

inst.eecs.berkeley.edu/~cs61c

UC Berkeley CS61C : Machine Structures

Lecture 19 – Running a Program II aka Compiling, Assembling, Linking, Loading



2007-03-02

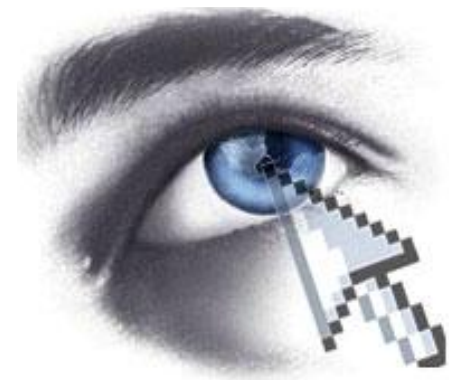
Hi to Carlos Restrepo from Houston, TX... (“thanks to UC Berkeley for this!”)

Lecturer SOE Dan Garcia

www.cs.berkeley.edu/~ddgarcia

Gaze-controlled UI! ⇒

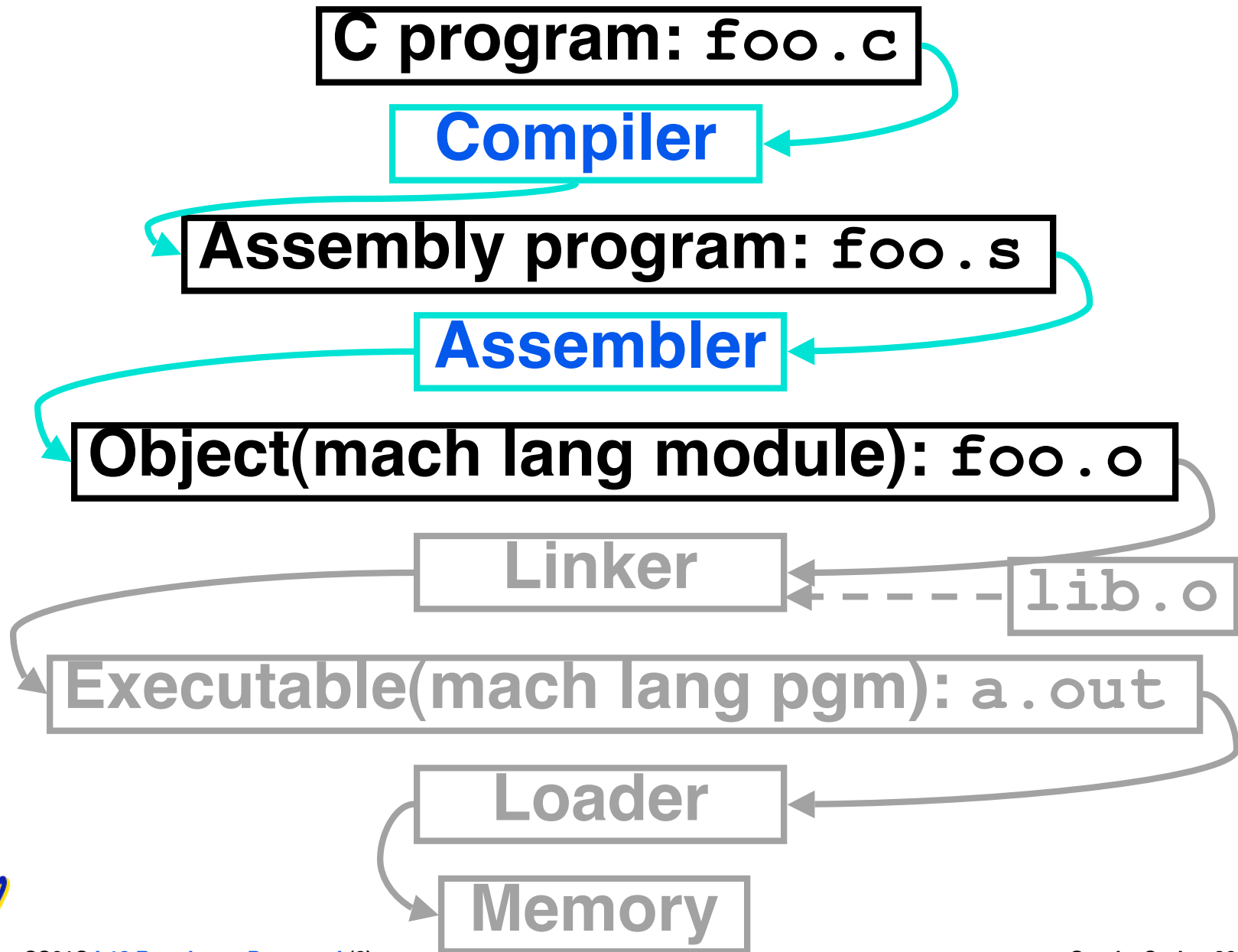
Researchers at Stanford have designed a system that allows a user to “click links, highlight text, and scroll” simply by looking at the screen.



