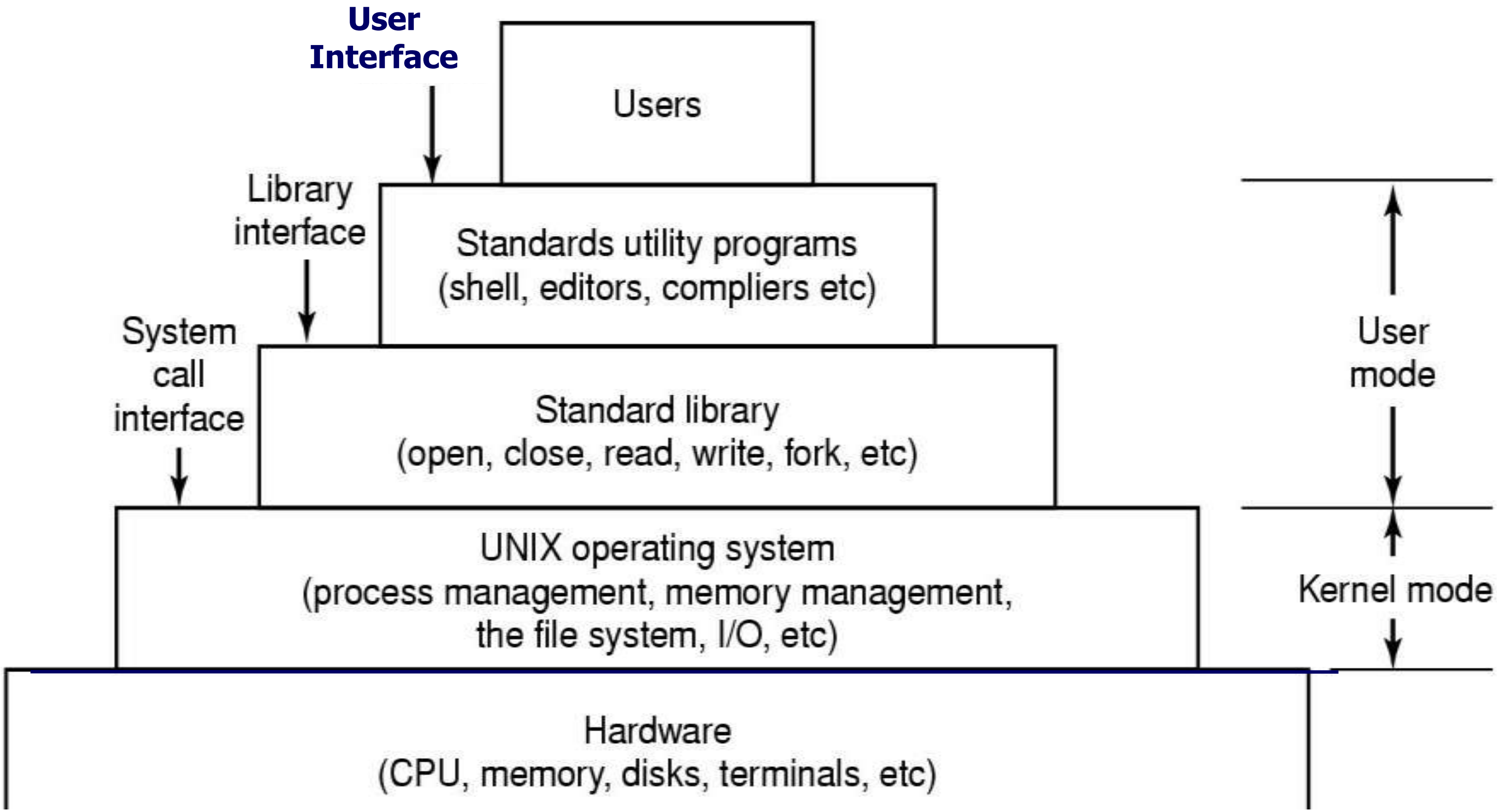
Computer System Organization

Today’s agenda

Overview of how things work

- Compilation and linking system
- Operating system
- Computer organization

A software view



How it works

hello.c program

```
#include <stdio.h>
#define FOO 4
int main() {
   printf(“hello, world %d\n”, FOO);
}
```

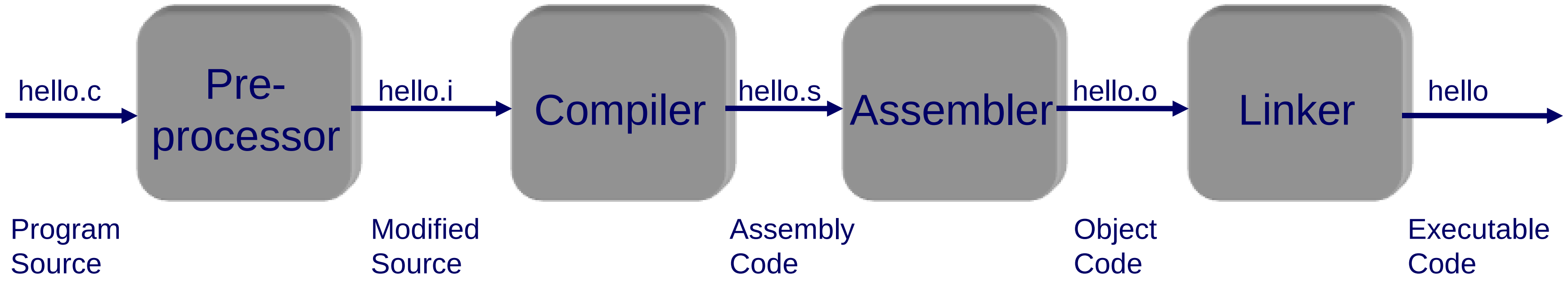
The Compilation system

gcc is the *compiler driver*

gcc invokes several other *compilation phases*

- **Preprocessor**
- **Compiler**
- **Assembler**
- **Linker**

What does each one do? What are their outputs?



hello.c

Program Source

Pre-processor

hello.i

Modified Source

Compiler

hello.s

Assembly Code

Assembler

hello.o

Object Code

Linker

hello

Executable Code

Preprocessor

First, gcc compiler driver invokes cpp to generate expanded C source

- cpp just does text substitution
- Converts the C source file to another C source file
- Expands `#defines`, `#includes`, etc.
- Output is another C source file

```
#include <stdio.h>
#define FOO 4
int main(){
     printf(“hello, world %d\n”, FOO);
}
```

```
…
extern int printf (const char *__restrict __format, ...);
…
int main() {
 printf("hello, world %d\n", 4);
}
```

Preprocesser

Included files:

```
#include <foo.h>
#include “bar.h”
```

Defined constants:

```
#define MAXVAL   40000000
```

By convention, all capitals tells us it’s a constant, not a variable.

