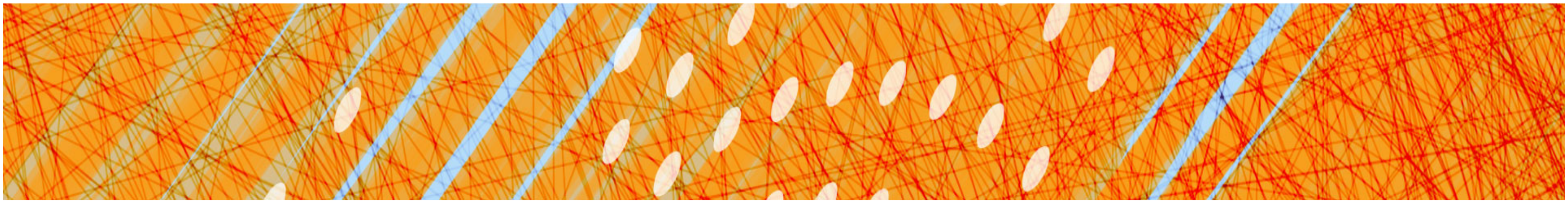


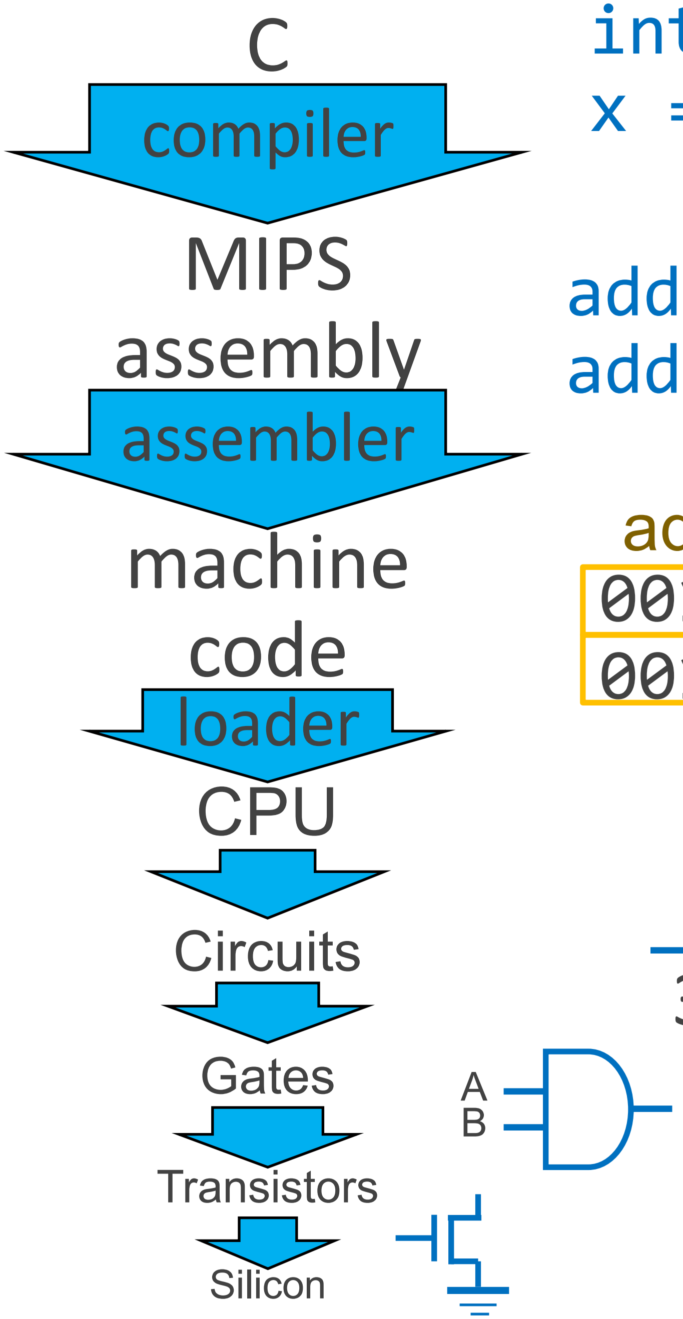
Assemblers, Linkers, and Loaders

CS 3410
Computer System Organization & Programming

Cornell CIS
COMPUTING AND INFORMATION SCIENCE

[K. Bala, A. Bracy, E. Sirer, and H. Weatherspoon]

