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# UCB CS61C : Machine Structures

## Lecture 16 – Running a Program (Compiling, Assembling, Linking, Loading)


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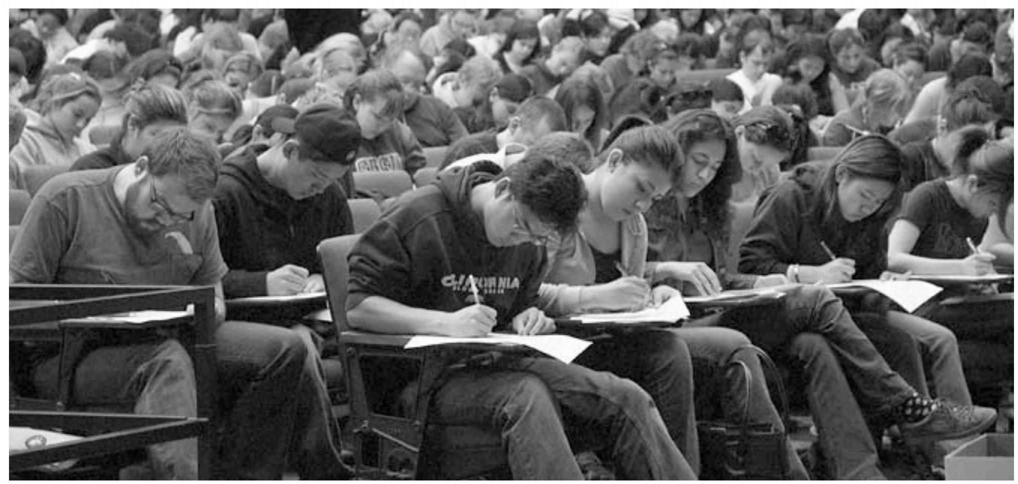
## SOME EECS FACULTY CONSIDERING LAPTOP BAN

Research shows laptops and tablets in class lower performance of people around them. Ban? Make 'em sit in the back? EECS faculty mulling over!

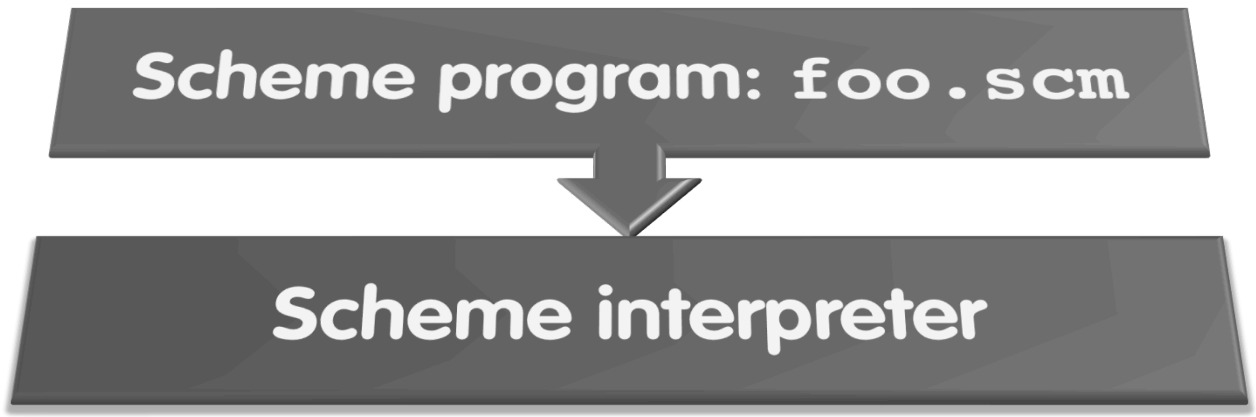


wapo.st/1rd6LOR

# Administrivia…

- Midterm Exam - You get to bring
  - Your study sheet
  - Your green sheet
  - Pens & Pencils
- What you don't need to bring
  - Calculator, cell phone, pagers
- Conflicts? DSP accomodations? Email Head TA

