Assemblers, Linkers, and Loaders

CS 3410
Computer System Organization & Programming

These slides are the product of many rounds of teaching CS 3410 by Professors Weatherspoon, Bala, Bracy, and Sirer.

Big Picture: Where are we going?

C

compiler

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

MIPS assembly

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

r0 = 0

r5 = r0 + 10

r5 = r15 + 15

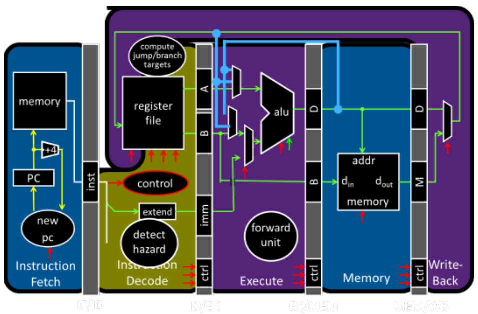
assembler

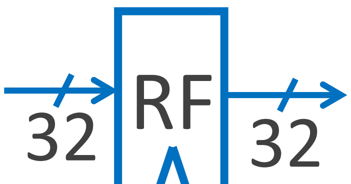
machine code

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

loader

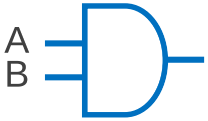
CPU



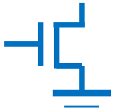


Circuits

Gates



Transistors



Silicon

Big Picture: Where are we going?

C

compiler

MIPS assembly

assembler

machine code

loader

CPU

Circuits

Gates

Transistors

Silicon

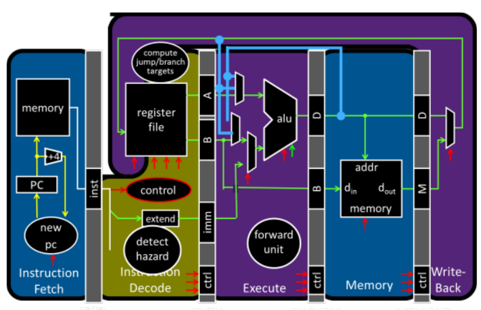
```
int x = 10;
x = 2 * x + 15;
```

High Level Languages

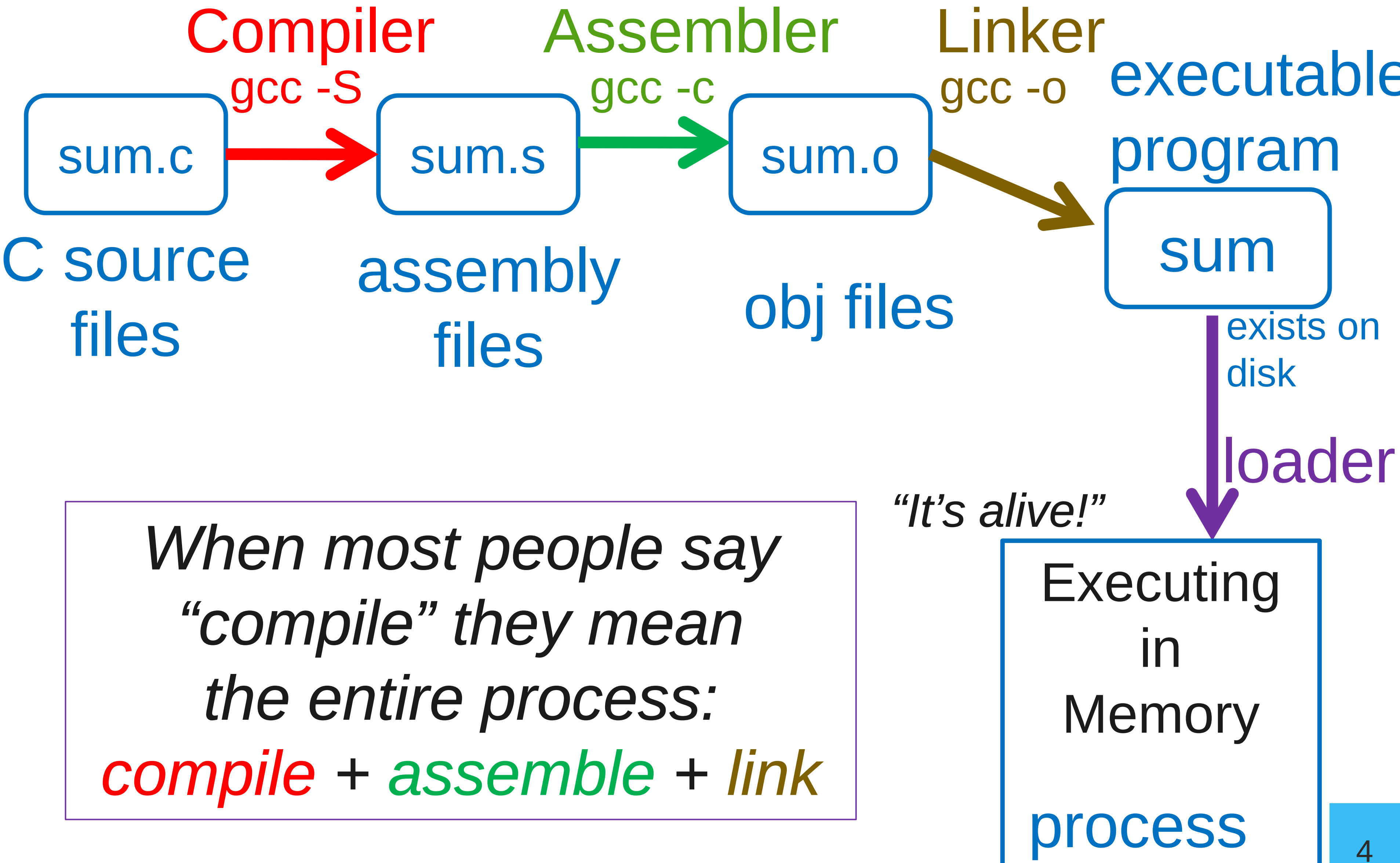
```
addi r5, r0, 10
muli r5, r5, 2
addi r5, r5, 15
```

```
00100000000001010000000000001010
00000000000001010010100001000000
0010000010100101000000
```

