COMPUTER ORGANIZATION AND DESIGN
The Hardware/Software Interface

EECS 2021

Computer Organization
Fall 2015

Based on slides by the author and prof. Mary Jane Irwin of PSU.

Chapter Summary

- Stored-program concept
- Assembly language
- Number representation
- Instruction representation
- Supporting procedures in hardware
- MIPS addressing
- Some real-world stuff
- Fallacies and Pitfalls

Chapter 2 — Instructions: Language of the Computer — 2

Stored-Program Concept

- Program instructions are stored in the memory.
- Every cycle, an instruction is read from the memory (fetched).
- The instruction is examined to decide what to do (decode)
- Then we perform the operation stated in the instruction (execute)
- Fetch-Decode-Execute cycle.

Chapter 2 — Instructions: Language of the Computer — 5

Instruction Set

§2.1 Introduction

- The repertoire of instructions of a computer
- Different computers have different instruction sets
  - But with many aspects in common
- Early computers had very simple instruction sets
  - Simplified implementation
- Many modern computers also have simple instruction sets RISC vs. CISC

Chapter 2 — Instructions: Language of the Computer — 6

The MIPS Instruction Set

- Used as the example throughout the book
- Stanford MIPS commercialized by MIPS Technologies (www.mips.com)
- Large share of embedded core market
  - Applications in consumer electronics, network/storage equipment, cameras, printers, …
- Typical of many modern ISAs
  - See MIPS Reference Data tear-out card, and Appendixes B and E

Chapter 2 — Instructions: Language of the Computer — 7

The Four Design Principles

1. Simplicity favors regularity.
2. Smaller is faster.
3. Make the common case fast.
4. Good design demands good compromises

Chapter 2 — Instructions: Language of the Computer — 8

Arithmetic Operations

§2.2 Operations of the Computer Hardware

- Add and subtract, three operands
  - Two sources and one destination

```
add a, b, c  # a gets b + c
```

- All arithmetic operations have this form
- ***Design Principle 1:* Simplicity favors regularity**
  - Regularity makes implementation simpler
  - Simplicity enables higher performance at lower cost

Chapter 2 — Instructions: Language of the Computer — 9

Arithmetic Example

- C code:

```
f = (g + h) - (i + j);
```

- Compiled MIPS code: (almost, this is not really assembly)

```
add t0, g, h   # temp t0 = g + h
add t1, i, j   # temp t1 = i + j
sub f, t0, t1  # f = t0 - t1
```

Chapter 2 — Instructions: Language of the Computer — 10

Register Operands

§2.3 Operands of the Computer Hardware

- Arithmetic instructions use **register operands**
- MIPS has a 32 32-bit register file
  - Use for frequently accessed data
  - Numbered 0 to 31
  - 32-bit data called a "word"
- Assembler names
  - \$t0, \$t1, …, \$t9 for temporary values
  - \$s0, \$s1, …, \$s7 for saved variables
- ***Design Principle 2:* Smaller is faster**
  - c.f. main memory: millions of locations

Chapter 2 — Instructions: Language of the Computer — 11

Register name	Number	Usage
$zero	0	constant 0
$at	1	reserved for assembler
$v0	2	expression evaluation and results of a function
$v1	3	expression evaluation and results of a function
$a0	4	argument 1
$a1	5	argument 2
$a2	6	argument 3
$a3	7	argument 4
$t0	8	temporary (not preserved across call)
$t1	9	temporary (not preserved across call)
$t2	10	temporary (not preserved across call)
$t3	11	temporary (not preserved across call)
$t4	12	temporary (not preserved across call)
$t5	13	temporary (not preserved across call)
$t6	14	temporary (not preserved across call)
$t7	15	temporary (not preserved across call)
$s0	16	saved temporary (preserved across call)
$s1	17	saved temporary (preserved across call)
$s2	18	saved temporary (preserved across call)
$s3	19	saved temporary (preserved across call)
$s4	20	saved temporary (preserved across call)
$s5	21	saved temporary (preserved across call)
$s6	22	saved temporary (preserved across call)
$s7	23	saved temporary (preserved across call)
$t8	24	temporary (not preserved across call)
$t9	25	temporary (not preserved across call)
$k0	26	reserved for OS kernel
$k1	27	reserved for OS kernel
$gp	28	pointer to global area
$sp	29	stack pointer
$fp	30	frame pointer
$ra	31	return address (used by function call)

Register Operand Example

- C code:

```
f = (g + h) - (i + j);
```

  - f, …, j in $s0, …, $s4
- Compiled MIPS code: (This is a real assembly)

```
add $t0, $s1, $s2
add $t1, $s3, $s4
sub $s0, $t0, $t1
```


Memory Operands

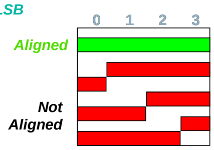
- Main memory used for composite data
  - Arrays, structures, dynamic data
- To apply arithmetic operations
  - Load values from memory into registers
  - Store result from register to memory
- Memory is byte addressed
  - Each address identifies an 8-bit byte
- Words are aligned in memory
  - Address must be a multiple of 4
- MIPS is Big Endian **(The commercial MIPS, not really, but in this course)**
  - Most-significant byte at least address of a word
  - *c.f.* Little Endian: least-significant byte at least address

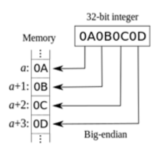
Memory Access

Another way to put it
Big Endian: leftmost byte is word address
Little Endian: rightmost byte is word address

