CS 61C:
Great Ideas in Computer Architecture
Running a Program - CALL (Compiling, Assembling, Linking, and Loading)

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http://inst.eecs.Berkeley.edu/~cs61c/sp16

Integer Multiplication (1/3)

- Paper and pencil example (unsigned):

```
Multiplicand  1000    8
Multiplier   x1001    9
             ------
              1000
             0000
            0000
           +1000
           --------
           01001000   72
```

- 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 registers:
    - 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
- This isn't just about size but also performance:
  - Multiplication is slow, by separating out when you start from when you need it this can potentially improve performance

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
  - Pseudo-inst. `mul` expands to `mult/mflo`

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
```

Levels of Representation/Interpretation

High Level Language Program (e.g., C)

Compiler

Assembly Language Program (e.g., MIPS)

Assembler

Machine Language Program (MIPS)

Machine Interpretation

Hardware Architecture Description (e.g., block diagrams)

Architecture Implementation

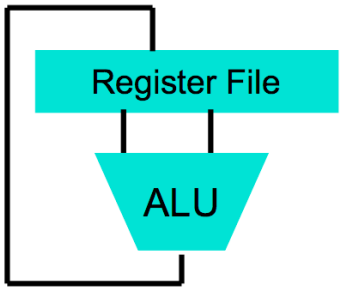
Logic Circuit Description (Circuit Schematic Diagrams)

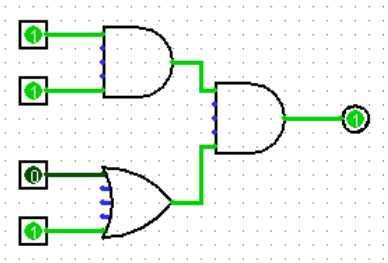
```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

```
lw   $t0, 0($2)
lw   $t1, 4($2)
sw   $t1, 0($2)
sw   $t0, 4($2)
```

Anything can be represented as a *number*, i.e., data or instructions

```
0000 1001 1100 0110 1010 1111 0101 1000
1010 1111 0101 1000 0000 1001 1100 0110
1100 0110 1010 1111 0101 1000 0000 1001
0101 1000 0000 1001 1100 0110 1010 1111
```

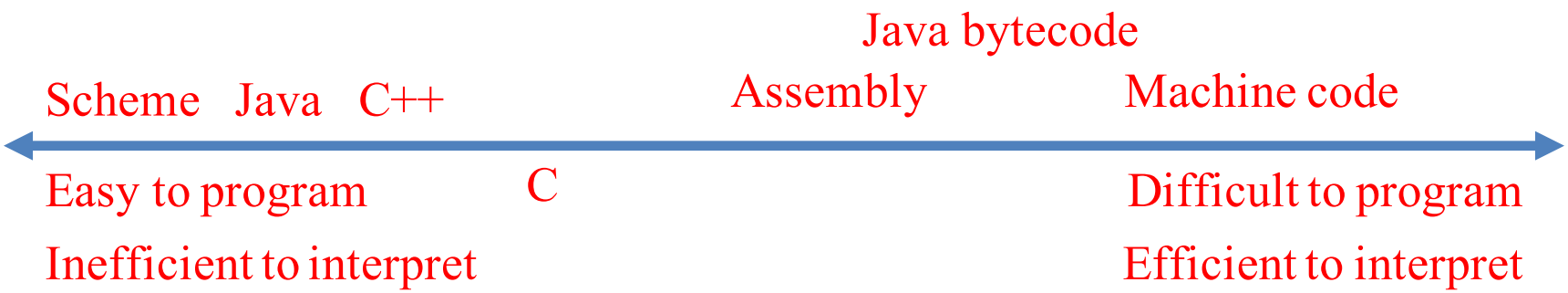




+ How to take a program and run it

Language Execution Continuum

- An Interpreter is a program that executes other programs.

