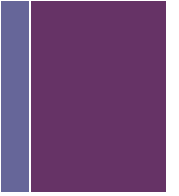




Linking

+ Example C Program



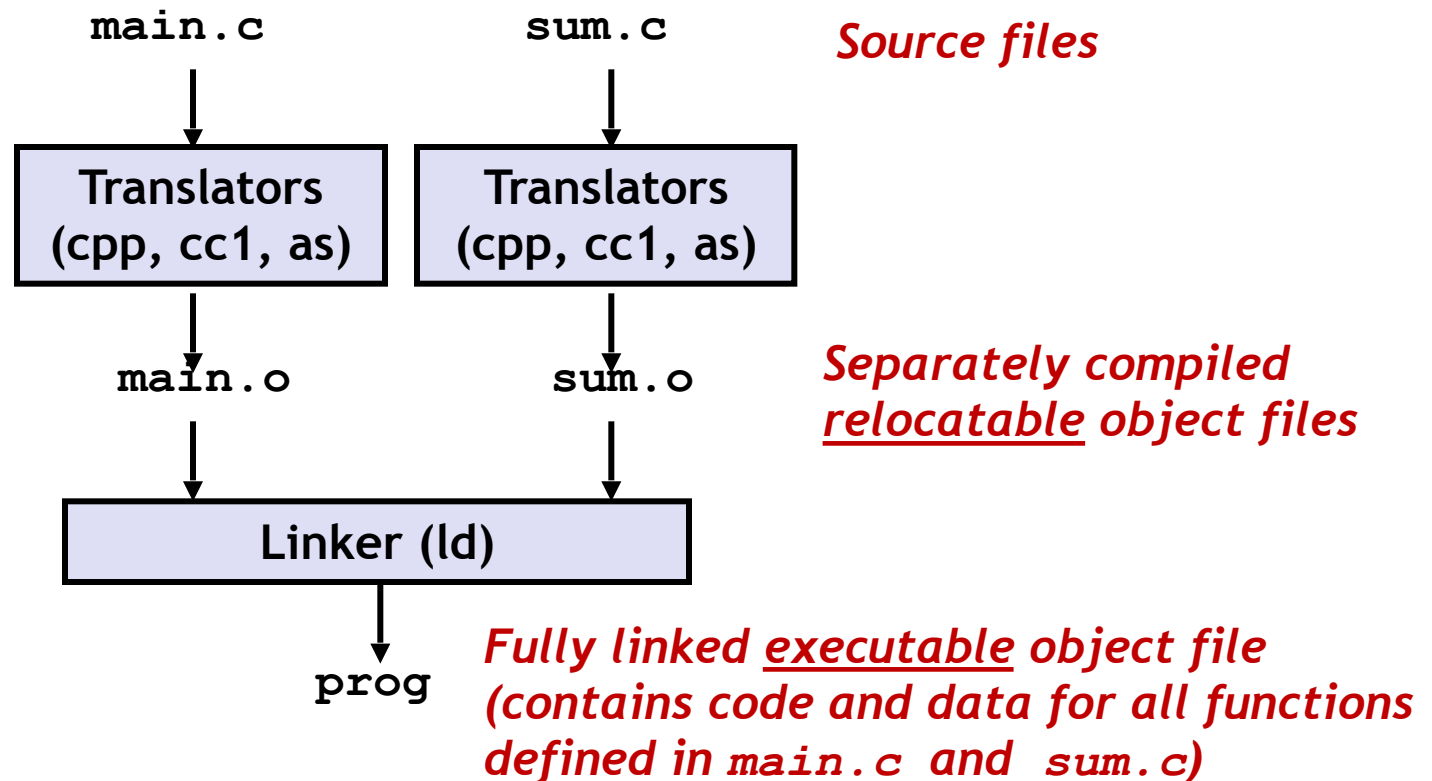
```
int sum(int *a, int n);  
  
int array[2] = {1, 2};  
  
int main()  
{  
    int val = sum(array, 2);  
    return val;  
}
```

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

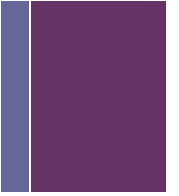
+ Static Linking

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

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



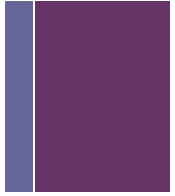
+ Why Linkers?



