CALL (Compiler/Assembler/Linker/Loader)

Administrivia…

- Exam is on October 19th from 7-9 pm
  - Sorry for the disruption. What happened?
  - There was an error in room booking and our exam wasn't booked at the start of the semester...
  - So when we found out it was too late to get enough space to seat everyone!
    - This isn't helped by being at a University that hasn't built a large lecture hall in well, forever!
  - Final will clobber the midterm if you can't make the new exam date
- Remember, if you prefer a remote exam you can do so for any reason
  - Remote exams will be remote proctored
  - We will also have two alternate (remote only) exam slots: 9-11pm and 7-9am the next day for those with conflicts

Agenda

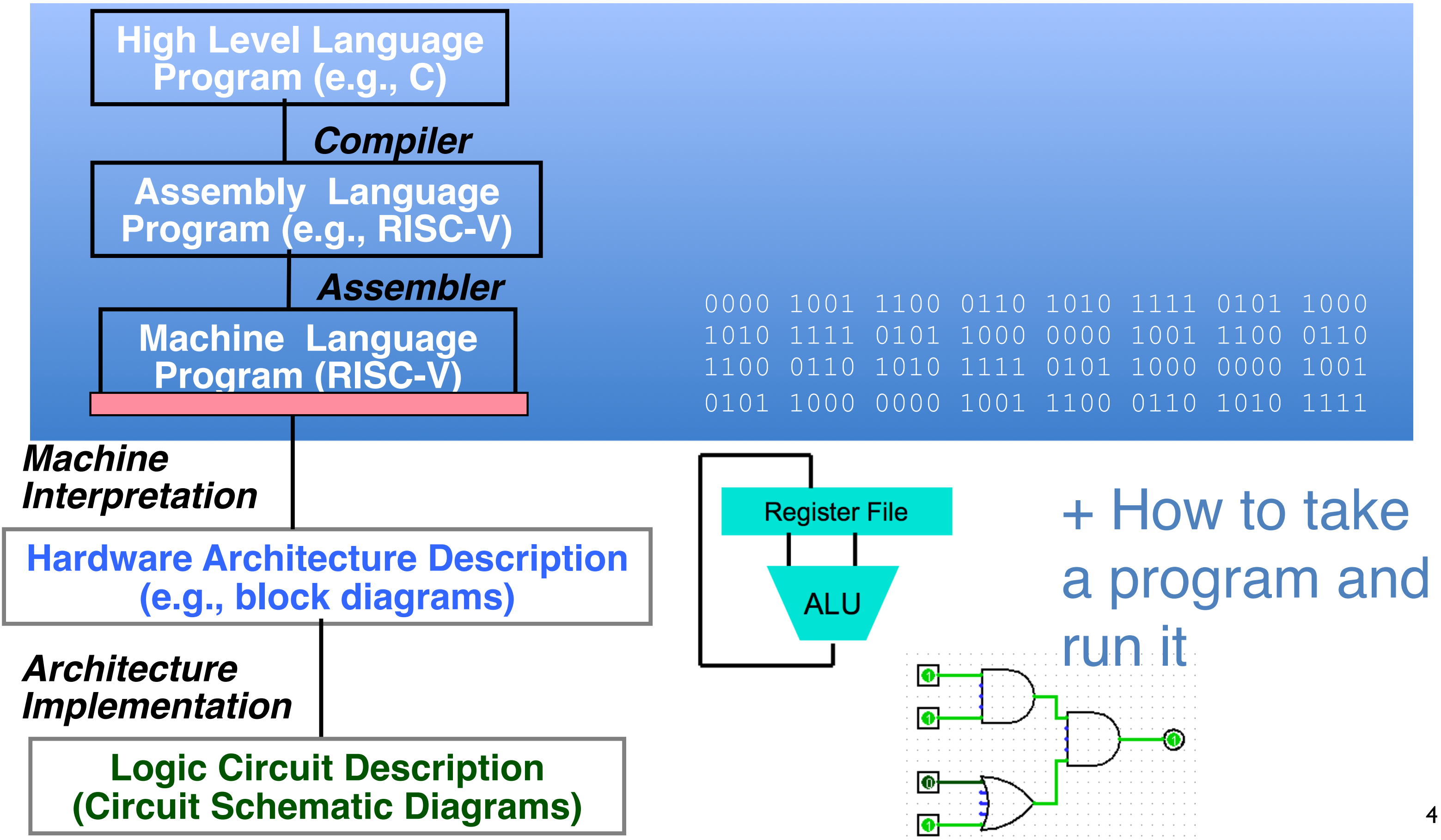
- Interpretation vs Compilation
- The CALL chain
- Producing Machine Language