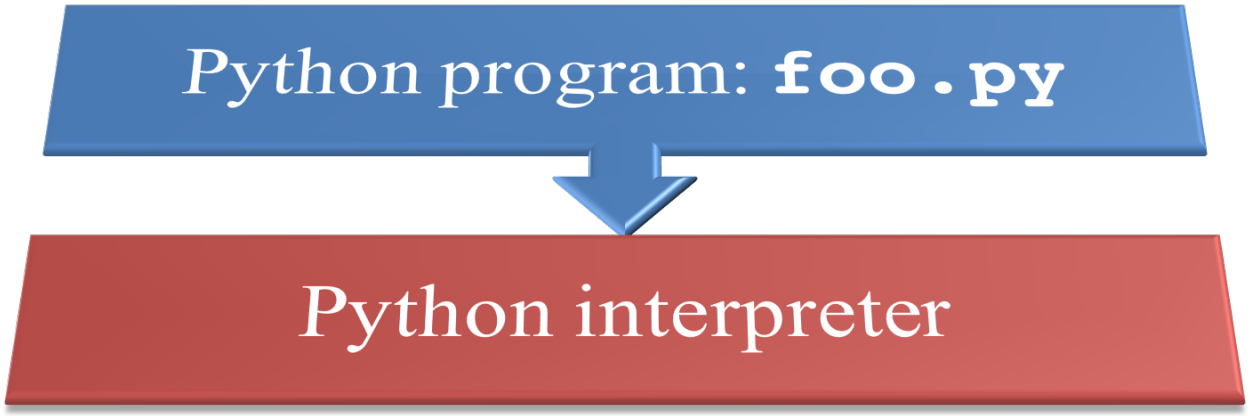


- Language translation gives us another option
- In general, we interpret a high-level language when efficiency is not critical and translate to a lower-level language to increase performance
  - Although this is becoming a "distinction without a difference" Many intepreters do a "just in time" runtime compilation to bytecode that either is emulated or directly compiled to machine code (e.g. LLVM)

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 Python program **`foo.py`**

Interpretation



