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UC Berkeley CS61C : Machine Structures

Lecture 18 – Running a Program I
aka Compiling, Assembling, Linking, Loading

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Lecturer SOE Dan Garcia

www.cs.berkeley.edu/~ddgarcia

Router Security Hole! ⇒

Huge security hole has been found – if you have a home router, crackers can break in and replace your bank's web page with their 'faked' web page (it's called pharming) and gather your information!

www.technologyreview.com/Infotech/18231/

Review

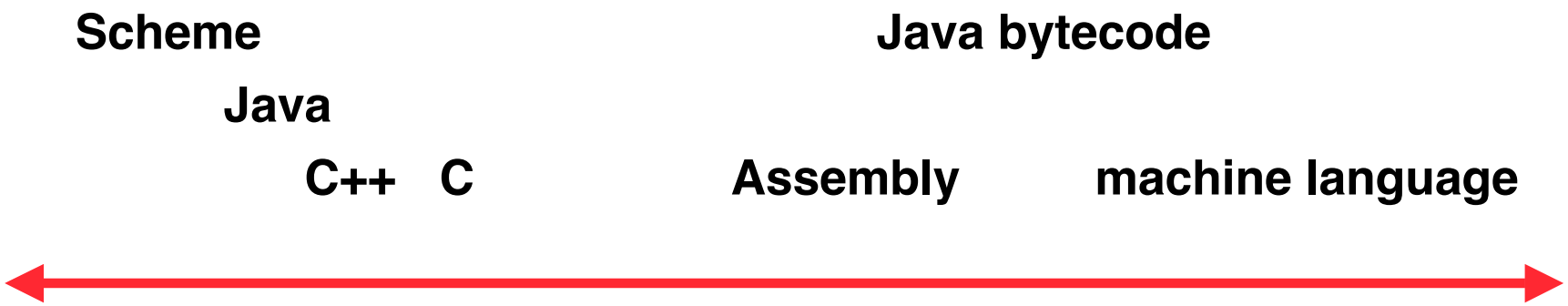
- **Disassembly is simple and starts by decoding `opcode` field.**
  - **Be creative, efficient when authoring C**
- **Assembler expands real instruction set (TAL) with pseudoinstructions (MAL)**
  - **Only TAL can be converted to raw binary**
  - **Assembler's job to do conversion**
  - **Assembler uses reserved register `$at`**
  - **MAL makes it much easier to write MIPS**

Overview

- Interpretation vs Translation
- Translating C Programs
  - Compiler
  - Assembler
  - Linker (next time)
  - Loader (next time)
- An Example (next time)

Language Execution Continuum

- An *Interpreter* is a program that executes other programs.

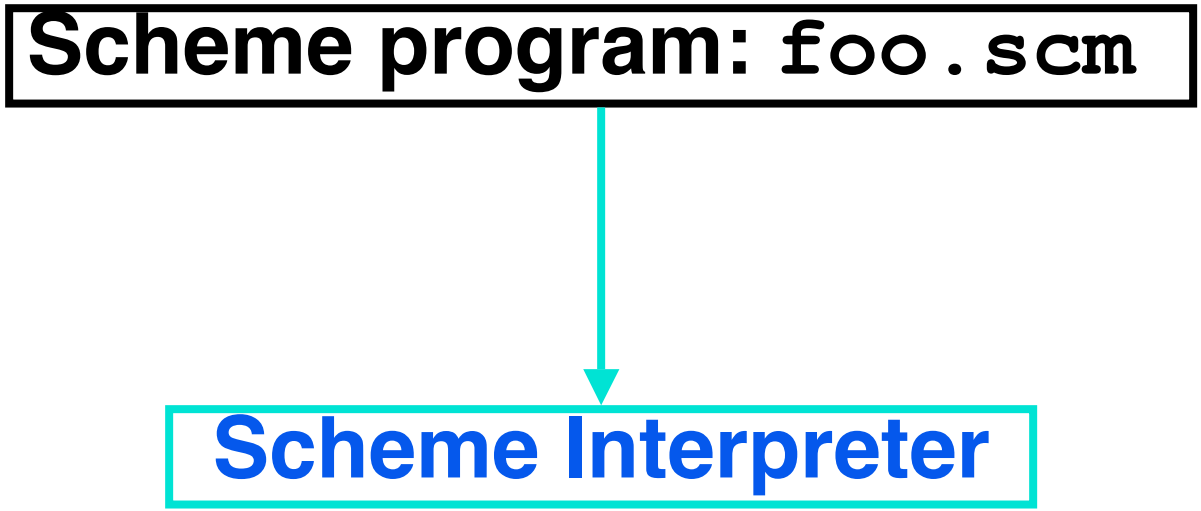


- Language *translation* gives us another option.
- In general, we interpret a high level language when efficiency is not critical and translate to a lower level language to improve performance

