Lecturer SOE
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UCB CS61C : Machine Structures

Lecture 19 – Running a Program II (Compiling, Assembling, Linking, Loading)

2008-03-05

Hello to **Neil Sharma** from **the 3rd row**!

BODY MOVEMENTS → POWER!

Researchers at Princeton have developed a flexible electricity-producing sheet of rubber that can use body movements into electricity. Breathing generates 1 W, walking around the room generates 70 W. Shoes may be the best place, to power/recharge cell phones & iPods.

www.nytimes.com/2010/03/02/science/02obribbon.html

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

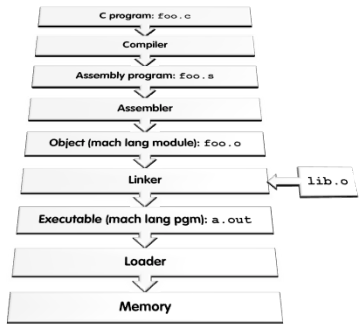
- List of "items" this file needs the address later.
- What are they?
  - Any label jumped to: `j` or `jal`
    - internal
    - external (including lib files)
  - Any piece of data connected with an address
    - such as the `la` instruction

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`

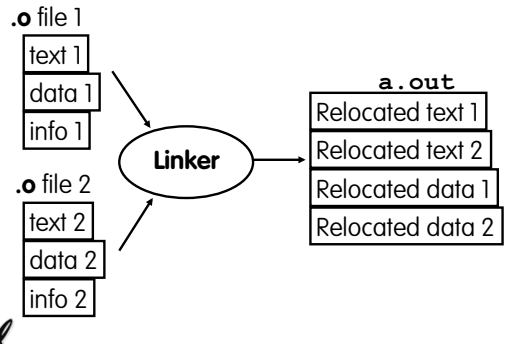
Where Are We Now?



Linker (1/3)

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

Linker (2/3)



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

Four Types of Addresses we'll discuss

- PC-Relative Addressing (`beq`, `bne`)
  - never relocate
- Absolute Address (`j`, `jal`)
  - always relocate
- External Reference (usually `jal`)
  - always relocate
- Data Reference (often `lui` and `ori`)
  - always relocate

Absolute Addresses in MIPS

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

j/jal	xxxxx

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

lw/sw	$gp	$x	address

  - What about conditional branches?

beq/bne	$rs	$rt	address

  - PC-relative addressing preserved even if code moves

Resolving References (1/2)

- Linker assumes first word of first text segment is at address **`0x00000000`**.
  - (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:
  - 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)

Static vs Dynamically linked libraries

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

en.wikipedia.org/wiki/Dynamic_linking

Dynamically linked libraries

- 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)
  - – 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

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.

Dynamically linked libraries

- The prevailing approach to dynamic linking uses machine code as the "lowest common denominator"
  - The linker does not use information about how the program or library was compiled (i.e., what compiler or language)
  - This can be described as "linking at the machine code level"
  - This isn't the only way to do it...

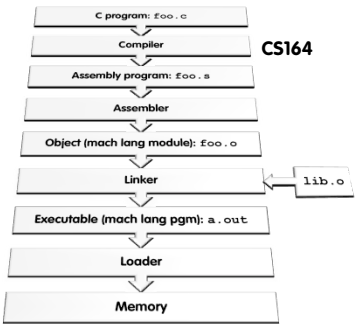
Administrivia…Midterm on Monday!

- Review Sat @ Time/location TBA
- Exam Mon @ 7-10pm in 1 Pimentel
- Covers labs, hw, proj, lec, book through today
- Bring…
  - NO cells, calculators, pagers, PDAs
  - 2 writing implements (we'll provide write-in exam booklets) – pencils ok!
  - Your green sheet (make sure to correct green sheet bugs)

Upcoming Calendar

Week #	Mon	Wed	Thu Lab	Fri
#7 This week	MIPS Inst Format III	Running Program I	Running Program	Running Program II
#8 Next week	SDS I Midterm 7-10pm 1 Pimentel	SDS II (TA)	SDS	SDS III (TA)
#9 Next next week	Students Explain Midterm!	SDS IV	SDS	CPU I (no class, see webcast)
Next[3] week	**Spring Break!**			

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

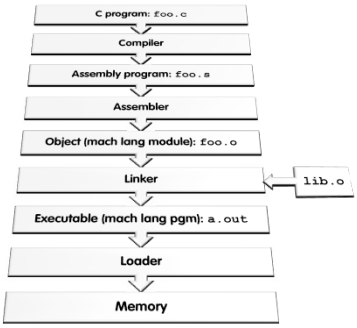
Loader (2/3)

- 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

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

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). 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.

Things to Remember 3/3

- Stored Program concept is very powerful. It means that instructions sometimes act just like data. Therefore we can use programs to manipulate other programs!
  - Compiler ⇒ Assembler ⇒ Linker (⇒ Loader)

Big Endian vs. Little Endian

Big-endian and little-endian derive from Jonathan Swift's *Gulliver's Travels* in which the Big Endians were a political faction that broke their eggs at the large end ("the primitive way") and rebelled against the Lilliputian King who required his subjects (the Little Endians) to break their eggs at the small end.