Macros:

```
#define MIN(x,y)    ((x)<(y) ? (x):(y))
#define RIDX(i, j, n)  ((i) * (n) + (j))
```

Preprocesser

Conditional compilation:

```
#ifdef …    or  #if defined( … )
#endif
```

- Code you think you may need again (e.g. debug print statements)
  - Include or exclude code based on `#define, #ifdef`
  - `gcc -D DEBUG` equivalent to `#define DEBUG`
  - More readable than commenting code out

http://thefengs.com/wuchang/courses/cs201/class/03/def

Preprocesser

Portability

- Compilers with “built in” constants defined
- Use to conditionally include code
  - Operating system specific code

    `#if defined(__i386__) || defined(WIN32) || …`
  - Compiler-specific code

    `#if defined(__INTEL_COMPILER)`
  - Processor-specific code

    `#if defined(__SSE__)`

Compiler

Next, gcc compiler driver invokes cc1 to generate assembly code

- Translates high-level C code into assembly
  - Variable abstraction mapped to memory locations and registers
  - Logical and arithmetic functions mapped to underlying machine opcodes

Compiler

```
…
extern int printf (const char *__restrict __format, ...);
…
int main() {
   printf("hello, world %d\n", 4);
}
```

```
        .section        .rodata
    .LC0:
        .string "hello, world %d\n“
        .text
    main:
        pushq   %rbp
        movq    %rsp, %rbp
        movl    $4, %esi
        movl    $.LC0, %edi
        movl    $0, %eax
        call    printf
        popq    %rbp
        ret
```

Assembler

Next, gcc compiler driver invokes as to generate object code

- Translates assembly code into binary object code that can be directly executed by CPU

Assembler

```
        .section        .rodata
    .LC0:
        .string "hello, world %d\n"
        .text
    main:
        pushq   %rbp
        movq    %rsp, %rbp
        movl    $4, %esi
        movl    $.LC0, %edi
        movl    $0, %eax
        call    printf
        popq    %rbp
        ret
```

```
Hex dump of section '.rodata':
   0x004005d0 01000200 68656c6c 6f2c2077 6f726c64 ....hello, world
   0x004005e0 2025640a 00                          %d..

Disassembly of section .text:

000000000040052d <main>:
   40052d:  55                      push   %rbp
   40052e:  48 89 e5                mov    %rsp,%rbp
   400531:  be 04 00 00 00          mov    $0x4,%esi
   400536:  bf d4 05 40 00          mov    $0x4005d4,%edi
   40053b:  b8 00 00 00 00          mov    $0x0,%eax
   400540:  e8 cb fe ff ff          callq  400410 <printf@plt>
   400545:  5d                      pop    %rbp
   400546:  c3                      retq
```

Linker

Finally, gcc compiler driver calls linker (ld) to generate executable

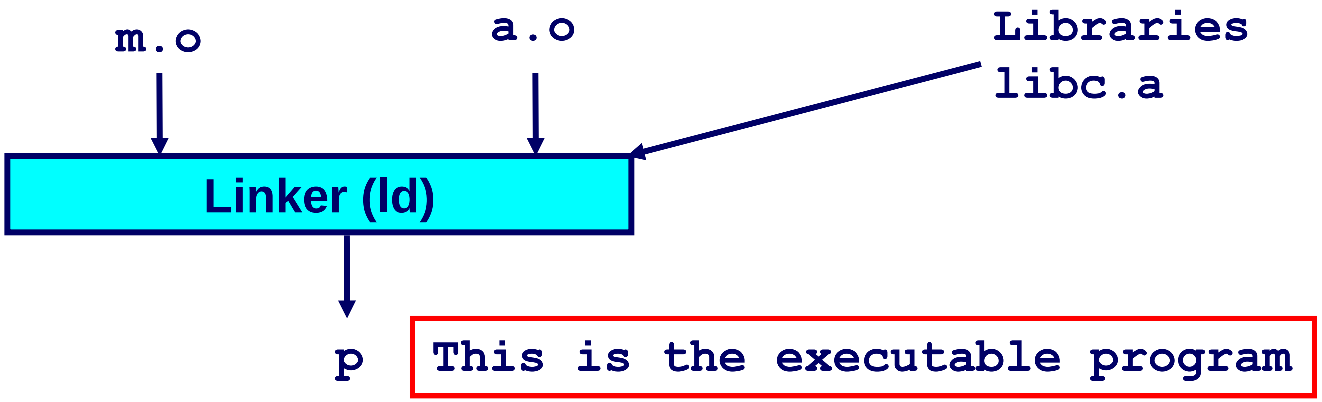
- Merges multiple relocatable (`.o`) object files into a single executable program
- Copies library object code and data into executable
- Relocates relative positions in library and object files to absolute ones in final executable

Linker

Resolves external references

- *External reference*: reference to a symbol defined in another object file (e.g. `printf`)
- Updates all references to these symbols to reflect their new positions.
  - References in both code and data

```
printf();     /* reference to symbol printf */
int *xp=&x;   /* reference to symbol x */
```



This is the executable program

Benefits of linking

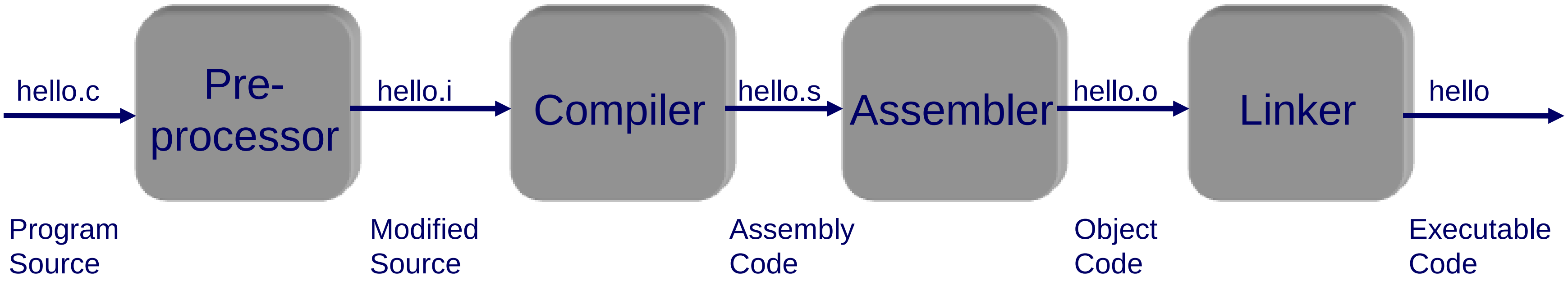
Modularity and space

- 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
- Compilation efficiency
  - Change one source file, compile, and then relink.
  - No need to recompile other source files.
- Space efficiency
  - Libraries of common functions can be aggregated into a single file used by all programs

Summary of compilation process

Compiler driver **(cc or gcc) coordinates all steps**

- **Invokes preprocessor (`cpp`), compiler (`cc1`), assembler (`as`), and linker (`ld`).**
- **Passes command line arguments to appropriate phases**



hello.c → Pre-processor → hello.i → Compiler → hello.s → Assembler → hello.o → Linker → hello

