Great Ideas in Computer Architecture

Running a Program: CALL

Instructor: Stephan Kaminsky

Justin Nesselrotte @jnesselr · Nov 13
Replying to @alicegoldfuss
Me: *does major refactor*
Tests: ✅
Me: I don't believe you
1 3 57

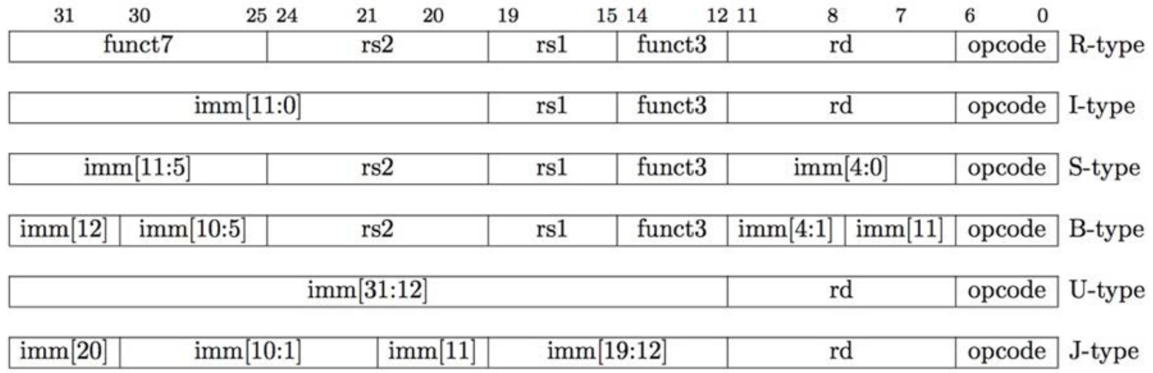
Rosy, the Illyfather, speaks! @rosyatr... · Nov 13
Me: *deliberately breaks something, just to be sure*
Tests: ✅
Me: oh no
2 3 78

boo radley: TurkeyOps @boo_radley · Nov 13
Me: *changes nothing*
Tests: ❌
Me: oh no
1 4 57

Rosy, the Illyfather, speaks! @rosyatr... · Nov 13
Me: *runs tests again*
Tests: ✅
Me: oh no no no
2 55

Review

- *Instruction formats* designed to be similar but still capable of handling all instructions



31	30 25	24 21	20	19 15	14 12	11 8	7	6 0	
funct7		rs2		rs1	funct3	rd		opcode	R-type
imm[11:0]				rs1	funct3	rd		opcode	I-type
imm[11:5]		rs2		rs1	funct3	imm[4:0]		opcode	S-type
imm[12]	imm[10:5]	rs2		rs1	funct3	imm[4:1]	imm[11]	opcode	B-type
imm[31:12]						rd		opcode	U-type
imm[20]	imm[10:1]		imm[11]	imm[19:12]		rd		opcode	J-type

- Branches and Jumps move relative to current address

- Assembly/Disassembly: Use RISC-V Green Sheet to convert

Great Idea #1: Levels of Representation/Interpretation

Higher-Level Language Program (e.g. C)

Compiler

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

Assembler

Machine Language Program (RISC-V)

We are here

Machine Interpretation

Hardware Architecture Description (e.g. block diagrams)

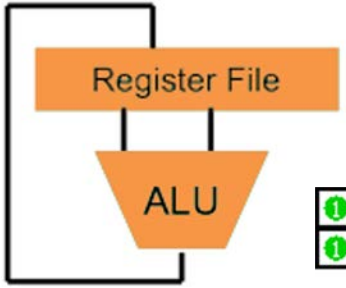
Architecture Implementation

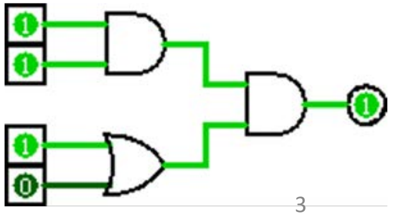
Logic Circuit Description (Circuit Schematic Diagrams)

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

```
lw    t0, 0(x2)
lw    t1, 4(x2)
sw    t1, 0(x2)
sw    t0, 4(x2)
```

