Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

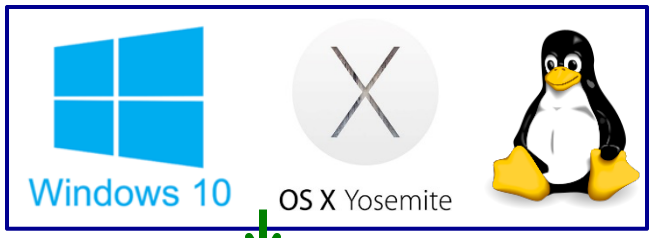
Assembly language:

```
get_mpg(car*):
        lw      a5,0(a0)
        lw      a4,4(a0)
        divw    a5,a5,a4
        fcvt.s.w        fa0,a5
        ret
```

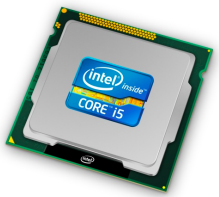
Machine code:

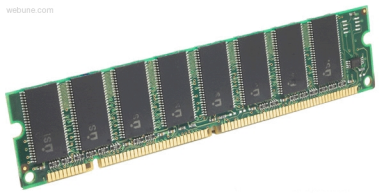
```
01110100000110000
10001101000001000000010
1000100111000010
11000001111110100011111
```

OS:



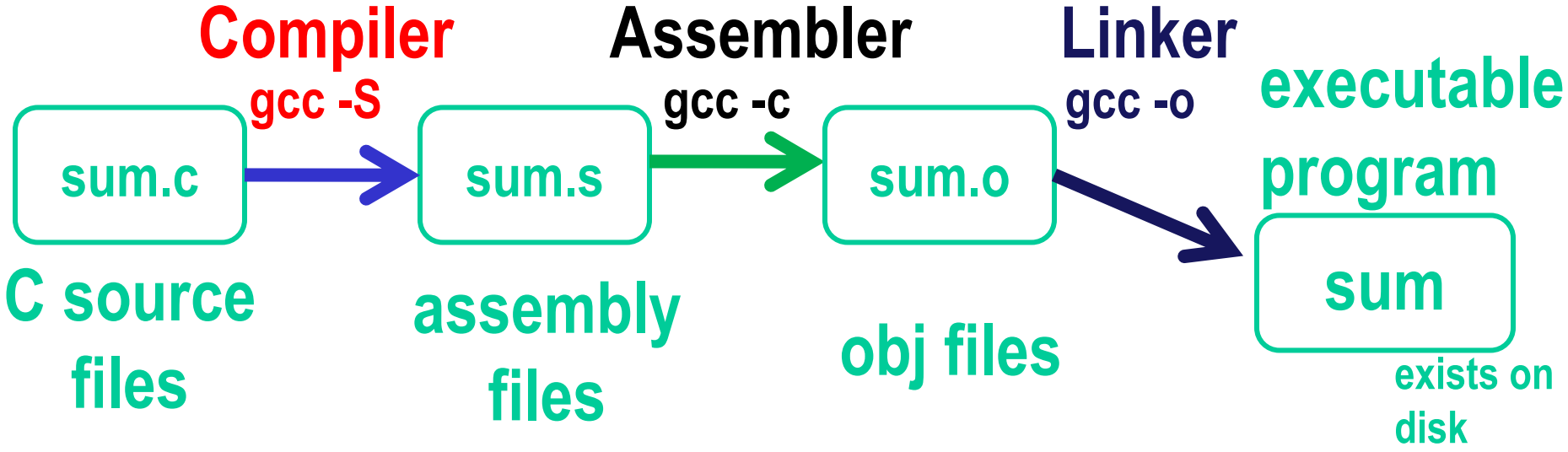
Computer system:





Memory & data
Arrays and Structs
Integers & floats
RISC V assembly
Procedures & stacks
Executables
Memory & caches
Processor Pipeline
Performance
Parallelism

From Writing to Running



When most people say "compile" they mean the entire process:

compile* + *assemble* + *link

"It's alive!"

Executing in Memory

process

Example: sum.c

- Compiler output is assembly files
- Assembler output is obj files
- Linker joins object files into one executable
- Loader brings it into memory and starts execution

Example: sum.c

```
#include <stdio.h>
int n = 100;
int main (int argc, char* argv[ ]) {
    int i;
    int m = n;
    int sum = 0;

    for (i = 1; i <= m; i++) {
        sum += i;
    }
    printf ("Sum 1 to %d is %d\n", n, sum);
}
```

Example: sum.c

- # Compile

```
[VM] riscv32-unknown-elf-gcc  -S sum.c
```

- # Assemble

```
[VM] riscv32-unknown-elf-gcc  -c sum.s
```

- # Link

```
[VM] riscv32-unknown-elf-gcc  -o sum sum.o
```

- # Load

```
[VM] qemu-riscv32 sum
Sum 1 to 100 is 5050
RISC-V program exits with status 0 (approx. 2007 instructions in 143000 nsec at 14.14034 MHz)
```

Compiler

Input: Code File (.c)

- Source code
- #includes, function declarations & definitions, global variables, *etc.*

Output: Assembly File (RISC-V)

- RISC-V assembly instructions

  (.s file)

```
for (i = 1; i <= m; i++) {
    sum += i;
}
```

```
li   x2,1
lw   x3,fp,28
slt  x2,x3,x2
```

sum.s (abridged)

```
        .globl  n
        .data
        .type    n, @object
n:      .word   100
        .rdata
$str0:  .string  "Sum 1 to %d is %d\n"
        .text
        .globl  main
        .type   main, @function
main:   addiu    $sp,$sp,-48
        sw       $ra,44($sp)
        sw       $fp,40($sp)
        move     $fp,$sp
        sw       $a0,-36($fp)   $a0
        sw       $a1,-40($fp)   $a1
        la       $a5,n
        lw       $a5,0($a5)     n=100
        sw       $a5,-28($fp)   m=n=100
        sw       $0,-24($fp)    sum=0
        li       $a5,1
        sw       $a5,-20($fp)   i=1
        lw       $a4,-20($fp)   i=1
        lw       $a5,-28($fp)   m=100
        blt      $a5,$a4,       if(m < i)
                                100 < 1
        lw       $a4,-24($fp)   0(sum)
        lw       $a5,-20($fp)   1(i)
        addu     $a5,$a4,$a5    1=(0+1)
        sw       $a5,-24($fp)   sum=1
        lw       $a5,-20($fp)   a5=i=1
        addi     $a5,$a5,1      i=2=(1+1)
        sw       $a5,-20($fp)   i=2
        j
        la   $a0 $4,$str0       str
        lw   $a1 $a1,-28($fp)   m=100
        lw   $a2 $a2,-24($fp)   sum
        jal      printf
        li       $a0,0          main returns 0
        mv       $sp,$fp
        lw       $ra,44($sp)
        lw       $fp,40($sp)
        addiu    $sp,$sp,48
        jr       $ra
```

prologue

call printf

epilogue

Assembler

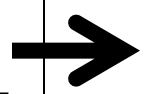
Input: Assembly File (.s)