- **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**

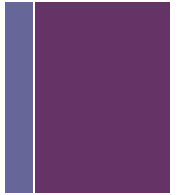
- *Time*: Separate compilation

- 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.

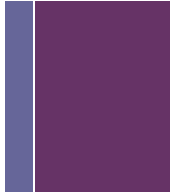
+ What Do Linkers Do?



- **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 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*)

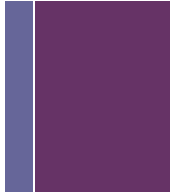


- **Step 2: Relocation**

- 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.

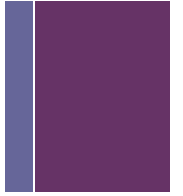
Let's look at these two steps in more detail....

+ Three Kinds of Object Files (Modules)



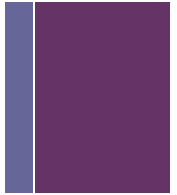
- **Relocatable object file (.o file)**
 - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
 - Each .o file is produced from exactly one source (.c) file
- **Executable object file (a.out file)**
 - Contains code and data in a form 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..**
 - Relocatable object files (.o),
 - Executable object files (a.out)
 - Shared object files (.so)
- **Generic name: ELF binaries**

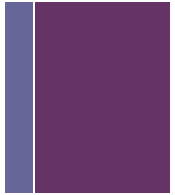
+ ELF Object File Format



- **Elf header**
 - Word size, byte ordering, file type (.o, exe, .so), machine type, etc.
- **Segment header table**
 - Page size, virtual addresses memory segments, segment sizes. (Stuff we will cover later.)
- **.text section**
 - Code
- **.rodata section**
 - Read only data: printf strings, etc.
- **.data section**
 - Initialized global variables
- **.bss section**
 - Uninitialized global variables
 - “Block Started by Symbol”
 - *“Better Save Space”*

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

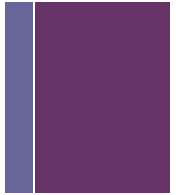
+ ELF Object File Format (cont.)



- **.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.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.

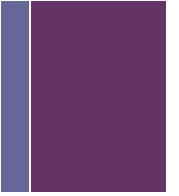
- **External symbols**

- 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 with the static attribute.
- *Local linker symbols are **not** local program variables*