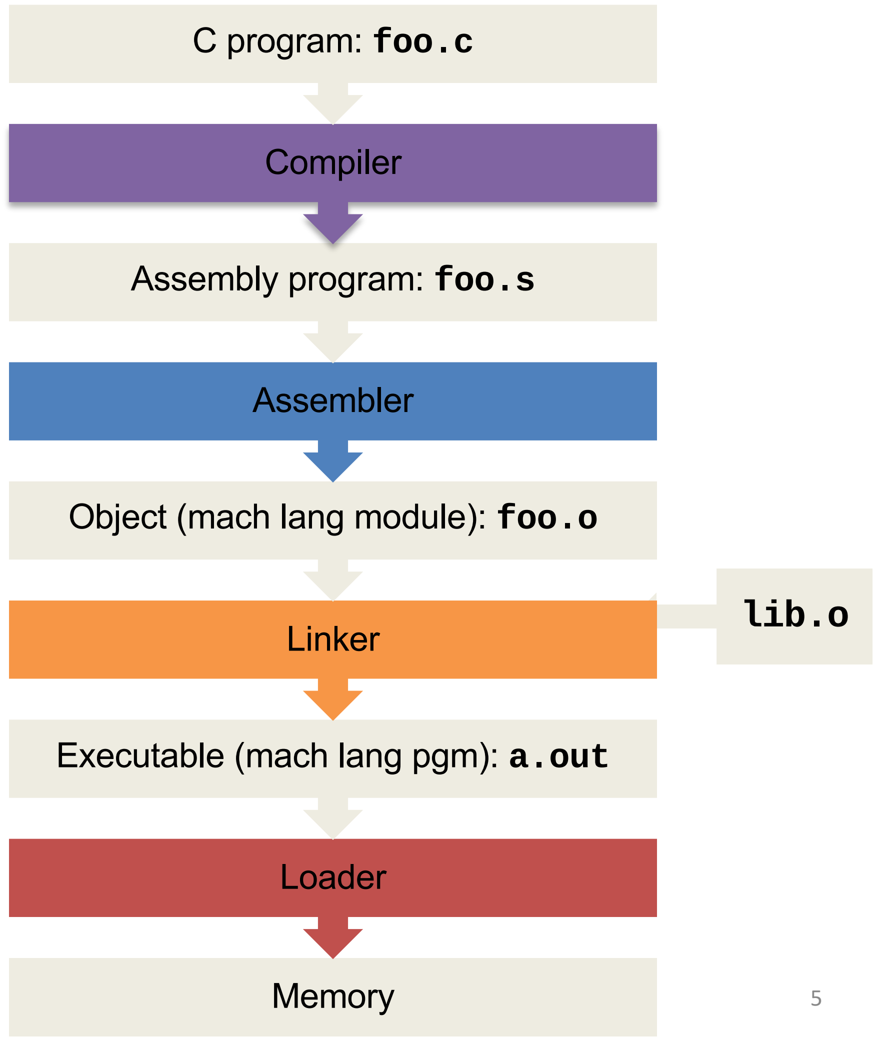
```
0000 1001 1100 0110 1010 1111 0101 1000
1010 1111 0101 1000 0000 1001 1100 0110
1100 0110 1010 1111 0101 1000 0000 1001
0101 1000 0000 1001 1100 0110 1010 1111
```





COMPILER
ASSEMBLER
LINKER
LOADER

- Review/Intro
- **Translation**
- Compiler
- Assembler
- Linker
- Loader
- Example



Translation vs. Interpretation (1/3)

- 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
- Directly *interpret* a high level language when efficiency is not critical
- *Translate* to a lower level language when increased performance is desired

Translation vs. Interpretation (2/3)

- Generally easier to write an interpreter
- Interpreter closer to high-level, so can give better error messages (e.g. Python, Venus)
- Interpreter is slower (~10x), but code is smaller (~2x)
- Interpreter provides instruction set independence: can run on any machine

Translation vs. Interpretation (3/3)

- 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 (e.g. Microsoft keeps all their source code secret)
  - Alternative model, “open source”, creates value by publishing the source code and fostering a community of developers