- assembly instructions, pseudo-instructions
- program data (strings, variables), layout directives

Output: Object File in binary machine code RISC-V instructions in executable form

(.o file in Unix, .obj in Windows)

```
addi r5, r0, 10
muli r5, r5, 2
addi r5, r5, 15
```



```
00000000101000000000010100010011
00000000000100010100000101000000
00000000111100101000001010010011
```

RISC-V Assembly Instructions

Arithmetic/Logical

- ADD, SUB, AND, OR, XOR, SLT, SLTU
- ADDI, ANDI, ORI, XORI, LUI, SLL, SRL, SLTI, SLTIU
- MUL, DIV

Memory Access

- LW, LH, LB, LHU, LBU,
- SW, SH, SB

Control flow

- BEQ, BNE, BLE, BLT, BGE
- JAL, JALR

Special

- LR, SC, SCALL, SBREAK

Pseudo-Instructions

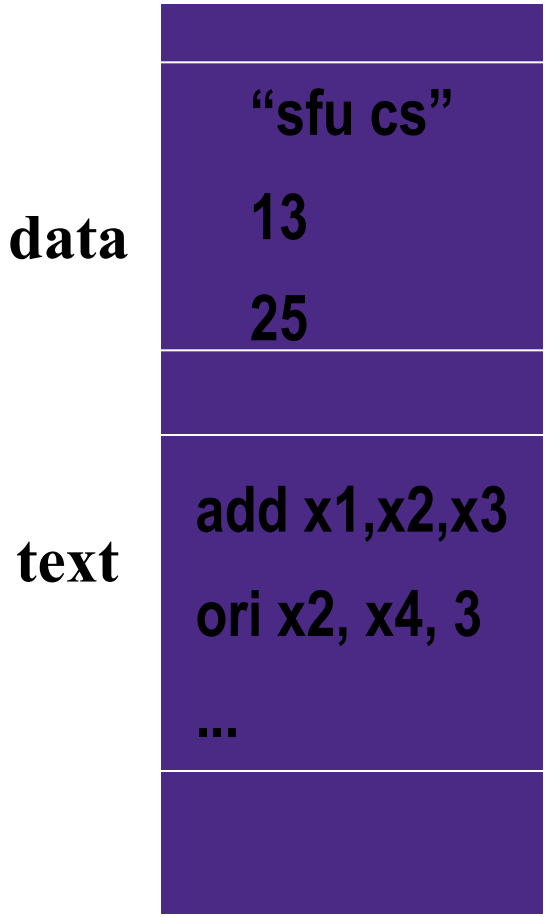
Assembly shorthand, technically not machine instructions, but easily converted into 1+ instructions that are

Pseudo-Insns	Actual Insns	Functionality
NOP	ADDI x0, x0, 0	# do nothing
MV reg, reg	ADD r2, r0, r1	# copy between regs
LI reg, 0x45678	LUI reg, 0x4 ORI reg, reg, 0x5678	#load immediate
LA reg, label		# load address (32 bits)
B label	BEQ x0, x0, label	# unconditional branch

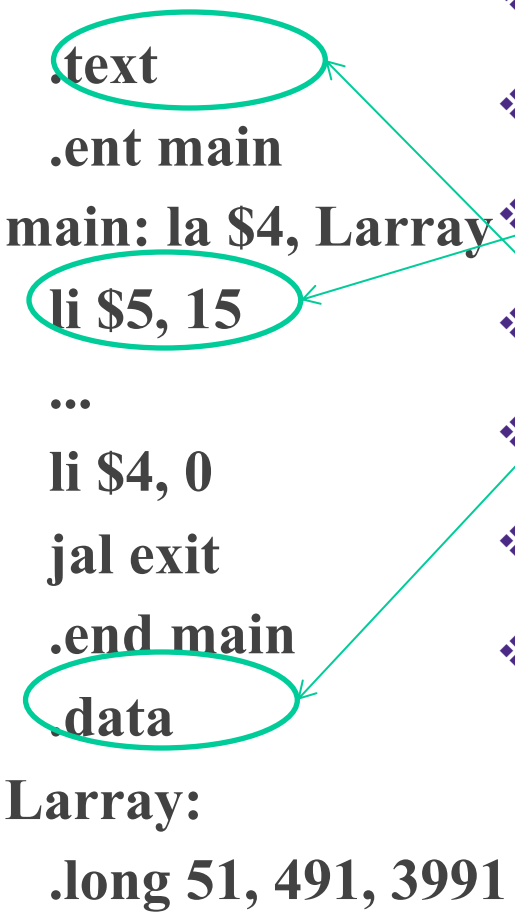
+ a few more…

Program Layout

- Programs consist of segments used for different purposes
  - Text: holds instructions
  - Data: holds statically allocated program data such as variables, strings, etc.



Assembling Programs



- Assembly files consist of a mix of
- + instructions
- + pseudo-instructions
- + assembler (data/layout) directives
  (Assembler lays out binary values in memory based on directives)
- Assembled to an Object File
  - Header
  - Text Segment
  - Data Segment
  - Relocation Information
  - Symbol Table
  - Debugging Information

math.c

Symbols and References

```
int pi = 3;
int e = 2;
static int randomval = 7;

extern int usrid;
extern int printf(char *str, …);

int square(int x) { … }
static int is_prime(int x) { … }
int pick_prime() { … }
int get_n() {
        return usrid;
}
```

(extern == defined in another file)

Global labels: Externally visible "exported" symbols

- Can be referenced from other object files
- Exported functions, global variables
- Examples: pi, e, userid, printf, pick_prime, pick_random

Local labels: Internally visible only

- Only used within this object file
- static functions, static variables, loop labels, …
- Examples: randomval, is_prime

Producing Machine Language (1/3)

- Simple Cases
  - Arithmetic and logical instructions, shifts, etc.
  - All necessary info contained in the instruction
- What about Branches and Jumps?
  - Branches and Jumps require a *relative address*
  - Once pseudo-instructions are replaced by real ones, we know by how many instructions to branch, so no problem

Producing Machine Language (2/3)

- "Forward Reference" problem
  - Branch instructions can refer to labels that are "forward" in the program:

```
     or   s0, x0,  x0
L1:  slt  t0, x0,  a1
     beq  t0, x0,  L2
     addi a1, a1, -1
     j    L1
L2:  add  t1, a0, a1
```

  - Solution: Make two passes over the program

Two Passes Overview

- Pass 1:
  - Expands pseudo instructions encountered
  - Remember position of labels
  - Take out comments, empty lines, etc
  - Error checking
- Pass 2:
  - Use label positions to generate relative addresses (for branches and jumps)
  - Outputs the object file, a collection of instructions in binary code

Handling forward references

Example:

```
        bne x1, x2, L
        sll x0, x0, 0
L:   addi x2, x3, 0x2
```

