14-513 18-613

Linking

15-213/18-213/14-513/15-513/18-613:
Introduction to Com
14^{th} Lecture, Octobe

Today

- **Linking**
  - Motivation
  - What it does
  - How it works
  - Dynamic linking
- **Case study: Libr**

Understanding linking can help you avoid nasty errors and make you a better programmer.

Example C Program

```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;
}
```

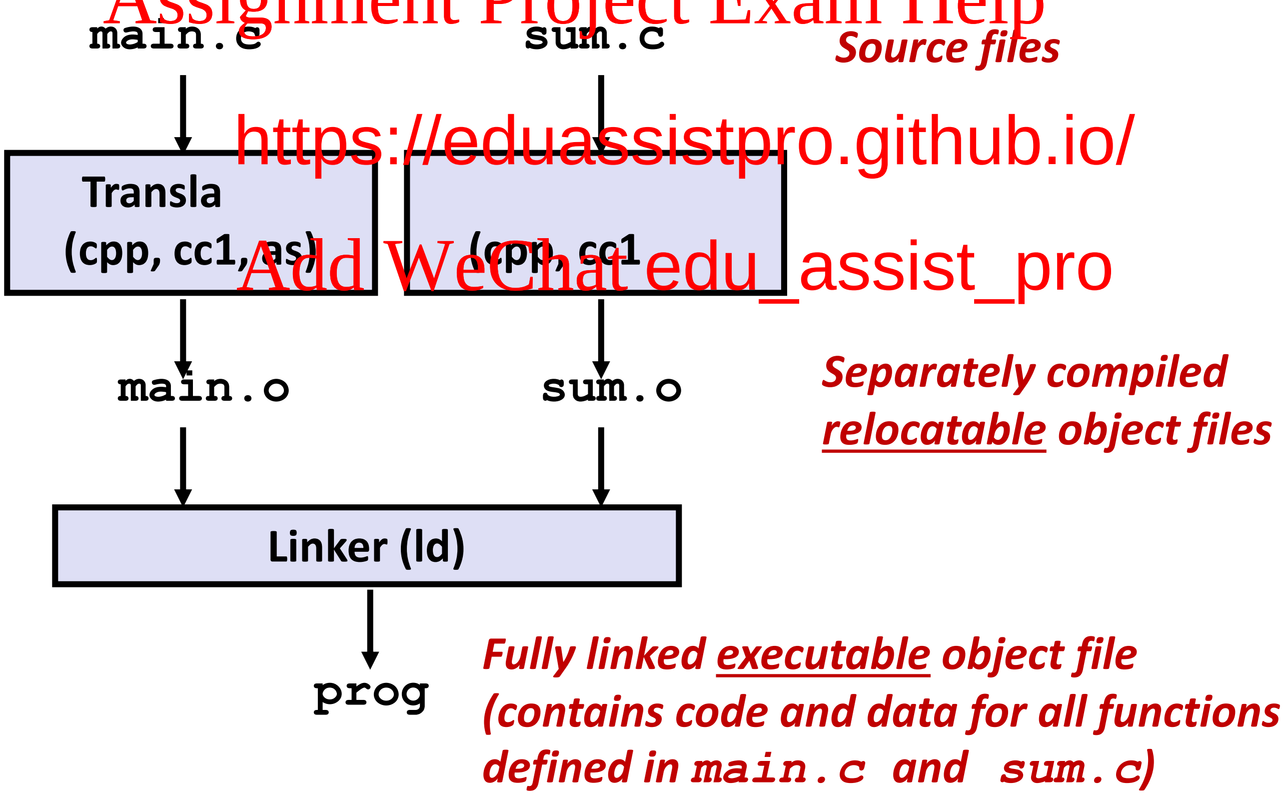
main.c

```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

- 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 librari on this later)
    - e.g., Math library, standard C li

Why Linkers? (cont)

- **Reason 2: Efficiency**
  - Time: Separate compilation. How does that save time?
    - Change one source file, compile, and then relink.
    - No need to recompile other source files.
    - Can compile
  - Space: Libraries.
    - Common functions can be aggr single file...
    - **Option 1: *Static Linking***
      - Executable files and running memory images contain only the library code they actually use
    - **Option 2: *Dynamic linking***
      - Executable files contain no library code
      - During execution, single copy of library code can be shared across all executing processes

What Do Linkers Do?

- **Step 1: Symbol resolution**

  - Programs define and reference *symbols* (global variables and functions):
    - `void swap() {…}   /* define symbol swap */`
    - `swap();                               mbol swap */`
    - `int *xp =                         l xp, reference x */`

  - Symbol definitions are stored in obj   embler) in *symbol table*.
    - Symbol table is an array of entries
    - Each entry includes name, size, and location of symbol.

  - **During symbol resolution step, the linker associates each symbol reference with exactly one symbol definition.**

Symbols in Example C Program

Definitions

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

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

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

main.c

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

        i = 0; i < n; i++) {
          += a[i];

          s;
}
```

sum.c

Reference

What Do Linkers Do? (cont)

- **Step 2: Relocation**
  - Merges separate code and data sections into single sections

  - Relocates symb in the `.o` files to their final absol

ecutable.

