LINKING… HOW BASIC MECHANISMS ENABLE SOPHISTICATED WRAPPERS

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CS4414 Lecture 13

SYSTEMS PROGRAMMING IS ABOUT TAKING CONTROL OVER EVERYTHING

We have seen that a systems programmer learns to “program” the hardware, operating system and software, including the C++ compiler itself, which we “program” via templates.

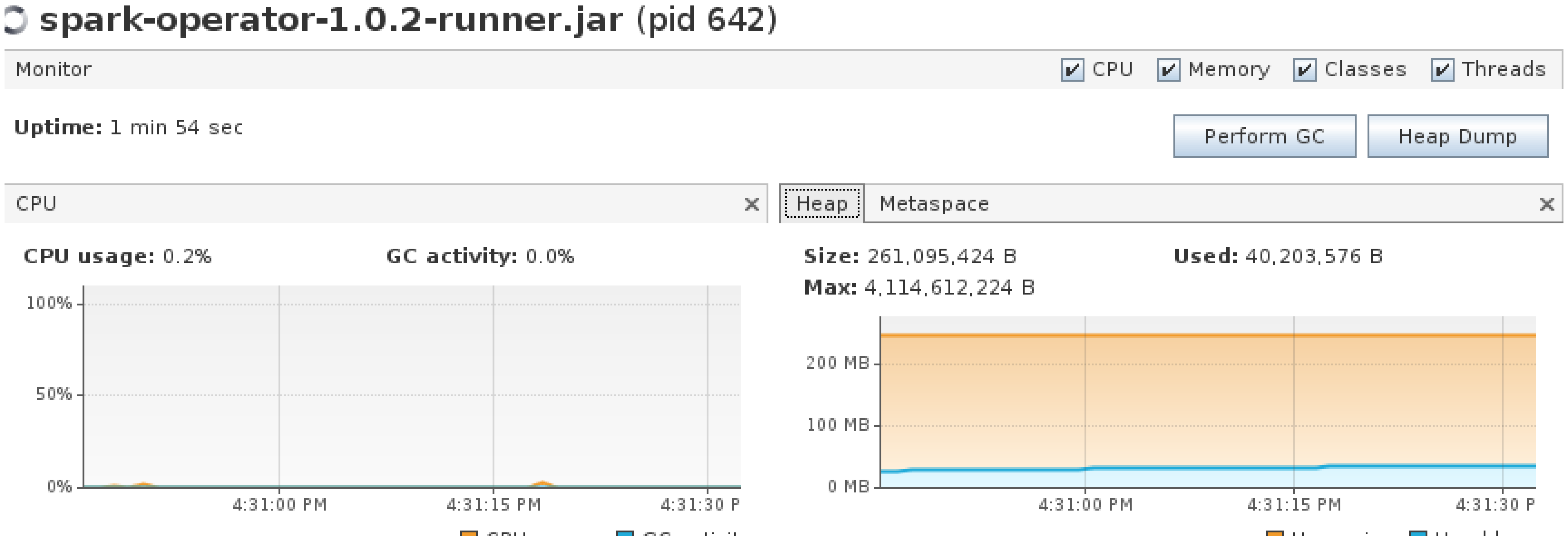
Today we will look at how linking works, and by doing so, we will discover another obscure example of a programmable feature that you might not normally expect to be able to control!

Libtorch_cuda.so is too large (>2GB) - PyTorch Forums

Why is torch wheel so huge (582MB)?

CORE SCENARIO – PART I

Libraries can be quite big – some are huge. The memory of your computer can easily be completely filled by copies of libraries – maybe identical ones!



spark-operator-1.0.2-runner.jar (pid 642)

Monitor ☑ CPU ☑ Memory ☑ Classes ☑ Threads

Uptime: 1 min 54 sec

Perform GC | Heap Dump

CPU

CPU usage: 0.2% **GC activity:** 0.0%

Heap | Metaspace

Size: 261,095,424 B **Used:** 40,203,576 B
Max: 4,114,612,224 B

CORE SCENARIO – PART II

We are given a system that has pre-implemented programs in it (compiled code plus libraries).

But now we want to change the behavior of some existing API.

Can it be done?

IDEA MAP FOR TODAY

Libraries

Compiling to an object file

Static versus dynamic linking in Linux.

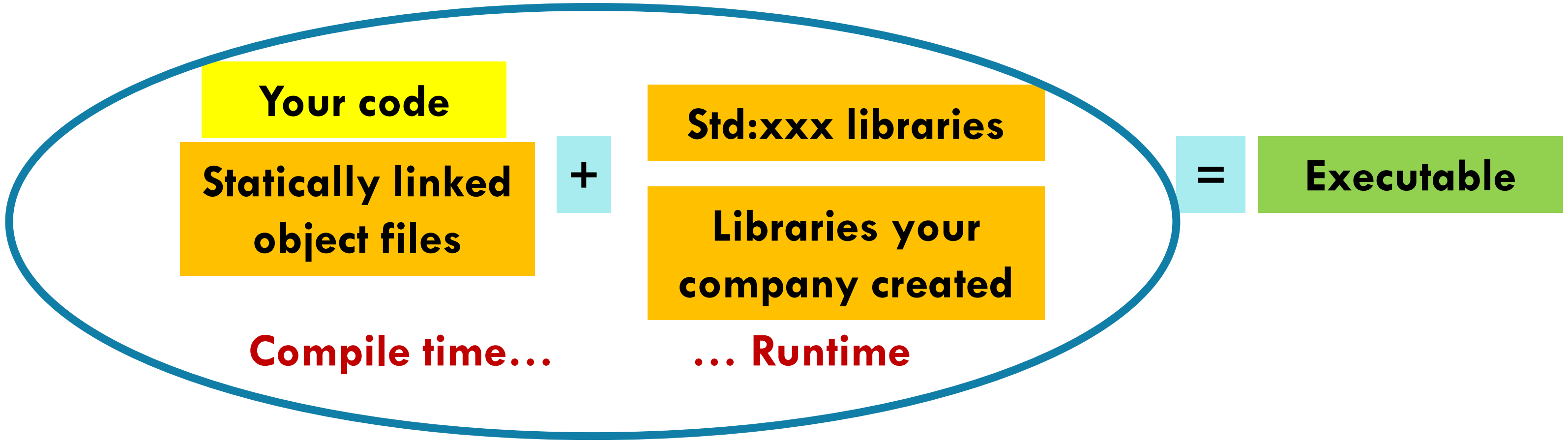
Main part of lecture.
Be sure to understand this.

Dynamic linking: -shared -fPIC compilation. DLL segments, issue of base address

Wrappers for method interpositioning: a "super hacker" technique!

Insane/weird part, introduces some amazing features

LINKING



Your code

Statically linked object files

+

Std:xxx libraries

Libraries your company created

=

Executable

Compile time…

… Runtime

A linker takes a collection of object files and combines them into an object file. But this object file will still depend on libraries.

Next it cross-references this single object file against libraries, resolving any references to methods or constants in those libraries.

If everything needed has been found, it outputs an executable image.

