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

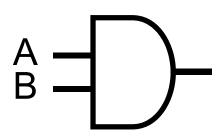
00000000101000000000001010010011

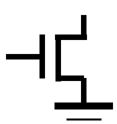
00000000000100010100000010000000

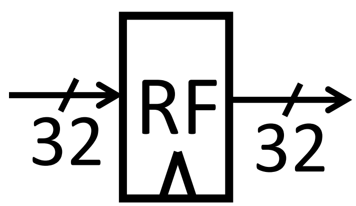
00000000111100101000001010010011

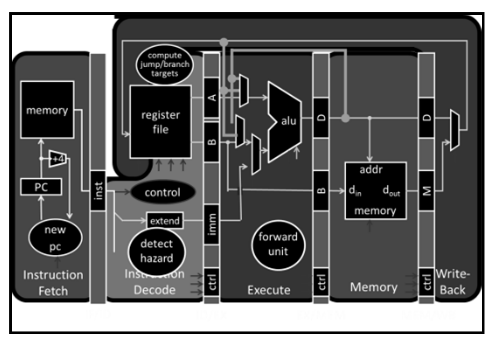
15 r5 r5 op = addi

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









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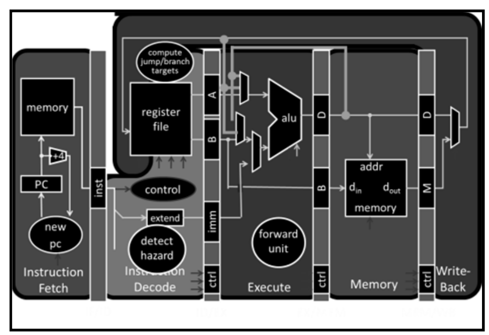
int x = 10;
x = 2 * x + 15;
```

High Level Languages

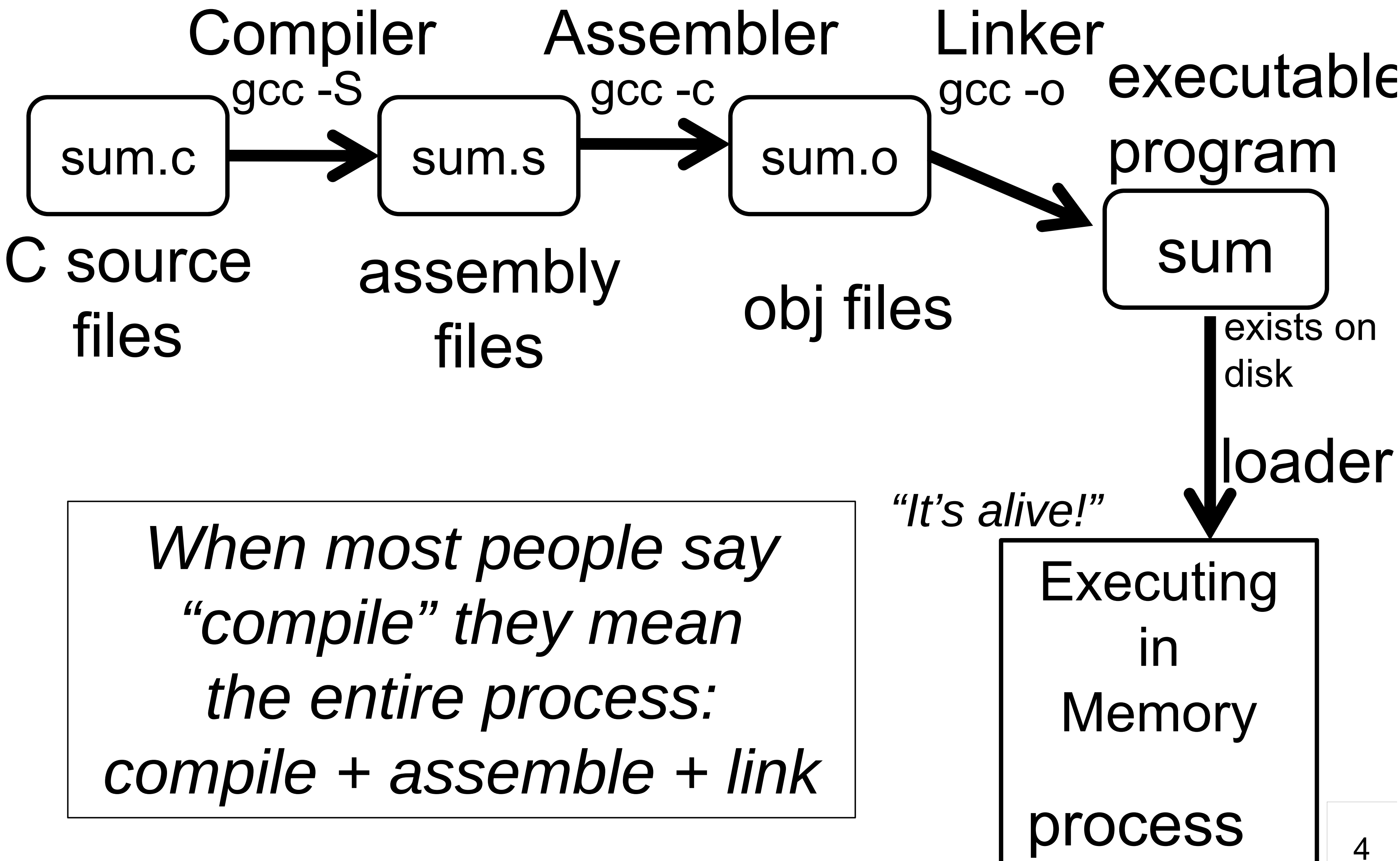
```
addi x5, x0, 10
muli x5, x5, 2
addi x5, x5, 15
```