  - Updates all references to these sy t 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 obje**
  - Contains code and data in a form t ied 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)

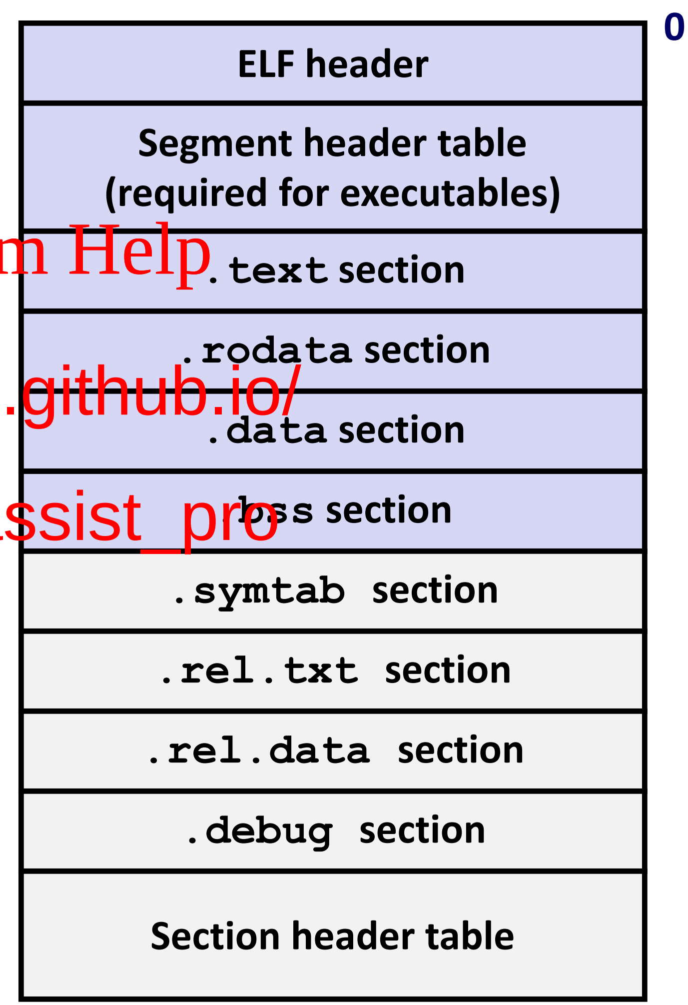
- **Standard binary format for object files**

- **One unified format for**
  - Relocatable object files (`.o`),
  - Executable obje
  - Shared object fil

- **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 address memory segments (sections), segment sizes.
- **`.text` section**
  - Code
- **`.rodata` section**
  - Read only data: jump tables, string consta
- **`.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 fo
  - Addresses of instr
    modified in the ex
  - 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

0

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

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 symbol**
  - Global symbols *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,

int main(int argc,char **argv)
{
    int val = sum(array, 2);
    return val;
}
                                main.c
```

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

                s = 0;

                0; i < n; i++) {
                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(i
  int b = a + incr;
  return b;
}

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

Names:

- `incr`
- `foo`
- `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
    return x++;
}

int g() {
    static int x = 19;
    return x += 14;
}

int h() {
    return x += 27;
}
```

static-local.c

Com space in `.data` for each `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***: procedures and initialized globals
  - ***Weak***: uninitialized globals
    - Or ones dec

p1.c

strong → `int foo=5;`

strong → `p1() { }`

```
int foo=5;

p1() {
}
```

```
p2() {
}
```

weak

strong

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 s le weak symbols, choose the stro**
  - References to the weak symbol res ong symbol

- **Rule 3: If there are multiple weak symbols, pick an arbitrary one**
  - Can override this with `gcc -fno-common`

- **Puzzles on the next slide**

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() {}`	t 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.

Type Mismatch Example

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

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

mismatch-main.c

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

mismatch-variable.c

- **Compiles without any errors or warnings**
- **What gets printed?**

Global Variables

- **Avoid if you can**

- **Otherwise**
  - Use **`static`** if you can
  - Initialize if you d
  - Use **`extern`** if al variable
    - Treated as weak symbol
    - But also causes linker error if not defined in some file