Program Source

Modified Source

Assembly Code

Object Code

Executable Code

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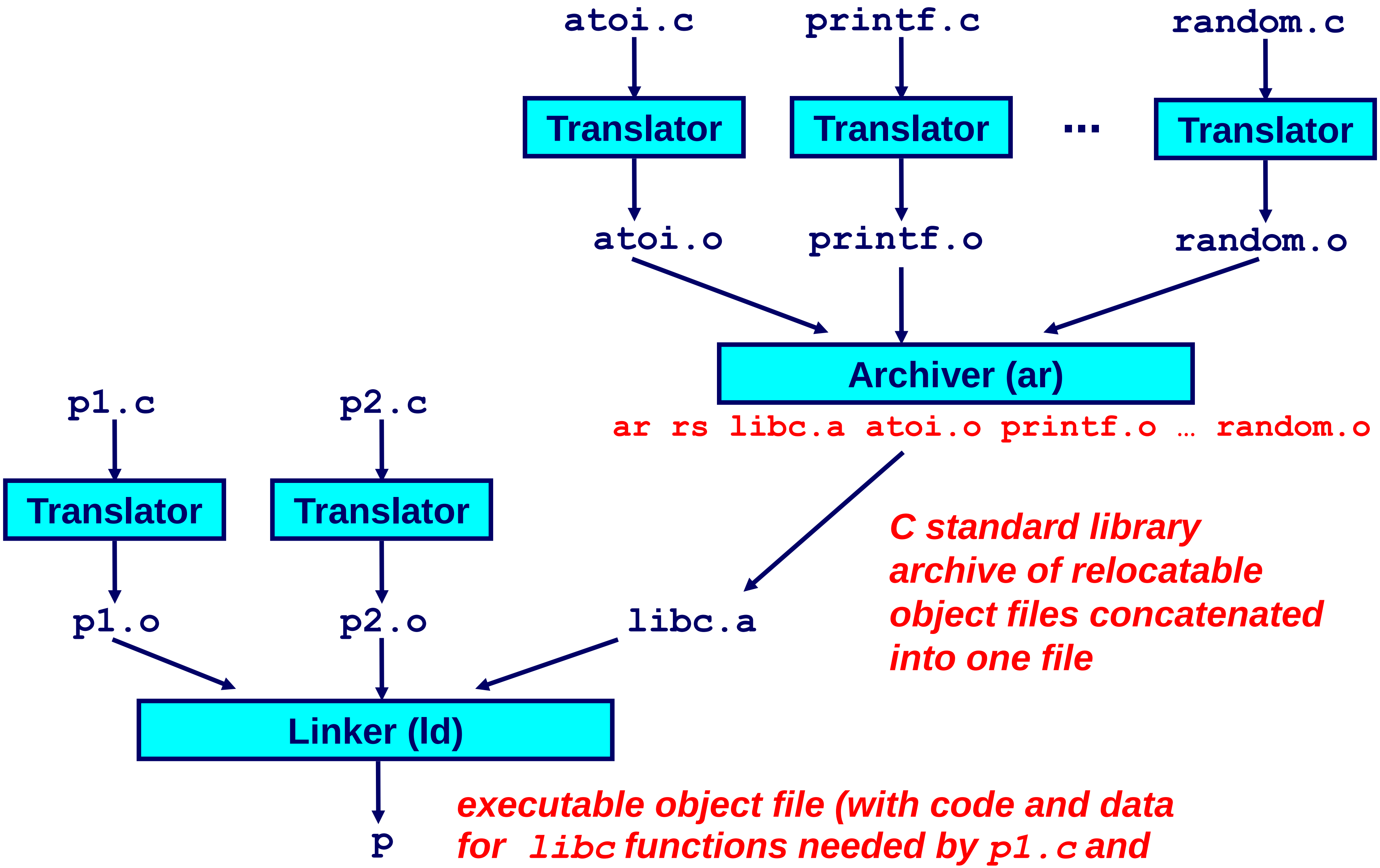
Creating and using libc



`atoi.c` `printf.c` … `random.c`

Translator **Translator** … **Translator**

`atoi.o` `printf.o` `random.o`

Archiver (ar)

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

`libc.a`

C standard library archive of relocatable object files concatenated into one file

`p1.c` `p2.c`

Translator **Translator**

`p1.o` `p2.o` `libc.a`

Linker (ld)

`p`

executable object file (with code and data for `libc` functions needed by `p1.c` and `p2.c` copied in)

LibC libraries

`libc.a` (the C standard library)

- 5 MB archive of more than 1000 object files.
- I/O, memory allocation, signals, strings, time, random numbers

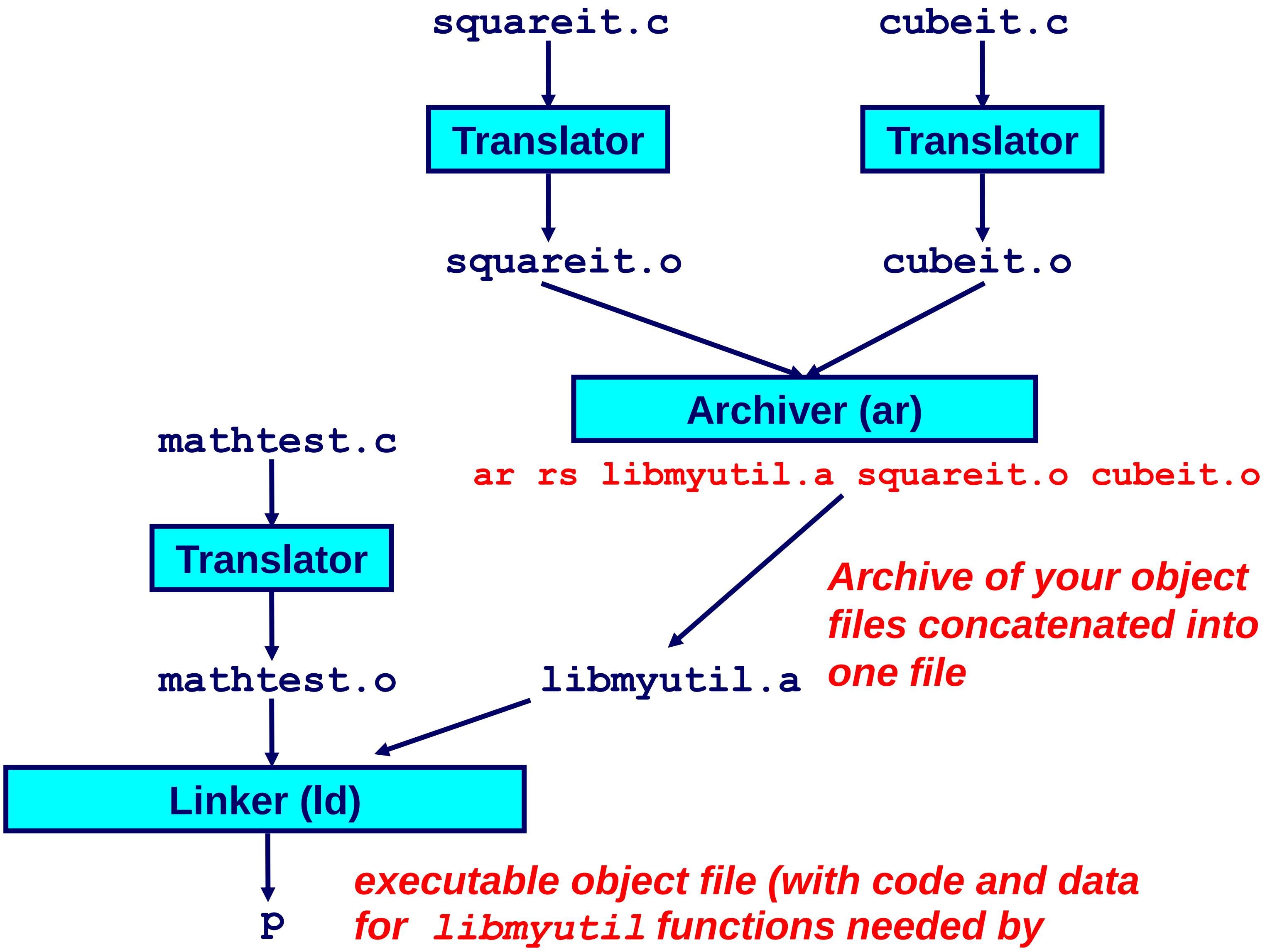
`libm.a` (the C math library)