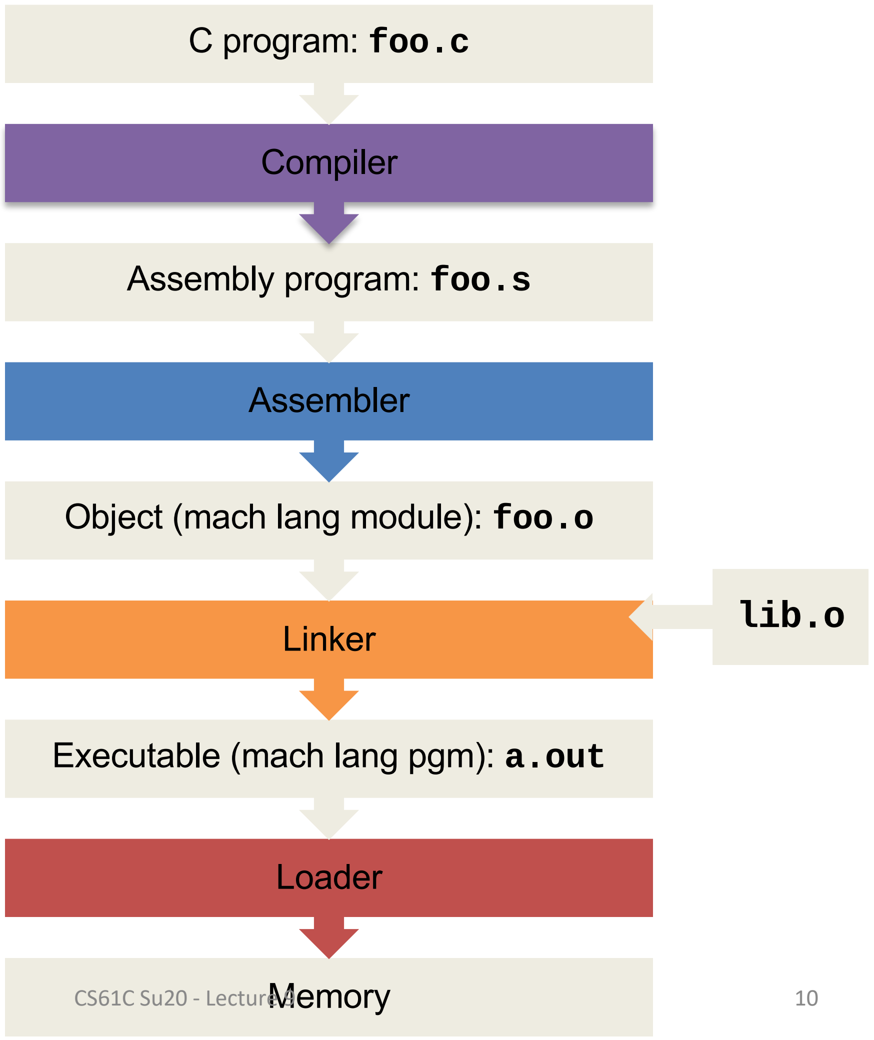
C Translation

- **Recall:** A key feature of C is that it allows you to compile files *separately*, later combining them into a single executable
- What can be accessed across files?
  - Functions
  - Global variables

C Translation

Steps to Starting a Program:

1) **C**ompiler
2) **A**ssembler
3) **L**inker
4) **L**oader



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- Translation
- **Compiler**
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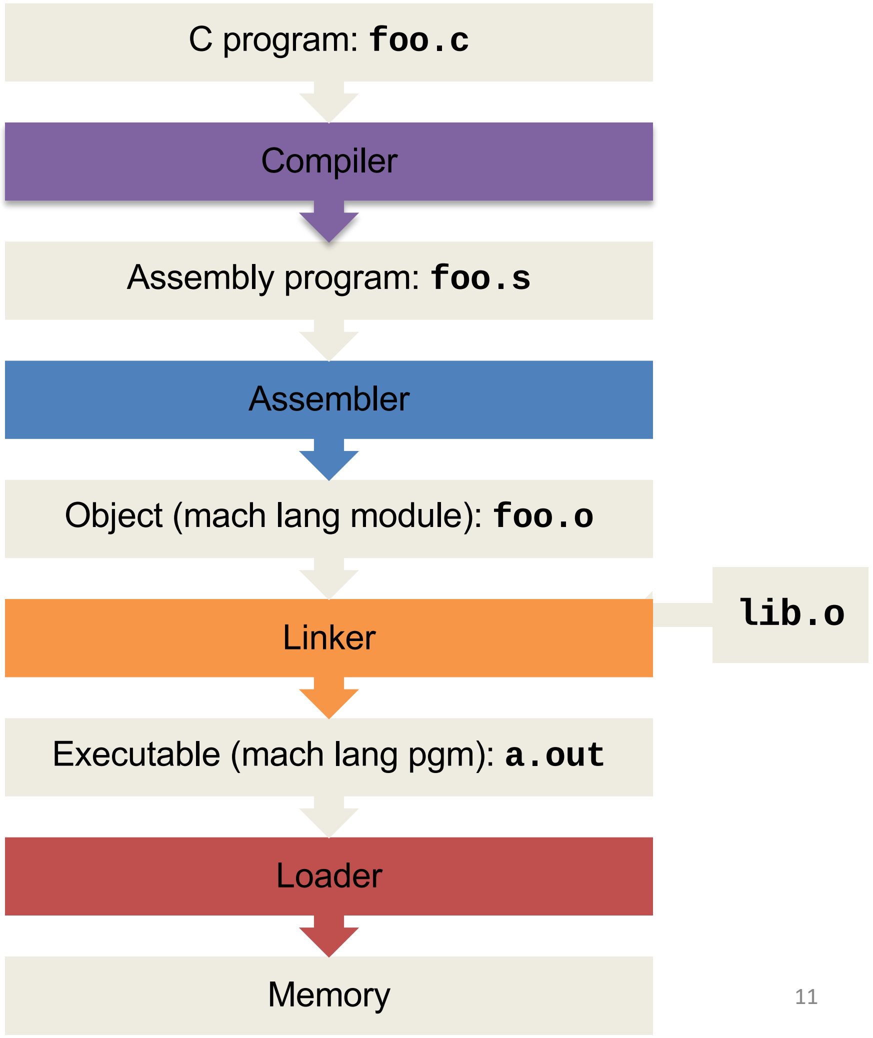