Use of `extern` in .h Files (#1)

c1.c

```
#include "global.h"

int f() {
  return g+1;
}
```

global.h

```
extern int g;
int f();
```


c2.c

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

int g = 0;

int main(int argc, char argv[]) {
  int t = f();
  printf("Calling f yields %d\n", t);
  return 0;
}
```

Linking Example


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

int array[2] = {1,

int main(int argc,char **argv)
{
    int val = sum(array, 2);
    return val;
}
```

main.c

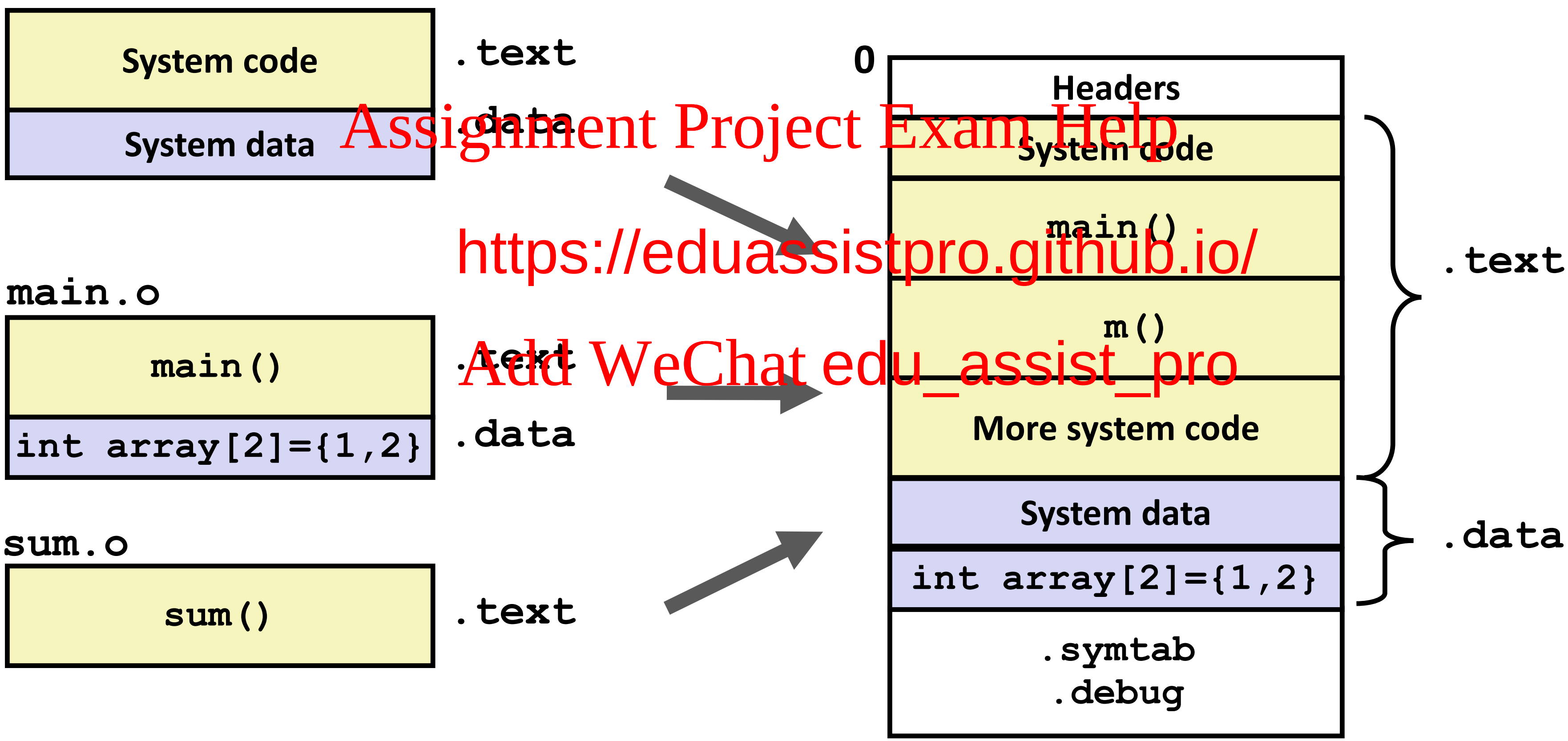
```
int sum(int *a, int n)

                s = 0;

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

sum.c

Step 2: Relocation

Relocatable Object Files

Executable Object File



Relocation Entries

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

int main(int argc, char**
argv)
{
    int val = sum(array, 2);
    return val;
}
```



```
0000000000000000 <main>:
   0:   48 83 ec 08             sub
   4:   be 02 00 00 00          mov
   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

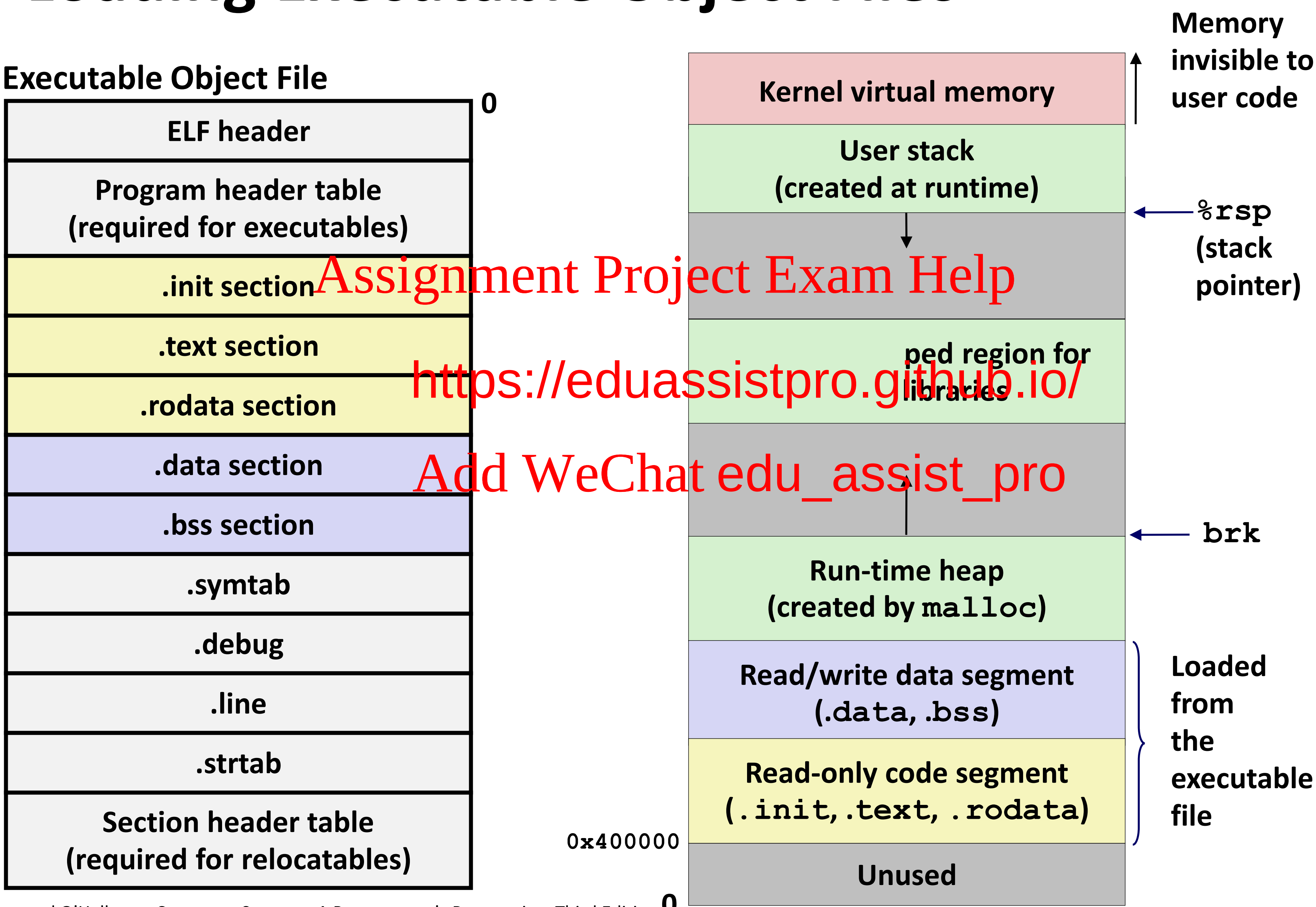
```
00000000004004d0 <main>:
  4004d0:      48 83 ec 08       sub    $0x8,%rsp
  4004d4:      be 02 00 00 00    mov    $0x2,%esi
  4004d9:      bf 18 10 60 00    mov    $0x601018,%edi  # %edi = &array
  4004de:      e8 05 00 00 00    callq  4004e8 <sum>     # sum()
  4004e3:      48 83 c4 08       add    $0x8,%rsp
  4004e7:      c3

