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# Computer Architecture and Operating Systems

## Lecture 4: Linking and Loading

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# 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;

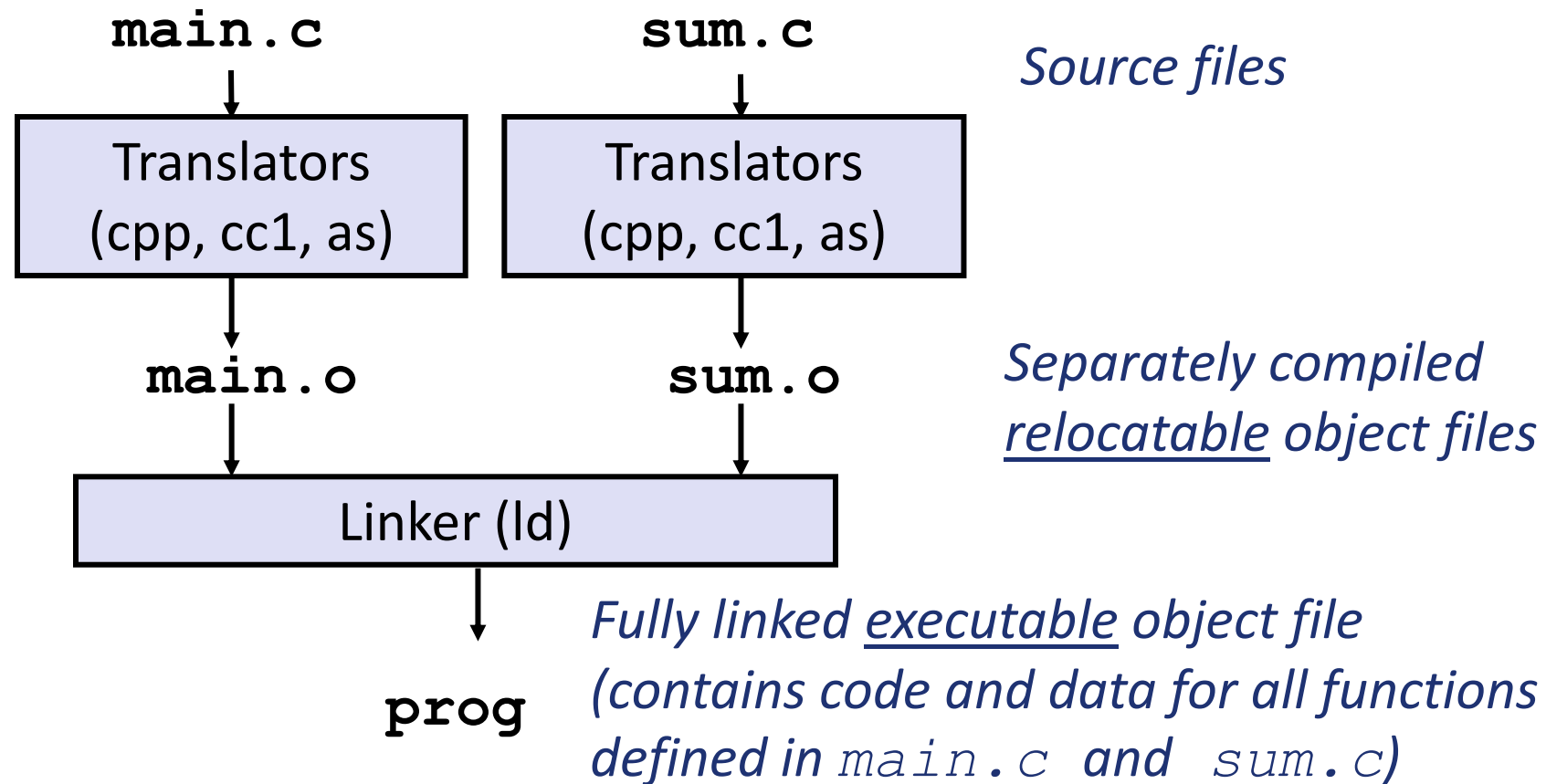
    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```