www.technologyreview.com/Infotech/18254/
CS61C L18 Running a Program I (1)

Garcia, Spring 2007 © UCB

Review



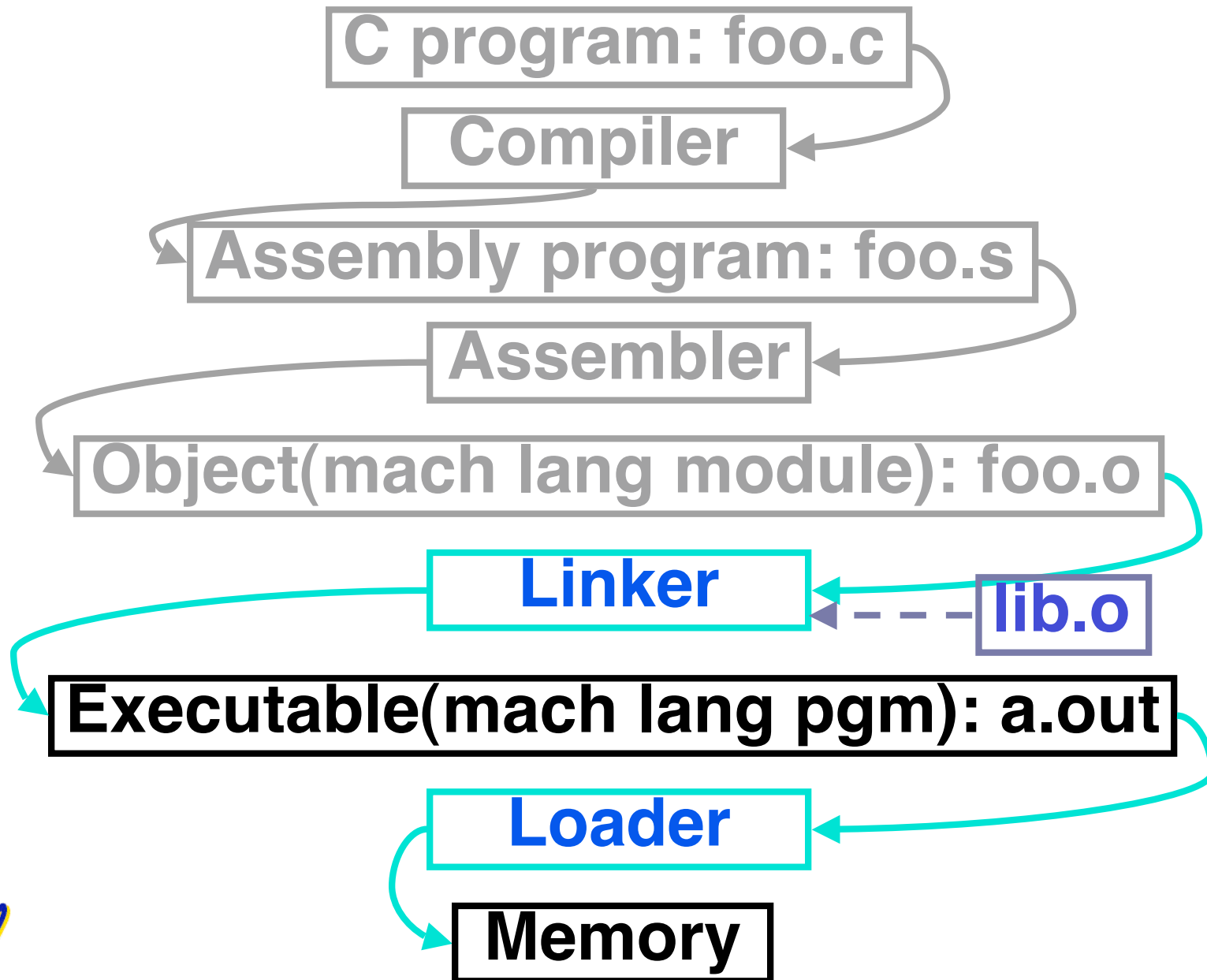
Object File Format (review)

- **object file header**: size and position of the other pieces of the object file
- **text segment**: the machine code
- **data segment**: binary representation of the data in the source file
- **relocation information**: identifies lines of code that need to be “handled”
- **symbol table**: list of this file’s labels and data that can be referenced
- **debugging information**
- A standard format is ELF (except MS)



http://www.skyfree.org/linux/references/ELF_Format.pdf

Where Are We Now?