- 2 MB archive of more than 400 object files.
- floating point math (sin, cos, tan, log, exp, sqrt, …)

```
% ar -t /usr/lib/x86_64-linux-gnu/libc.a | sort
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
…
```

```
% ar -t /usr/lib/x86_64-linux-gnu/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
…
```

Creating your own static libraries



`ar rs libmyutil.a squareit.o cubeit.o`

Archive of your object files concatenated into one file

executable object file (with code and data for `libmyutil` functions needed by `mathtest.c` copied in)

Creating your own static libraries

Suppose you have utility code in squareit.c and cubeit.c that all of your programs use

- Create a library libmyutil.a using ar and ranlib and link library in statically

```
libmyutil.a : squareit.o cubeit.o
        ar rvu libmyutil.a squareit.o cubeit.o
        ranlib libmyutil.a
```

- Compile your program that uses library calls and link in library statically

```
gcc -o mathtest mathtest.c -L. -lmyutil
```

  - Note: Only the library code “mathtest” needs from libmyutil is copied directly into binary
  - List functions in binary or library

```
nm libmyutil.a
```

http://thefengs.com/wuchang/courses/cs201/class/03/libexample

Problems with static libraries

Multiple copies of common code on disk

- “`gcc program.c –lc`” creates an `a.out` with `libc` object code copied into it (`libc.a`)
- Almost all programs use libc!
- Large number of binaries on disk with the same code in it

Libraries and linking

Two types of libraries

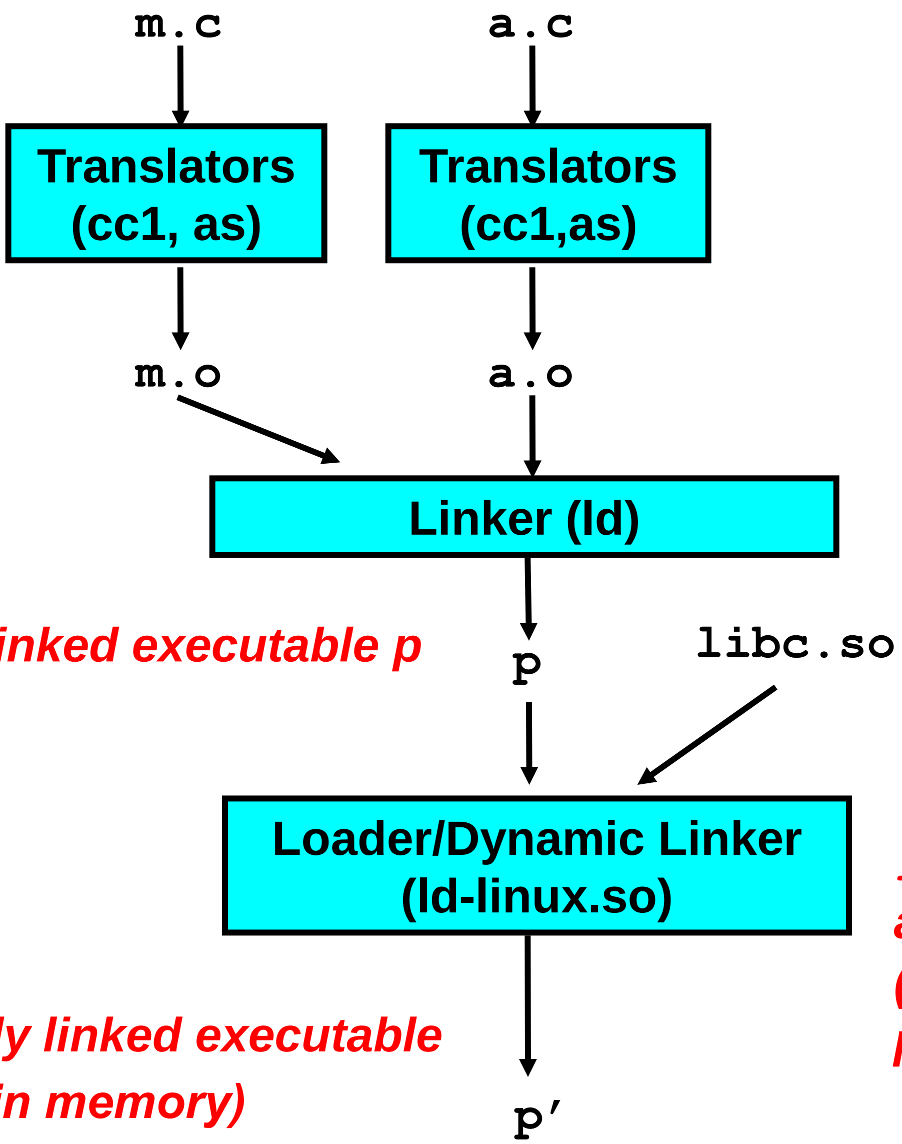
- Static libraries
  - Library of code that linker copies into the executable at compile time
- Dynamic shared object libraries
  - Code loaded at run-time by system loader upon program execution

Dynamic libraries

Have binaries compiled with a reference to a library of shared objects on disk

- Libraries loaded at run-time from file system rather than copied in at compile-time
- "`ldd <binary>`" to see dependencies
  - `gcc` flag "`–shared`" to create dynamic shared object files (`.so`)
- Caveat
  - How does one ensure dynamic libraries are present across all run-time environments?
  - Static linking (via `gcc's –static` flag) to create self-contained binaries and avoid problems with DLL versions

Dynamically Linked Shared Libraries



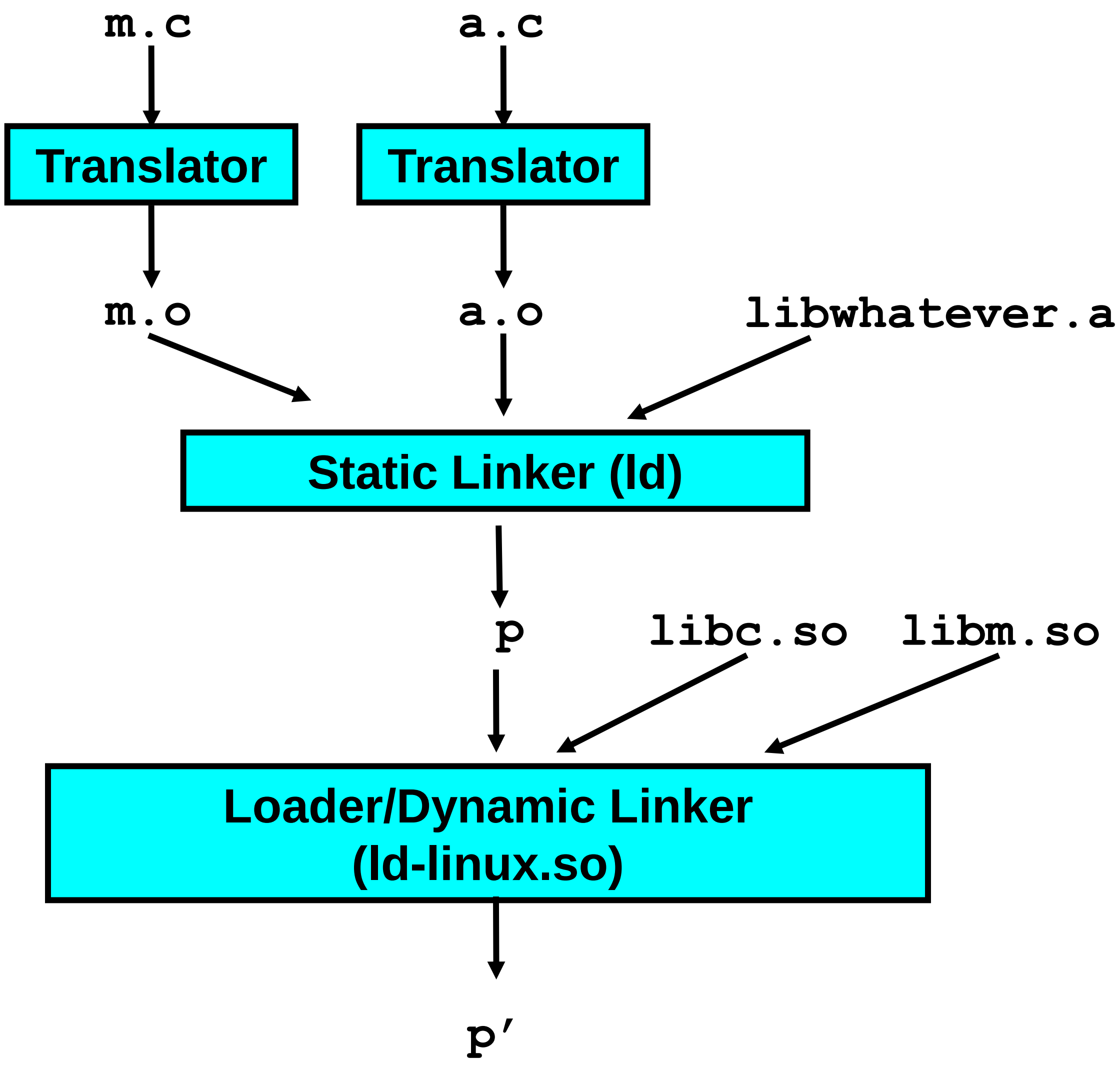
Partially linked executable p (on disk)

