

# Linking

15-213: Introduction to Computer Systems  
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# 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;

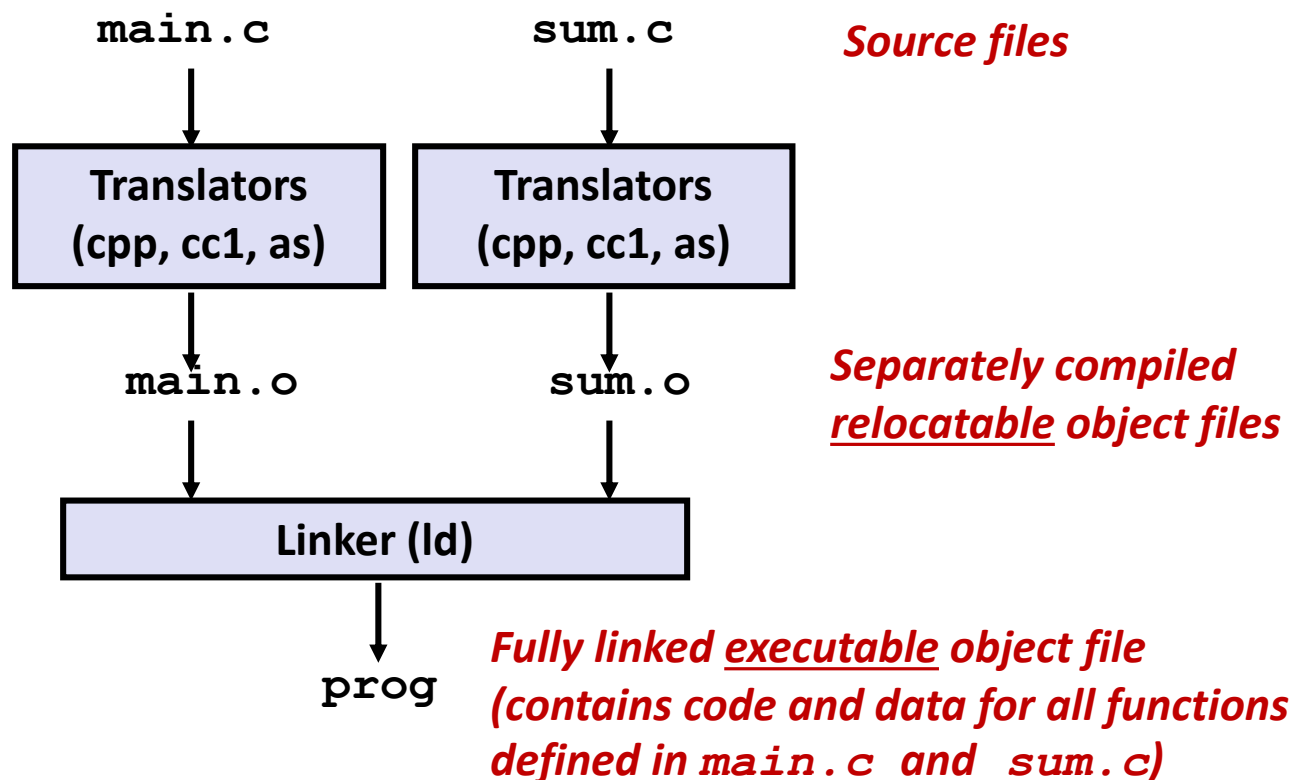
    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```

*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.