Instruction Set Architecture (ISA)



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);
}
```

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
```

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
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.

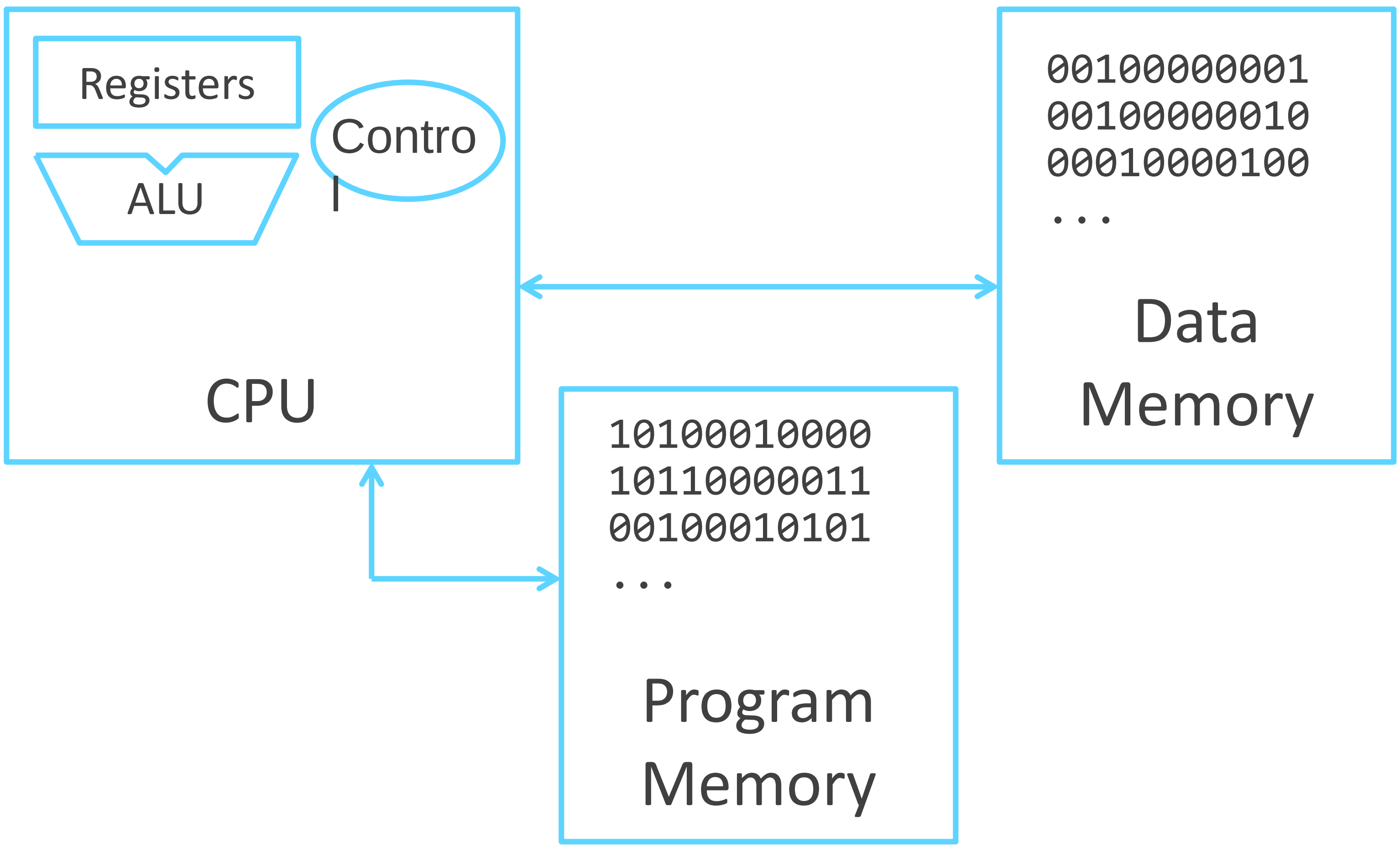
Assembling Programs

```
.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 $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