Interpretation vs Translation

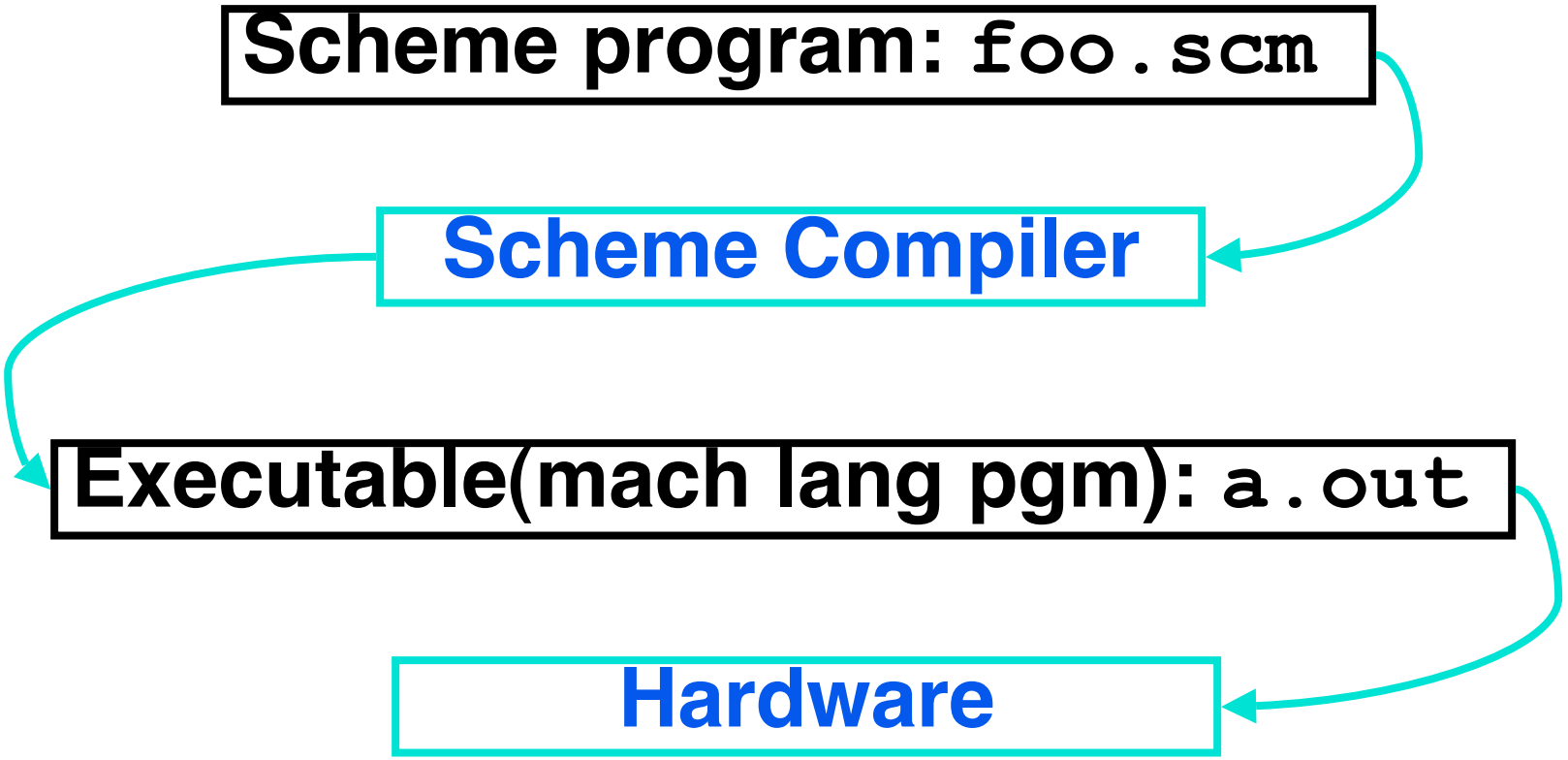
- How do we run a program written in a source language?
- Interpreter: Directly executes a program in the source language
- Translator: Converts a program from the source language to an equivalent program in another language
- For example, consider a Scheme program `foo.scm`

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.