The assembler will change this to

```
bne x1, x2, +8
sll x0, x0, 0
addi x2, x3, 0x2
```

Final machine code

```
0X00208413 # bne
0x00001033 # sll
0x00018113 # addi
```

actually:

```
0000 0000 0010...
0000 0000 0000...
0000 0000 0000...
```

Object file

Object File

Header

- Size and position of pieces of file

Text Segment

- instructions

Data Segment

- static data (local/global vars, strings, constants)

Debugging Information

- line number → code address map, *etc.*

Symbol Table

- External (exported) references
- Unresolved (imported) references

Object File Formats

Unix

- a.out
- COFF: Common Object File Format
- ELF: Executable and Linking Format

Windows

- PE: Portable Executable

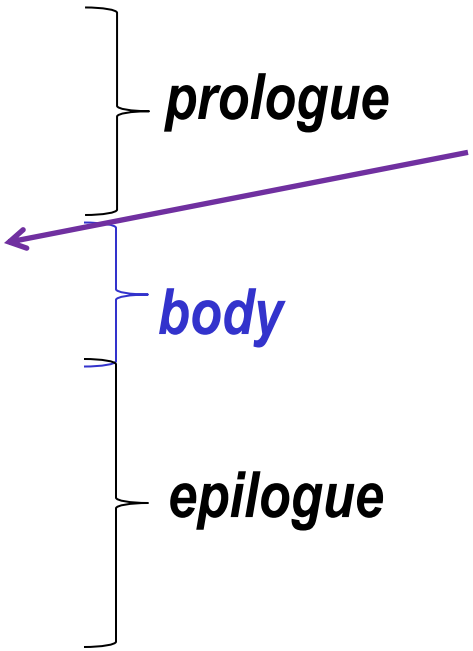
All support both executable and object files

Objdump disassembly

```
> riscv32-unknown-elf--objdump --disassemble math.o
```

Disassembly of section .text:

```
00000000 <get_n>:
   0:   27bdfff8  addi sp,sp,-8
   4:   afbe0000  sw   fp,0(sp)
   8:   03a0f021  mv   fp,sp
   c:   3c020000  lui  a0,
  10:   8c420008  lw   a0,8(a0)
  14:   03c0e821  mv    sp,fp
  18:   8fbe0000  lw   fp,0(sp)
  1c:   27bd0008  addi sp,sp,8
  20:   03e00008  jr   ra
```



elsewhere in another file: int = 41;

```
int get_n() {
  return    ;
}
```

Objdump symbols

[f]unction
[O]bject
[l]ocal
[g]lobal

```
> riscv-unknown-elf--objdump --syms math.o
```

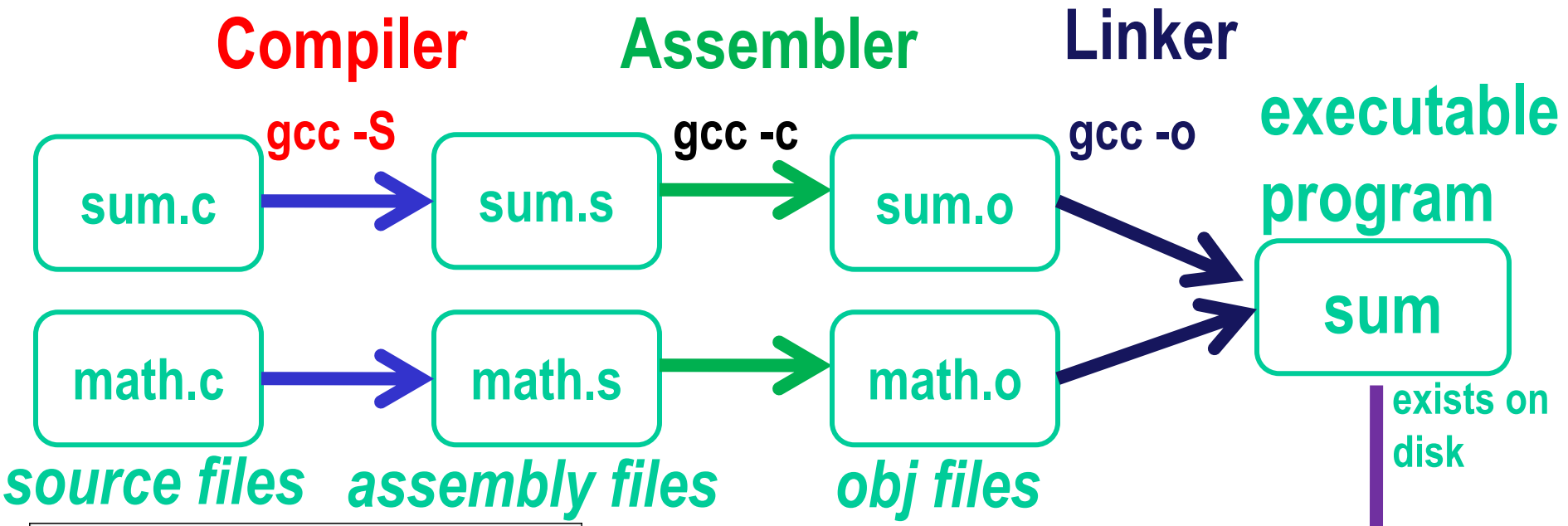
segment *size*

```
SYMBOL TABLE:
00000000 l  df *ABS*                00000000 math.c
00000000 l  d  .text                00000000 .text
00000000 l  d  .data                00000000 .data
00000000 l  d  .bss                 00000000 .bss
00000008 l  O  .data                00000004 randomval
00000060 l     .text                00000028 is_prime
00000000 l  d  .rodata              00000000 .rodata
00000000 l  d  .comment             00000000 .comment
00000000 g  O  .data                00000004 pi
00000004 g  O  .data                00000004 e
00000000 g     .text                00000028 get_n
00000028 g     .text                00000038 square
00000088 g     .text                0000004c pick_prime
00000000       *UND*                00000000 usrid
00000000       *UND*                00000000 printf
```

static local fn
@ addr 0x60
size = 0x28 bytes

external references (undefined)

Separate Compilation & Assembly



http://xkcd.com/303/

small change ?

