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CS61C : Machine Structures

Lecture #13: CALL

2006-07-19

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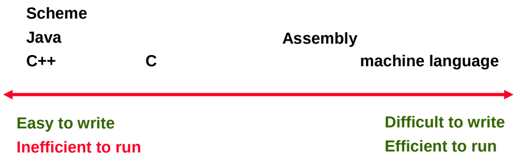
CALL Overview

- Interpretation vs Translation
- Translating C Programs
  - Compiler
  - Assembler
  - Linker
  - Loader
- An Example

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

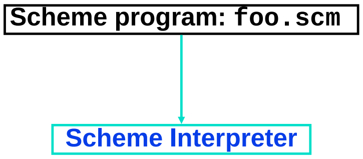
Language Continuum



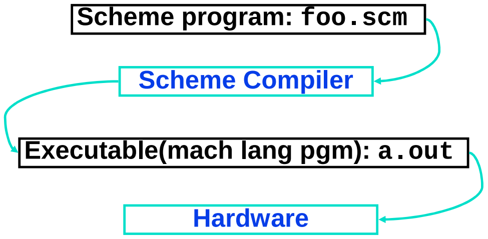
- Interpret a high level language if efficiency is not critical
- Translate (compile) to a lower level language to improve performance

- Scheme example …

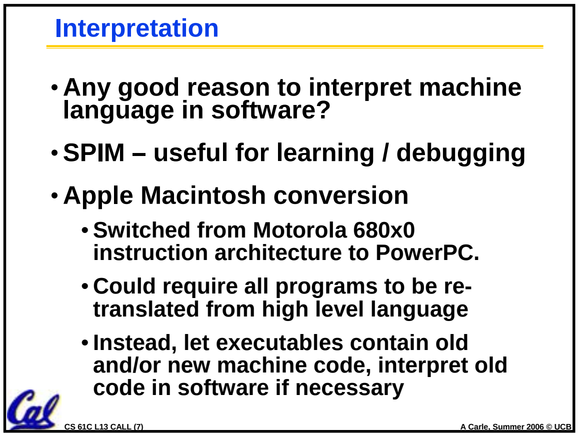
Interpretation



Translation

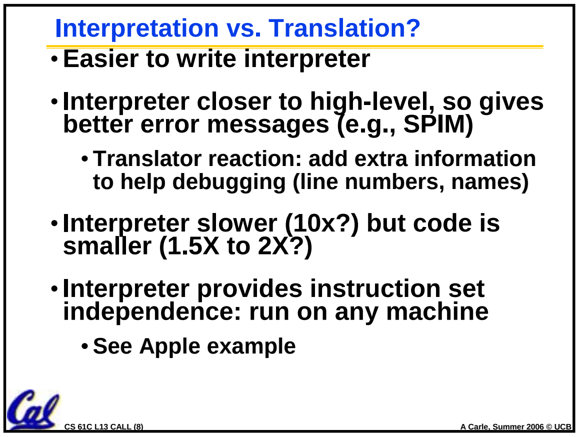


° Scheme Compiler is a translator from Scheme to machine language.



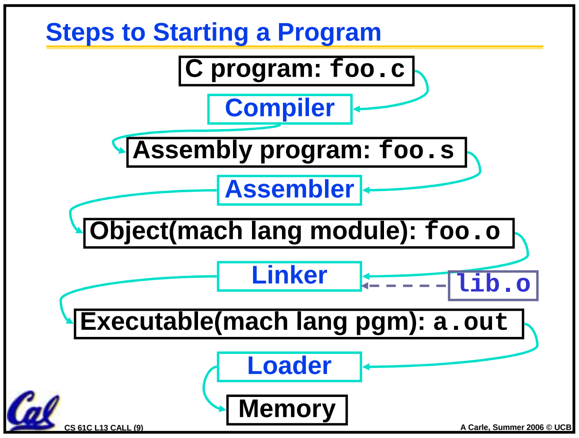
Interpretation

- 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.
  - 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



Interpretation vs. Translation?