Compiler

- **Input:** Higher-level language (HLL) code (e.g. C, Java in files such as `foo.c`)
- **Output:** Assembly Language Code (e.g. `foo.s` for RISC-V)

- Note that the output may contain pseudo-instructions
- In reality, there’s a preprocessor step before this to handle #directives but it’s not very exciting

Compilers Are Non-Trivial

- There’s a whole course about them – CS164
  - We won’t go into much detail in this course
  - For the very curious and highly motivated: http://www.sigbus.info/how-i-wrote-a-self-hosting-c-compiler-in-40-days.html
- Some examples of the task’s complexity:
  - Operator precedence: 2 + 3 * 4
  - Operator associativity: a = b = c;
  - Determining locally whether a program is valid
    - if (a) { if (b) { … /*long distance*/ … } } } //extra bracket

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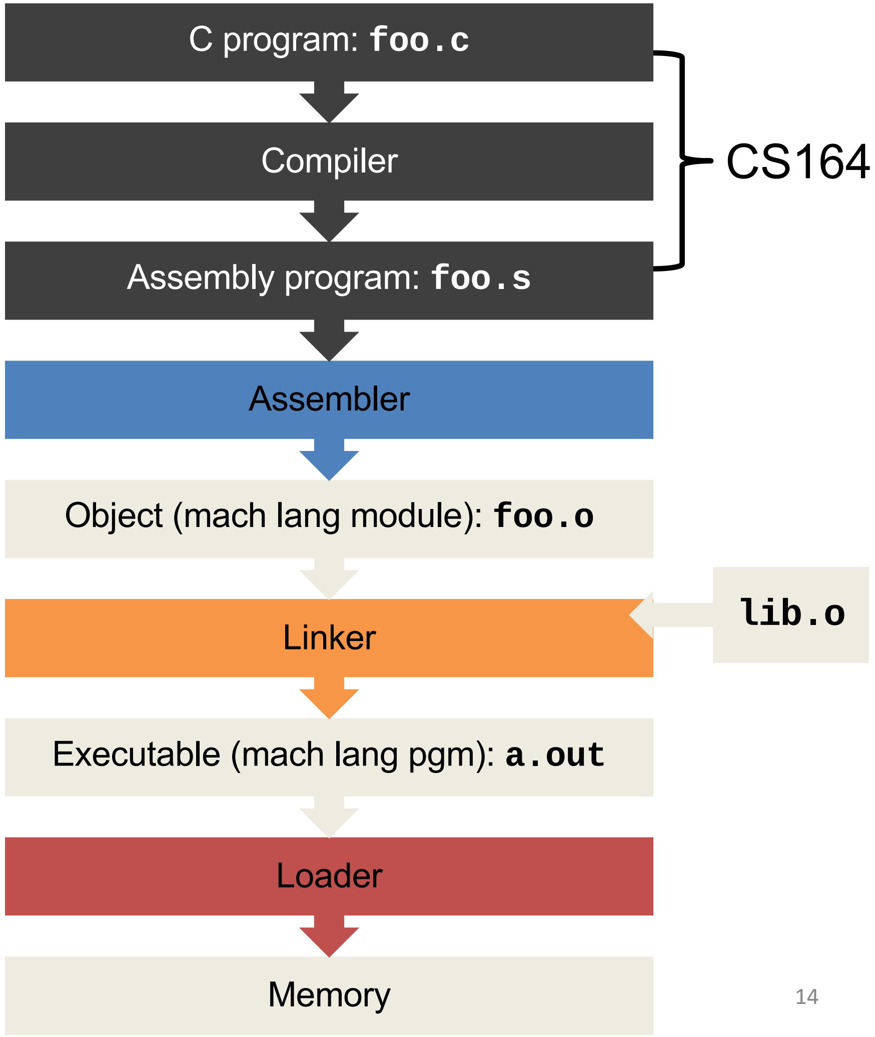

Assembler

- **Input:** Assembly language code (e.g. `foo.s` for RISC-V)
- **Output:** Object code (True Assembly), information tables (e.g. `foo.o` for RISC-V)
  - Object file
- Reads and uses directives
- Replaces pseudo-instructions
- Produces machine language

Assembler Directives

(For more info, see p.B-5 and B-7 in P&H)

- 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-terminates it
  - `.word` $w_1…w_n$: Store the *n* 32-bit quantities in successive memory words

Pseudo-instruction Replacement

Pseudo	Real
mv t0, t1	addi t0,t1,0
neg t0, t1	sub t0, zero, t1
li t0, imm	addi t0, zero, imm
not t0, t1	xori t0, t1, -1
beqz t0, loop	beq t0, zero, loop
la t0, str	lui t0, str[31:12]
	addi t0, t0, str[11:0]
	OR
	auipc t0, str[31:12]
	addi t0, t0, str[11:0]

Producing Machine Language (1/3)

- Simple Cases
  - Arithmetic and logical instructions, shifts, etc.
  - All necessary info contained in the instruction
- What about Branches and Jumps?
  - Branches and Jumps require a *relative address*
  - Once pseudo-instructions are replaced by real ones, we know by how many instructions to branch, so no problem