Interpretation

- Any good reason to interpret machine language in software?
- SPIM – useful for learning / debugging
- Apple Macintosh conversion
  - Switched from Motorola 680x0 instruction architecture to PowerPC.
  - Now similar issue with switch to x86.
  - Could require all programs to be re-translated from high level language
  - Instead, let executables contain old and/or new machine code, interpret old code in software if necessary (emulation)

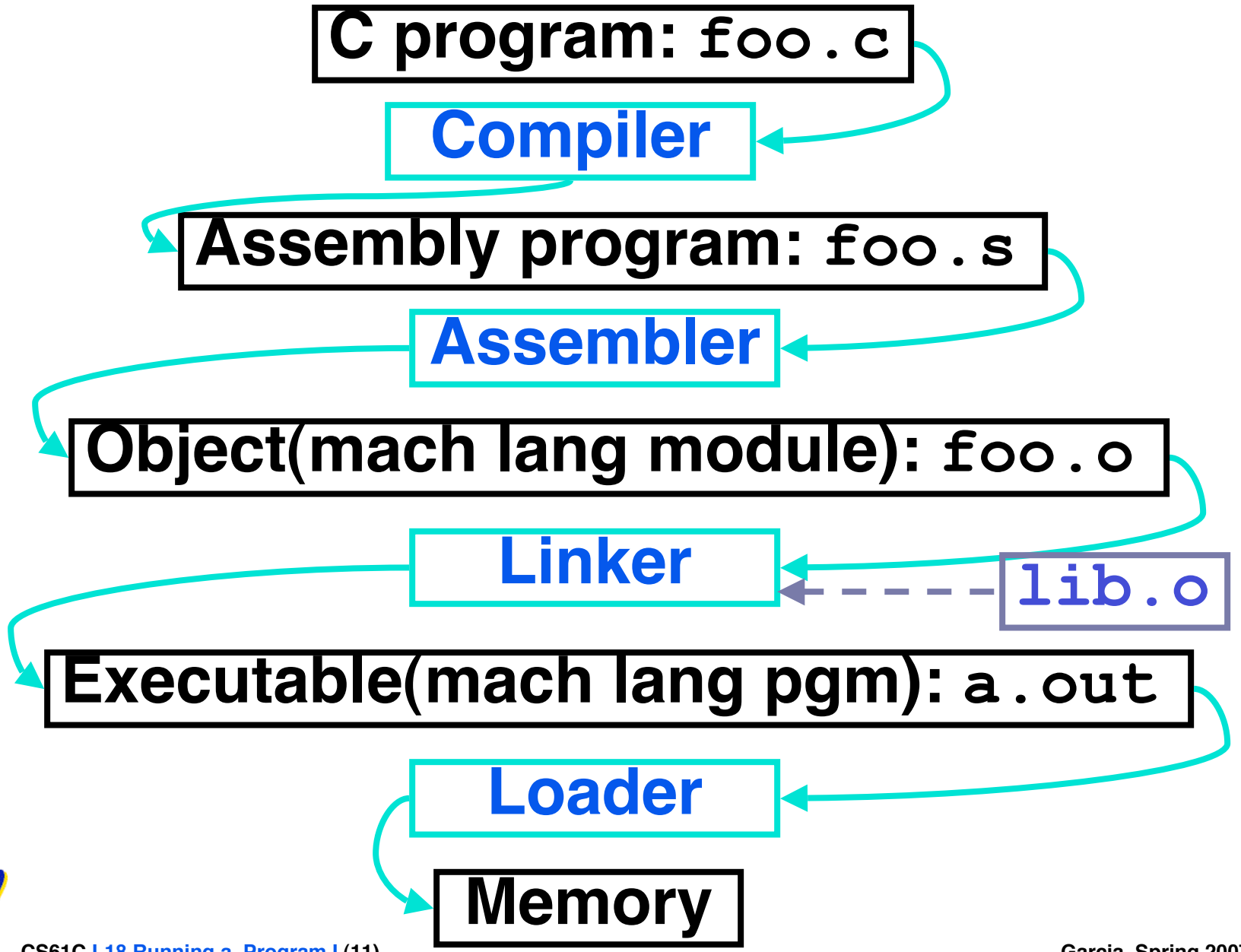
Interpretation vs. Translation? (1/2)

