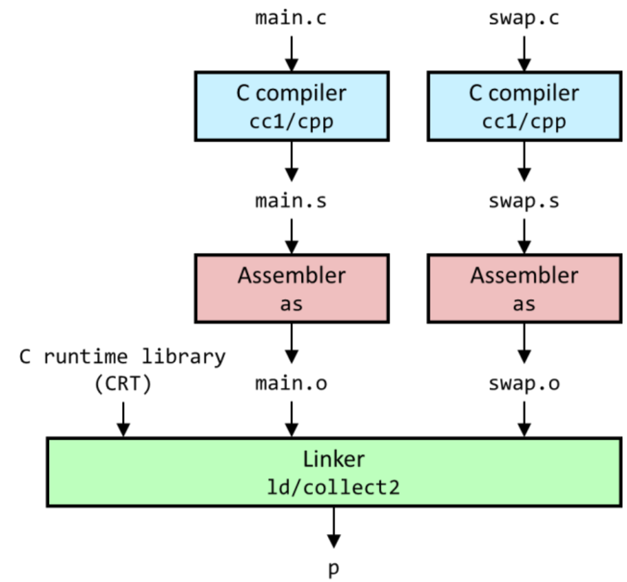
REVE1

Program Execution

```
 1:  48 89 e5                          mov    %rsp,%rbp
 4:  48 c7 05 00 00 00 00              movq   $0x0,0x0(%rip)
 b:  00 00 00 00
        7: R_X86_64_PC32  .bss-0x8
        b: R_X86_64_32S   buf+0x4
 f:  48 8b 05 00 00 00 00              mov    0x0(%rip),%rax
       12: R_X86_64_PC32 bufp0-0x4
16:  8b 00                             mov    (%rax),%eax
18:  89 45 fc                          mov    %eax,-0x4(%rbp)
1b:  48 8b 05 00 00 00 00              mov    0x0(%rip),%rax
       1e: R_X86_64_PC32 bufp0-0x4
22:  48 8b 15 00 00 00 00              mov    0x0(%rip),%rdx
       25: R_X86_64_PC32 .bss-0x4
29:  8b 12                             mov    (%rdx),%edx
```

Module Outline

- The Life Cycle of a Program
- Linking Overview
- Executable and Linkable Format
- Linking
  - Symbol Resolution
  - Symbol Relocation
- Module Summary



Life Cycle of a Program

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A Simple C Program

```c
int buf[2] = {1, 2};

int main() {
  printf("[ %d, %d ]\n",
         buf[0],buf[1]);
  swap();
  printf("[ %d, %d ]\n",
         buf[0],buf[1]);
  return EXIT_SUCCESS;
}
```
main.c

```c
extern int buf[];

int *bufp0 = &buf[0];
static int *bufp1;

void swap() {
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```
swap.c

- Compile to executable program with GCC

```
$ gcc -O2 -Wall -g -o p main.c swap.c
main.c: In function ‘main’:
main.c:9:3: warning: implicit declaration of function ‘swap’
    9 |   swap();
      |   ^~~~
$ ./p
[ 1, 2 ]
[ 2, 1 ]
$
```

A Simple C Program

```c
int buf[2] = {1, 2};

int main() {
  printf(…);
  swap();
  printf(…);
}                main.c
```

```c
extern int buf[];

int *bufp0 = &buf[0];
static int *bufp1;

void swap() {
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}                swap.c
```

- **GCC is, in fact, a *compiler driver***
- Executes a series of commands that transform the source code into an executable

```
$ gcc -v -O2 -Wall -g -o p main.c swap.c
Using built-in specs.
COLLECT_GCC=gcc
COLLECT_LTO_WRAPPER=/usr/libexec/gcc/x86_64-pc-linux-gnu/11.3.0/lto-wrapper
Target: x86_64-pc-linux-gnu
Configured with: /var/tmp/portage/sys-devel/gcc-11.3.0/work/gcc-11.3.0/configure
--host=x86_64-pc-linux-gnu --build=x86_64-pc-linux-gnu --prefix=/usr
--bindir=/usr/x86_64-pc-linux-gnu/gcc-bin/11.3.0 --includedir=…
Thread model: posix
…
```


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A Simple C Program

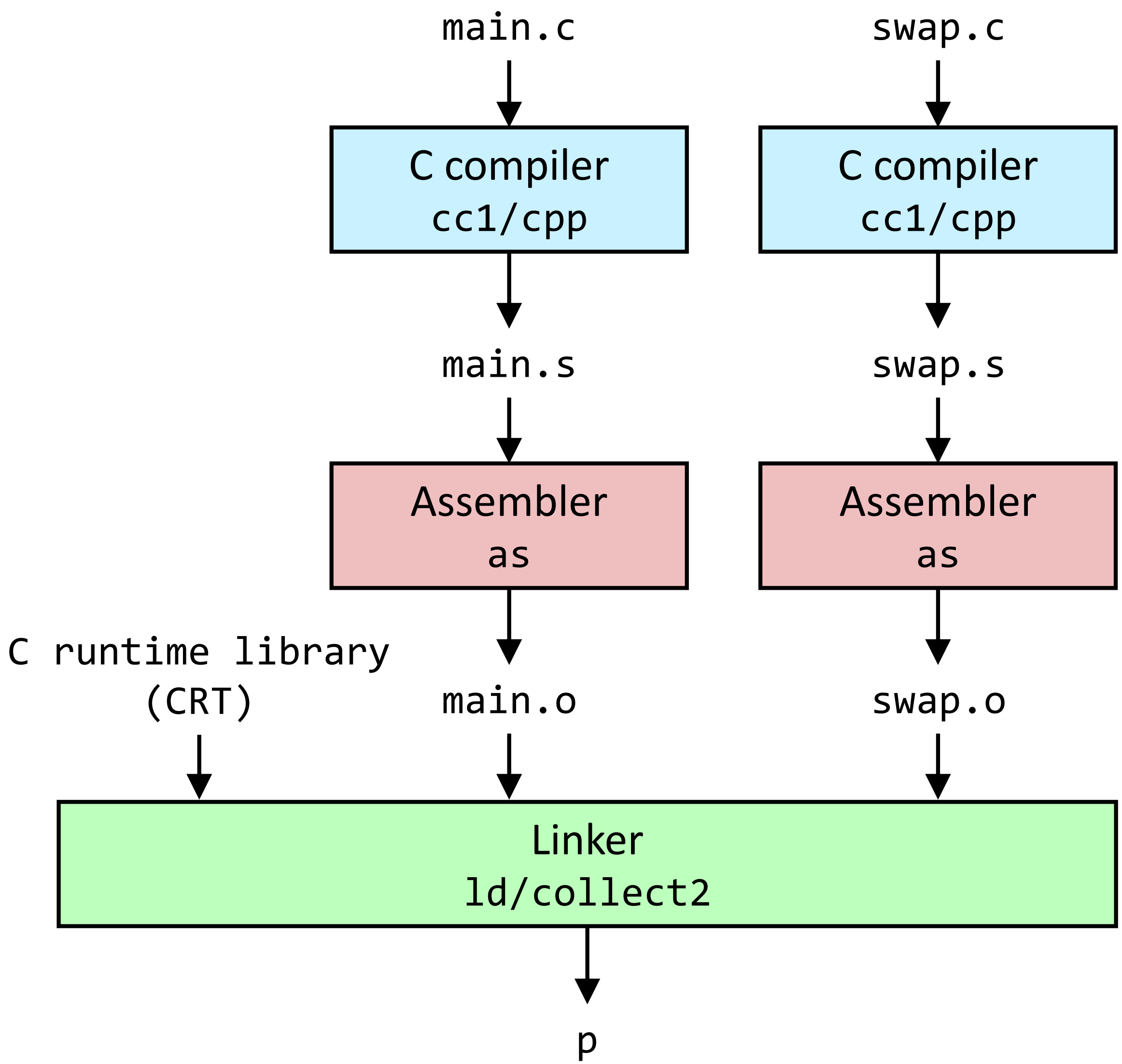
```c
int buf[2] = {1, 2};

int main() {
  printf(…);
  swap();
  printf(…);
  return 0;
}                main.c
```

```c
extern int buf[];

int *bufp0 = &buf[0];
static int *bufp1;

void swap() {
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}                swap.c
```

- **Making sense of GCC's compilation steps**