Big Picture: Where are we going?



```
int x = 10;
x = x + 15;
```

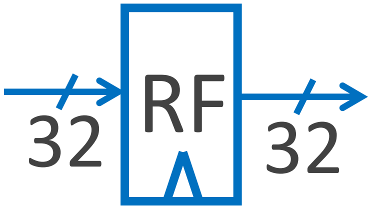
```
addi r5, r0, 10
addi r5, r5, 15
```

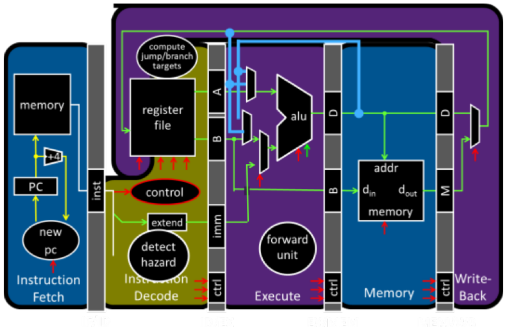
r0 = 0

r5 = r0 + 10

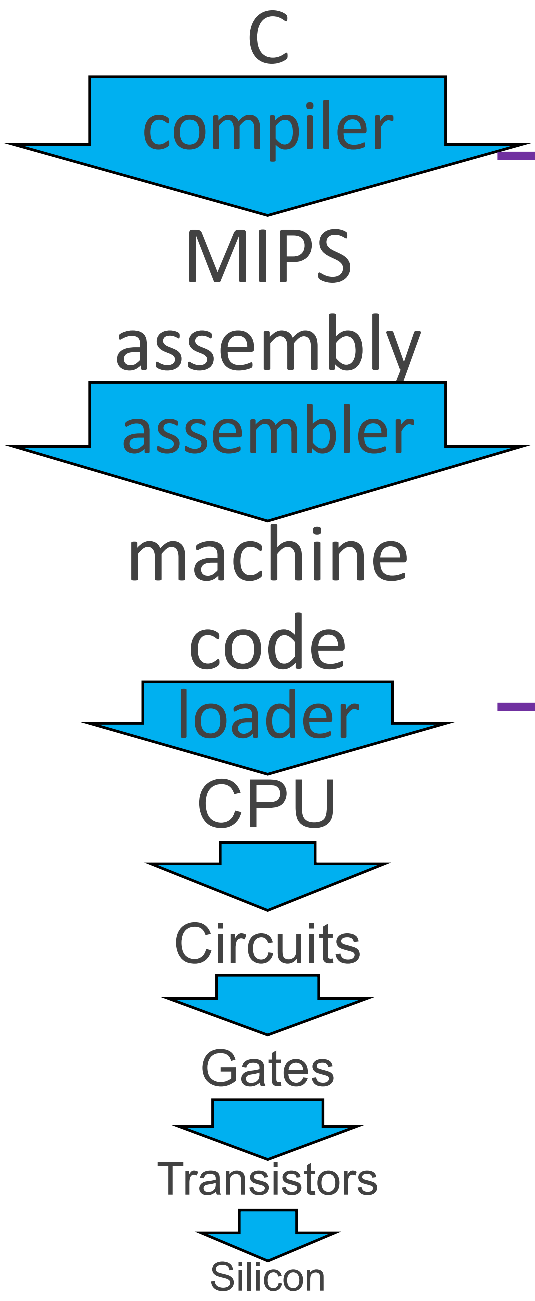
r5 = r15 + 15

addi	r0	r5	10
001000	00000	00101	0000000000001010
001000	00101	00101	0000000000001111





Big Picture: Where are we going?


C

compiler

MIPS assembly

assembler

machine code

loader

CPU

Circuits

Gates

Transistors

Silicon

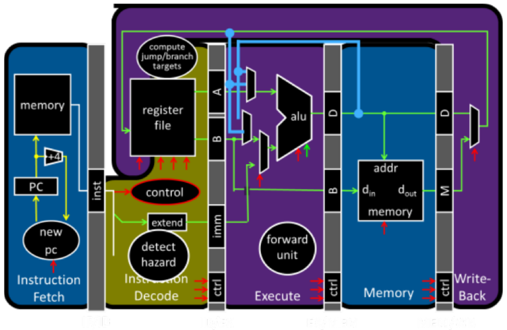
```
int x = 10;
x = 2 * x + 15;
```

High Level Languages

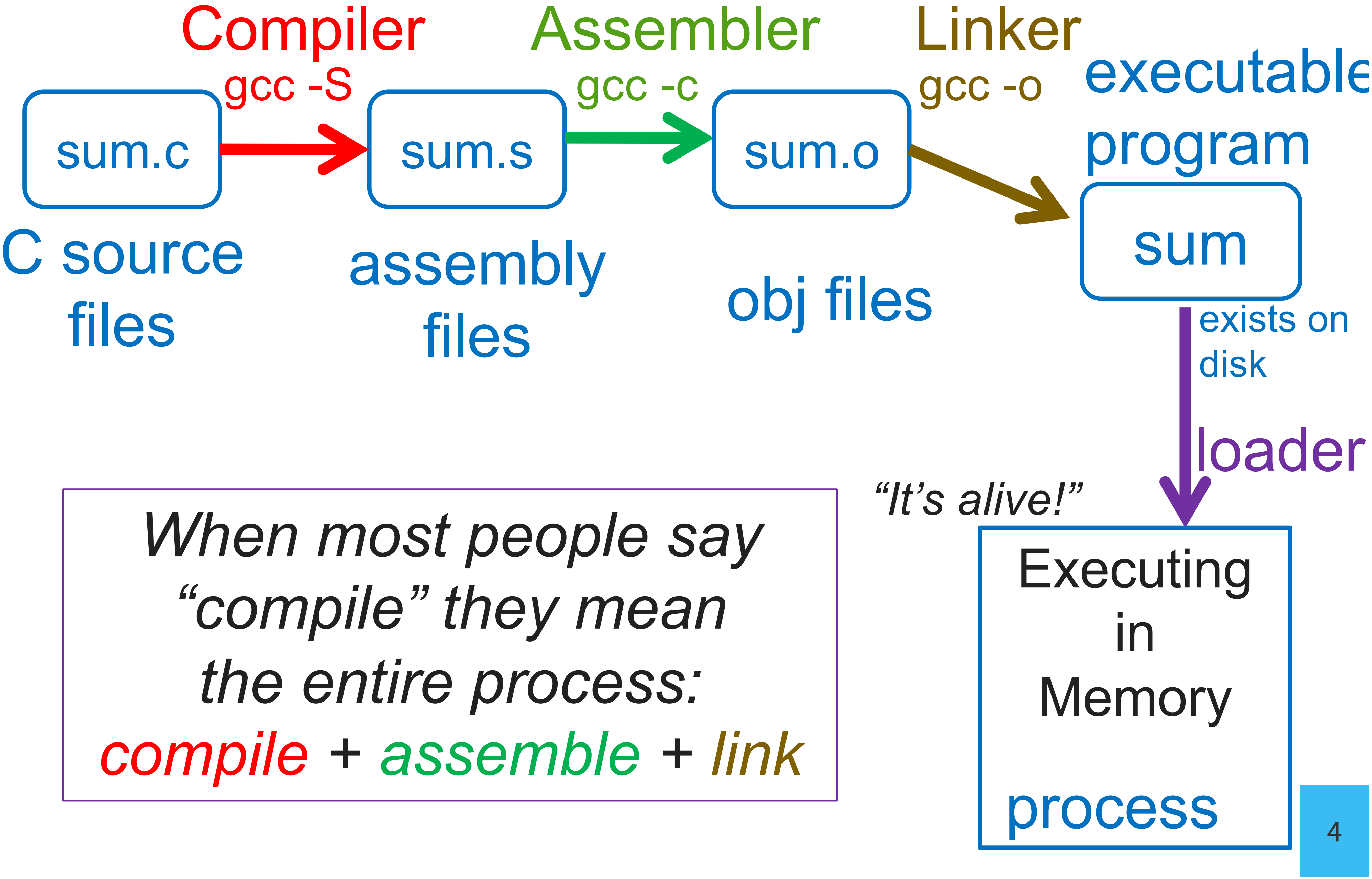
```
addi r5, r0, 10
muli r5, r5, 2
addi r5, r5, 15
```

```
00100000000001010000000000001010
00000000000001010010100001000000
00100000101001010000000
```

Instruction Set Architecture (ISA)



From Writing to Running



Compiler

gcc -S

Assembler

gcc -c

Linker

gcc -o

sum.c

C source files

sum.s

assembly files

sum.o

obj files

executable program

sum

exists on disk

loader

“It’s alive!”