00000000004004e8 <sum>:
  4004e8:      b8 00 00 00 00                  0,%eax
  4004ed:      ba 00 00 00 00                  0,%edx
  4004f2:      eb 09                           4fd <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
```


`callq` instruction uses PC-relative addressing for sum():

`0x4004e8` = `0x4004e3` + `0x5`

Source: `objdump -d prog`

Loading Executable Object Files



Quiz Time!

Check out:

https://canvas.cmu.edu/courses/10968

Libraries: Packaging a Set of 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 file
    - Programmer rograms
    - 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

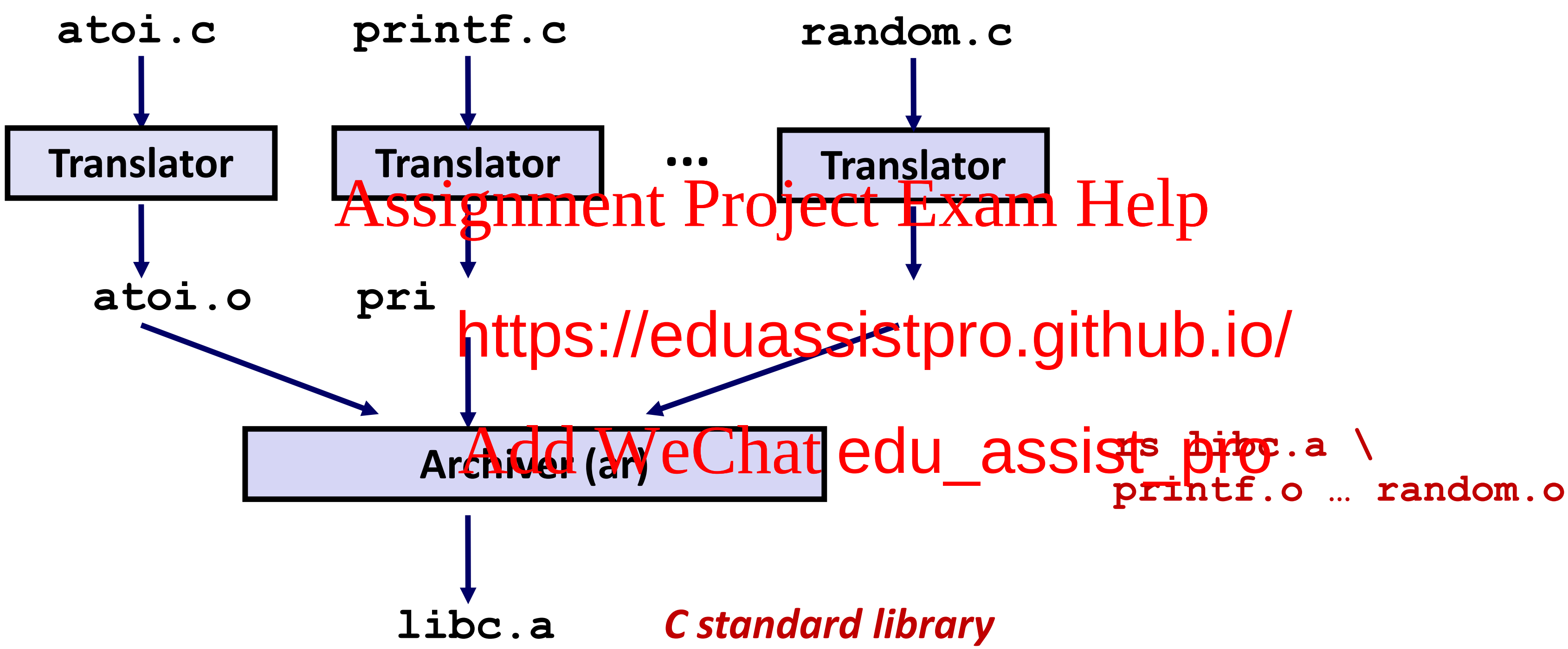
Old-fashioned Solution: Static Libraries

- **Static libraries (.a archive files)**
  - Concatenate related relocatable object files into a single file with an index (called an *archive*).

  - Enhance linker s lved external references by looking for th ives.

  - If an archive member file resolves r 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 44
- floating point mat