*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 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

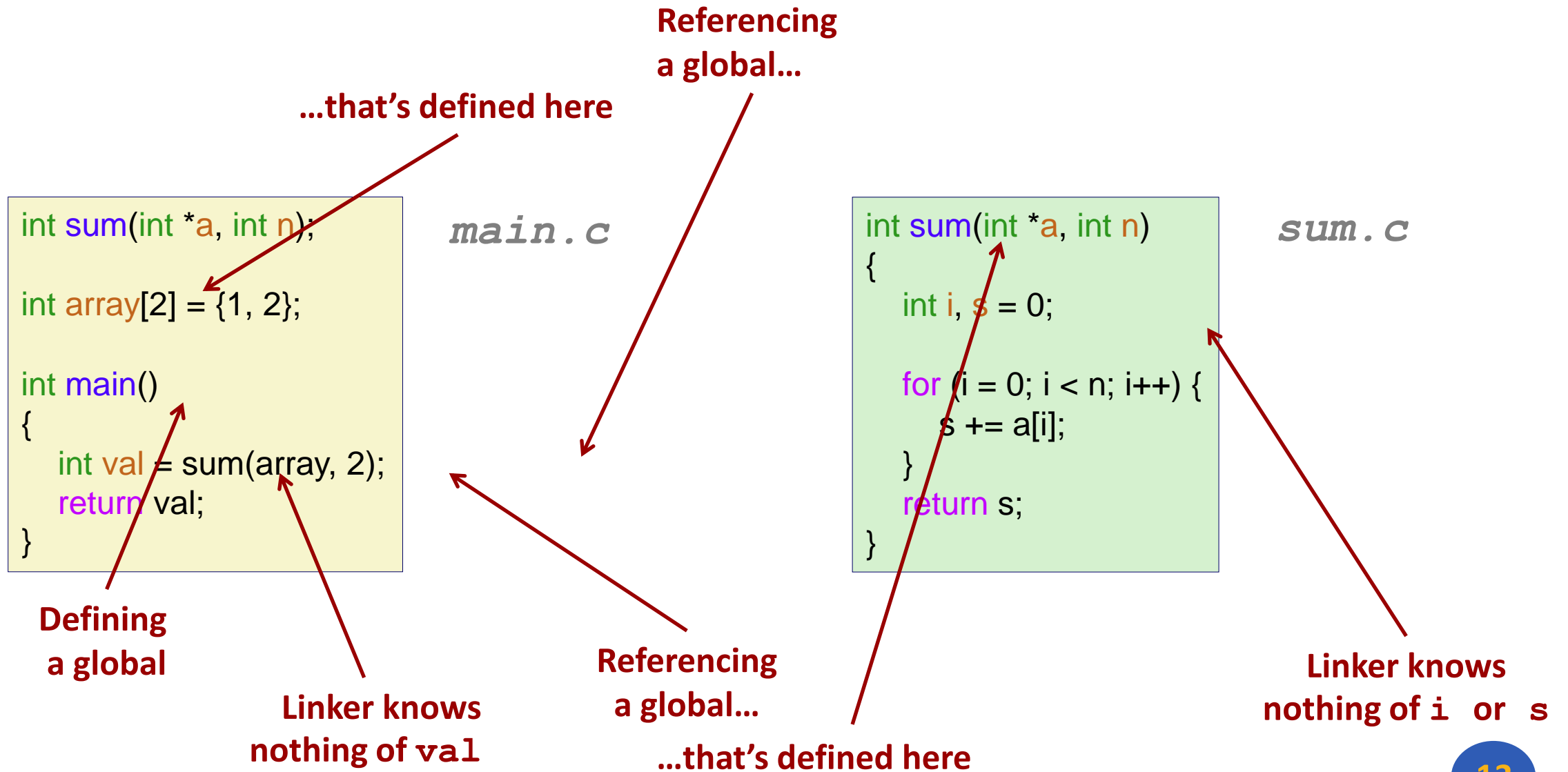
ELF header
Segment header table (required for executables)
.text section
.rodata section
.data section
.bss section
.symtab section
.rel.txt section
.rel.data section
.debug section
Section header table