Levels of Representation/Interpretation

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

```
lw    t0, 0(a2)
lw    t1, 4(a2)
sw    t1, 0(a2)
sw    t0, 4(a2)
```

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



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

Compiler

Assembly Language Program (e.g., RISC-V)

Assembler

Machine Language Program (RISC-V)

```
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
```

Machine Interpretation

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

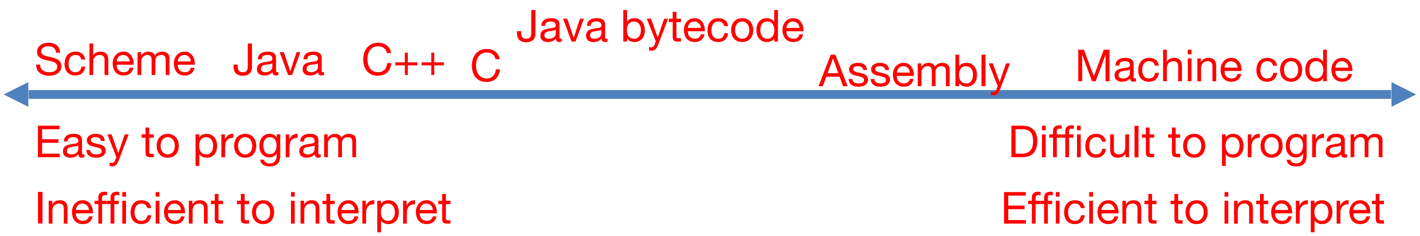
Architecture Implementation

Logic Circuit Description (Circuit Schematic Diagrams)

+ How to take a program and run it

Language Execution Continuum

- An Interpreter is a program that executes other programs.



Scheme Java C++ C Java bytecode Assembly Machine code

Easy to program

Inefficient to interpret

Difficult to program

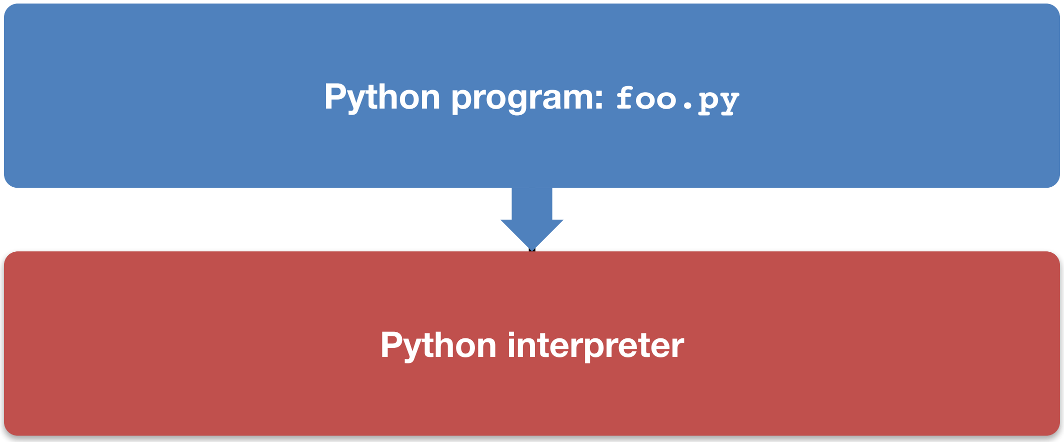
Efficient to interpret

- 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. the JVM)

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?
- Simulators: Useful for learning / debugging
- Apple CPU Transitions
  - Switched from Motorola 680x0 instruction architecture to PowerPC and later from PowerPC to x86
  - We’re seeing this again right now with the M1 chips (which use arm64)!
  - 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
  - Translator reaction: add extra information to help debugging (line numbers, names):
    This is what `gcc -g` does, it tells the compiler to add all the debugging information
- Interpreter slower (10x?), code smaller (2x? or not?)
- 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 when you reexecute a function
  - This is especially true of web browsers:
    They dynamically compile JavaScript using first a quick & dirty compiler and, if the code is repeatedly called, a more aggressive compiler