- Generally easier to write interpreter
- Interpreter closer to high-level, so can give better error messages (e.g., SPIM)
  - Translator reaction: add extra information to help debugging (line numbers, names)
- Interpreter slower (10x?) but code is smaller (1.5X to 2X?)
- Interpreter provides instruction set independence: run on any machine
  - Apple switched to PowerPC. Instead of retranslating all SW, let executables contain old and/or new machine code, interpret old code in software if necessary

Interpretation vs. Translation? (2/2)

- Translated/compiled code almost always more efficient and therefore higher performance:
  - Important for many applications, particularly operating systems.
- Translation/compilation helps "hide" the program "source" from the users:
  - One model for creating value in the marketplace (eg. Microsoft keeps all their source code secret)
  - Alternative model, "open source", creates value by publishing the source code and fostering a community of developers.

Steps to Starting a Program (translation)



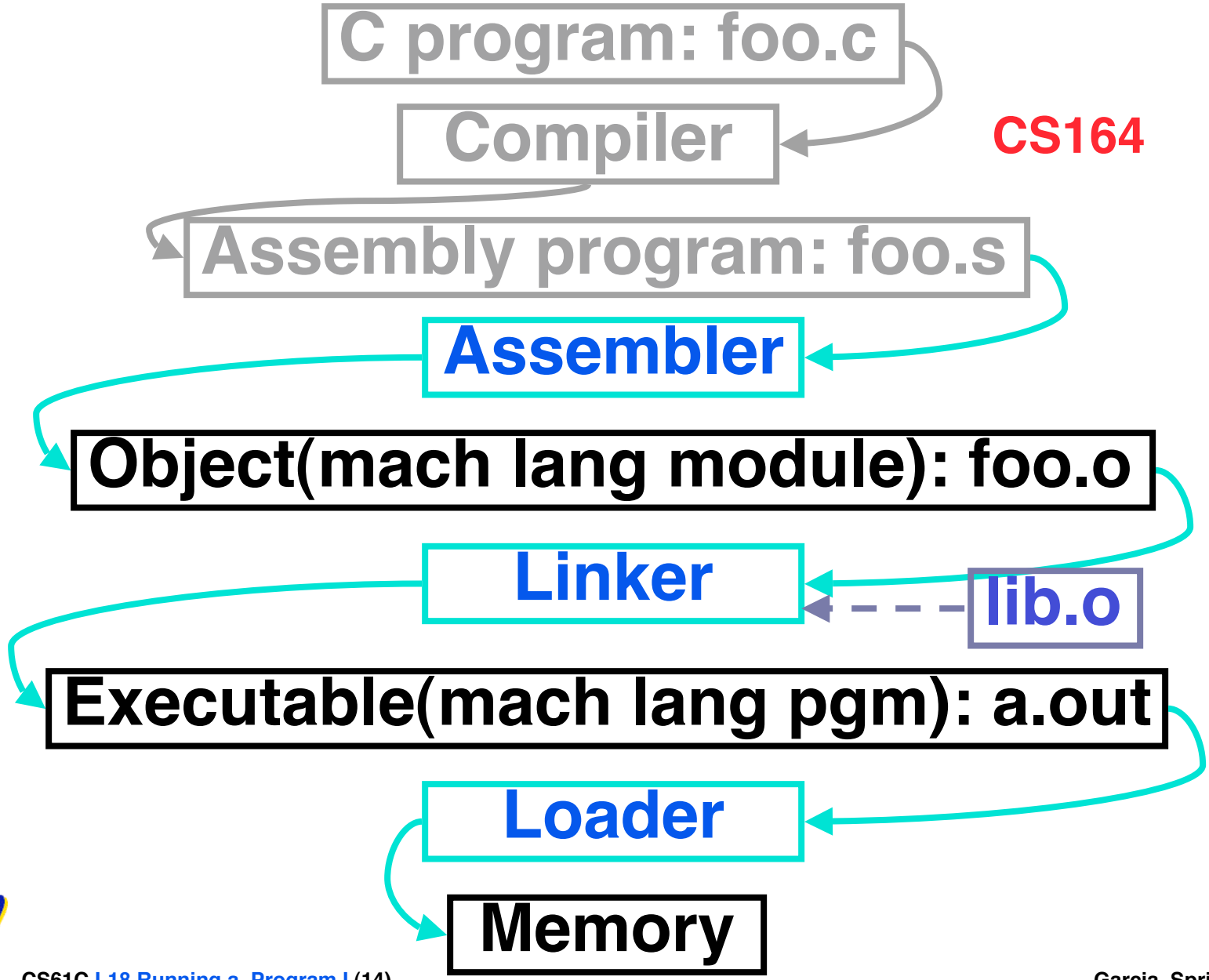
Compiler

- 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 (last lecture) For example:
- `mov $s1,$s2` ⇒ `or $s1,$s2,$zero`

Administrivia…

- Exam on monday (7-10pm 2050 VLSB)
  - You're responsible for all material up through Fri
- Project due next Friday

Where Are We Now?



Assembler

- Input: Assembly Language Code (e.g., `foo.s` for MIPS)
- Output: Object Code, information tables (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)` `sw $a1, 36($sp)`
`mul $t7,$t6,$t5`	`mul $t6,$t5` `mflo $t7`
`addu $t0,$t6,1`	`addiu $t0,$t6,1`
`ble $t0,100,loop`	`slti $at,$t0,101` `bne $at,$0,loop`
`la $a0, str`	`lui $at,left(str)` `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” for which this file needs the address.
- 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

Peer Instruction

Which of the instructions below are MAL and which are TAL?

```
A. addi $t0, $t1, 40000
B. beq  $s0, 10, Exit
C. sub  $t0, $t1, 1
```

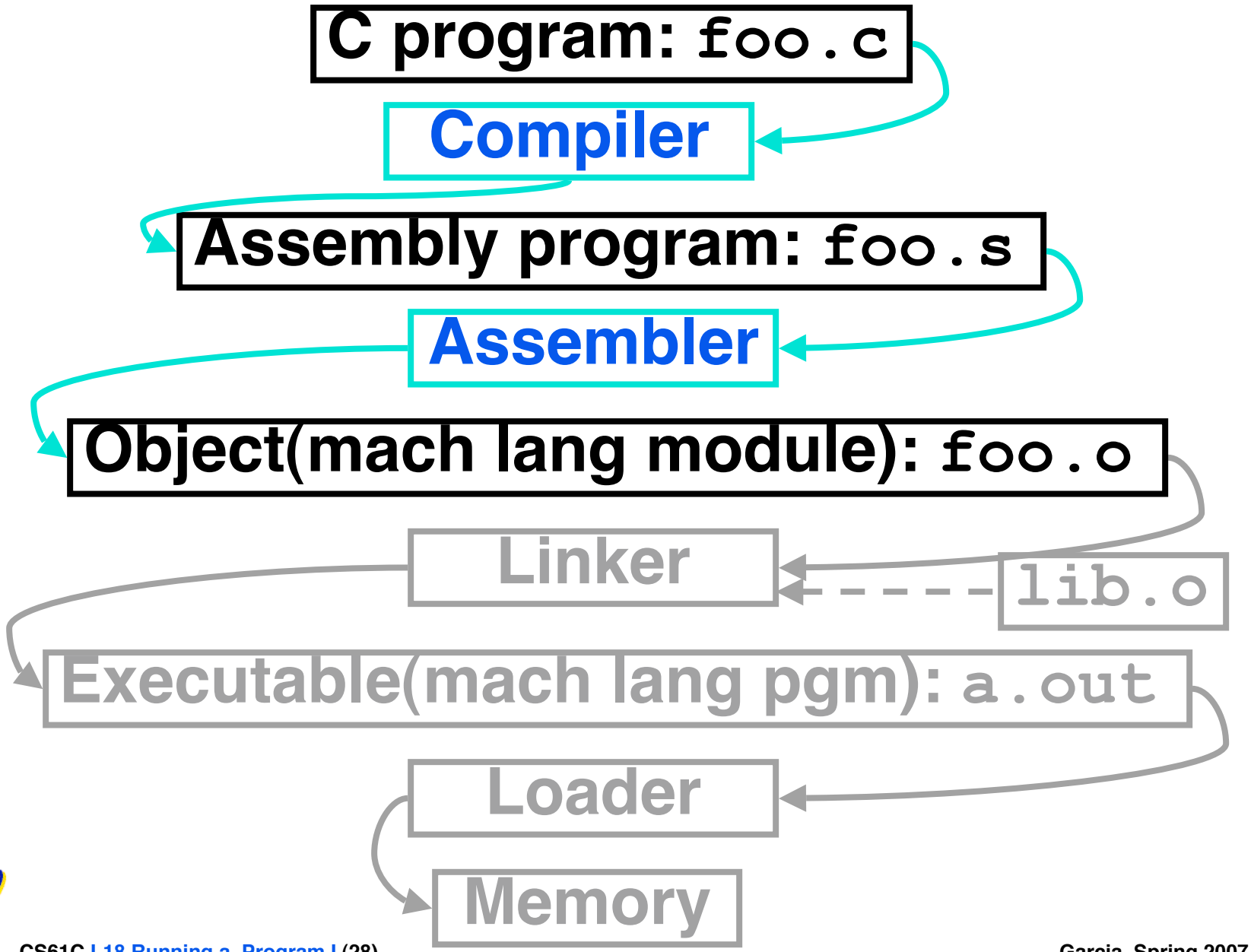
	ABC
1:	MMM
2:	MMT
3:	MTM
4:	MTT
5:	TMM
6:	TMT
7:	TTM
8:	TTT