```
% ar -t /usr/lib/libc.a | sort
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
…
```



```
/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

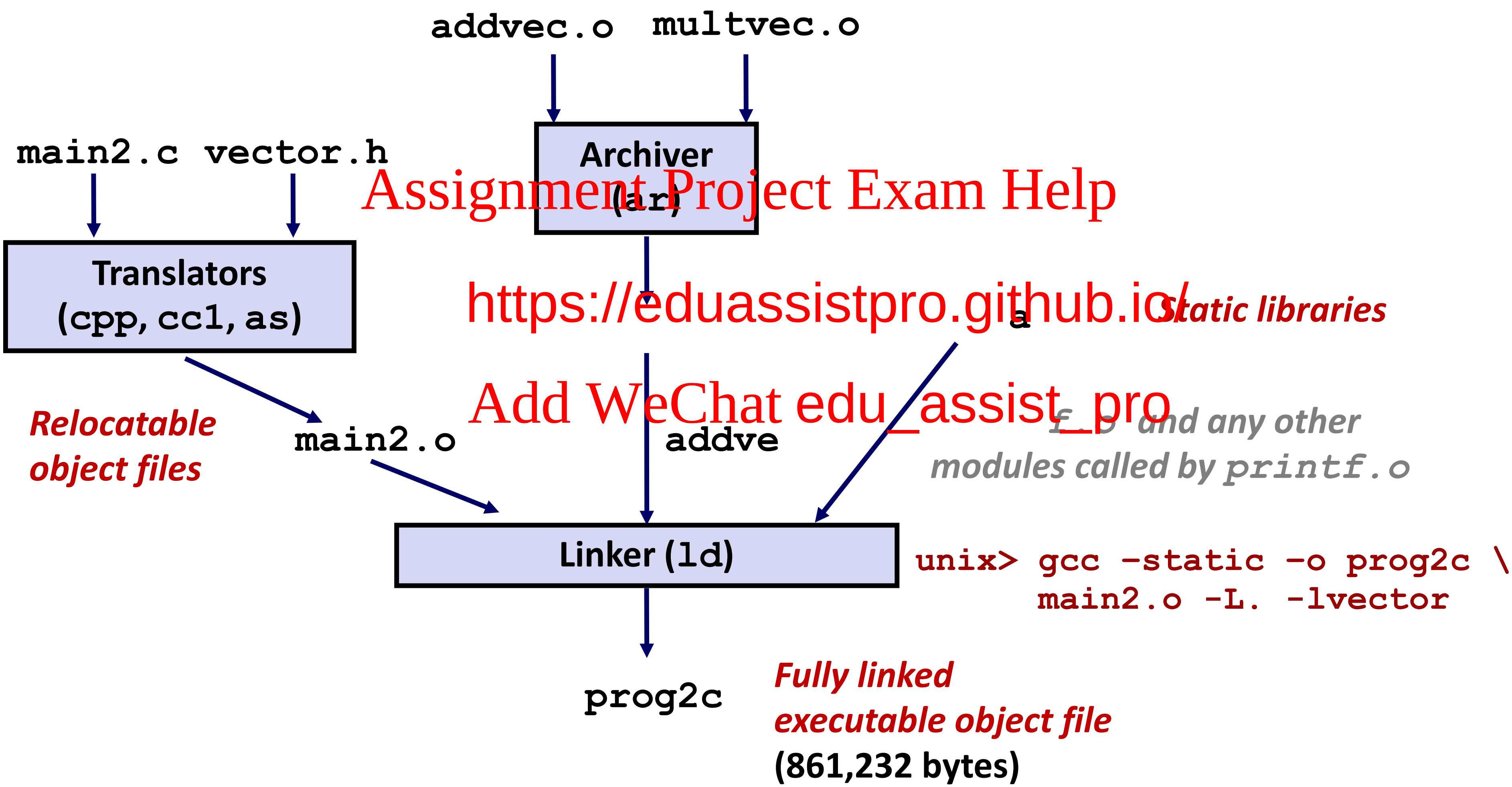
```
void addvec(int *x, int *y,
            int *z, int n) {
    int i;

                i < n; i++)
              x[i] + y[i];
}
```