**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

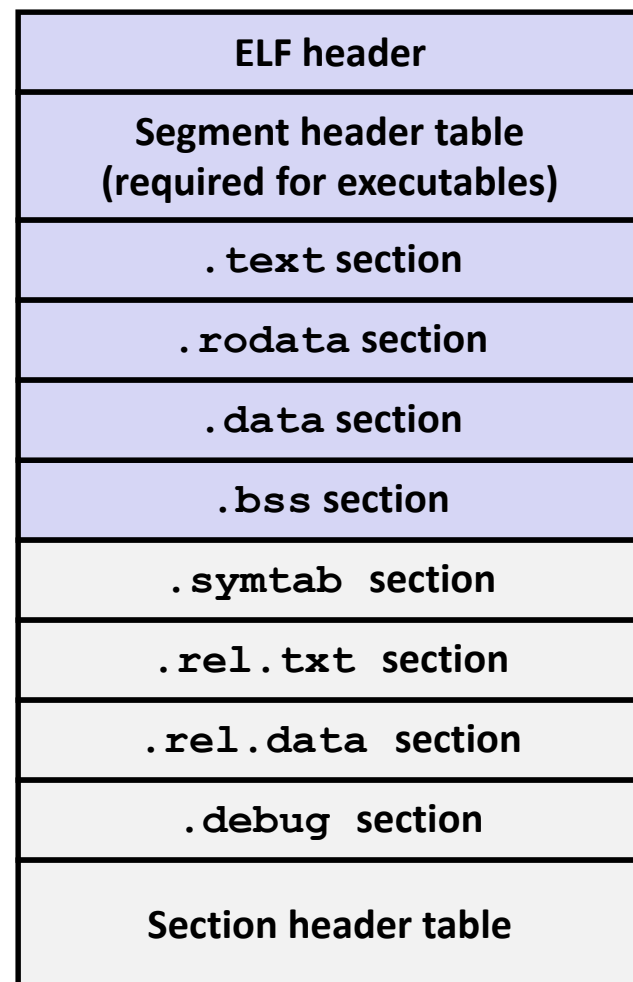
- Read only data: jump tables, ...

## ■ .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 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

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

0

# 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

```
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

# 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`