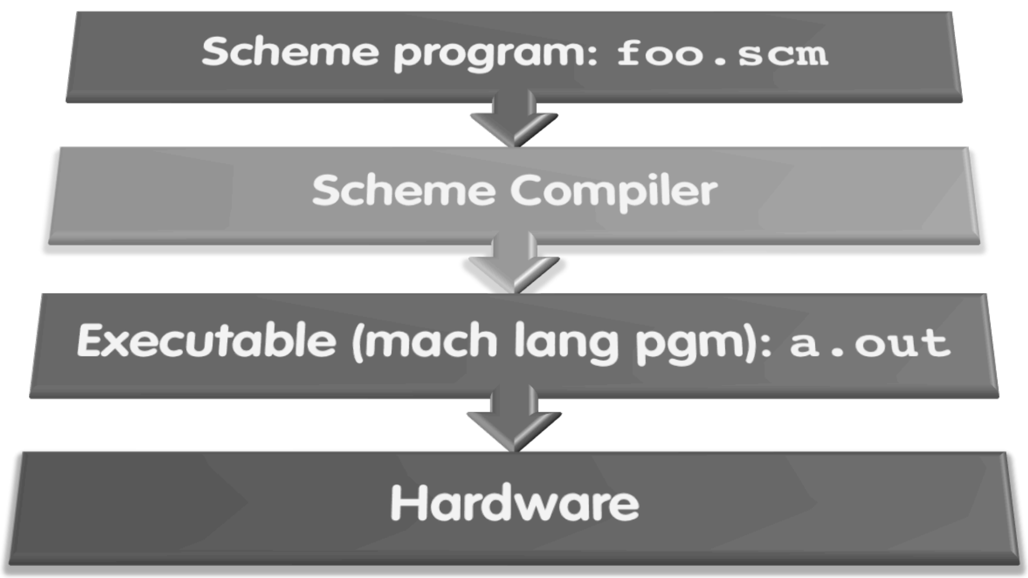
# Interpretation



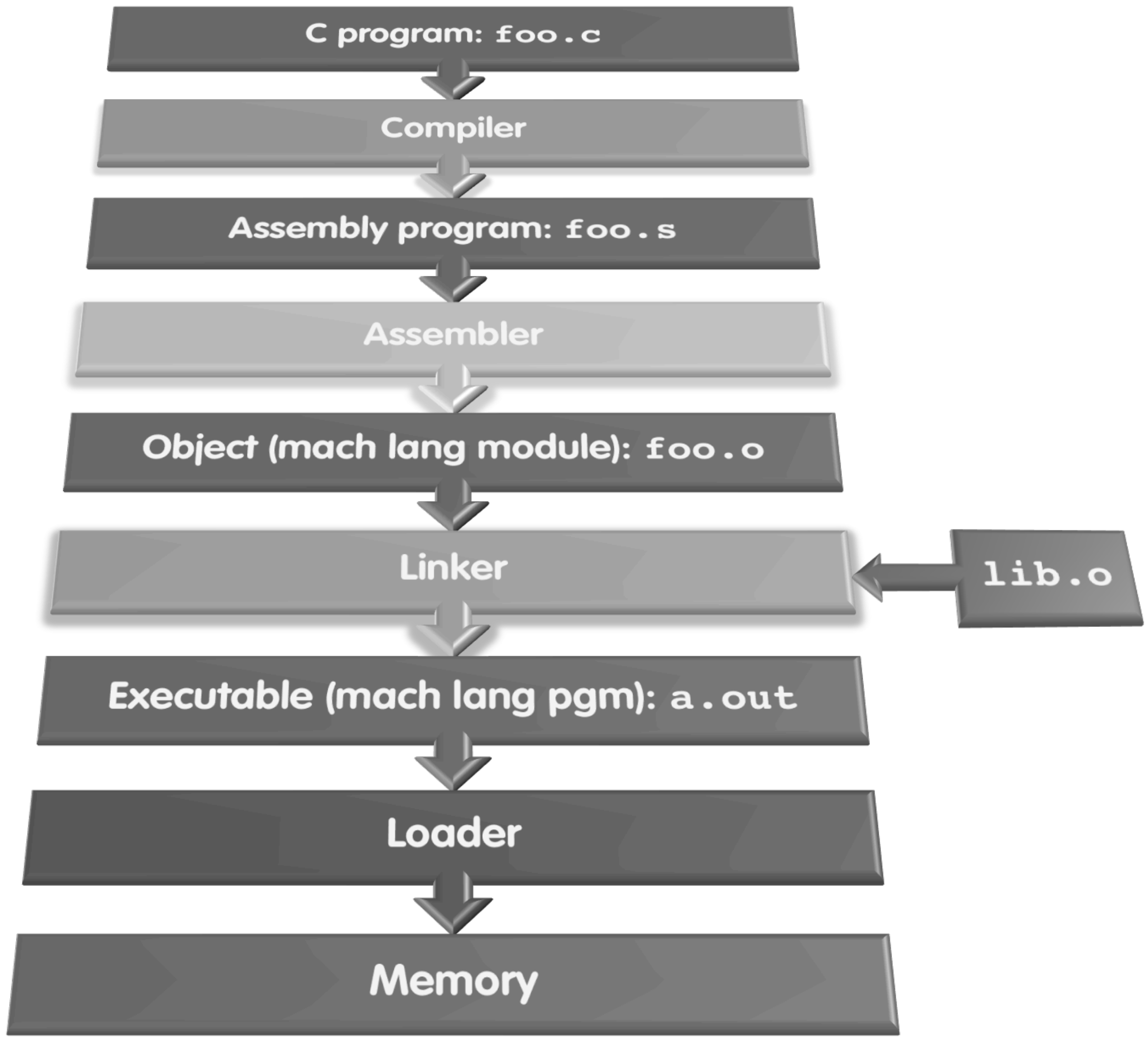

- Scheme Interpreter is just a program that reads a scheme program and performs the functions of that scheme program.