- Easier to write interpreter
- Interpreter closer to high-level, so gives 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
  - See Apple example



Steps to Starting a Program

C program: `foo.c`

Compiler

Assembly program: `foo.s`

Assembler

Object(mach lang module): `foo.o`

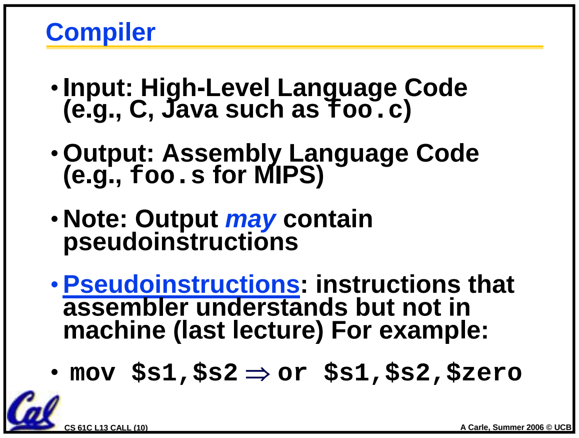
Linker

`lib.o`

Executable(mach lang pgm): `a.out`

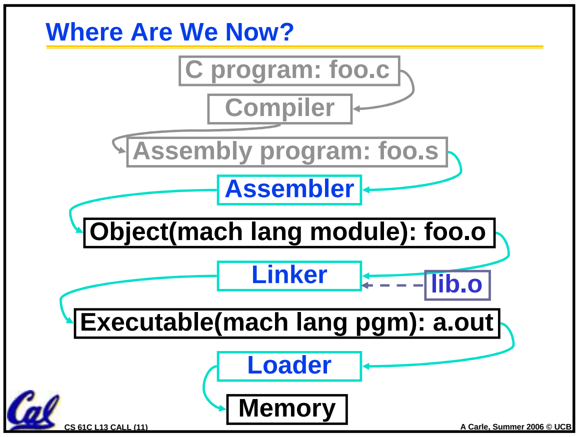
Loader

Memory



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`



Where Are We Now?

C program: foo.c

Compiler

Assembly program: foo.s

Assembler

Object(mach lang module): foo.o

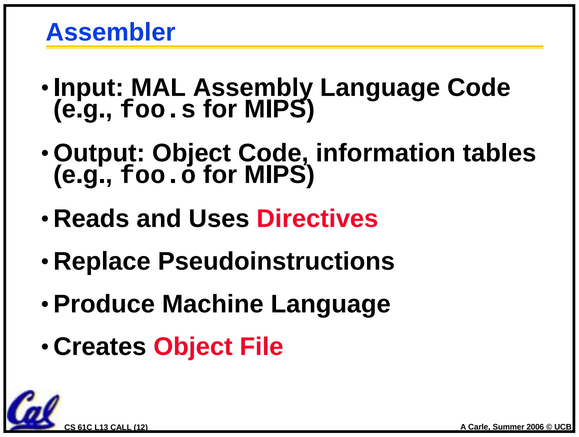
Linker

lib.o

Executable(mach lang pgm): a.out

Loader

Memory



Assembler

- Input: MAL 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
  - `.data`: Subsequent items put in user data segment
  - `.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          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)
```

Producing Machine Language (1/3)

- Constraint on Assembler:
  - The object file output (foo.o) may be only one of many object files in the final executable:
    - C: #include “my_helpers.h”
    - C: #include <stdio.h>
- Consequences:
  - Object files won’t know their base addresses until they are linked/loaded!
  - References to addresses will have to be adjusted in later stages

Producing Machine Language (2/3)

- Simple Case
  - Arithmetic, Logical, Shifts, and so on.
  - All necessary info is within the instruction already.
- What about Branches?
  - PC-Relative and in-file
  - In TAL, we know by how many instructions to branch.
- So these can be handled easily.

Producing Machine Language (3/3)

- What about jumps (`j` and `jal`)?
  - Jumps require absolute address.
- 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 for use by linker/loader…

1: Symbol Table

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

2: Relocation Table

- List of “items” needed by this file.
  - Any label jumped to: `j` or `jal`
    - internal
    - external (including lib files)
  - Any named piece of data
    - Anything referenced by the `la` instruction
    - static variables
  - Contains base address of instruction w/dependency, dependency name

Question

- Which lines go in the symbol table and/or relocation table?