```
int f()
{
    static int x = 0;
    return x;
}

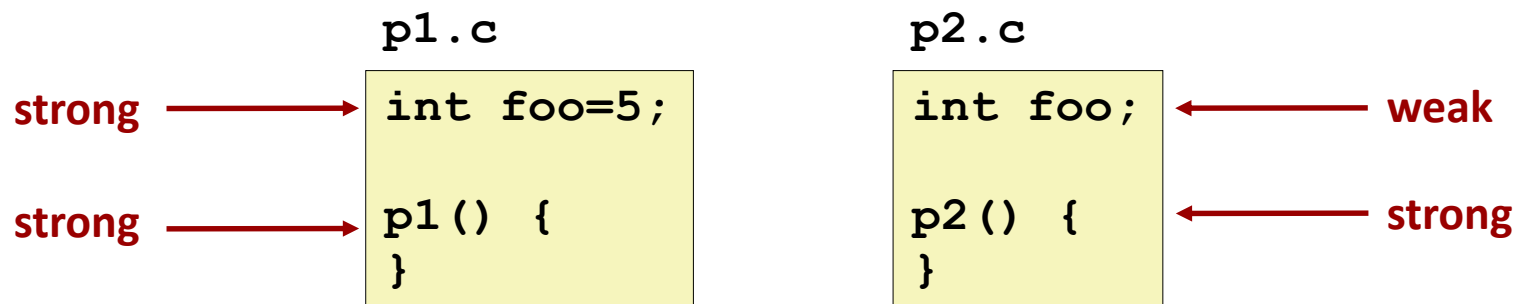
int g()
{
    static int x = 1;
    return x;
}
```

Compiler allocates space in `.data` for each definition of `x`

Creates local symbols in the symbol table with unique names, e.g., `x.1` and `x.2`.

# How Linker Resolves Duplicate Symbol Definitions

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





# 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`

# 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.

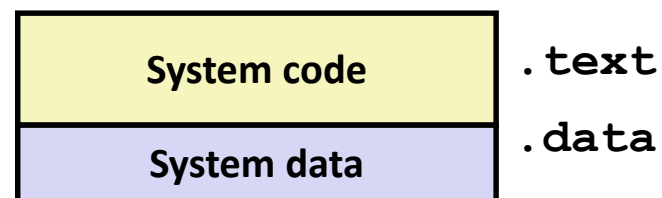
**Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.**

# Global Variables

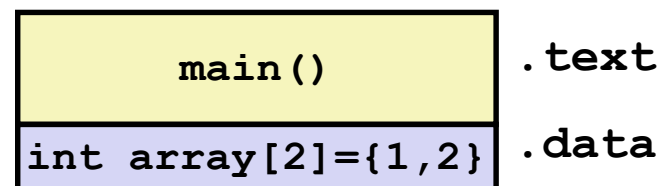
- **Avoid if you can**
  
- **Otherwise**
  - Use **static** if you can
  - Initialize if you define a global variable
  - Use **extern** if you reference an external global variable

# Step 2: Relocation

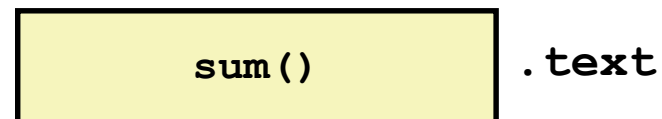
## Relocatable Object Files



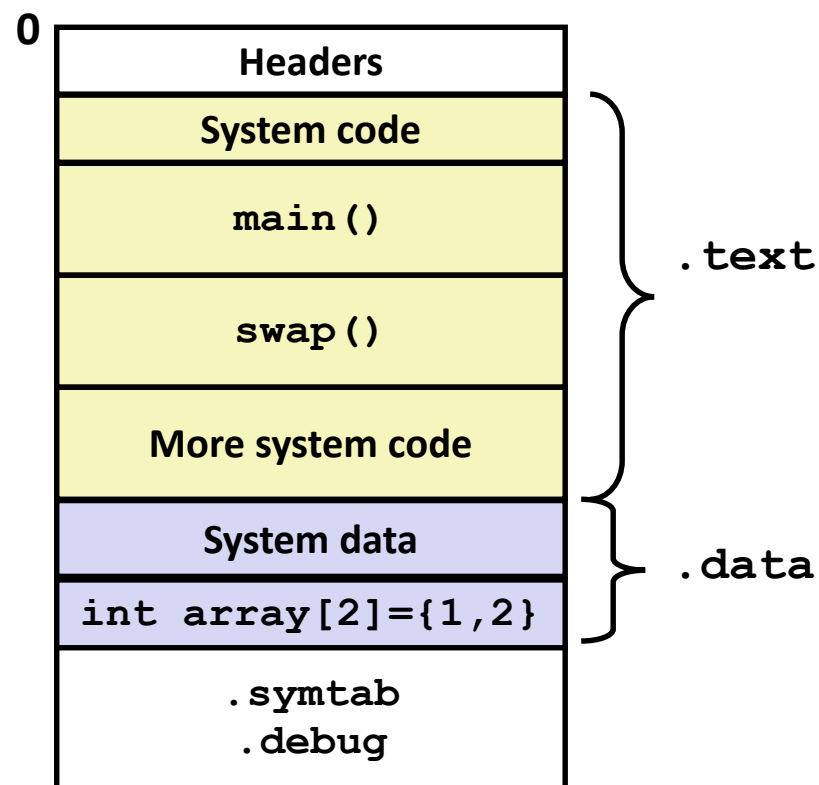
main.o



sum.o



## Executable Object File



# Relocation Entries

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