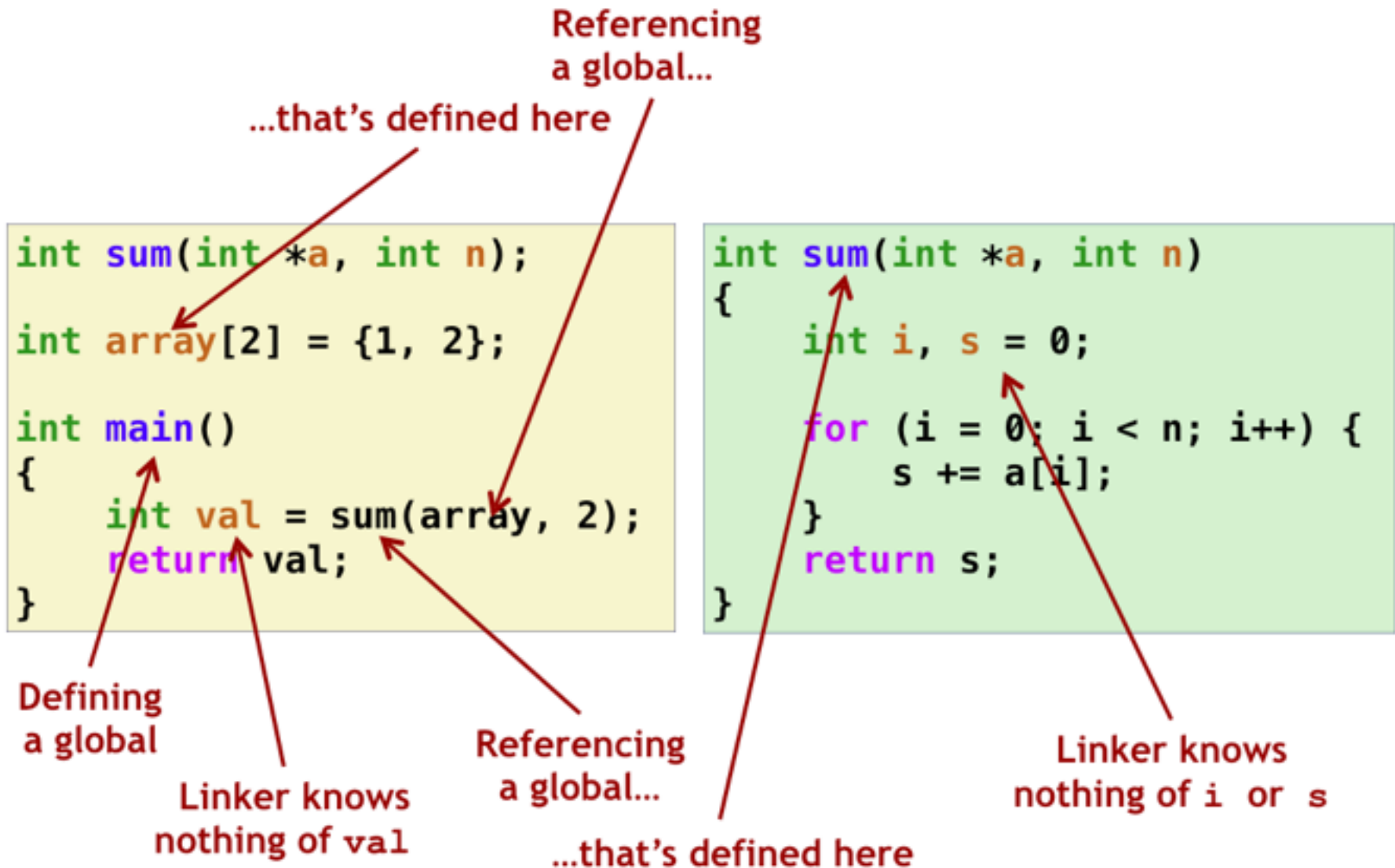
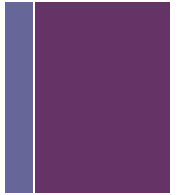
+ Step 1: Symbol Resolution