EXAMPLE C PROGRAM (C++ IS THE SAME)

```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

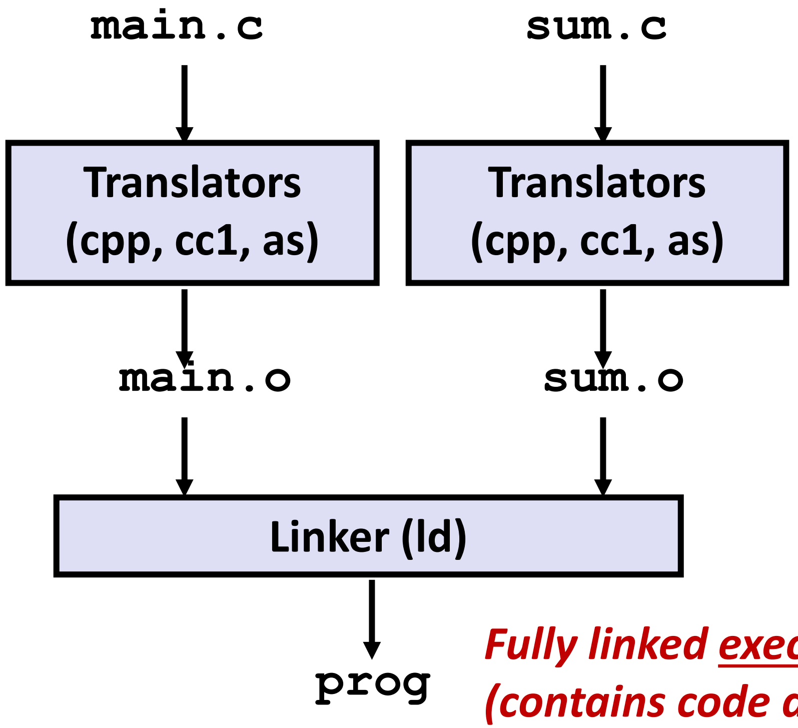
```c
int sum(int *a, int n)
{
    int i, s = 0;

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

sum.c

LINKING

Gcc is really a “*compiler driver*”: It launches a series of sub-programs

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



Source files

Separately compiled relocatable object files

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. But later we need to combine all of these.

Each C++ class normally has its own hpp file (declares the type signatures of the methods and fields) and a separate cpp file (implements the class).

For fancy templated classes, C++ itself creates the needed cpp files, one for each distinct type-parameters list.

AN OBJECT FILE IS AN INTERMEDIATE FORM

An object file contains “incomplete” machine instructions, with locations that may still need to be filled in:

- Addresses of methods defined in other object files, or libraries
- Addresses of data and bss segments, in memory

After linking, all the “resolved” addresses will have been inserted at those previously unresolved locations in the object file.

TWO FORMS OF ADDRESSING

For today's lecture, we think mostly of "absolute" addresses in the virtual address space, and "base-relative" ones where some sort of pointer exists, and the object is at an offset from it.

Both are supported very efficiently by Intel and AMD/ARM

So the compiler thinks "which choice is best"?

WHICH DOES IT PICK?

For branching inside a single method, it favors absolute addressing if feasible, but can also use “PC relative” ones.

For accessing data in a data segment, it can use “base relative” addressing. Useful if we have multiple code segments and each has its own data segment.

In general, absolute addressing is a tiny bit faster.

REASON 2 FOR LINKINGS: LIBRARIES

Libraries aggregate common functions or classes.

Static linking combines modules of a program, but also used to be the main way of linking to libraries:

- Executables include copies of any library modules they reference (but just those .o files, not others in the library)
- Executable is complete and self-sufficient. It should run on any machine with a compatible architecture.

REASON 2: LIBRARIES

Dynamic linking is more common today

- Your executable program doesn't need to contain library code
- At execution, single copy of library code is shared, but the dynamic linker does need to be able to find the library file (a ".so" file)

If a dynamically linked executable is launched on a machine that lacks the DLL, you will get an error message (usually, on startup, but there are some obscure cases where it happens later, when the DLL is needed)

HOW LINKING WORKS: 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 the **symbol table.**

- Symbol table is an array of entries
- Each table entry includes name, type, size, and location of symbol.
- With C++ the “location” is the “namespace” that declared the class

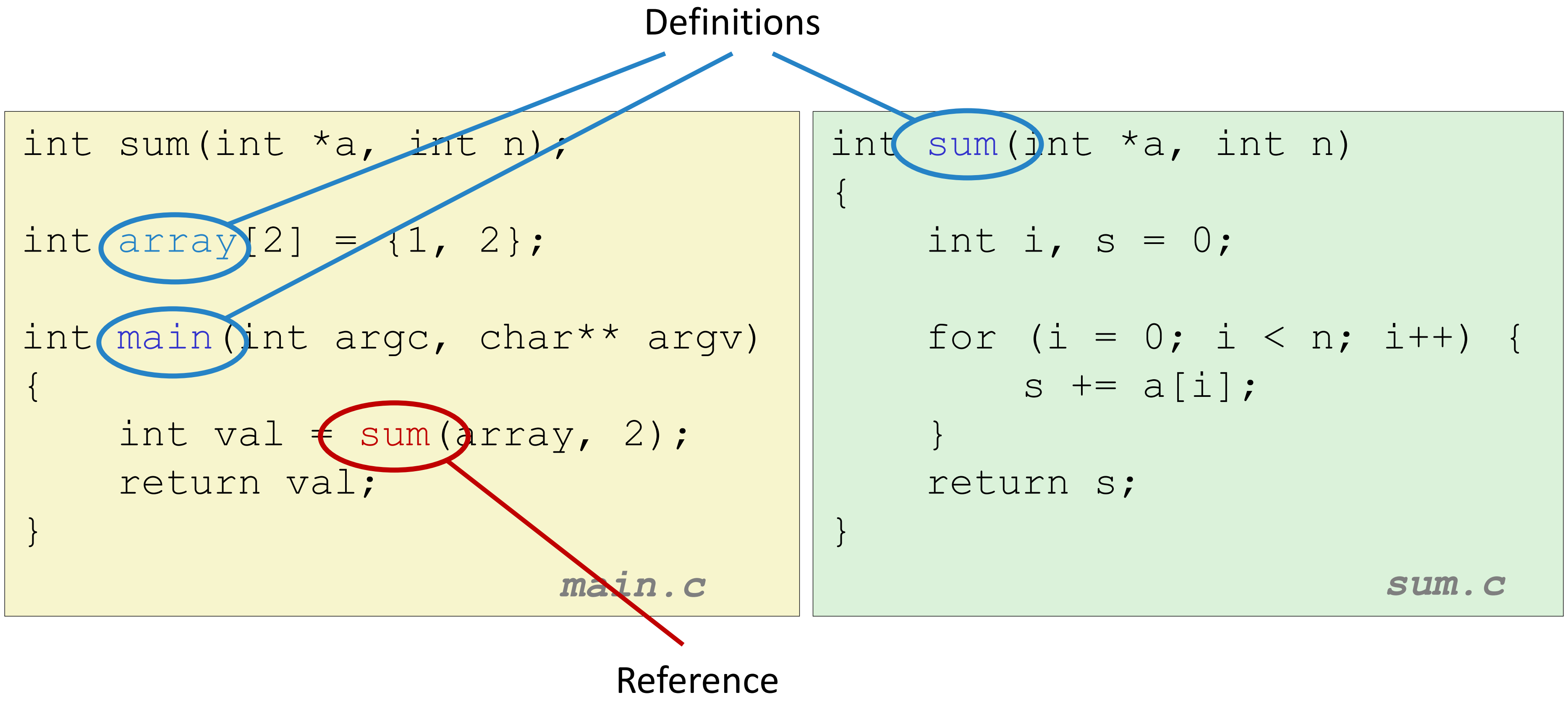
… THREE CASES

A symbol can be defined by the object file.

It can be undefined, in which case the linker is required to find the definition and link the object file to the definition.

It can be *multiply defined*. This is normally an error… but we will see one tricky way that it <u>can</u> be done, and even be useful!

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

LINKERS CAN "MOVE THINGS AROUND". WE CALL THIS "RELOCATION"

A linker merges code and data sections into single sections

- ➢ As part of this it *relocates* symbols from their relative locations in the .o files to their final absolute memory locations in the executable.
- ➢ It updates references to these symbols to reflect their new positions.

OBJECT FILE FORMAT (ELF)

Elf header

- ➢ Word size, byte ordering, file type (.o, exec, .so), machine type,

Segment header table

- ➢ Page size, virtual address memory segments + sizes.