```
int main()
```

```
{
    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*

# 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

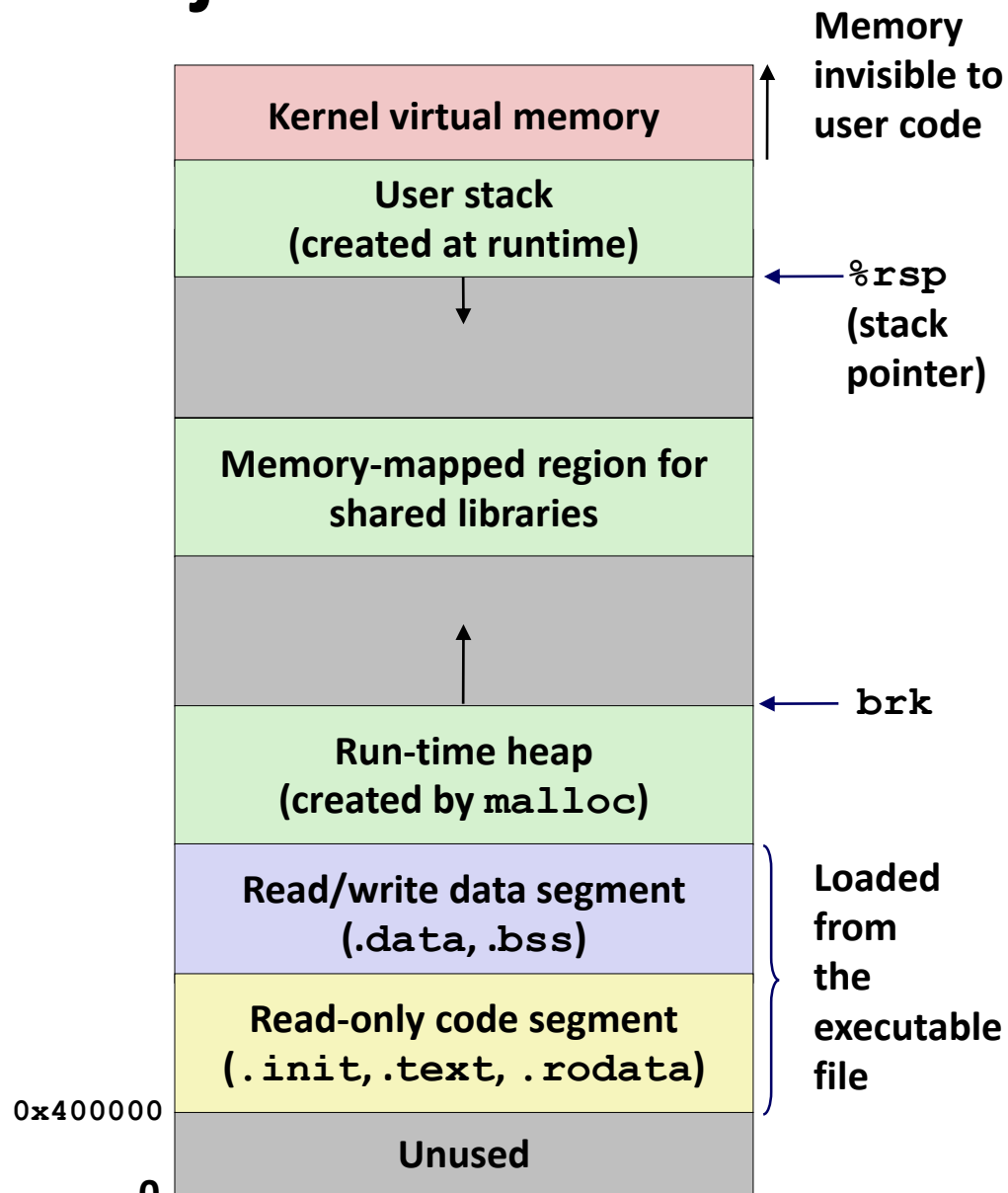
```

Using PC-relative addressing for sum():  $0x4004e8 = 0x4004e3 + 0x5$