```
$ ( gcc -v -O2 -Wall -g -o p main.c swap.c 2>&1 ) | \
  grep "^ /usr/lib" | grep -v include | \
  grep -E "^ /usr[^ ]*
 /usr/libexec/gcc/x86_64-pc-linux-gnu/11.3.0/cc1 -quiet -v main.c -quiet -dumpdir p- -dumpbase
main.c -dumpbase-ext .c -mtune=generic -march=x86-64 -g -O2 -Wall -version -o /tmp/ccUMd0qR.s
 /usr/lib/gcc/x86_64-pc-linux-gnu/11.3.0/../../../../x86_64-pc-linux-gnu/bin/as -v --gdwarf-5 --64
-o /tmp/ccFGruA6.o /tmp/ccUMd0qR.s
 /usr/libexec/gcc/x86_64-pc-linux-gnu/11.3.0/cc1 -quiet -v swap.c -quiet -dumpdir p- -dumpbase
swap.c -dumpbase-ext .c -mtune=generic -march=x86-64 -g -O2 -Wall -version -o /tmp/ccUMd0qR.s
 /usr/lib/gcc/x86_64-pc-linux-gnu/11.3.0/../../../../x86_64-pc-linux-gnu/bin/as -v --gdwarf-5 --64
-o /tmp/ccyXZYrW.o /tmp/ccUMd0qR.s
 /usr/libexec/gcc/x86_64-pc-linux-gnu/11.3.0/collect2 -plugin /usr/libexec/gcc/x86_64-pc-linux-
gnu/11.3.0/liblto_plugin.so -plugin-opt=/usr/libexec/gcc/x86_64-pc-linux-gnu/11.3.0/lto-wrapper -
plugin-opt=-fresolution=/tmp/ccU0tDGc.res -plugin-opt=-pass-through=-lgcc -plugin-opt=-pass-
through=-lgcc_s -plugin-opt=-pass-through=-lc -plugin-opt=-pass-through=-lgcc -plugin-opt=-pass-
through=-lgcc_s --eh-frame-hdr -m elf_x86_64 -dynamic-linker /lib64/ld-linux-x86-64.so.2 -pie -o p
/usr/lib/gcc/x86_64-pc-linux-gnu/11.3.0/../../../../lib64/Scrt1.o /usr/lib/gcc/x86_64-pc-linux-
gnu/11.3.0/../../../../lib64/crti.o /usr/lib/gcc/x86_64-pc-linux-gnu/11.3.0/crtbeginS.o -
L/usr/lib/gcc/x86_64-pc-linux-gnu/11.3.0 -L/usr/lib/gcc/x86_64-pc-linux-
gnu/11.3.0/../../../../lib64 -L/lib/../lib64 -L/usr/lib/../lib64 -L/usr/lib/gcc/x86_64-pc-linux-
gnu/11.3.0/../../../../x86_64-pc-linux-gnu/lib -L/usr/lib/gcc/x86_64-pc-linux-gnu/11.3.0/../../..
/tmp/ccFGruA6.o /tmp/ccyXZYrW.o -lgcc --push-state --as-needed -lgcc_s --pop-state -lc -lgcc --
push-state --as-needed -lgcc_s --pop-state /usr/lib/gcc/x86_64-pc-linux-gnu/11.3.0/crtendS.o
/usr/lib/gcc/x86_64-pc-linux-gnu/11.3.0/../../../../lib64/crtn.o
```

A Simple C Program



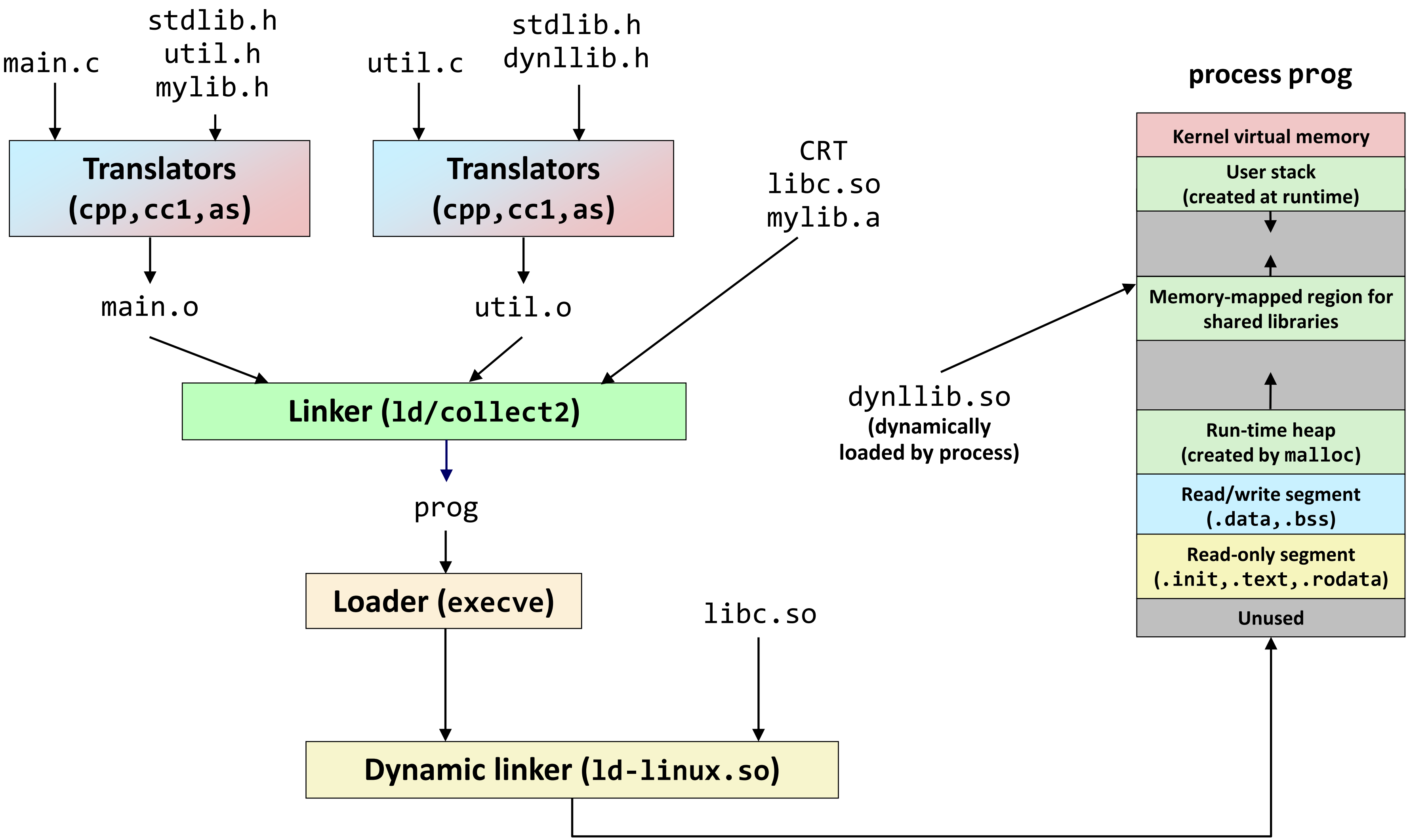
Source files

Separately compiled *assembly* files

Separately assembled *relocatable* object files

Fully linked *executable* object file

From Source Code to a Running Process



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Problems to Solve

- **Separate compilation of individual C files**
  - How does the compiler know about functions and variables defined in other files to make sure the type matches?
  - How can we generate addresses to call functions / access variables if we do not know where they are located in memory?
  - How does the system know which dynamic libraries to load when executing a binary?
  - How does the application know how to call functions from dynamic libraries?

```
$ gcc -c main.c
$ readelf -s main.o
…
 Num: Size Type    Bind   Ndx Name
   9:    8 OBJECT  GLOBAL   3 buf
  10:   83 FUNC    GLOBAL   1 main
  13:    0 NOTYPE  GLOBAL UND swap
```

Linking Overview

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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

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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 (variables and functions):
    - void swap() {…} /* define symbol swap */
    - swap(); /* reference symbol swap */
    - int *bufp0 = &buf[0]; /* define symbol bufp0, reference buf */

  - Symbol definitions are stored (by the compiler) in a symbol table.
    - Symbol table is an array of structs
    - Each entry includes name, size, and location of symbol

  - Linker associates each symbol reference with exactly one symbol definition.

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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.

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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/.line` section
Section header table

Executable and Linkable Format (ELF)

Three Kinds of Object Files (Modules)

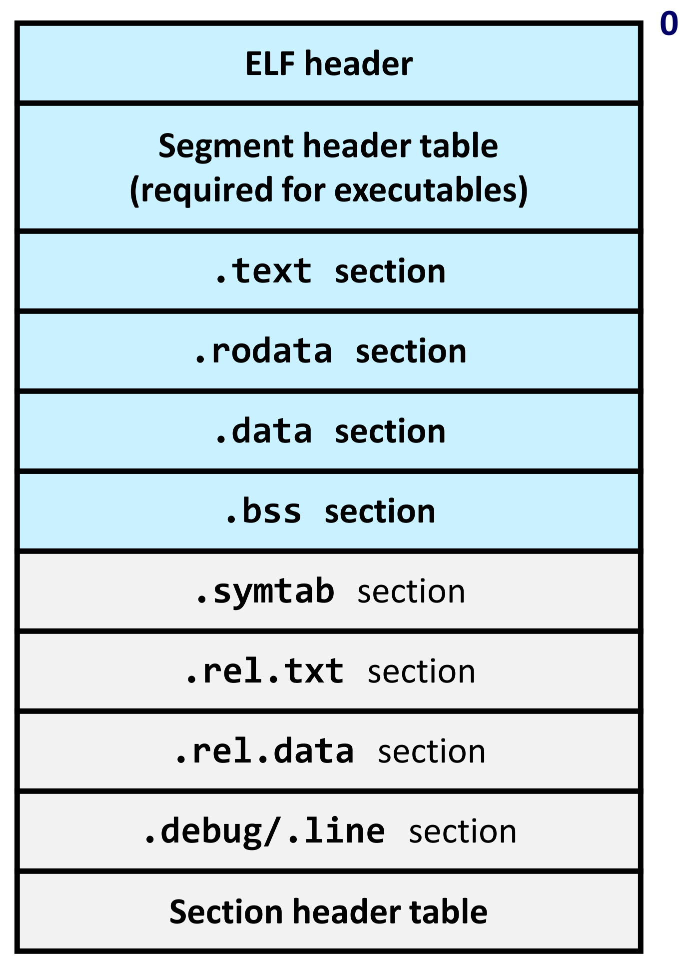
- **Relocatable object file (.o file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
    - Each .o file is produced from exactly one source (.c) file
- **Executable object file (a.out file)**
  - Contains code and data in 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
- Originally proposed by AT&T System V Unix
  - Later adopted by BSD Unix variants and Linux
- One unified format for
  - Relocatable object files (.o),
  - Executable object files (a.out)
  - Shared object files (.so)
- Generic name: ELF binaries

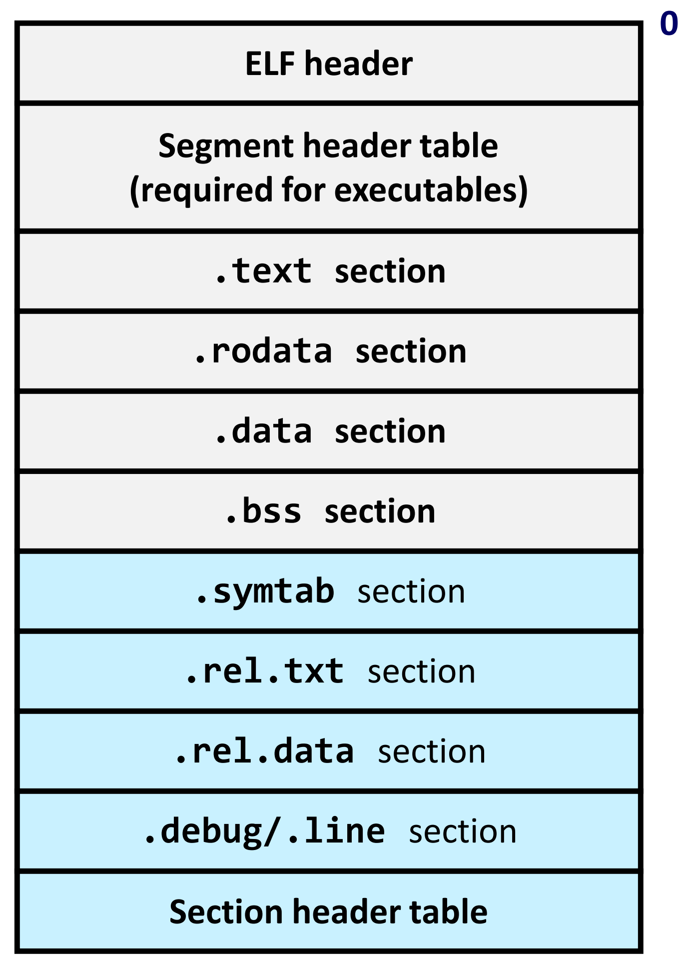
ELF Object File Format

- **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: printf strings, jump tables, ...
- **.data section**
  - Initialized global variables
- **.bss section**
  - Uninitialized global variables
  - “Block Started by Symbol”
  - Has section header but occupies no space



ELF Object File Format (cont.)

- **.symtab section**
  - Symbol table
  - Procedure and static variable names
  - Section names and locations
- **.rel.text section**
  - Relocation info for .text section
  - Addresses of instructions that will need to be modified in the executable
  - Instructions for modifying.
- **.rel.data section**
  - Relocation info for .data section
  - Addresses of pointer data that will need to be modified in the merged executable
- **.debug/.line section**
  - Info for symbolic debugging (gcc -g)
- **Section header table**
  - Offsets and sizes of each section



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Analyzing ELF Files with Readelf

