Assemblers, Linkers, and Loaders

Hakim Weatherspoon
CS 3410
Computer Science
Cornell University

[Weatherspoon, Bala, Bracy, and Sirer]

Big Picture: Where are we going?

C

compiler

RISC-V assembly

assembler

machine code

CPU

Circuits

Gates

Transistors

Silicon

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

x0 = 0
x5 = x0 + 10
x5 = x5<<1 #x5 = x5 * 2
x5 = x15 + 15

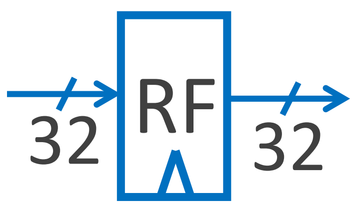
```
addi x5, x0, 10
muli x5, x5, 2
addi x5, x5, 15
```

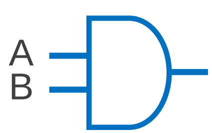
10	r0		r5	op = addi
000000001010	00000	000	00101	0010011

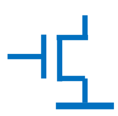
00000000000100010100000101000000 (op = r-type, x5, shamt=1, x5, func=sll)

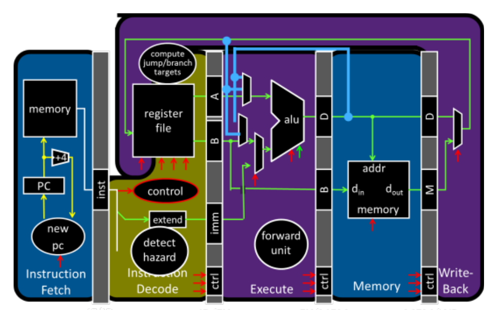
000000001111	00101	000	00101	0010011
15	r5		r5	op = addi

op = r-type   x5   shamt=1   x5   func=sll









Big Picture: Where are we going?

C

compiler

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

High Level Languages

RISC-V assembly

```
addi x5, x0, 10
muli x5, x5, 2
addi x5, x5, 15
```

assembler

machine code

```
00000000101000000000001010010011
00000000001000101000001010000000
00000000111100101000001010010011
```

Instruction Set Architecture (ISA)