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

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

+ Step 1: Symbol Resolution



+ 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 = 1;
    return x;
}

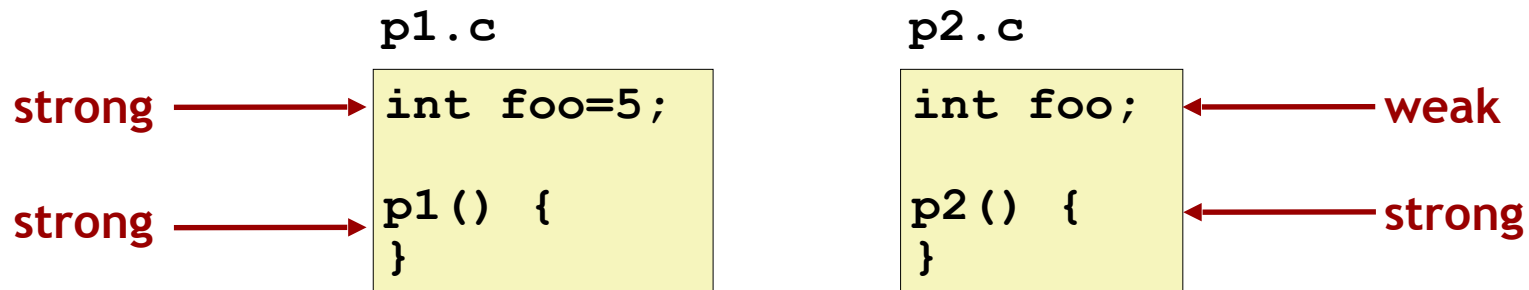
int g()
{
    static int x = 2;
    return x;
}
```

Compiler allocates space in .data for each definition of `x` because they are initialized.

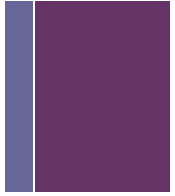
Creates local symbols in the symbol table with unique names, e.g., `x.1` and `x.2`.

+ Resolving Duplicate Symbol Definitions

- All symbol references must be mapped to 1 definition.
 - How to choose when there are duplicates?
- Taxonomy of symbol definitions aids decision.
- Program symbols are either strong or weak
 - **Strong**: procedures and initialized globals
 - **Weak**: uninitialized globals

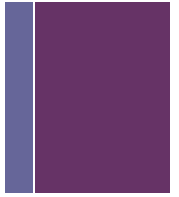


+ Linker's Symbol Rules



- **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 any one**
 - Can override this with `gcc -fno-common`
 - Probably a good idea to use above flag

+ 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() {}
```

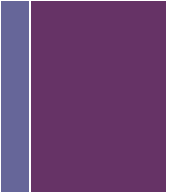
Writes to **x** in **p2** *will* overwrite **y**!
Nasty!

```
int x=7;  
p1() {}
```

```
int x;  
p2() {}
```

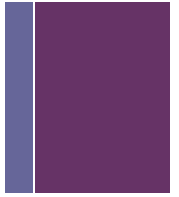
References to **x** will refer to the same initialized variable.

+ Global Variables

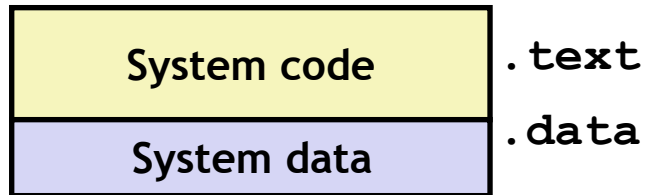


- **Avoid**
 - ...if you can
- **Otherwise...**
 - Use **static** if you can
 - Initialize if you define a global variable
 - Use **extern** if you reference an external global variable