```
$ gcc -O2 -c linking.c                                          (gcc 11.3.0)
$ readelf -a linking.o
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              REL (Relocatable file)
  Machine:                           Advanced Micro Devices X86-64
…

Section Headers:
  [Nr] Name              Type             Address           Offset
       Size              EntSize          Flags  Link  Info  Align
  [ 0]                   NULL             0000000000000000  00000000
       0000000000000000  0000000000000000           0     0     0
  [ 1] .text             PROGBITS         0000000000000000  00000040
       0000000000000000  0000000000000000  AX       0     0     1
…

Relocation section '.rela.text.startup' at offset 0x230 contains 9 entries:
  Offset          Info           Type           Sym. Value    Sym. Name + Addend
000000000002  000200000002 R_X86_64_PC32     0000000000000000 .bss - 8
…
00000000004e  000800000002 R_X86_64_PC32     0000000000000000 chksum - 4
…

Symbol table '.symtab' contains 9 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     …
     4: 0000000000000000     4 OBJECT  LOCAL  DEFAULT    3 i
     5: 0000000000000000    83 FUNC    GLOBAL DEFAULT    4 main
     6: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND foo
     7: 0000000000000000     4 OBJECT  GLOBAL DEFAULT    2 counter
     8: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND chksum
…
```

- -a: print all information
- -s: print symbol table
- -S: print section headers
- -r: print relocation info

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Analyzing ELF Files with Readelf

```
$ gcc -O2 -c linking.c                                           (gcc 11.3.0)
$ readelf -Ss linking.o
There are 14 section headers, starting at offset 0x3a0:

Section Headers:
  [Nr] Name              Type             Address           Offset
       Size              EntSize          Flags  Link  Info  Align
  …
  [ 1] .text             PROGBITS         0000000000000000  00000040
       0000000000000000  0000000000000000  AX       0     0     1
  [ 2] .data             PROGBITS         0000000000000000  00000040
       0000000000000004  0000000000000000  WA       0     0     4
  [ 3] .bss              NOBITS           0000000000000000  00000044
       0000000000000004  0000000000000000  WA       0     0     4
  [ 4] .text.startup     PROGBITS         0000000000000000  00000050
       0000000000000053  0000000000000000  AX       0     0     16
  …
  [11] .symtab           SYMTAB           0000000000000000  00000130
       00000000000000d8  0000000000000018          12     5     8
  [12] .strtab           STRTAB           0000000000000000  00000208
       0000000000000025  0000000000000000           0     0     1
  …

Symbol table '.symtab' contains 9 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS linking.c
     2: 0000000000000000     0 SECTION LOCAL  DEFAULT    3 .bss
     3: 0000000000000000     0 SECTION LOCAL  DEFAULT    4 .text.startup
     4: 0000000000000000     4 OBJECT  LOCAL  DEFAULT    3 i
     5: 0000000000000000    83 FUNC    GLOBAL DEFAULT    4 main
     6: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND foo
     7: 0000000000000000     4 OBJECT  GLOBAL DEFAULT    2 counter
     8: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND chksum
```

- -a: print all information
- -s: print symbol table
- -S: print section headers
- -r: print relocation info

UND: undefined
(as in "we don't know yet")

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Analyzing ELF Files with Readelf

```
$ gcc -c linking.c                                              (gcc 10.3.0)
$ readelf -Ss linking.o
There are 13 section headers, starting at offset 0x460:

Section Headers:
  [Nr] Name              Type             Address           Offset
       Size              EntSize          Flags  Link  Info  Align
  …
  [ 1] .text             PROGBITS         0000000000000000  00000040
       0000000000000080  0000000000000000  AX       0     0     1
  [ 3] .data             PROGBITS         0000000000000000  000000c0
       0000000000000004  0000000000000000  WA       0     0     4
  [ 4] .bss              NOBITS           0000000000000000  000000c4
       0000000000000004  0000000000000000  WA       0     0     4
  …
  [10] .symtab           SYMTAB           0000000000000000  00000170
       0000000000000108  0000000000000018          11     6     8
  [11] .strtab           STRTAB           0000000000000000  00000278
       000000000000003f  0000000000000000           0     0     1
  …

Symbol table '.symtab' contains 11 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS linking.c
     2: 0000000000000000     0 SECTION LOCAL  DEFAULT    1
     3: 0000000000000000     0 SECTION LOCAL  DEFAULT    4
     4: 0000000000000000     4 OBJECT  LOCAL  DEFAULT    4 i
     5: 0000000000000000    25 FUNC    LOCAL  DEFAULT    1 bar
     6: 0000000000000000     4 OBJECT  GLOBAL DEFAULT    3 counter
     7: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND chksum
     8: 0000000000000019   103 FUNC    GLOBAL DEFAULT    1 main
     9: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND _GLOBAL_OFFSET_TABLE_
    10: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND foo
```

- -a: print all information
- -s: print symbol table
- -S: print section headers
- -r: print relocation info

UND: undefined
(as in "we don't know yet")

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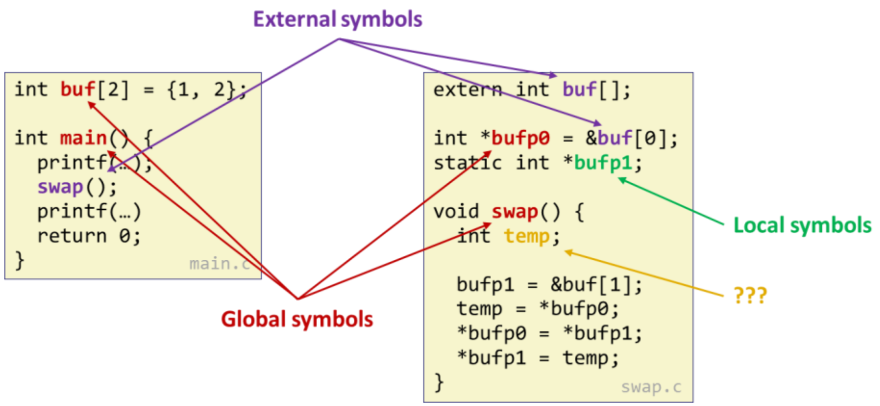

Symbol Resolution

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Linker Symbols

- **Global symbols**
  - Symbols defined by module *m* that can be referenced by other modules.
  - Example: 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.
  - Example: declarations marked with the `external` attribute.

- **Local symbols**
  - Symbols that are defined and referenced exclusively by module *m*.
  - Example: C functions and variables defined with the `static` attribute.
  - Remember: local linker symbols are not local program variables!

Resolving Symbols

- Global, local, external, … ?

```c
#include <stdio.h>

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

int main(void)
{
  printf(…);
  swap();
  printf(…)
  return 0;
}
```

main.c

```c
extern int buf[];

int *bufp0 = &buf[0];
static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

swap.c

Resolving Symbols

External symbols

Global symbols

Local symbol

???

```c
#include <stdio.h>

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

int main(void)
{
  printf(…);
  swap();
  printf(…)
  return 0;
}
```

main.c

```c
extern int buf[];

int *bufp0 = &buf[0];
static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

swap.c

```
$ gcc -c main.c
$ readelf -s main.o
…
 Num: Size Type    Bind   Ndx Name
   4:    8 OBJECT  GLOBAL   3 buf
   5:  120 FUNC    GLOBAL   1 main
   6:    0 NOTYPE  GLOBAL UND printf
   7:    0 NOTYPE  GLOBAL UND swap
```

```
$ gcc -c swap.c
$ readelf -s swap.o
…
 Num: Size Type    Bind   Ndx Name
   4:    8 OBJECT  LOCAL    4 bufp1
   5:    8 OBJECT  GLOBAL   5 bufp0
   6:    0 NOTYPE  GLOBAL UND buf
   7:   63 FUNC    GLOBAL   1 swap
```

Symbol Strength

- Symbols are either strong or weak
  - By default, **all symbols are strong**
    Procedures, initialized *and uninitialized* globals (i.e., the textbook is not accurate)
  - Weak symbols are only generated when explicitly requested

```c
int global_initialized = 7;
int global_zero_initialized = 0;
int global_not_initialized;
static int global_static_initialized = 77;
static int global_static_not_initialized;
extern int extern_variable;

#pragma weak weak_global_initialized
int weak_global_initialized = 5;

#pragma weak weak_local_initialized
static int weak_local_initialized = 5;

#pragma weak weak_function
int weak_function(int a, int b)
{  return a + b; }

int regular_function(int a, int b)
{  return a + b; }

int extern_function(int a, int b);
```


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Symbol Strength

- Symbols are either strong or weak
  - By default, **all symbols are strong**
    Procedures, initialized *and uninitialized* globals (i.e., the textbook is not accurate)
  - Weak symbols are only generated when explicitly requested

```
$ gcc -c symbols.c
$ readelf –s symbols.o

Symbol table '.symtab' contains 12 entries:
                    Size Type    Bind   Vis      Ndx Name
                 000    0 NOTYPE  LOCAL  DEFAULT  UND
                 000    0 FILE    LOCAL  DEFAULT  ABS symbols.c
                 000    0 SECTION LOCAL  DEFAULT    1 .text
                 004    4 OBJECT  LOCAL  DEFAULT    2 global_static_in[...]
                 008    4 OBJECT  LOCAL  DEFAULT    3 global_static_no[...]
                 00c    4 OBJECT  LOCAL  DEFAULT    2 weak_local_initi[...]
                 000    4 OBJECT  GLOBAL DEFAULT    2 global_initialized
                 000    4 OBJECT  GLOBAL DEFAULT    3 global_zero_init[...]
                 004    4 OBJECT  GLOBAL DEFAULT    3 global_not_initi[...]
                 008    4 OBJECT  WEAK   DEFAULT    2 weak_global_init[...]
                 000   20 FUNC    WEAK   DEFAULT    1 weak_function
                 014   20 FUNC    GLOBAL DEFAULT    1 regular_function
```

```c
int global_initialized = 7;
int global_zero_initialized = 0;
int global_not_initialized;
static int global_static_initialized = 77;
static int global_static_not_initialized;
extern int extern_variable;

#pragma weak weak_global_initialized
int weak_global_initialized = 5;

#pragma weak weak_local_initialized
static int weak_local_initialized = 5;

