UCB CS61C: Machine Structures

Lecture 16 – Running a Program (Compiling, Assembling, Linking, Loading)

2013-03-01

FACULTY “RE-IMAGINE” UGRAD EDUCATION

Highlights: Big Ideas courses, more team teaching, Academic Honor code, report avg and median grades to share context, meaning.
Administrivia...

- Midterm Exam on **Monday @ 7-9pm**
  - You’re responsible for all material up through today
  - Find where to go on Piazza

- You get to bring
  - Your study sheet (2-sided!)
  - Pens & Pencils

- What you don’t need to bring
  - Calculator, cell phone, pagers
  - MIPS Green Sheet (attached to back of exam)

- Conflicts? E-mail Justin (head TA)

- Dan’s OH today are cancelled
Interpretation

Scheme program: foo.scm

Scheme interpreter

- Scheme Interpreter is just a program that reads a scheme program and performs the functions of that scheme program.
Translation

- Scheme Compiler is a translator from Scheme to machine language.
- The processor is a hardware interpreter of machine language.
Steps to Starting a Program (translation)

1. C program: `foo.c`
2. Compiler
3. Assembly program: `foo.s`
4. Assembler
5. Object (mach lang module): `foo.o`
6. Linker
7. Executable (mach lang pgm): `a.out`
8. Loader
9. Memory
10. `lib.o`
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 pseudo-instructions

**Pseudo-instructions**: instructions that assembler understands but not in machine

For example:

- `move $s1,$s2` $\rightarrow$ `add $s1,$s2,$zero`
Where Are We Now?

C program: foo.c

Compiler

Assembly program: foo.s

Assembler

Object (mach lang module): foo.o

Linker

Executable (mach lang pgm): a.out

Loader

Memory

CS164
Assembler

- Input: Assembly Language Code (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 to 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

- Asm. treats convenient variations of machine language instructions as if real instructions

Pseudo:
- `subu $sp,$sp,32`
- `sd $a0, 32($sp)`
- `mul $t7,$t6,$t5`
- `addu $t0,$t6,1`
- `la $a0, str`

Real:
- `addiu $sp,$sp,-32`
- `sw $a0, 32($sp)`
- `sw $a1, 36($sp)`
- `mul $t6,$t5`
- `mflo $t7`
- `addiu $t0,$t6,1`
- `slti $at,$t0,101`
- `bne $at,$0,loop`
- `lui $at,left(str)`
- `ori $a0,$at,right(str)`
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
“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
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 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 later.
- What are they?
  - Any label jumped to: j or jal
    - internal
    - external (including lib files)
  - Any piece of data
    - 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?

- C program: `foo.c`
- Compiler
- Assembly program: `foo.s`
- Assembler
- Object (mach lang module): `foo.o`
- Linker
- Executable (mach lang pgm): `a.out`
- Loader
- Memory
- Libraries: `lib.o`
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)

.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
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` format: 
      - Jump, jump and link

- Loads and stores to variables in static area, relative to global pointer
  - `lw/sw` format: 
    - Load and store

- What about conditional branches?
  - `beq/bne` format: 
    - Branch on equal, not equal

- 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)
Where Are We Now?

1. C program: foo.c
2. Compiler
3. Assembly program: foo.s
4. Assembler
5. Object (mach lang module): foo.o
6. Linker
7. Executable (mach lang pgm): a.out
8. Loader
9. Memory
Loader Basics

- 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 ... 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
Conclusion

- Compiler converts a single HLL file into a single assembly lang. 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.
- 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)
Which of the following instr. may need to be edited during link phase?

Loop:  
  lui $at, 0xABCD  
  ori $a0,$at, 0xFEDC  
  bne $a0,$v0, Loop  

1) (b) FT  
2) (a) FF  
3) (c) TF  
4) (d) TT
Peer Instruction Answer

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

Loop:  
  lui $at, 0xABC
  ori $a0,$at, 0xFEDC
  bne $a0,$v0, Loop

1. a) FF
2. b) FT
3. c) TF
4. d) TT

- data reference; relocate
- PC-relative branch; OK
Bonus slides

- These are extra slides that used to be included in lecture notes, but have been moved to this, the “bonus” area to serve as a supplement.
- The slides will appear in the order they would have in the normal presentation.
Language Execution Continuum

- An **Interpreter** is a program that executes other programs.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Java</th>
<th>C++</th>
<th>C</th>
<th>Assembly</th>
<th>Java bytecode</th>
<th>Machine language</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy to program</td>
<td>Inefficient to interpret</td>
<td>Efficient to interpret</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difficult to program</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- 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 up performance.
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 Scheme program `foo.scm`
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.
    - 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, stk)
  - 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.