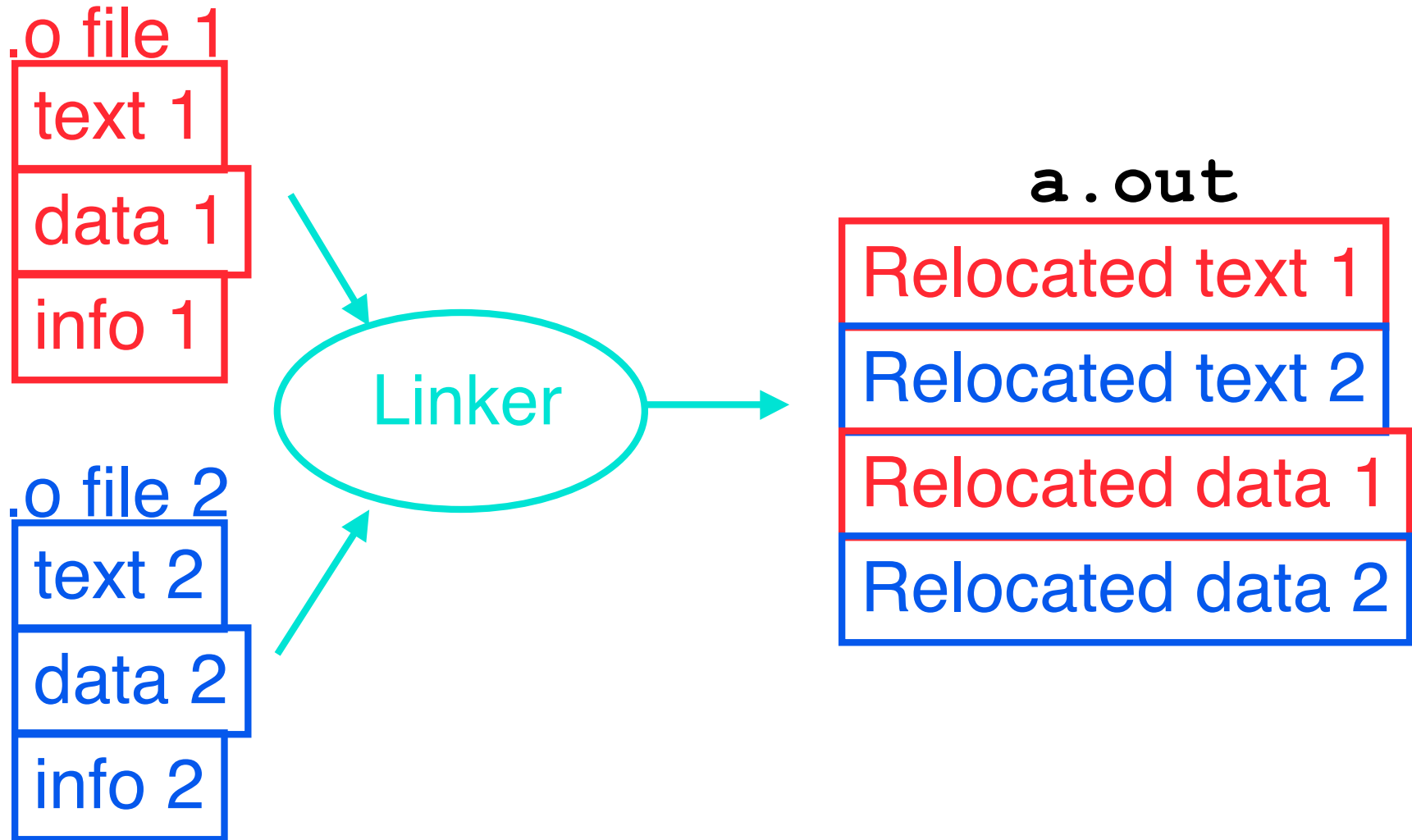


Linker (1/3)