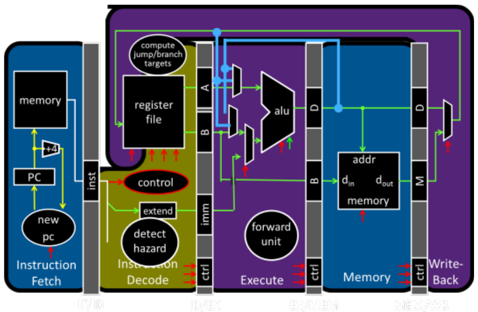
CPU

Circuits

Gates

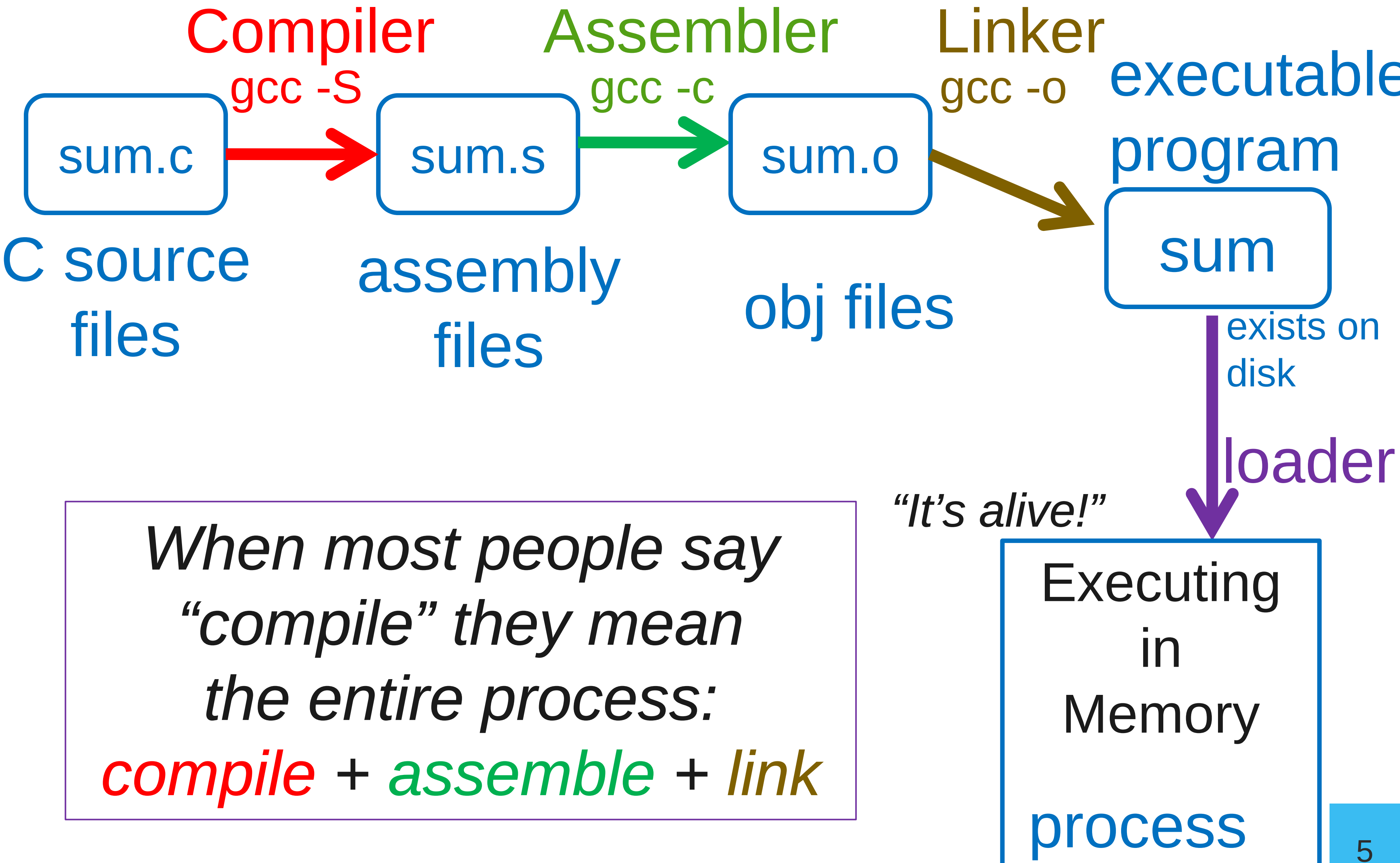
Transistors

Silicon



RISC-y Business Office Hours Marathon and Pizza Party!

From Writing to Running



When most people say "compile" they mean the entire process:
compile + *assemble* + *link*

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
  [ugclinux] riscv-unknown-elf-gcc –S sum.c

- # Assemble
  [ugclinux] riscv-unknown-elf-gcc –c sum.s

- # Link
  [ugclinux] riscv-unknown-elf-gcc –o sum sum.o

- # Load
  [ugclinux] 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)
        sw       $a1,-40($fp)
        la       $a5,n
        lw       $a5,0($a5)
        sw       $a5,-28($fp)
        sw       $0,-24($fp)
        li       $a5,1
        sw       $a5,-20($fp)
$L2:    lw       $a4,-20($fp)
        lw       $a5,-28($fp)
        blt      $a5,$a4,$L3

        lw       $a4,-24($fp)
        lw       $a5,-20($fp)
        addu     $a5,$a4,$a5
        sw       $a5,-24($fp)
        lw       $a5,-20($fp)
        addi     $a5,$a5,1
        sw       $a5,-20($fp)
        j        $L2
$L3:    la       $4,$str0
        lw       $a1,-28($fp)
        lw       $a2,-24($fp)
        jal      printf
        li       $a0,0
        mv       $sp,$fp
        lw       $ra,44($sp)
        lw       $fp,40($sp)
        addiu    $sp,$sp,48
        jr       $ra
```

sum.s (abridged)

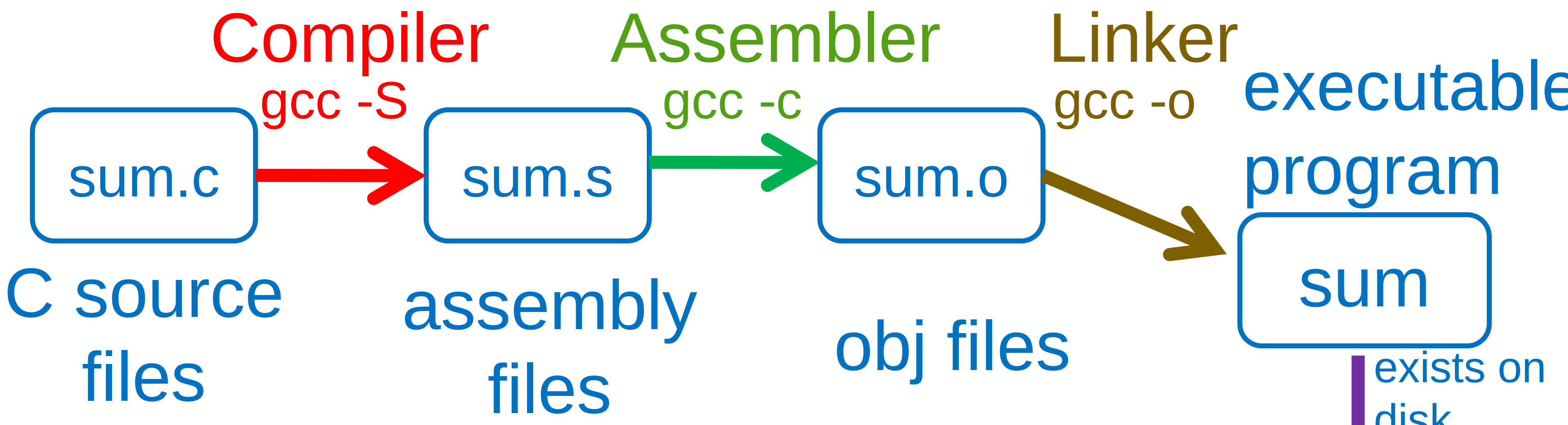
```
        .globl  n
        .data
        .type    n, @object
n:      .word   100
        .rdata
$str0:  .string  "Sum 1 to %d is %d\n"
        .text
        .globl  main
        .type   main, @function
main:   addiu    $sp,$sp,-48
        sw       $ra,44($sp)
        sw       $fp,40($sp)
        move     $fp,$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