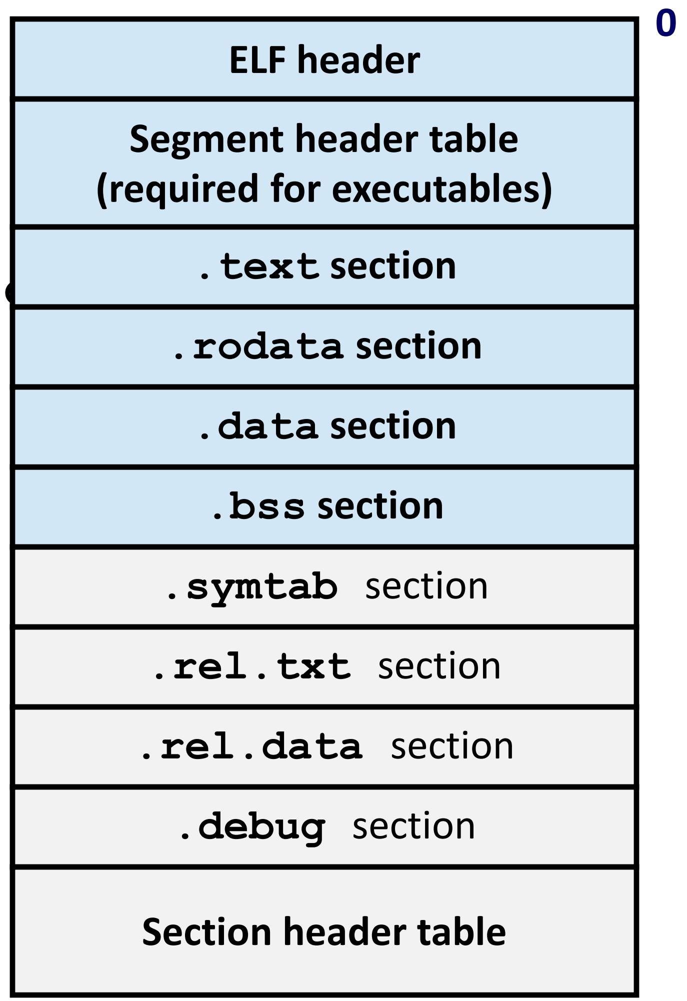
.text section (code)

.rodata section (read-only data, jump offsets, strings)

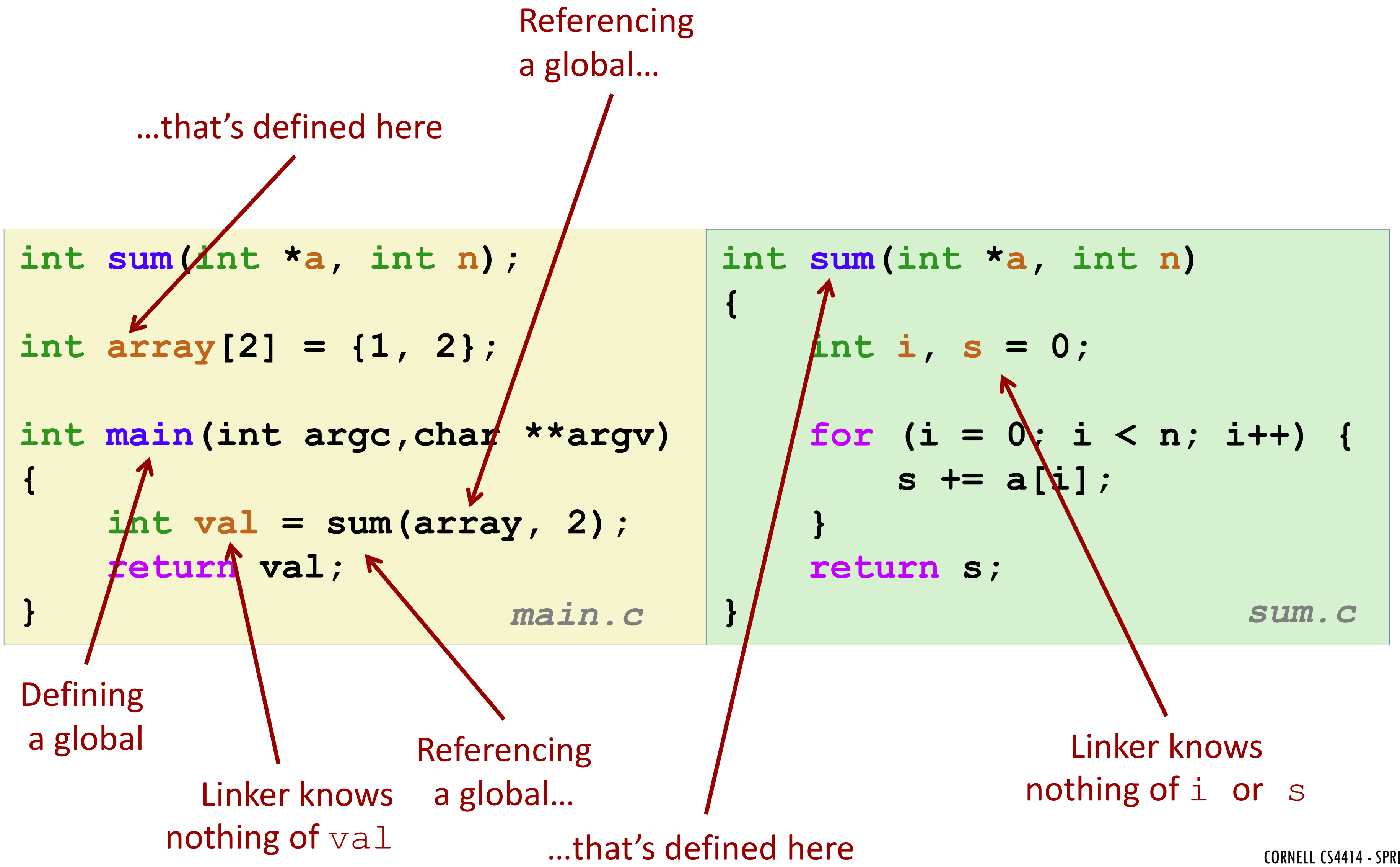
.data section (initialized global variables)

.bss section (name “bss” is lost in history)

- ➢ Global variables that weren’t initialized: zeros.
- ➢ Has section header but occupies no space



EXAMPLE OF 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 incr = 1;
static int foo(int a) {
  int b = a + incr;
  return b;
}

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

Names:

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

Can find this with `readelf`:

```
linux> readelf -s symbols.o
```

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

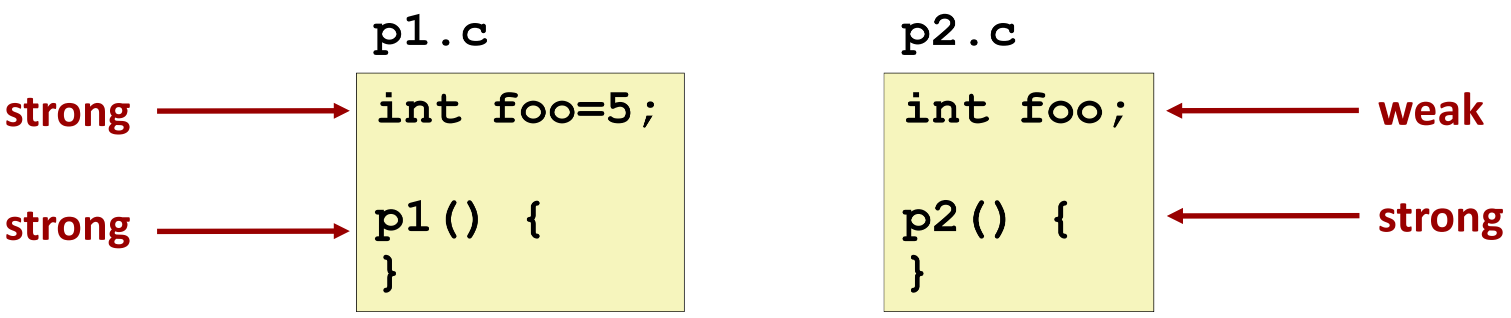
Compiler allocates space in `.data` for each definition of `x`

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: methods (code blocks) and initialized globals
- Weak: uninitialized globals (or with specifier extern)



p1.c

strong

```
int foo=5;
```

strong

```
p1() {
}
```

p2.c

```
int foo;
```

weak

```
p2() {
}
```

strong

… but be aware that the “weak” case can cause real trouble!