Shared library of dynamically relocatable object files

`libc.so` functions called by `m.c` and `a.c` are loaded, linked, and (potentially) shared among processes.

Fully linked executable p' (in memory)

The Complete Picture



The (Actual) Complete Picture

Dozens of processes use libc.so

- **Each process reads libc.so from disk and loads private copy into address space**
- **Multiple copies of the *exact* code resident in memory for each!**
- **Modern operating systems keep one copy of library in read-only memory**
  - **Single shared copy**
  - **Shared virtual memory (page-sharing) to reduce memory use**

Program execution

gcc/cc output an executable in the ELF format (Linux)

- Executable and Linkable Format

Standard unified binary format for

- Relocatable object files (`.o`),
- Shared object files (`.so`)
- Executable object files

Equivalent to Windows Portable Executable (PE) format

ELF Object File Format

ELF header

- Magic number, type (.o, exec, .so), machine, byte ordering, etc.

Program header table

- Page size, addresses of memory segments (sections), segment sizes.

`.text` section

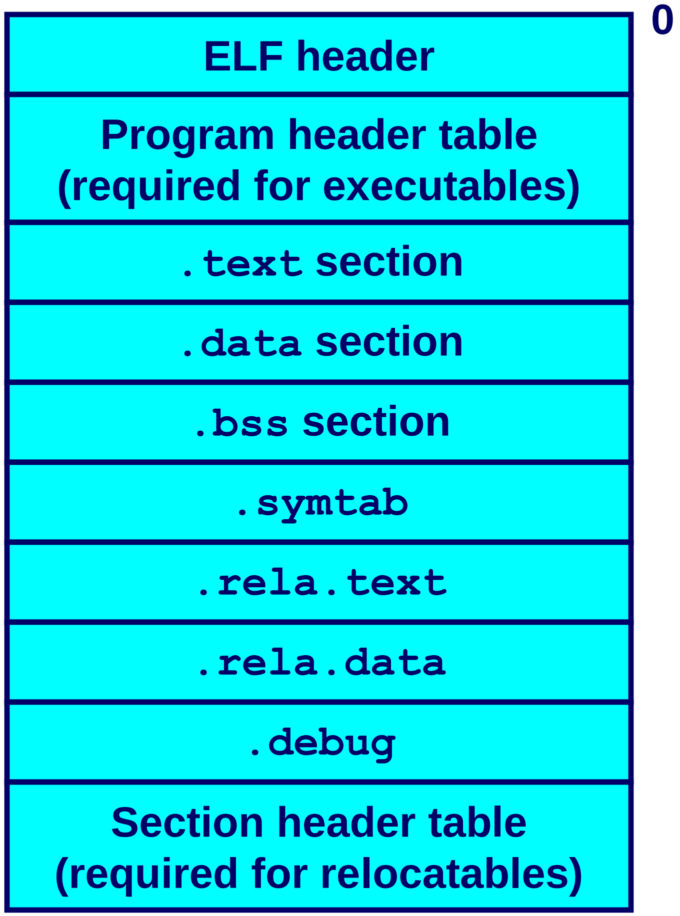
- Code

`.data` section

- Initialized (static) data

`.bss` section

- Uninitialized (static) data
- “Block Started by Symbol”



0

ELF header

Program header table
(required for executables)

`.text` section

`.data` section

`.bss` section

`.symtab`

`.rela.text`

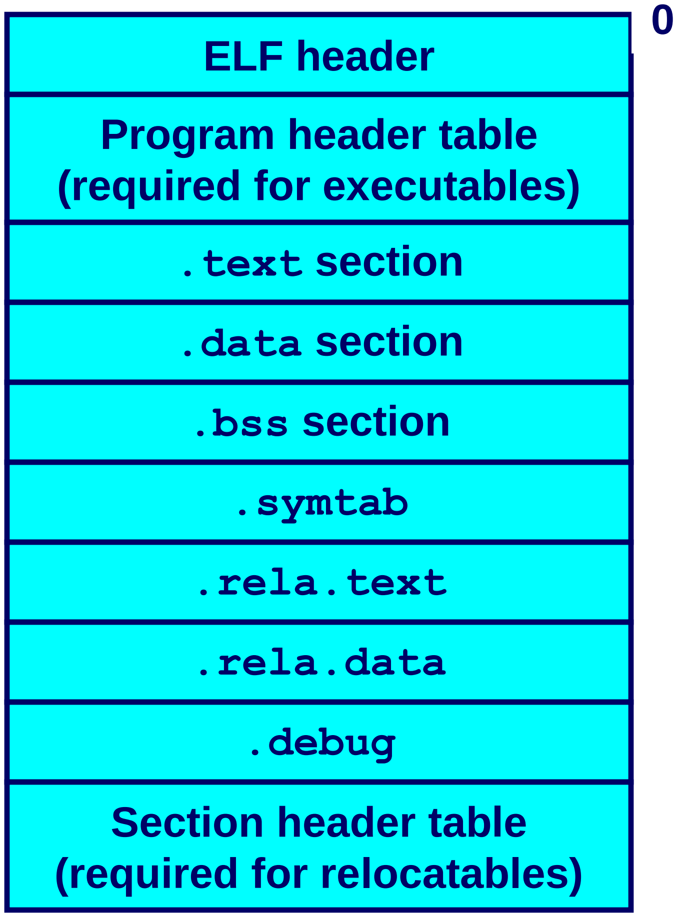
`.rela.data`

`.debug`

Section header table
(required for relocatables)

ELF Object File Format (cont)