```
my_func:
   lui $a0 my_arrayh       # a (from la)
   ori $a0 $a0 my_arrayl   # b (from la)
   jal add_link             # c
   bne $a0,$v0, my_func     # d
```

A:	Symbol: my_func	relocate: my_array
B:	-	relocate: my_array
C:	-	relocate: add_link
D:	-	-

Peer Instruction 1

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 an interpreter (rather than a translater) mainly because of (at least one of): ease of writing, better error msgs, smaller object code.

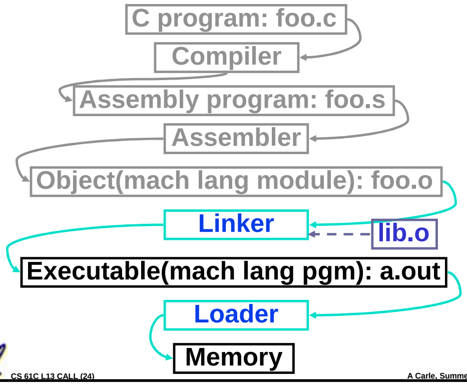
Administrivia

- HW 4
  - Due Online Friday
- Project 2
  - Released Today
  - Due ?
- Midterm 2
  - Plan for August 4th

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

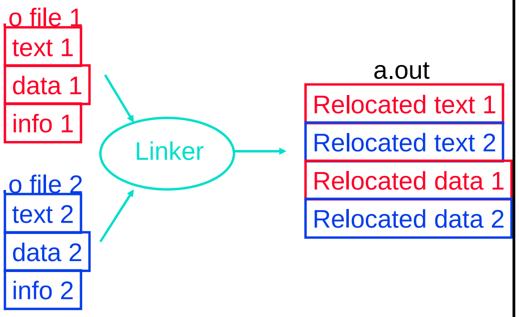
Where Are We Now?



Link Editor/Linker (1/3)

- Input: Object Code, information tables (e.g., `foo.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 is >40 M lines of code!
  - Link Editor name from editing the "links" in jump and link instructions

Link Editor/Linker (2/3)



Link Editor/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 and handle each entry
  - That is, fill in all absolute addresses

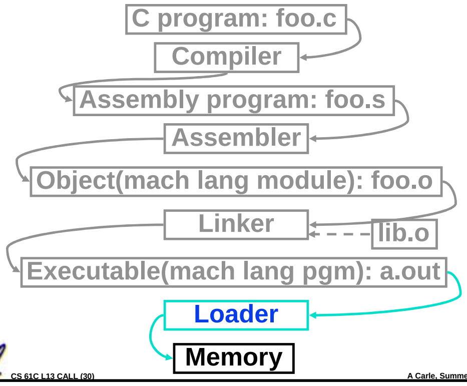
Resolving References (1/2)

- Linker *assumes* first word of first text segment is at address 0x00000000.
- 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 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 (1/3)

- 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 (2/3)

- So what does a loader 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 (this may be anywhere in memory)

Loader (3/3)

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

Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

```
#include <stdio.h>
int main (int argc, char *argv[]) {
 int i;
 int sum = 0;