- 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.
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
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...
#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
"
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"
## Assembly step 1:

Remove pseudoinstructions, assign addresses

<table>
<thead>
<tr>
<th>Line</th>
<th>Instruction</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>addiu $29,$29,-32</td>
<td>$00 ($29)</td>
</tr>
<tr>
<td>04</td>
<td>sw $31,20($29)</td>
<td>$04 ($29)</td>
</tr>
<tr>
<td>08</td>
<td>sw $4, 32($29)</td>
<td>$08 ($29)</td>
</tr>
<tr>
<td>0c</td>
<td>sw $5, 36($29)</td>
<td>$0c ($29)</td>
</tr>
<tr>
<td>10</td>
<td>sw $0, 24($29)</td>
<td>$10 ($29)</td>
</tr>
<tr>
<td>14</td>
<td>sw $0, 28($29)</td>
<td>$14 ($29)</td>
</tr>
<tr>
<td>18</td>
<td>lw $14, 28($29)</td>
<td>$18 ($29)</td>
</tr>
<tr>
<td>1c</td>
<td>multu $14, $14</td>
<td>$1c ($29)</td>
</tr>
<tr>
<td>20</td>
<td>mflo $15</td>
<td>$20 ($29)</td>
</tr>
<tr>
<td>24</td>
<td>lw $24, 24($29)</td>
<td>$24 ($29)</td>
</tr>
<tr>
<td>28</td>
<td>addu $25,$24,$15</td>
<td>$28 ($29)</td>
</tr>
<tr>
<td>2c</td>
<td>sw $25, 24($29)</td>
<td>$2c ($29)</td>
</tr>
<tr>
<td>30</td>
<td>addiu $8,$14, 1</td>
<td>$30 ($29)</td>
</tr>
<tr>
<td>34</td>
<td>sw $8, 28($29)</td>
<td>$34 ($29)</td>
</tr>
<tr>
<td>38</td>
<td>slti $1,$8, 101</td>
<td>$38 ($29)</td>
</tr>
<tr>
<td>3c</td>
<td>bne $1,$0, loop</td>
<td>$3c ($29)</td>
</tr>
<tr>
<td>40</td>
<td>lui $4, l.str</td>
<td>$40 ($29)</td>
</tr>
<tr>
<td>44</td>
<td>ori $4,$4,r.str</td>
<td>$44 ($29)</td>
</tr>
<tr>
<td>48</td>
<td>lw $5, 24($29)</td>
<td>$48 ($29)</td>
</tr>
<tr>
<td>4c</td>
<td>jal printf</td>
<td>$4c ($29)</td>
</tr>
<tr>
<td>50</td>
<td>add $2, $0, $0</td>
<td>$50 ($29)</td>
</tr>
<tr>
<td>54</td>
<td>lw $31, 20($29)</td>
<td>$54 ($29)</td>
</tr>
<tr>
<td>58</td>
<td>addiu $29,$29,32</td>
<td>$58 ($29)</td>
</tr>
<tr>
<td>5c</td>
<td>jr $31</td>
<td>$5c ($29)</td>
</tr>
</tbody>
</table>
### Assembly step 2

Create relocation table and symbol table

- **Symbol Table**

<table>
<thead>
<tr>
<th>Label</th>
<th>address (in module)</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>main:</td>
<td>0x0000000000</td>
<td>global text</td>
</tr>
<tr>
<td>loop:</td>
<td>0x0000000018</td>
<td>local text</td>
</tr>
<tr>
<td>str:</td>
<td>0x0000000000</td>
<td>local data</td>
</tr>
</tbody>
</table>

- **Relocation Information**

<table>
<thead>
<tr>
<th>Address</th>
<th>Instr.</th>
<th>type</th>
<th>Dependency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00000040</td>
<td>lui</td>
<td></td>
<td>l.str</td>
</tr>
<tr>
<td>0x00000044</td>
<td>ori</td>
<td></td>
<td>r.str</td>
</tr>
<tr>
<td>0x0000004c</td>
<td>jal</td>
<td></td>
<td>printf</td>
</tr>
</tbody>
</table>
Assembly step 3