$L2:    lw      $a4,-20($fp)    i=1
        lw      $a5,-28($fp)    m=100
        blt     $a5,$a4,$L3     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       $L2
$L3:    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
```

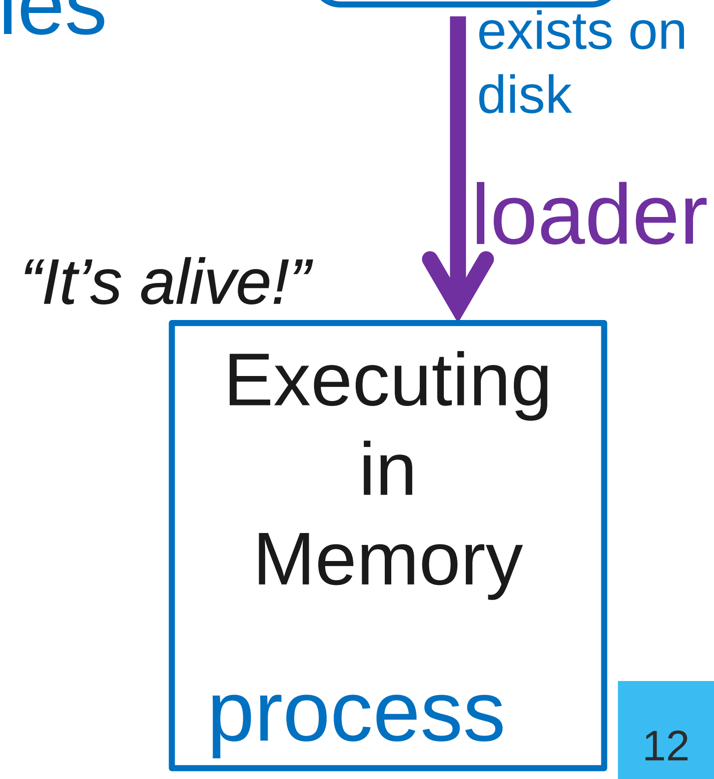
prologue (addiu … sw $a1)

call printf (la … jal)

epilogue (li … jr)

From Writing to Running





When most people say "compile" they mean the entire process:
compile + *assemble* + *link*

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
```

→

```
00000000101000000000000000101001 0011
```

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

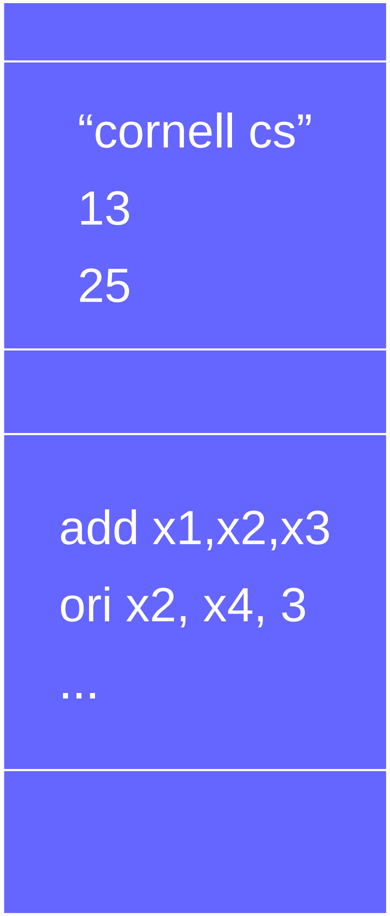
Assembly shorthand, technically not machine instructions, but easily converted into 1+ instructions that are

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.