→ **recompile one module only**

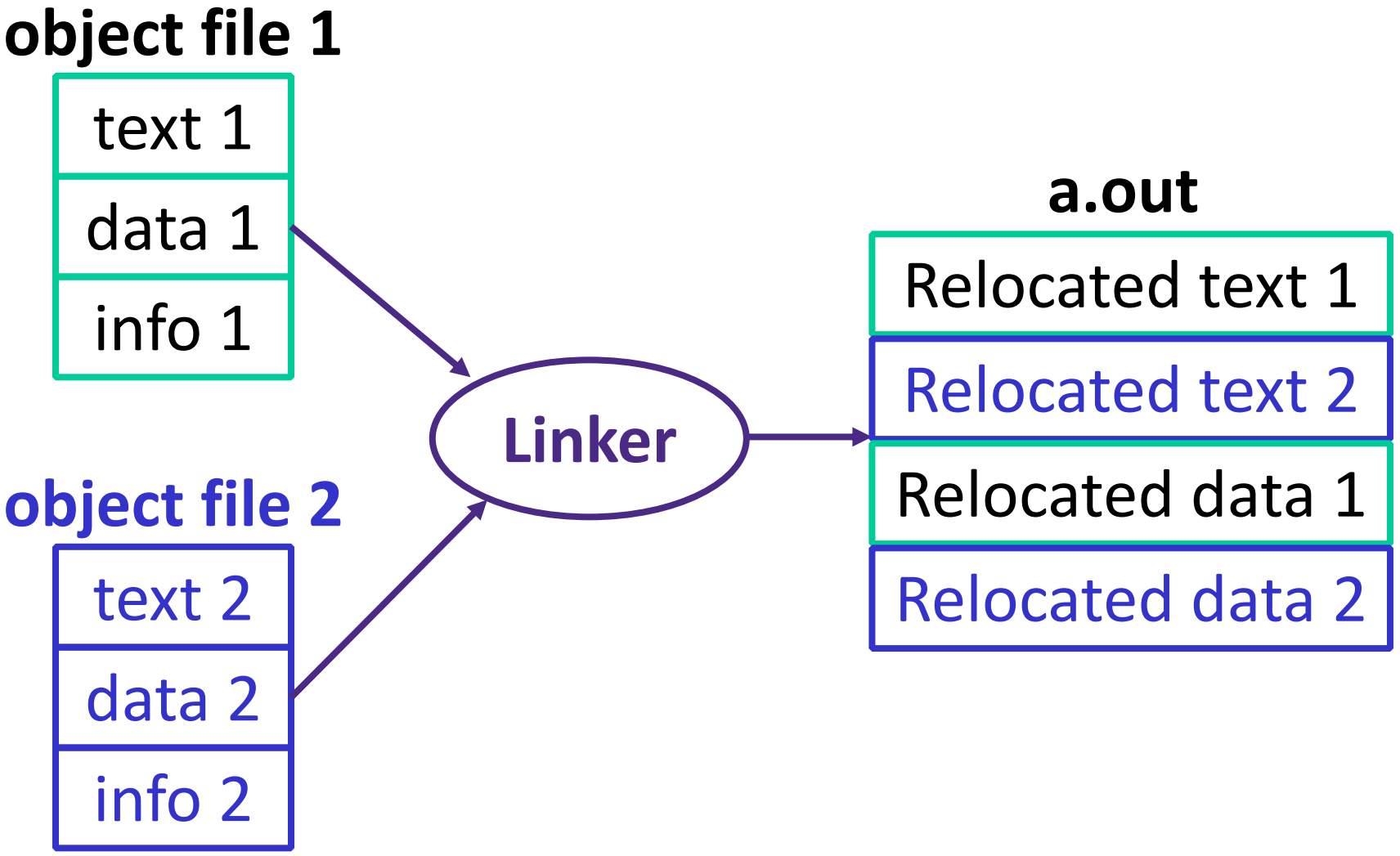
Executing in Memory process

Linker (1/3)

- **Input:** Object Code files, information tables (e.g. `foo.o`, `lib.o` for RISC-V)
- **Output:** Executable Code (e.g. `a.out` for RISC-V)

- Combines several object (`.o`) files into a single executable ("linking")
- Enables separate compilation of files
  - Changes to one file do not require recompilation of whole program
  - Old name "Link Editor" from editing the "links" in jump and link instructions

Linker (2/3)


object file 1
text 1
data 1
info 1
object file 2
text 2
data 2
info 2
Linker
a.out
Relocated text 1
Relocated text 2
Relocated data 1
Relocated data 2

Linker (3/3)

1) Take text segment from each .o file and put them together
2) Take data segment from each .o file, put them together, and concatenate this onto end of text segments
3) Resolve References
   - Go through Relocation Table; handle each entry
   - i.e. fill in all absolute addresses

Resolving References (1/2)

- Linker assumes the first word of the first text segment is at 0x10000 for RV32.
  - More later when we study “virtual memory”
- Linker knows:
  - Length of each text and data segment
  - Ordering of text and data segments
- Linker calculates:
  - Absolute address of each label to be jumped to (internal or external) and each piece of data being referenced

Resolving References (2/2)

- To resolve references:
  1) Search for reference (data or label) in all "user" symbol tables
  2) If not found, search library files (e.g. `printf`)
  3) Once absolute address is determined, fill in the machine code appropriately
- Output of linker: executable file containing text and data (plus header)

Three Types of Addresses

- PC-Relative Addressing (beq, bne, jal)
  - never relocate

External Function Reference (usually jal)
  - always relocate

Static Data Reference (often auipc and addi)
  - always relocate
  - RISC-V often uses auipc rather than lui so that a big block of stuff can be further relocated as long as it is fixed relative to the pc

Static Libraries

Static Library: Collection of object files
(think: like a zip archive)

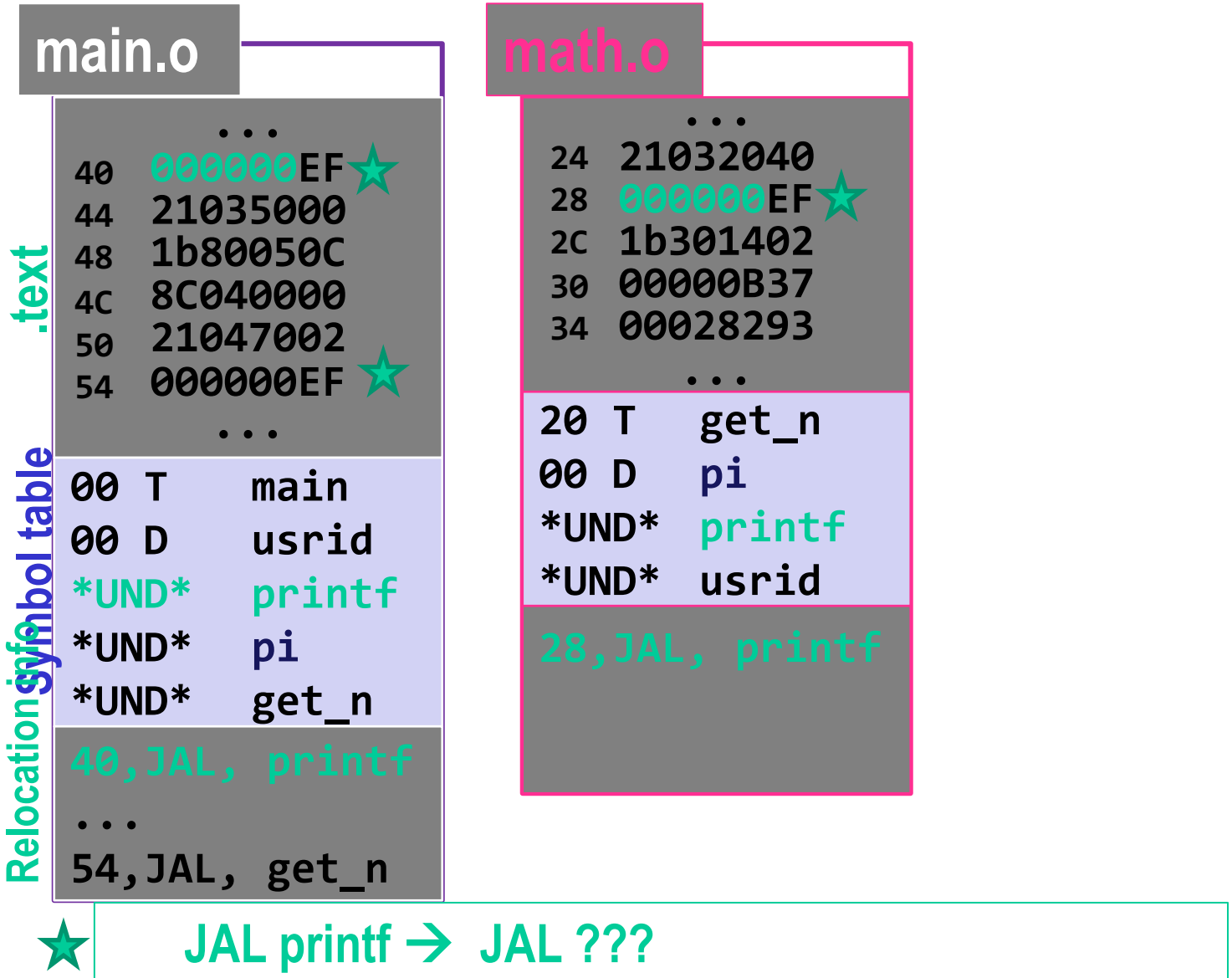
Q: Every program contains the entire library?!?