addvec.c

```
void              *x, int *y,
                  *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 an, 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
```

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
    - Rebuild ever
    - https://security.googleblog.co -2015-7547-glibc-getaddrinfo-stack.html

- **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 libra ally linked.

- **Dynamic linking ram 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

What dynamic libraries are required?

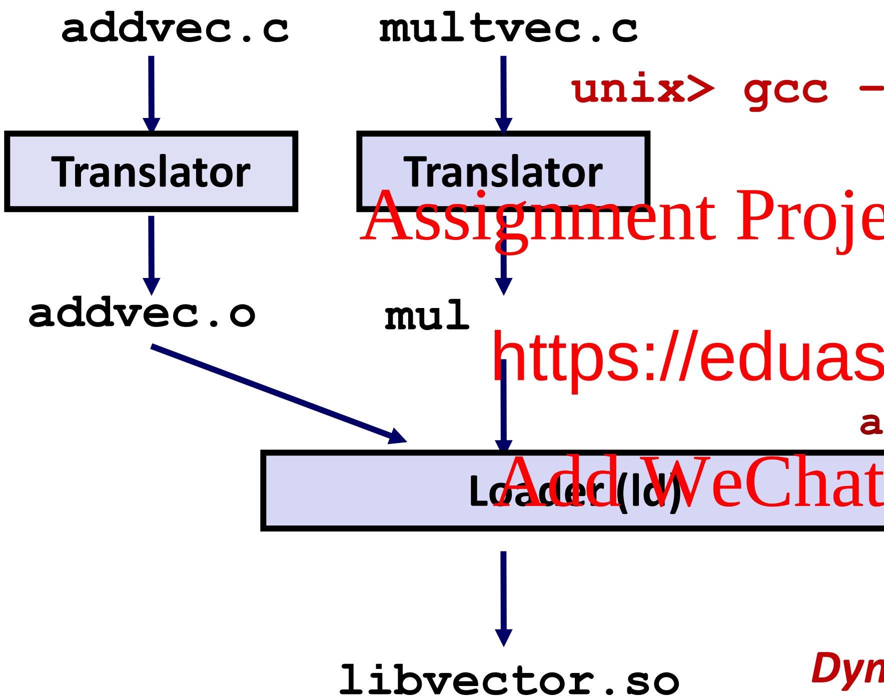
- **.interp section**
  - Specifies the dynamic linker to use (i.e., **`ld-linux.so`**)
- **.dynamic section**
  - Specifies the names, etc of the dynamic libraries to use
  - Follow an exam

(NEEDED) [libm.so.6]

- **Where are the libraries found?**
  - Use "**`ldd`**" to find out:

```
unix> ldd prog
  linux-vdso.so.1 =>  (0x00007ffcf2998000)
  libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007f99ad927000)
  /lib64/ld-linux-x86-64.so.2 (0x00007f99adcef000)
```