Executing in Memory

process

When most people say “compile” they mean the entire process:
compile + assemble + link

sum.c

```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);
}
```

Compiler

Input: Code File (.c)

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

Output: Assembly File (MIPS)

- MIPS assembly instructions (.s file)

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

```
li  $2,1
lw  $3,28($fp)
slt $2,$3,$2
```

sum.s (abridged)

```
        .globl   n
        .data
        .type     n, @object
n:      .word    100
        .rdata
$str0:  .ascii   "Sum 1 to %d is %d\n"
        .text
        .globl   main
        .type    main, @function
main:    addiu    $sp,$sp,-48
         sw       $31,44($sp)
         sw       $fp,40($sp)
         move     $fp,$sp
         sw       $4,48($fp)
         sw       $5,52($fp)
         la       $2,n
         lw       $2,0($2)
         sw       $2,28($fp)
         sw       $0,32($fp)
         li       $2,1
         sw       $2,24($fp)
```

```
$L2:    lw       $2,24($fp)
        lw       $3,28($fp)
        slt      $2,$3,$2
        bne      $2,$0,$L3
        lw       $3,32($fp)
        lw       $2,24($fp)
        addu     $2,$3,$2
        sw       $2,32($fp)
        lw       $2,24($fp)
        addiu    $2,$2,1
        sw       $2,24($fp)
        b        $L2
$L3:    la       $4,$str0
        lw       $5,28($fp)
        lw       $6,32($fp)
        jal      printf
        move     $sp,$fp
        lw       $31,44($sp)
        lw       $fp,40($sp)
        addiu    $sp,$sp,48
        j        $31
```

sum.s (abridged)

```
        .globl  n
        .data
        .type   n, @object
n:      .word   100
        .rdata
$str0:  .ascii  "Sum 1 to %d is %d\n"
        .text
        .globl  main
        .type   main, @function
main:   addiu   $sp,$sp,-48
        sw      $31,44($sp)
        sw      $fp,40($sp)
        move    $fp,$sp
        sw      $4,48($fp)      $a0
        sw      $5,52($fp)      $a1
        la      $2,n            $v0
        lw      $2,0($2)        $v0=100
        sw      $2,28($fp)      m=100
        sw      $0,32($fp)      sum=0
        li      $2,1
        sw      $2,24($fp)      i=1
```

prologue

```
$L2:    lw      $2,24($fp)      i=1
        lw      $3,28($fp)      m=100
        slt     $2,$3,$2        if(m < i)
        bne     $2,$0,$L3       100 < 1
        lw      $3,32($fp)      v1=0(sum)
        lw      $2,24($fp)      v0=1(i)
        addu    $2,$3,$2        v0=1(0+1)
        sw      $2,32($fp)      sum=1
        lw      $2,24($fp)      i=1
        addiu   $2,$2,1         i=2 (1+1)
        sw      $2,24($fp)      i=2
        b       $L2
$L3:    la   $a0 $4,$str0       str
        lw   $a1 $5,28($fp)     m=100
        lw   $a2 $6,32($fp)     sum
        jal     printf
        move    $sp,$fp
        lw      $31,44($sp)
        lw      $fp,40($sp)
        addiu   $sp,$sp,48
        j       $31
```

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

MIPS instructions in executable form

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

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

→

```
00100000000001010000000000001010
00000000000001010010100001000000
00100000101001010000000000001111
```

MIPS Assembly Instructions

Arithmetic/Logical

- ADD, ADDU, SUB, SUBU, AND, OR, XOR, NOR, SLT, SLTU
- ADDI, ADDIU, ANDI, ORI, XORI, LUI, SLL, SRL, SLLV, SRLV, SRAV, SLTI, SLTIU
- MULT, DIV, MFLO, MTLO, MFHI, MTHI

Memory Access

- LW, LH, LB, LHU, LBU, LWL, LWR
- SW, SH, SB, SWL, SWR

Control flow

- BEQ, BNE, BLEZ, BLTZ, BGEZ, BGTZ
- J, JR, JAL, JALR, BEQL, BNEL, BLEZL, BGTZL

Special

- LL, SC, SYSCALL, BREAK, SYNC, COPROC

Pseudo-Instructions

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

Pseudo-Insns	Actual Insns	Functionality
NOP	SLL r0, r0, 0	# do nothing
MOVE reg, reg	ADD r2, r0, r1	# copy between regs
LI reg, 0x45678	LUI reg, 0x4 ORI reg, reg, 0x5678	#load immediate
BLT reg, reg, label	SLT r1, rA, rB BNE r1, r0, label	# branch less than

+ *a few more…*

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 symbols

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

Handling forward references

Example:

```
          bne $1, $2, L        Looking for L
          sll $0, $0, 0
      L: addiu $2, $3, 0x2     Found L
```

The assembler will change this to

```
        bne $1, $2, +1
        sll $0, $0, 0
        addiu $2, $3, $0x2
```

Final machine code

```
  0X14220001 # bne       actually:   000101...
  0x00000000 # sll                   000000...
  0x24620002 # addiu                 001001...
```