# Translation

- Scheme Compiler is a translator from Scheme to machine language.
- The processor is a hardware interpeter of machine language.



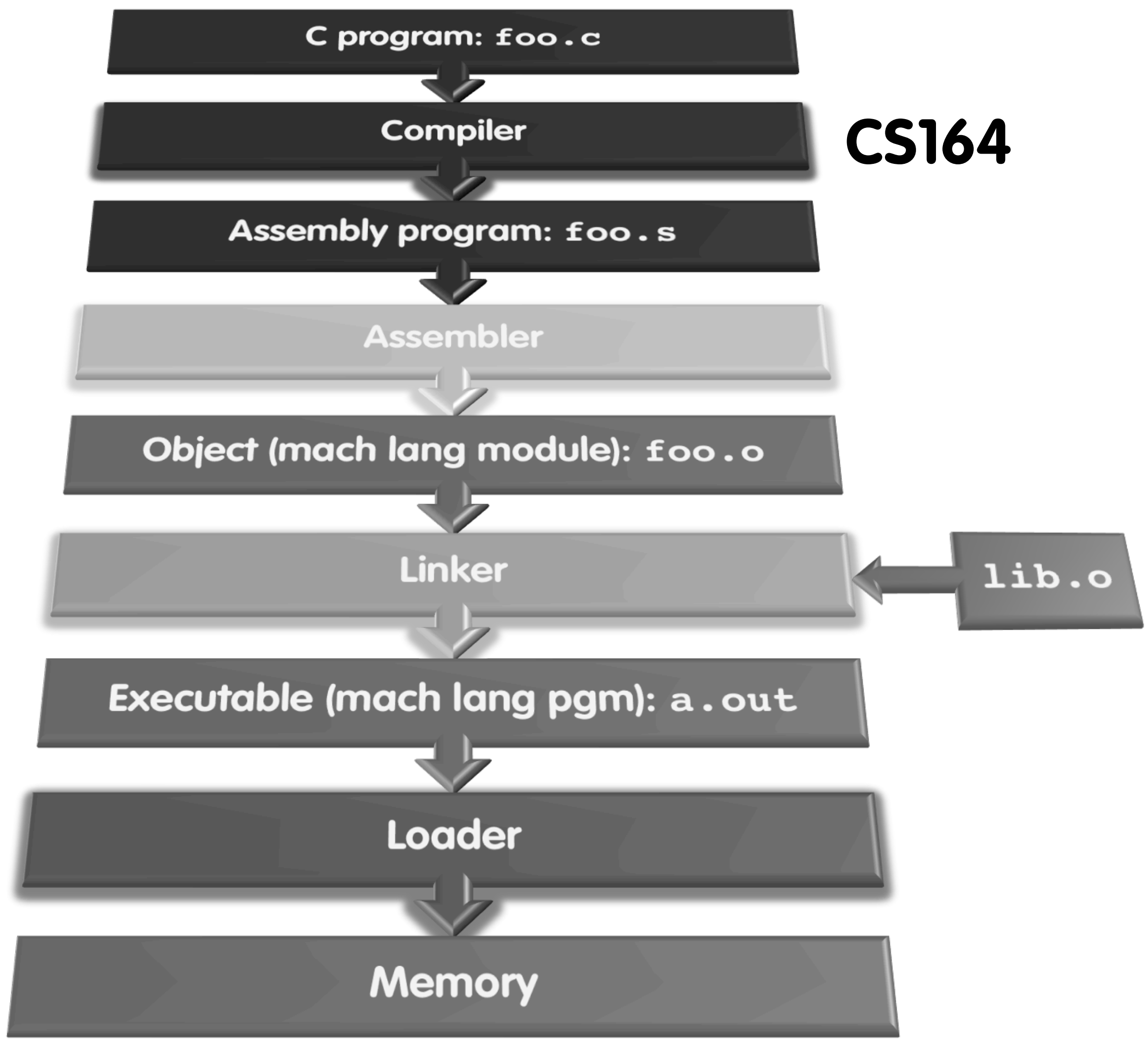
# Steps to Starting a Program (translation)



