

Today

- **Linking**
- Case study: Library interpositioning



Example C Program

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

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

int main()
{
    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;
}
```

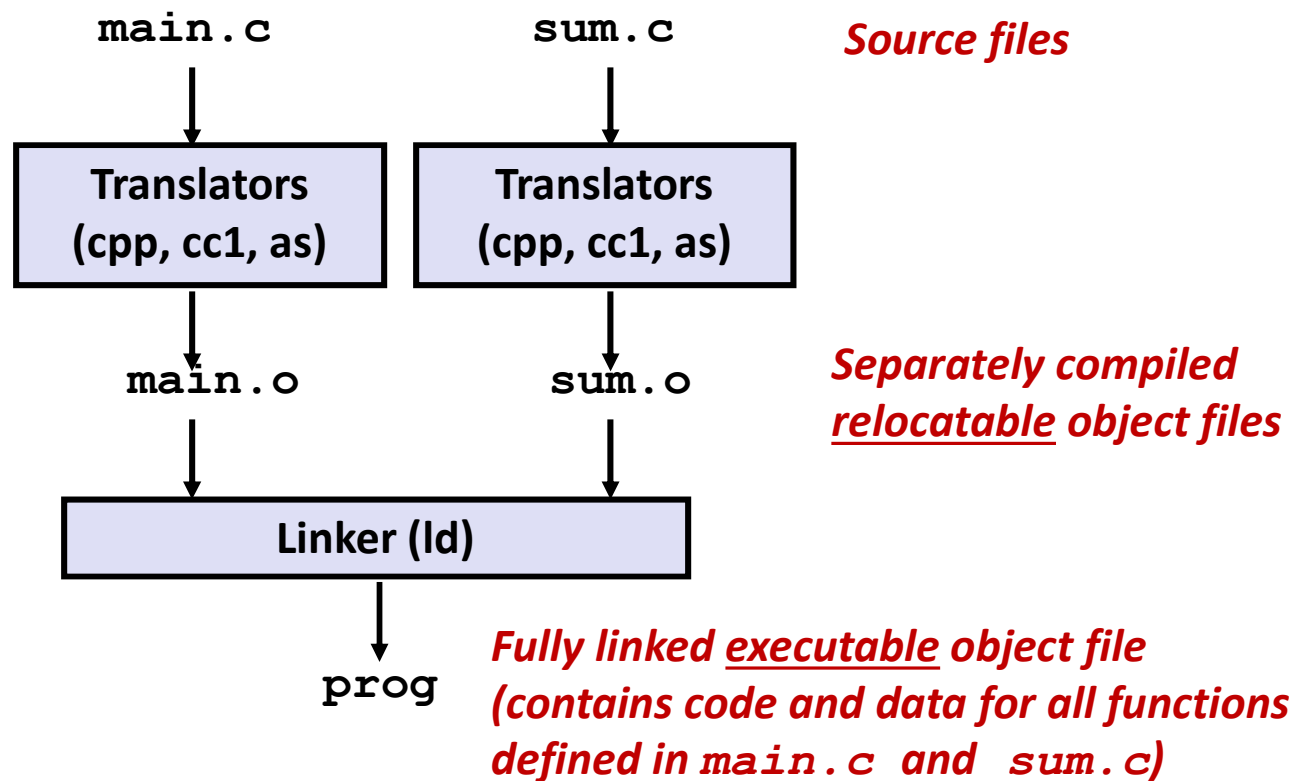
sum.c



Static Linking

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

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



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* (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 `structs`
 - Each entry includes name, size, and location of symbol.
- **During symbol resolution step, the 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.

■ 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**



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.



Step 1: Symbol Resolution

Referencing a global...
...that's defined here

```
int sum(int *a, int n);  
int array[2] = {1, 2};  
  
int main()  
{  
    int val = sum(array, 2);  
    return val;  
}  
  
main.c
```

Defining
a global

Linker knows
nothing of val

Referencing
a global...

...that's defined here

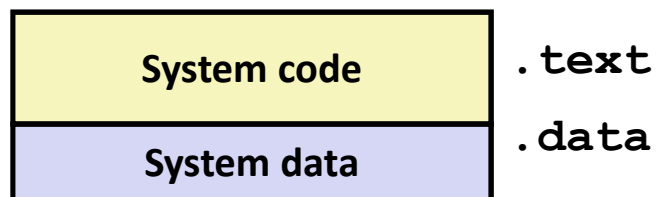
```
int sum(int *a, int n)  
{  
    int i, s = 0;  
    for (i = 0; i < n; i++) {  
        s += a[i];  
    }  
    return s;  
}  
  