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

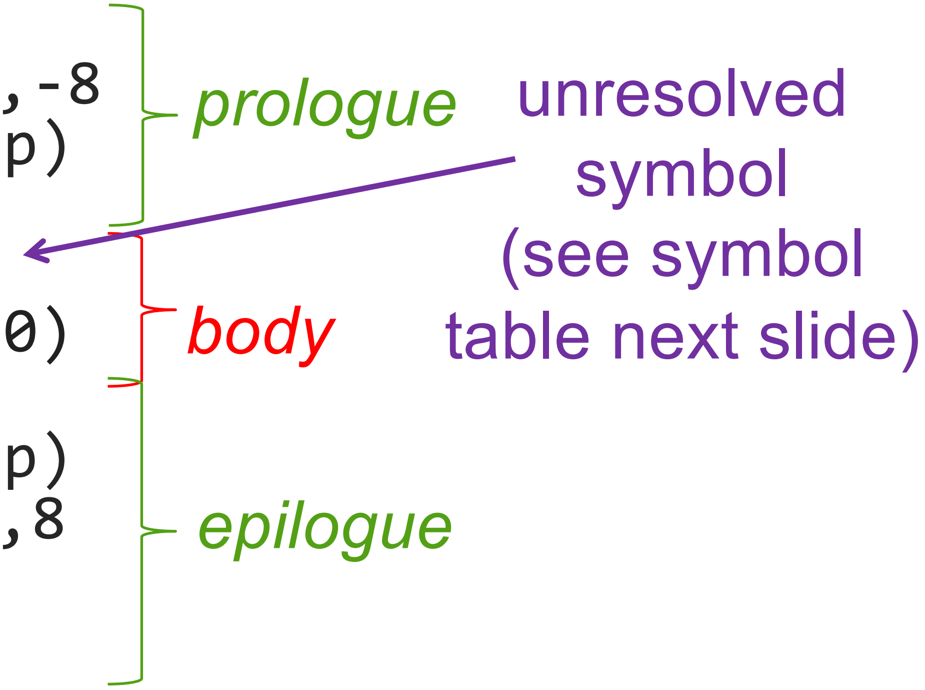
All support both executable and object files

Objdump disassembly

```
> objdump --disassemble math.o

Disassembly of section .text:

00000000 <get_n>:
   0:   27bdfff8  addiu sp,sp,-8
   4:   afbe0000  sw    s8,0(sp)
   8:   03a0f021  move  s8,sp
   c:   3c020000  lui   v0,0x0
  10:   8c420008  lw    v0,8(v0)
  14:   03c0e821  move  sp,s8
  18:   8fbe0000  lw    s8,0(sp)
  1c:   27bd0008  addiu sp,sp,8
  20:   03e00008  jr    ra
  24:   00000000  nop
```



elsewhere in another file: int usrid = 41;

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

Objdump symbols

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

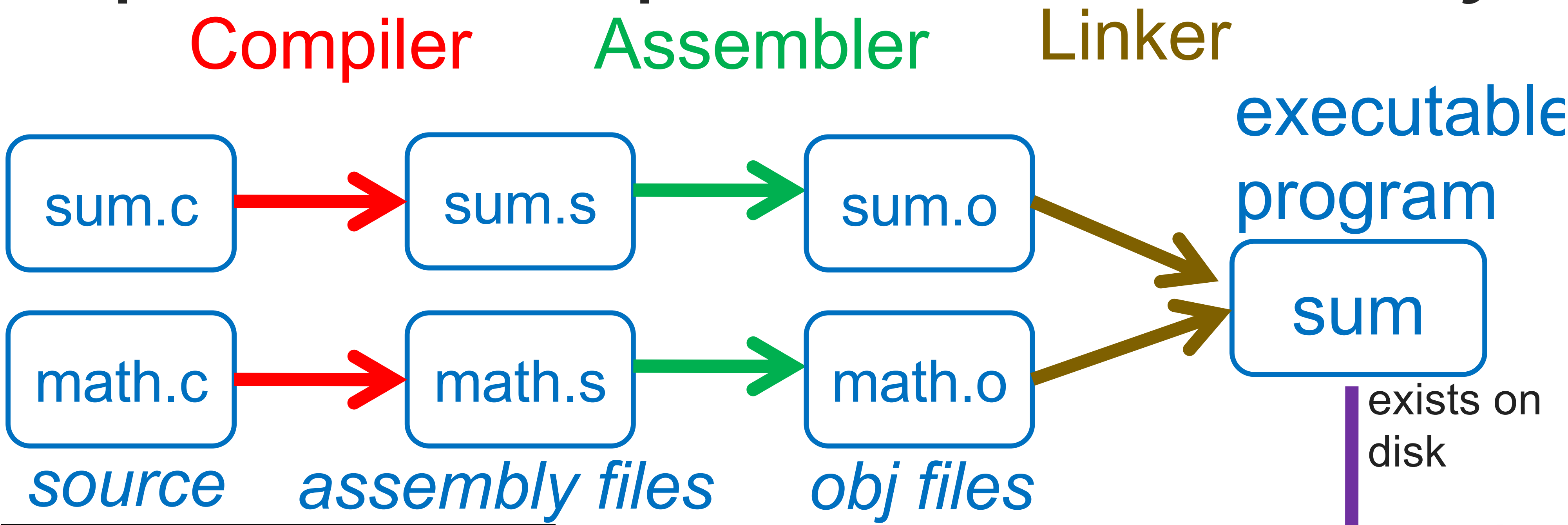
```
> mipsel-linux-objdump --syms math.o
```

```
SYMBOL TABLE:       segment              size
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  F  .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  F  .text        00000028 get_n
00000028 g  F  .text        00000038 square
00000088 g  F  .text        0000004c pick_prime
00000000       *UND*        00000000 usrid
00000000       *UND*        00000000 printf
```

static local fn
@ addr 0x60
size = x28 bytes

external references (undefined)

Separate Compilation & Assembly



Compiler

Assembler

Linker

executable program

sum.c

sum.s

sum.o

math.c

math.s

math.o

sum

exists on disk

source

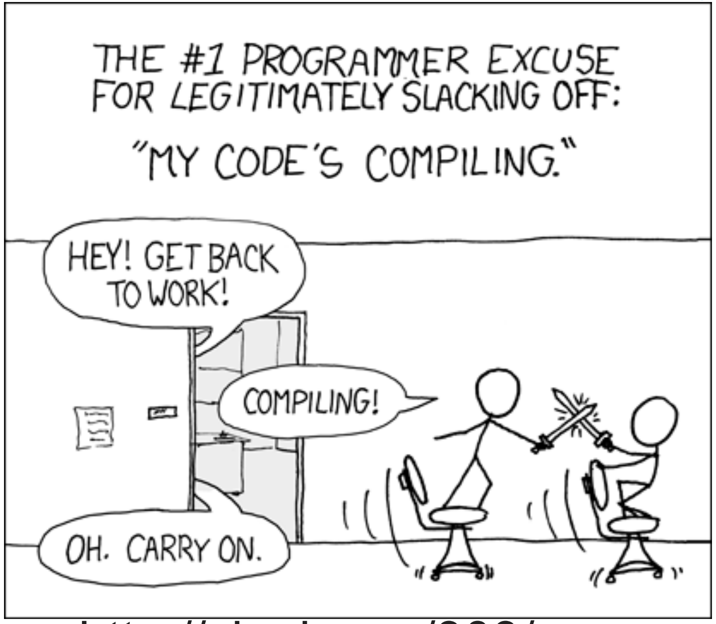
assembly files

obj files

loader

Executing in Memory

process



http://xkcd.com/303/

small change ?