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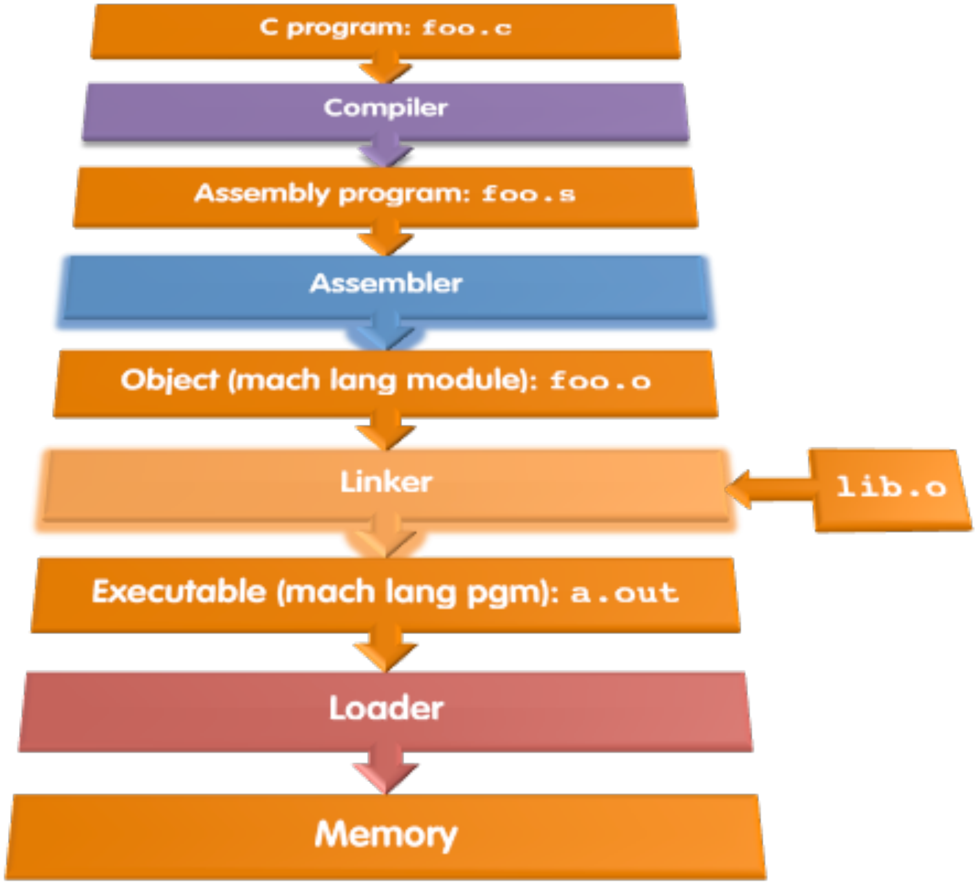
Steps Compiling a C program