Dynamic Library Example

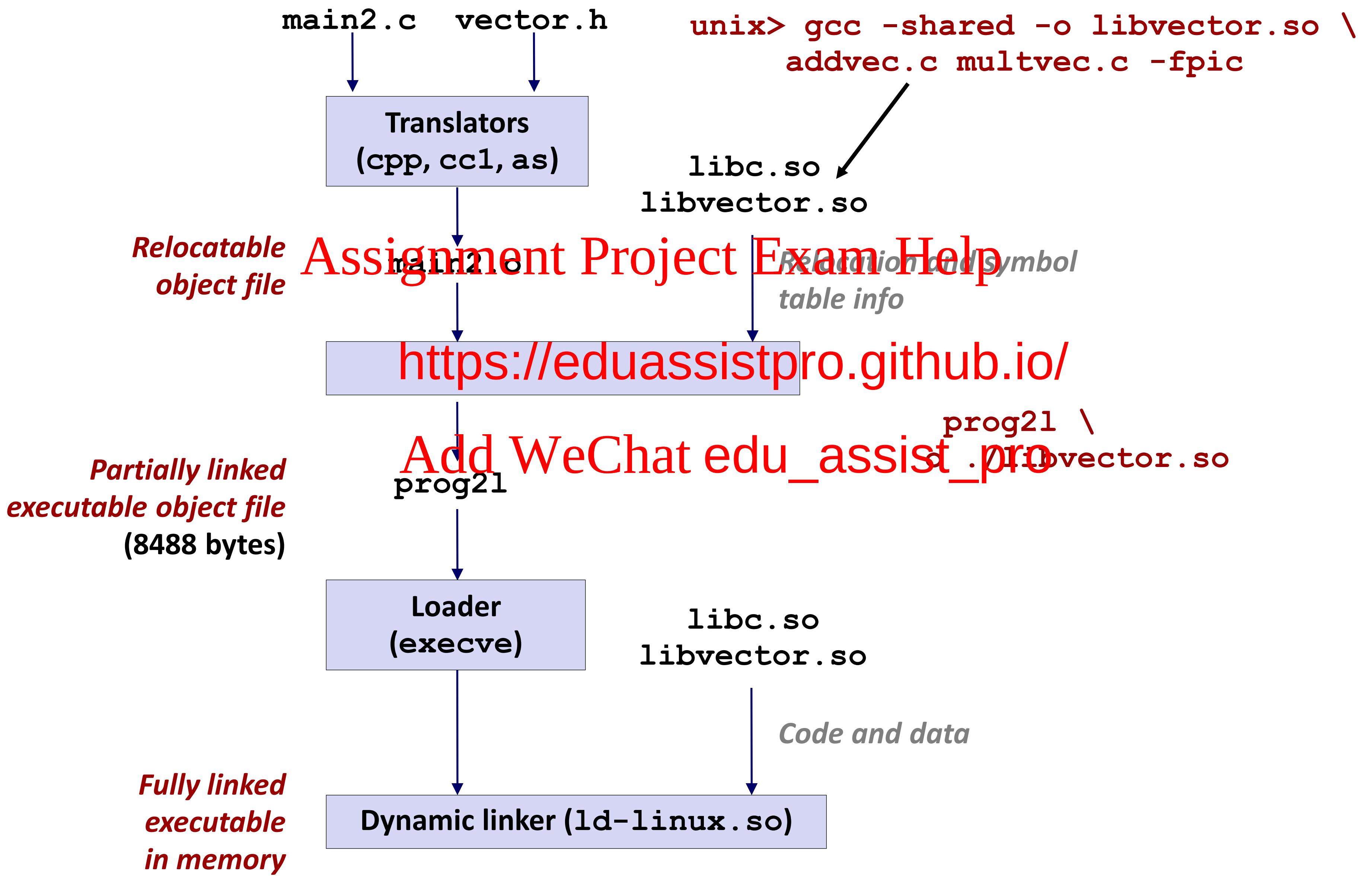



```
unix> gcc -Og -c addvec.c multvec.c -fpic
```

```
d -o libvector.so \
a                  ec.o
```