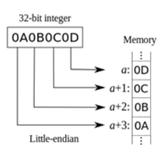
little endian	*LSB*			*MSB*
Bytes address	0	1	2	3
big endian	*MSB*			*LSB*

Alignment restriction: requires that objects fall on address that is multiple of their size





Big-Endian



Little-Endian

Loading and Storing Bytes

- MIPS provides special instructions to move bytes

```
lb    $t0, 1($s3)  #load byte from memory
sb    $t0, 6($s3)  #store byte to  memory
```

- What 8 bits get loaded and stored?
  - load byte places the byte from memory in the rightmost 8 bits of the destination register
    - what happens to the other bits in the register?
  - store byte takes the byte from the rightmost 8 bits of a register and writes it to the byte in memory
    - leaving the other bytes in the memory word unchanged

Example

- Given the following code sequence and memory state what is the state of the memory after executing the code?

```
add  $s3, $zero, $zero
lb   $t0, 1($s3)
sb   $t0, 6($s3)
```

Memory

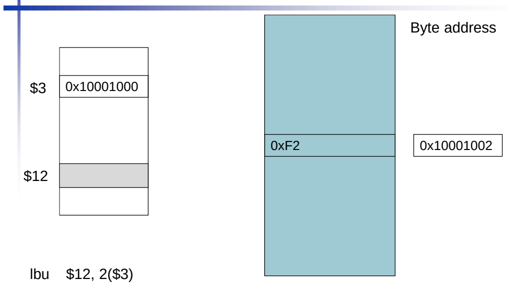
24	0x 0 0 0 0 0 0 0 0	24
20	0x 0 0 0 0 0 0 0 0	20
16	0x 0 0 0 0 0 0 0 0	16
12	0x 1 0 0 0 0 0 1 0	12
8	0x 0 1 0 0 0 4 0 2	8
4	0x F F F F F F F F	4
0	0x 0 0 9 0 1 2 A 0	0

Data

- What value is left in $t0?
  - $t0 = 0x00000090
- What word is changed in Memory and to what?
  - mem(4) = 0xFFFF90FF
- What if the machine was little Endian?
  - $t0 = 0x00000012
  - mem(4) = 0xFF12FFFF

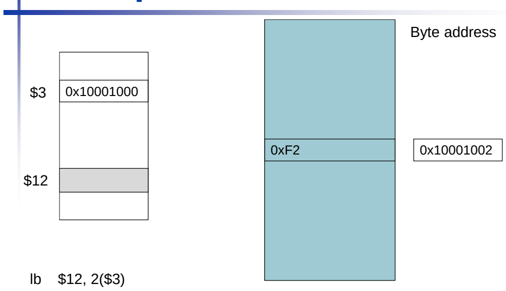
Chapter 2 — Instructions: Language of the Computer — 18

Example



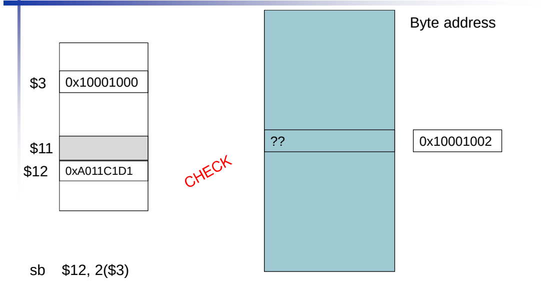
Chapter 2 — Instructions: Language of the Computer — 19

Example



Chapter 2 — Instructions: Language of the Computer — 20

Example



Chapter 2 — Instructions: Language of the Computer — 21

Byte/Halfword Operations

- Could use bitwise operations
- MIPS byte/halfword load/store
  - String processing is a common case

```
lb rt, offset(rs)      lh rt, offset(rs)
```

  - Sign extend to 32 bits in rt

```
lbu rt, offset(rs)     lhu rt, offset(rs)
```

  - Zero extend to 32 bits in rt

```
sb rt, offset(rs)      sh rt, offset(rs)
```

  - Store just rightmost byte/halfword

Chapter 2 — Instructions: Language of the Computer — 22

Memory Operand Example 1

- C code:

  `g = h + A[8];`

  - g in $s1, h in $s2, base address of A in $s3
- Compiled MIPS code:
  - Index 8 requires offset of 32
    - 4 bytes per word

```
lw  $t0, 32($s3)    # load word
add $s1, $s2, $t0
```

offset (points to 32) · base register (points to $s3)

Chapter 2 — Instructions: Language of the Computer — 23

Memory Operand Example 2

- C code:

```
A[12] = h + A[8];
```

  - h in $s2, base address of A in $s3
- Compiled MIPS code:
  - Index 8 requires offset of 32

```
lw  $t0, 32($s3)    # load word
add $t0, $s2, $t0
sw  $t0, 48($s3)    # store word
```


Registers vs. Memory

- Registers are faster to access than memory
- Operating on memory data requires loads and stores
  - More instructions to be executed
- Compiler must use registers for variables as much as possible
  - Only spill to memory for less frequently used variables
  - Register optimization is important!

Immediate Operands

- Constant data specified in an instruction

```
addi $s3, $s3, 4
```

- No subtract immediate instruction
  - Just use a negative constant

```
addi $s2, $s1, -1
```

- ***Design Principle 3:* Make the common case fast**
  - Small constants are common
  - Immediate operand avoids a load instruction

The Constant Zero

- MIPS register 0 ($zero) is the constant 0
  - Cannot be overwritten
- Useful for common operations
  - E.g., move between registers

```
add $t2, $s1, $zero
```