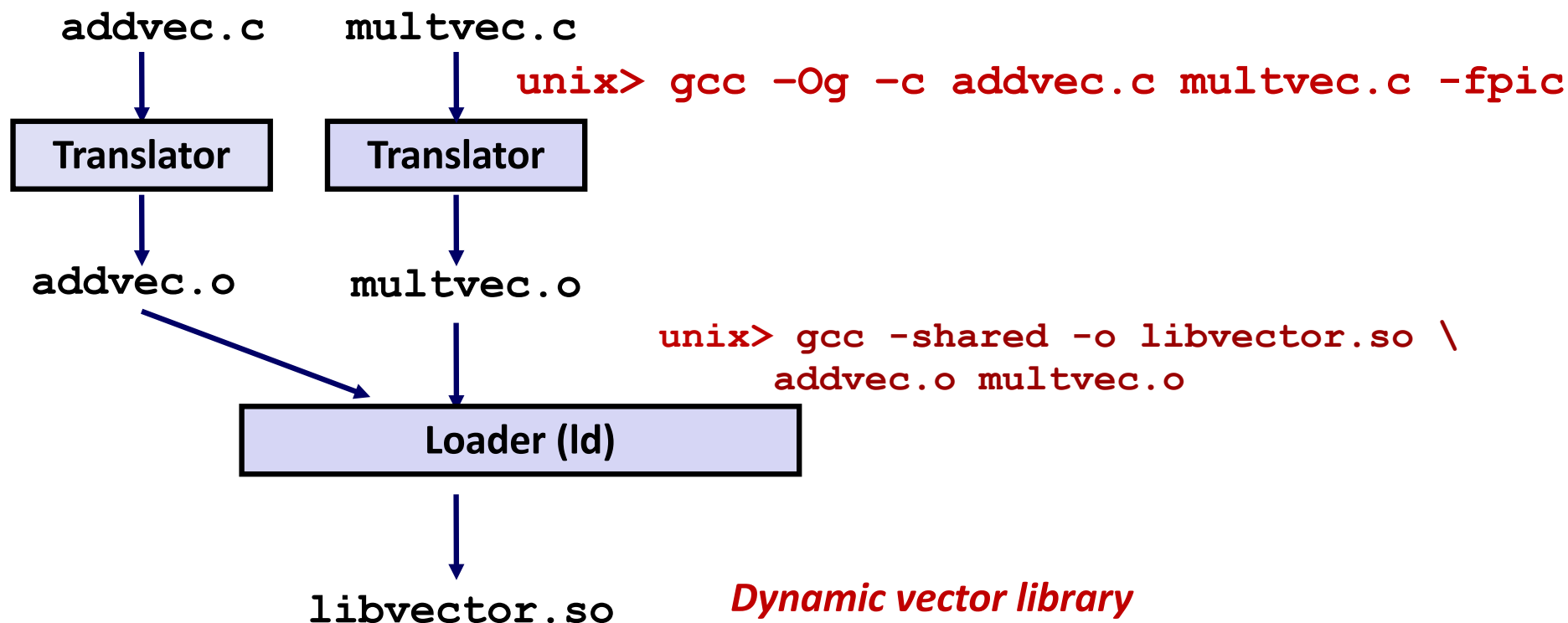 - Follow an example of `prog`

  `(NEEDED)                    Shared library: [libm.so.6]`

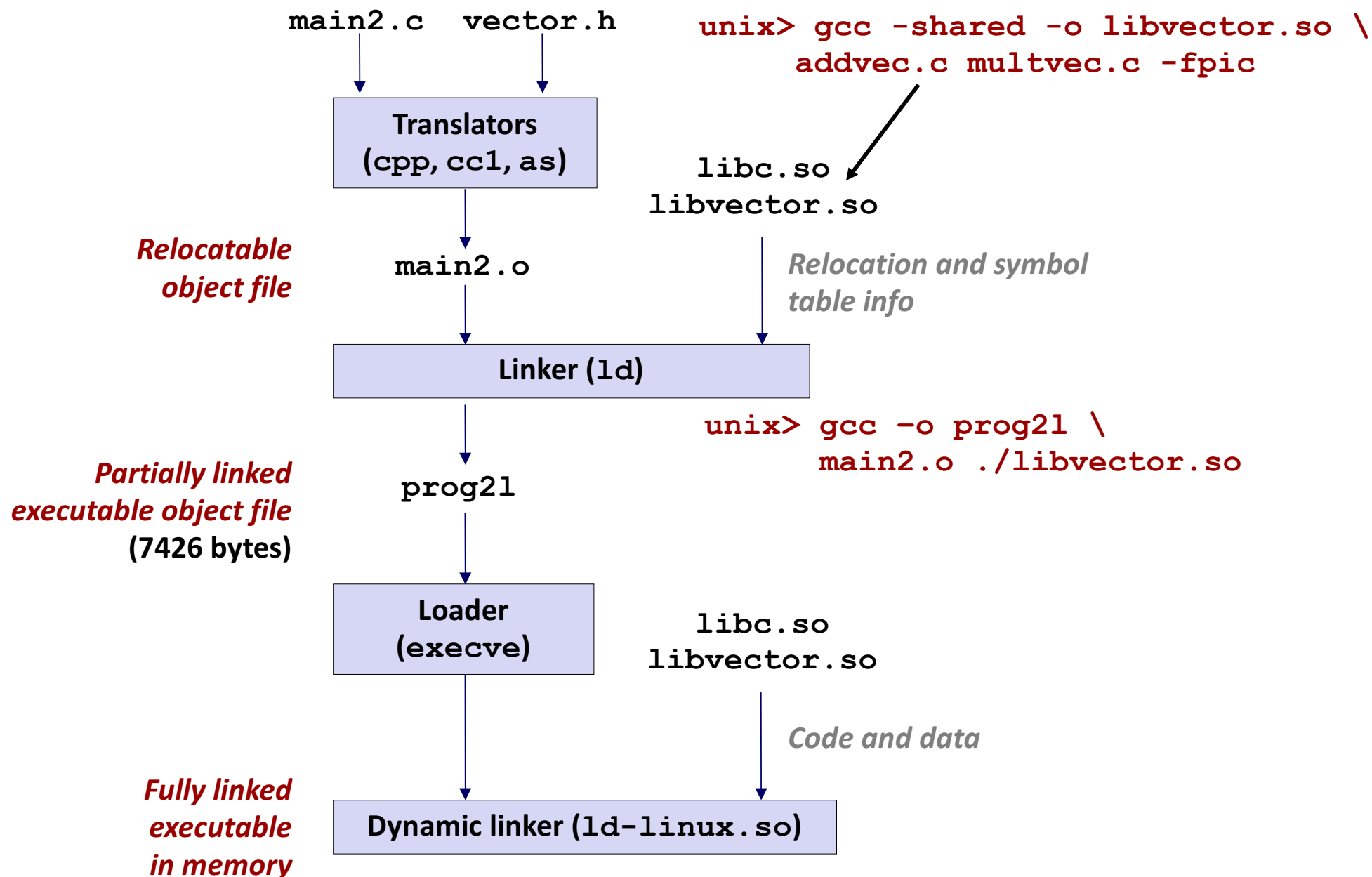- **Where are the libraries found?**
  - Use "`ldd`" to find out:

```
unix> ldd prog
    linux-vdso.so.1 =>  (0x00007ffcf2998000)
    libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f99ad927000)
    /lib64/ld-linux-x86-64.so.2 (0x00007f99adcef000)
```

Dynamic Library Example

```
addvec.c    multvec.c
```

unix> gcc –Og –c addvec.c multvec.c -fpic

```
Translator    Translator
```

```
addvec.o    multvec.o
```