0

# 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



# 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;
}
```

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

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

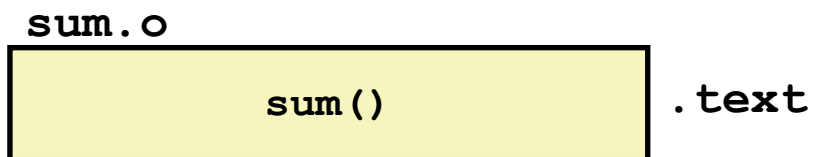
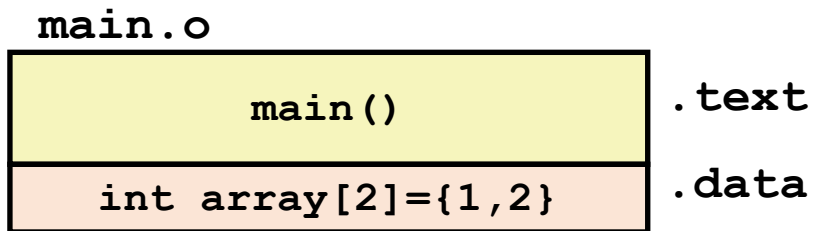
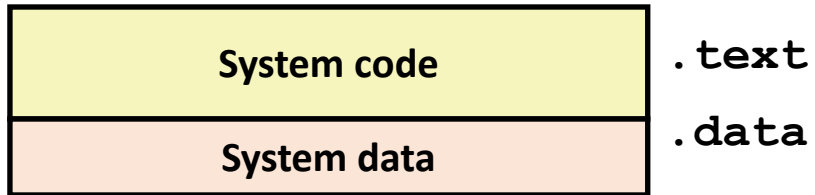
Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.

# Global Variables

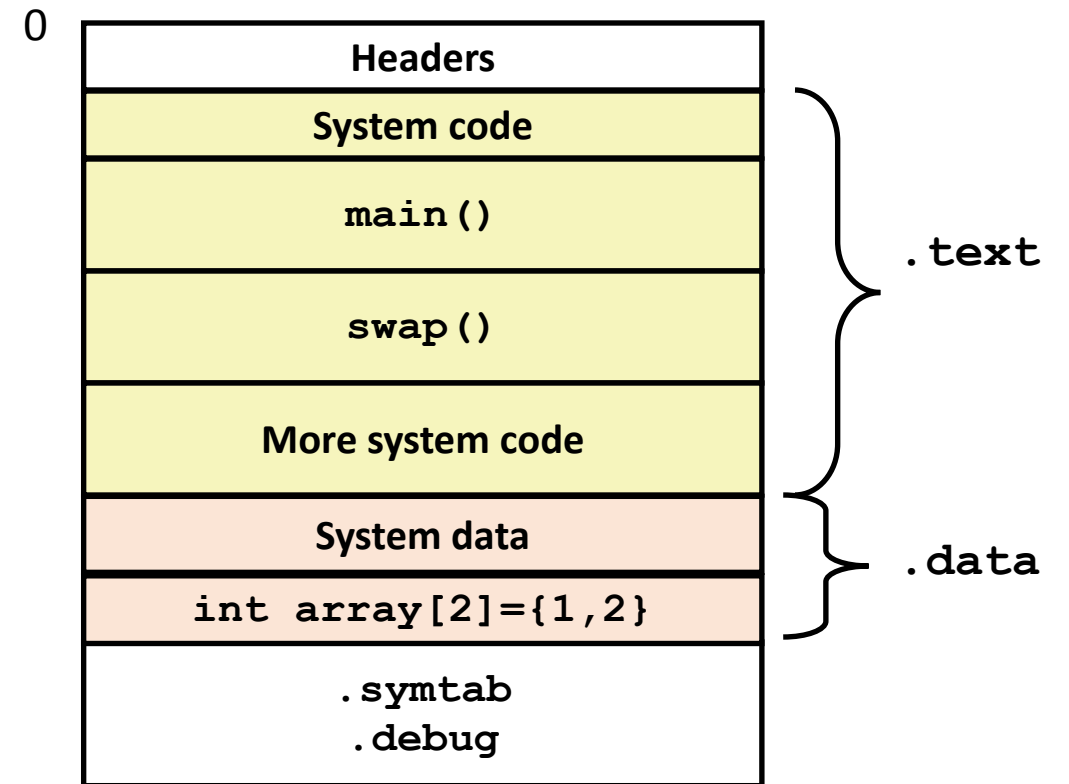
- Avoid if you can
- Otherwise
  - Use **static** if you can
  - Initialize if you define a global variable
  - Use **extern** if you reference an external global variable

# Step 2: Relocation

## Relocatable Object Files



## Executable Object File



# Relocation Entries

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

*main.c*

0000000000000000 <main>:

0:	ff010113	addi	sp,sp,-16	
4:	00113423	sd	ra,8(sp)	
8:	00200593	li	a1,2	
c:	00000537	lui	a0,0x0	
		c: R_RISCV_HI20	array	# Relocation entry
		c: R_RISCV_RELAX	*ABS*	
10:	00050513	mv	a0,a0	# %a0 = &array
		10: R_RISCV_LO12_I	array	
		10: R_RISCV_RELAX	*ABS*	
14:	00000097	auipc	ra,0x0	
		14: R_RISCV_CALL	sum	# Relocation entry
		14: R_RISCV_RELAX	*ABS*	
18:	000080e7	jalr	ra # 14 <main+0x14>	# sum()
1c:	00813083	ld	ra,8(sp)	
20:	01010113	addi	sp,sp,16	
24:	00008067	ret		

*main.o*

Source: `objdump -r -d main.o`

# Relocated .text section

0000000000010430 <main>:

```
10430: ff010113      addi    sp,sp,-16
10434: 00113423      sd      ra,8(sp)
10438: 00200593      li      a1,2
1043c: 83018513      addi    a0,gp,-2000 # 12030 <array> # %a0 = &array
10440: 010000ef      jal     ra,10450 <sum> # sum()
10444: 00813083      ld      ra,8(sp)
10448: 01010113      addi    sp,sp,16
1044c: 00008067      ret
```

0000000000010450 <sum>:

```
10450: 02b05a63      blez    a1,10484 <sum+0x34>
10454: 00050793      mv      a5,a0
10458: fff5871b      addiw   a4,a1,-1
1045c: 02071693      slli    a3,a4,0x20
10460: 01e6d713      srli    a4,a3,0x1e
10464: 00450513      addi    a0,a0,4 # 12004 <__TMC_END__+0x4>
10468: 00a70733      add     a4,a4,a0
```

Using PC-relative addressing for sum():  $0x010450 = 0x010440 + 0x10$

Source: `objdump -dx prog`

# Loading Executable Object Files

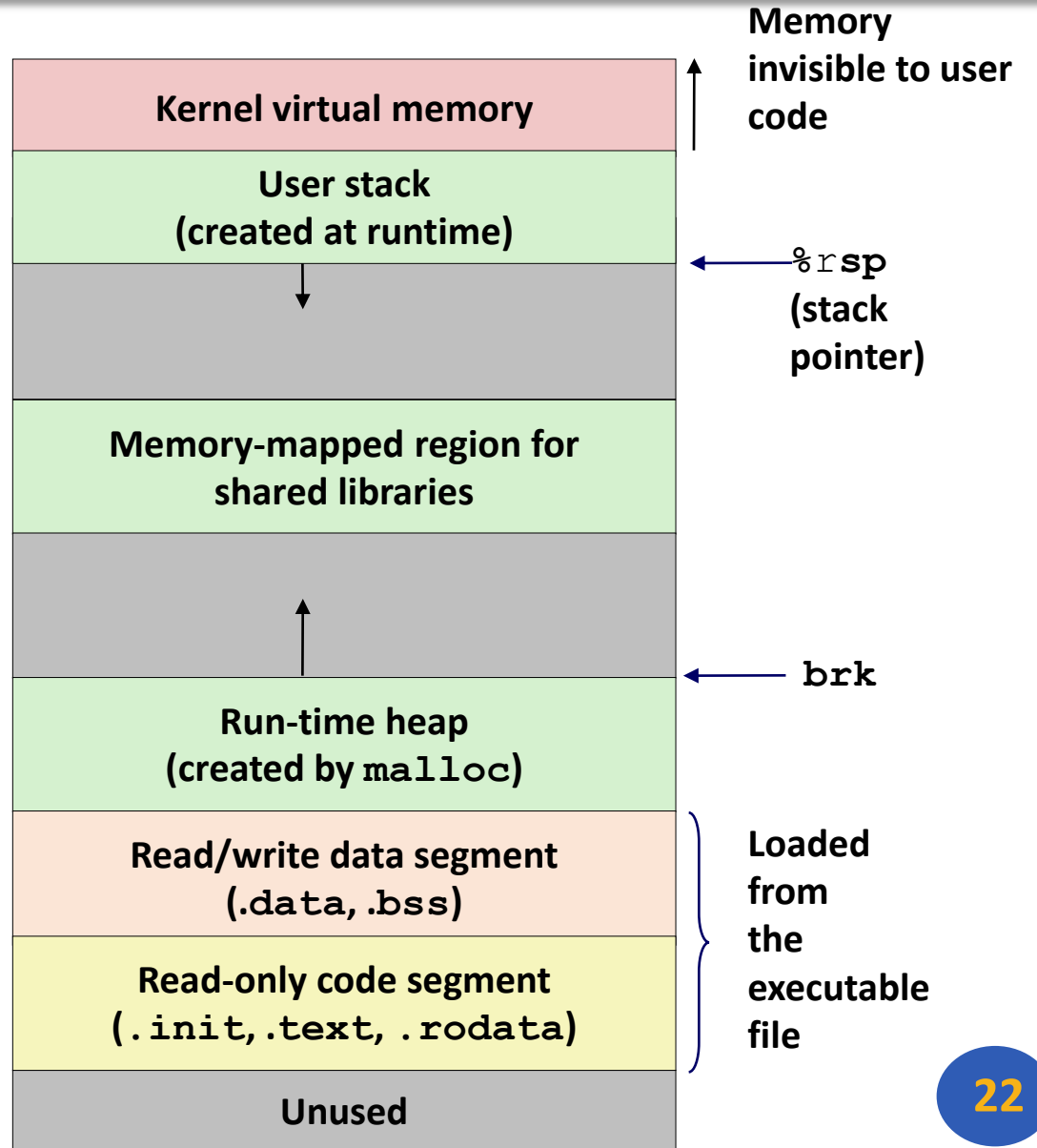
## Executable Object File

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

0x400000

0



# Packaging Commonly Used Functions

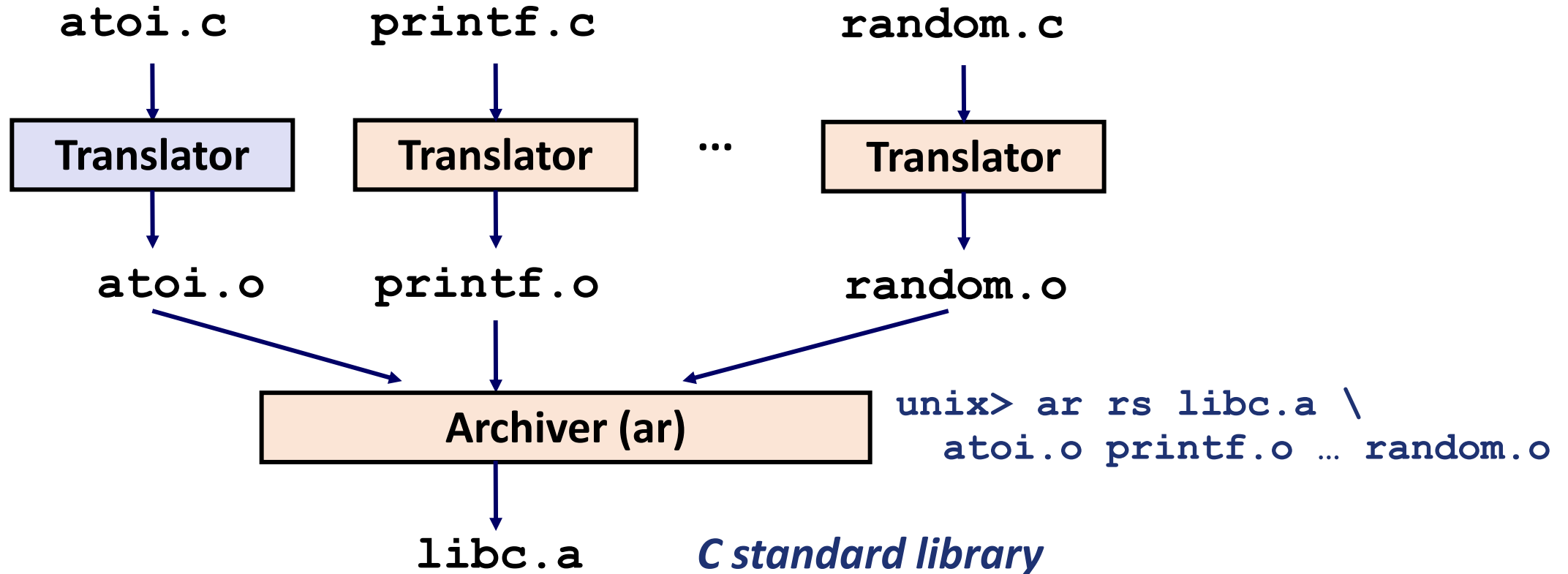
- How to package functions commonly used by programmers?
  - Math, I/O, memory management, string manipulation, etc.
- Awkward, given the linker framework so far:
  - **Option 1:** Put all functions into a single source file
    - Programmers link big object file into their programs
    - Space and time 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];
}
```