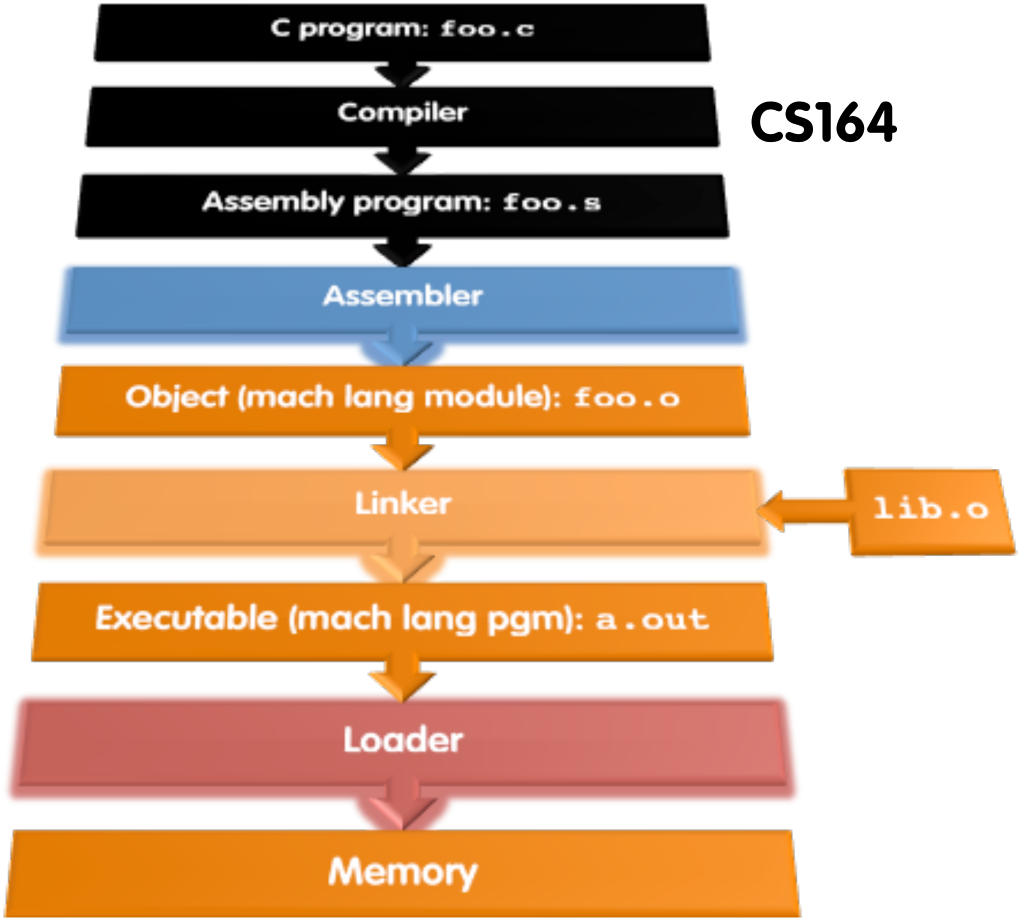
Compiler

- Input: High-Level Language Code (e.g., **`foo.c`**)
- Output: Assembly Language Code (e.g., **`foo.s`** for RISC-V)
  - Code matches the ***calling convention*** for the architecture
- Note: Output *may* contain pseudo-instructions
- Pseudo-instructions: instructions that assembler understands but not in machine
  For example:
  - **`j label`** ⇒ **`jal x0 label`**

Steps In The Compiler

- Lexer:
  - Turns the input into "tokens", recognizes problems with the tokens
- Parser:
  - Turns the tokens into an "Abstract Syntax Tree", recognizes problems in the program structure
- Semantic Analysis and Optimization:
  - Checks for semantic errors, may reorganize the code to make it better
- Code generation:
  - Output the assembly code

Where Are We Now?



CS164

Assembler: A dumb compiler for assembly language

- Input: Assembly Language Code (e.g., **`foo.s`**)
- Output: Object Code, information tables (e.g., **`foo.o`**)
- Reads and Uses Directives
- Replace Pseudo-instructions
- Produce ***Machine Language*** rather than just ***Assembly Language***
- Creates Object File

Assembler Directives

- 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

  `.string 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
`nop`	`addi x0, x0, 0`
`not rd, rs`	`xori rd, rs, -1`
`beqz rs, offset`	`beq rs, x0, offset`
`bgt rs, rt, offset`	`blt rt, rs, offset`
`j offset`	`jal x0, offset`
`ret`	`jalr x0, x1, offset`

`call offset` (if too big for just a `jal`)	`auipc x6, offset[31:12]`
	`jalr x1, x6, offset[11:0]`

`tail offset` (if too far for a j)	`auipc x6, offset[31:12]`
	`jalr x0, x6, offset[11:0]`

So what is "tail" about...

- Often times your code has a convention like this:

  -
    ```
    { ...
      lots of code
      return foo(y);
    }
    ```
  - It can be a recursive call to `foo()` if this is within `foo()`, or call to a different function...
- So for efficiency...
  - Evaluate the arguments for `foo()` and place them in `a0-a7`...
  - Restore `ra`, all callee saved registers, and `sp`
  - Then call `foo()` ***with `j` or `tail`***
- Then when `foo()` returns, it can return ***directly*** to where it needs to return to
  - Rather than returning to wherever `foo()` was called and returning from there
  - ***Tail Call Optimization***

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Producing Machine Language (1/3)

- Simple Case
  - Arithmetic, Logical, Shifts, and so on
  - All necessary info is within the instruction already:
    Just convert into the binary representations we saw on last time
- 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   s0, x0, x0
L1: slt  t0, x0,  $a1
    beq  t0, x0, L2
    addi a1, a1, -1
    jal  x0, L1
L2: add  $t1, $a0, $a1
```

  - Solved by taking 2 passes over the program
    - First pass remembers position of labels
      - Can do this when we expand pseudo instructions
    - Second pass uses label positions to generate code

Producing Machine Language (3/3)