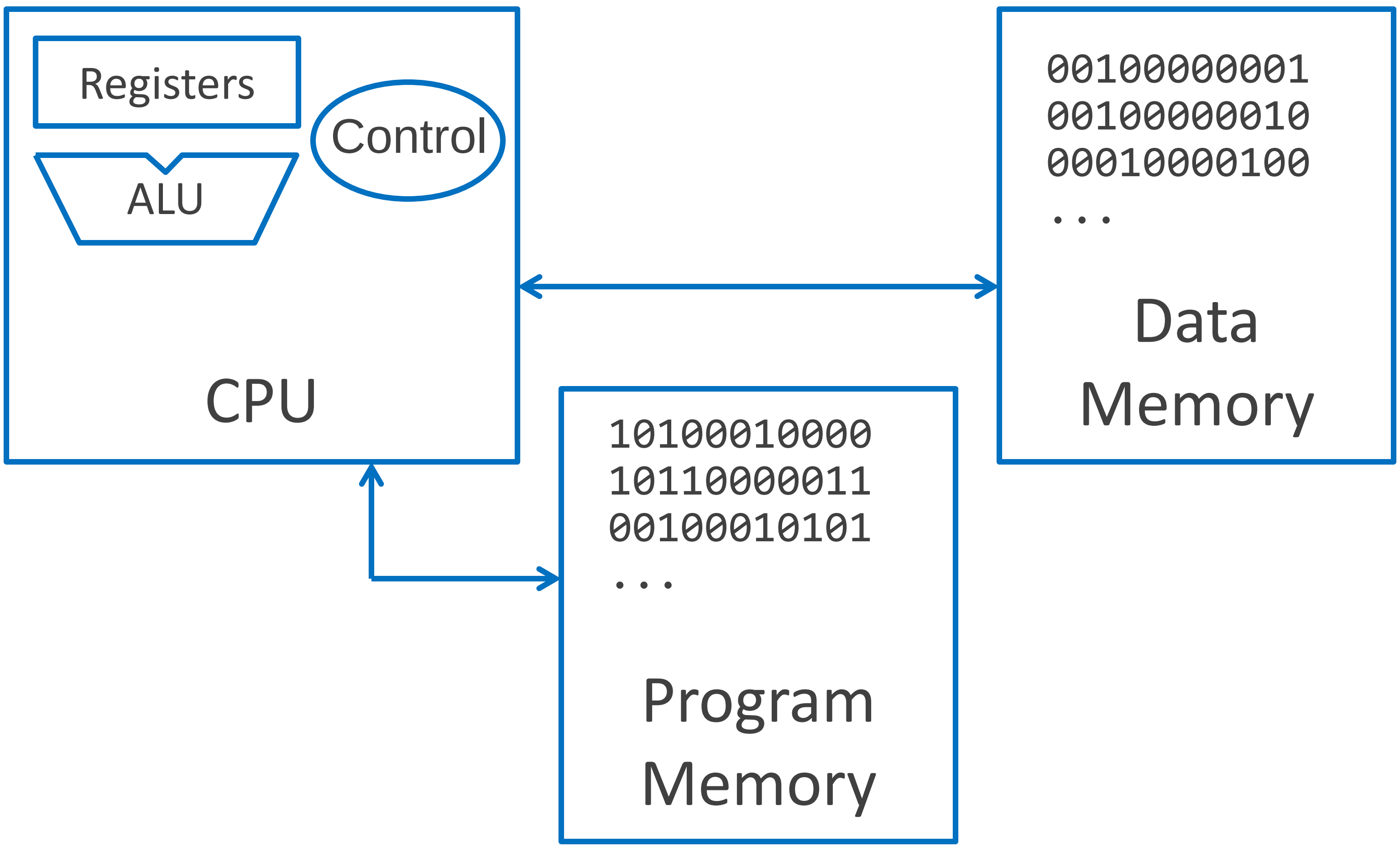
Assembling Programs

```
.text
   .ent main
main: la $4, Larray
   li $5, 15
   ...
   li $4, 0
   jal exit
   .end main
.data
Larray:
   .long 51, 491, 3991
```