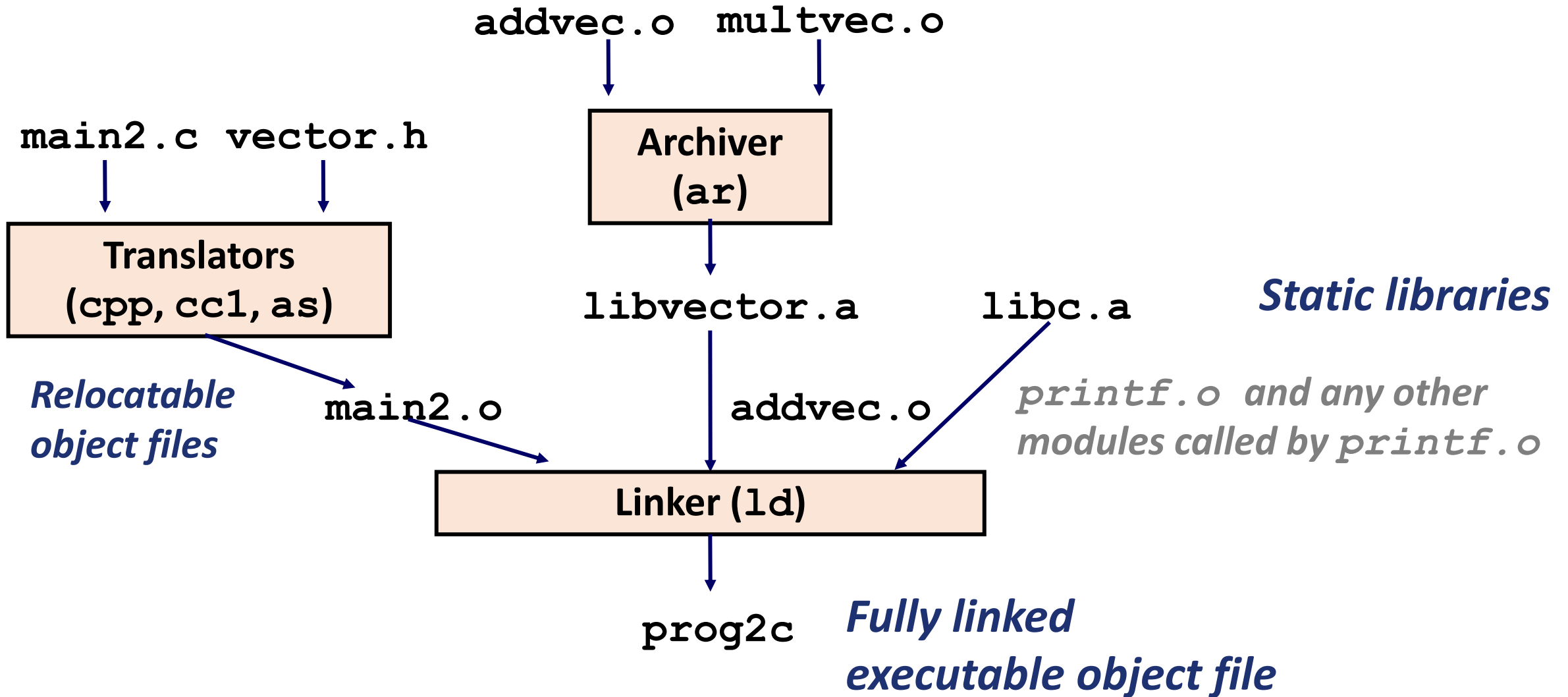
*addvec.c*

```
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'
```