```
00000000101000000000001010010011
00000000001000101000001010000000
00000000111100101000001010010011
```

Instruction Set Architecture (ISA)



From Writing to Running



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

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);
}
```

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
```

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
```

→

```
00000000101000000000001010010011
0000000000100010100000101
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

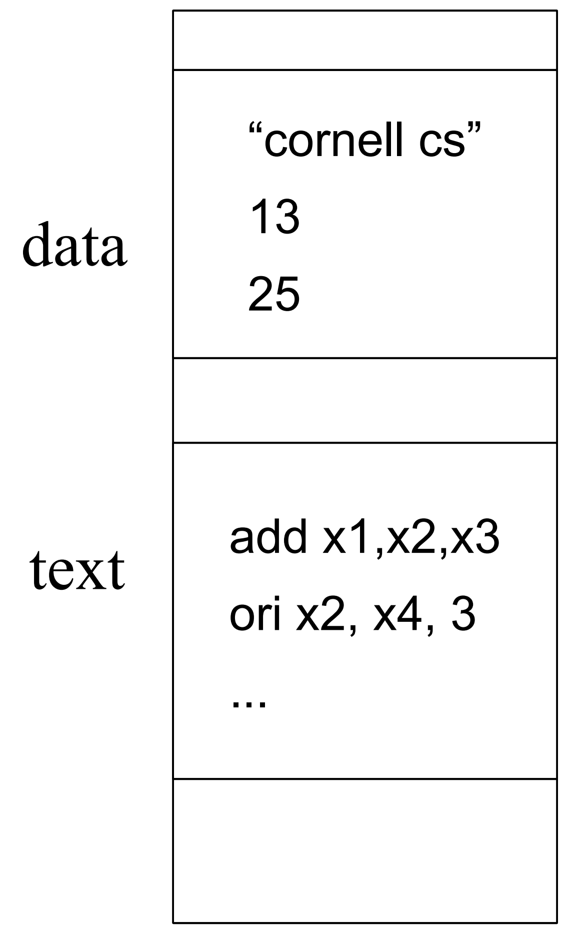
Assembly shorthand, technically not machine instructions, but easily converted into 1+ instructions that are