# Compiler

- Input: High-Level Language Code
  (e.g., C, Java such as **`foo.c`**)
- Output: Assembly Language Code
  (e.g., **`foo.s`** for MIPS)
- Note: Output *may* contain pseudoinstructions
- Pseudoinstructions: instructions that assembler understands but not in machine
  For example:
  - **`move $s1,$s2`** ⇒ **`or $s1,$s2,$zero`**

# Where Are We Now?



# Assembler

- Input: Assembly Language Code (MAL) (e.g., `foo.s` for MIPS)
- Output: Object Code, information tables (TAL) (e.g., `foo.o` for MIPS)
- Reads and Uses Directives
- Replace Pseudoinstructions
- Produce Machine Language
- Creates Object File

# Assembler Directives (p. A-51 to A-53)

- Give directions to assembler, but do not produce machine instructions
  - **`.text`:** Subsequent items put in user text segment (machine code)
  - **`.data`:** Subsequent items put in user data segment (binary rep of data in source file)
  - **`.globl sym`:** declares `sym` global and can be referenced from other files
  - **`.asciiz str`:** Store the string **`str`** in memory and null-terminate it
  - **`.word w1…wn`:** Store the *n* 32-bit quantities in successive memory words

# Pseudoinstruction Replacement

- Asm. treats convenient variations of machine language instructions as if real instructions

| Pseudo: | Real: |
| --- | --- |
| `subu $sp,$sp,32` | `addiu $sp,$sp,-32` |
| `sd $a0, 32($sp)` | `sw $a0, 32($sp)`<br>`sw $a1, 36($sp)` |
| `mul $t7,$t6,$t5` | `mul $t6,$t5`<br>`mflo $t7` |
| `addu $t0,$t6,1` | `addiu $t0,$t6,1` |
| `ble $t0,100,loop` | `slti $at,$t0,101`<br>`bne $at,$0,loop` |
| `la $a0, str` | `lui $at,left(str)`<br>`ori $a0,$at,right(str)` |

# Producing Machine Language (1/3)

- Simple Case
  - Arithmetic, Logical, Shifts, and so on.
  - All necessary info is within the instruction already.
- What about Branches?
  - PC-Relative
  - So once pseudo-instructions are replaced by real ones, we know by how many instructions to branch.
- So these can be handled.

# Producing Machine Language (2/3)

- "Forward Reference" problem
  - Branch instructions can refer to labels that are "forward" in the program:

```
    or   $v0, $0,  $0
L1: slt  $t0, $0,  $a1
    beq  $t0, $0,  L2
    addi $a1, $a1, -1
    j    L1
L2: add  $t1, $a0, $a1
```

  - Solved by taking 2 passes over the program.
    - First pass remembers position of labels
    - Second pass uses label positions to generate code

# Producing Machine Language (3/3)

- What about jumps (`j` and `jal`)?
  - Jumps require absolute address.
  - So, forward or not, still can't generate machine instruction without knowing the position of instructions in memory.
- What about references to data?
  - `la` gets broken up into `lui` and `ori`
  - These will require the full 32-bit address of the data.
- These can't be determined yet, so we create two tables…

# Symbol Table

- List of “items” in this file that may be used by other files.
- What are they?
  - Labels: function calling
  - Data: anything in the `.data` section; variables which may be accessed across files