- 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

Assembling Programs

- Assembly using a (modified) Harvard architecture
  - Need segments since data and program stored together in memory



Takeaway

- Assembly is a low-level task
  - Need to assemble assembly language into machine code binary. Requires
    - Assembly language instructions
    - *pseudo-instructions*
    - And Specify layout and data using *assembler directives*

  - Today, we use a modified Harvard Architecture (Von Neumann architecture) that mixes data and instructions in memory

    … but kept in separate *segments*

    … and has separate caches

Symbols and References

math.c

```
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 x1, x2, L        Looking for L
        sll x0, x0, 0
L:     addi x2, x3, 0x2      Found L
```

The assembler will change this to

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

Final machine code

```
0X00208413 # bne       actually:  0000 0000 0010...
0x00001033 # sll                  0000 0000 0000...
0x00018113 # addi                 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

```
> riscv-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  a0,0x0
  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
```

prologue (lines 0–8)

body (lines c–10)

epilogue (lines 14–20)

unresolved symbol (see symbol table next slide) → 0x0

elsewhere in another file: int usrid = 41;

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

Objdump symbols

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

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

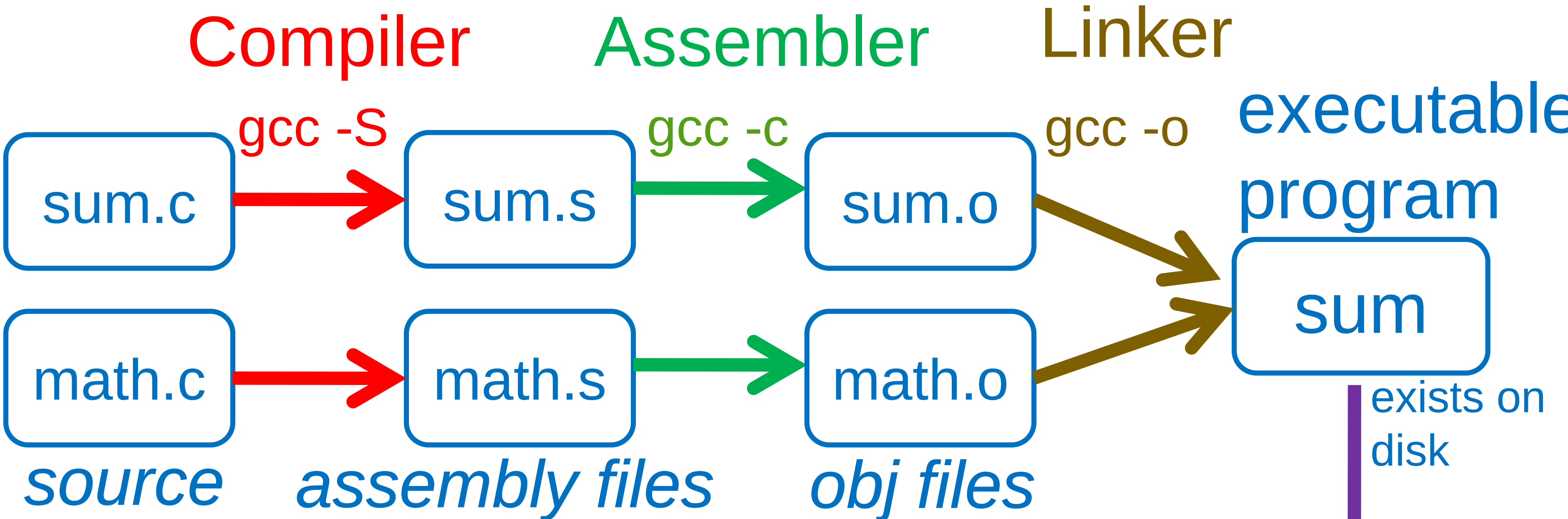
segment *size*

```
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    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 = 0x28 bytes

external references (undefined)