A: No, Linker picks only object files needed to resolve undefined references at link time

e.g. libc.a contains many objects:

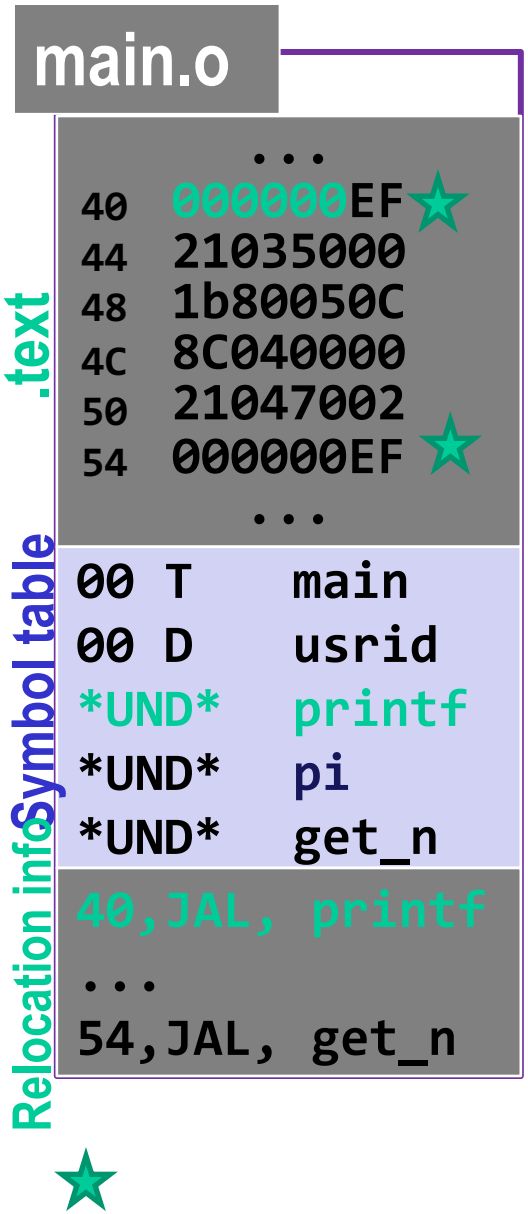
- printf.o, fprintf.o, vprintf.o, sprintf.o, snprintf.o, …
- read.o, write.o, open.o, close.o, mkdir.o, readdir.o, …
- rand.o, exit.o, sleep.o, time.o, ….

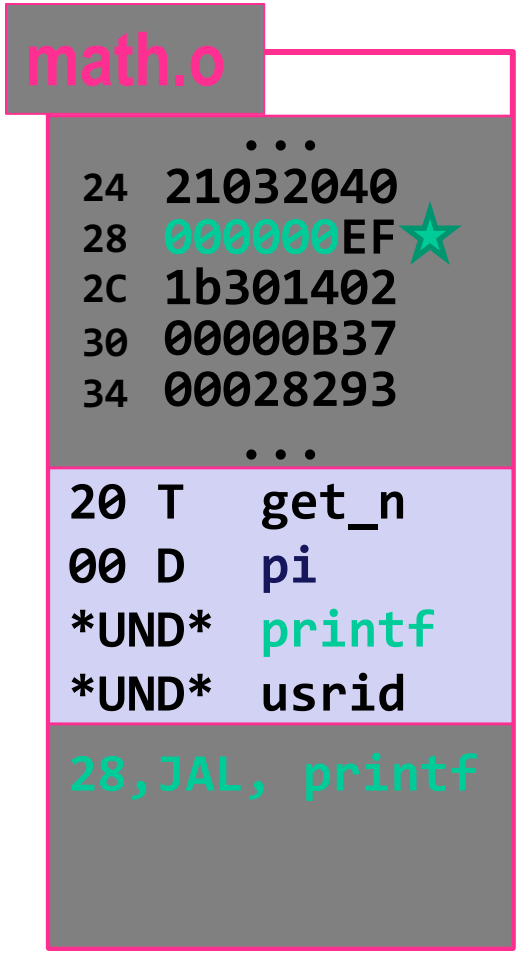
Linker Example: Resolving an External Fn Call

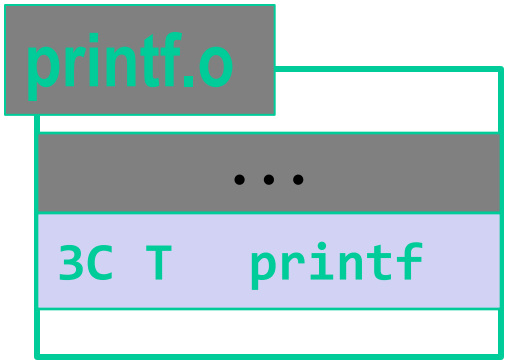


JAL printf → JAL ???