```
> 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;
}
```

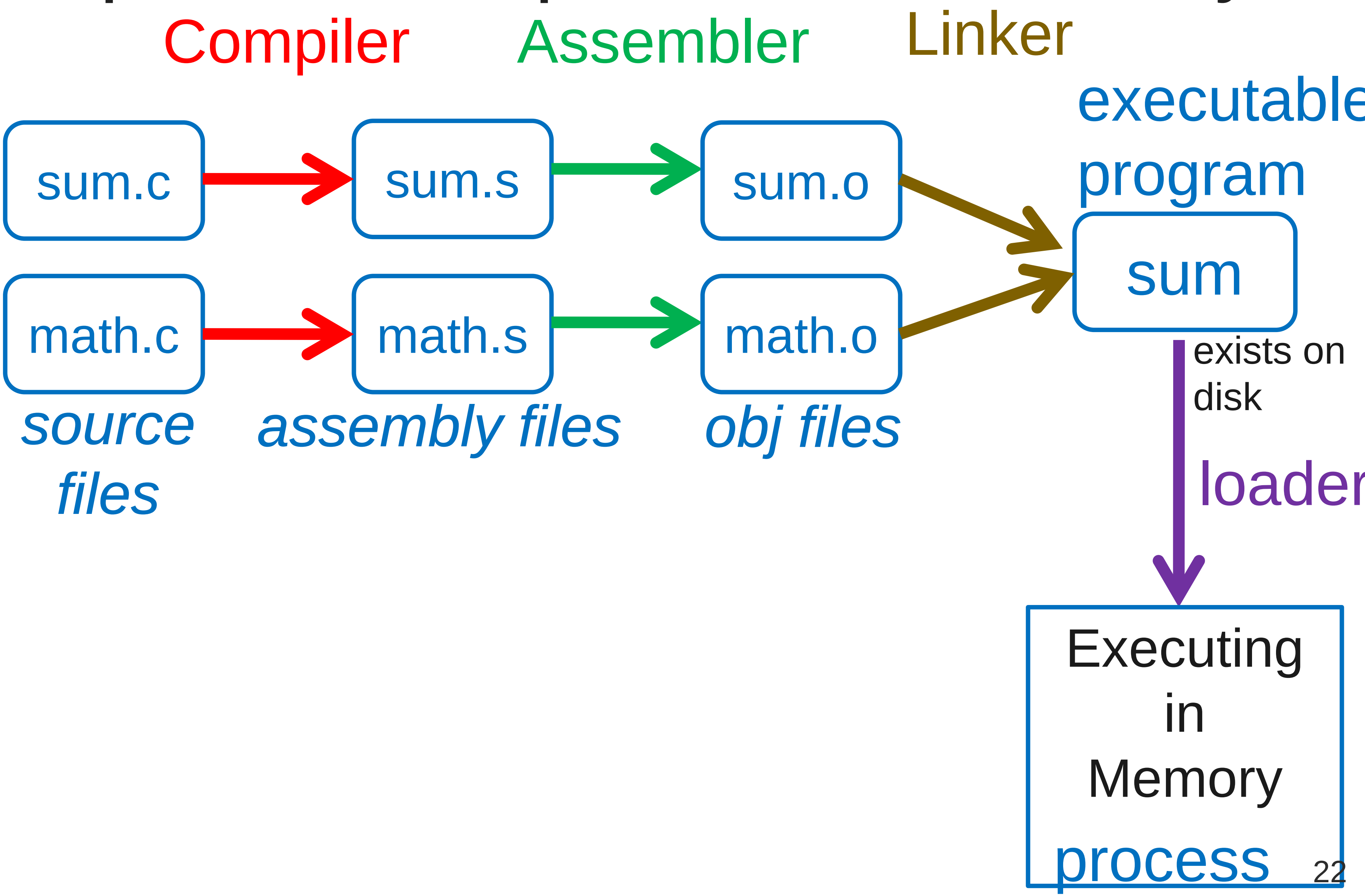
Objdump symbols

[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

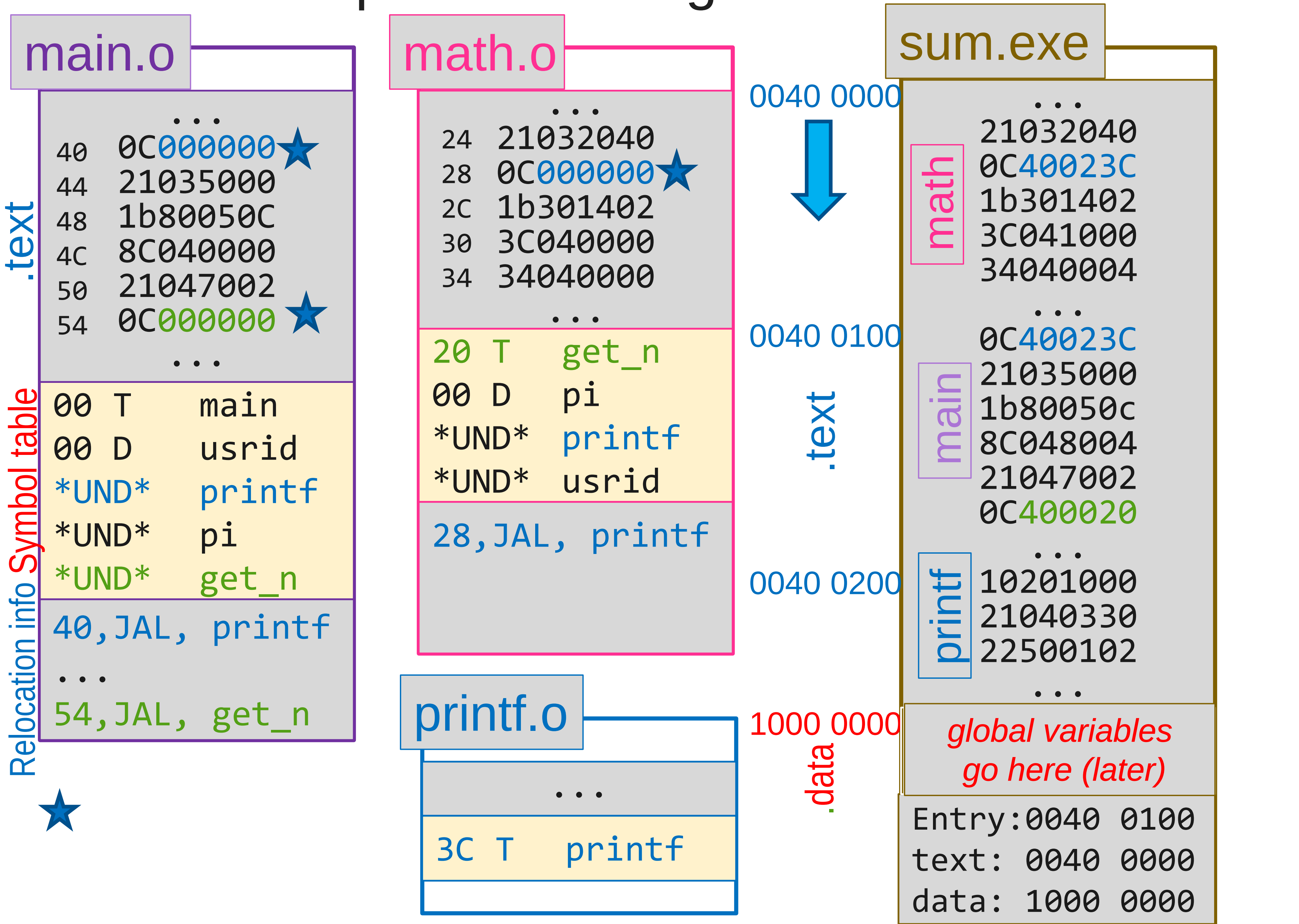