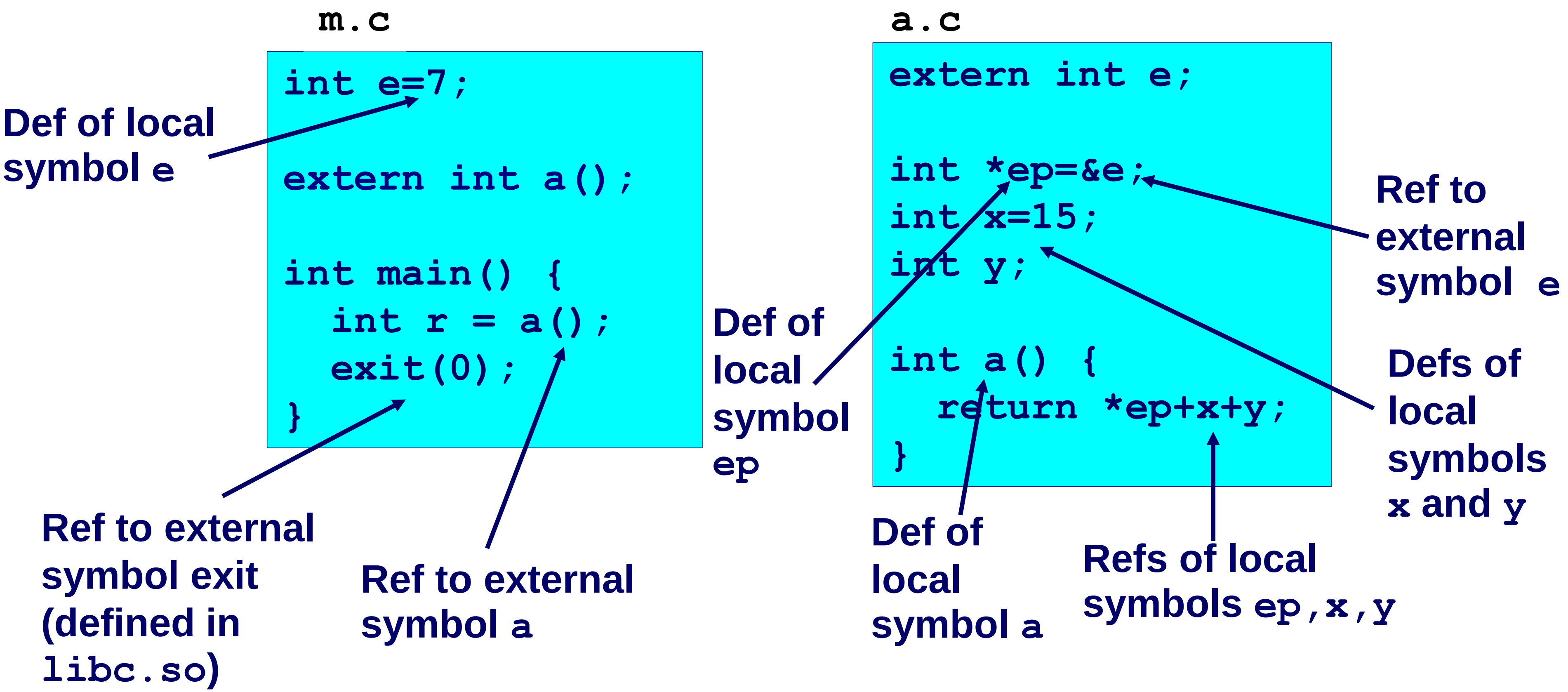
- `.symtab` section
  - Symbol table
  - Procedure and static variable names
  - Section names and locations
- `.rela.text` section
  - Relocation info for `.text` section
- `.rela.data` section
  - Relocation info for `.data` section
- `.debug` section
  - Info for symbolic debugging (`gcc -g`)



Relocation code example

Symbols for code and data

- *Definitions* and *references*
- References can be either *local* or *external*.
- Addresses of references must be resolved when loaded



`m.c`

```
int e=7;

extern int a();

int main() {
   int r = a();
   exit(0);
}
```

`a.c`

```
extern int e;

int *ep=&e;
int x=15;
int y;

int a() {
   return *ep+x+y;
}
```

Def of local symbol `e`

Ref to external symbol exit (defined in `libc.so`)

Ref to external symbol `a`

Def of local symbol `ep`

Ref to external symbol `e`

Defs of local symbols `x` and `y`

Def of local symbol `a`

Refs of local symbols `ep,x,y`

Merging Object Files into an Executable Object File

```
int e=7;

extern int a();

int main() {
  int r = a();
  exit(0);
}
```

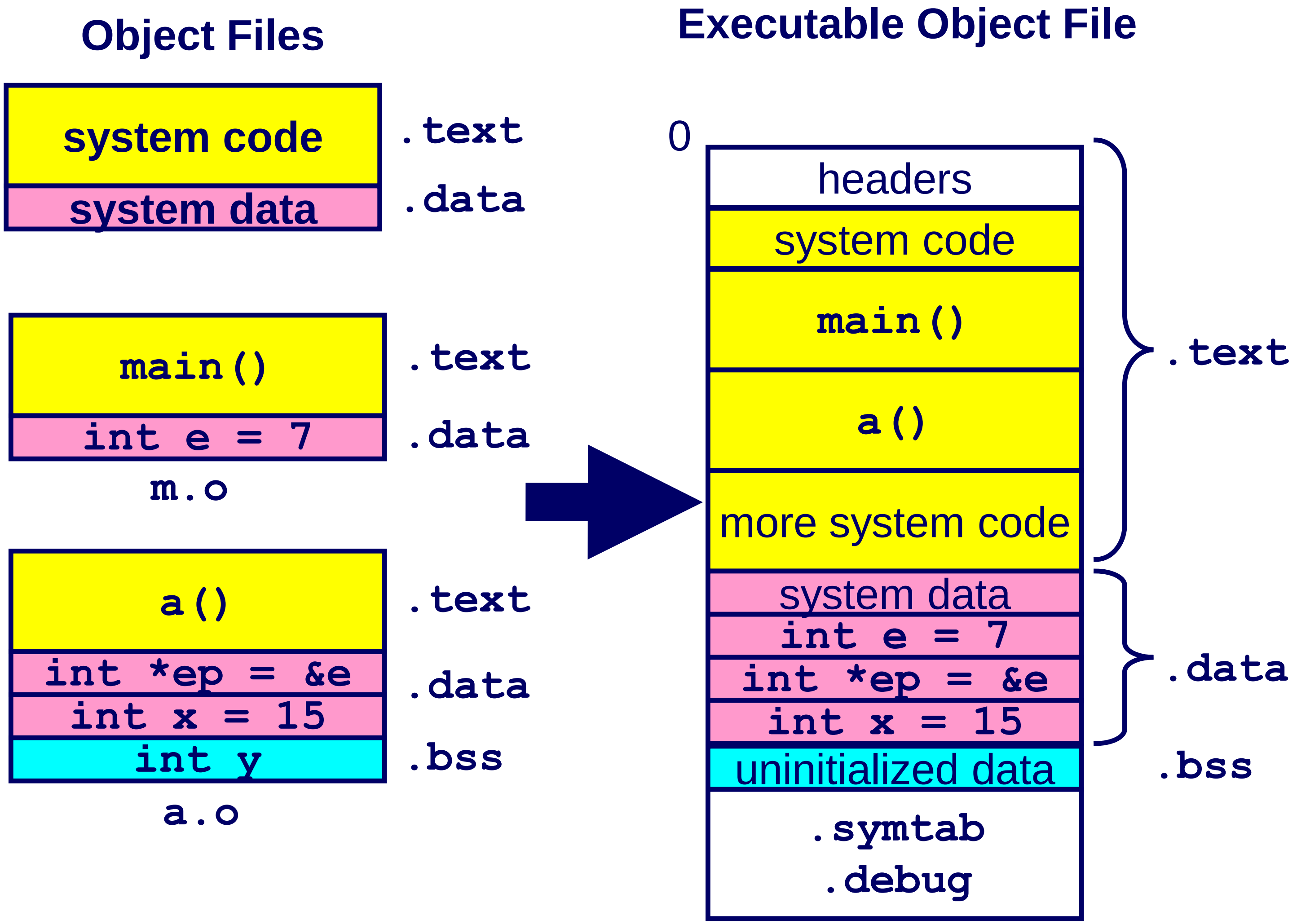
m.c

```
extern int e;

int *ep=&e;
int x=15;
int y;

int a() {
  return *ep+x+y;
}
```

a.c



Object Files

system code — .text
system data — .data

main() — .text
int e = 7 — .data
m.o

a() — .text
int *ep = &e — .data
int x = 15
int y — .bss
a.o

Executable Object File

0
headers
system code
main()
a()
more system code
} .text
system data
int e = 7
int *ep = &e
int x = 15
} .data
uninitialized data — .bss
.symtab
.debug