Dynamic vector library

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(int argc, c
{
    void *handle;
    void (*addvec)(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);
    }
  . . .
```

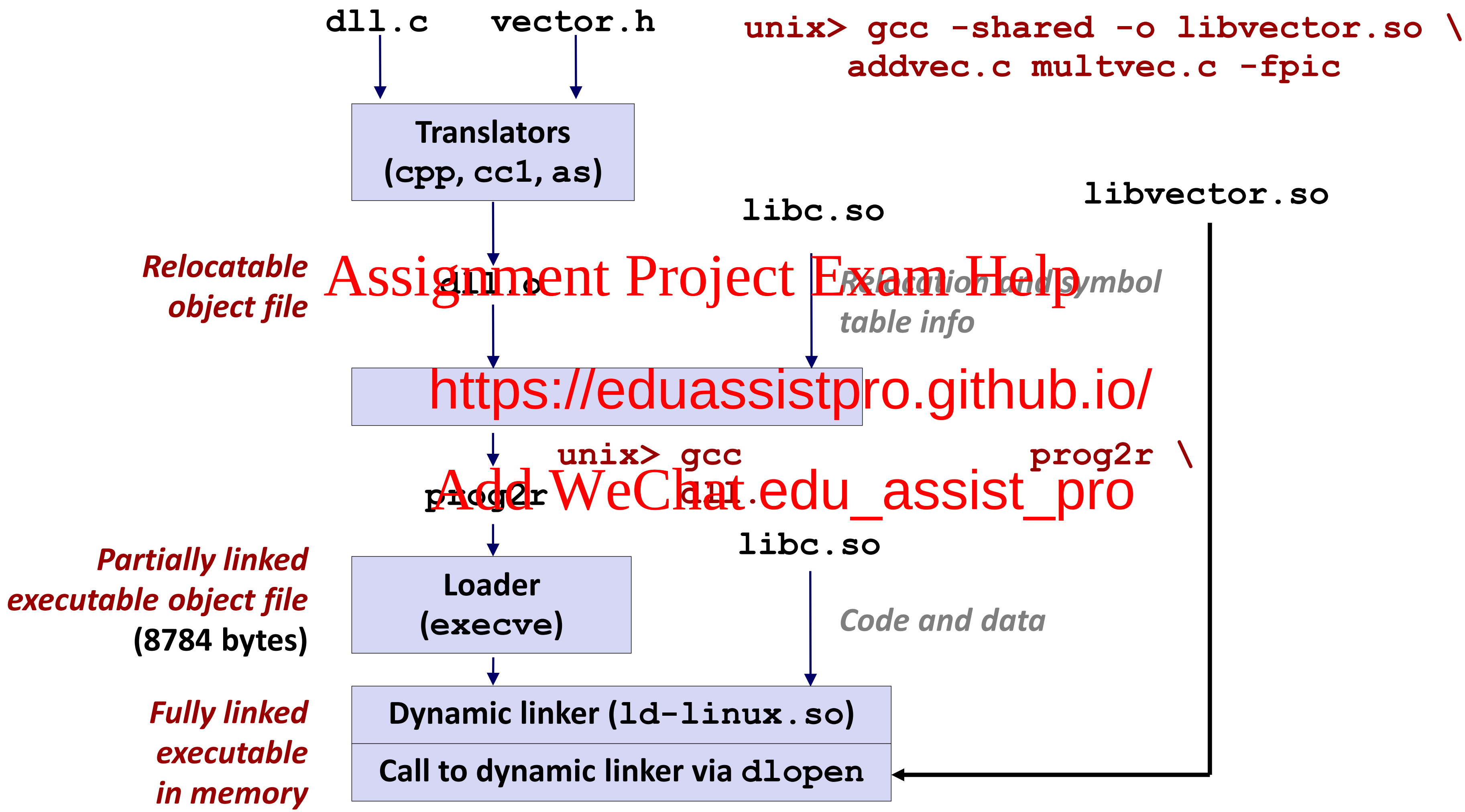
dll.c

Dynamic Linking at Run-time (cont)

```
    ...

    /* 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() jus          ther function */
    addvec(x, y, z, 2);
    printf("z = [%d %d]\n", z[0], z

    /* Unload the shared library */
    if (dlclose(handle) < 0) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
    return 0;
}
```

dll.c

Dynamic Linking at Run-time



Linking Summary

- **Linking is a technique that allows programs to be constructed from multiple object files.**

- **Linking can happen at different times in a program's lifetime:**

  - Compile time (w
  - Load time (when a program is load ry)

  - Run time (while a program is executing)

- **Understanding linking can help you avoid nasty errors and make you a better programmer.**

Today

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

Case Study: Library Interpositioning

- **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: ed

  - Link time: When e 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 Fa [illegible] reacherous 1-year old bug in their i [illegible] ing

  - Code in the SPDY networking stack [illegible] 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 (cont)

- **Monitoring and Profiling**
  - Count number of calls to functions
  - Characterize call sites and arguments to functions
  - Malloc tracing
    - Detecting m
    - **Generating**

- **Error Checking**
  - C Programming Lab used customized versions of malloc/free to do careful error checking
  - Other labs (malloc, shell, proxy) also use interpositioning to enhance checking capabilities

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 code.

- Three solutions: interpose on the library `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 = ma
    printf("malloc                                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 -DCOMPIL
gcc -Wall -I. -o intc int.c myma
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

Link-time Interpositioning

```
#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 = __                              all libc malloc */
    printf("malloc(%d) = %p\n",                 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

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`

Load/Run-time Interpositioning

```
#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;
}
```

mymalloc.c

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

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"); ss of libc free */
    if ((error = dlerror()) != NULL) {
        fputs(error, stderr);
        exit(1);
    }
    freep(ptr); /* Call libc free */
    printf("free(%p)\n", ptr);
}
#endif
```

mymalloc.c

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>
```

<malloc.h> leads to clude/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)
```

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 t   s

    - **`malloc`** → **`__wrap_mallo`**

    - **`__real_malloc`** → **`mallo`**

- **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)
```

Linking Recap

- **Usually: Just happens, no big deal**
- **Sometimes: Strange errors**
  - Bad symbol resolution
  - Ordering dependence of linked .o, .a, and .so files
- **For power users**
  - Interpositioning out source