Separate Compilation & Assembly

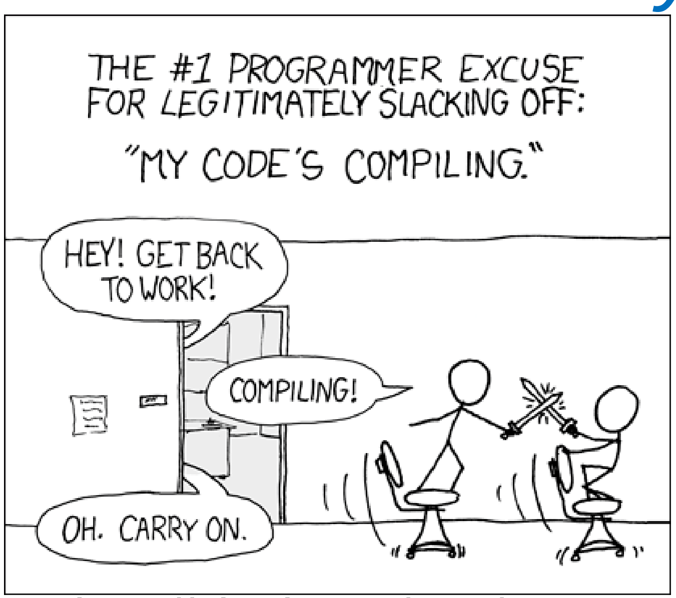


exists on disk

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	
	qemu-riscv32	sum	Class RISC-V 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

.text

```
...
40  000000EF
44  21035000
48  1b80050C
4C  8C040000
50  21047002
54  000000EF
...
```

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  000000EF
2C  1b301402
30  00000B37
34  00028293
...
```

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

```
28,JAL, printf
```

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

iClicker Question 1

main.o

.text

```
...
40 000000EF ★
44 21035000
48 1b80050C
4C 8C040000
50 21047002
54 000000EF ★
...
```

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 000000EF ★
2C 1b301402
30 00000B37
34 00028293
...
```