- What about jumps (**`j`** and **`jal`**)?
  - Jumps within a file are PC relative (and we can easily compute)
  - Jumps to ***other*** files we can't
- What about references to static data?
  - **`la`** (Load Address, basically **`li`** but for a location) gets broken up into **`lui`** and **`addi`**
  - 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 external label jumped to: **`jal`**
    - external (including lib files)
  - Any piece of data in static section
    - such as the **`la`** instruction

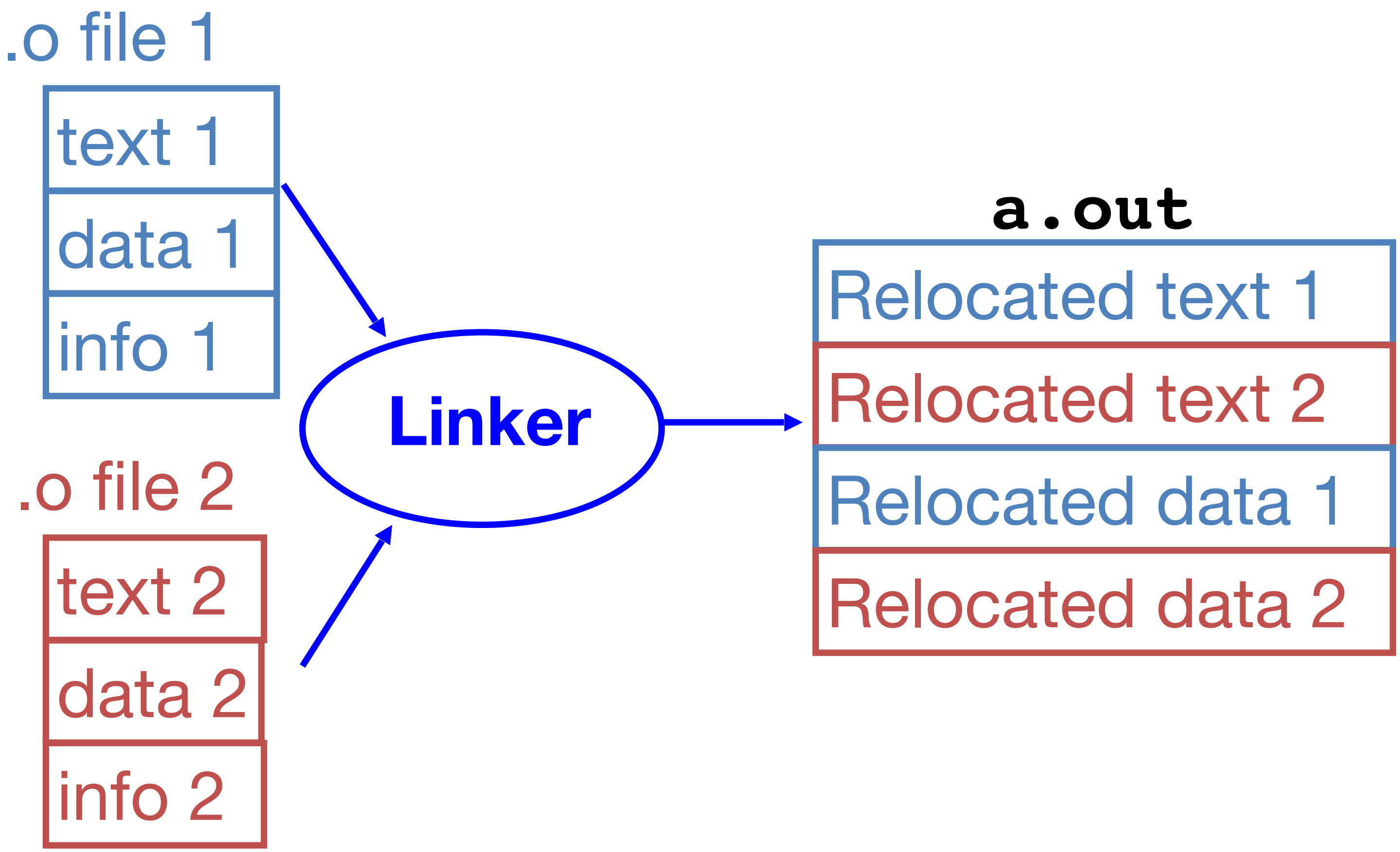
Object File Format

- 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 Microsoft) http://www.skyfree.org/linux/references/ELF_Format.pdf

Linker (1/3)

- Input: Object code files with information tables (e.g., `foo.o`,`libc.o`)
- Output: Executable code
  (e.g., `a.out`)
- Combines several object (`.o`) files into a single executable ("linking")
- Enable separate compilation of files
  - Changes to one file do not require recompilation of the whole program
    - Windows 7 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