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
    j    L1
L2: add  t1, a0, a1
```

  - Solution: Make two passes over the program

Two Passes Overview

- Pass 1:
  - Expands pseudo instructions encountered
  - Remember position of labels
  - Take out comments, empty lines, etc
  - Error checking
- Pass 2:
  - Use label positions to generate relative addresses (for branches and jumps)
  - Outputs the object file, a collection of instructions in binary code

Producing Machine Language (3/3)

- What about jumps to external labels?
  - Requiring knowing a final address
  - Forward or not, 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 `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" that may be used by other files
  - *Each* file has its own symbol table
- What are they?
  - Labels: function calling
  - Data: anything in the `.data` section; variables may be accessed across files
- Keeping track of the labels fixes the forward reference problem

Relocation Table

- List of “items” this file will need the address of later (currently undetermined)
- What are they?
  - Any external label jumped to: `jal` or `jalr`
    - internal
    - external (including library files)
  - Any piece of data
    - such as anything referenced in the `data` section

Object File Format

1) object file header: size and position of the other pieces of the object file
2) text segment: the machine code
3) data segment: data in the source file (binary)
4) relocation table: identifies lines of code that need to be "handled"
5) symbol table: list of this file's labels and data that can be referenced
6) debugging information

- A standard format is ELF (except MS) `http://www.skyfree.org/linux/references/ELF_Format.pdf`

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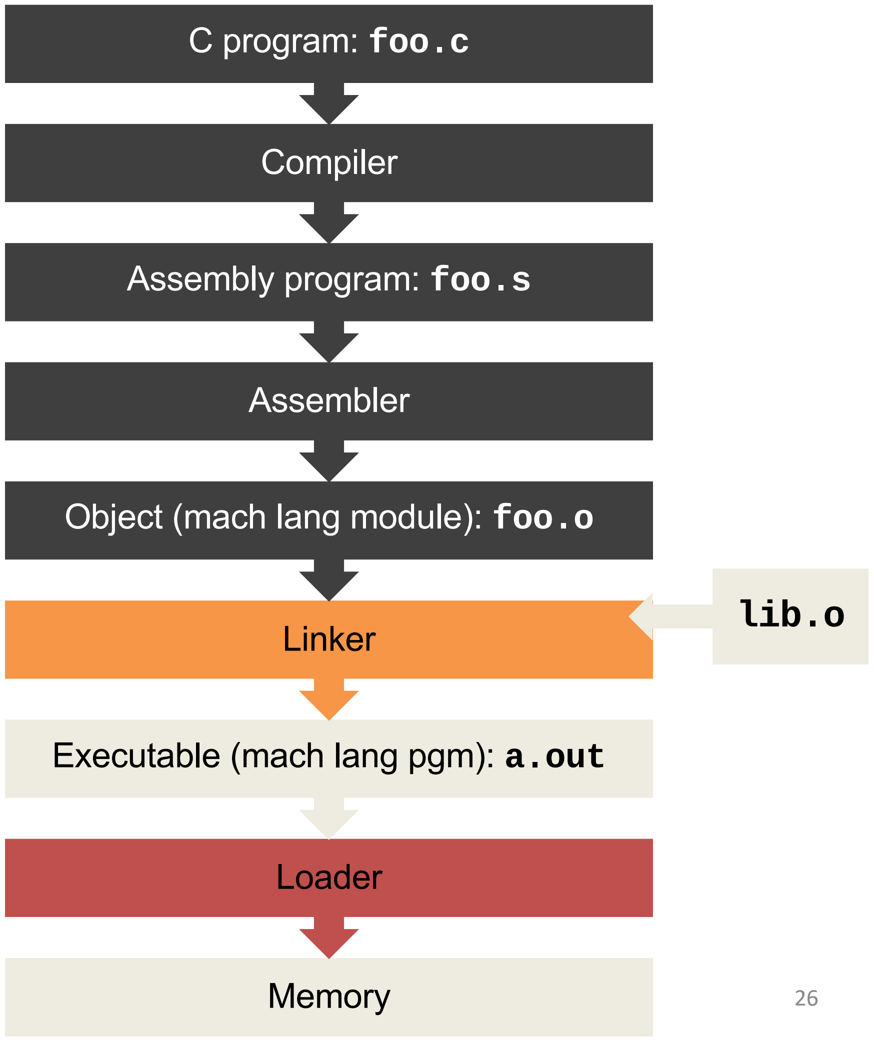
- Loader
- Example

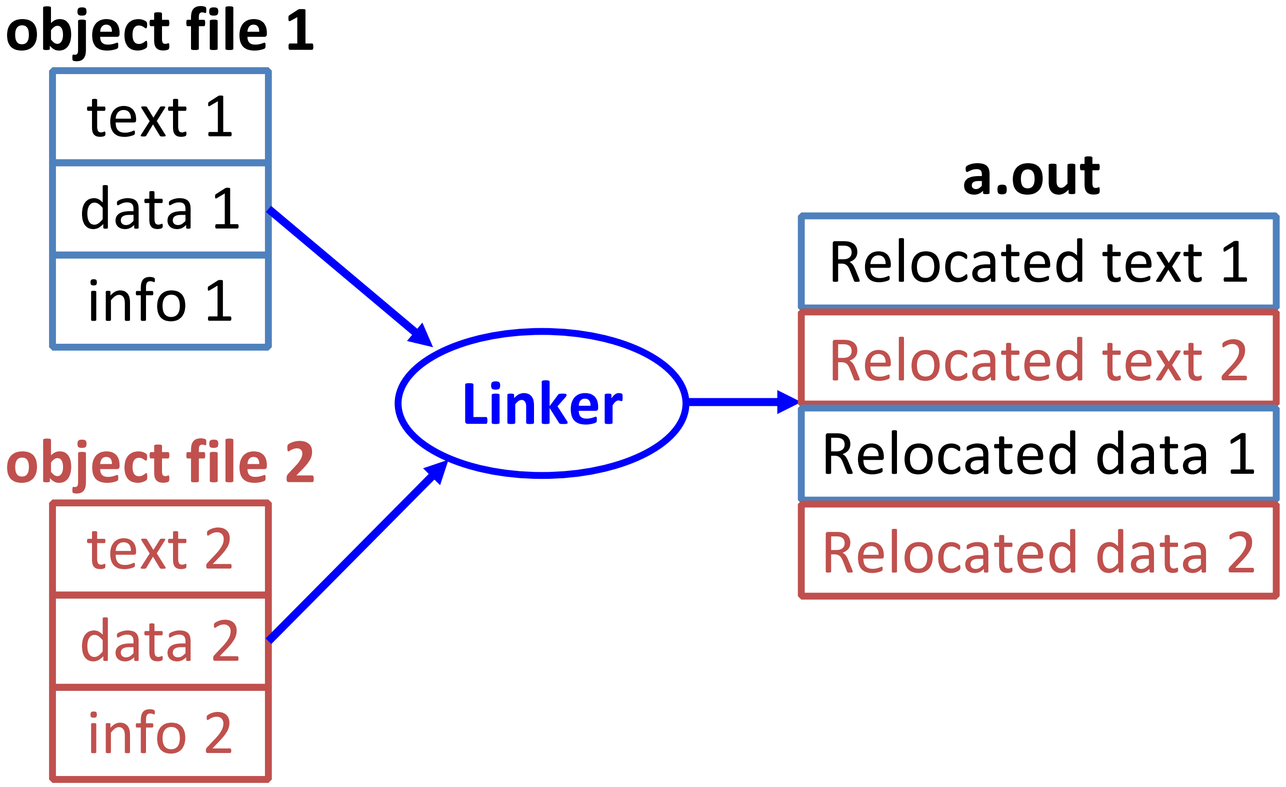


Linker (1/3)

- **Input:** Object Code files, information tables (e.g. `foo.o`, `lib.o` for RISC-V)
- **Output:** Executable Code (e.g. `a.out` for RISC-V)

- Combines several object (`.o`) files into a single executable ("linking")
- Enables separate compilation of files
  - Changes to one file do not require recompilation of whole program
  - Old name "Link Editor" from editing the "links" in jump and link instructions

Linker (2/3)


object file 1
text 1
data 1
info 1
object 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)

1) Take text segment from each `.o` file and put them together
2) Take data segment from each `.o` file, put them together, and concatenate this onto end of text segments
3) Resolve References
   - Go through Relocation Table; handle each entry
   - i.e. fill in all absolute addresses

Three Types of Addresses

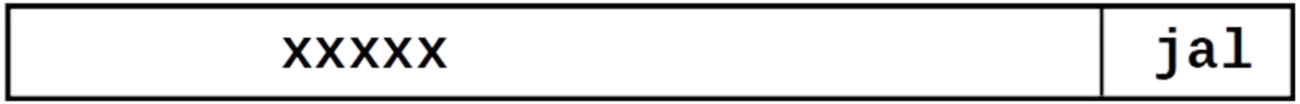
- PC-Relative Addressing (beq, bne, jal)
  - never relocate

External Function Reference (usually jal)
  - always relocate

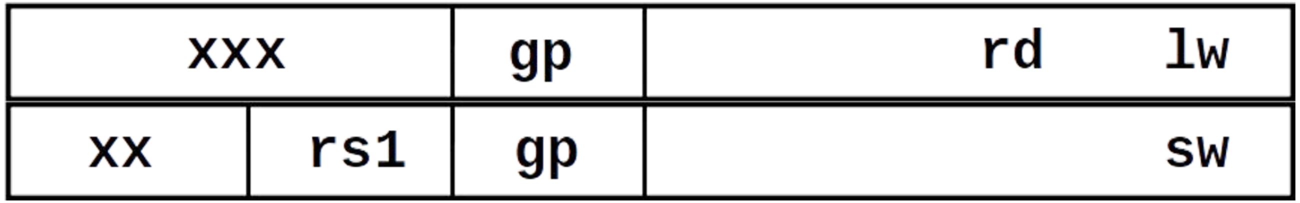
Static Data Reference (often auipc and addi)
  - always relocate
  - RISC-V often uses auipc rather than lui so that a big block of stuff can be further relocated as long as it is fixed relative to the pc

Absolute Addresses in RISC-V

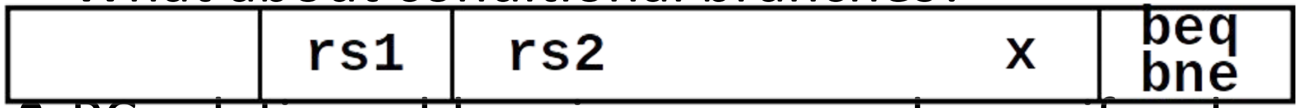
- Which instructions need relocation editing?