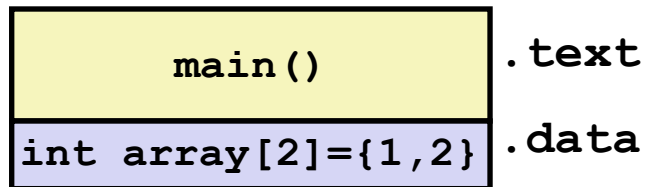
+ Step 2: Relocation



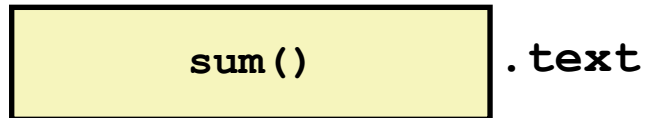
Relocatable Object Files



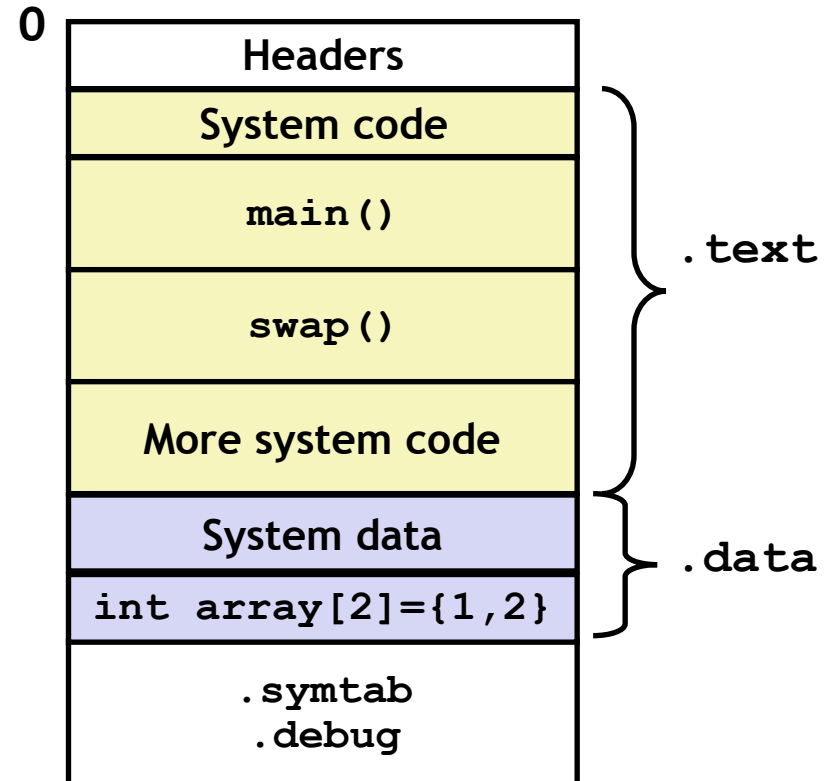
main.o



sum.o



Executable Object File



+ Relocation Entries



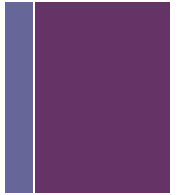
```
int array[2] = {1, 2};

int main()
{
    int val = sum(array, 2);
    return val;
}
```

```
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
                             # Relocation entry
                             a: R_X86_64_32 array

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

+ 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
```

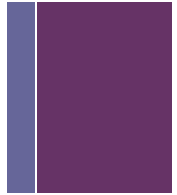
Using PC-relative addressing for sum(): $0x4004e8 = 0x4004e3 + 0x5$

^^^^^^^^^^^^ (page 207 of book)