Three Types of Addresses

- PC-Relative Addressing (**`beq, bne, jal`**)
  - never relocate
- External Function Reference (usually **`jal`**)
  - always relocate
- Static Data Reference (often **`auipc`** and **`addi`**)
  - always relocate
  - RISC-V often uses **`auipc`** rather than **`lui`** so that a big block of stuff can be further relocated as long as it is fixed relative to the pc

Absolute Addresses in RISC-V

- Which instructions need relocation editing?
  - Jump and link: ONLY for external jumps

`jal`	`rd`	`xxxxx`

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

`lw/sw`	`gp`	`x?`	`XXXXX`

  - What about conditional branches?

`beq`	`rs`	`rt`	`XXXXXX`

  - PC-relative addressing preserved even if code moves

Resolving References (1/2)

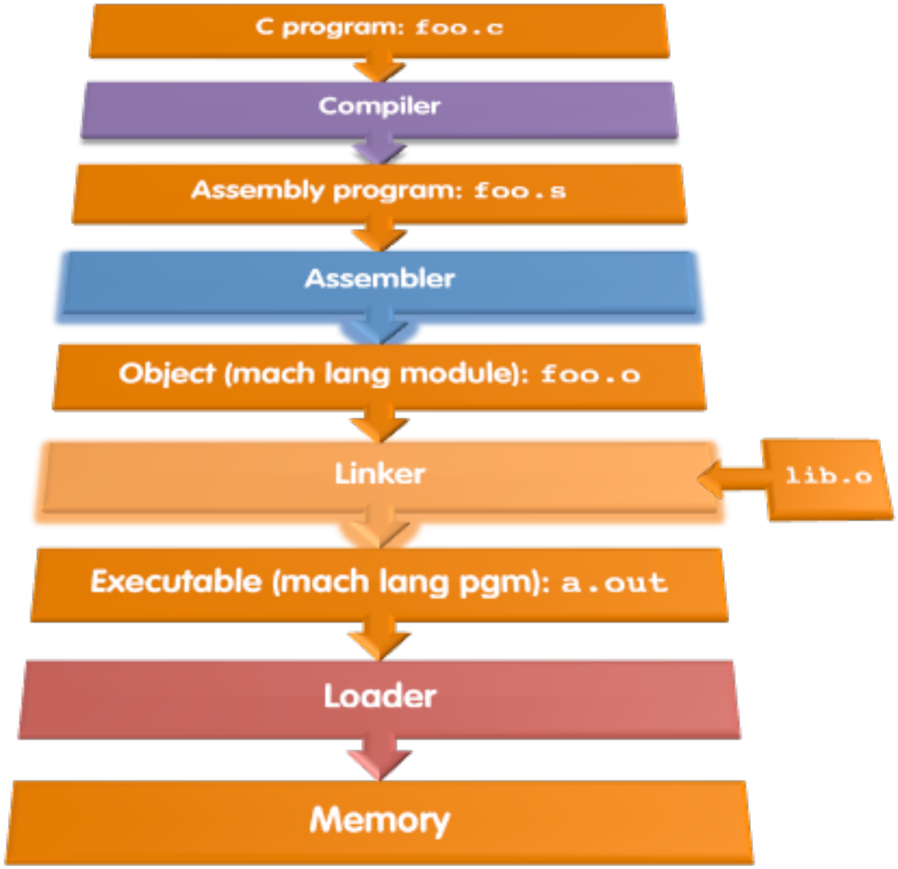
- Linker assumes first word of first text segment is at address **`0x04000000`**.
  - (More later when we study “virtual memory”)
- Linker knows:
  - length of each text and data segment
  - ordering of text and data segments
- Linker calculates:
  - absolute address of each label to be jumped to and 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)

To Summarize

- 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.