# Relocation Table

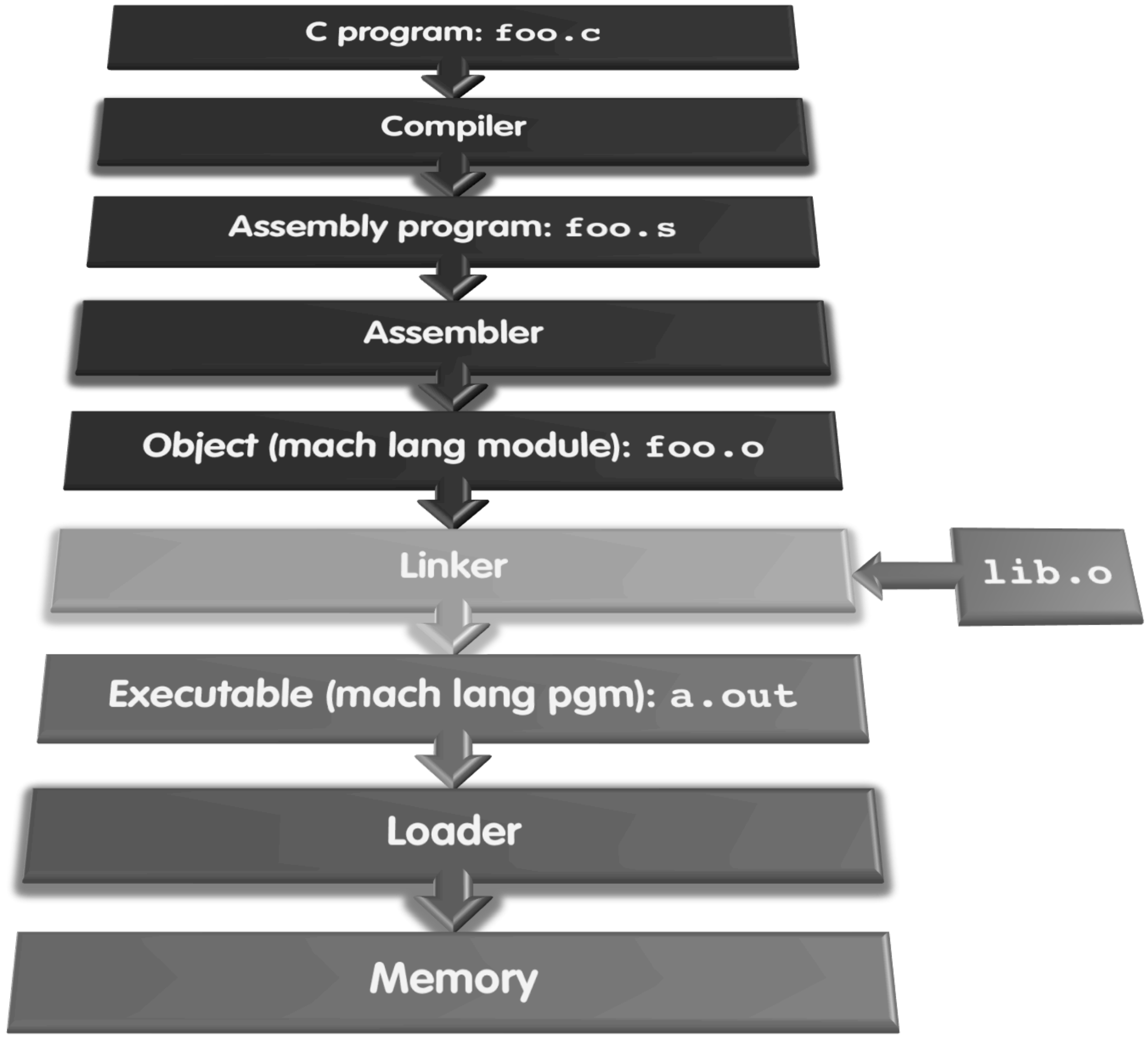
- List of "items" this file needs the address later.
- What are they?
  - Any label jumped to: `j` or `jal`
    - internal
    - external (including lib files)
  - Any piece of data
    - such as the `la` instruction