- **Input: Object Code files, information tables (e.g., `foo.o`, `libc.o` for MIPS)**
- **Output: Executable Code (e.g., `a.out` for MIPS)**
- **Combines several object (`.o`) files into a single executable (“**linking**”)**
- **Enable Separate Compilation of files**
 - **Changes to one file do not require recompilation of whole program**
 - **Windows NT source is > 40 M lines of code!**
 - **Old name “Link Editor” from editing the “links” in jump and link instructions**



Linker (2/3)



Linker (3/3)

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



Four Types of Addresses we'll discuss

- **PC-Relative Addressing (beq, bne):**
never relocate
- **Absolute Address (j, jal):** always relocate
- **External Reference (usually jal):**
always relocate
- **Data Reference (often lui and ori):**
always relocate



Absolute Addresses in MIPS

- Which instructions need relocation editing?
- J-format: jump, jump and link

j/jal	xxxxxx
-------	--------

- Loads and stores to variables in static area, relative to global pointer

lw/sw	\$gp	\$x	address
-------	------	-----	---------

- What about conditional branches?

beq/bne	\$rs	\$rt	address
---------	------	------	---------

- PC-relative addressing preserved even if code moves



Resolving References (1/2)

- Linker *assumes* first word of first text segment is at address 0x00000000.
(More on this 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:**
 - search for reference (data or label) in all “user” symbol tables
 - if not found, search library files (for example, for `printf`)
 - once absolute address is determined, fill in the machine code appropriately
- **Output of linker: executable file containing text and data (plus header)**



Static vs Dynamically linked libraries

- What we've described is the traditional way: “statically-linked” approach
 - The library is now part of the executable, so if the library updates, we don't get the fix (have to recompile if we have source)
 - It includes the entire library even if not all of it will be used.
 - Executable is self-contained.
- An alternative is **dynamically linked libraries** (DLL), common on Windows & UNIX platforms



Dynamically linked libraries

en.wikipedia.org/wiki/Dynamic_linking

*This does add quite a bit of complexity to the compiler, linker, and operating system.
However, it provides many benefits:*

- **Space/time issues**

- + Storing a program requires less disk space
- + Sending a program requires less time
- + Executing two programs requires less memory (if they share a library)
- – At runtime, there's time overhead to do link

- **Upgrades**

- + Replacing one file (libXYZ.so) upgrades every program that uses library “XYZ”



- – Having the executable isn't enough anymore

Dynamically linked libraries

- **The prevailing approach to dynamic linking uses machine code as the “lowest common denominator”**
 - **the linker does not use information about how the program or library was compiled (i.e., what compiler or language)**
 - **this can be described as “linking at the machine code level”**
 - **This isn’t the only way to do it...**



Administrivia...Midterm in 5 days!

- **Review Sunday @ 2pm in 10 Evans**
- **Midterm Monday @ 7-10pm Here**
- **Covers labs,hw,proj,lec,book through today**
- **Bring...**
 - **NO backpacks, cells, calculators, pagers, PDAs**
 - **2 writing implements (we'll provide write-in exam booklets) – pencils ok!**
 - **One handwritten (both sides) 8.5"x11" paper**
 - **One green sheet (make sure to correct green sheet bugs)**