LINKER WITH MULTIPLE WEAK DECLARATIONS

```
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 might 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. But C++ “namespaces” create a private naming scope.

GLOBAL TYPE MISMATCHES CAUSE BUGS

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

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

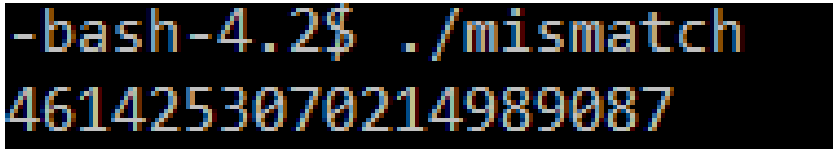
mismatch-main.c

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

mismatch-variable.c

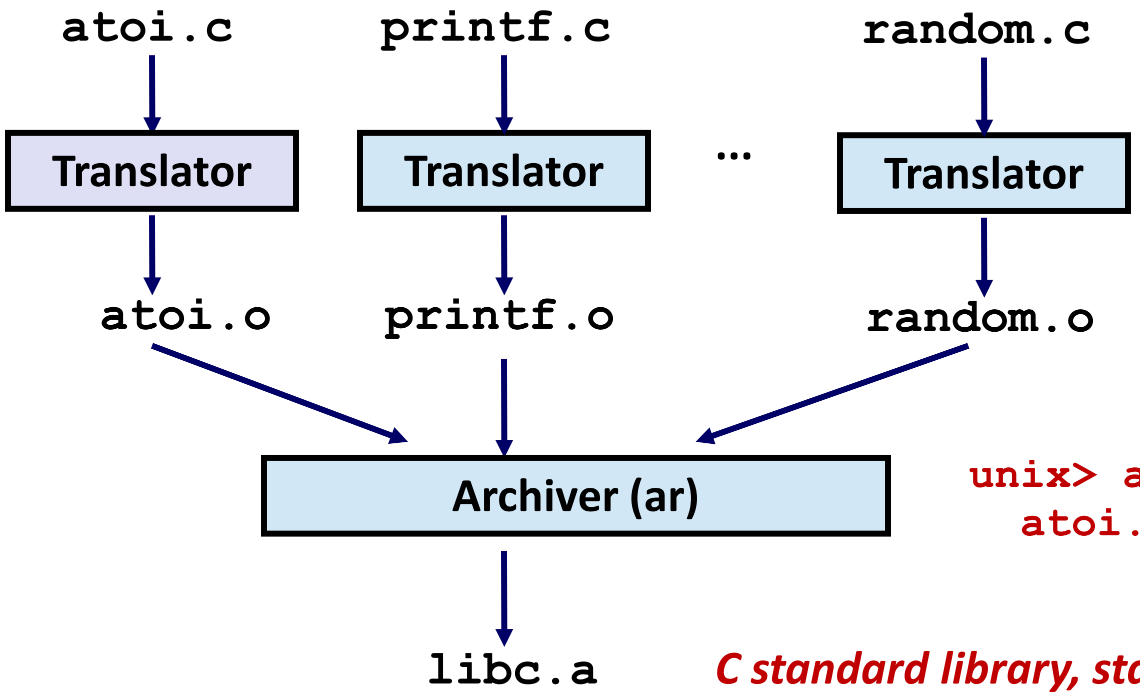
Compiles without any errors or warnings, yet this is a bug!

What gets printed?



```
-bash-4.2$ ./mismatch
4614253070214989087
```

STATIC LIBRARIES



```
unix> ar rs libc.a \
  atoi.o printf.o … random.o
```

C standard library, static version

- Archiver creates a single file that contains all the .o files, plus a lookup table (basically, a “directory”) that the linker can use to find the files.

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

```
#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

libvector.a

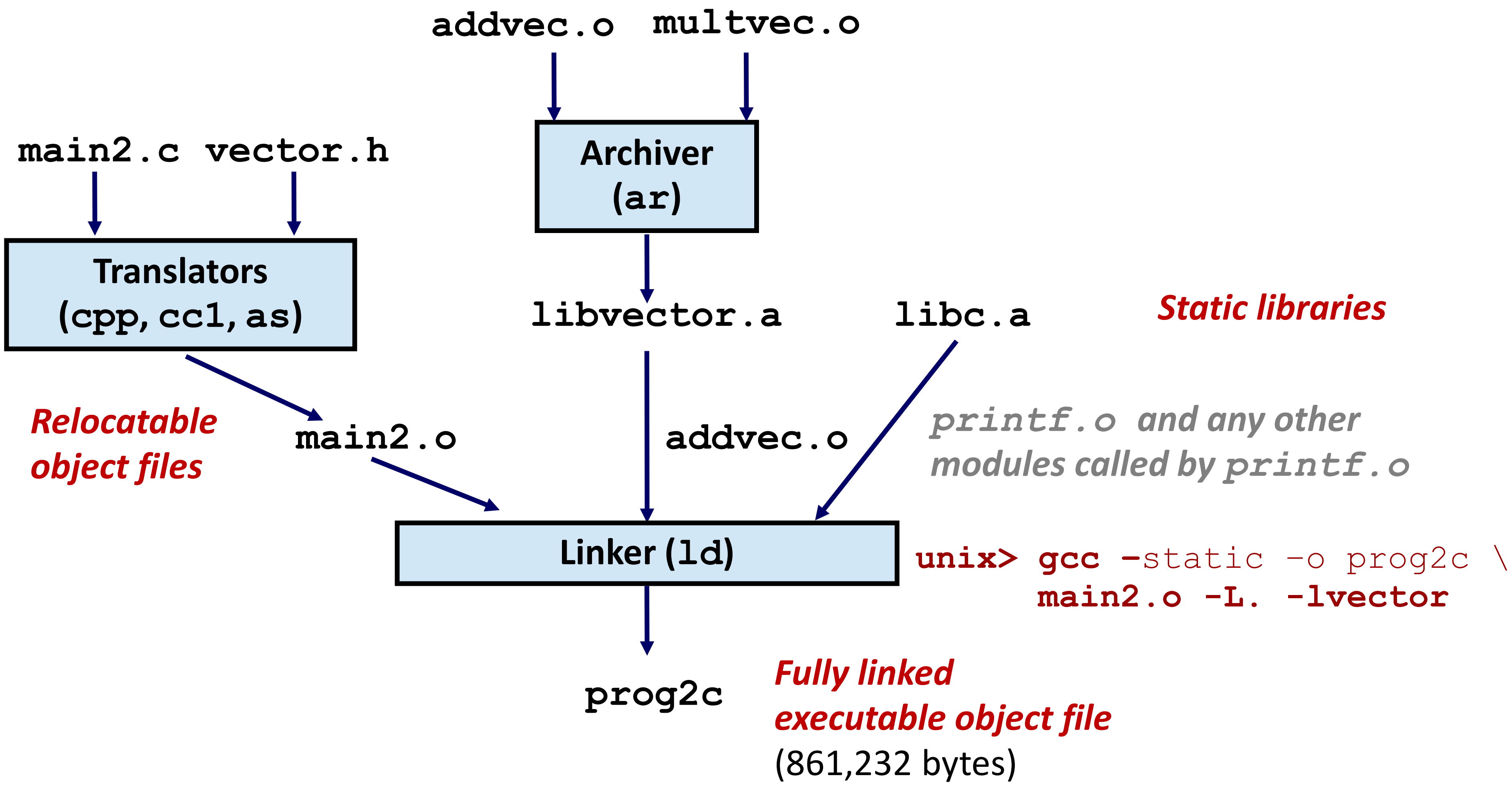
```
void addvec(int *x, int *y,
            int *z, int n) {
    int i;

    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



addvec.o multvec.o

Archiver (ar)

main2.c vector.h

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 prog2c \
      main2.o -L. -lvector
```