# Object File Format

- 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

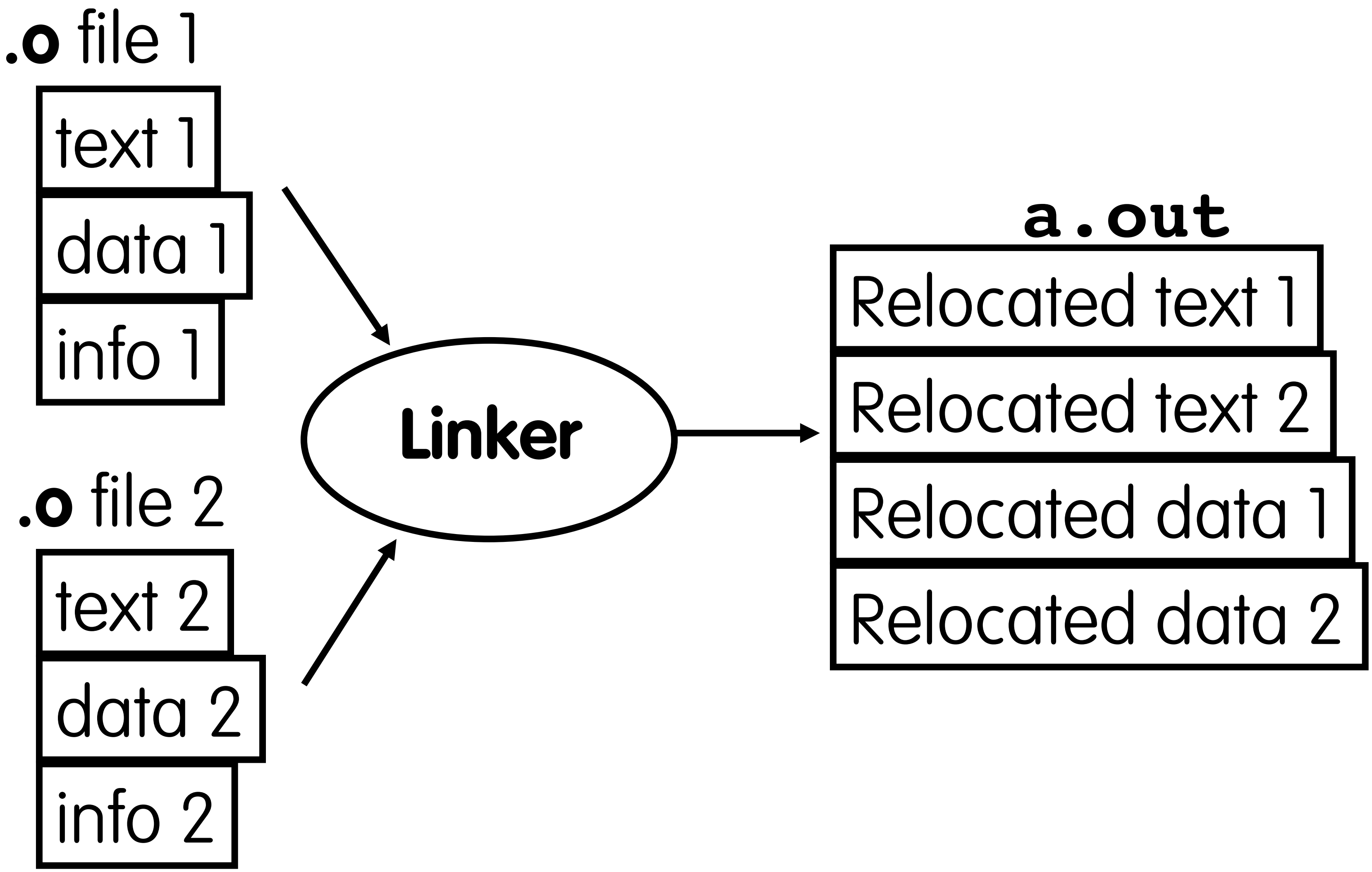
# Where Are We Now?



# 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 was > 40 M lines of code!
  - Old name "Link Editor" from editing the "links" in jump and link instructions

# Linker (2/3)


.o file 1
text 1
data 1
info 1
.o file 2
text 2
data 2
info 2
Linker
a.out
Relocated text 1
Relocated text 2
Relocated data 1
Relocated data 2

# 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; 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` | `xxxxx` |