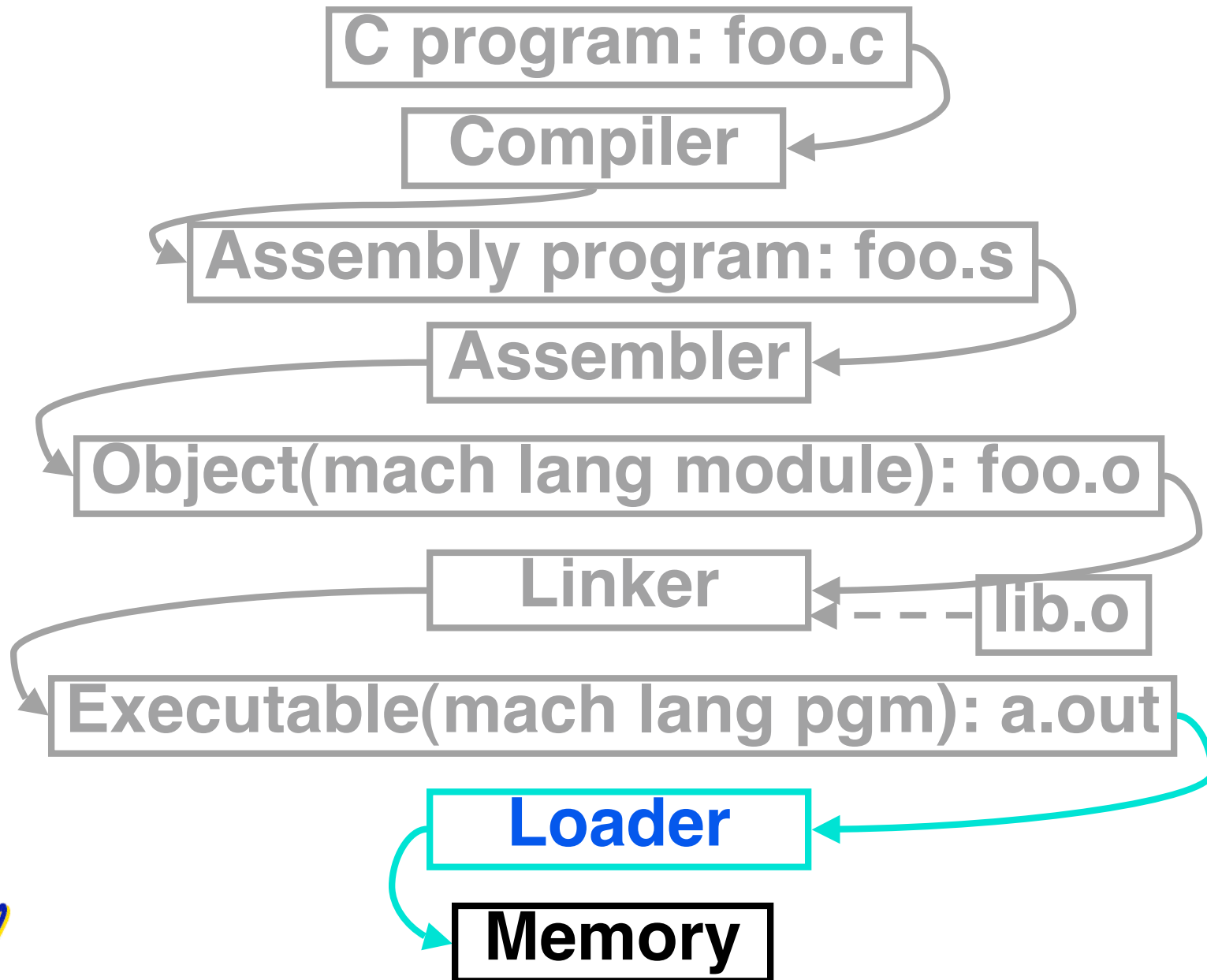


Upcoming Calendar

Week #	Mon	Wed	Thu Lab	Fri
#7 This week	MIPS Inst Format III (TA Brian)	Running Program I	Running Program	Running Program II
#8 Midterm week Sun 2pm Review 10 Evans	SDS I Midterm 7pm-10pm HERE (2050 VLSB)	SDS II (TA Valerie)	SDS	SDS III (TA David)



Where Are We Now?



Loader (1/3)

- **Input: Executable Code (e.g., a.out for MIPS)**
- **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 (2/3)

- **So what does a loader do?**
- **Reads executable file's header to determine size of text and data segments**
- **Creates new address space for program large enough to hold text and data segments, along with a stack segment**
- **Copies instructions and data from executable file into the new address space**



Loader (3/3)

- Copies arguments passed to the program onto the stack
- Initializes machine registers
 - Most registers cleared, but stack pointer assigned address of 1st free stack location
- 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