prog2c

Fully linked executable object file
(861,232 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 -static -o prog2c -L. -lvector main2.o
main2.o: In function `main':
main2.c:(.text+0x19): undefined reference to `addvec'
collect2: error: ld returned 1 exit status
```

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 in system libraries? Must rebuild everything!

Example: hugely disruptive 2016 library issue:

https://security.googleblog.com/2016/02/cve-2015-7547-glibc-getaddrinfo-stack.html

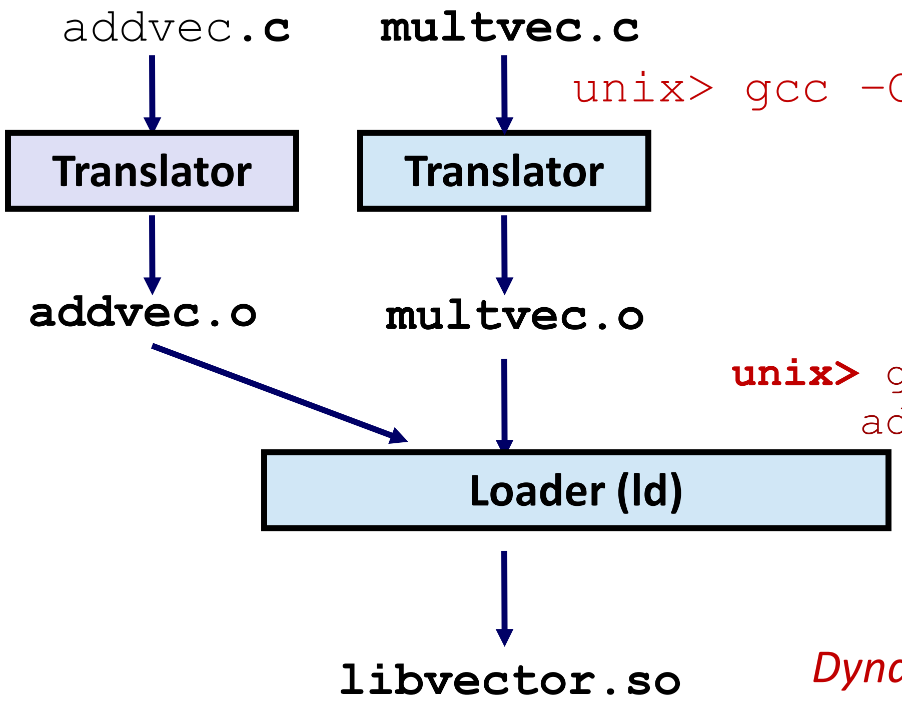
SHARED LIBRARIES

Shared libraries save space and resolve this issue.

Term refers to:

- Object files that contain code and data.
- Saved in a special directly (LOADPATH points to it).
- Loaded and linked into an application dynamically, at either load-time or run-time
- Also called: dynamic link libraries, DLLs, .so files

DYNAMIC LIBRARY EXAMPLE

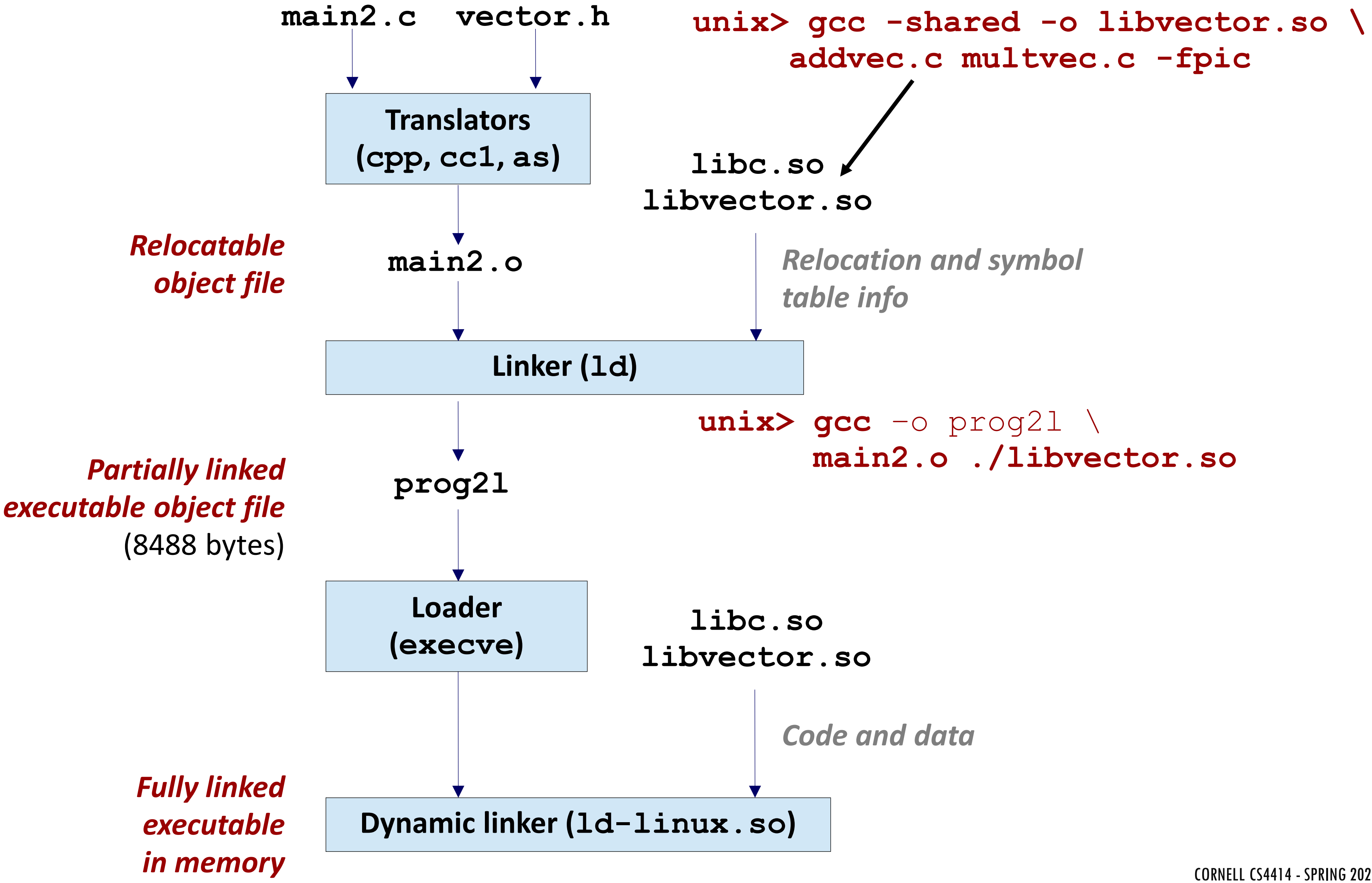