  - 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

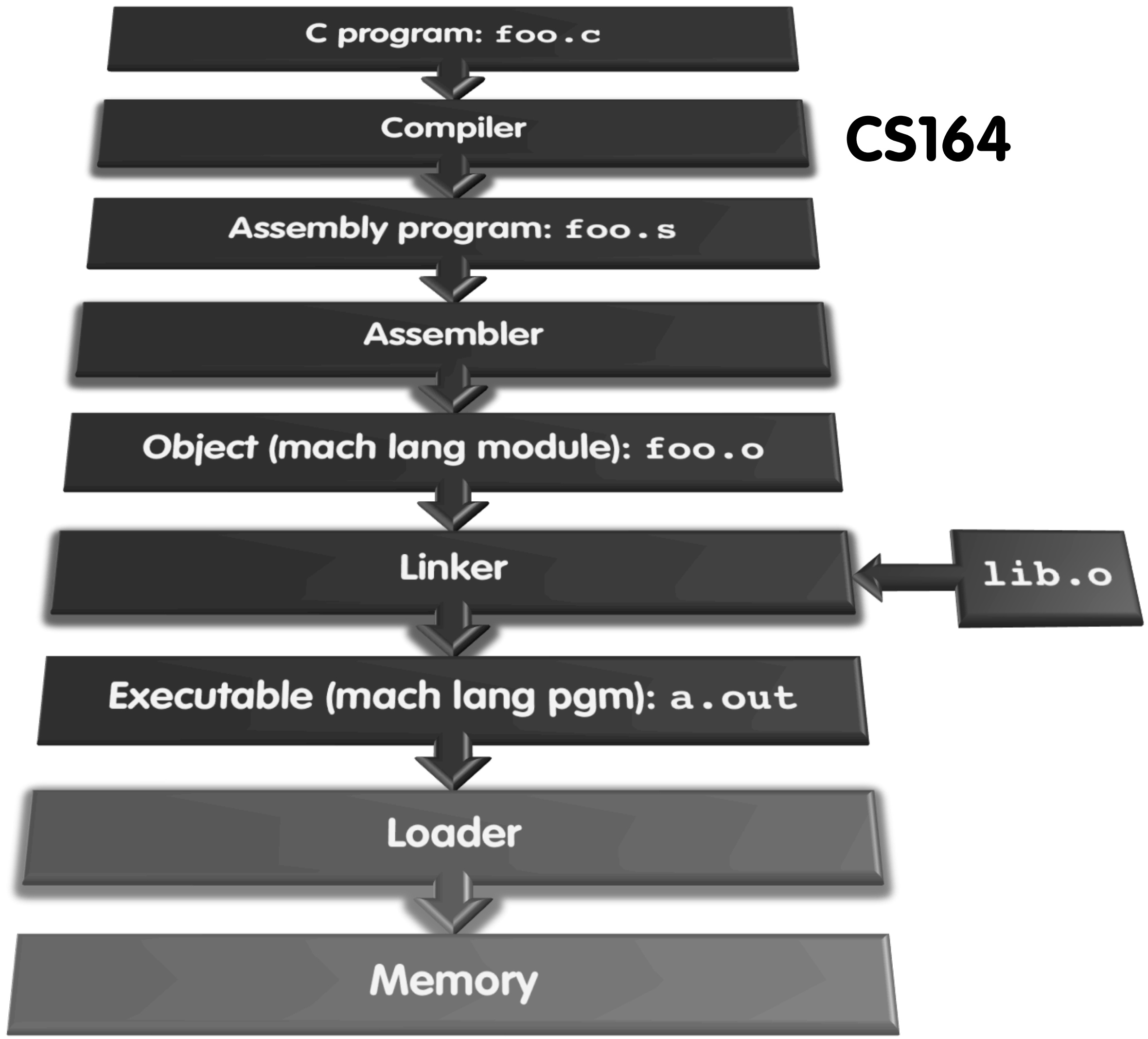
# Resolving References (1/2)

- Linker assumes first word of first text segment is at address **`0x00000000`**.
  - (More 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)