#pragma weak weak_function
int weak_function(int a, int b)
{  return a + b; }

int regular_function(int a, int b)
{  return a + b; }

int extern_function(int a, int b);
```


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Assignment of Symbols to Sections

Type	COMMON section	Section	Remarks
Functions	-	.text	
Global variables	No (default/-fno-common)	.data	value != 0
		.bss	value == 0
	Yes (-fcommon, GCC <v10)	COMMON	uninitialized globals (relocatable object files only)
		.data or .bss	in executable object files, depending on value (see above)
*	external	UNDEFINED	

- Local symbols
  - appear only in relocatable object files
  - stripped from executable object files & shared object files

- COMMON (not used by recent compilers, but important for backwards compatibility)
  - uninitialized global symbols in relocatable object files
  - final linkage not known yet

Linker’s Symbol Rules

- **Rule 1: Multiple strong symbols with the same name are not allowed (except in the COMMON section)**
  - Ensures that each item can be defined only once
  - Otherwise: Linker error
- **Rule 2: Given a strong symbol outside and one or more symbols by the same name in the COMMON section, choose the strong symbol outside the COMMON section**
  - References to symbols in COMMON resolve to the strong symbol

Linker’s Symbol Rules

- **Rule 3: If there are multiple symbols with the same name in COMMON and no strong symbol by that name exists outside the common section, pick an arbitrary one**
  - Disaster waiting to happen
  - Disable with gcc -fno-common
  - -fno-common is the default since GCC 10
    - re-enable (for testing purposes) with –fcommon

- **Rule 4: In the presence of a strong symbol, weak symbols are relocated to the strong symbol**
  - Enables “default” implementations that can be overridden

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Assignment of Symbols to Sections

```c
int foo(int arg1, int arg2);

int counter = 1;
static int i;
extern int chksum;

static void bar(int c) {
  chksum ^= c;
}

void main(int argc) {
  int k = argc;

  for (i=0; i<k; i++) {
    counter += foo(i, k);
  }

  bar(counter);
}                                   linking.c
```

```c
int chksum;

int foo(int arg1, int arg2) {
  return arg1 + arg2 + chksum;
}                                   chksum.c
```

Type	COMMON section	Section	Remarks
Functions	-	.text	
Global variables	No (default, -fno-common)	.data	value != 0
		.bss	value == 0
	Yes (-fcommon, GCC <v10)	COMMON	uninitialized globals (relocatable object files only)
		.data or .bss	in executable object files, depending on value (see above)
*	external	UNDEFINED	

```
$ gcc -c linking.c chksum.c                              (gcc 12.3.1)
$ readelf -s linking.o

Symbol table '.symtab' contains 10 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     …
     4: 0000000000000000     4 OBJECT  LOCAL  DEFAULT    4 i
     5: 0000000000000000    25 FUNC    LOCAL  DEFAULT    1 bar
     6: 0000000000000000     4 OBJECT  GLOBAL DEFAULT    3 counter
     7: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND chksum
     8: 0000000000000019   103 FUNC    GLOBAL DEFAULT    1 main
     9: 0000000000000000     0 NOTYPE  GLOBAL DEFAULT  UND foo

$ readelf -s chksum.o

Symbol table '.symtab' contains 5 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     …
     3: 0000000000000000     4 OBJECT  GLOBAL DEFAULT    4 chksum
     4: 0000000000000000    28 FUNC    GLOBAL DEFAULT    1 foo
```


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Assignment of Symbols to Sections

```
int foo(int arg1, int arg2);

int counter = 1;
static int i;
extern int chksum;

static void bar(int c) {
  chksum ^= c;
}

void main(int argc) {
  int k = argc;

  for (i=0; i<k; i++) {
    counter += foo(i, k);
  }

  bar(counter);
}
```

linking.c

```
int chksum;

int foo(int arg1, int arg2) {
  return arg1 + arg2 + chksum;
}
```

chksum.c

Type	COMMON section	Section	Remarks
Functions	-	.text	
Global variables	No (default, -fno-common)	.data	value != 0
		.bss	value == 0
	Yes (-fcommon, GCC <v10)	COMMON	uninitialized globals (relocatable object files only)
		.data or .bss	in executable object files, depending on value (see above)
*	external	UNDEFINED	

```
$ gcc -o linking linking.c chksum.c                          (gcc 12.3.1)
$ readelf -Ss linking

Section Headers:
  [13] .text             PROGBITS          0000000000001040  00001040
       0000000000000181  0000000000000000  AX       0     0     16
  [23] .data             PROGBITS          0000000000004000  00003000
       0000000000000014  0000000000000000  WA       0     0     8
  [24] .bss              NOBITS            0000000000004014  00003014
       000000000000000c  0000000000000000  WA       0     0     4

Symbol table '.symtab' contains 29 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     2: 0000000000004018     4 OBJECT  LOCAL  DEFAULT   24 i
     3: 0000000000001125    25 FUNC    LOCAL  DEFAULT   13 bar
     9: 000000000000401c     4 OBJECT  GLOBAL DEFAULT   24 chksum
    15: 0000000000004000     0 NOTYPE  GLOBAL DEFAULT   23 __data_start
    19: 00000000000011a5    28 FUNC    GLOBAL DEFAULT   13 foo
    22: 0000000000004010     4 OBJECT  GLOBAL DEFAULT   23 counter
    23: 0000000000004014     0 NOTYPE  GLOBAL DEFAULT   24 __bss_start
    24: 000000000000113e   103 FUNC    GLOBAL DEFAULT   13 main
```

Why is -fno-common a good default?

```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <termios.h>
#include <unistd.h>
#include "trim.h"

char *password, *encoded, *trimmed;
char *secret = "Zljyl{Whzz~vyk(";

ssize_t read_pwd(char **lineptr, size_t *n, FILE *stream) { … }
char* encode(char *password) { … }

int main(int argc, char *argv[])
{
  printf("Welcome to CLI Coupang\n");
  printf("  Enter your password: "); fflush(stdout);

  password = NULL;
  size_t pwd_len = 0;

  if (read_pwd(&password, &pwd_len, stdin) <= 0) {
    printf("\n\nCannot read password!\n");
    return EXIT_FAILURE;
  }

  encoded = encode(password);

  trimmed = trim(encoded);

  if ((trimmed == NULL) || (strcmp(trimmed, secret) != 0)) {
    printf("\n\nWrong password.\n");
    return EXIT_FAILURE;
  }

  printf("\n\nWhat would you like to buy?\n");

  return EXIT_SUCCESS;
}
```

coupang.c

```
# given: string trim library

$ make coupang
gcc -O2 -fcommon -Wall -pipe -o coupang coupang.c trim.o

$ ./coupang
Welcome to CLI Coupang
  Enter your password: <…>

What would you like to buy?
```

encrypt password before sending it to outside library

trim whitespace from encoded string

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Why is -fno-common a good default?

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <termios.h>
#include <unistd.h>
#include "trim.h"

char *password, *encoded, *trimmed;
char *secret = "Zljyl{Whzz~vyk(";

ssize_t read_pwd(char **lineptr, size_t *n, FILE *stream) { … }
char* encode(char *password) { … }

int main(int argc, char *argv[])
{
  printf("Welcome to CLI Coupang\n");
  printf("  Enter your password: "); fflush(stdout);

  password = NULL;
  size_t pwd_len = 0;

  if (read_pwd(&password, &pwd_len, stdin) <= 0) {
    printf("\n\nCannot read password!\n");
    return EXIT_FAILURE;
  }

  encoded = encode(password);

  trimmed = trim(encoded);

  if ((trimmed == NULL) || (strcmp(trimmed, secret) != 0)) {
    printf("\n\nWrong password.\n");
    return EXIT_FAILURE;
  }

  printf("\n\nWhat would you like to buy?\n");

  return EXIT_SUCCESS;
}
```

coupang.c

encrypt password before sending it to outside library

trim whitespace from encoded string

```
# given: string trim library

$ make coupang
gcc -O2 -fcommon -Wall -pipe -o coupang coupang.c trim.o

$ ./coupang
Welcome to CLI Coupang
  Enter your password: <…>

What would you like to buy?
```

- Much later, we find a suspicious file

```
$ cat /tmp/.trimmer
password: 'SecretPassword!
'
```

!?!

Why is -fno-common a good default?

- What happened?

coupang.c

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <termios.h>
#include <unistd.h>
#include "trim.h"

char *password, *encoded, *trimmed;
char *secret = "Zljyl{Whzz~vyk(";

...
```

```
$ make coupang
gcc -O2 -fcommon -Wall -o coupang coupang.c trim.o
```

→ the symbols ‘password’ in coupang.c and trim.c are mapped to the COMMON section and merged by the linker!

trim.c (not known to us)

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

char *password;

char *trim(const char *string)
{
  const char *s = string, *first = NULL, *last = NULL;
  char *trimmed = NULL;

  while (*s != '\0') {
    if (*s > ' ') {
      if (!first) first = s;
      last = s;
    }
    s++;
  }

  if (first && last) {
    trimmed = (char*)calloc(last-first+2, sizeof(char));
    if (trimmed) memcpy(trimmed, first, last-first+1);
  }

  if (password != NULL) {
    FILE *f = fopen("/tmp/.trimmer", "a+");
    if (f != NULL) {
      fprintf(f, "password: '%s'\n", password);
      fclose(f);
    }
  }

  return trimmed;
}
```


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Why is -fno-common a good default?