Resolve local PC-relative labels

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

<table>
<thead>
<tr>
<th>Address</th>
<th>Binary Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x000000</td>
<td>00100111101111011111111111111110</td>
</tr>
<tr>
<td>0x000004</td>
<td>1010111110111111110000000000010100</td>
</tr>
<tr>
<td>0x000008</td>
<td>1010111110100100000000000000001000</td>
</tr>
<tr>
<td>0x00000c</td>
<td>1010111110100101000000000000001000</td>
</tr>
<tr>
<td>0x000010</td>
<td>1010111110100000000000000000001100</td>
</tr>
<tr>
<td>0x000014</td>
<td>1010111110100000000000000000001110</td>
</tr>
<tr>
<td>0x000018</td>
<td>1000111110101110000000000000001110</td>
</tr>
<tr>
<td>0x00001c</td>
<td>1000111110111000000000000000001100</td>
</tr>
<tr>
<td>0x000020</td>
<td>0000000111000111000000000000011001</td>
</tr>
<tr>
<td>0x000024</td>
<td>0010010111001000000000000000000001</td>
</tr>
<tr>
<td>0x000028</td>
<td>0010010010000000000000000000000101</td>
</tr>
<tr>
<td>0x00002c</td>
<td>1010111110101000000000000000001110</td>
</tr>
<tr>
<td>0x000030</td>
<td>0000000000000000000000000000011100</td>
</tr>
<tr>
<td>0x000034</td>
<td>0000000011000001111110000000001000</td>
</tr>
<tr>
<td>0x000038</td>
<td>0001010000100001111111111111111111</td>
</tr>
<tr>
<td>0x00003c</td>
<td>1010111111011100100000000000001100</td>
</tr>
<tr>
<td>0x000040</td>
<td>0011100000001000000000000000000000</td>
</tr>
<tr>
<td>0x000044</td>
<td>1000111110100101000000000000000000</td>
</tr>
<tr>
<td>0x000048</td>
<td>000011000000100000000000000001110110</td>
</tr>
<tr>
<td>0x00004c</td>
<td>0010010000000000000000000000000000</td>
</tr>
<tr>
<td>0x000050</td>
<td>1000111110111111100000000000001010</td>
</tr>
<tr>
<td>0x000054</td>
<td>0010011110111010000000000000010000</td>
</tr>
<tr>
<td>0x000058</td>
<td>0000001111100000000000000000010000</td>
</tr>
<tr>
<td>0x00005c</td>
<td>0000000000000000000000000000010001</td>
</tr>
</tbody>
</table>
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 preceding example was a much simplified version of how ELF and other standard formats work, meant only to demonstrate the basic principles.
Integer Multiplication (1/3)

- Paper and pencil example (unsigned):

  Multiplicand  1000  8
  Multiplier    $\times$1001  9

  1000
  0000
  0000
  0000

  +1000

  01001000

- $m$ bits $\times$ $n$ 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 regs:
    - 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
Example:

- in C: \[ a = b \times c; \]

- 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)

\[
\begin{align*}
\text{mult } & \$s2,\$s3 & \# b\times c \\
\text{mfhi } & \$s0 & \# \text{upper half of} \\
\text{mflo } & \$s1 & \# \text{product into } \$s1
\end{align*}
\]

- Note: Often, we only care about the lower half of the product.
Integer Division (1/2)

- Paper and pencil example (unsigned):

\[
\begin{array}{c|c|c}
\text{Divisor} & \overline{1001} & \text{Quotient} \\
1000 & 1001010 & \text{Dividend} \\
-1000 & & \\
101011010 & & \\
-1000 & & \\
10 & & \text{Remainder} \\
101 & & \text{(or Modulo result)} \\
1010 & & \\
-1000 & & \\
10 & & \\
\end{array}
\]

- Dividend = Quotient x Divisor + Remainder
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:

```c
a = c / d;  // quotient
b = c % d;  // remainder
```

In MIPS:

```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
```
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:

<table>
<thead>
<tr>
<th>BYTE3</th>
<th>BYTE2</th>
<th>BYTE1</th>
<th>BYTE0</th>
</tr>
</thead>
<tbody>
<tr>
<td>00000000</td>
<td>00000000</td>
<td>00000100</td>
<td>00000001</td>
</tr>
</tbody>
</table>

### Big Endian

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

### Little Endian

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

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