- **The order in which BYTES are stored in memory**
- **Bits always stored as usual. (E.g., 0xC2=0b 1100 0010)**

Consider the number 1025 as we normally write it:

BYTE3 BYTE2 BYTE1 BYTE0

00000000 00000000 00000100 00000001

Big Endian

- ADDR3 ADDR2 ADDR1 ADDR0
  BYTE0 BYTE1 BYTE2 BYTE3
  00000001 00000100 00000000 00000000
- ADDR0 ADDR1 ADDR2 ADDR3
  BYTE3 BYTE2 BYTE1 BYTE0
  00000000 00000000 00000100 00000001

Little Endian

- ADDR3 ADDR2 ADDR1 ADDR0
  BYTE3 BYTE2 BYTE1 BYTE0
  00000000 00000000 00000100 00000001
- ADDR0 ADDR1 ADDR2 ADDR3
  BYTE0 BYTE1 BYTE2 BYTE3
  00000001 00000100 00000000 00000000

www.webopedia.com/TERM/b/big_endian.html
searchnetworking.techtarget.com/sDefinition/0,,sid7_gci211659,00.html
www.noveltheory.com/TechPapers/endian.asp
en.wikipedia.org/wiki/Big_endian

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: MAL

```
__.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
 jr $ra
 .data
 .align  0
str:
 .asciiz "The sum
 of sq from 0 ..
 100 is %d\n"
```

Where are 7 pseudo-instructions?

Compilation: MAL

```
__.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
 jr $ra
 .data
 .align  0
str:
__.asciiz "The sum
 of sq from 0 ..
 100 is %d\n"
```

7 pseudo-instructions underlined

Assembly step 1:

Remove pseudoinstructions, assign addresses

```
00 addiu $29,$29,-32
04 sw    $31,20($29)
08 sw    $4, 32($29)
0c sw    $5, 36($29)
10 sw    $0, 24($29)
14 sw    $0, 28($29)
18 lw    $14, 28($29)
1c multu $14, $14
20 mflo  $15
24 lw    $24, 24($29)
28 addu  $25,$24,$15
2c sw    $25, 24($29)
```

```
30 addiu $8,$14, 1
34 sw    $8,28($29)
38 slti  $1,$8, 101
3c bne   $1,$0, loop
40 lui   $4, l.str
44 ori   $4,$4,r.str
48 lw    $5,24($29)
4c jal   printf
50 add   $2, $0, $0
54 lw    $31,20($29)
58 addiu $29,$29,32
5c jr    $31
```


Assembly step 2

Create relocation table and symbol table

- Symbol Table

Label	address (in module)	type
main:	0x00000000	global text
loop:	0x00000018	local text
str:	0x00000000	local data

- Relocation Information

Address	Instr. type	Dependency
0x00000040	lui	l.str
0x00000044	ori	r.str
0x0000004c	jal	printf

Assembly step 3

Resolve local PC-relative labels

```
00 addiu $29,$29,-32
04 sw    $31,20($29)
08 sw    $4, 32($29)
0c sw    $5, 36($29)
10 sw    $0, 24($29)
14 sw    $0, 28($29)
18 lw    $14, 28($29)
1c multu $14, $14
20 mflo  $15
24 lw    $24, 24($29)
28 addu  $25,$24,$15
2c sw    $25, 24($29)
```

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


Assembly step 4

- Generate object (`.o`) file:
  - Output binary representation for
    - ext segment (instructions),
    - data segment (data),
    - symbol and relocation tables.
  - Using dummy "placeholders" for unresolved absolute and external references.

Text segment in object file

```
0x000000   00100111101111011111111111100000
0x000004   10101111101111110000000000010100
0x000008   10101111101001000000000000100000
0x00000c   10101111101001010000000000100100
0x000010   10101111101000000000000000011000
0x000014   10101111101000000000000000011100
0x000018   10001111101011100000000000011100
0x00001c   10001111101111000000000000011000
0x000020   00000001110011100000000000011001
0x000024   00100101110010000000000000000001
0x000028   00101001000000010000000001100101
0x00002c   10101111101010000000000000011100
0x000030   00000000000000000001111000000010010
0x000034   00000011000011111100100000100001
0x000038   00010100001000000111111111110111
0x00003c   10101111101110010000000000011000
0x000040   00111100000001000000000000000000
0x000044   10001111101001010000000000000000
0x000048   00001100000100000000000011101100
0x00004c   00100100000000000000000000000000
0x000050   10001111101111110000000000010100
0x000054   00100111101111010000000000100000
0x000058   00000011111000000000000000001000
0x00005c   00000000000000000000100000100001
```


Link step 1: combine `prog.o`, `libc.o`

- Merge text/data segments
- Create absolute memory addresses
- Modify & merge symbol and relocation tables
- Symbol Table
  - Label / Address

```
main:   0x00000000
loop:   0x00000018
str:    0x10000430
printf: 0x000003b0   …
```

- Relocation Information
  - Address / Instr. Type / Dependency

```
0x00000040   lui    l.str
0x00000044   ori    r.str
0x0000004c   jal    printf   …
```


Link step 2:

- Edit Addresses in relocation table
  - (shown in TAL for clarity, but done in binary)

```
00 addiu $29,$29,-32
04 sw    $31,20($29)
08 sw    $4, 32($29)
0c sw    $5, 36($29)
10 sw    $0, 24($29)
14 sw    $0, 28($29)
18 lw    $14, 28($29)
1c multu $14, $14
20 mflo  $15
24 lw    $24, 24($29)
28 addu  $25,$24,$15
2c sw    $25, 24($29)
```

```
30 addiu $8,$14, 1
34 sw    $8,28($29)
38 slti  $1,$8, 101
3c bne   $1,$0, -10
40 lui   $4, 4096
44 ori   $4,$4,1072
48 lw    $5,24($29)
4c jal   812
50 add   $2, $0, $0
54 lw    $31,20($29)
58 addiu $29,$29,32
5c jr    $31
```


Link step 3:

- Output executable of merged modules.
  - Single text (instruction) segment
  - Single data segment
  - Header detailing size of each segment
- NOTE:
  - The preceeding example was a much simplified version of how ELF and other standard formats work, meant only to demonstrate the basic principles.