```
unix> gcc -Og -c addvec.c multvec.c -fpic
```

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

Dynamic vector library

DYNAMIC LINKING AT LOAD-TIME



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

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

FOR DYNAMIC LINKING, RELOCATION OCCURS AT RUNTIME

The program using the DLL is coded to access DLL methods via a special “indirection” table.

Initially this table has on entry per library method but all of them are “wired” to call “load on first access”

This method automatically loads the DLL and patches references

REMINDER: MMAPPED FILE

A file… but fully loaded into memory by the kernel

Those physical pages can now show up as virtual pages in any address space that calls mmap() and has permission

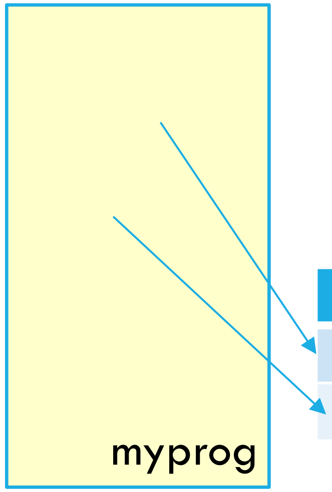
The pages are only in memory "once". The page table entries are small so the overheads are minor.

STEPS IN DLL LOADING

Automatic, but what the method does is

- Map the DLL file itself into memory. If it is already in memory the single copy will be shared. This is our space savings ☺
- That new DLL will need its own private copy of the data and bss segment. Allocate space, and remember the base address.
- Now, when foo(x) gets called, we just load that base address in a designated register and call (*address_of_foo)(x) !

… STEPS IN DLL LOADING AS GRAPHIC

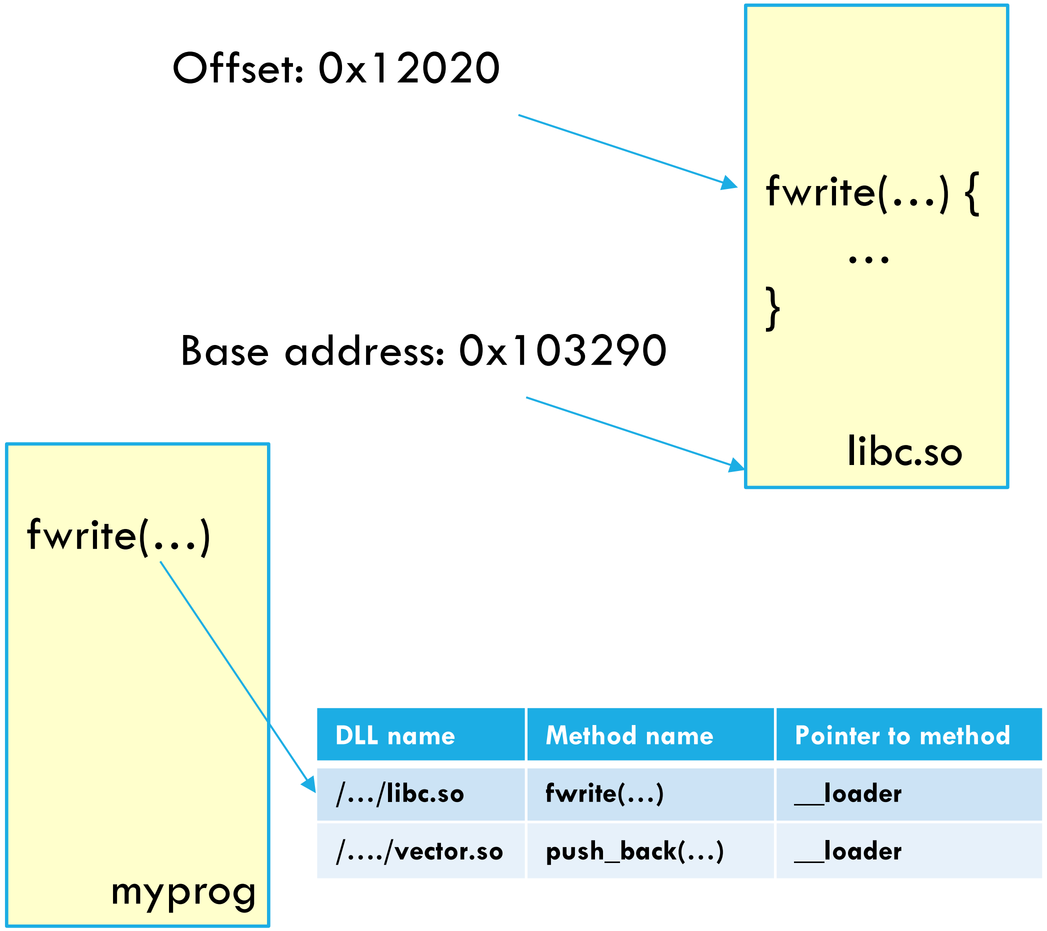


DLL name	Method name	Pointer to method
/…/libc.so	fwrite(…)	__loader
/…./vector.so	push_back(…)	__loader

Initially, myprog doesn’t have the DLL loaded.

Calls to methods like “fwrite” will actually call __loader via function-pointer indirection

… STEPS IN DLL LOADING AS GRAPHIC

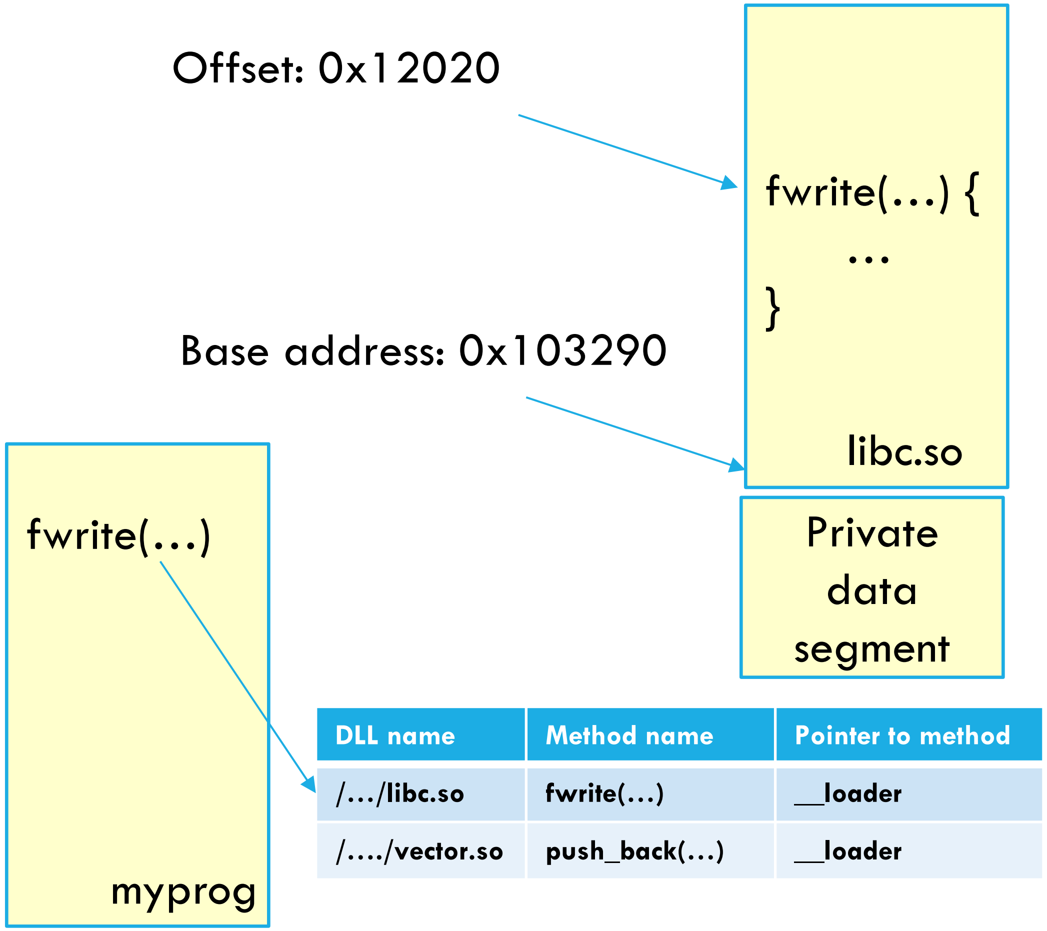


DLL name	Method name	Pointer to method
/…/libc.so	fwrite(…)	__loader
/…./vector.so	push_back(…)	__loader

On the first call, __loader is invoked and uses Linux file mapping (**mmap**) to map the DLL into memory. The pages of this segment will be shared, read-only, with other users.

This lets the loader learn the base address of the new segment

… STEPS IN DLL LOADING AS GRAPHIC

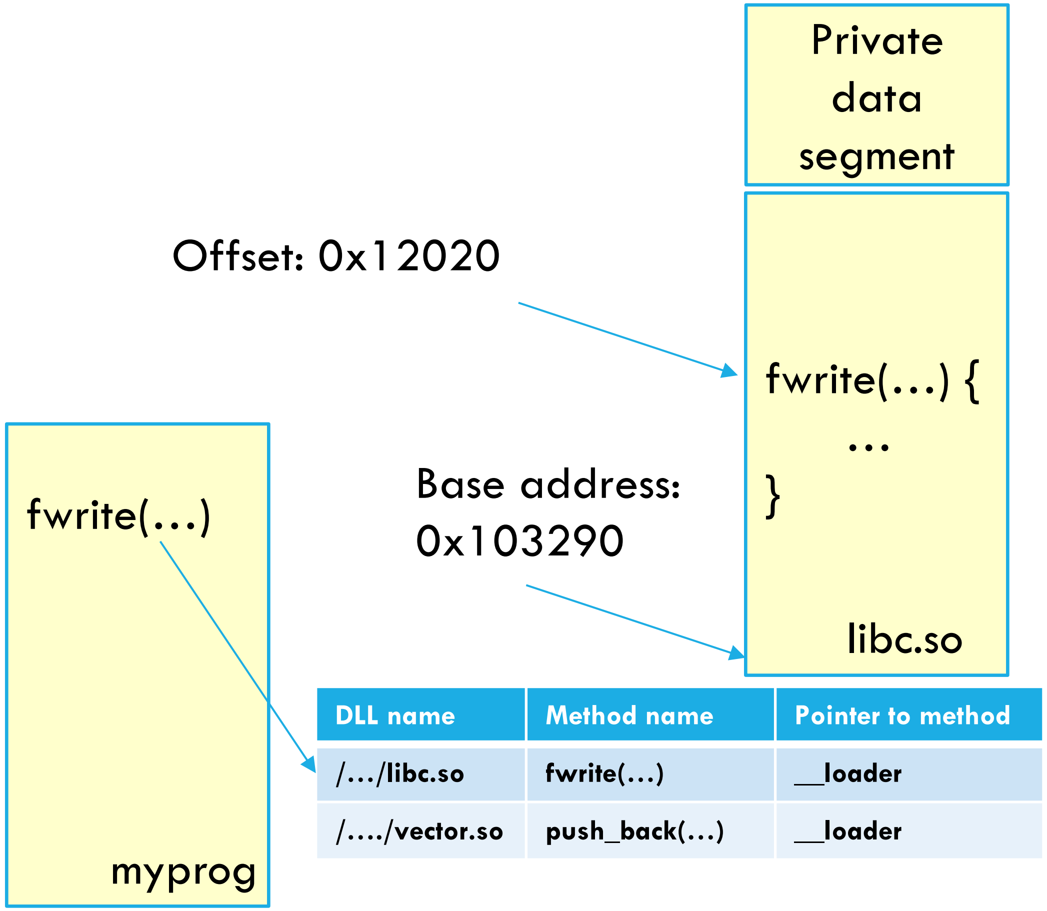


DLL name	Method name	Pointer to method
/…/libc.so	fwrite(…)	__loader
/…./vector.so	push_back(…)	__loader

Next, it makes a clone (a private copy) of the data segment and bss segment used by libc.so. The mapped segment has a read-only copy.

This is because each process using the DLL needs its own version of the global variables

… STEPS IN DLL LOADING AS GRAPHIC



Private data segment

Offset: 0x12020

fwrite(…) {
…
}

libc.so

Base address: 0x103290

fwrite(…)

myprog

DLL name	Method name	Pointer to method
/…/libc.so	fwrite(…)	__loader
/…./vector.so	push_back(…)	__loader

Now the loader can patch up the indirection table.

A call to fwrite will go to a little method that (1) puts the base address of libc.so and the associated data segment into a register, then calls the version in the mapped memory region

WHEN FWRITE IS INVOKED…

Main “calls” the wrapper function.

That wrapper arranges for c++ to put the base address in the base address register (the prior value is pushed to the stack)

The call occurs and frwrite runs

The prior value of the base address register is popped and restored

WHY DID WE SAVE MEMORY?