sum.c
```

Linker knows
nothing of i or s

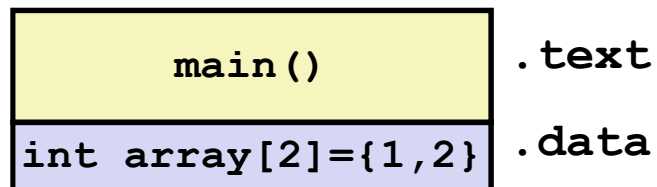


Step 2: Relocation

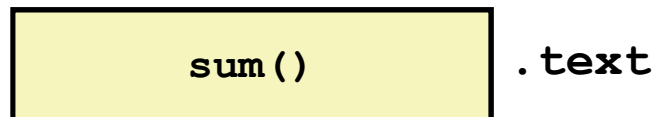
Relocatable Object Files



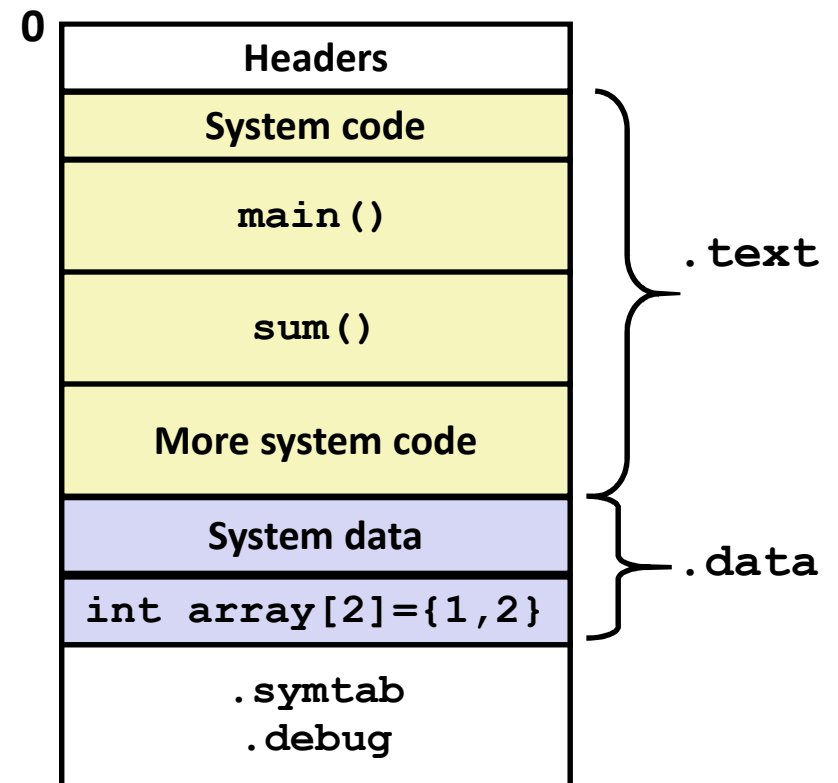
main.o



sum.o



Executable Object File



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



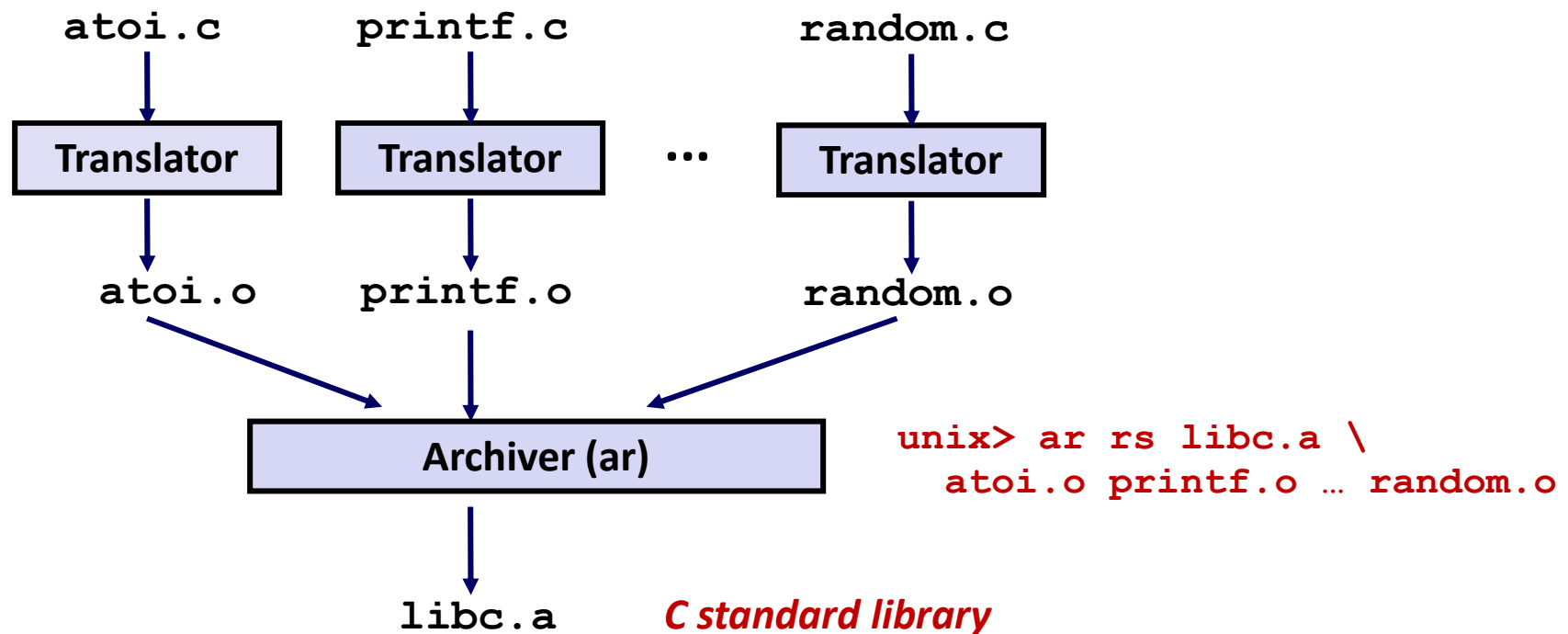
Old-fashioned Solution: Static Libraries

■ **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