Relocation

Compiler does not know where code will be loaded into memory upon execution

- Instructions and data that depend on location must be “fixed” to actual addresses
- i.e. variables, pointers, jump instructions

`.rela.text` section

- Addresses of instructions that will need to be modified in the executable
- Instructions for modifying
- (e.g. `a()` in `m.c`)

`.rela.data` section

- Addresses of pointer data that will need to be modified in the merged executable
- (e.g. `ep` in `a.c`)

```
readelf -a
```

Relocation example

m.c

```c
int e=7;

extern int a();

int main() {
   int r = a();
   exit(0);
}
```

a.c

```c
extern int e;

int *ep=&e;
int x=15;
int y;

int a() {
   return *ep+x+y;
}
```

What is in .text, .data, .rela.text, and .rela.data?

```
readelf -a a.o          ; .rela.text contains ep, x, and y from a()
                        ; .rela.data contains e to initialize ep

objdump -d a.o          ; Shows relocations in .text

objdump -d m            ; After linking, references placed at fixed
                        ;   relative offset to RIP
```

http://thefengs.com/wuchang/courses/cs201/class/03/elf_example

Relocation example

m.c

```
int e=7;

extern int a();

int main() {
  int r = a();
  exit(0);
}
```

a.c

```
extern int e;

int *ep=&e;
int x=15;
int y;

int a() {
  return *ep+x+y;
}
```

```
readelf -a m.o    ; .rela.text contains a and exit from main()

objdump -d m.o    ; Show relocations in.text

objdump -d m      ; After linking, symbols resolved in <main>
                  ;   for <a> and <exit>
```

Operating system

Program runs on top of operating system that implements abstract view of resources

- Files as an abstraction of storage and network devices
- System calls an abstraction for OS services
- Virtual memory a uniform memory space abstraction for each process
  - Gives the illusion that each process has entire memory space
- A process (in conjunction with the OS) provides an abstraction for a virtual computer
  - Slices of CPU time to run in
  - CPU state
  - Open files
  - Thread of execution
  - Code and data in memory

Protection

- Protects the hardware/itself from user programs
- Protects user programs from each other
- Protects files from unauthorized access

Program execution

The operating system creates a process.

- Including among other things, a virtual memory space

System loader reads program from file system and loads its code into memory

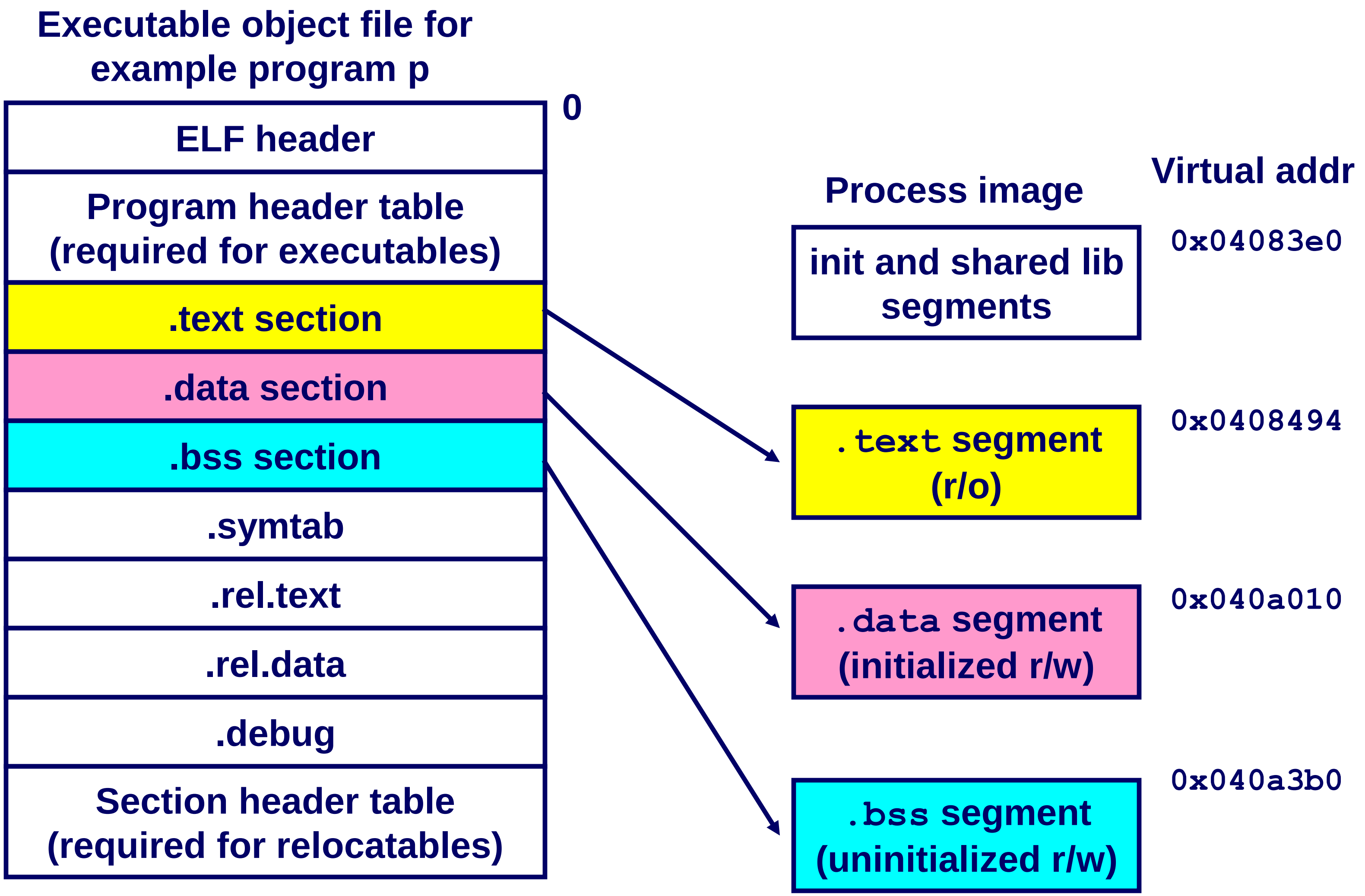
- Program includes any statically linked libraries
- Done via DMA (direct memory access)

System loader loads dynamic shared objects/libraries into memory

Links everything together and then starts a thread of execution running

- Note: the program binary in file system remains and can be executed again
- Program is a cookie recipe, processes are the cookies

Loading Executable Binaries



Executable object file for example program p

0

ELF header

Program header table (required for executables)

.text section

.data section

.bss section

.symtab

.rel.text

.rel.data

.debug

Section header table (required for relocatables)

Process image

Virtual addr

init and shared lib segments

`0x04083e0`

`.text` segment (r/o)

`0x0408494`

`.data` segment (initialized r/w)

`0x040a010`

`.bss` segment (uninitialized r/w)

`0x040a3b0`

Where are programs loaded in memory?