The segment holding libc.so could be huge – it is hard to get used to “sizes” of things, but shared libraries can be very large.

Many of them have really big in-memory data structures or helper data of various kinds, like ML models.

This can add up to gigabytes. Now those will be shared, in read-only mapped memory

HOW DOES THE C++ COMPILER KNOW THAT FWRITE(…) WILL LIVE IN A DLL?

… it does <u>need</u> to know, because the DLL can land at a different place in each process using it.

- Every process has its own address space layout.

So, gcc needs to use pointer and base-relative addressing

But who tells it? **You do. The DLL developer must "say this"**

GCC OPTIONS USED HERE

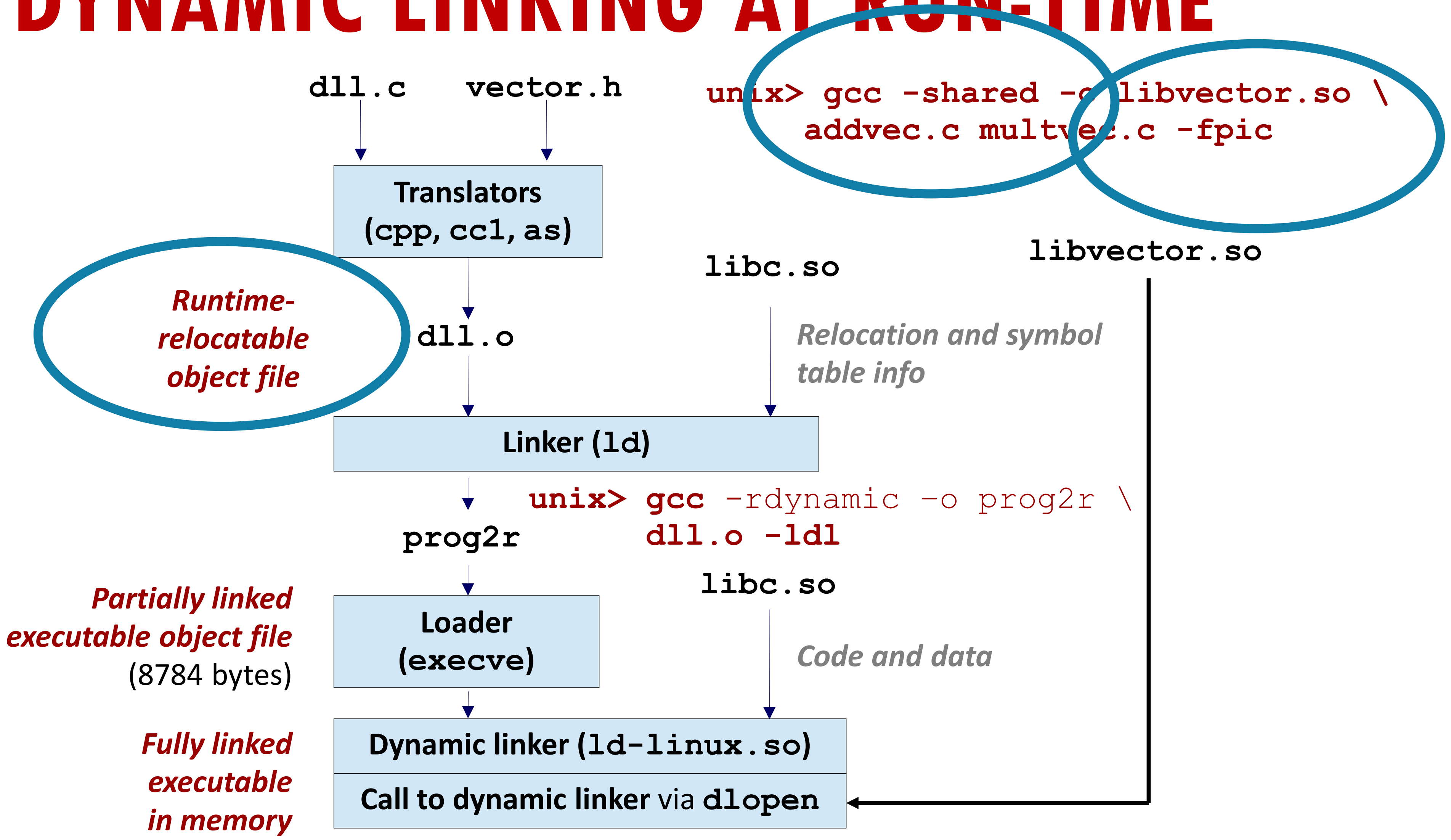
1) –shared, -fpic: To create position independent code (next slide)

2) –o something.so: To output result as a DLL

3) –rdynamic: Includes dynamic symbol names for gprof, gdb

4) –ldr: “dr” is the directory to look for the .so file in

DYNAMIC LINKING AT RUN-TIME



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

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

dll.c
vector.h
Translators
(cpp, cc1, as)
libc.so
libvector.so
Runtime-relocatable object file
dll.o
Relocation and symbol table info
Linker (ld)
prog2r
libc.so
Partially linked executable object file
(8784 bytes)
Loader
(execve)
Code and data
Fully linked executable in memory
Dynamic linker (ld-linux.so)
Call to dynamic linker via dlopen

RUNTIME ERRORS

At runtime, your program searches for the .so file

What if it can't find it?

- You will get an error message during execution, and the executable will terminate. Depending on the version of Linux, this occurs when you launch the program, or when it tries to access something in the dll

Some dll files also have "versioning" data. On these, your program might crash because of an "incompatible dll version number"

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

GETTING VERY FANCY: LIBRARY INTERPOSITIONING (FOR SERIOUS HACKERS!)

Documented in Section 7.13 of book

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.

1-2-3 RECIPE FOR INTERPOSITIONING

Given an executable that obtains **something** from a library.

Create a .o file that defines **something,** using the same API the executable expected. Relink the executable against your .o file.

Now your implementation of **something** will be called

1-2-3 RECIPE FOR INTERPOSITIONING

… but what if you wanted to call the standard **something** from inside your replacement?

If it were to call **something**, that would just be a recursive call.

… So, have it call _**something.** This will be undefined… claim that it is in a library

1-2-3 RECIPE FOR INTERPOSITIONING

So now we have the original executable, and it calls your version of **something**, which calls _**something.**

Create a new DLL library that defines _**something.** It calls the original **something, from the original DLL.**

Now we have "wrapped" **something**!

… SHORTCUT

There are also linker arguments you can use to just tell the linker you wish to wrap some method.

Eliminates the need to create the extra helper DLL.

Time permitting, I'll show you an example that wraps malloc

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

Changing a local resource into one accessed over a network

EXAMPLE PROGRAM