# Where Are We Now?



# Loader Basics

- 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

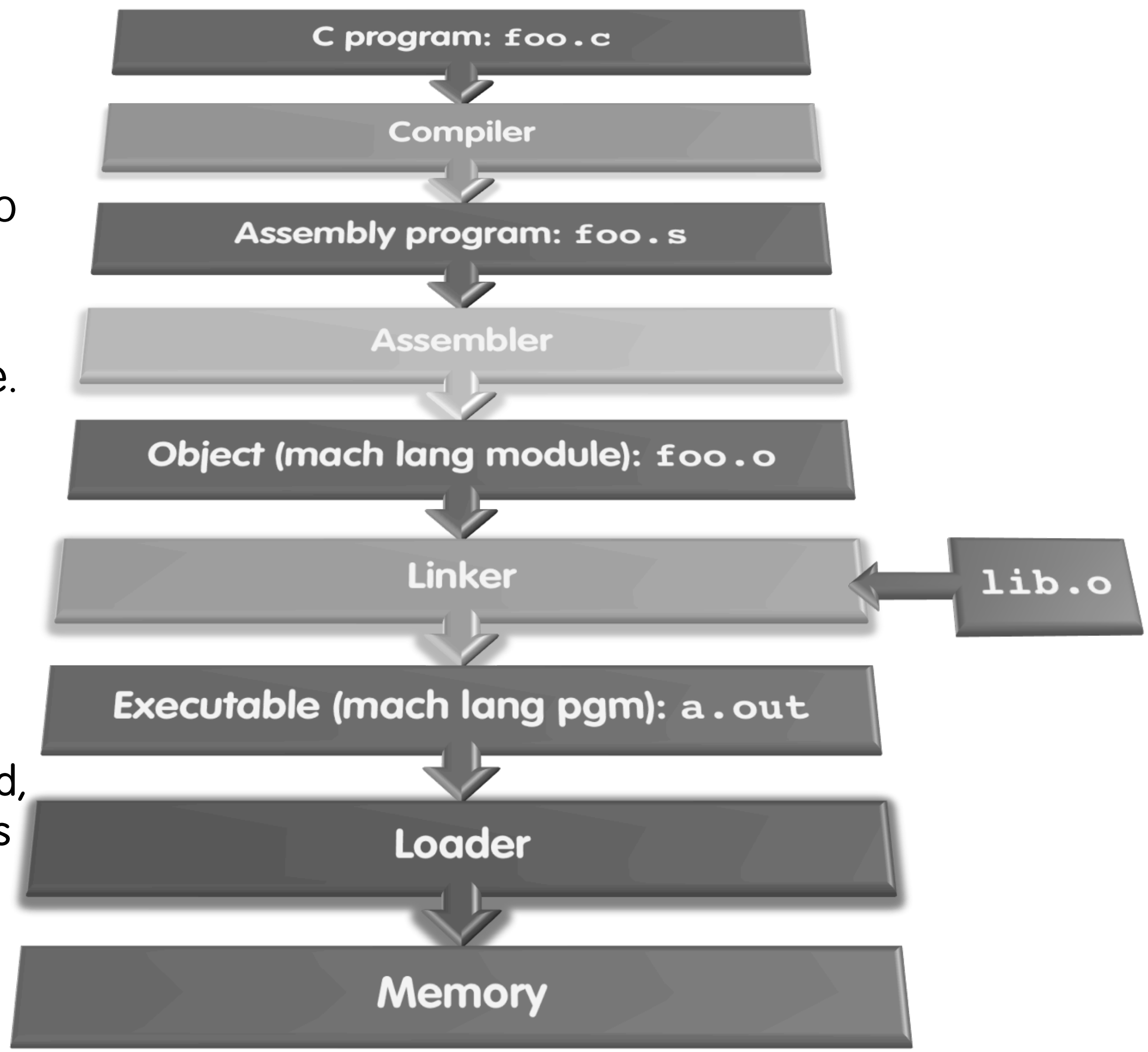
# Loader … what does it do?

- 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
- 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 & sets the PC
  - If main routine returns, start-up routine terminates program with the exit system call

# Conclusion

- 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 ⇒ Assembler ⇒ Linker (⇒ Loader)

- Compiler converts a single HLL file into a single assembly lang. file.
- Assembler removes pseudo instructions, converts what it can to machine language, and creates a checklist for the linker (relocation table). A `.s` file becomes 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.



# Peer Instruction

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

```
Loop: lui $at, 0xABCD          }
      ori $a0,$at, 0xFEDC      }# 1
      bne $a0,$v0, Loop         # 2
```

```
   12
a) FF
b) FT
c) TF
d) TT
```

# Peer Instruction

1) Assembler will ignore the instruction **`Loop:nop`** because it does nothing.

2) Java designers used a translater AND interpreter (rather than just a translater) mainly because of (at least 1 of): ease of writing, better error msgs, smaller object code.

| | 12 |
|---|---|
| a) | FF |
| b) | FT |
| c) | TF |
| d) | TT |