Pseudo-Insns	Actual Insns	Functionality
NOP	SLL x0, x0, 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
LA reg, label		# load address (32 bits)
B		# unconditional branch
BLT reg, reg, label	SLT r1, rA, rB BNE r1, r0, label	# branch less than

+ 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.



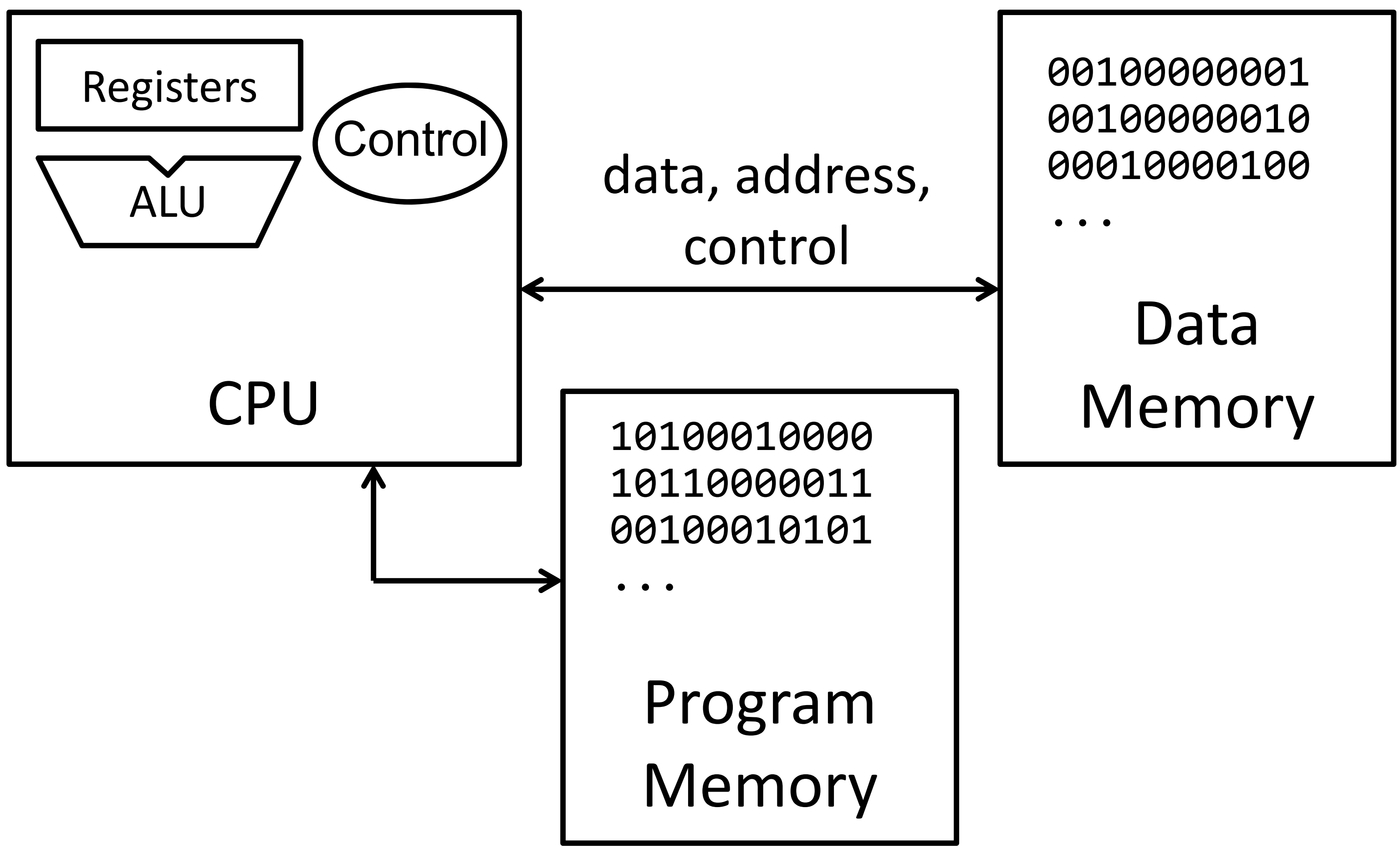
Assembling Programs

```
.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
       sll x0, x0, 0
L:    addi x2, x3, 0x2
```

Looking for L

Found L

The assembler will change this to

```
bne x1, x2, +1
sll x0, x0, 0
addi x2, x3, 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

```
> mipsel-linux-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;
}
```