  - J-format: jump/jump and link



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



- What about conditional branches?



- PC-relative addressing preserved even if code moves

Resolving References (1/2)

- Linker assumes the first word of the first text segment is at 0x10000 for RV32.
  - 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:
  1) Search for reference (data or label) in all "user" symbol tables
  2) If not found, search library files (e.g. `printf`)
  3) Once absolute address is determined, fill in the machine code appropriately
- Output of linker: executable file containing text and data (plus header)

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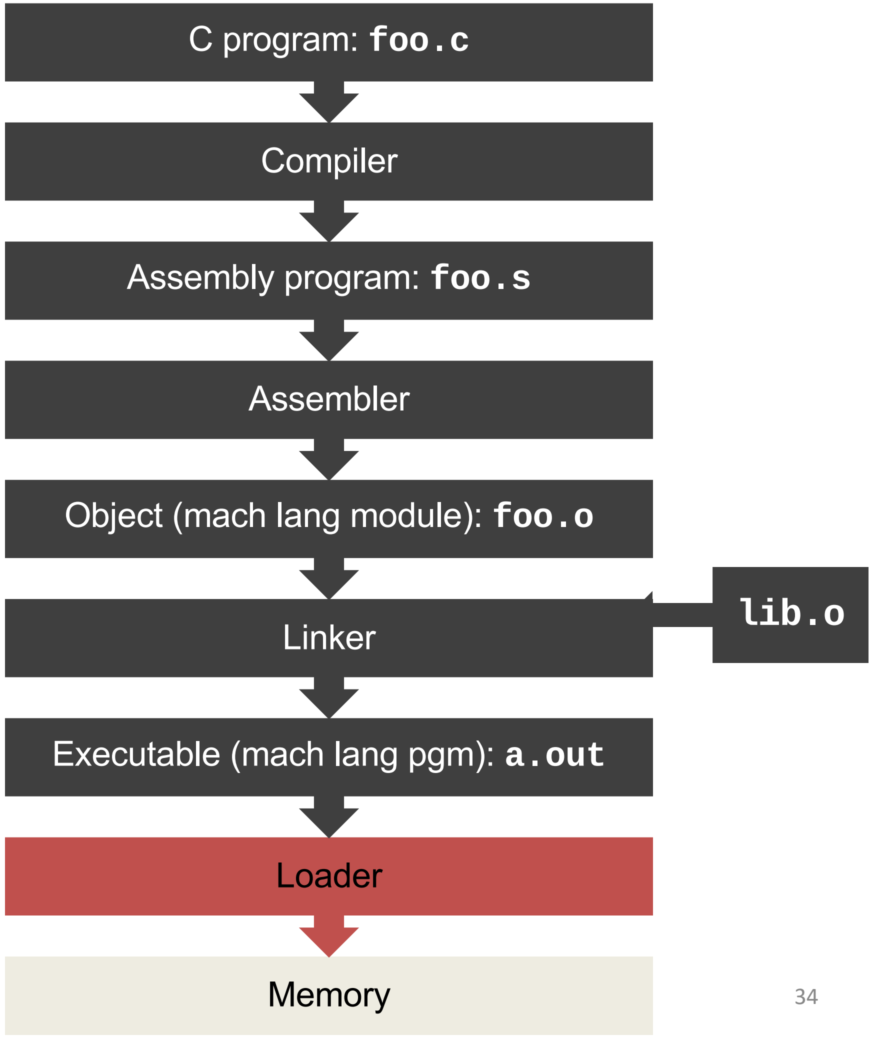
- Example



Loader

- **Input:** Executable Code (e.g. `a.out` for RISC-V)
- **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

1) Reads executable file's header to determine size of text and data segments
2) Creates new address space for program large enough to hold text and data segments, along with a stack segment
<more on this later>
3) Copies instructions and data from executable file into the new address space

Loader

4) Copies arguments passed to the program onto the stack
5) Initializes machine registers
   - Most registers cleared, but stack pointer assigned address of 1st free stack location
6) 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

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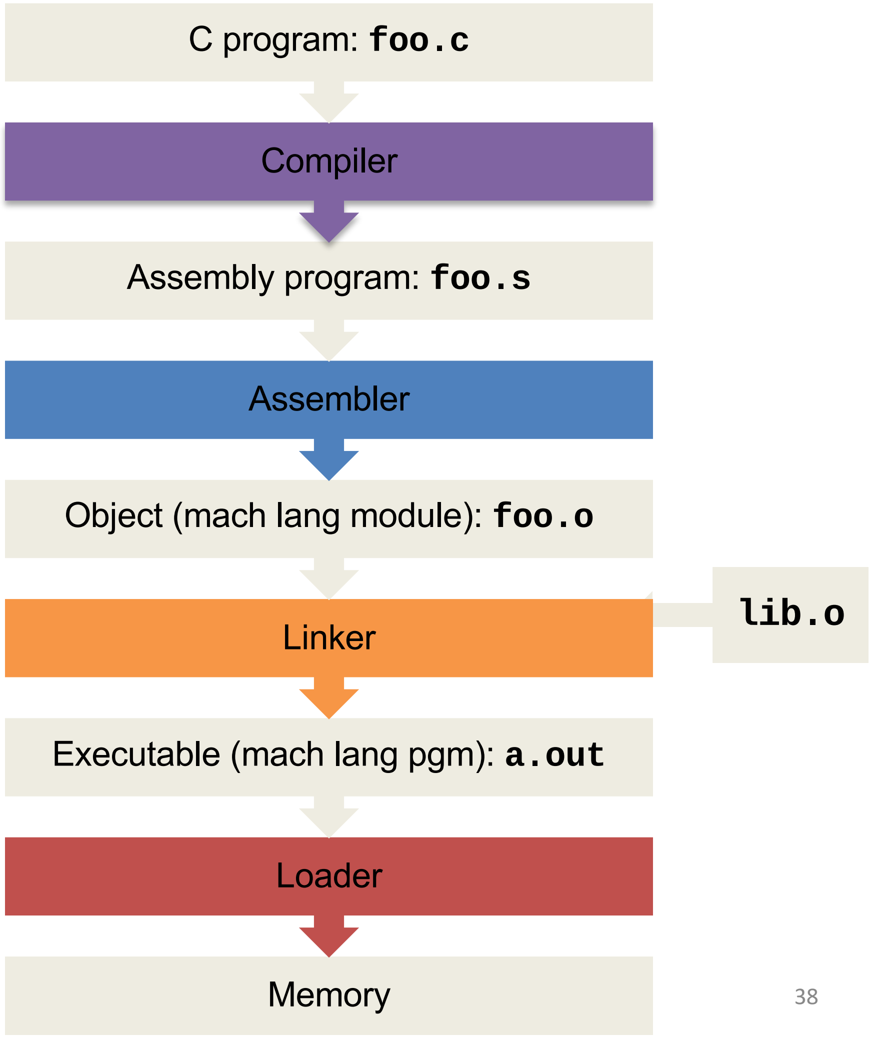
- **Example**



C.A.L.L. Example

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

Compiled Hello.c: Hello.s