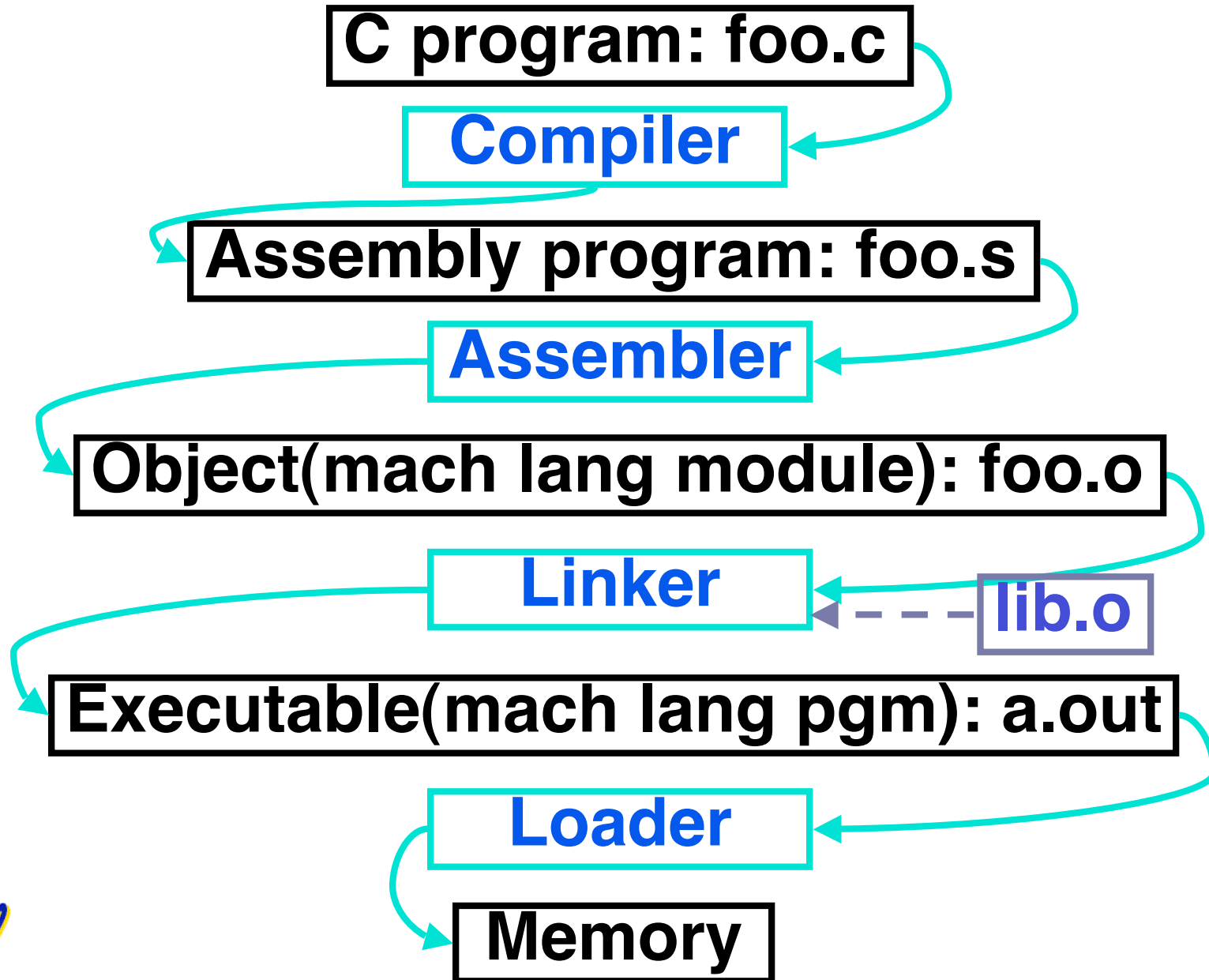
Peer Instruction

Which of the following instr. may need to be edited during link phase?

```
Loop: lui $at, 0xABCD  
      ori $a0,$at, 0xFEDC } # A  
      jal add_link      # B  
      bne $a0,$v0, Loop # C
```

	ABC
0:	FFF
1:	FFT
2:	FTF
3:	FTT
4:	TFF
5:	TFT
6:	TF
7:	TTT

Things to Remember (1/3)



Things to Remember (2/3)

- **Compiler converts a single HLL file into a single assembly language file.**
- **Assembler removes pseudoinstructions, converts what it can to machine language, and creates a checklist for the linker (relocation table). This changes each .s file into a .o file.**
 - **Does 2 passes to resolve addresses, handling internal forward references**
- **Linker combines several .o files and resolves absolute addresses.**
 - **Enables separate compilation, libraries that need not be compiled, and resolves remaining addresses**
- **Loader loads executable into memory and begins execution.**



Things to Remember 3/3

- **Stored Program concept is very powerful. It means that instructions sometimes act just like data. Therefore we can use programs to manipulate other programs!**

Compiler \Rightarrow Assembler \Rightarrow Linker (\Rightarrow Loader)



Bonus slides

- **These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.**
- **The slides will appear in the order they would have in the normal presentation**

BONUS



Big Endian vs. Little Endian

Big-endian and little-endian derive from Jonathan Swift's *Gulliver's Travels* in which the Big Endians were a political faction that broke their eggs at the large end ("the primitive way") and rebelled against the Lilliputian King who required his subjects (the Little Endians) to break their eggs at the small end.