- Python interpreter is just a program that reads a python program and performs the functions of that python program
  - Well, that's an exaggeration, the interpreter converts to a simple bytecode that the interpreter runs… Saved copies end up in .pyc files

Interpretation

- Any good reason to interpret machine language in software?
- MARS– useful for learning / debugging
- Apple Macintosh conversion
  - Switched from Motorola 680x0 instruction architecture to PowerPC.
    - 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)

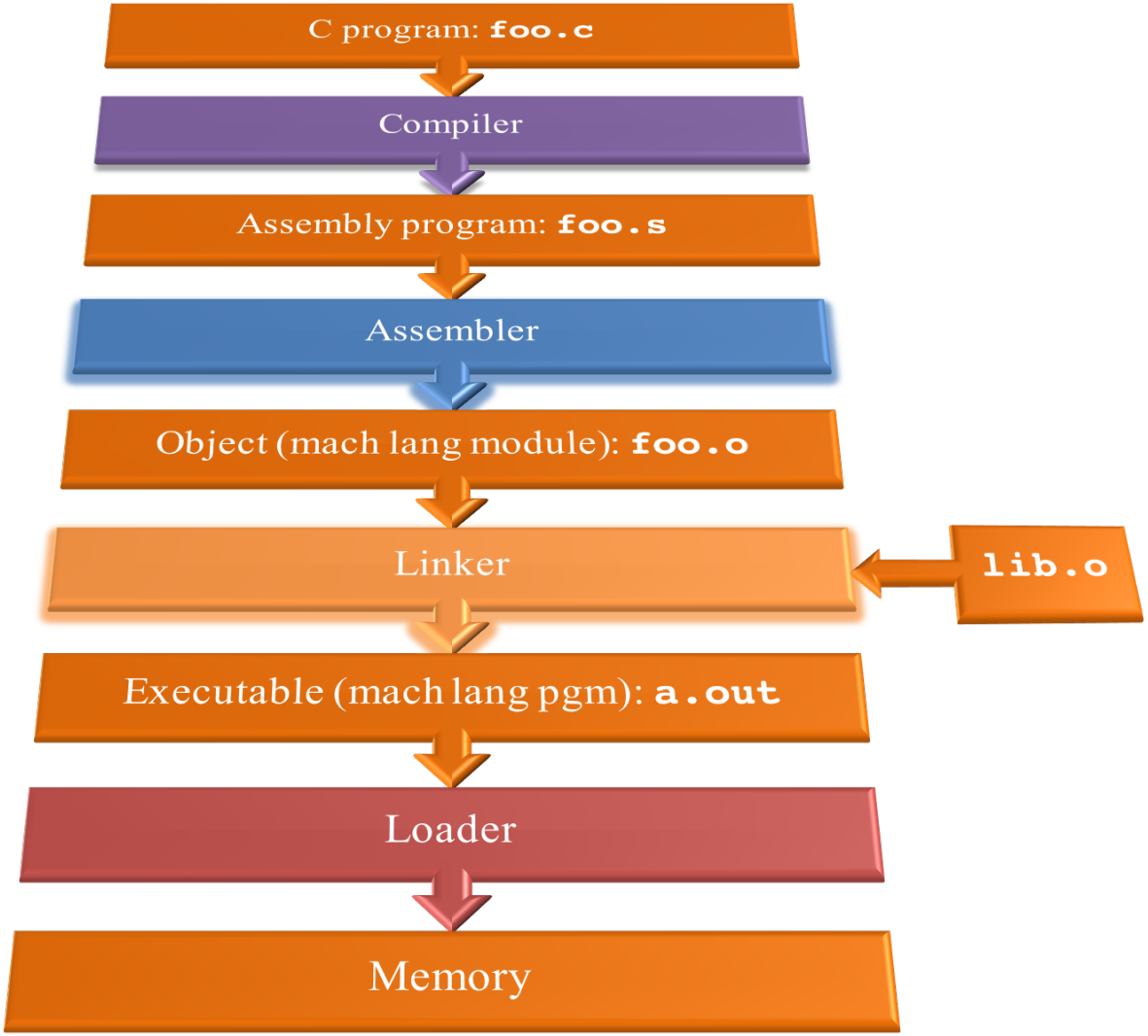
Interpretation vs. Translation? (1/2)