- 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 libc.a | sort
...
fork.o
...
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
...
```

```
% ar -t 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

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

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

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

libvector.a

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

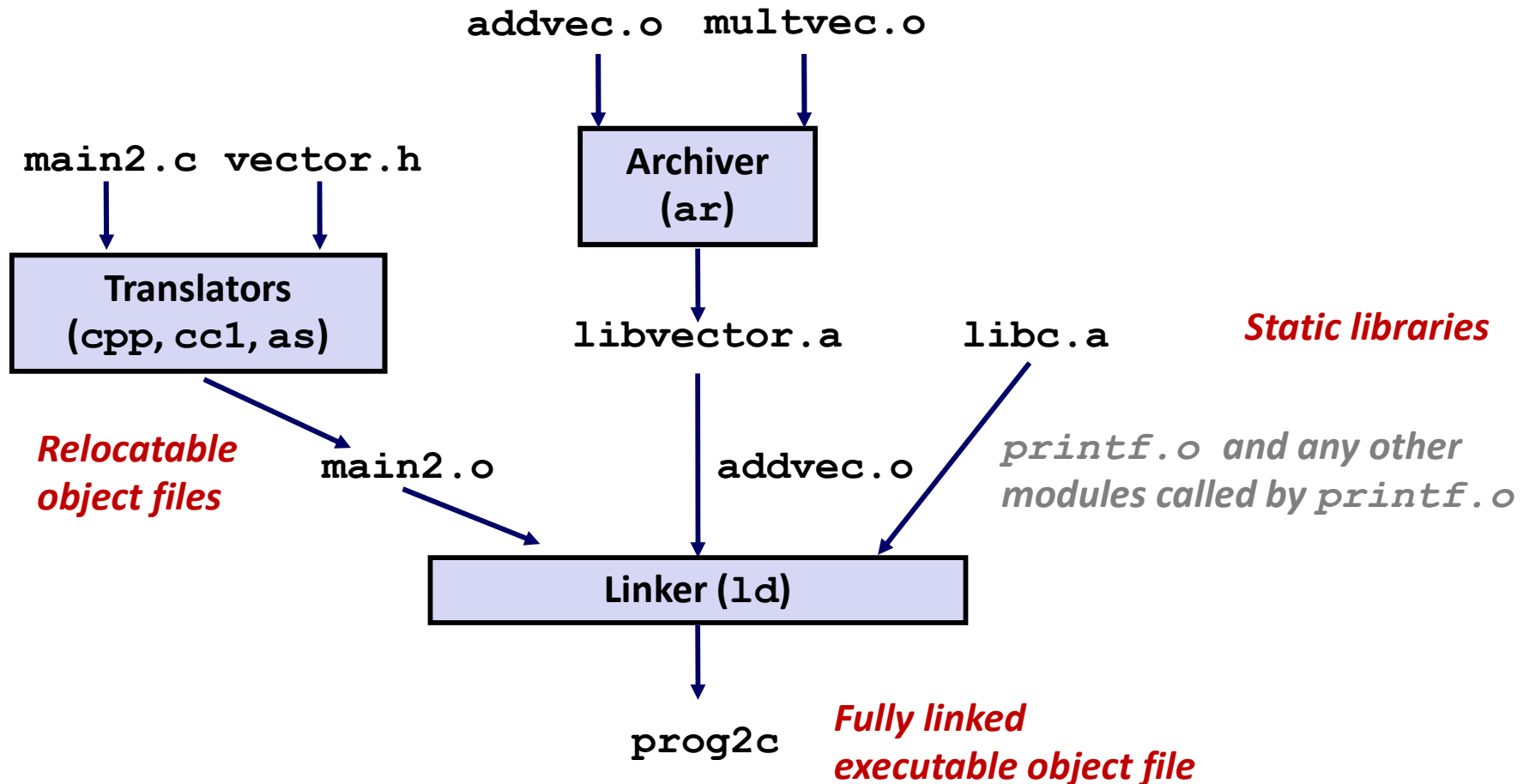