- The order in which BYTES are stored in memory
- Bits always stored as usual. (E.g., 0xC2=0b 1100 0010)

Consider the number 1025 as we normally write it:

BYTE3 **BYTE2** **BYTE1** **BYTE0**
00000000 **00000000** **00000100** **00000001**

Big Endian

- ADDR3 ADDR2 ADDR1 ADDR0
 BYTE0 **BYTE1** **BYTE2** **BYTE3**
 00000001 00000100 00000000 00000000
- ADDR0 ADDR1 ADDR2 ADDR3
 BYTE3 **BYTE2** **BYTE1** **BYTE0**
 00000000 00000000 00000100 00000001

Little Endian

- ADDR3 ADDR2 ADDR1 ADDR0
 BYTE3 **BYTE2** **BYTE1** **BYTE0**
 00000000 00000000 00000100 00000001
- ADDR0 ADDR1 ADDR2 ADDR3
 BYTE0 **BYTE1** **BYTE2** **BYTE3**
 00000001 00000100 00000000 00000000

www.webopedia.com/TERM/b/big_endian.html
searchnetworking.techtarget.com/sDefinition/0,,sid7_gci211659,00.html
www.noveltheory.com/TechPapers/Endian.asp
en.wikipedia.org/wiki/Big_endian

Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

C Program Source Code: prog.c

```
#include <stdio.h>

int main (int argc, char *argv[]) {

    int i, sum = 0;

    for (i = 0; i <= 100; i++)
        sum = sum + i * i;

    printf ("The sum of sq from 0 .. 100 is
%d\n", sum);

}
```

“printf” lives in “libc”



Compilation: MAL

```
.text
.align 2
.globl main
main:
    subu $sp, $sp, 32
    sw $ra, 20($sp)
    sd $a0, 32($sp)
    sw $0, 24($sp)
    sw $0, 28($sp)
loop:
    lw $t6, 28($sp)
    mul $t7, $t6, $t6
    lw $t8, 24($sp)
    addu $t9, $t8, $t7
    sw $t9, 24($sp)
```

```
    addu $t0, $t6, 1
    sw $t0, 28($sp)
    ble $t0, 100, loop
    la $a0, str
    lw $a1, 24($sp)
    jal printf
    move $v0, $0
    lw $ra, 20($sp)
    addiu $sp, $sp, 32
    jr $ra
    .data
    .align 0
str:
    .asciiz "The sum
of sq from 0
100 is %d\n"
```

Where are
7 pseudo-
instructions?



Compilation: MAL

```
.text
.align 2
.globl main
main:
subu $sp, $sp, 32
sw $ra, 20($sp)
sd $a0, 32($sp)
sw $0, 24($sp)
sw $0, 28($sp)
loop:
lw $t6, 28($sp)
mul $t7, $t6, $t6
lw $t8, 24($sp)
addu $t9, $t8, $t7
sw $t9, 24($sp)
```

```
addu $t0, $t6, 1
sw $t0, 28($sp)
ble $t0, 100, loop
la $a0, str
lw $a1, 24($sp)
jal printf
move $v0, $0
lw $ra, 20($sp)
addiu $sp, $sp, 32
jr $ra      7 pseudo-
            instructions
.data      underlined
.align 0
str:
.asciiz "The sum
of sq from 0 ..
100 is %d\n"
```



Assembly step 1:

- Remove pseudoinstructions, assign addresses

```
00 addiu $29,$29,-32  
04 sw      $31,20($29)  
08 sw      $4, 32($29)  
0c sw      $5, 36($29)  
10 sw      $0, 24($29)  
14 sw      $0, 28($29)  
18 lw      $14, 28($29)  
1c multu   $14, $14  
20 mflo    $15  
24 lw      $24, 24($29)  
28 addu    $25,$24,$15  
2c sw      $25, 24($29)
```

```
30 addiu $8,$14, 1  
34 sw      $8,28($29)  
38 slti   $1,$8, 101  
3c bne    $1,$0, loop  
40 lui    $4, l.str  
44 ori    $4,$4,r.str  
48 lw      $5,24($29)  
4c jal     printf  
50 add    $2, $0, $0  
54 lw      $31,20($29)  
58 addiu   $29,$29,32  
5c jr      $31
```