Unresolved references to printf and get_n



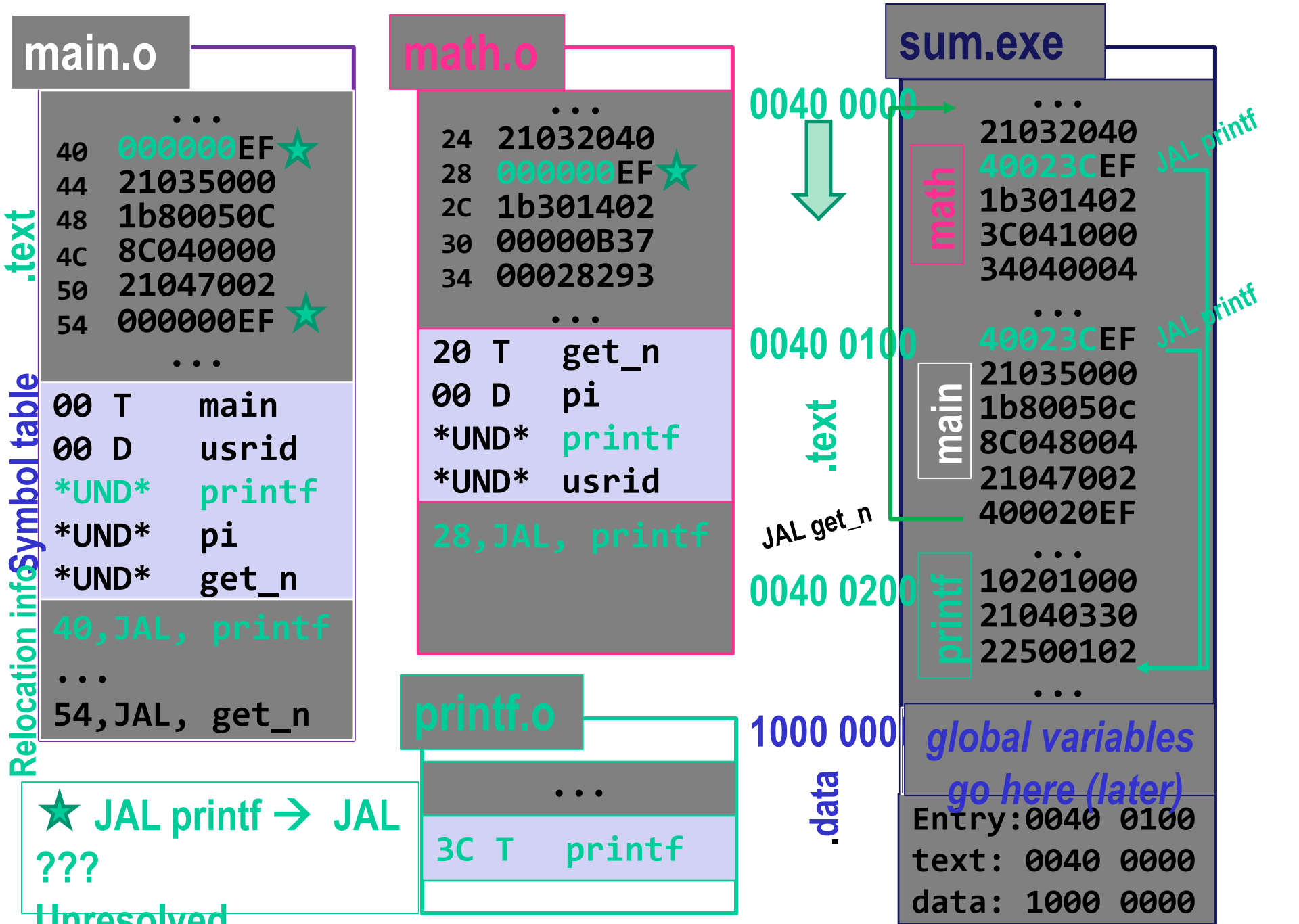


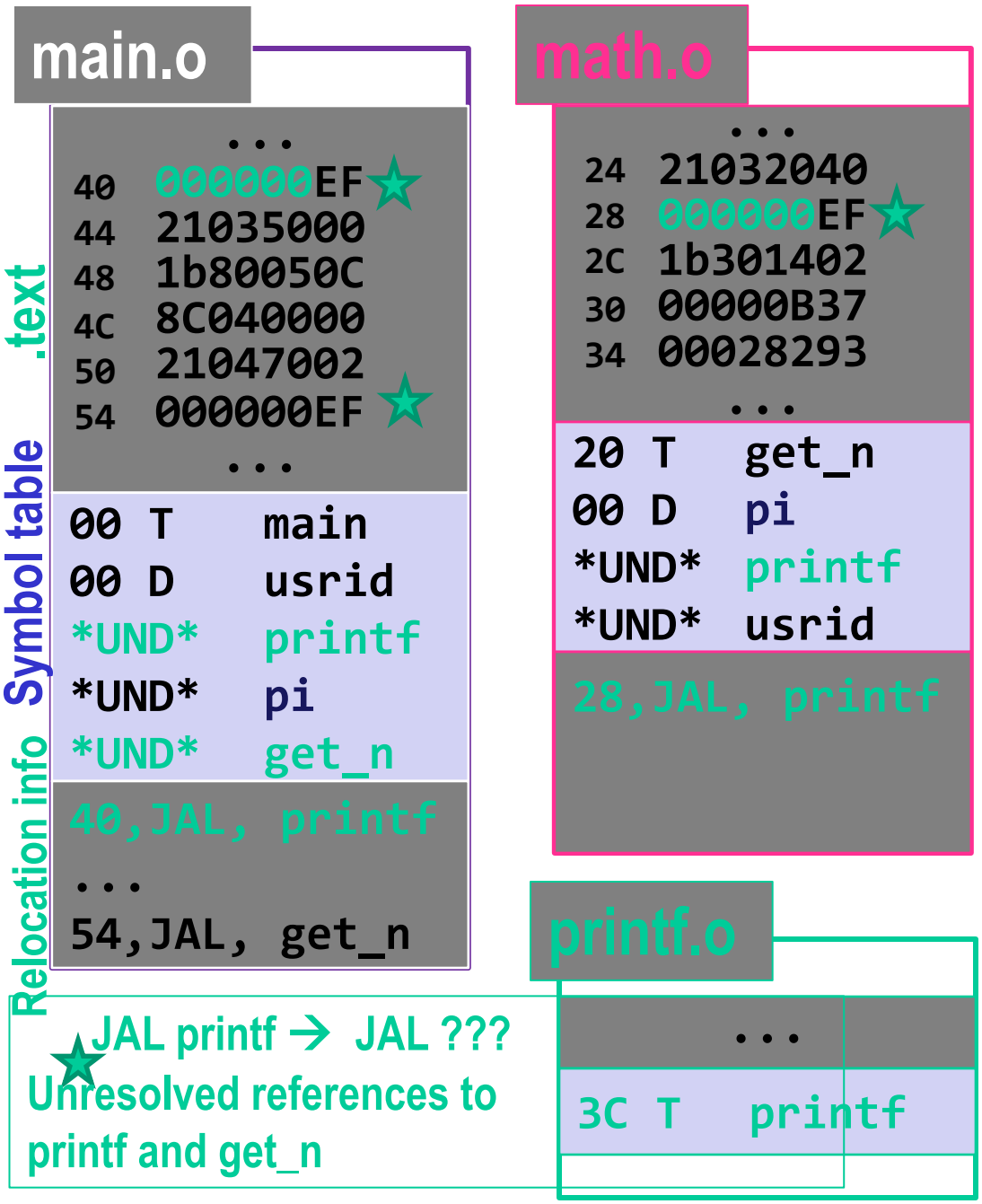


Which symbols are undefined according to **both** main.o and math.o's symbol table?