→ recompile one module only

Linkers

Linker combines object files into an executable file

- Resolve as-yet-unresolved symbols
- Each has illusion of own address space
  → Relocate each object's text and data segments
- Record top-level entry point in executable file

End result: a program on disk, ready to execute

E.g.	./sum	Linux
	./sum.exe	Windows
	simulate sum	Class MIPS simulator

Static Libraries

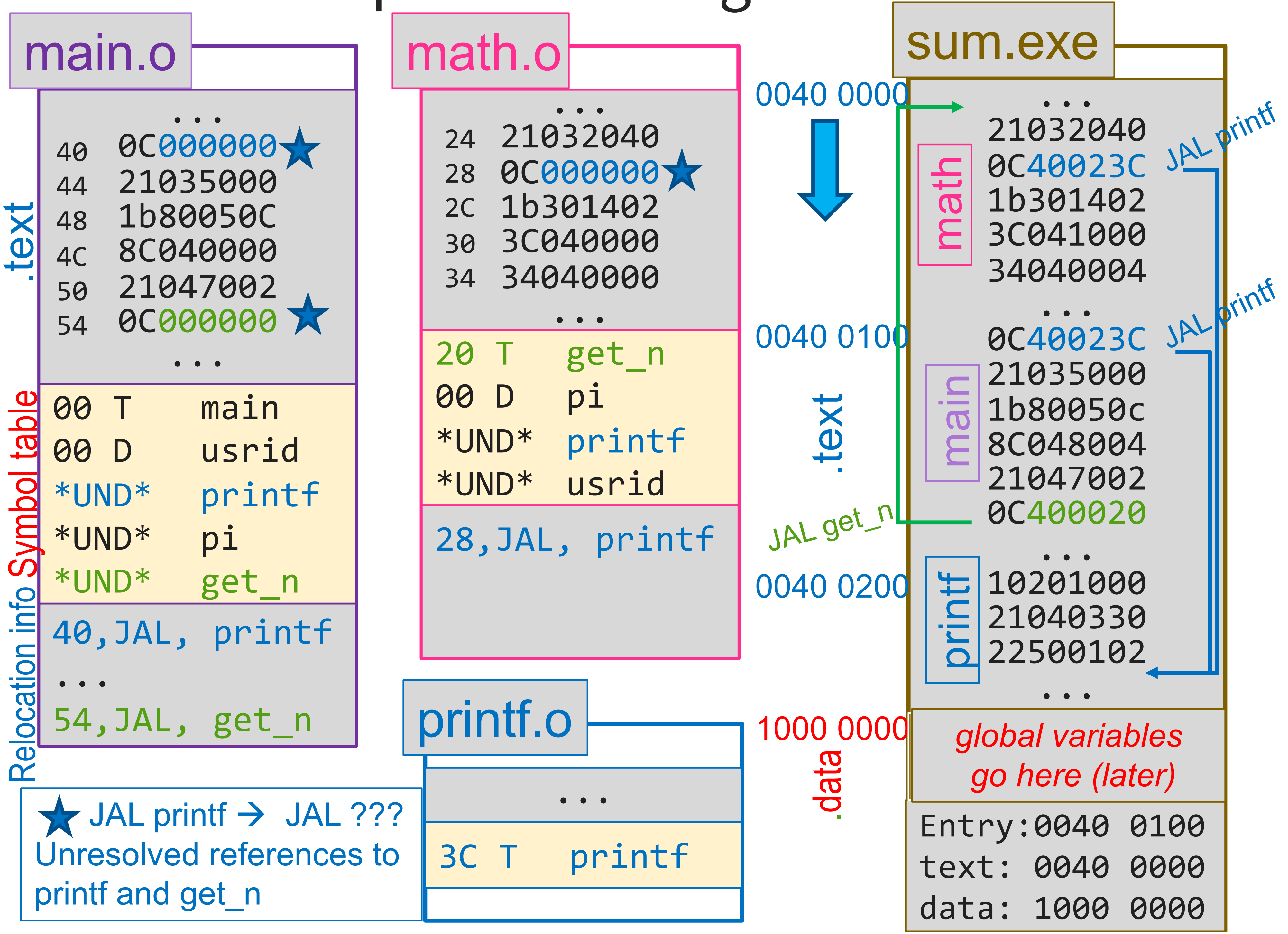
Static Library: Collection of object files (think: like a zip archive)

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



main.o

```
      ...
40  0C000000 ★
44  21035000
48  1b80050C
4C  8C040000
50  21047002
54  0C000000 ★
      ...
```

```
00 T      main
00 D      usrid
*UND*     printf
*UND*     pi
*UND*     get_n
```

```
40,JAL, printf
...
54,JAL, get_n
```

math.o

```
      ...
24  21032040
28  0C000000 ★
2C  1b301402
30  3C040000
34  34040000
      ...
```

```
20 T    get_n
00 D    pi
*UND*   printf
*UND*   usrid
```

```
28,JAL, printf
```