E.g.	./sum	Linux
	./sum.exe	Windows
	simulate sum	Class MIPS simulator

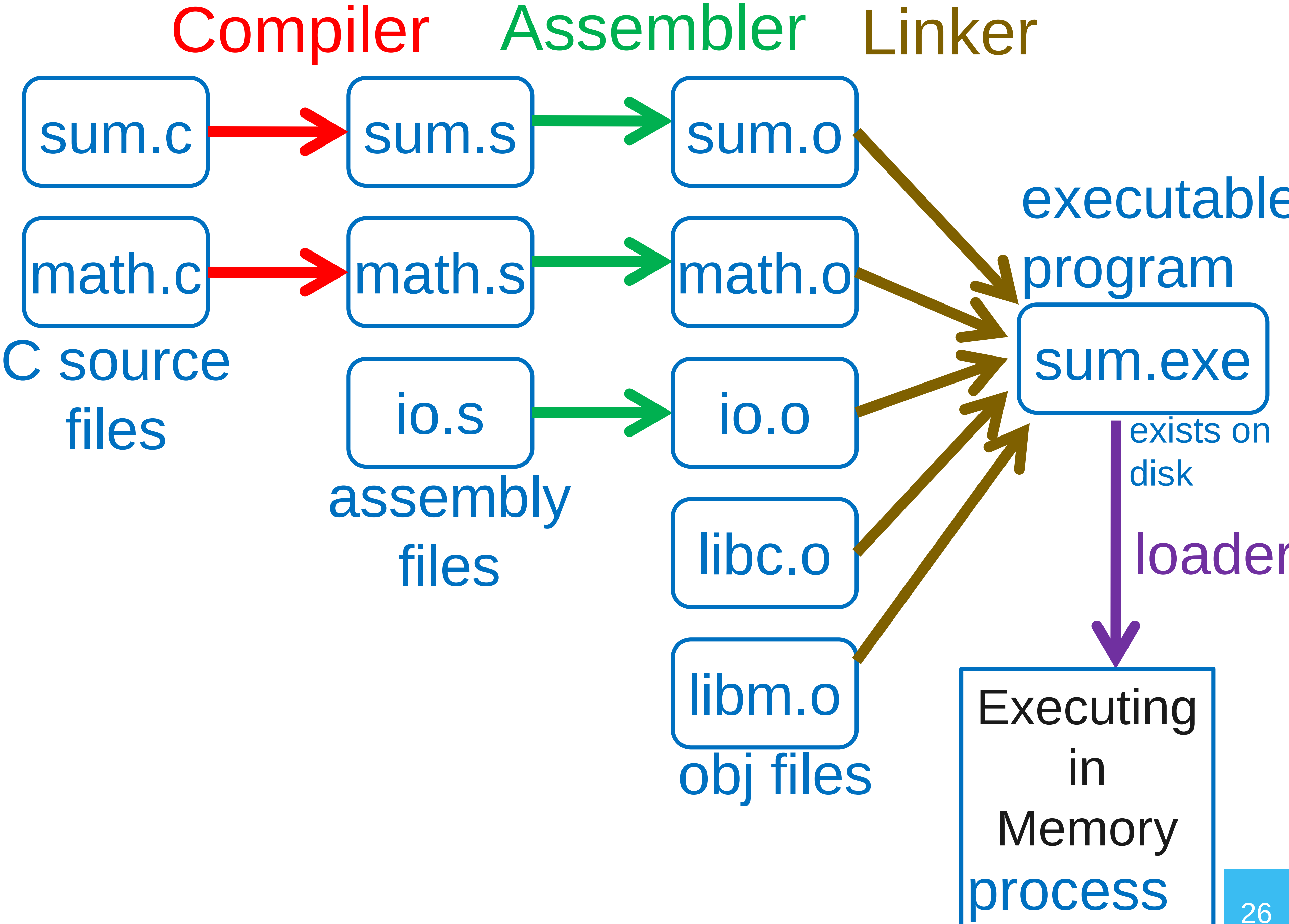
Static Libraries

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

Q: Every program contains the entire library?!?

Linker Example: Resolving an External Fn Call




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 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)