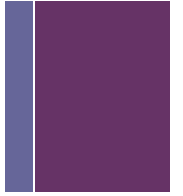
Library Management

+ Packaging Commonly Used Functions



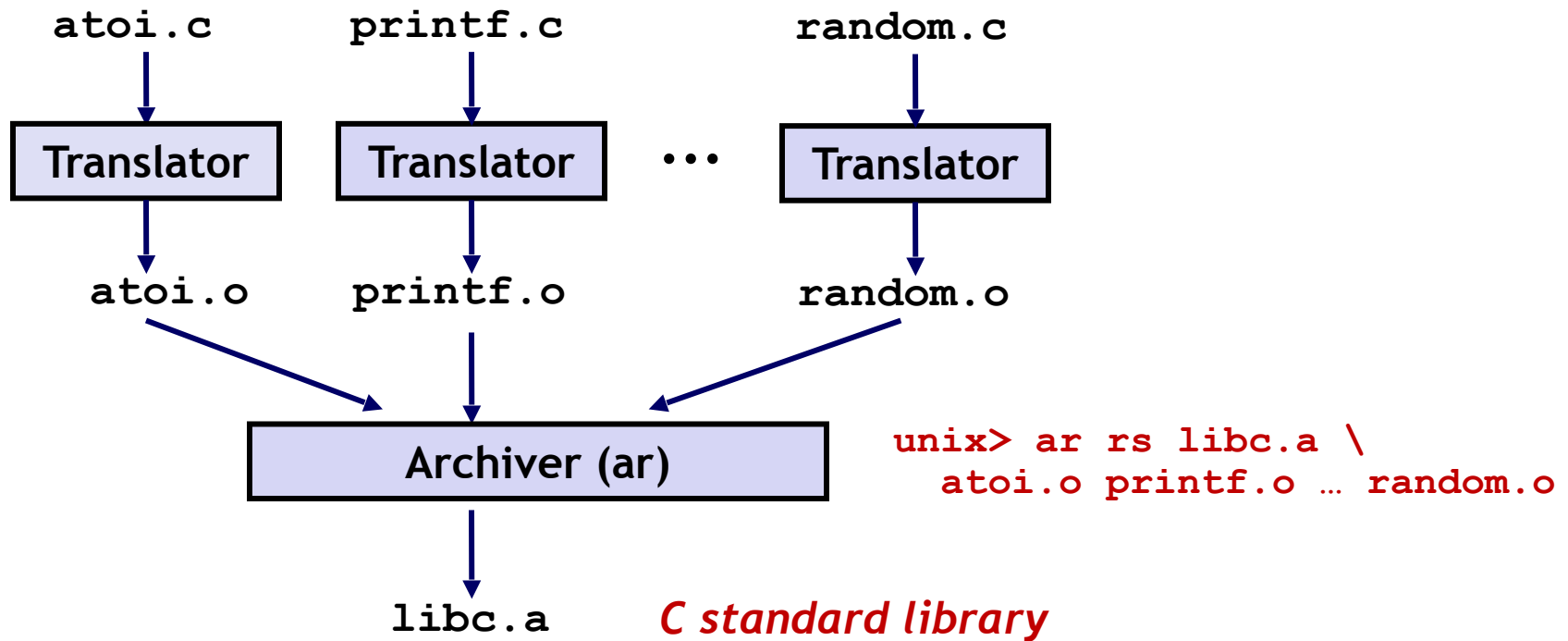
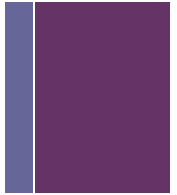
- **How to package functions commonly used by programmers?**
 - Math, I/O, memory management, string manipulation, etc.
- **Awkward, given the linker framework so far:**
 - **Option 1:** Put all functions into a single source file
 - Programmers link big object file into their programs
 - Space and time inefficient
 - **Option 2:** Put each function in a separate source file
 - Programmers link appropriate binaries into their programs
 - More efficient, but burdensome on the programmer

+ Old & Busted: 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

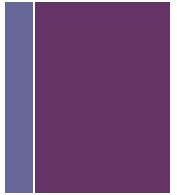
libm.a (the C math library)