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

```
Loader (ld)
```

```
libvector.so
```

Dynamic vector library

Dynamic Linking at Load-time

```
main2.c   vector.h
```

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

**Translators
(cpp, cc1, as)**

```
libc.so
libvector.so
```

*Relocatable
object file*

```
main2.o
```

*Relocation and symbol
table info*

Linker (ld)

unix> gcc -o prog2l \
          main2.o ./libvector.so

*Partially linked
executable object file*
(7426 bytes)

```
prog2l
```

**Loader
(execve)**

```
libc.so
libvector.so
```

Code and data

*Fully linked
executable
in memory*

Dynamic linker (ld-linux.so)

Dynamic Linking at Run-time

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

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

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

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

dll.c

Dynamic Linking at Run-time (cont)

```c
    ...

    /* 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;
}
                                                              dll.c
```
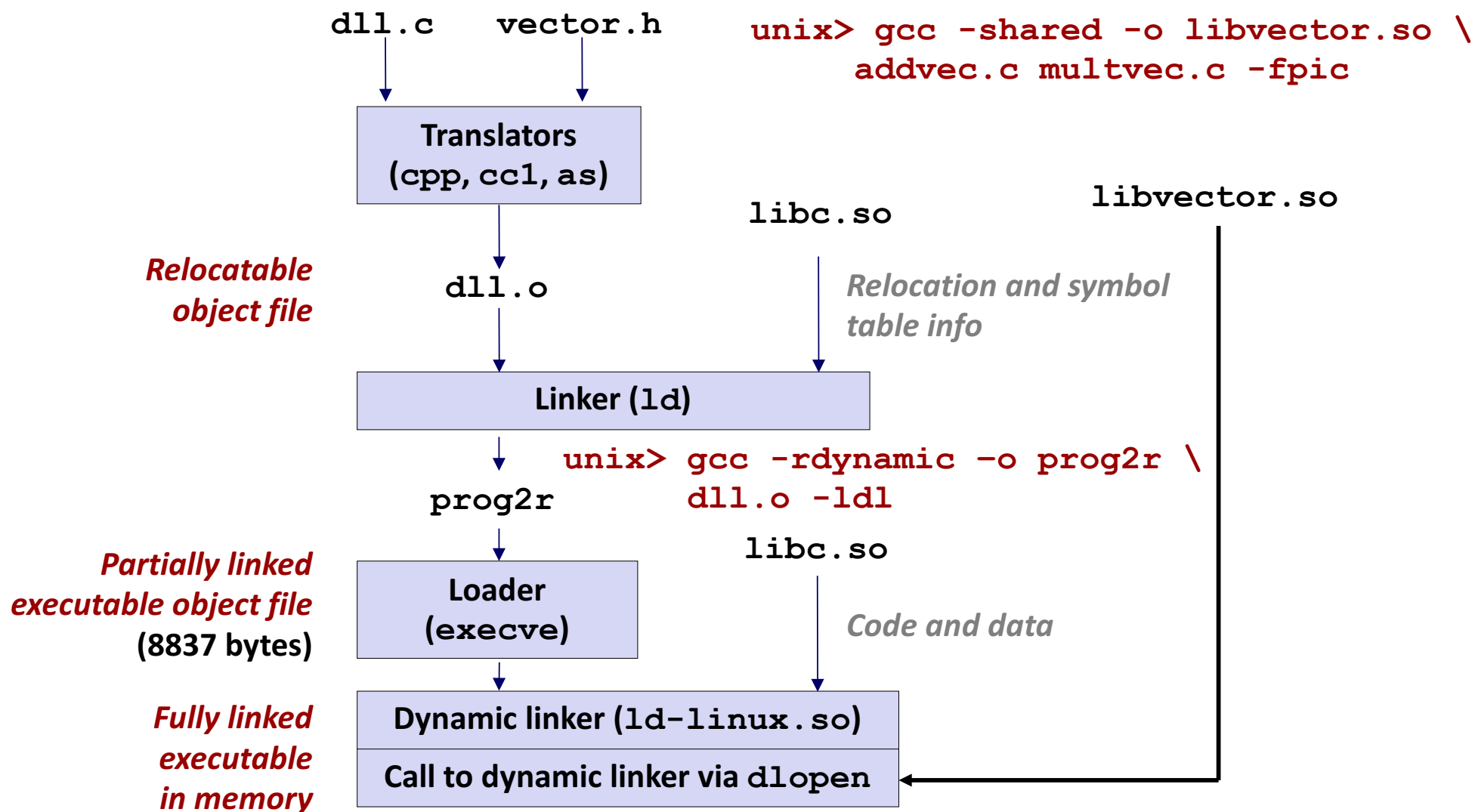
Dynamic Linking at Run-time