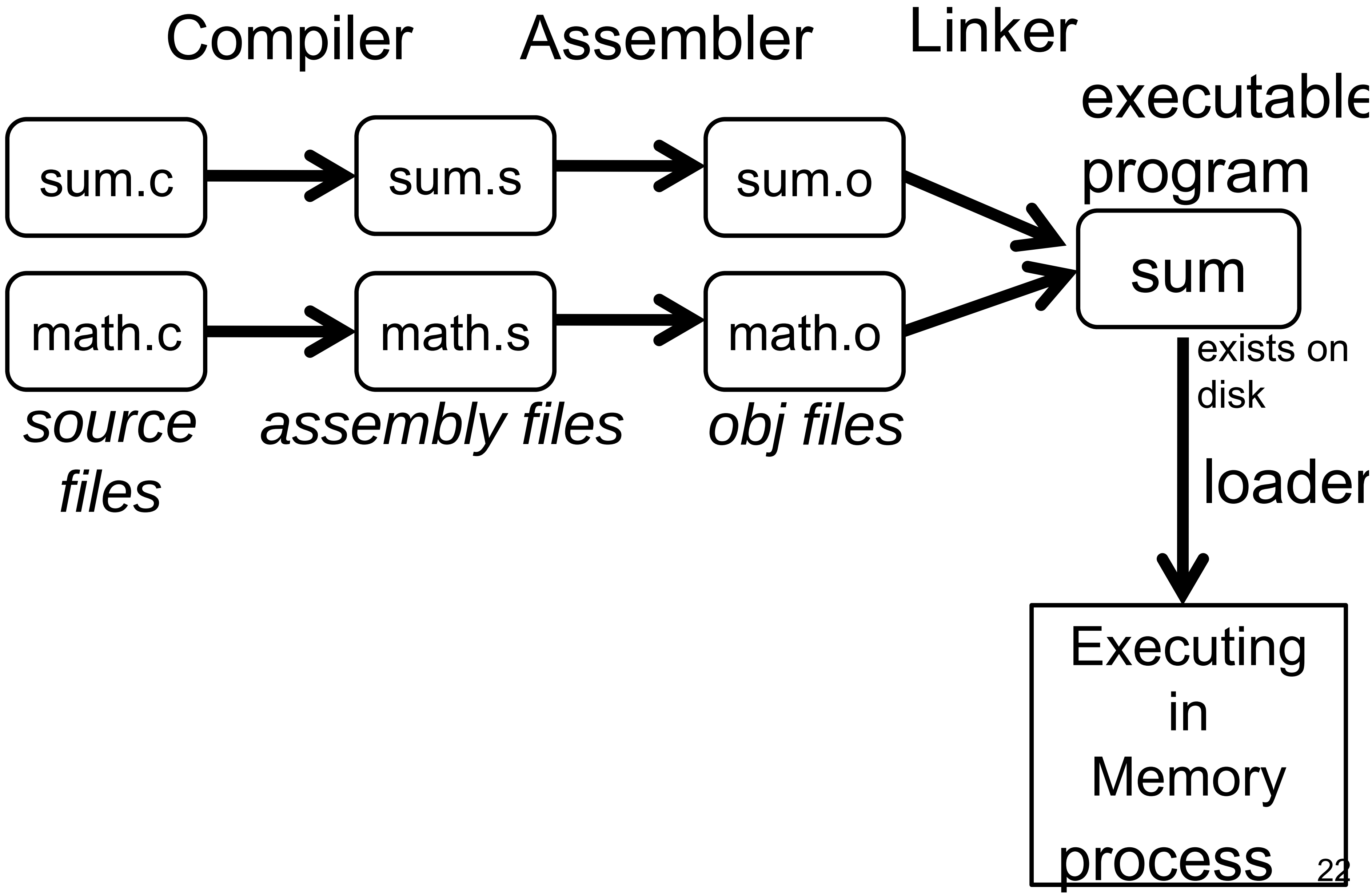
Objdump symbols

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

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

```
                      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
```

Separate Compilation & Assembly



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 RISC-V simulator

Static Libraries

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

Q: Every program contains the entire library?!?