Loader Basics

- Input: Executable Code (e.g., **`a.out`**)
- 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’s tasks
  - And these days, the loader actually does a lot of the linking:
    Linker's 'executable' is actually only partially linked, instead still having external references

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

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: Assembly Language:
i = t0, sum = a1

```
  .text
  .align 2
  .globl main
main:
  addi sp, sp, -4
  sw ra, 0(sp)
  mv t0, x0
  mv a1, x0
  li t1, 100
  j check
loop:
  mul t2, t0, t0
  add a1, a1, t2
  addi t0, t0, 1
```

Pseudo-Instructions?

```
check:
  blt t0, t1 loop:
  la $a0, str
  jal printf
  mv a0, x0
  lw ra, 0(sp)
  addi sp, sp 4
  ret
  .data
  .align  0
str:
  .asciiz "The sum of sq from 0
  .. 100 is %d\n"
```

Compilation: Assembly Language: i = t0, sum = a1

```
   .text
   .align 2
   .globl main
main:
   addi sp, sp, -4
   sw ra, 0(sp)
   mv t0, x0
   mv a1, x0
   li t1, 100
   j check
loop:
   mul t2, t0, t0
   add a1, a1, t2
   addi t0, t0, 1
```

Pseudo-Instructions? Underlined

```
check:
   blt t0, t1 loop:
   la $a0, str
   jal printf
   mv a0, x0
   lw ra, 0(sp)
   addi sp, sp 4
   ret
   .data
   .align  0
str:
   .asciiz "The sum of sq from 0
   .. 100 is %d\n"
```

Assembly step 1:
Remove Pseudo Instructions, assign jumps

```
   .text
   .align 2
   .globl main
main:
   addi sp, sp, -4
   sw ra, 0(sp)
   addi t0, x0, 0
   addi a1, x0, 0
   addi t1, x0, 100
   jal x0, 12
loop:
   mul t2, t0, t0
   add a1, a1, t2
   addi t0, t0, 1
```

Pseudo-Instructions? Underlined

```
check:
   blt t0, t1 -16
   lui a0, l.str
   addi a0, a0, r.str
   jal printf
   addi a0, x0, 0
   lw ra, 0(sp)
   addi sp, sp 4
   jalr x0, ra
   .data
   .align  0
str:
   .asciiz "The sum of sq from 0
   .. 100 is %d\n"
```

Assembly step 2

Create relocation table and symbol table

- Symbol Table

Label	address (in module)	type
`main:`	`0x00000000`	`global text`
`loop:`	`0x00000014`	`local text`
`str:`	`0x00000000`	`local data`

- Relocation Information

Address	Instr. type	Dependency
`0x0000002c`	`lui`	`l.str`
`0x00000030`	`addi`	`r.str`
`0x00000034`	`jal`	`printf`

Assembly step 3

- Generate object (`.o`) file:
  - Output binary representation for
    - text segment (instructions)
    - data segment (data)
    - symbol and relocation tables
  - Using dummy “placeholders” for unresolved absolute and external references
- And then… We link!

Linking Just Resolves References...

- So take all the .o files
  - Squish the different segments together
- For each entry in the relocation table:
  - Replace it with the actual address for the symbol table of the item you are linking to
- Result is a single binary

Static vs. Dynamically Linked Libraries

- What we've described is the traditional way: statically-linked approach
  - 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)
  - Includes the entire library even if not all of it will be used
  - Executable is self-contained
- Alternative is dynamically linked libraries (DLL), common on Windows & UNIX platforms

Dynamically Linked Libraries

`en.wikipedia.org/wiki/Dynamic_linking`

- 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)
    - We will see how this is possible when we talk about virtual memory
  - – 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
    - Can create a mess with dependencies, thus "Linux Containers"

Overall, dynamic linking adds quite a bit of complexity to the compiler, linker, and operating system. However, it provides many benefits that often outweigh these

Final Review C Program: `Hello.c`

```
#include <stdio.h>
int main()
{
  printf("Hello, %s\n", "world");
  return 0;
}
```

Compiled `Hello.c`: `Hello.s`

```
.text                                # Directive: enter text section
  .align 2                           # Directive: align code to 2^2 bytes
  .globl main                        # Directive: declare global symbol main
main:                                # label for start of main
  addi sp,sp,-16                     # allocate stack frame
  sw   ra,12(sp)                     # save return address
  lui  a0,%hi(string1)               # compute address of
  addi a0,a0,%lo(string1)            #   string1
  lui  a1,%hi(string2)               # compute address of
  addi a1,a1,%lo(string2)            #   string2
  call printf                        # call function printf
  lw   ra,12(sp)                     # restore return address
  addi sp,sp,16                      # deallocate stack frame
  li   a0,0                          # load return value 0
  ret                                # return
  .section .rodata                   # Directive: enter read-only data section
  .balign 4                          # Directive: align data section to 4 bytes
string1:                             # label for first string
  .string "Hello, %s!\n"             # Directive: null-terminated string
string2:                             # label for second string
  .string "world"                    # Directive: null-terminated string
```