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

```
28,JAL, printf
```

printf.o

```
...
```

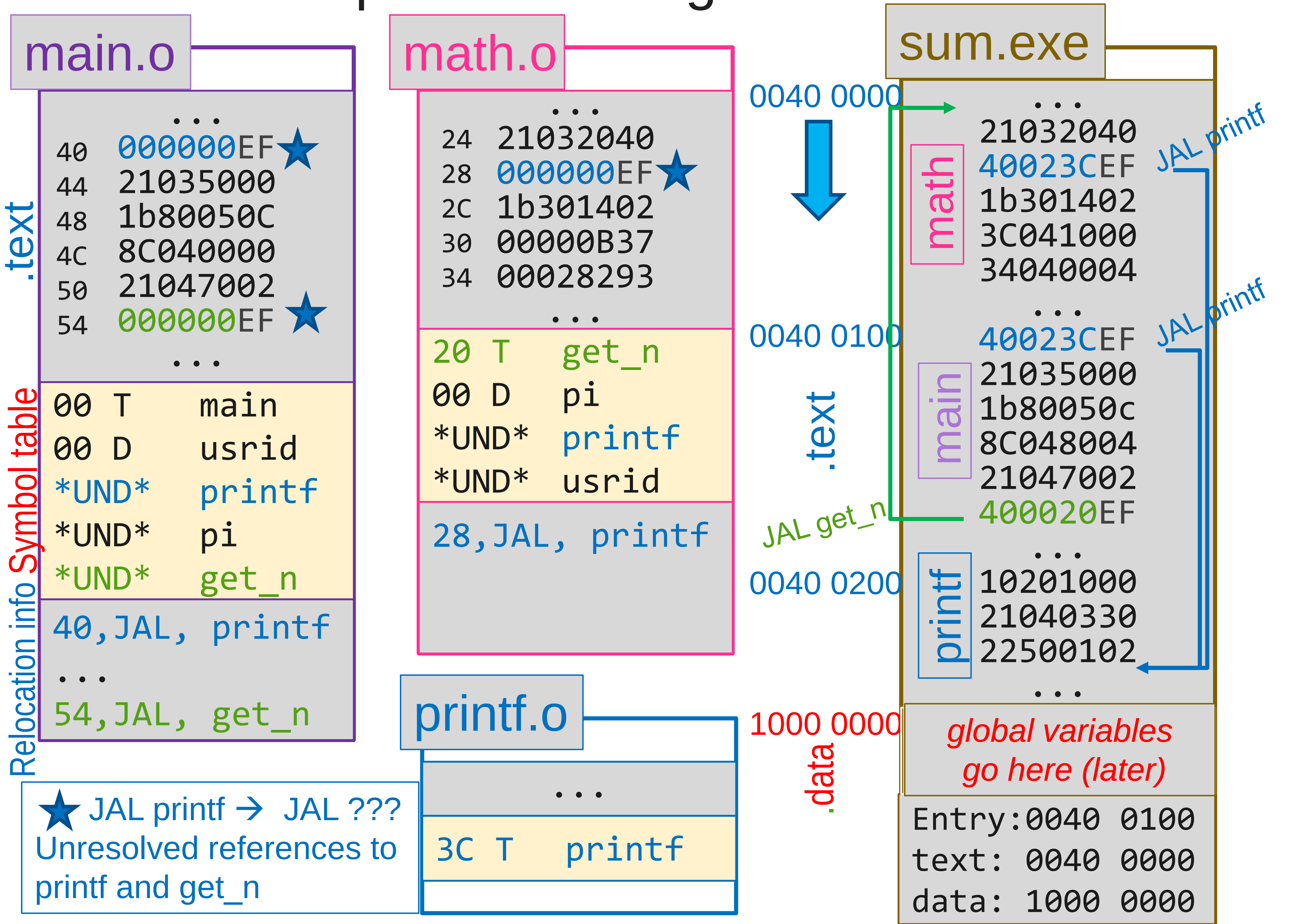
```
3C T   printf
```

★ JAL printf → JAL ???
Unresolved 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

Linker Example: Resolving an External Fn Call



iClicker Question 2

main.o

.text
```
   ...
40 000000EF ★
44 21035000
48 1b80050C
4C 8C040000
50 21047002
54 000000EF ★
   ...
```

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 000000EF ★
2C 1b301402
30 00000B37
34 00028293
   ...
```

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