Assembly step 2

- Create relocation table and symbol table
- Symbol Table

Label	address (in module)	type
main:	0x00000000	global text
loop:	0x00000018	local text
str:	0x00000000	local data

- Relocation Information

Address	Instr. type	Dependency
0x00000040	lui	l.str
0x00000044	ori	r.str
0x0000004c	jal	printf



Assembly step 3

•Resolve local PC-relative labels

```
00 addiu $29,$29,-32
04 sw    $31,20($29)
08 sw    $4, 32($29)
0c sw    $5, 36($29)
10 sw    $0, 24($29)
14 sw    $0, 28($29)
18 lw    $14, 28($29)
1c multu $14,$14
20 mflo  $15
24 lw    $24, 24($29)
28 addu  $25,$24,$15
2c sw    $25, 24($29)
30 addiu $8,$14, 1
34 sw    $8,28($29)
38 slti  $1,$8, 101
3c bne   $1,$0, -10
40 lui   $4, l.str
44 ori   $4,$4, r.str
48 lw    $5,24($29)
4c jal   printf
50 add   $2,$0,$0
54 lw    $31,20($29)
58 addiu $29,$29,32
5c jr    $31
```



Assembly step 4

- **Generate object (.o) file:**
 - **Output binary representation for**
 - **ext segment (instructions),**
 - **data segment (data),**
 - **symbol and relocation tables.**
 - **Using dummy “placeholders” for unresolved absolute and external references.**



Text segment in object file

```
0x000000 0010011110111101111111111111100000
0x000004 101011111011111100000000000010100
0x000008 101011111010010000000000000100000
0x00000c 1010111110100101000000000000100100
0x000010 1010111110100000000000000000011000
0x000014 1010111110100000000000000000011100
0x000018 1000111110101110000000000000011100
0x00001c 1000111110111000000000000000011000
0x000020 0000000111001110000000000000011001
0x000024 001001011100100000000000000000001
0x000028 0010100100000001000000000001100101
0x00002c 1010111110101000000000000000011100
0x000030 000000000000000000000111100000010010
0x000034 000000110000011111100100000100001
0x000038 0001010000010000001111111111110111
0x00003c 1010111110111001000000000000011000
0x000040 0011110000000010000000000000000000
0x000044 1000111110100101000000000000000000
0x000048 0000110000010000000000000000011101100
0x00004c 0010010000000000000000000000000000
0x000050 1000111110111111000000000000010100
0x000054 00100111101111010000000000000100000
0x000058 00000011111000000000000000000001000
0x00005c 00000000000000000000000001000000100001
```



Link step 1: combine prog.o, libc.o

- Merge text/data segments
- Create absolute memory addresses
- Modify & merge symbol and relocation tables
- Symbol Table

• Label	Address	
main:	0x00000000	
loop:	0x00000018	
str:	0x10000430	
printf:	0x000003b0	...

- Relocation Information

• Address	Instr.	Type	Dependency	
0x00000040	lui		l.str	
0x00000044	ori		r.str	
0x0000004c	jal		printf	...



Link step 2:

- Edit Addresses in relocation table

- (shown in TAL for clarity, but done in binary)

00	addiu	\$29, \$29, -32	30	addiu	\$8, \$14, 1
04	sw	\$31, 20 (\$29)	34	sw	\$8, 28 (\$29)
08	sw	\$4, 32 (\$29)	38	slti	\$1, \$8, 101
0c	sw	\$5, 36 (\$29)	3c	bne	\$1, \$0, <u>-10</u>
10	sw	\$0, 24 (\$29)	40	lui	\$4, <u>4096</u>
14	sw	\$0, 28 (\$29)	44	ori	\$4, \$4, <u>1072</u>
18	lw	\$14, 28 (\$29)	48	lw	\$5, 24 (\$29)
1c	multu	\$14, \$14	4c	jal	<u>812</u>
20	mflo	\$15	50	add	\$2, \$0, \$0
24	lw	\$24, 24 (\$29)	54	lw	\$31, 20 (\$29)
28	addu	\$25, \$24, \$15	58	addiu	\$29, \$29, 32
2c	sw	\$25, 24 (\$29)	5c	jr	\$31



Link step 3:

- **Output executable of merged modules.**
 - **Single text (instruction) segment**
 - **Single data segment**
 - **Header detailing size of each segment**

- **NOTE:**
 - **The preceding example was a much simplified version of how ELF and other standard formats work, meant only to demonstrate the basic principles.**