printf.o

```
...
```

```
3C T   printf
```

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

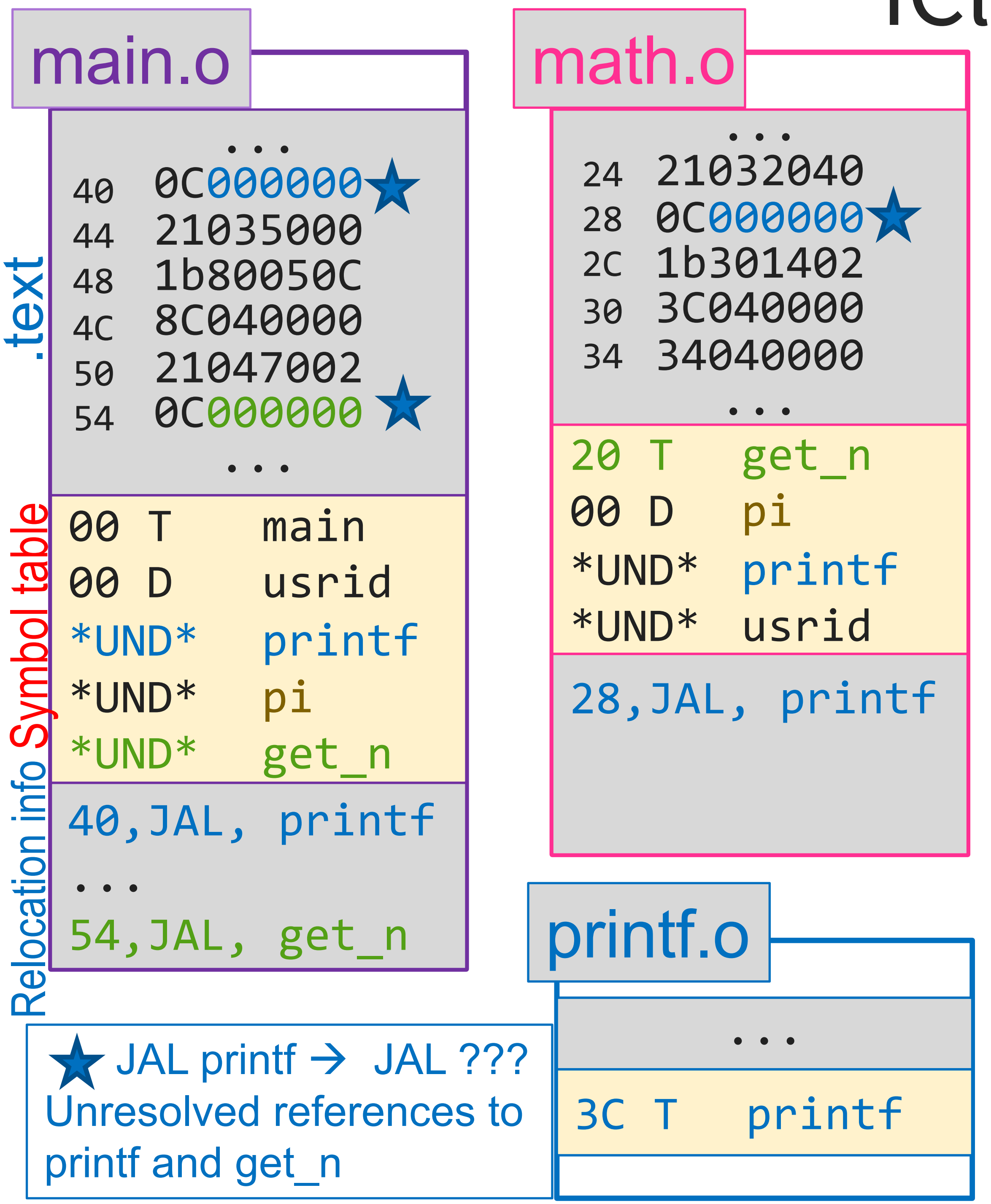
sum.exe

```
0040 0000      ...
               21032040
               0C40023C
               1b301402
               3C041000
               34040004
                 ...
0040 0100      0C40023C
               21035000
               1b80050c
               8C048004
               21047002
               0C400020
                 ...
0040 0200      10201000
               21040330
               22500102
                 ...
1000 0000
```

global variables go here (later)

```
Entry:0040 0100
text: 0040 0000
data: 1000 0000
```

iClicker Question 1



main.o

.text

```
   ...
40  0C000000 ★
44  21035000
48  1b80050C
4C  8C040000
50  21047002
54  0C000000 ★
   ...
```

Symbol table

```
00 T     main
00 D     usrid
*UND*    printf
*UND*    pi
*UND*    get_n
```

Relocation info

```
40,JAL, printf
...
54,JAL, get_n
```

math.o

```
   ...
24  21032040
28  0C000000 ★
2C  1b301402
30  3C040000
34  34040000
   ...
```

```
20 T    get_n
00 D    pi
*UND*   printf
*UND*   usrid
```

```
28,JAL, printf
```