```
#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.

We won't cover this example if we are short on time; it is not required and you won't see questions about these slides on a quiz

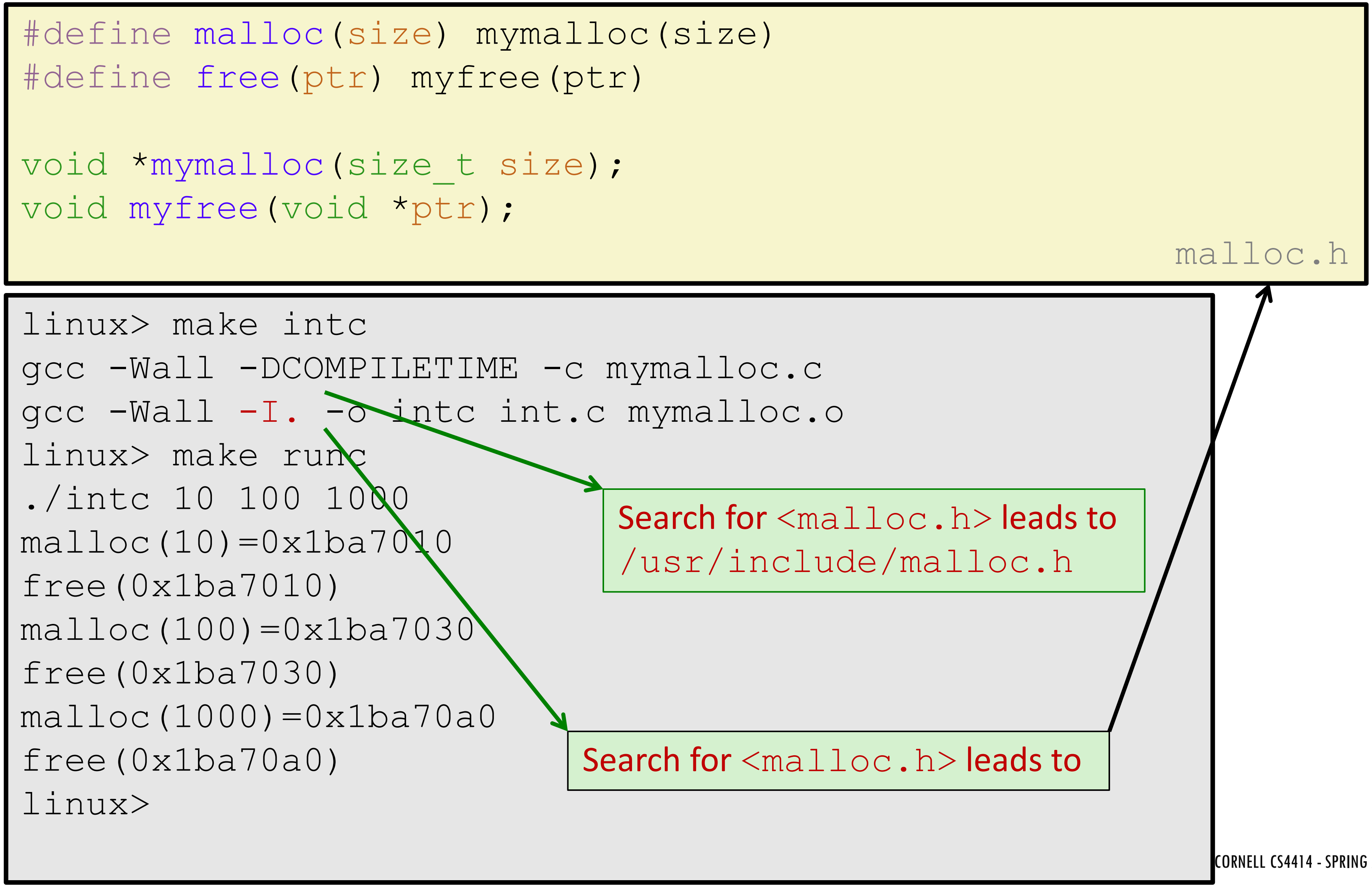
COMPILE-TIME INTERPOSITIONING

```c
#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

Time permitting

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 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

Time permitting

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

Time permitting

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`

Time permitting

LOAD/RUN-TIME INTERPOSITIONING

Observe that we DON’T have `#include <malloc.h>`

```
#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 */
    return ptr;
}
```

mymalloc.c

Time permitting

LOAD/RUN-TIME INTERPOSITIONING

```
/* 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 */}
#endif
```

mymalloc.c

Time permitting

NOTE: DON’T CALL PRINTF IN MALLOC/FREE

We going overloading malloc…

… but this means that debugging our code using a printf wouldn’t work: calling anything that does a malloc can cause a recursion that wouldn’t terminate!

… printf(“something”) turns into std::cout << “something”, and this in turn creates a std::string(“something”). **Program crashes.**

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:

```
env LD_PRELOAD=./mymalloc.so ./intr 10 100 1000)
```

Time permitting

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

```
env LD_PRELOAD=./mymalloc.so gcc -c int.c)
```

Time permitting

LINKING SUMMARY

Usually: Just happens, no big deal

But there are many sophisticated features and options!

When using these fancier options, expect strange errors

- Bad symbol resolution
- Ordering dependence of linked .o, .a, and .so files

For power users, it takes effort but then you can do:

- Interpositioning to trace programs with & without source