dll.c   vector.h

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

**Translators
(cpp, cc1, as)**

libc.so   libvector.so

*Relocatable
object file*

dll.o   *Relocation and symbol
                          table info*

Linker (ld)

unix> gcc -rdynamic –o prog2r \
          dll.o -ldl

prog2r

libc.so

*Partially linked
executable object file*
(8837 bytes)

**Loader
(execve)**

Code and data

*Fully linked
executable
in memory*

Dynamic linker (ld-linux.so)

Call to dynamic linker via dlopen

Linking Summary

■ **Linking is a technique that allows programs to be constructed from multiple object files.**

■ **Linking can happen at different times in a program's lifetime:**

- Compile time (when a program is compiled)
- Load time (when a program is loaded into memory)
- Run time (while a program is executing)

■ **Understanding linking can help you avoid nasty errors and make you a better programmer.**

Today

- **Linking**

- **Case study: Library interpositioning**

Case Study: Library Interpositioning

- **Library interpositioning : 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 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)
  - Behind the scenes encryption

- **Debugging**
  - In 2014, two Facebook engineers debugged a treacherous 1-year old bug in their iPhone app using interpositioning
  - Code in the SPDY networking stack was writing to the wrong location
  - Solved by intercepting calls to Posix write functions (write, writev, pwrite)

  Source: Facebook engineering blog post at:

  https://code.facebook.com/posts/313033472212144/debugging-file-corruption-on-ios/

Some Interpositioning Applications

- **Monitoring and Profiling**
  - Count number of calls to functions
  - Characterize call sites and arguments to functions
  - Malloc tracing
    - Detecting memory leaks
    - **Generating address traces**

- **Error Checking**
  - C Programming Lab used customized versions of malloc/free to do careful error checking

Example program

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

int main(int argc,
         char *argv[])
{
  int i;
  for (i = 1; i < argc; i++) {
    void *p =
           malloc(atoi(argv[i]));
    free(p);
  }
  return(0);
}
                              int.c
```

- **Goal: trace the addresses and sizes of the allocated and freed blocks, without breaking the program, and without modifying the source code.**

- **Three solutions: interpose on the library `malloc` and `free` functions at compile time, link time, and load/run time.**

Compile-time Interpositioning

```
#ifdef COMPILETIME
#include <stdio.h>
#include <malloc.h>

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

/* free wrapper function */
void myfree(void *ptr)
{
    free(ptr);
    printf("free(%p)\n", ptr);
}
#endif
```
mymalloc.c

Compile-time Interpositioning

```c
#define malloc(size) mymalloc(size)
#define free(ptr) myfree(ptr)


void *mymalloc(size_t size);
void myfree(void *ptr);
```
<div align="right">

`malloc.h`
</div>