    for (i = 0; i < n; i++)
        z[i] = x[i] + y[i];
}
addvec.c
```

```
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



"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

■ 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

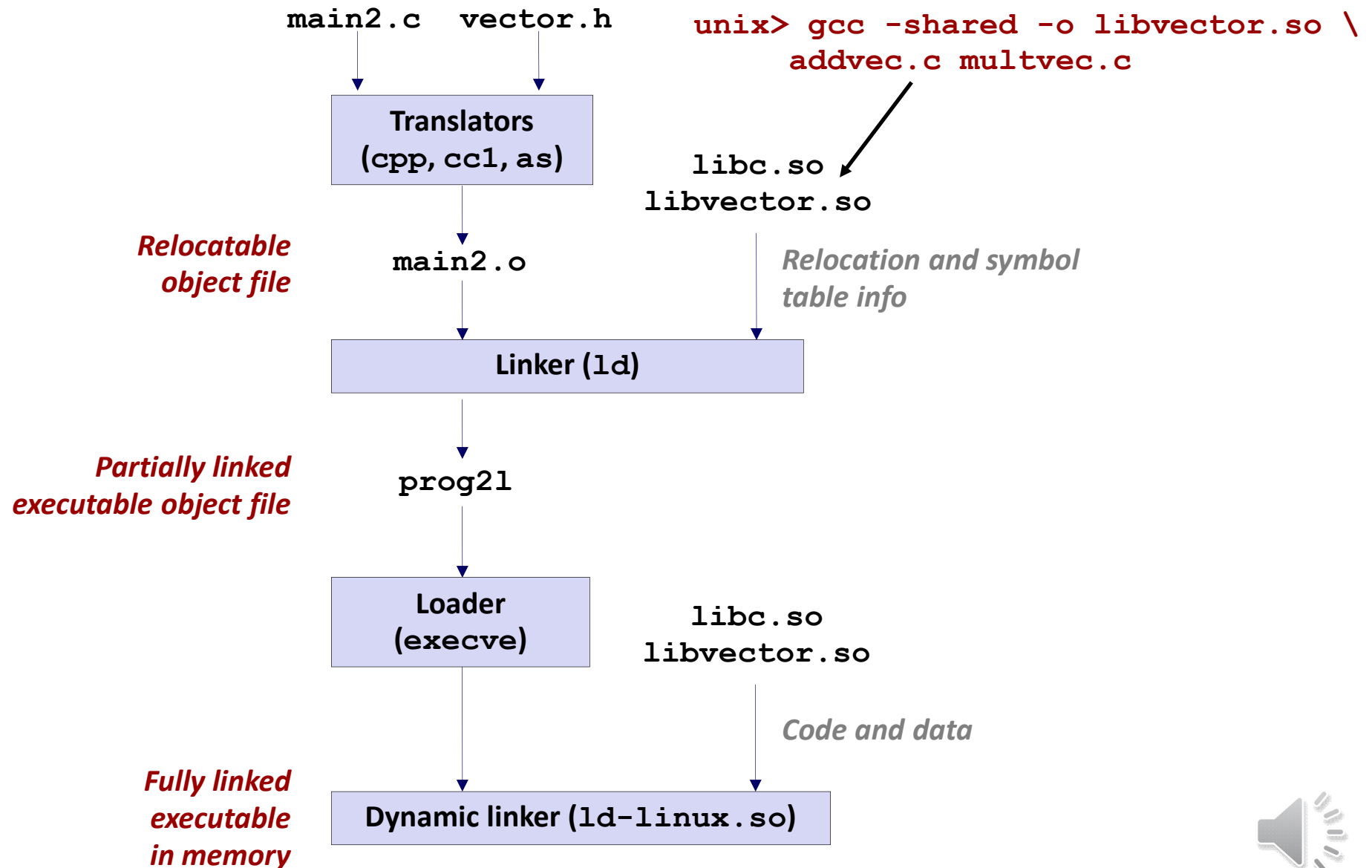


Shared Libraries (cont.)

- **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



Dynamic Linking at Load-time



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**