- Generally easier to write interpreter
- Interpreter closer to high-level, so can give better error messages (e.g., MARS)
  - Translator reaction: add extra information to help debugging (line numbers, names)
- Interpreter slower (10x?), code smaller (2x?)
- Interpreter provides instruction set independence: run on any machine

Interpretation vs. Translation? (2/2)

- Translated/compiled code almost always more efficient and therefore higher performance:
  - Important for many applications, particularly operating systems.
- Compiled code does the hard work once: during compilation
  - Which is why most “interpreters” these days are really “just in time compilers”: don’t throw away the work processing the program

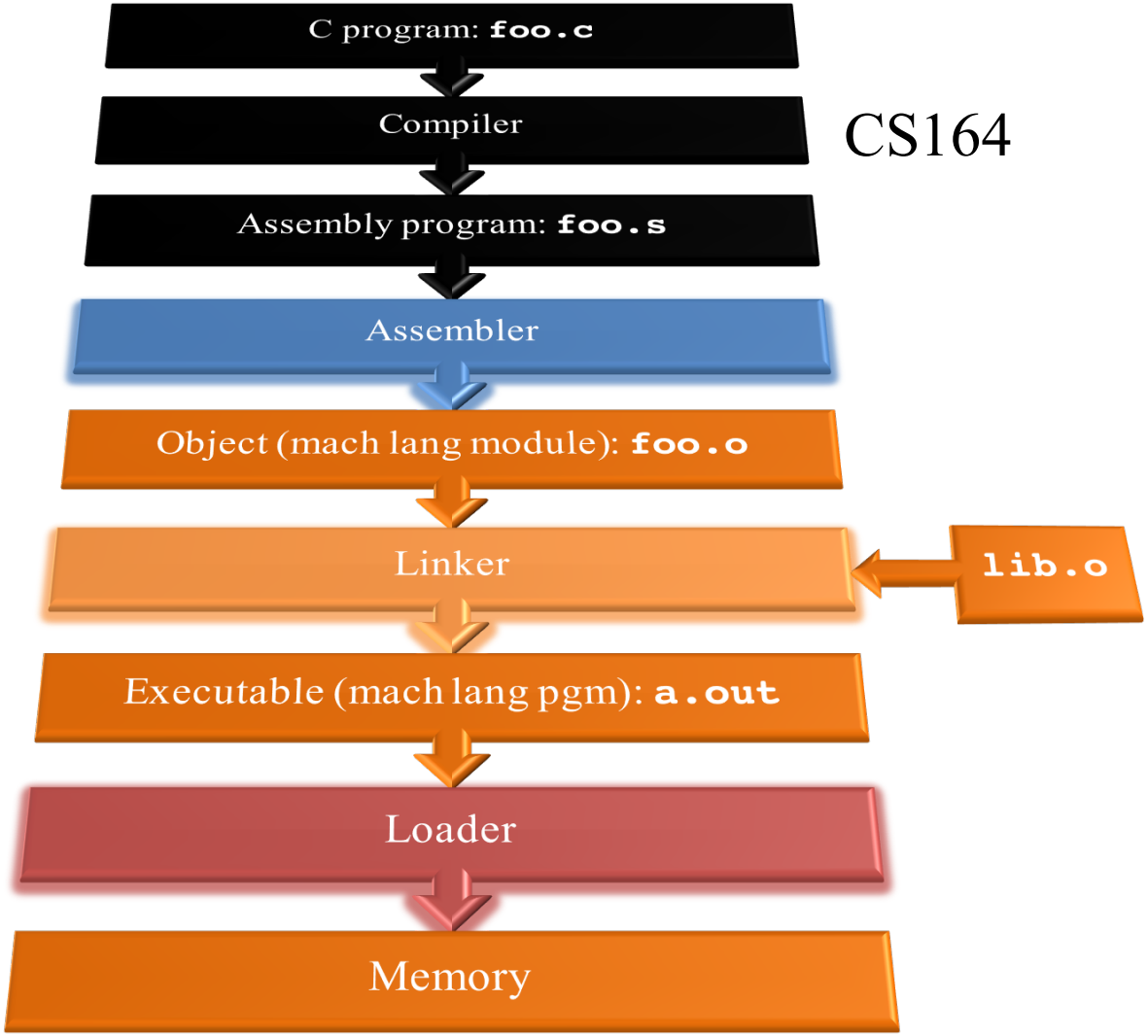
Steps in compiling a C program



Compiler

- Input: High-Level Language Code (e.g., **`foo.c`**)
- Output: Assembly Language Code (e.g. MAL) (e.g., **`foo.s`** for MIPS)
- Note: Output *may* contain pseudo-instructions
- Pseudo-instructions: instructions that assembler understands but not in machine For example:
  - **`move $s1,$s2`** ⇒ **`add $s1,$s2,$zero`**

Where Are We Now?



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Assembler

- Input: Assembly Language Code (e.g. MAL) (e.g., **`foo.s`** for MIPS)
- Output: Object Code, information tables (TAL) (e.g., **`foo.o`** for MIPS)

- Reads and Uses Directives
- Replace Pseudo-instructions
- Produce Machine Language
- Creates Object File

Assembler Directives (p. A-51.. 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

Pseudo-instruction Replacement

- Assembler 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`	`mult $t6,$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)`

Clicker/Peer Instruction

Which of the following is a correct TAL instruction sequence for la $v0, FOO?* (aka store the 32-bit immediate value FOO in $v0)

%hi(label), tells assembler to fill upper 16 bits of label's addr

%lo(label), tells assembler to fill lower 16 bits of label's addr

A: ori $v0, %hi(FOO)
    addiu $v0, %lo(FOO)

B: ori $v0, %lo(FOO)
    lui $v0, %hi(FOO)

C: lui $v0, %lo(FOO)
    ori $v0, %hi(FOO)

D: lui $v0, %hi(FOO)
    ori $v0, %lo(FOO)

E: la $v0, FOO is already a TAL instruction

*Assume the address of FOO is 0xABCD0124

Administrivia

- Starting next week, section 124 will be W 3-4 in 310 soda
  - This section should be rather light, so if you want questions answered, this may be a good choice to attend
- Project 2-1 due date will be firmed up in the staff meeting today (probably a Saturday due date)

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 static 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