- 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;
}
```

libvector.a

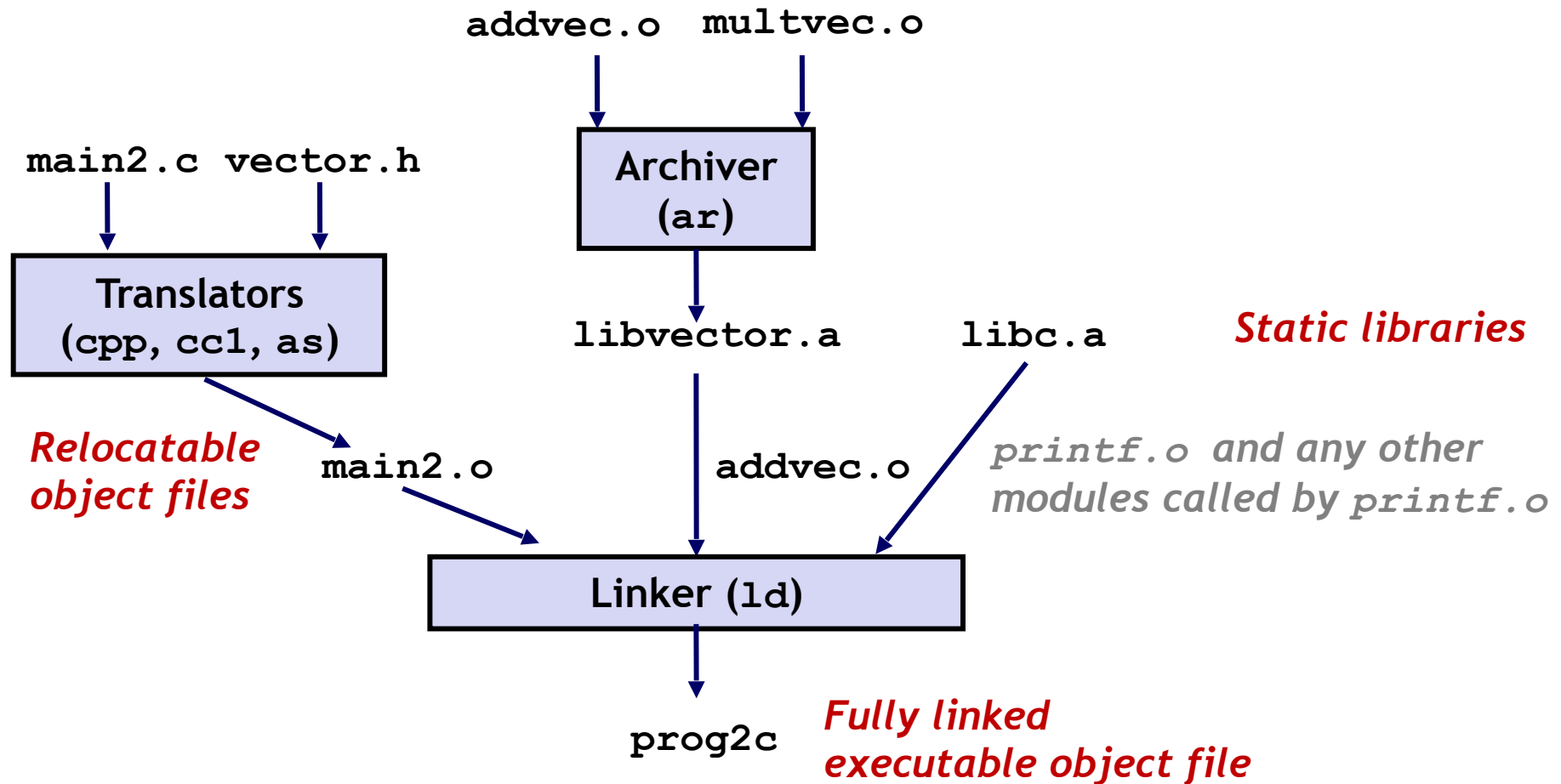
```
void addvec(int *x, int *y,
            int *z, int n) {
    int i;

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

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

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

+ 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 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.

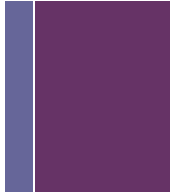
```
unix> gcc -L . libtest.o -l my_lib
unix> gcc -L . -l my_lib libtest.o
libtest.o: In function `main':
libtest.o(.text+0x4): undefined reference to `libfun'
```