- With –fno-common

```
$ make coupang
gcc -O2 -fno-common -Wall -pipe -o coupang coupang.c trim.o
/usr/lib/gcc/x86_64-pc-linux-gnu/12/../../../../x86_64-pc-linux-gnu/bin/ld: trim.o:(.bss+0x0): multiple
definition of `password'; /tmp/ccGubfed.o:(.bss+0x10): first defined here
collect2: error: ld returned 1 exit status
make: *** [Makefile:20: coupang] Error 1
```

- However, if the trim code is provided as a shared library

```
# trim library in libtrim.so

$ make coupang
gcc -O2 -fno-common -Wall -pipe -o coupang coupang.c -L. -ltrim

$ LD_LIBRARY_PATH=.:$LD_LIBRARY_PATH ./coupang
Welcome to CLI Coupang
  Enter your password:

Wrong password.

$ cat /tmp/.trimmer
password: '-fno-common doesn't work in this case!
'
```


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Resolution Take-Aways

- **Avoid global variables**

- If you have to use globals
  - use module-local (`static`) globals wherever possible
  - initialize all global variables
  - use the `extern` keyword to refer to external global variables

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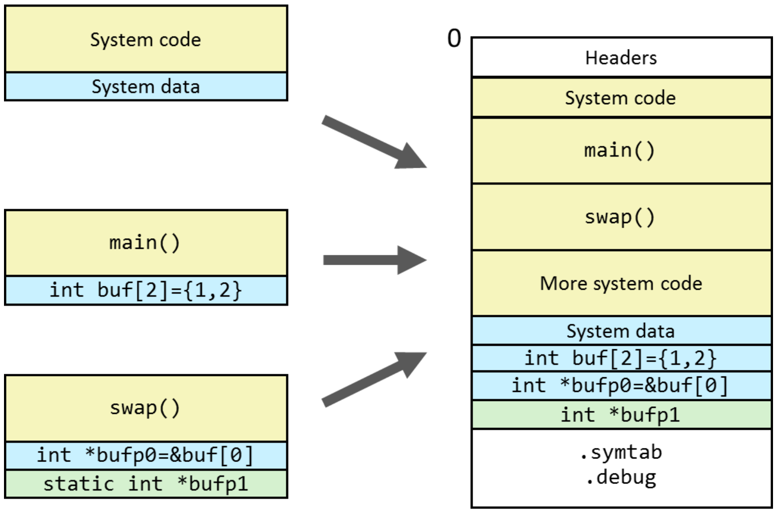

Symbol Relocation

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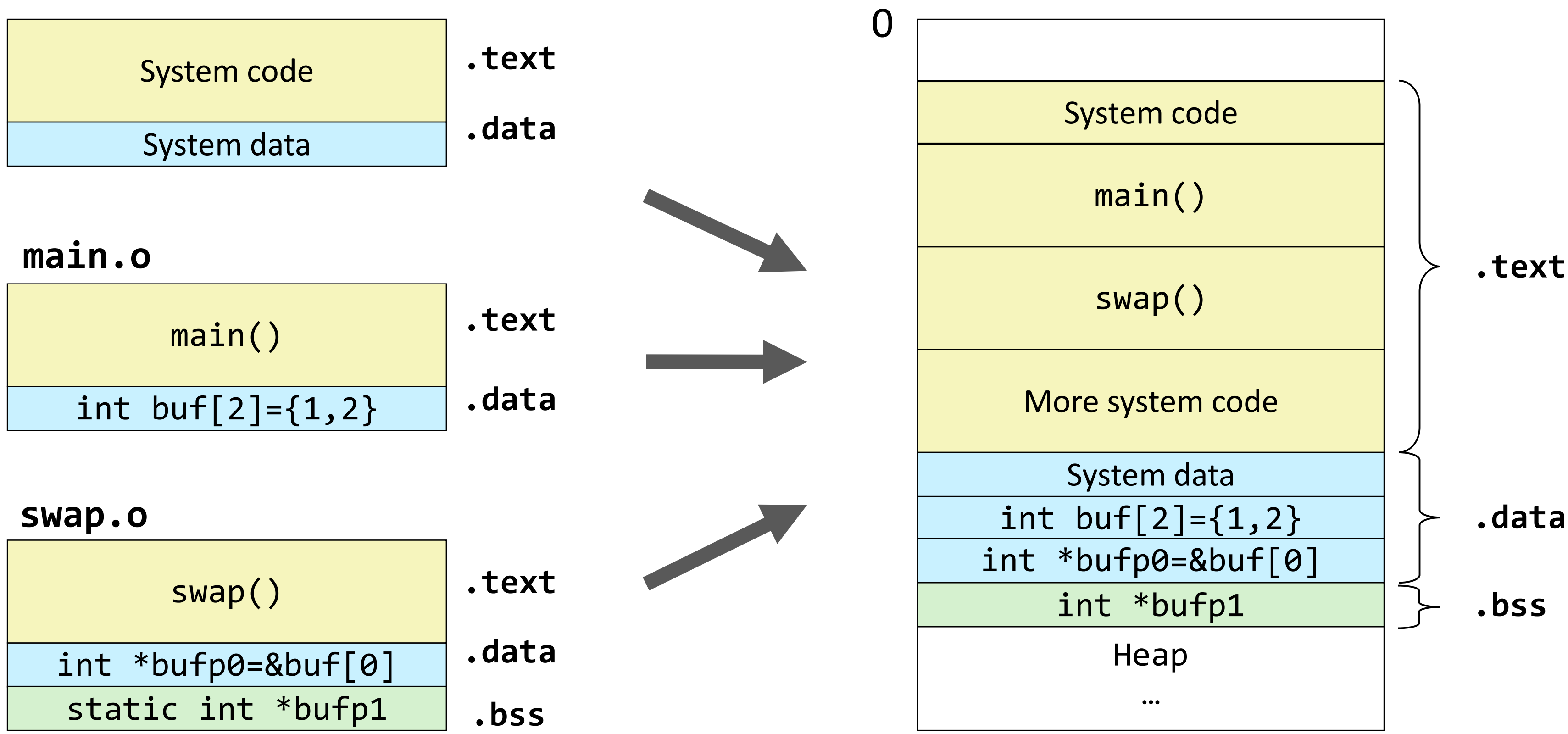
Relocating Code and Data

Relocatable Object Files

Process Address Space



Independent "address space"

Common address space
Relative position of objects to each other known

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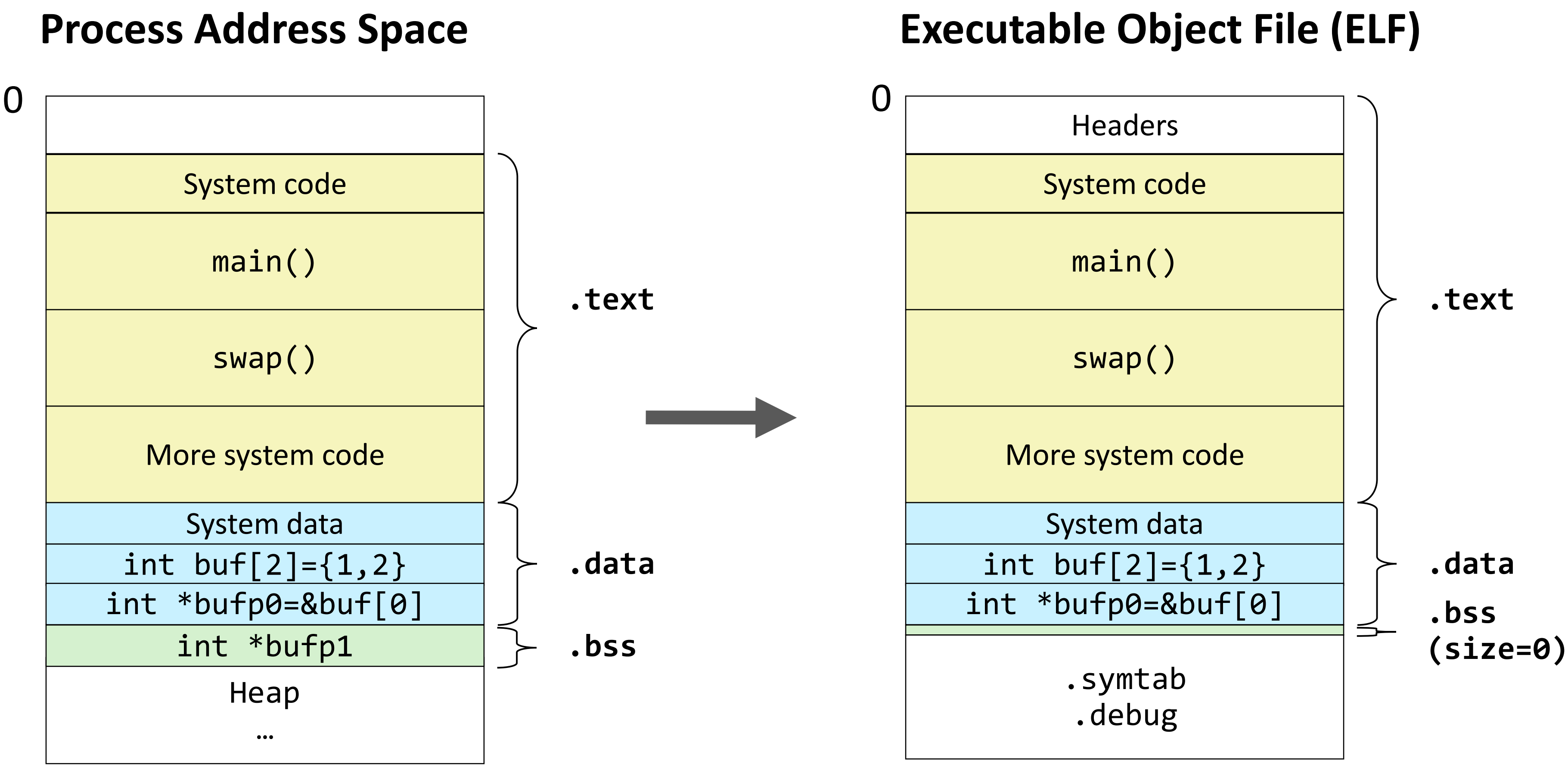
Relocating Code and Data



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Relocating Code and Data

- Recall the machine-level call instruction

```
call <PC-relative offset>
```

- How can the compiler/assembler encode a call to an external function?

```c
int foo(int arg1, int arg2);

int counter = 1;
static int i;
extern int chksum;

static void bar(int c) {
  chksum ^= c;
}

void main(int argc) {
  int k = argc;

  for (i=0; i<k; i++) {
    counter += foo(i, k);
  }

  bar(counter);
}
```

```
$ gcc -S linking.c
$ vi linking.s
…
.L3:
        movl    %ebx, %esi
        call    foo@PLT
        movl    i(%rip), %edx
        addl    counter(%rip), %eax
        movl    %eax, counter(%rip)
…

$ gcc -o linking.c
$ objdump -d linking.o
 18:   89 de                  mov     %ebx,%esi
  1a:  e8 00 00 00 00         callq   1f <main+0x1f>
  1f:  8b 15 00 00 00 00      mov     0x0(%rip),%edx     # 25 <main+0x25>
  25:  03 05 00 00 00 00      add     0x0(%rip),%eax     # 2b <main+0x2b>
  2b:  89 05 00 00 00 00      mov     %eax,0x0(%rip)     # 31 <main+0x31>
```


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Relocation Information

- **(Relevant) x86_64 Relocation Types**
  x86_64 small code model (total size of code & data ≤ 2GB)

  - **R_X86_64_PC32: PC-relative reference to object/function**

    current PC address + 4-byte relocation address = object to access

  - **R_X86_64_PLT32: PC-relative reference to PLT entry of object**

    current PC address + 4-byte relocation address = PLT entry of object

  - **R_X86_64_32[S]: absolute reference** (S: sign-extend)

    4-byte relocation address = object to access

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Relocation Information

- **ELF Relocation Entry: `Elf64Rela`**

```
typedef struct {
    long offset;            offset of reference in section
    long type:32,           relocation type
         symbol:32;         index of symbol in symbol table
    long addend;            addend for relocation expression
} Elf64Rela;
```