printf.o

```
...
```

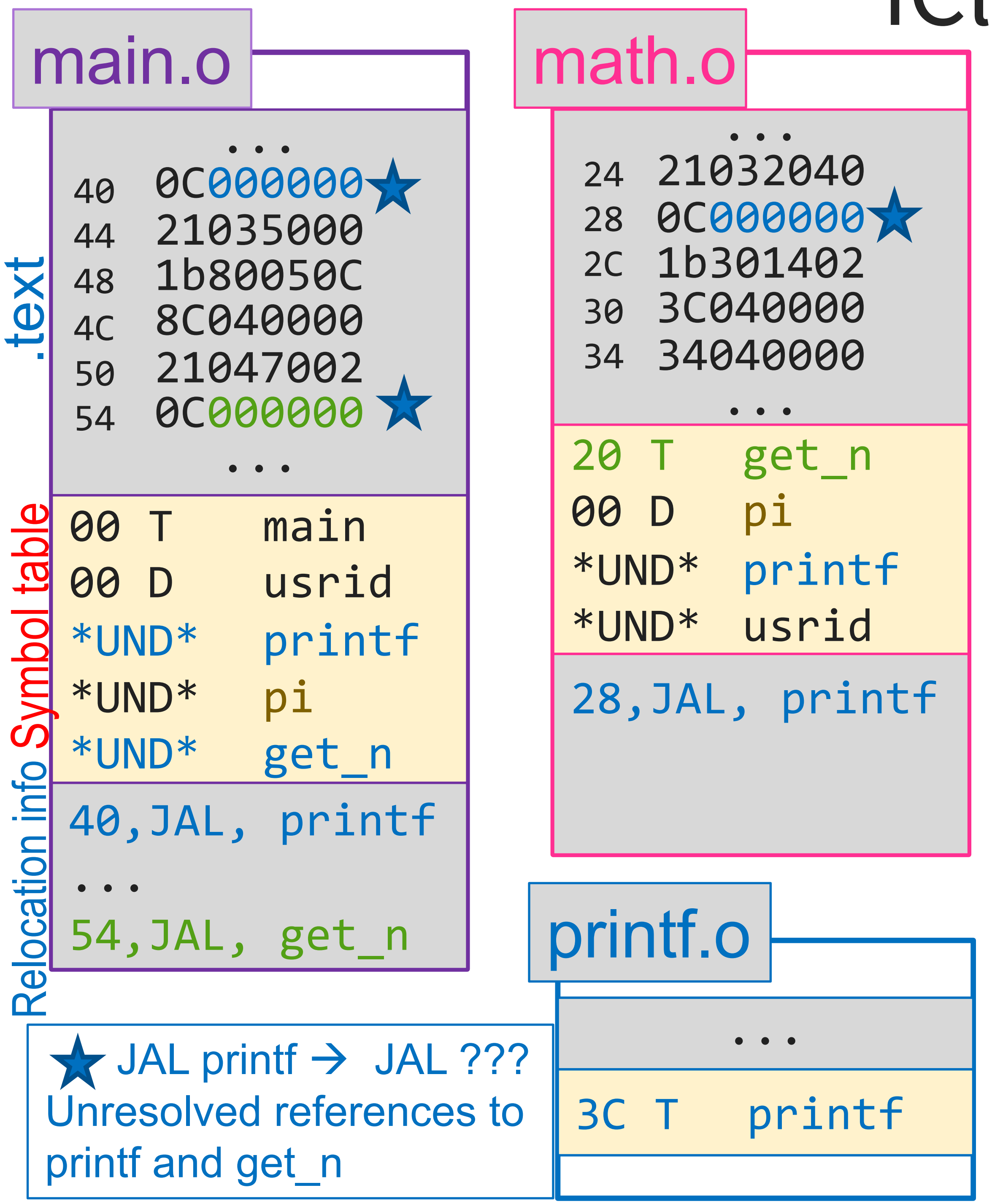
```
3C T   printf
```

★ 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

iClicker Question 2



main.o

.text

```
   ...
40 0C000000 ★
44 21035000
48 1b80050C
4C 8C040000
50 21047002
54 0C000000 ★
   ...
```

Symbol table

```
00 T     main
00 D     usrid
*UND*    printf
*UND*    pi
*UND*    get_n
```

Relocation info

```
40,JAL, printf
...
54,JAL, get_n
```

math.o

```
   ...
24 21032040
28 0C000000 ★
2C 1b301402
30 3C040000
34 34040000
   ...
```

```
20 T     get_n
00 D     pi
*UND*    printf
*UND*    usrid
```

```
28,JAL, printf
```

printf.o

```
...
```

```
3C T   printf
```

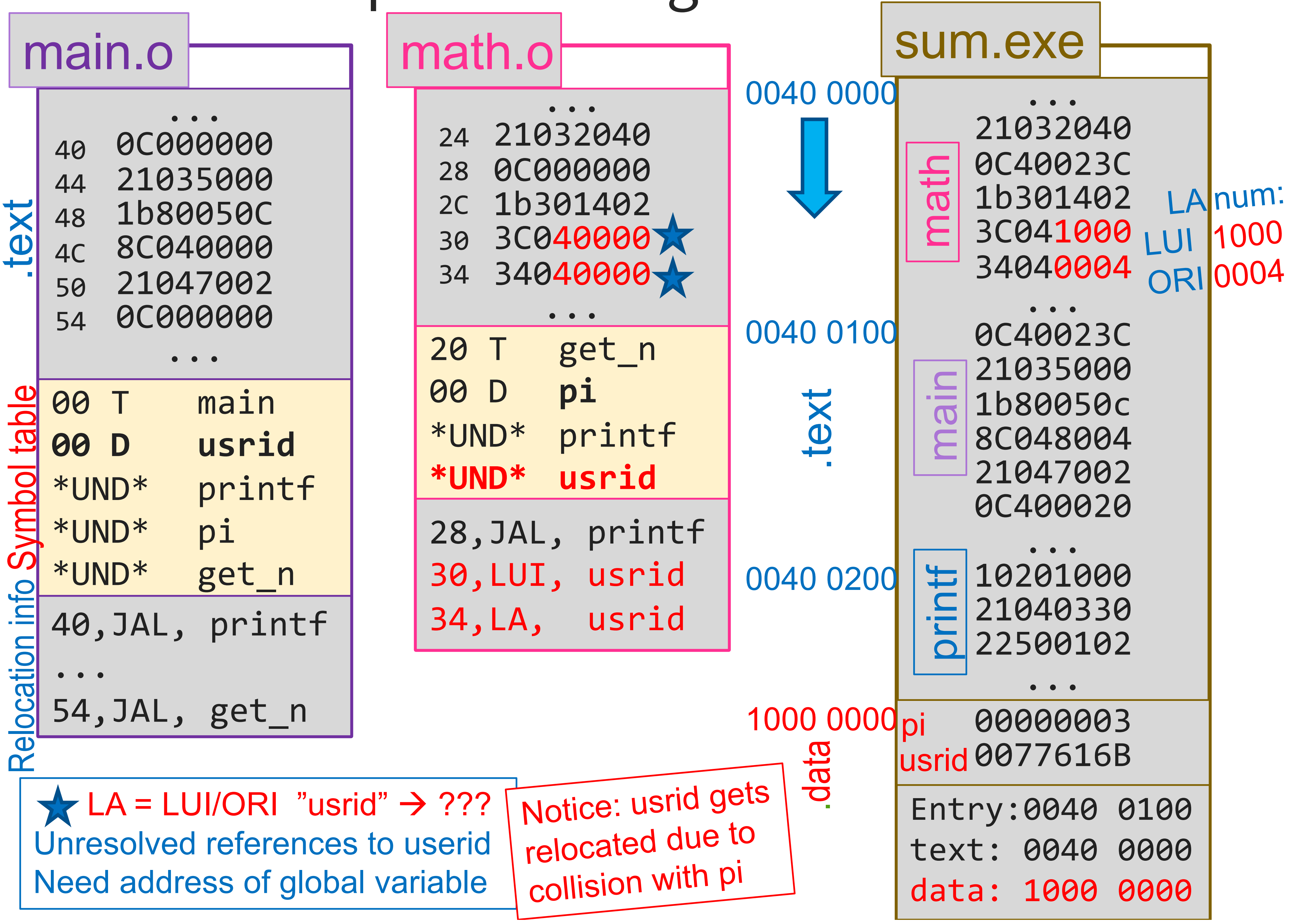
★ JAL printf → JAL ???