An evolution….

Primitive operating systems

- Single tasking.
- Physical memory addresses go from zero to N.

The problem of loading is simple

- Load the program starting at address zero
- Use as much memory as it takes.
- Linker binds the program to absolute addresses at compile-time
- Code starts at zero
- Data concatenated after that
- etc.

Where are programs loaded, cont'd

Next imagine a multi-tasking operating system on a primitive computer.

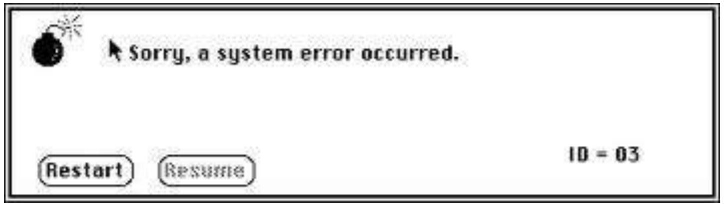
- Physical memory space, from zero to N.
- Applications share space
- Memory allocated at load time in unused space
- Linker does not know where the program will be loaded
- Binds together all the modules, but keeps them relocatable

How does the operating system load this program?

- Not a pretty solution, must find contiguous unused blocks

How does the operating system provide protection?

- Not pretty either


Sorry, a system error occurred.

ID = 03

Where are programs loaded, cont’d

Next, imagine a multi-tasking operating system on a modern computer, with hardware-assisted virtual memory (Intel 80286/80386)

OS creates a virtual memory space for each program.

- As if program has all of memory to itself.

Back to the simple model

- The linker statically binds the program to virtual addresses
- At load time, OS allocates memory, creates a virtual address space, and loads the code and data.
- Binaries are simply virtual memory snapshots of programs (Windows .com format)

Modern linking and loading

Reduce storage via dynamic linking and loading

- Single, uniform VM address space still
- But, library code must vie for addresses at load-time
  - Many dynamic libraries, no fixed/reserved addresses to map them into
  - Code must be relocatable again
  - Useful also as a security feature to prevent predictability in exploits (Address-Space Layout Randomization)

Extra

More on the linking process (ld)

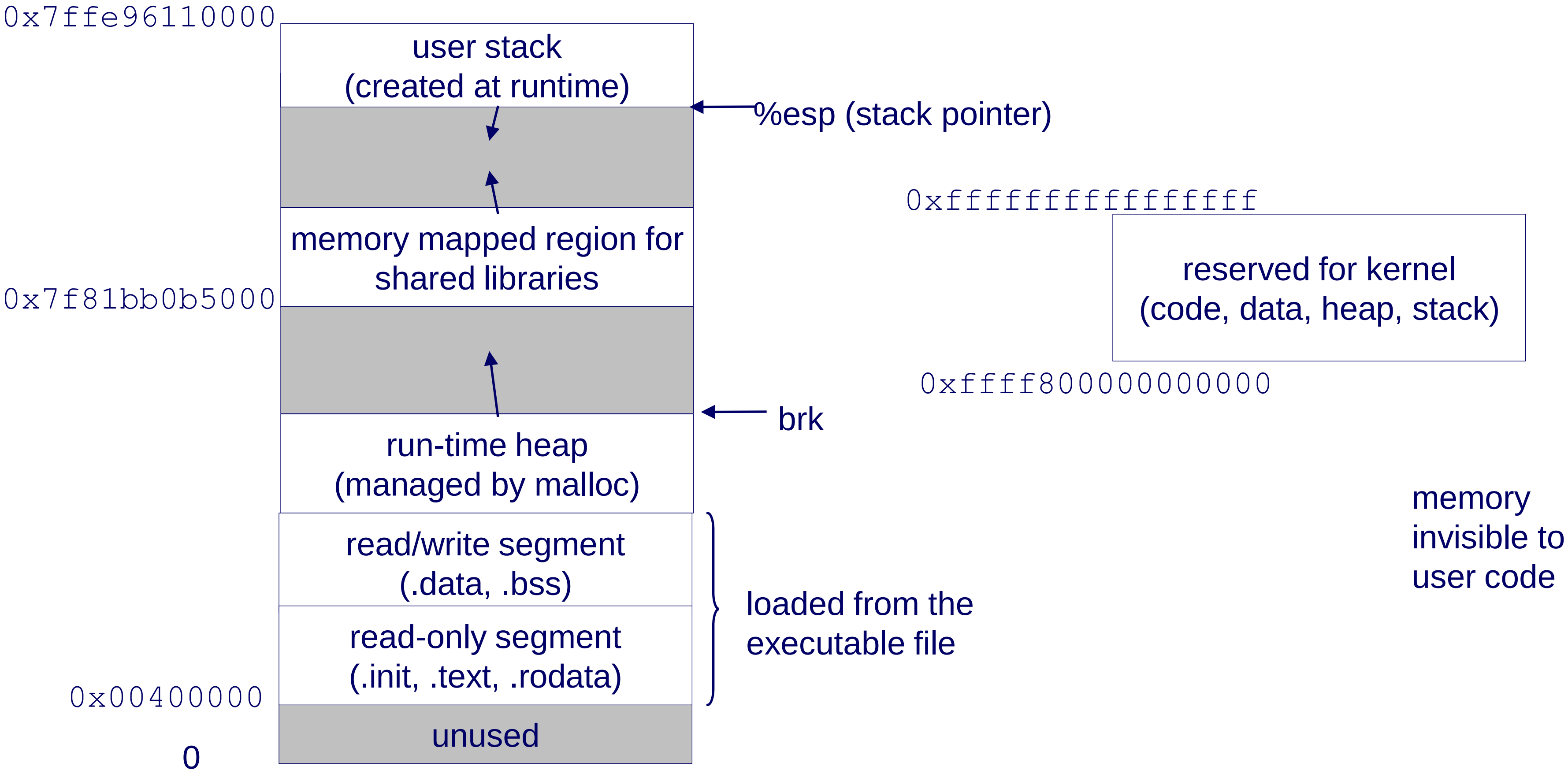
Resolves multiply defined symbols with some restrictions

- Strong symbols = initialized global variables, functions
- Weak symbols = uninitialized global variables, functions used to allow overrides of function implementations
- Simulates inheritance and function overiding (as in C++)
- Rules
  - Multiple strong symbols not allowed
  - Choose strong symbols over weak symbols
  - Choose any weak symbol if multiple ones exist

Modern 64-bit memory map

48-bit canonical address space implementations

- Reduce width of addresses to make page-tables smaller
- Kernel addresses have high-bit set



`0x7ffe96110000`

user stack
(created at runtime)

%esp (stack pointer)

`0x7f81bb0b5000`

memory mapped region for
shared libraries

brk

run-time heap
(managed by malloc)

read/write segment
(.data, .bss)

read-only segment
(.init, .text, .rodata)

loaded from the
executable file

`0x00400000`

unused

0

`0xffffffffffffffff`

reserved for kernel
(code, data, heap, stack)

`0xffff800000000000`

memory
invisible to
user code

`cat /proc/self/maps`