A) printf
B) pi
C) get_n
D) usr
E) printf & pi

JAL printf → JAL ???
Unresolved references to printf and get_n

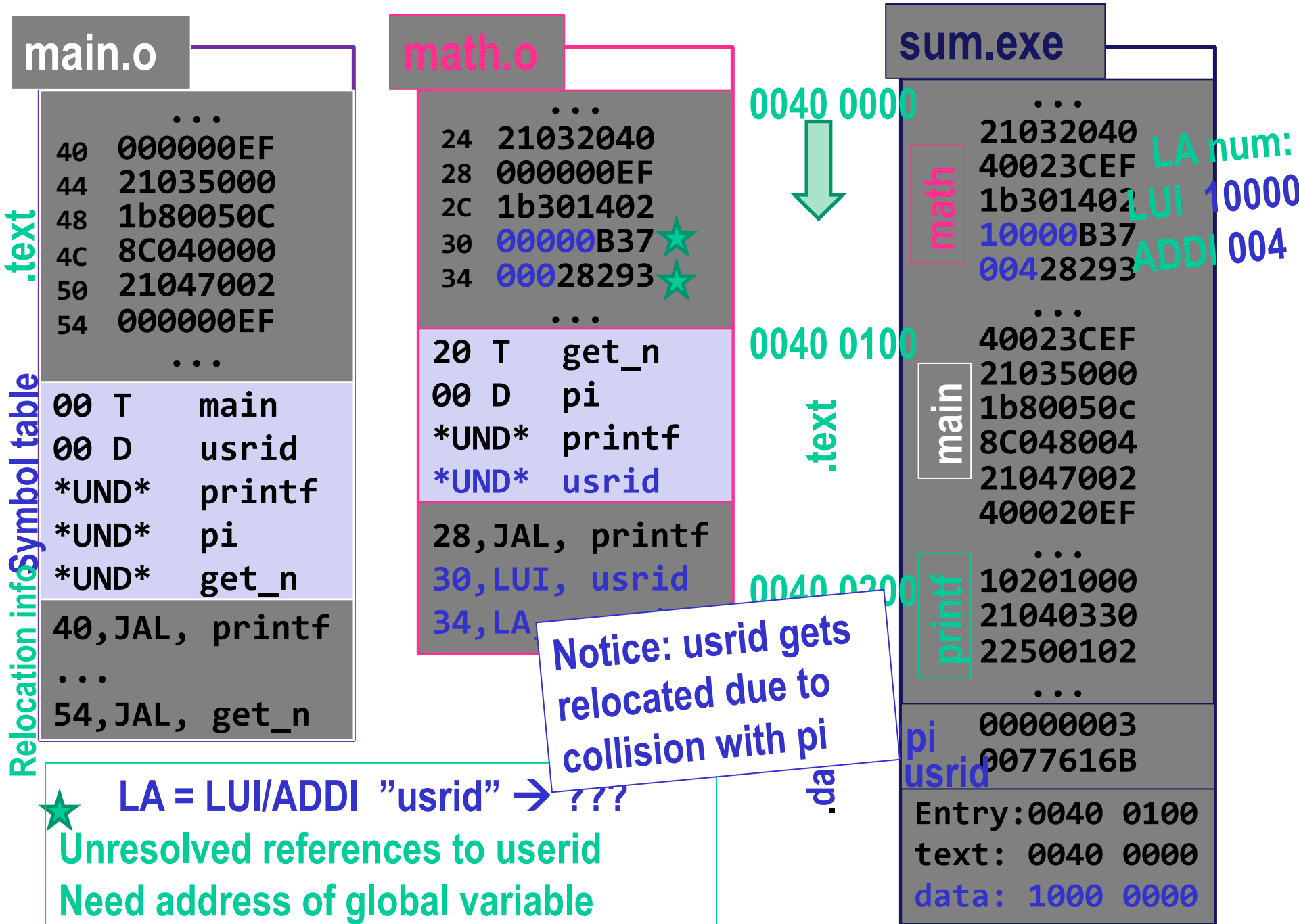

main.o
...
40 000000EF
44 21035000
48 1b80050C
4C 8C040000
50 21047002
54 000000EF
...
.text
00 T main
00 D usrid
UND printf
UND pi
UND get_n
Symbol table
40,JAL, printf
...
54,JAL, get_n
Relocation info
math.o
...
24 21032040
28 000000EF
2C 1b301402
30 00000B37
34 00028293
...
20 T get_n
00 D pi
UND printf
UND usrid
28,JAL, printf
printf.o
...
3C T printf
JAL printf → JAL ???
Unresolved
sum.exe
0040 0000
0040 0100
0040 0200
1000 000
.text
.data
math
main
printf
JAL get_n
JAL printf
JAL printf
...
21032040
40023CEF
1b301402
3C041000
34040004
...
40023CEF
21035000
1b80050c
8C048004
21047002
400020EF
...
10201000
21040330
22500102
...
global variables go here (later)
Entry:0040 0100
text: 0040 0000
data: 1000 0000



Question 2

Which which 2 symbols are currently assigned the same location?

A) main & printf
B) usrid & pi
C) get_n & printf
D) main & usrid
E) main & pi


main.o
...
40 000000EF
44 21035000
48 1b80050C
4C 8C040000
50 21047002
54 000000EF
...
.text
00 T main
00 D usrid
UND printf
UND pi
UND get_n
Symbol table
40,JAL, printf
...
54,JAL, get_n
Relocation info
math.o
...
24 21032040
28 000000EF
2C 1b301402
30 00000B37
34 00028293
...
.text
20 T get_n
00 D pi
UND printf
UND usrid
28,JAL, printf
30,LUI, usrid
34,LA
.da
0040 0000
0040 0100
0040 0200
sum.exe
...
math
21032040
40023CEF
1b301402
10000B37
00428293
...
main
40023CEF
21035000
1b80050c
8C048004
21047002
400020EF
...
printf
10201000
21040330
22500102
...
pi
usrid
00000003
0077616B
Entry:0040 0100
text: 0040 0000
data: 1000 0000
LA num:
LUI 10000
ADDI 004
Notice: usrid gets relocated due to collision with pi
LA = LUI/ADDI "usrid" → ???
Unresolved references to userid
Need address of global variable

Question

Where does the assembler place the following symbols in the object file that it creates?