Unresolved references to printf and get_n

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

Linker Example: Loading a Global Variable



main.o

.text

```
     ...
40  0C000000
44  21035000
48  1b80050C
4C  8C040000
50  21047002
54  0C000000
     ...
```

Symbol table

```
00 T      main
00 D      usrid
*UND*     printf
*UND*     pi
*UND*     get_n
```

Relocation info

```
40,JAL, printf
...
54,JAL, get_n
```

math.o

```
     ...
24  21032040
28  0C000000
2C  1b301402
30  3C040000★
34  34040000★
     ...
```

```
20 T    get_n
00 D    pi
*UND*   printf
*UND*   usrid
```

```
28,JAL, printf
30,LUI, usrid
34,LA,  usrid
```

sum.exe

```
0040 0000          ...
          math     21032040
                   0C40023C
                   1b301402
                   3C041000
                   34040004
                   ...
0040 0100  main    0C40023C
                   21035000
                   1b80050c
                   8C048004
                   21047002
                   0C400020
                   ...
0040 0200  printf  10201000
                   21040330
                   22500102
                   ...
1000 0000  pi      00000003
           usrid   0077616B
```

.text

.data

LA num:
LUI 1000
ORI 0004

```
Entry:0040 0100
text: 0040 0000
data: 1000 0000
```

★ LA = LUI/ORI "usrid" → ???
Unresolved references to userid
Need address of global variable

Notice: usrid gets relocated due to collision with pi

iClicker 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

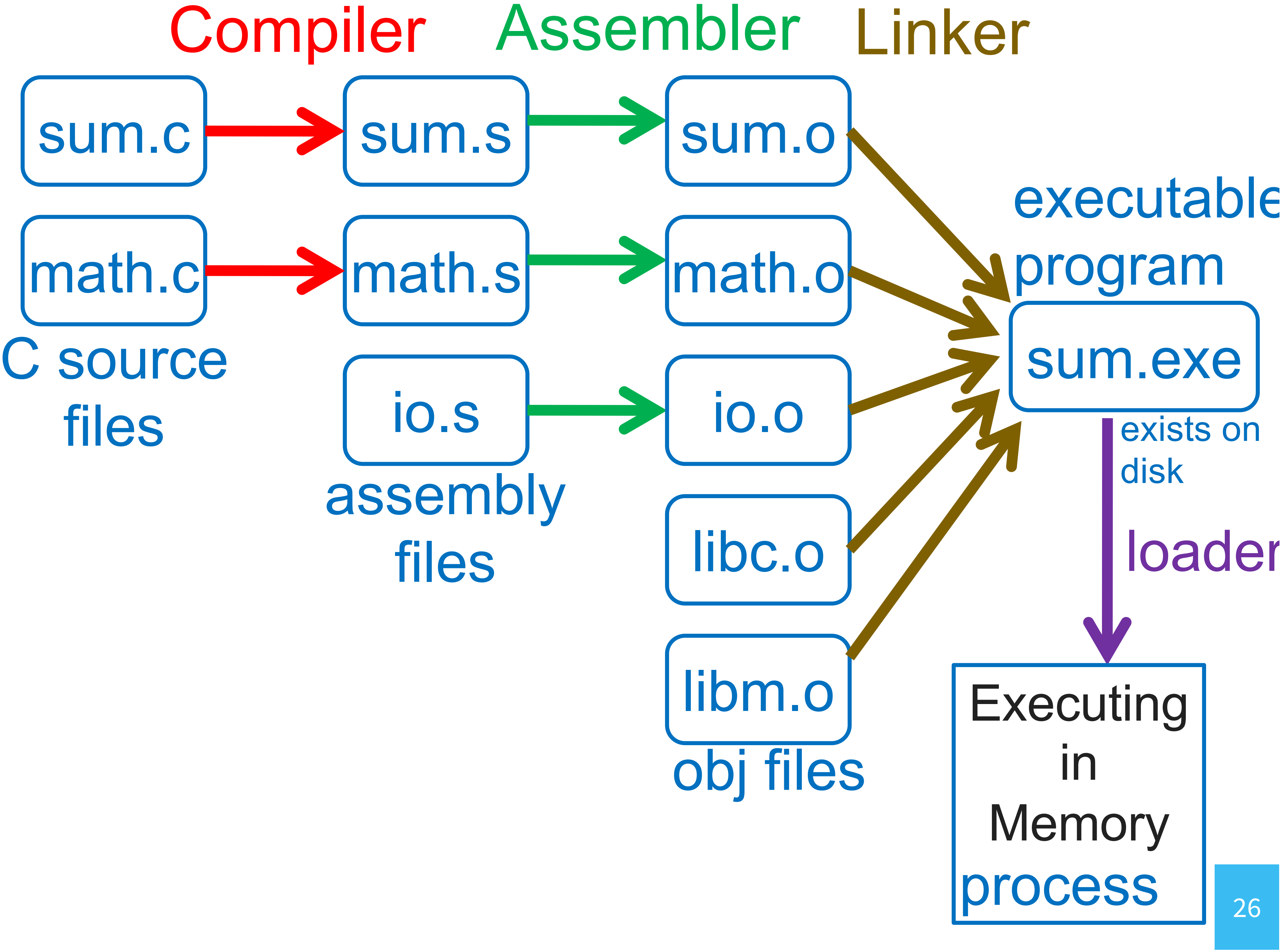
E. None of the above

```
#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



Compiler

Assembler

Linker

sum.c

sum.s

sum.o

math.c

math.s

math.o

C source files

io.s

io.o

assembly files

libc.o

libm.o

obj files

executable program

sum.exe

exists on disk

loader

Executing in Memory

process

Loaders

Loader reads executable from disk into memory

- Initializes registers, stack, arguments to first function
- Jumps to entry-point

Part of the Operating System (OS)

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

Takeaway

Compiler produces assembly files
(contain MIPS assembly, pseudo-instructions, directives, etc.)

Assembler produces object files
(contain MIPS machine code, missing symbols, some layout information, etc.)

Linker joins object files into one executable file
(contains MIPS machine code, no missing symbols, some layout information)

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