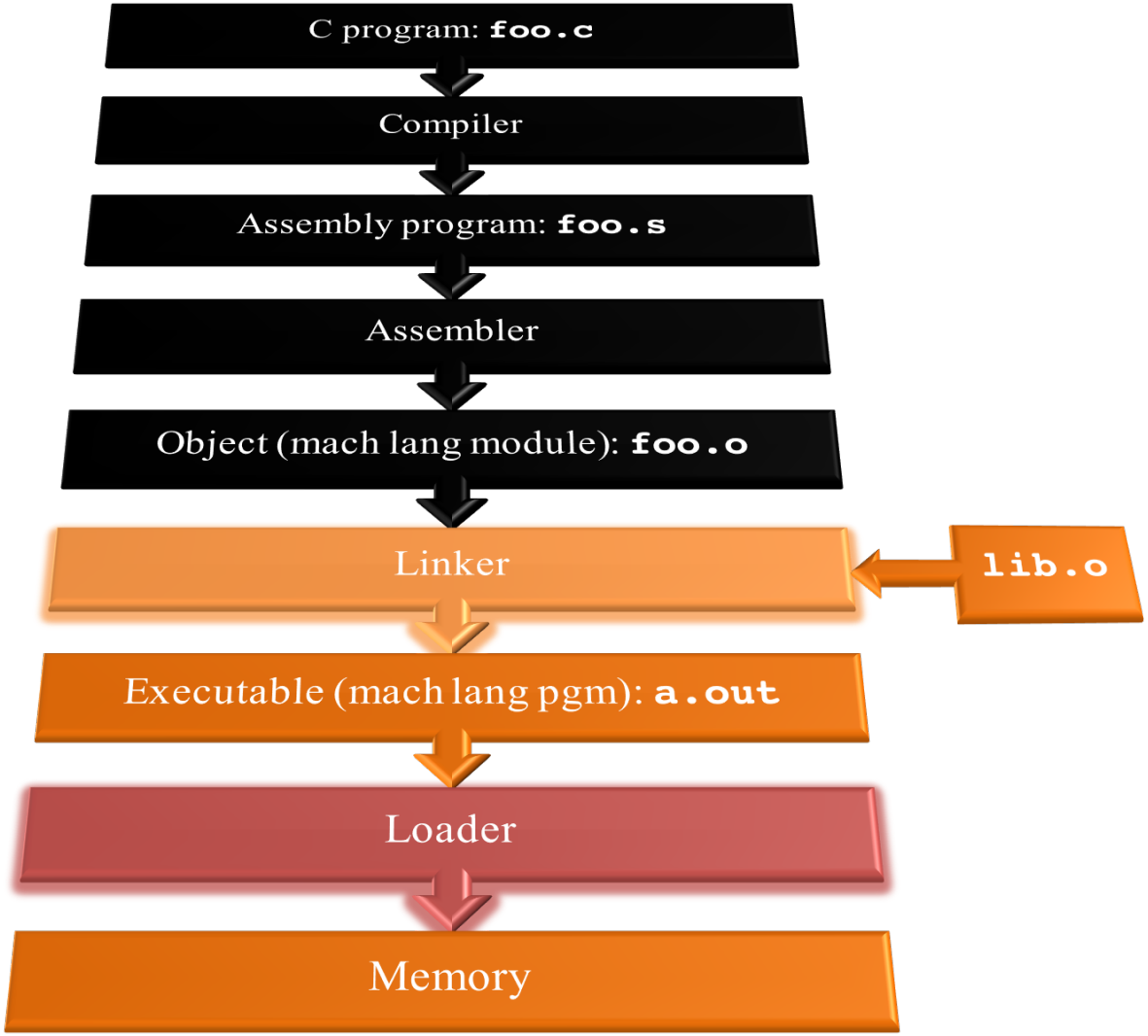
Relocation Table

- List of "items" this file needs the address of later
- What are they?
  - Any label jumped to: **`j`** or **`jal`**
    - internal
    - external (including lib files)
  - Any piece of data in static section
    - 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 static data in the source file
- relocation information: identifies lines of code that need to be fixed up later
- symbol table: list of this file's labels and static 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?



In Conclusion…

- Compiler converts a single HLL file into a single assembly language 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.