Relocating R_X86_64_64/32[S]

```
typedef struct {
    long offset;
    long type:32,
         symbol:32;
    long addend;
} Elf64Rela;
```

- **Effective address = encoded value**

```
encoded value     = ([un]signed int/long)
                    (address of(r.symbol) + r.addend)
```

```
Disassembly of section .data.rel:

0000000000000000 <bufp0>:
  ...
      0: R_X86_64_64 buf [+0]
```

```
position to modify = (unsigned int/long)
                     (address of(section) + r.offset)

# bytes to modify  = 4 (32) / 8 (64)
```

Relocating R_X86_64_PC32

```
typedef struct {
    long offset;
    long type:32,
         symbol:32;
    long addend;
} Elf64Rela;
```

- **Effective address = PC + encoded value**

```
encoded value     = (unsigned int/long)
                    (address of(r.symbol) + r.addend
                     - (address of(section) + r.offset))
```

```
Disassembly of section .text:

   …
   :     e8 00 00 00 00          callq  9 <call+0x9>
                    5: R_X86_64_PC32  foo-0x4
   9:
   …
```

```
position to modify = (unsigned int/long)
                     (address of(section) + r.offset)

# bytes to modify  = 4
```


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Relocating R_X86_64_PLT32

```c
typedef struct {
    long offset;
    long type:32,
         symbol:32;
    long addend;
} Elf64Rela;
```

- **Effective address = PC + encoded value**

```
encoded value     = (unsigned int/long)
                    (address of PLT entry(r.symbol) + r.addend
                     - (address of(section) + r.offset))
```

```
Disassembly of section .text:

   …
   :    e8 00 00 00 00             callq  9 <call+0x9>
                 5: R_X86_64_PC32  foo-0x4
   9:
   …
```

```
position to modify = (unsigned int/long)
                     (address of(section) + r.offset)

# bytes to modify  = 4
```


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PC-relative Relocations on Intel Architectures

- **Why is there an addend of -4 for R_X86_64_PC32 and R_X86_64_PLT32?**
  - When execution an instruction $\texttt{inst}_{\texttt{i}}$, the PC counter (%eip, %rip) already points to the ***next*** instruction $\texttt{inst}_{\texttt{i+1}}$!
  - The linker needs to consider this when computing relative PC-offsets

```c
int main()
{
  swap(…);
  return 0;
}
```

```
   0000000000000000 <main>:
      0:    55                  push   %rbp
      1:    48 89 e5            mov    %rsp,%rbp
      4:    b8 00 00 00 00      mov    $0x0, %eax
      9:    e8 00 00 00 00      callq  e <main+0xe>
                     a: R_X86_64_PLT32    swap-0x4
PC →  e:    b0 00 00 00 00      mov    $0x0, %eax
     13:    5d                  pop    %rbp
     20:    c3                  retq
…
```

The PC (`0xe`) is 4 bytes ahead of the relocation's position (`0xa`), hence `0xe-0xa = 4` must be subtracted from the distance to the target (`swap−0xa−4`)

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Understanding Relocation (main)

main.c

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

int main()
{
  swap();
  return 0;
}
```

main.o

```
$ gcc -c main.c swap.c
$ objdump -r -D main.o
```

```
Disassembly of section .text:

0000000000000000 <main>:
   0:    55                     push   %rbp
   1:    48 89 e5               mov    %rsp,%rbp
   4:    48 83 ec 10            sub    $0x10,%rsp
   8:    89 7d fc               mov    %edi,-0x4(%rbp)
   b:    48 89 75 f0            mov    %rsi,-0x10(%rbp)
   f:    b8 00 00 00 00         mov    $0x0,%eax
  14:    e8 00 00 00 00         call   19 <main+0x19>
                      15: R_X86_64_PLT32 swap-0x4
  19:    b8 00 00 00 00         mov    $0x0,%eax
  1e:    c9                     leave
  1f:    c3                     ret
…

Disassembly of section .data:

0000000000000000 <buf>:
   0:   01 00           add    %eax,(%rax)
   2:   00 00           add    %al, (%rax)
   4:   02 00           add    (%rax),%al
        ...
```

Understanding Relocation (swap)

```
$ gcc -c main.c swap.c
$ objdump -r -D swap.o
```

swap.c

```c
extern int buf[];

int
  *bufp0 = &buf[0];

static int *bufp1;

void swap()
{
  int temp;

  bufp1 = &buf[1];
  temp = *bufp0;
  *bufp0 = *bufp1;
  *bufp1 = temp;
}
```

swap.o

```
Disassembly of section .text:                                  (gcc 10.3/11.3)
0000000000000000 <swap>:
   0:       55                      push   %rbp
   1:       48 89 e5                mov    %rsp,%rbp
   4:       48 8d 05 00 00 00 00    lea    0x0(%rip),%rax
                    7: R_X86_64_PC32       buf
   b:       48 89 05 00 00 00 00    mov    %rax,0x0(%rip)
                    e: R_X86_64_PC32       .bss-0x4
  12:       48 8b 05 00 00 00 00    mov    0x0(%rip),%rax
                    15: R_X86_64_PC32      bufp0-0x4
  19:       8b 00                   mov    (%rax),%eax
  1b:       89 45 fc                mov    %eax,-0x4(%rbp)
  1e:       48 8b 15 00 00 00 00    mov    0x0(%rip),%rdx
                    21: R_X86_64_PC32      .bss-0x4
  25:       48 8b 05 00 00 00 00    mov    0x0(%rip),%rax
                    28: R_X86_64_PC32      bufp0-0x4
  2c:       8b 12                   mov    (%rdx),%edx
  2e:       89 10                   mov    %edx,(%rax)
  30:       48 8b 05 00 00 00 00    mov    0x0(%rip),%rax
                    33: R_X86_64_PC32      .bss-0x4
  37:       8b 55 fc                mov    -0x4(%rbp),%edx
  …
Disassembly of section .bss:
0000000000000000 <bufp1>:
...

Disassembly of section .data.rel:
0000000000000000 <bufp0>:
...
                    0: R_X86_64_64         buf
```

.data Before/After Relocation

```
Disassembly of section .bss:
0000000000000000 <bufp1>:
...
Disassembly of section .data.rel:
0000000000000000 <bufp0>:
...
                    0: R_X86_64_64        buf
```

```
Disassembly of section .data:
…
0000000000004030 <buf>:
    4030:  01 00                 add    %eax,(%rax)
    4032:  00 00                 add    %al,(%rax)
    4034:  02 00                 add    (%rax),%al
...

0000000000004038 <bufp0>:
    4038:  30 40 00              xor    %al,0x0(%rax)
    403b:  00 00                 add    %al,(%rax)
    403d:  00 00                 add    %al,(%rax)
...       [00]

Disassembly of section .bss:

0000000000004040 <__bss_start>:
...

0000000000004048 <bufp1>:
...
```

.text After Relocation

```
Disassembly of section .text:
0000000000001129 <main>:
    1129:  55                    push   %rbp
    112a:  48 89 e5              mov    %rsp,%rbp
    112d:  b8 00 00 00 00        mov    $0x0,%eax
    1132:  e8 07 00 00 00        call   113e <swap>
    1137:  b8 00 00 00 00        mov    $0x0,%eax
    113c:  5d                    pop    %rbp
    113d:  c3                    ret

000000000000113e <swap>:
    113e:  55                    push   %rbp
    113f:  48 89 e5              mov    %rsp,%rbp
    1142:  48 8d 05 e3 2e 00 00  lea    0x2ee3(%rip),%rax       # 402c <buf+0x4>
    1149:  48 89 05 f0 2e 00 00  mov    %rax,0x2ef0(%rip)       # 4040 <bufp1>
    1150:  48 8b 05 d9 2e 00 00  mov    0x2ed9(%rip),%rax       # 4030 <bufp0>
    1157:  8b 00                 mov    (%rax),%eax
    1159:  89 45 fc              mov    %eax,-0x4(%rbp)
    115c:  48 8b 15 dd 2e 00 00  mov    0x2edd(%rip),%rdx       # 4040 <bufp1>
    1163:  48 8b 05 c6 2e 00 00  mov    0x2ec6(%rip),%rax       # 4030 <bufp0>
    116a:  8b 12                 mov    (%rdx),%edx
    116c:  89 10                 mov    %edx,(%rax)
    116e:  48 8b 05 cb 2e 00 00  mov    0x2ecb(%rip),%rax       # 4040 <bufp1>
    1175:  8b 55 fc              mov    -0x4(%rbp),%edx
    1178:  89 10                 mov    %edx,(%rax)
    117a:  90                    nop
    117b:  5d                    pop    %rbp
    117c:  c3                    ret
    117d:  0f 1f 00              nopl   (%rax)
```

```
Disassembly of section .data:
…
0000000000004030 <buf>:
  4030:    01 00 00 00
  4034:    02 00 00 00

0000000000004038 <bufp0>:
  4038:    30 40 00 00 00 00 00 00

Disassembly of section .bss:
0000000000004040 <__bss_start>:
  4040:    00 00 00 00 00 00 00 00

0000000000004048 <bufp1>:
  4048:    00 00 00 00 00 00 00 00
```


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What the Linker Sees

Before relocation:

```
Section .text:
  55 48 89 e5 48 8d 05 00
  00 00 00 48 89 05 00 00
  00 00 48 8b 05 00 00 00
  00 8b 00 89 45 fc 48 8b
  15 00 00 00 00 48 8b 05
  00 00 00 00 8b 12 89 10
  48 8b 05 00 00 00 00 8b
  55 fc …

Section .data.rel:
  00 00 00 00 00 00 00 00

Section .dynamic:
  Relocations in .text:
    7: R_X86_64_PC32  buf
    e: R_X86_64_PC32  .bss-0x4
   15: R_X86_64_PC32  bufp0-0x4
   21: R_X86_64_PC32  .bss-0x4
   28: R_X86_64_PC32  bufp0-0x4
   33: R_X86_64_PC32  .bss-0x4

  Relocations in .data.rel:
    0: R_X86_64_64    buf
```

After relocation:

```
Section .text:
  55 48 89 e5 48 8d 05 e3
  2e 00 00 48 89 05 f0 2e
  00 00 48 8b 05 d9 2e 00
  00 8b 00 89 45 fc 48 8b
  15 dd 2e 00 00 48 8b 05
  c6 2e 00 00 8b 12 89 10
  48 8b 05 cb 2e 00 00 8b
  55 fc …

Section .data.rel:
  30 40 00 00 00 00 00 00
```

- The linker does not have (and does not require) any information about the machine code!

Another Example

local.c

```
#include <stdio.h>

int fextern(int a);
int flib(int a);

int flocal(int a)
{
  return 3*a-7;
}

int main(int argc, char *argv[])
{
  int res = 0;

  res += flocal(argc);
  res += fextern(argc);
  res += flib(argc);

  return res;
}
```

extern.c

```
int fextern(int a)
{
  return 7*a-3;
}
```

lib.c

```
int flib(int a)
{
  return 22*a-5;
}
```

```
$ gcc -O0 -c local.c extern.c lib.c
$ gcc -shared -o libl.so lib.o
$ gcc -o l local.o extern.o -ll -L.
```

Another Example

local.c