 for (i = 0; i <= 100; i = i + 1)
    sum = sum + i * i;
 printf ("The sum from 0 .. 100 is %d\n",
    sum);
}
```

Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

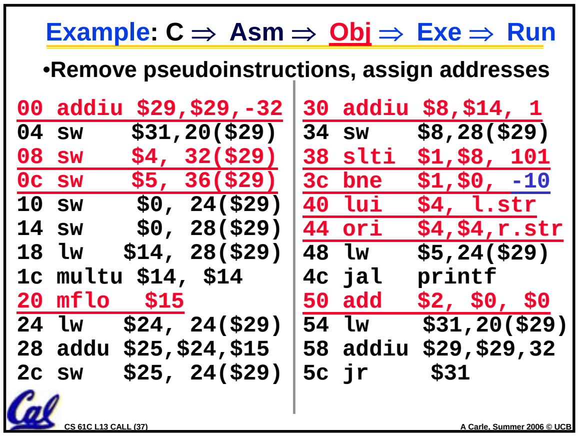
```
 .text
 .align  2
 .globl  main
main:
 subu $sp,$sp,32
 sw  $ra, 20($sp)
 sd  $a0, 32($sp)
 sw  $0, 24($sp)
 sw  $0, 28($sp)
loop:
 lw  $t6, 28($sp)
 mul $t7, $t6,$t6
 lw  $t8, 24($sp)
 addu $t9,$t8,$t7
 sw  $t9, 24($sp)
 addu $t0, $t6, 1
 sw  $t0, 28($sp)
 ble $t0,100, loop
 la  $a0, str
 lw  $a1, 24($sp)
 jal printf
 move $v0, $0
 lw  $ra, 20($sp)
 addiu $sp,$sp,32
 j   $ra
 .data
 .align  0
str:
 .asciiz "The sum from 0 .. 100 is %d\n"
```

Where are 7 pseudo-instructions?

Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

```
 .text
 .align  2
 .globl  main
main:
 subu $sp,$sp,32
 sw  $ra, 20($sp)
 sd  $a0, 32($sp)
 sw  $0, 24($sp)
 sw  $0, 28($sp)
loop:
 lw  $t6, 28($sp)
 mul $t7, $t6,$t6
 lw  $t8, 24($sp)
 addu $t9,$t8,$t7
 sw  $t9, 24($sp)
 addu $t0, $t6, 1
 sw  $t0, 28($sp)
 ble $t0,100, loop
 la  $a0, str
 lw  $a1, 24($sp)
 jal printf
 move $v0, $0
 lw  $ra, 20($sp)
 addiu $sp,$sp,32
 j   $ra
 .data
 .align  0
str:
 .asciiz "The sum from 0 .. 100 is %d\n"
```

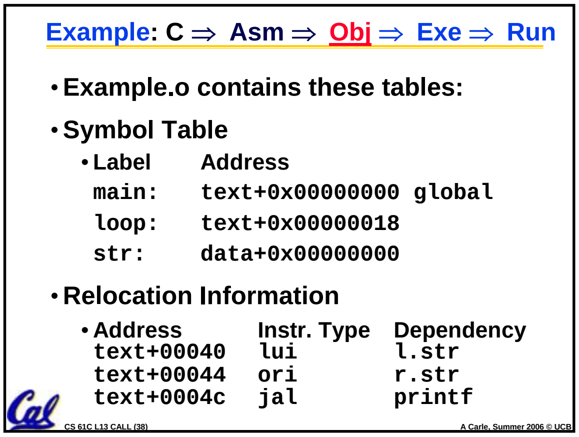
7 pseudo-instructions underlined



Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

•Remove pseudoinstructions, assign addresses