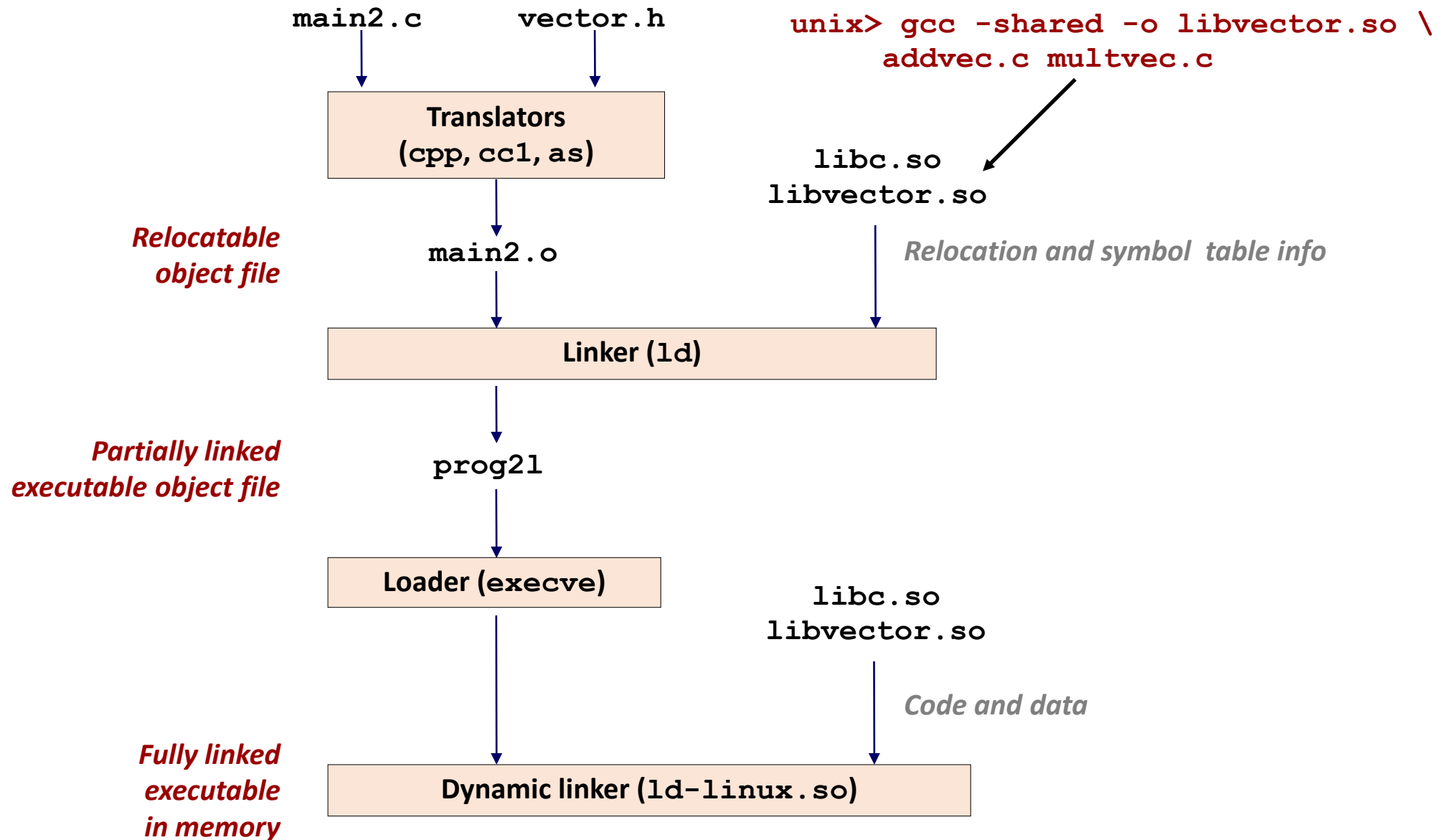
# Modern Solution: Shared Libraries

- 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





# 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);
    }
}
```

*dll.c*

# Dynamic Linking at Run-time

*dll.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;
}
```

# 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.

# 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**

# Example program

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

int main()
{
    int *p = malloc(32);
    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 `lib 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

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

```
void *mymalloc(size_t size);
void myfree(void *ptr);
```

malloc.h

```
linux> make intc
gcc -Wall -DCOMPILETIME -c mymalloc.c
gcc -Wall -I. -o intc int.c mymalloc.o
linux> make runc
./intc
malloc(32)=0x1edc010
free(0x1edc010)
linux>
```

# Link-time Interpositioning

mymalloc.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
```

# 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
malloc(32) = 0x1aa0010
free(0x1aa0010)
linux>
```

- 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

mymalloc.c

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

# Load/Run-time Interpositioning

mymalloc.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
```

# 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)
malloc(32) = 0xe60010
free(0xe60010)
linux>
```

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

# Interpositioning 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
- Load/Run Time
  - Implement custom version of malloc/free that use dynamic linking to load library malloc/free under different names

# Any Questions?

```
                .text
__start:      addi t1, zero, 0x18
                addi t2, zero, 0x21
cycle:        beq t1, t2, done
                slt t0, t1, t2
                bne t0, zero, if_less
                nop
                sub t1, t1, t2
                j cycle
                nop
if_less:      sub t2, t2, t1
                j cycle
done:         add t3, t1, zero
```