Peer Instruction

1. Assembler knows where a module's data & instructions are in relation to other modules.
2. Assembler will ignore the instruction `Loop: nop` because it does nothing.
3. 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.

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

And in conclusion…



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

Integer Multiplication (1/3)

- Paper and pencil example (unsigned):

```
Multiplicand  1000      8
Multiplier   x1001      9
              1000
             0000
            0000
          +1000
          01001000
```

  - m bits x n bits = m + n bit product

Integer Multiplication (2/3)

- In MIPS, we multiply registers, so:
  - 32-bit value x 32-bit value = 64-bit value
- Syntax of Multiplication (signed):
  - `mult` register1, register2
  - Multiplies 32-bit values in those registers & puts 64-bit product in special result regs:
    - puts product upper half in hi, lower half in lo
  - hi and lo are 2 registers separate from the 32 general purpose registers
  - Use `mfhi` register & `mflo` register to move from hi, lo to another register

Integer Multiplication (3/3)

- **Example:**
  - **in C:** `a = b * c;`
  - **in MIPS:**
    - **let b be $s2; let c be $s3; and let a be $s0 and $s1 (since it may be up to 64 bits)**

```
mult $s2,$s3    # b*c
mfhi $s0        # upper half of
                # product into $s0
mflo $s1        # lower half of
                # product into $s1
```

- **Note: Often, we only care about the lower half of the product.**

Integer Division (1/2)

- Paper and pencil example (unsigned):

```
                 1001   Quotient
Divisor 1000|1001010   Dividend
           -1000
              10
              101
              1010
             -1000
                10   Remainder
          (or Modulo result)
```

- Dividend = Quotient x Divisor + Remainder

Integer Division (2/2)

- Syntax of Division (signed):
  - `div` register1, register2
  - Divides 32-bit register 1 by 32-bit register 2:
  - puts remainder of division in `hi`, quotient in `lo`
- Implements C division (`/`) and modulo (`%`)
- Example in C:

```
a = c / d;
b = c % d;
```

- in MIPS: `a↔$s0;b↔$s1;c↔$s2;d↔$s3`

```
div  $s2,$s3     # lo=c/d, hi=c%d
mflo $s0         # get quotient
mfhi $s1         # get remainder
```