```
.text
  .align 2
  .globl main
main:
  addi sp,sp,-16
  sw   ra,12(sp)
  lui  a0,%hi(string1)
  addi a0,a0,%lo(string1)
  lui  a1,%hi(string2)
  addi a1,a1,%lo(string2)
  call printf
  lw   ra,12(sp)
  addi sp,sp,16
  li   a0,0
  ret
  .section .rodata
  .balign 4
string1:
  .string "Hello, %s!\n"
string2:
  .string "world"
```

```
# Directive: enter text section
# Directive: align code to 2^2 bytes
# Directive: declare global symbol main
# label for start of main
# allocate stack frame
# save return address
# compute address of
#   string1
# compute address of
#   string2
# call function printf
# restore return address
# deallocate stack frame
# load return value 0
# return
# Directive: enter read-only data
section
# Directive: align data section to 4
bytes
# label for first string
# Directive: null-terminated string
# label for second string
# 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: 00000097 auipc ra,0x0   # addr placeholder
1c: 000080e7 jalr ra    # addr placeholder
20: 00c12083 lw ra,12(sp)
24: 01010113 addi sp,sp,16
28: 00000513 addi a0,a0,0
2c: 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
```

Summary

- Compiler converts a single HLL file into a single assembly file `.c` → `.s`
- Assembler removes pseudo-instructions, converts what it can to machine language, and creates a checklist for linker (relocation table) `.s` → `.o`
  - Resolves addresses by making 2 passes (for internal forward references)
- Linker combines several object files and resolves absolute addresses `.o` → `.out`
  - Enable separate compilation and use of libraries
- Loader loads executable into memory and begins execution