# 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)



# 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

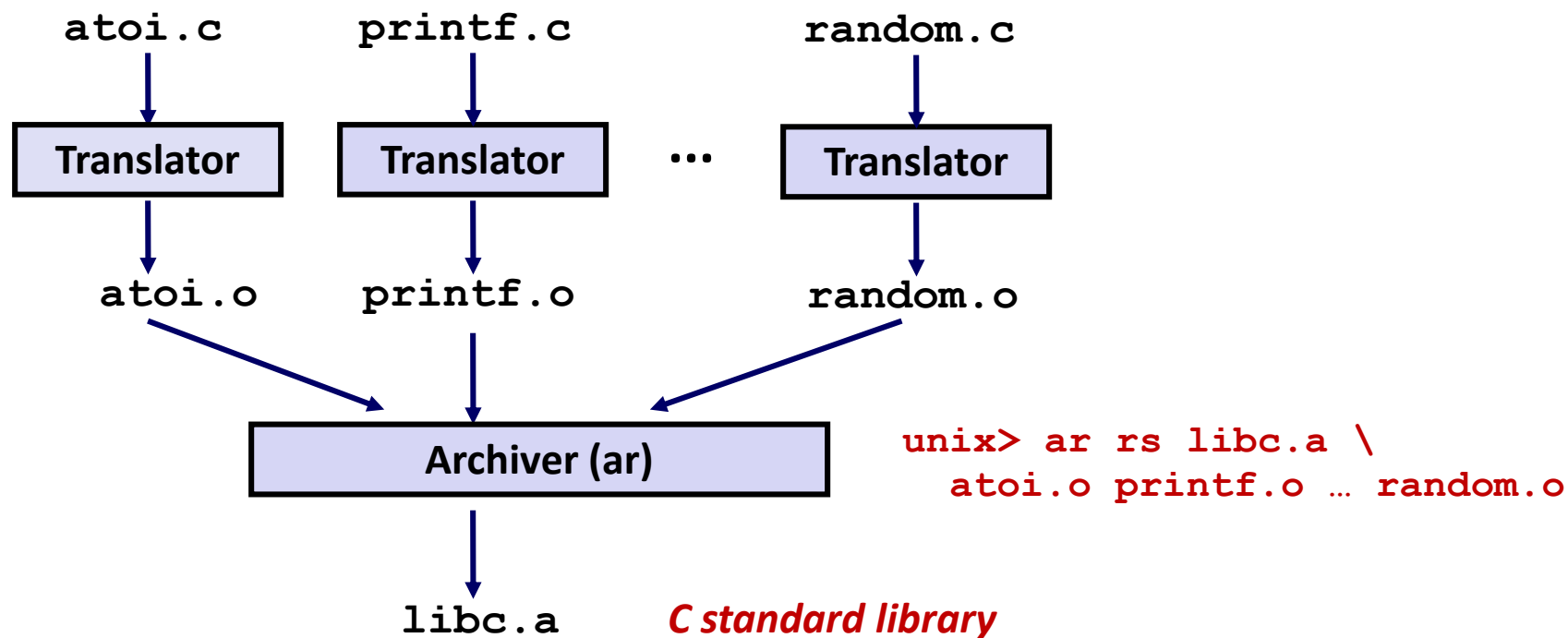


# Old-fashioned Solution: Static Libraries

## ■ **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];
}
```