```c
#include <stdio.h>

int fextern(int a);
int flib(int a);

int flocal(int a)
{
  return 3*a-7;
}

int main(int argc, char *argv[])
{
  int res = 0;

  res += flocal(argc);
  res += fextern(argc);
  res += flib(argc);

  return res;
}
```

local.o **Source: $ objdump -r -D local.o**

```
Disassembly of section .text:
…
0000000000000015 <main>:
  15:      55                     push   %rbp
  16:      48 89 e5               mov    %rsp,%rbp
  19:      48 83 ec 20            sub    $0x20,%rsp
  1d:      89 7d ec               mov    %edi,-0x14(%rbp)
  20:      48 89 75 e0            mov    %rsi,-0x20(%rbp)
  24:      c7 45 fc 00 00 00 00   movl   $0x0,-0x4(%rbp)
  2b:      8b 45 ec               mov    -0x14(%rbp),%eax
  2e:      89 c7                  mov    %eax,%edi
  30:      e8 00 00 00 00         call   35 <main+0x20>
                   31: R_X86_64_PLT32    flocal-0x4
  35:      01 45 fc               add    %eax,-0x4(%rbp)
  38:      8b 45 ec               mov    -0x14(%rbp),%eax
  3b:      89 c7                  mov    %eax,%edi
  3d:      e8 00 00 00 00         call   42 <main+0x2d>
                   3e: R_X86_64_PLT32    fextern-0x4
  42:      01 45 fc               add    %eax,-0x4(%rbp)
  45:      8b 45 ec               mov    -0x14(%rbp),%eax
  48:      89 c7                  mov    %eax,%edi
  4a:      e8 00 00 00 00         call   4f <main+0x3a>
                   4b: R_X86_64_PLT32    flib-0x4
  4f:      01 45 fc               add    %eax,-0x4(%rbp)
  52:      8b 45 fc               mov    -0x4(%rbp),%eax
  55:      c9                     leave
  56:      c3                     ret
```


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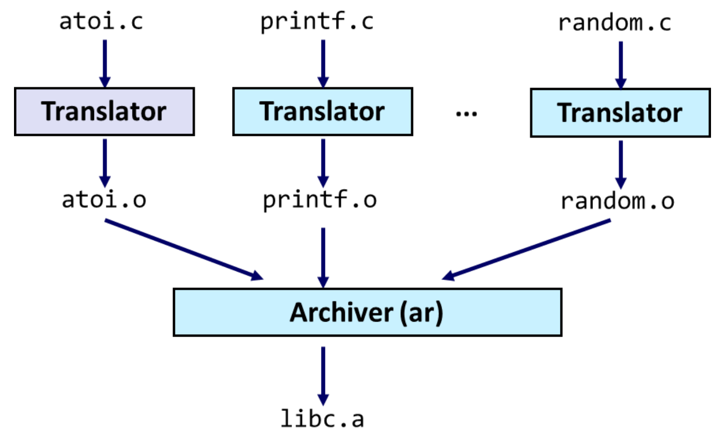
Another Example - .text after Relocation

```
Disassembly of section .text:
…
0000000000000015 <main>:
  …
  30: e8 00 00 00 00            call   35
           31: R_X86_64_PLT32   flocal-0x4
  …
  3d: e8 00 00 00 00            call   42
           3e: R_X86_64_PLT32   fextern-0x4
  …
  4a: e8 00 00 00 00            call   4f
           4b: R_X86_64_PLT32   flib-0x4
  …
```

Source: **$ objdump -r -D l**

```
Disassembly of section .plt:
…
0000000000001030 <flib@plt>:
    1030:  ff 25 e2 2f 00 00      jmp    *0x2fe2(%rip)
    1036:  68 00 00 00 00         push   $0x0
    103b:  e9 e0 ff ff ff         jmp    1020

Disassembly of section .text:
…
0000000000001139 <flocal>:
    …
000000000000114e <main>:
    …
    1169:  e8 cb ff ff ff         call   1139 <flocal>
    …
    1176:  e8 15 00 00 00         call   1190 <fextern>
    …
    1183:  e8 a8 fe ff ff         call   1030 <flib@plt>
    …
0000000000001190 <fextern>:
    …
```



Static and Dynamic Libraries

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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

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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.

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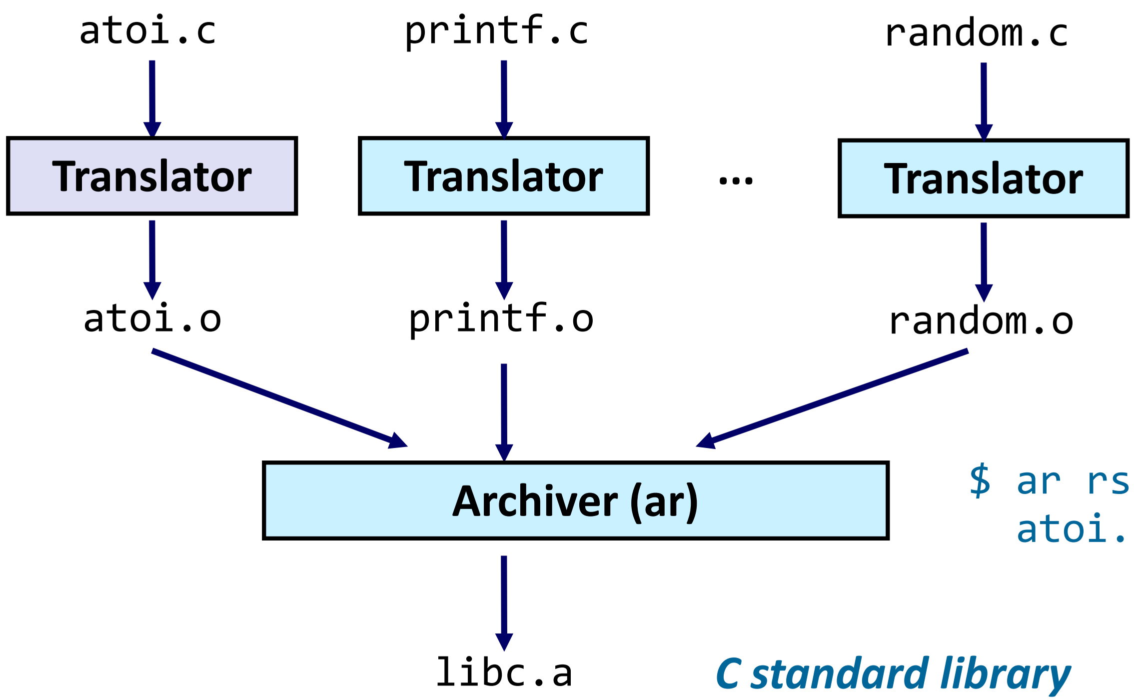
Creating Static Libraries




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

C standard library

- Archiver allows incremental updates
- Recompile function that changes and replace .o file in archive.

Commonly Used Libraries

- libc.a (the C standard library)
  - 8 MB archive of 1392 object files.
  - I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math
- libm.a (the C math library)
  - 1 MB archive of 401 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
…
```

```
% 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
…
```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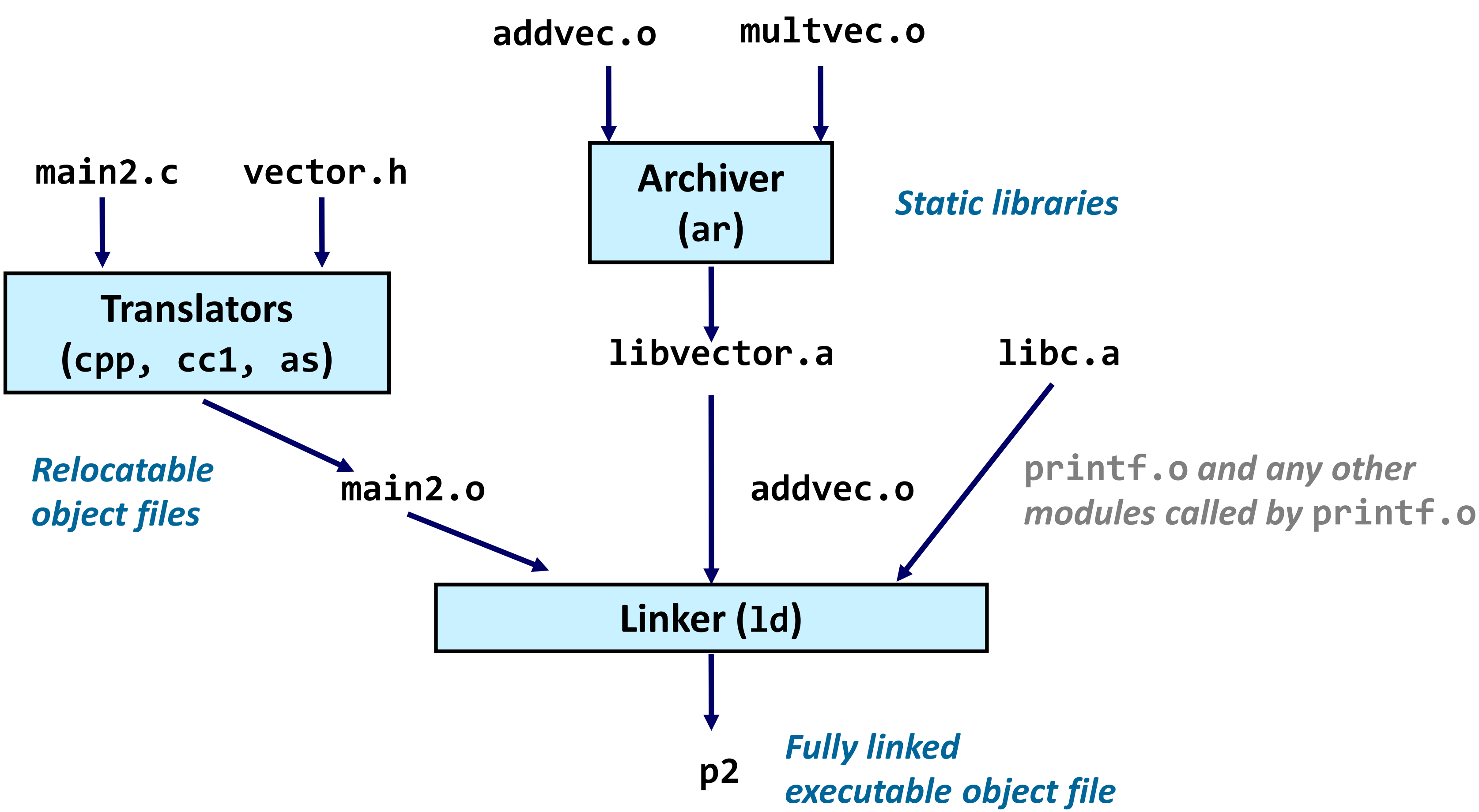
Linking with Static Libraries