```
28,JAL, printf
```

printf.o

```
...
```

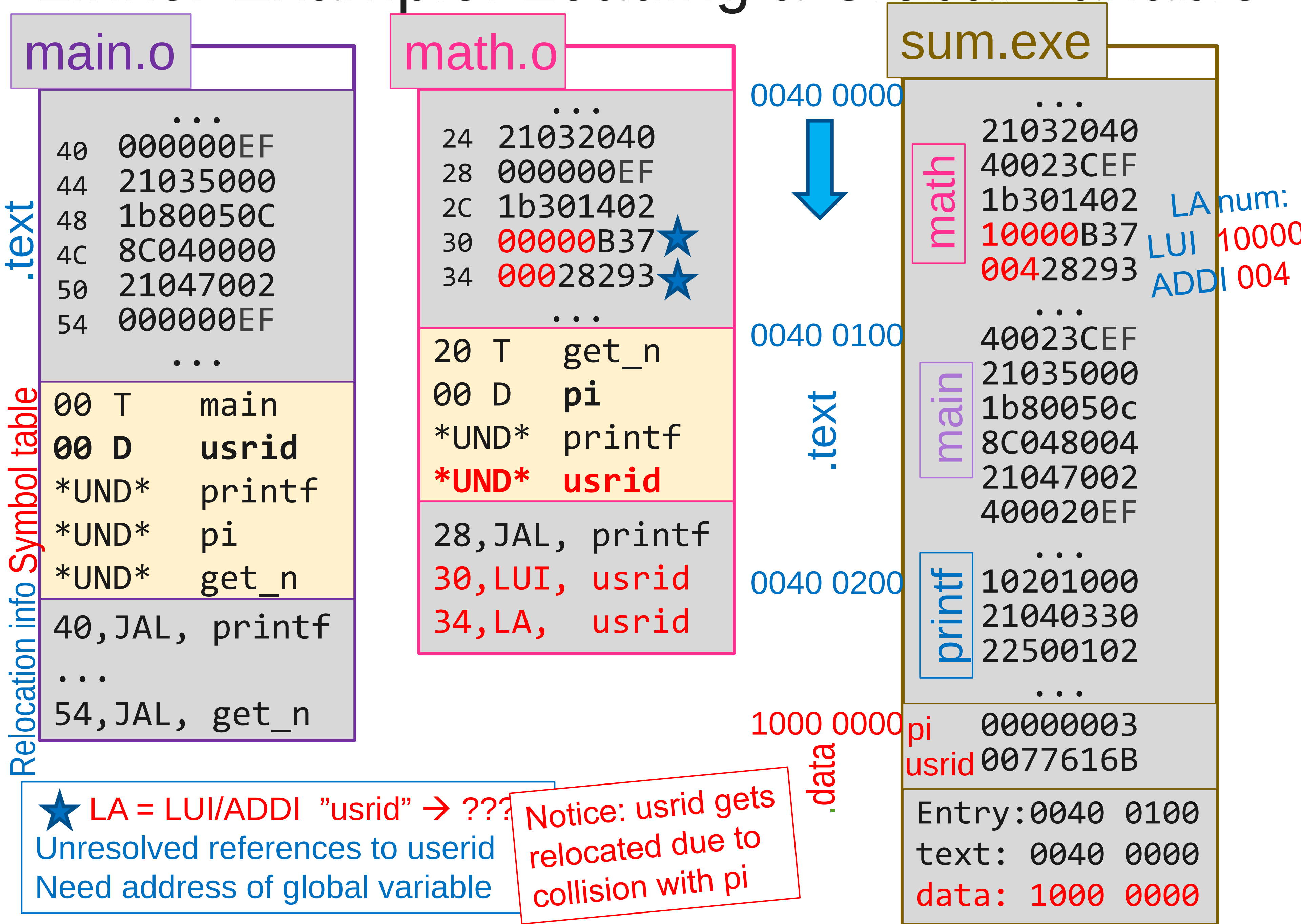
```
3C T    printf
```

★ JAL printf → JAL ???
Unresolved 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



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

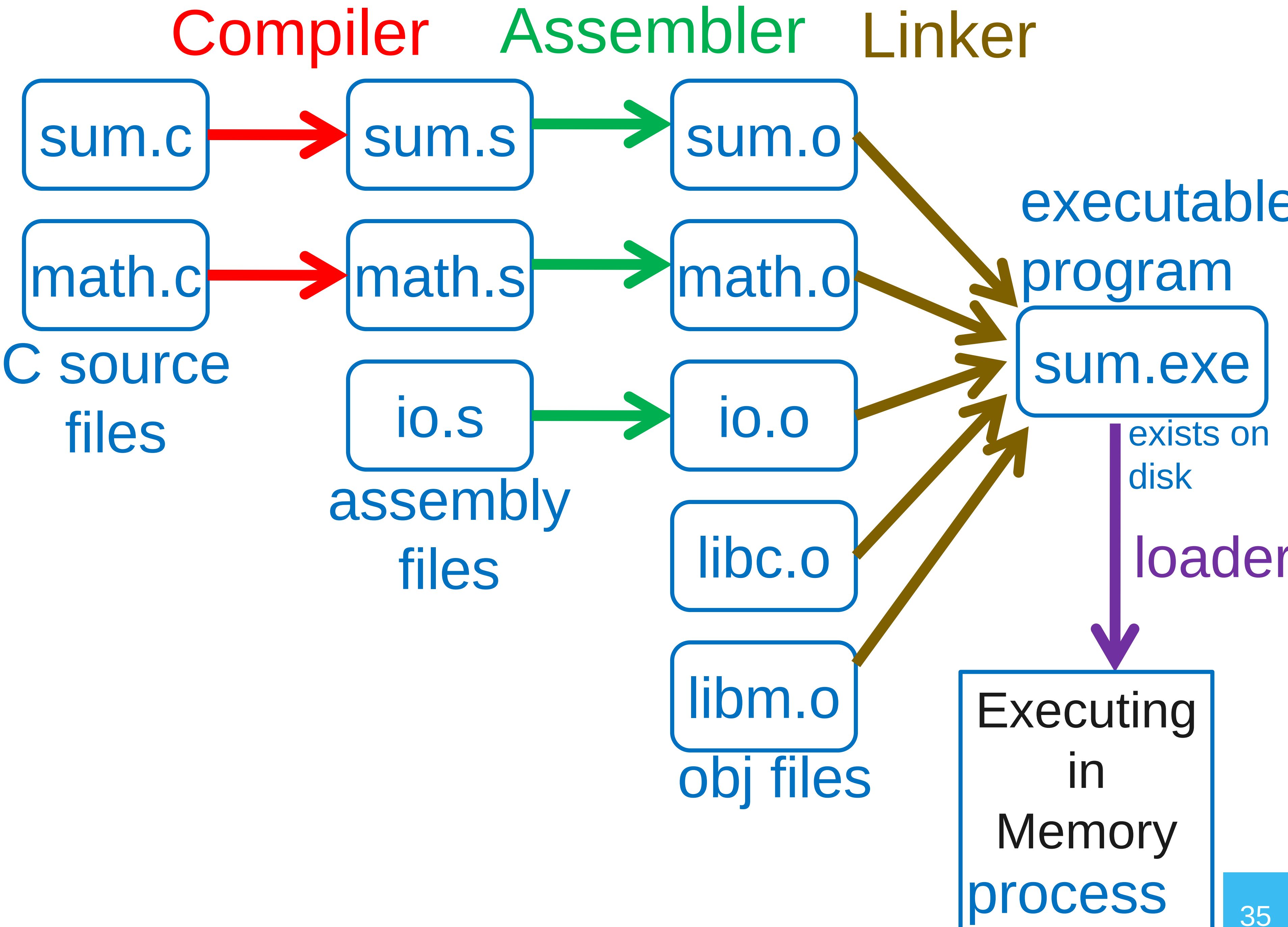
E. None of the above

```
#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
io.s
io.o
libc.o
libm.o
C source files
assembly files
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 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)