```
linux> make intc
gcc -Wall -DCOMPILETIME -c mymalloc.c
gcc -Wall -I. -o intc int.c mymalloc.o
linux> make runc
./intc 10 100 1000
malloc(10)=0x1ba7010
free(0x1ba7010)
malloc(100)=0x1ba7030
free(0x1ba7030)
malloc(1000)=0x1ba70a0
free(0x1ba70a0)
linux>
```

Search for <malloc.h> leads to /usr/include/malloc.h

Search for <malloc.h> leads to

Link-time Interpositioning

```c
#ifdef LINKTIME
#include <stdio.h>

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

/* malloc wrapper function */
void *__wrap_malloc(size_t size)
{
    void *ptr = __real_malloc(size); /* Call libc malloc */
    printf("malloc(%d) = %p\n", (int)size, ptr);
    return ptr;
}


/* free wrapper function */
void __wrap_free(void *ptr)
{
    __real_free(ptr); /* Call libc free */
    printf("free(%p)\n", ptr);
}
#endif
```

mymalloc.c

Link-time Interpositioning

```
linux> make intl
gcc -Wall -DLINKTIME -c mymalloc.c
gcc -Wall -c int.c
gcc -Wall -Wl,--wrap,malloc -Wl,--wrap,free -o intl \
    int.o mymalloc.o
linux> make runl
./intl 10 100 1000
malloc(10) = 0x91a010
free(0x91a010)
. . .
```

Search for **<malloc.h>** leads to
/usr/include/malloc.h

- **The "–Wl" flag passes argument to linker, replacing each comma with a space.**

- **The "--wrap,malloc" arg instructs linker 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 Interpositioning

```
#ifdef RUNTIME
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>
#include <dlfcn.h>
```

Observe that DON'T have
#include <malloc.h>

```
/* malloc wrapper function */
void *malloc(size_t size)
{
    void *(*mallocp)(size_t size);
    char *error;

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

Load/Run-time Interpositioning

```c
/* free wrapper function */
void free(void *ptr)
{
    void (*freep)(void *) = NULL;
    char *error;

    if (!ptr)
        return;

    freep = dlsym(RTLD_NEXT, "free"); /* Get address of libc free */
    if ((error = dlerror()) != NULL) {
        fputs(error, stderr);
        exit(1);
    }
    freep(ptr); /* Call libc free */
    printf("free(%p)\n", ptr);
}
#endif
```
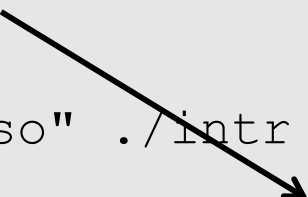
                                                    `mymalloc.c`

Load/Run-time Interpositioning

```
linux> make intr
gcc -Wall -DRUNTIME -shared -fpic -o mymalloc.so mymalloc.c -ldl
gcc -Wall -o intr int.c
linux> make runr
(LD_PRELOAD="./mymalloc.so" ./intr 10 100 1000)
malloc(10) = 0x91a010
free(0x91a010)
. . .
linux>
```

> Search for **<malloc.h>** leads to
> **/usr/include/malloc.h**

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

- **Type into (some) shells as:**

  `(setenv LD_PRELOAD "./mymalloc.so"; ./intr 10 100 1000)`

Interpositioning Recap

- **Compile Time**
  - Apparent calls to **malloc/free** get macro-expanded into calls to **mymalloc/myfree**
  - Simple approach. Must have access to source & recompile

- **Link Time**
  - Use linker trick to have special name resolutions
    - **malloc → __wrap_malloc**
    - **__real_malloc → malloc**

- **Load/Run Time**
  - Implement custom version of **malloc/free** that use dynamic linking to load library **malloc/free** under different names
  - Can use with ANY dynamically linked binary

```
(setenv LD_PRELOAD "./mymalloc.so"; gcc –c int.c)
```

Linking Recap

- **Usually: Just happens, no big deal**

- **Sometimes: Strange errors**
    - Bad symbol resolution
    - Ordering dependence of linked .o, .a, and .so files

- **For power users:**
    - Interpositioning to trace programs with & without source