Assembled Hello.s: Linkable Hello.o

```
00000000 <main>:
0:   ff010113 addi sp,sp,-16
4:   00112623 sw ra,12(sp)
8:   00000537 lui a0,0x0       # addr placeholder
c:   00050513 addi a0,a0,0     # addr placeholder
10:  000005b7 lui a1,0x0       # addr placeholder
14:  00058593 addi a1,a1,0     # addr placeholder
18:  000000ef jal ra           # addr placeholder
1c:  00c12083 lw ra,12(sp)
20:  01010113 addi sp,sp,16
24:  00000513 addi a0,a0,0
28:  00008067 jalr ra
```

Linked Hello.o: a.out

```
000101b0 <main>:
  101b0: ff010113 addi sp,sp,-16
  101b4: 00112623 sw   ra,12(sp)
  101b8: 00021537 lui  a0,0x21
  101bc: a1050513 addi a0,a0,-1520 # 20a10 <string1>
  101c0: 000215b7 lui  a1,0x21
  101c4: a1c58593 addi a1,a1,-1508 # 20a1c <string2>
  101c8: 288000ef jal  ra,10450    # <printf>
  101cc: 00c12083 lw   ra,12(sp)
  101d0: 01010113 addi sp,sp,16
  101d4: 00000513 addi a0,0,0
  101d8: 00008067 jalr  ra
```

And the Class So Far…

- Lots of C
  - Including Structures, Functions, Pointers, Pointers to Pointers, Unions, etc…
- Binary numbers
  - Can you count to 31 on the fingers of one hand? Two's Complement?
- Assembly
  - How it works
- CALL

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 RISC-V, we multiply registers, so:
  - 32-bit value x 32-bit value = 64-bit value
- Multiplication is ***not*** part of standard RISC-V…
  - Instead it is an ***optional*** extra:
    The compiler needs to produce a series of shifts and adds if the multiplier isn't present
    - Why on the exam we did the multiplication for you...
- Syntax of Multiplication (signed):
  - **`mul rd, rs1, rs2`**
  - **`mulh rd, rs1, rs2`**
  - Multiplies 32-bit values in those registers and returns either the lower or upper 32b result
    - If you do mulh/mul back to back, the architecture can fuse them
  - Also unsigned versions of the above

Integer Multiplication (3/3)

- Example:
  - in C: **`a = b * c;`**
    - **`int64_t a; int32_t b, c;`**
    - Aside, these types are defined in C99, in stdint.h
- in RISC-V:
  - let b be **`s2`**; let c be **`s3`**; and let a be **`s0`** and **`s1`** (since it may be up to 64 bits)

  -
    ```
    mulh s1, s2, s3
    mul s0, s2, s3
    ```

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 rd, rs1, rs2
    rem rd, rs1, rs2
    ```
  - Divides 32-bit rs1 by 32-bit rs2, returns the quotient (/) for div, remainder (%) for rem
  - Again, can fuse two adjacent instructions
- Example in C: a = c / d;   b = c % d;
- RISC-V:
  - a↔s0; b↔s1; c↔s2; d↔s3

  -
    ```
    div  s0, s2, s3
    rem  s1, s2, s3
    ```

Note Optimization...

- A recommended convention

  -
    ```
    mulh s1 s2 s3
    mul s0 s2 s3
    ```

  -
    ```
    div s0 s2 s3
    rem s1 s2 s3
    ```
- Not a ***requirement but***...
  - RISC-V says "if you do it this way, ***and*** the microarchitecture supports it, it can fuse the two operations into one"
    - Same logic behind much of the 16b ISA design:
      If you follow the convention you can get significant optimizations

Optional Coolness (not on the test): RISC-V 16b compressed ISA

- Not a complete ISA
- Instead an optimization for the most ***common*** instruction motifs:
  - Small immediates
  - Common registers (x0, ra/x1, sp/x2)
  - rs2 == rd
- Humans and the compiler don't know ***or care***
  - Every 16b instruction has a 32b counterpart
- So the assembler creates them in the same way they expand pseudo-instructions

EG, some examples...

- Load word/store word relative to the stack pointer
  - 6 bit immediate is word aligned and zero-extended: only positive offsets
  - Cuts the size of prolog/epilog by effectively 50%
- Common register load/store (s0-s1, a0-a5)
  - 5 bit immediate, also word aligned and zero-extended
- J/JAL with a 11 bit immediate
  - Writing link into either x0 or ra
- Branch equal/not equal zero