```
00 addiu $29,$29,-32   30 addiu $8,$14, 1
04 sw    $31,20($29)   34 sw    $8,28($29)
08 sw    $4, 32($29)   38 slti  $1,$8, 101
0c sw    $5, 36($29)   3c bne   $1,$0, -10
10 sw     $0, 24($29)  40 lui   $4, l.str
14 sw     $0, 28($29)  44 ori   $4,$4,r.str
18 lw    $14, 28($29)  48 lw    $5,24($29)
1c multu $14, $14      4c jal   printf
20 mflo   $15          50 add   $2, $0, $0
24 lw    $24, 24($29)  54 lw     $31,20($29)
28 addu $25,$24,$15    58 addiu $29,$29,32
2c sw    $25, 24($29)  5c jr     $31
```



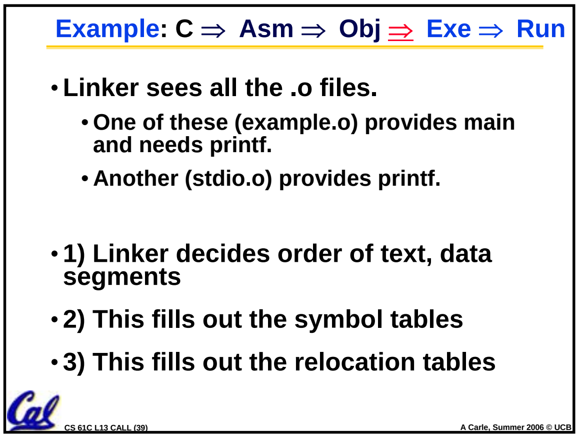
Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

- Example.o contains these tables:
- Symbol Table

Label	Address
`main:`	`text+0x00000000 global`
`loop:`	`text+0x00000018`
`str:`	`data+0x00000000`

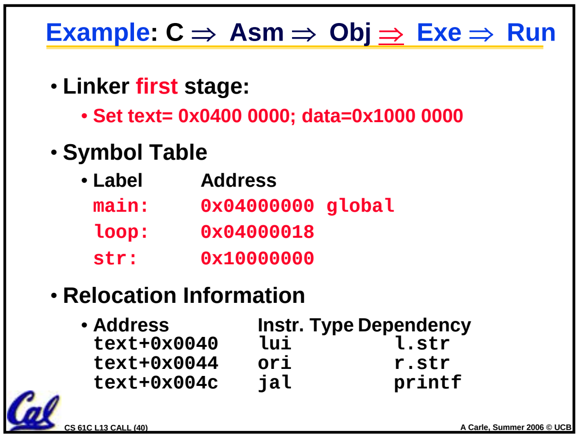
- Relocation Information

Address	Instr. Type	Dependency
`text+00040`	`lui`	`l.str`
`text+00044`	`ori`	`r.str`
`text+0004c`	`jal`	`printf`



Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

- Linker sees all the .o files.
  - One of these (example.o) provides main and needs printf.
  - Another (stdio.o) provides printf.
- 1) Linker decides order of text, data segments
- 2) This fills out the symbol tables
- 3) This fills out the relocation tables



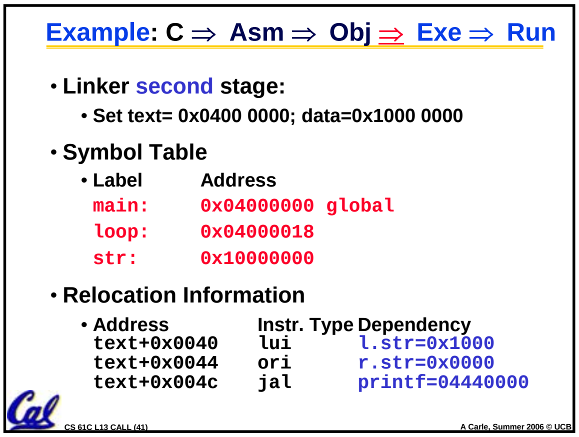
Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

- Linker first stage:
  - Set text= 0x0400 0000; data=0x1000 0000
- Symbol Table

Label	Address
`main:`	`0x04000000 global`
`loop:`	`0x04000018`
`str:`	`0x10000000`

- Relocation Information

Address	Instr. Type	Dependency
`text+0x0040`	`lui`	`l.str`
`text+0x0044`	`ori`	`r.str`
`text+0x004c`	`jal`	`printf`



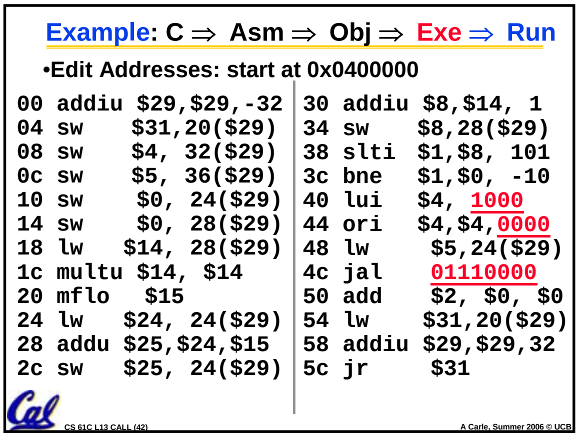
Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

- Linker second stage:
  - Set text= 0x0400 0000; data=0x1000 0000
- Symbol Table

Label	Address
`main:`	`0x04000000 global`
`loop:`	`0x04000018`
`str:`	`0x10000000`

- Relocation Information

Address	Instr. Type	Dependency
`text+0x0040`	`lui`	`l.str=0x1000`
`text+0x0044`	`ori`	`r.str=0x0000`
`text+0x004c`	`jal`	`printf=04440000`



Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

•Edit Addresses: start at 0x0400000