+ New Hotness: Shared Libraries



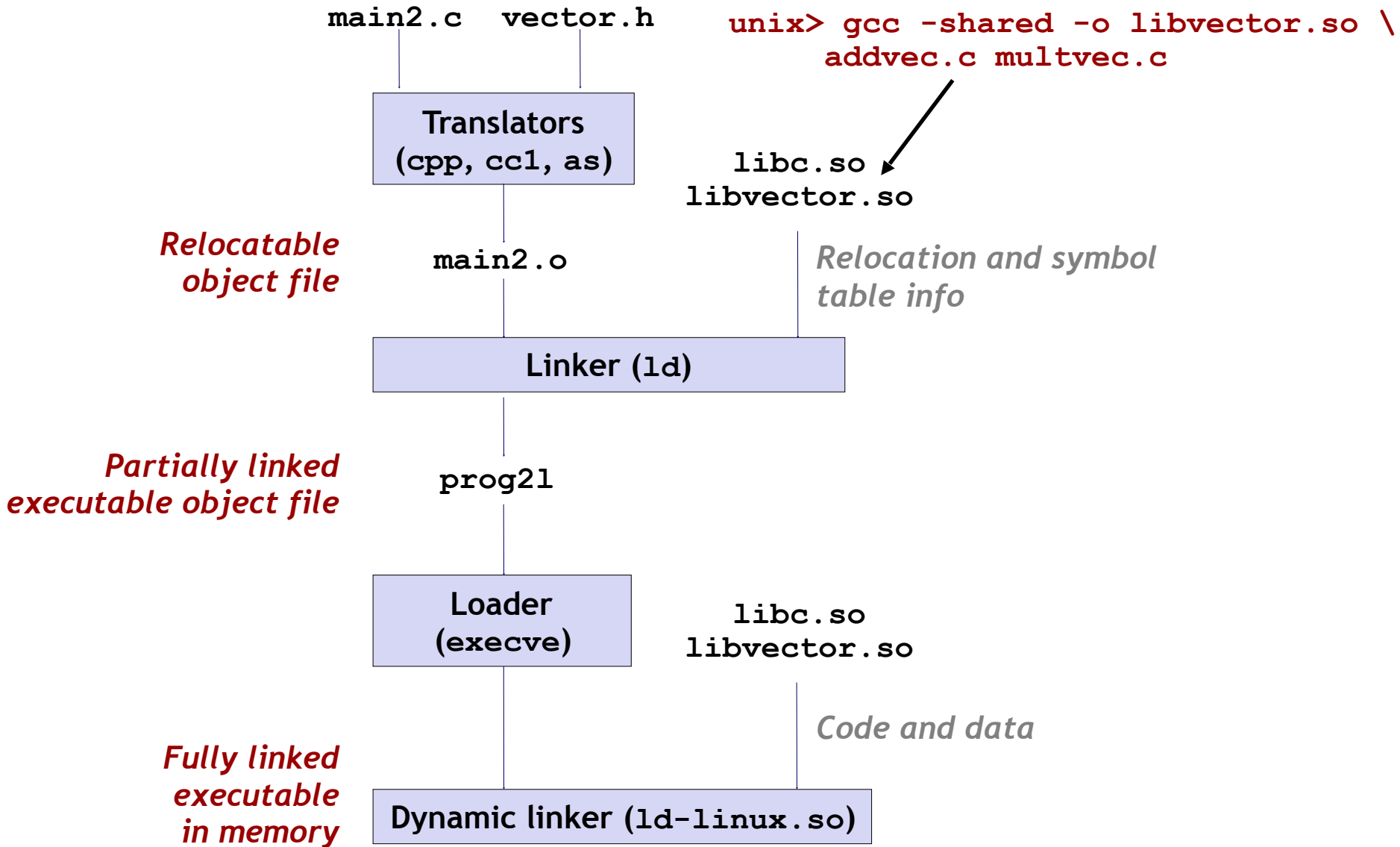
- **Static libraries have the following disadvantages:**
 - Duplication in the stored executables (every function needs libc)
 - Duplication in the running executables
 - Minor bug fixes of system libraries require each application to explicitly relink
- **Modern solution: Shared Libraries**
 - Object 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 (*con't*)

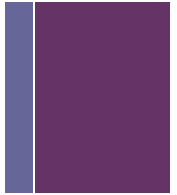


- **Dynamic linking can occur when executable is first loaded and run (load-time linking).**
 - Common case for Linux, handled by the dynamic linker (ld-linux.so).
 - Standard C library (libc.so) usually dynamically linked.
- **Dynamic linking can also occur after program has begun (run-time linking).**
 - In Linux, this is done by calls to the dlopen() interface.
- **Shared library routines can be shared by multiple processes.**
 - More on this when we learn about processes and virtual memory

+ Dynamic Linking at Load-time



+ Dynamic Linking at Run-time



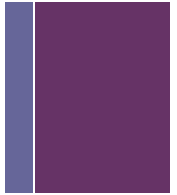
```
#include <stdio.h>
#include <stdlib.h>
#include <dlfcn.h>

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);
    }
}
```

+ Dynamic Linking at Run-time



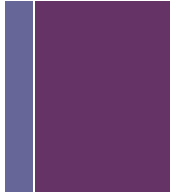
```
...

/* 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;
}
```

+ 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.**