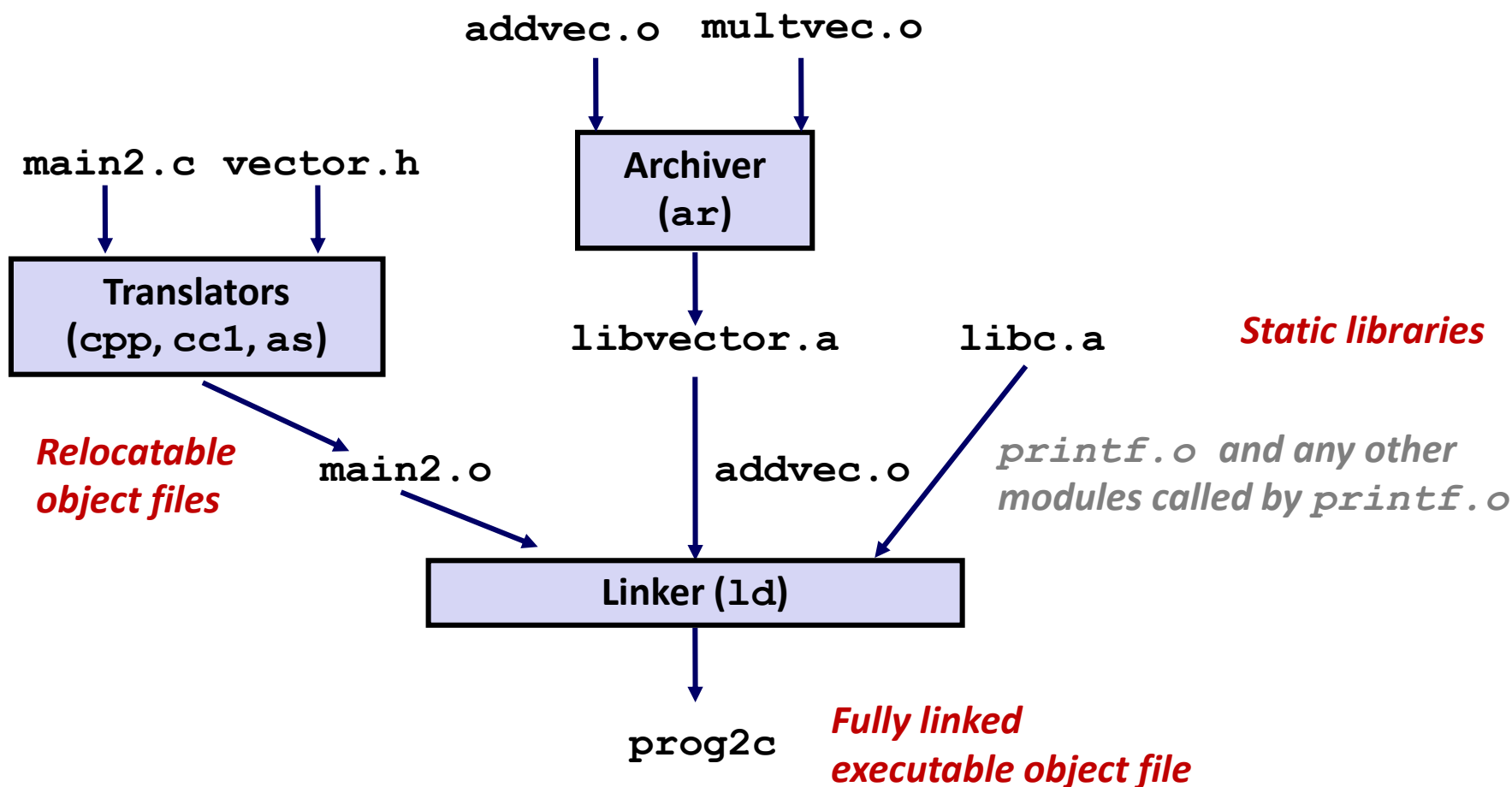
*addvec.c*

```
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 -lm  
unix> gcc -L. -lm 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

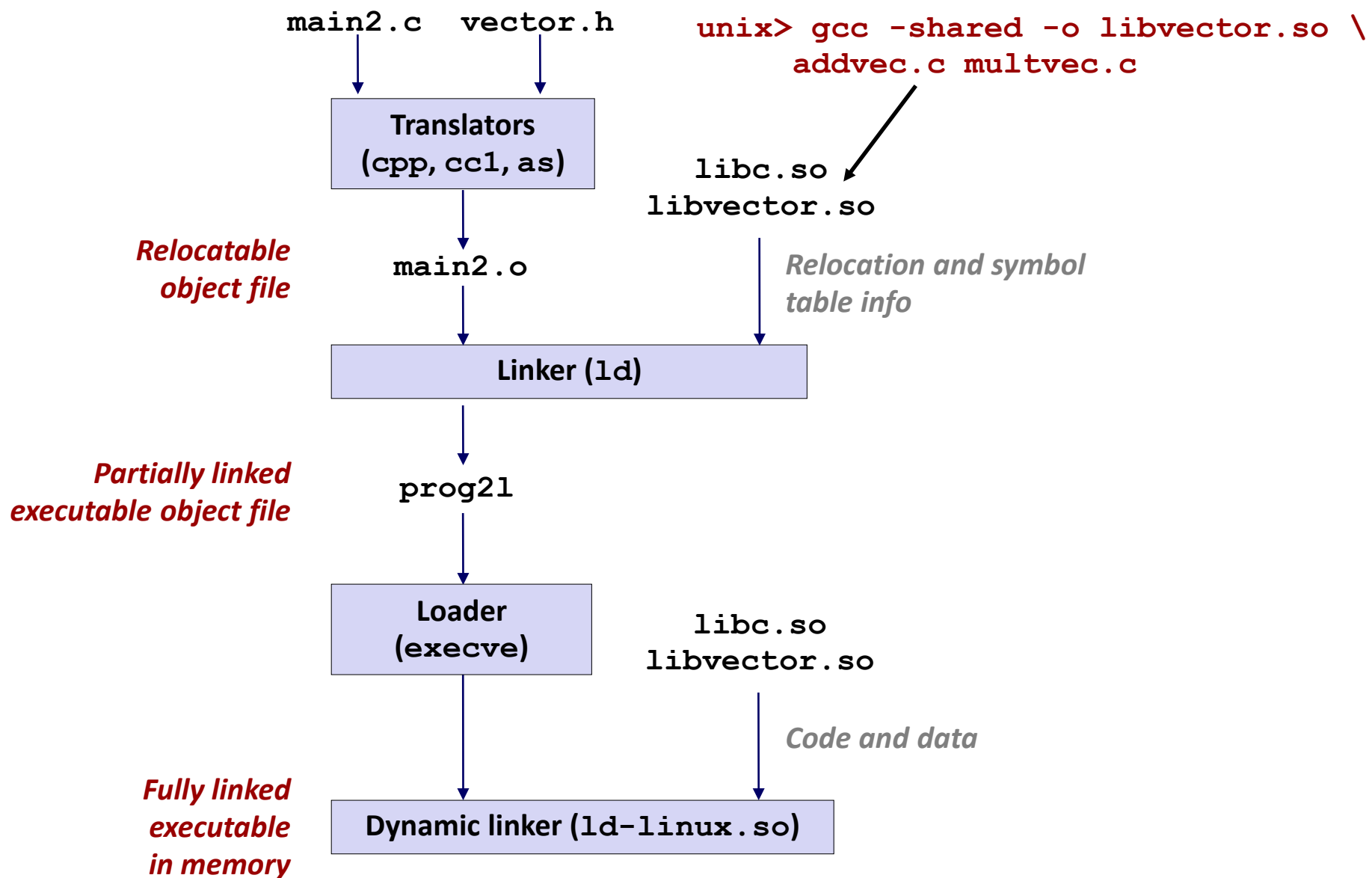
- Object files that contain code and data that are loaded and linked into an application *dynamically*, at either *load-time* or *run-time*
- Also called: dynamic link libraries, DLLs, `.so` files

# 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



# Dynamic Linking at Run-time

```
#include <stdio.h>
#include <stdlib.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 library that contains addvec() */
    handle = dlopen("./libvector.so", RTLD_LAZY);
    if (!handle) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
}
```

*d11.c*

# 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;**

**}**

*dll.c*

# 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.**