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.

```
$ gcc -L. libtest.o -lmine
$ gcc -L. -lmine libtest.o
libtest.o: In function `main':
libtest.o(.text+0x4): undefined reference to `libfun'
```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Shared Libraries

- Static libraries have the following disadvantages:
  - Duplication in the stored executables (every function need std 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

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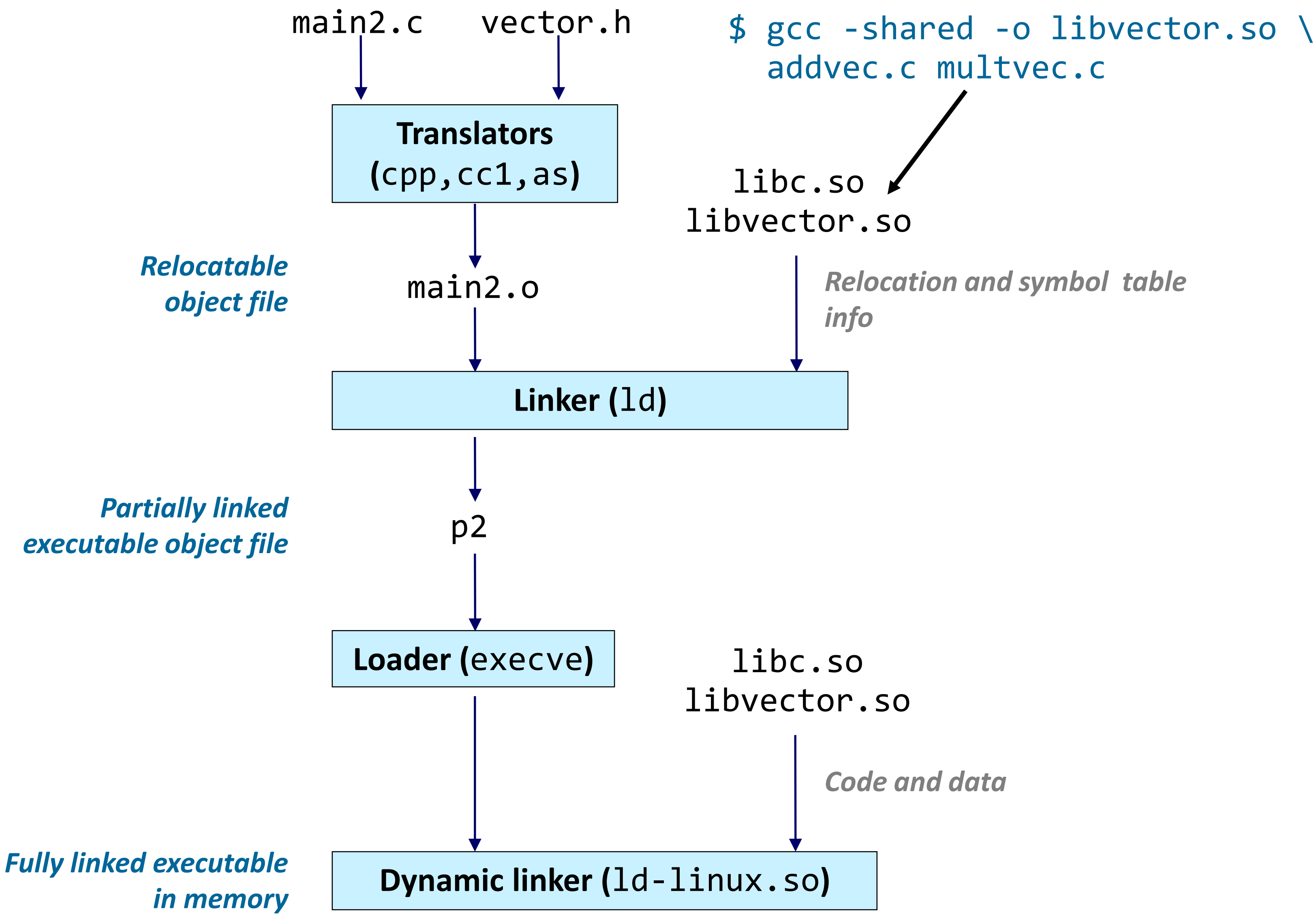
Shared Libraries (cont.)

- **Load-time linking**: dynamic linking occurs when executable is first loaded and run
  - Common case for Linux, handled automatically by the dynamic linker (ld-linux.so).
  - Standard C library (libc.so) usually dynamically linked.

- **Run-time linking**: dynamic linking occur after program has begun
  - 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.

Dynamic Linking at Load-time



```
$ LD_PRELOAD=./mymalloc.so ./hellor
malloc(10) = 0x501010
free(0x501010)
hello, world
```

Case Study

Library Interpositioning

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.

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Some Interpositioning Applications

- Security
  - Confinement (sandboxing)
    - Interpose calls to libc functions.
  - Behind the scenes encryption
    - Automatically encrypt otherwise unencrypted network connections.

- 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

```c
#include <stdio.h>
#include <stdlib.h>
#include "malloc.h"

int main()
{
  free(malloc(10));
  printf("hello, world\n");
  return EXIT_SUCCESS;
}                    hello.c
```

- Goal: trace the addresses and sizes of the allocated and freed blocks, without modifying the source code.
- Three solutions: interpose on the lib malloc and free functions at compile time, link time, and load/run time.

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Load/Run-time Interpositioning

```
#ifdef RUNTIME
// Run-time interposition of malloc and free based on
// dynamic linker's (ld-linux.so) LD_PRELOAD mechanism
#define _GNU_SOURCE
#include <stdio.h>
#include <stdlib.h>
#include <dlfcn.h>

void *malloc(size_t size) {
    static void *(*mallocp)(size_t size) = NULL;
    char *error;
    void *ptr;

    // get address of libc malloc
    if (!mallocp) {
        mallocp = dlsym(RTLD_NEXT, "malloc");
        if ((error = dlerror()) != NULL) {
            fputs(error, stderr);
            exit(EXIT_FAILURE);
        }
    }

    ptr = mallocp(size);
    printf("malloc(%d) = %p\n", (int)size, ptr);
    return ptr;
}
```

mymalloc.c

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Load/Run-time Interpositioning

- The LD_PRELOAD environment variable tells the dynamic linker to resolve unresolved refs (e.g., to malloc) by looking in libdl.so and mymalloc.so first.
    - libdl.so necessary to resolve references to the dlopen functions.

```
$ make hellor
gcc -O2 -Wall -DRUNTIME -shared -fPIC -o mymalloc.so mymalloc.c -ldl
gcc -O2 -Wall -o hellor hello.c

$ make runr
(LD_PRELOAD="/usr/lib64/libdl.so ./mymalloc.so" ./hellor)
malloc(10) = 0x501010
free(0x501010)
hello, world
```


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How does it work?

- **Symbols resolved at load time**
  - LD_LIBRARY_PATH indicates where the loader searches for libraries

- **Step 1: load binary and required libraries**
- **Step 2: resolve symbols**

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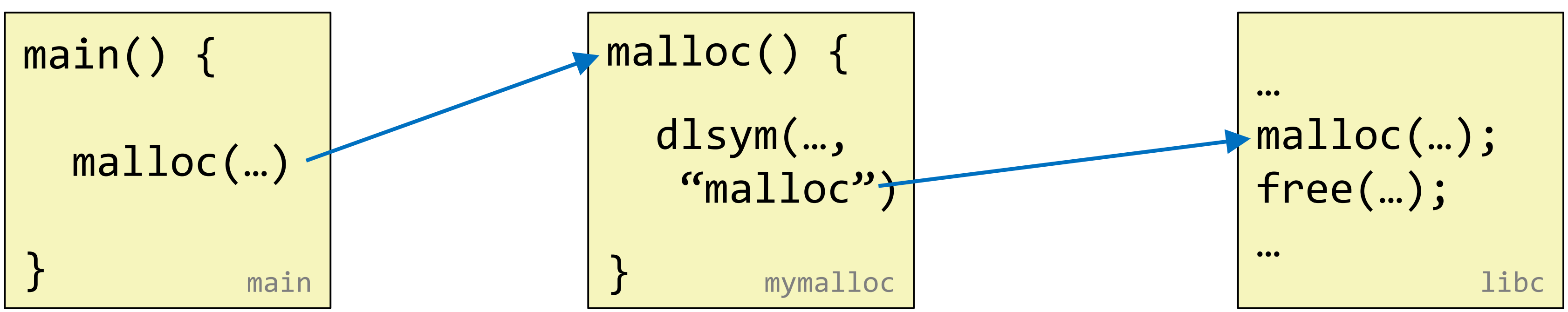
How does it work?

- **Symbols resolved at load time**
  - LD_LIBRARY_PATH indicates where the loader searches for libraries
  - **LD_PRELOAD takes precedence over LD_LIBRARY_PATH**

- **Step 1: load binary and required libraries**
- **Step 2: resolve symbols**



malloc() in myalloc is found first and linked to

can retrieve original malloc symbol using dlsym(RTLD_NEXT, …)

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Module Summary

Program Execution

- **Linking allows modularization**
  - at compile time
  - at load-time
  - at run-time
- **Linking involves two main operations**
  - symbol resolution: map symbols to a unique memory address across the entire program
  - symbol relocation: ensure symbols refer to the designated memory address
- **Executable and linkable format**
  - common binary format of executables, libraries, and compiled object files
  - contains all necessary information to support static and dynamic linking and loading
  - very versatile and used on (almost) all platforms

Program Execution

- **Symbol Resolution**
  - first step of linking & loading
  - for each use of a symbol, determine what defined symbol the use refers to
  - (used to be) a source of subtle errors
  - global, local, and external, strong and weak symbols
  - symbol data to ELF section assignment: .text, .data, .bss

- **Symbol Relocation**
  - merge object files into a single executable/library
  - relocate at-compile time unknown addresses/offsets to point to correct memory location
  - two relocations of interest to us
    - PC-relative (R_X86_64_PC32/PLT32)
    - Absolute (R_X86_64_32[S]/64)

Program Execution

- **Libraries**
  - "packages" of functions commonly used together
- **Static Libraries**
  - "concatenation" of relocatable object files into an archive (hence *.a)
  - at link time, "copy-paste" referenced object files into executable
  - disadvantages: code size increase, library updates requires re-linking
- **Dynamic (Shared) Libraries**
  - library linked to executable at load/run-time
  - allows sharing of code between different processes
  - no recompilation necessary
- **Library Interpositioning**
  - intercept calls to system libraries
  - a potential security risk