```
00 addiu $29,$29,-32   30 addiu $8,$14, 1
04 sw    $31,20($29)   34 sw    $8,28($29)
08 sw    $4, 32($29)   38 slti  $1,$8, 101
0c sw    $5, 36($29)   3c bne   $1,$0, -10
10 sw     $0, 24($29)  40 lui   $4, 1000
14 sw     $0, 28($29)  44 ori   $4,$4,0000
18 lw    $14, 28($29)  48 lw     $5,24($29)
1c multu $14, $14      4c jal    01110000
20 mflo   $15          50 add    $2, $0, $0
24 lw    $24, 24($29)  54 lw    $31,20($29)
28 addu $25,$24,$15    58 addiu $29,$29,32
2c sw    $25, 24($29)  5c jr     $31
```

Example: C ⇒ Asm ⇒ Obj ⇒ Exe ⇒ Run

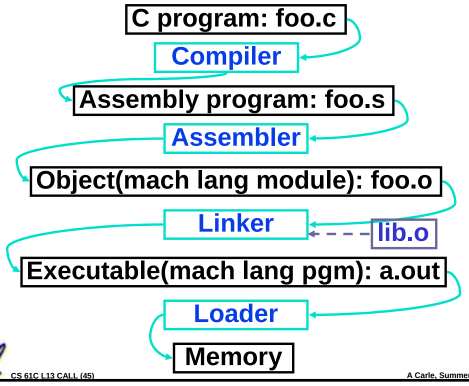
```
0x004000  00100111101111011111111111100000
0x004004  10101111101111110000000000010100
0x004008  10101111101001000000000000100000
0x00400c  10101111101001010000000000100100
0x004010  10101111101000000000000000011000
0x004014  10101111101000000000000000011100
0x004018  10001111101011100000000000011100
0x00401c  10001111101110000000000000011000
0x004020  00000001110011100000000000011001
0x004024  00100101110010000000000000000001
0x004028  00101001000000010000000001100101
0x00402c  10101111101010000000000000011100
0x004030  00000000000000000111100000010010
0x004034  00000011000011111100100000100001
0x004038  00010100001000001111111111110111
0x00403c  10101111101110010000000000011000
0x004040  00111100000001000001000000000000
0x004044  10001111101001010000000000011000
0x004048  00001100000100000000000011101100
0x00404c  00100100100001000000010000110000
0x004050  10001111101111110000000000010100
0x004054  00100111101111010000000000100000
0x004058  00000011111000000000000000001000
0x00405c  00000000000000000001000000100001
```

Peer Instruction 2

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

```
Loop: lui $at, 0xABCD          }# A
      ori $a0,$at, 0xFEDC      }
      jal add_link              # B
      bne $a0,$v0, Loop         # C
```

Things to Remember (1/3)



Things to Remember (2/3)

- Compiler converts a single HLL file into a single assembly language file.
- Assembler removes pseudoinstructions, converts what it can to machine language, and creates a checklist for the linker (relocation table). This changes each .s file into a .o file.
- Linker combines several .o files and resolves absolute addresses.
- Loader loads executable into memory and begins execution.

Things to Remember 3/3

- Stored Program concept mean instructions just like data, so can take data from storage, and keep transforming it until load registers and jump to routine to begin execution
  - Compiler ⇒ Assembler ⇒ Linker (⇒ Loader)
- Assembler does 2 passes to resolve addresses, handling internal forward references
- Linker enables separate compilation, libraries that need not be compiled, and resolves remaining addresses