A. Text Segment
B. Data Segment
C. Exported reference in symbol table
D. Imported reference in symbol table
E. None of the above

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

#define HEAP SIZE 16
static int ARR SIZE = 4;

int main() {
   char heap[HEAP SIZE];
   hl_init(heap, HEAP SIZE * sizeof(char));
   char* ptr = (char *) hl alloc(heap, ARR SIZE * sizeof(char));
   ptr[0] = 'h';
   ptr[1] = 'i';
   ptr[2] = '\0';
   printf(%s\n, ptr); return 0;
}
```

Q1: HEAP_SIZE
Q2: ARR_SIZE
Q3: hl_init

Loader

- **Input:**Executable Code (e.g. `a.out` for RISC-V)
- **Output:** <program is run>

- Executable files are stored on disk
- When one is run, loader's job is to load it into memory and start it running
- In reality, loader is the operating system (OS)
  - loading is one of the OS tasks

Loader

1) Reads executable file's header to determine size of text and data segments
2) Creates new address space for program large enough to hold text and data segments, along with a stack segment
   <more on this later>
3) Copies instructions and data from executable file into the new address space

Loader

4) Copies arguments passed to the program onto the stack
5) Initializes machine registers
   - Most registers cleared, but stack pointer assigned address of 1st free stack location
6) Jumps to start-up routine that copies program's arguments from stack to registers and sets the PC
   - If main routine returns, start-up routine terminates program with the exit system call

Shared Libraries

Q: Every program contains parts of same library?!?

A: No, they can use shared libraries

- Executables all point to single *shared library* on disk
- final linking (and relocations) done by the loader

Optimizations:

- Library compiled at fixed non-zero address
- Jump table in each program instead of relocations
- Can even patch jumps on-the-fly

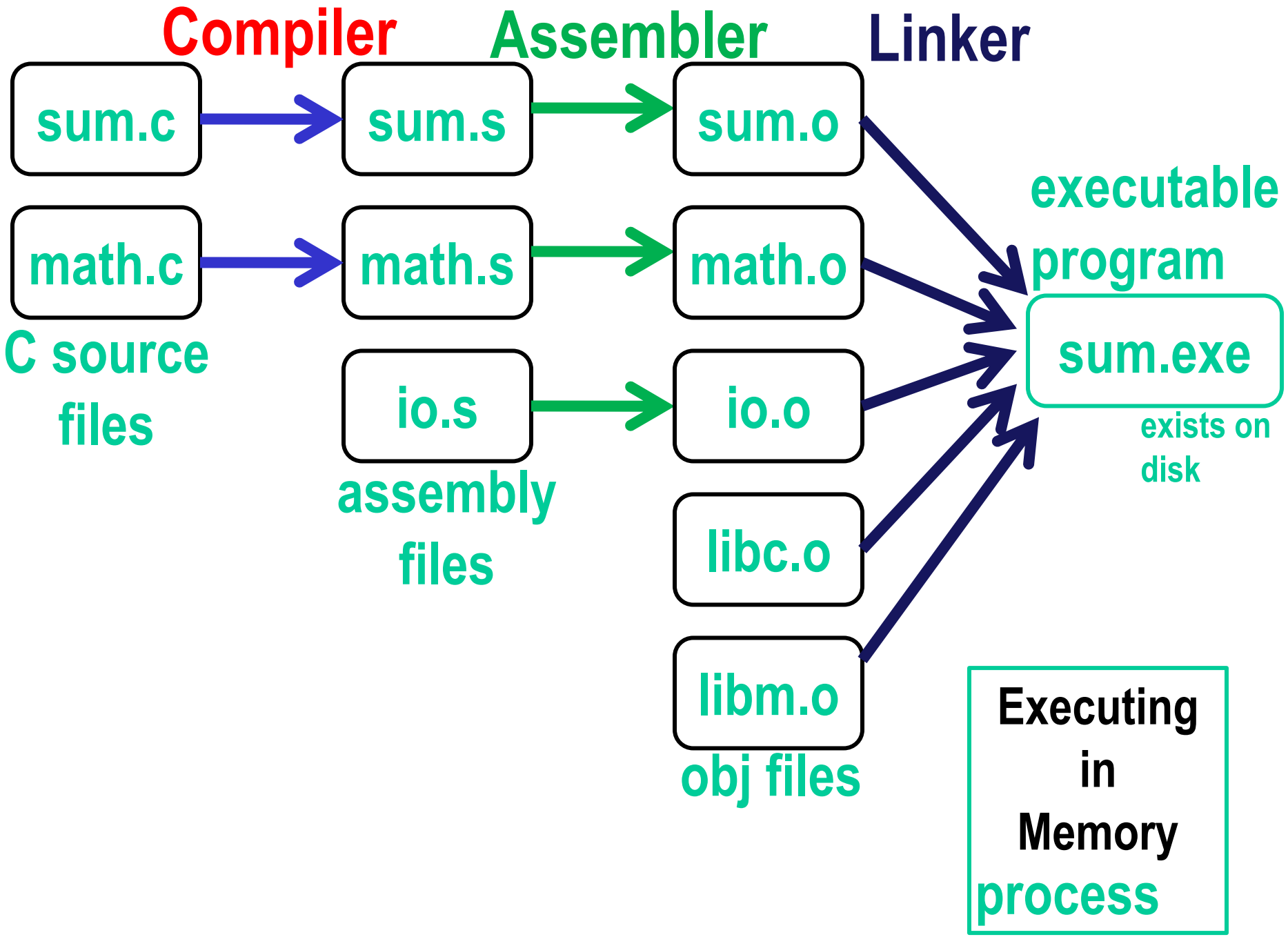
Static and Dynamic Linking

Static linking

- Big executable files (all/most of needed libraries inside)
- Don’t benefit from updates to library
- No load-time linking

Dynamic linking

- Small executable files (just point to shared library)
- Library update benefits all programs that use it
- Load-time cost to do final linking
  - But dll code is probably already in memory
  - And can do the linking incrementally, on-demand


Compiler
Assembler
Linker
sum.c
math.c
C source files
sum.s
math.s
io.s
assembly files
sum.o
math.o
io.o
libc.o
libm.o
obj files
executable program
sum.exe
exists on disk
Executing in Memory process

Summary

Compiler produces assembly files

(contain RISC-V assembly, pseudo-instructions, directives, etc.)

Assembler produces object files

(contain RISC-V machine code, missing symbols, some layout information, etc.)

Linker joins object files into one executable file

(contains RISC-V machine code, no missing symbols, some layout information)

Loader puts program into memory, jumps to 1st insn, and starts executing a *process* (machine code)

Peer Question

At what point in process are all the machine code bits determined for the following assembly instructions:

1) `add x6, x7, x8`

2) `jal x1, fprintf`

A: 1) & 2) After compilation

B: 1) After compilation, 2) After assembly

C: 1) After assembly, 2) After linking

D: 1) After assembly, 2) After loading

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