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

.text

0040 0000
```
...
math
21032040
0C40023C
1b301402
3C041000
34040004
...
```

LA num:
LUI 1000
ORI 0004

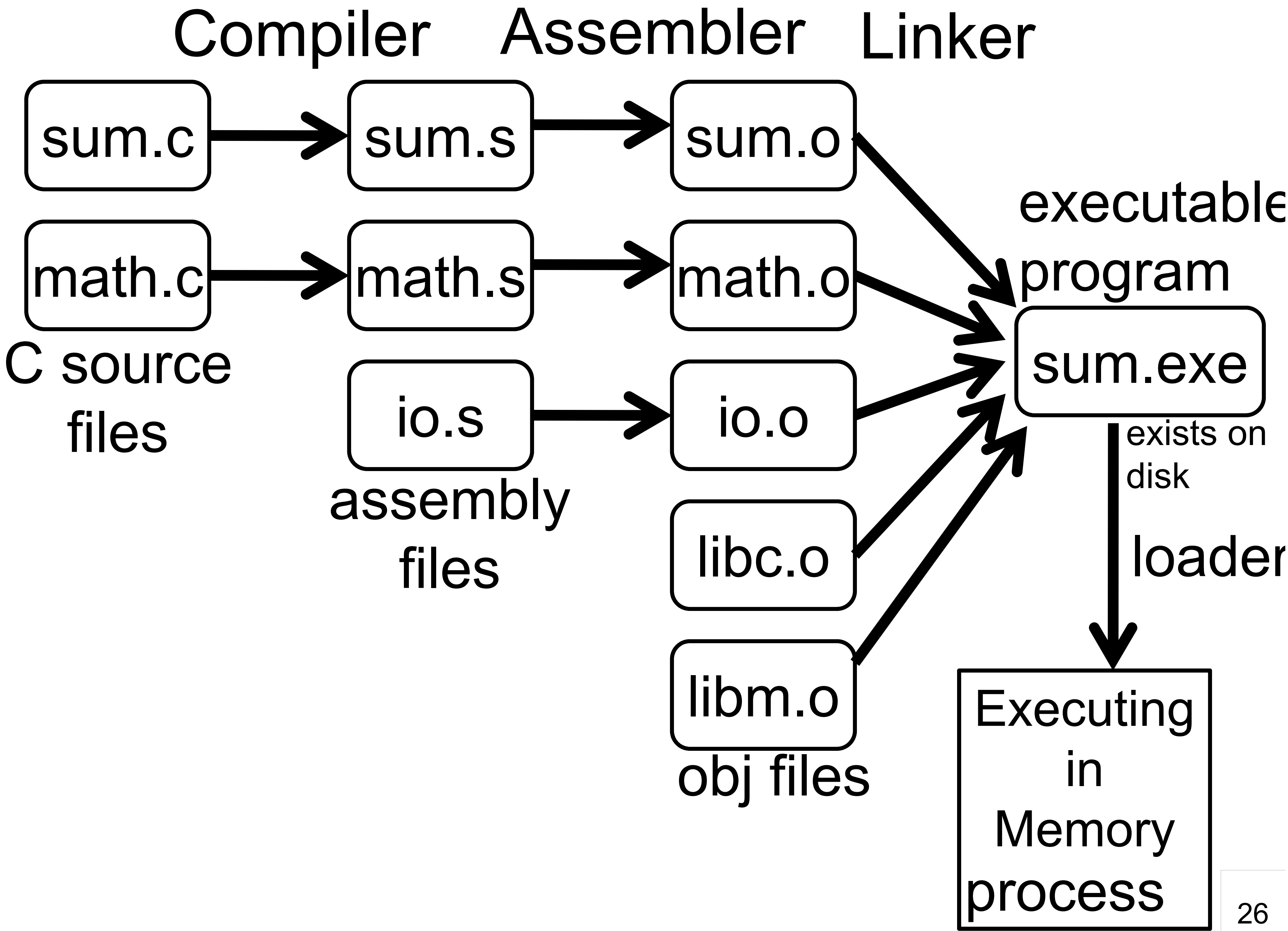
0040 0100
```
main
0C40023C
21035000
1b80050c
8C048004
21047002
0C400020
...
```

0040 0200
```
printf
10201000
21040330
22500102
...
```

.data

1000 0000
```
pi     00000003
usrid  0077616B
```

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


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?!

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)