CS2100 COMPUTER ORGANISATION

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Lecture #8

MIPS

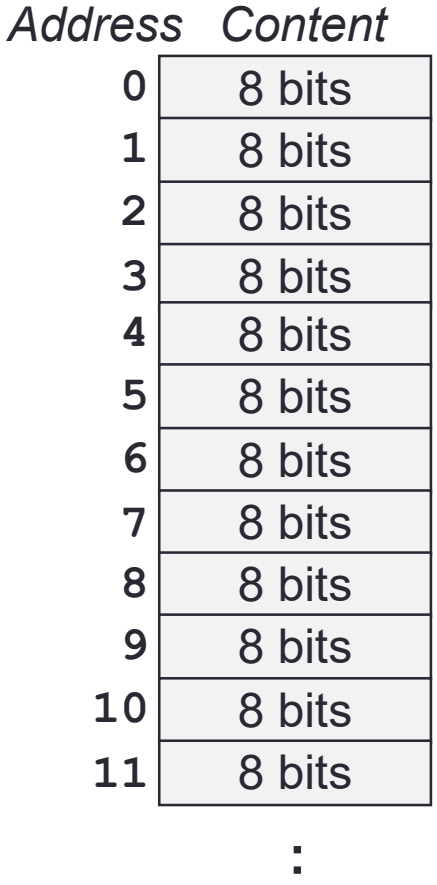
Part II: More Instructions

Lecture #8: MIPS Part 2: More Instructions

Lecture #8: MIPS Part 2: More Instructions

1. Memory Organisation (General)

- The main memory can be viewed as a large, single-dimension array of memory locations.
- Each location of the memory has an **address**, which is an index into the array.
  - Given a *k*-bit address, the address space is of size 2^k.
- The memory map on the right contains one byte (8 bits) in every location/address.
  - This is called byte addressing



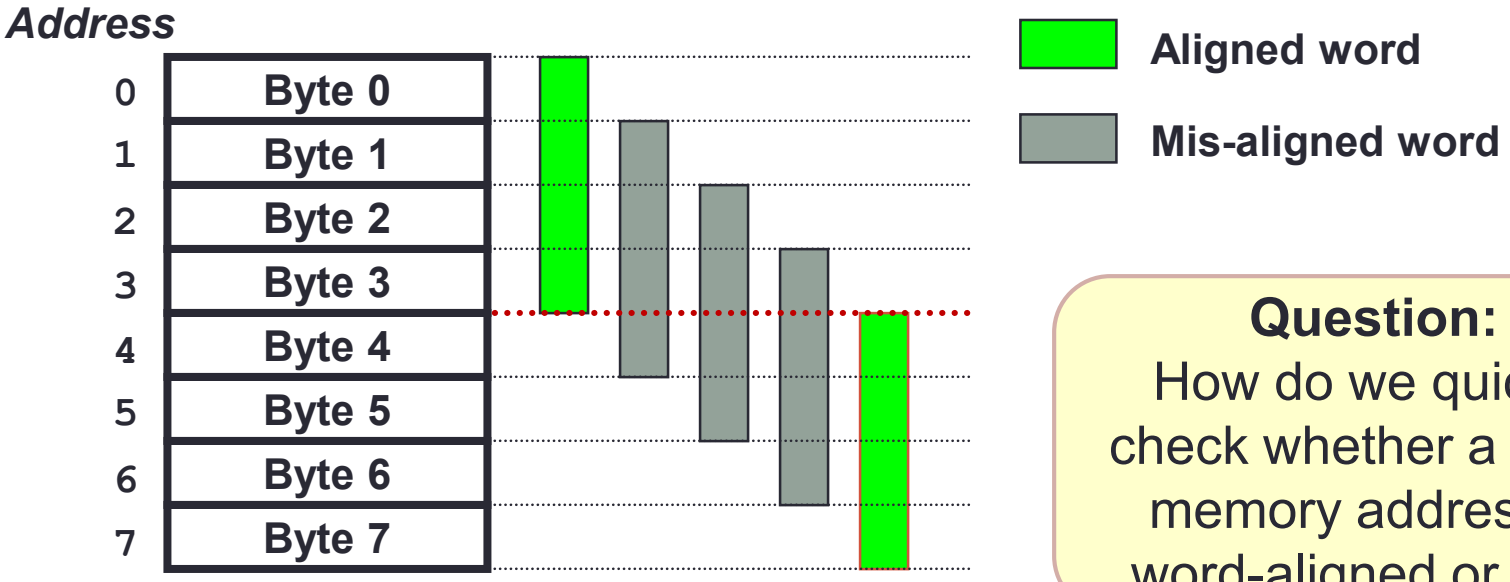
1.1 Memory: Transfer Unit

- Using distinct memory address, we can access:
  - a single **byte** (**byte addressable**) or
  - a single **word** (**word addressable**)
- **Word** is:
  - Usually $\mathbf{2^n}$ bytes
  - The common unit of transfer between processor and memory
  - Also commonly coincide with the register size, the integer size and instruction size in most architectures

1.2 Memory: Word Alignment

- **Word alignment**:
  - Words are aligned in memory if they begin at a byte address that is a multiple of the number of bytes in a word.

Example: If a word consists of 4 bytes, then:



Question:
How do we quickly check whether a given memory address is word-aligned or not?

2. MIPS Memory Instructions

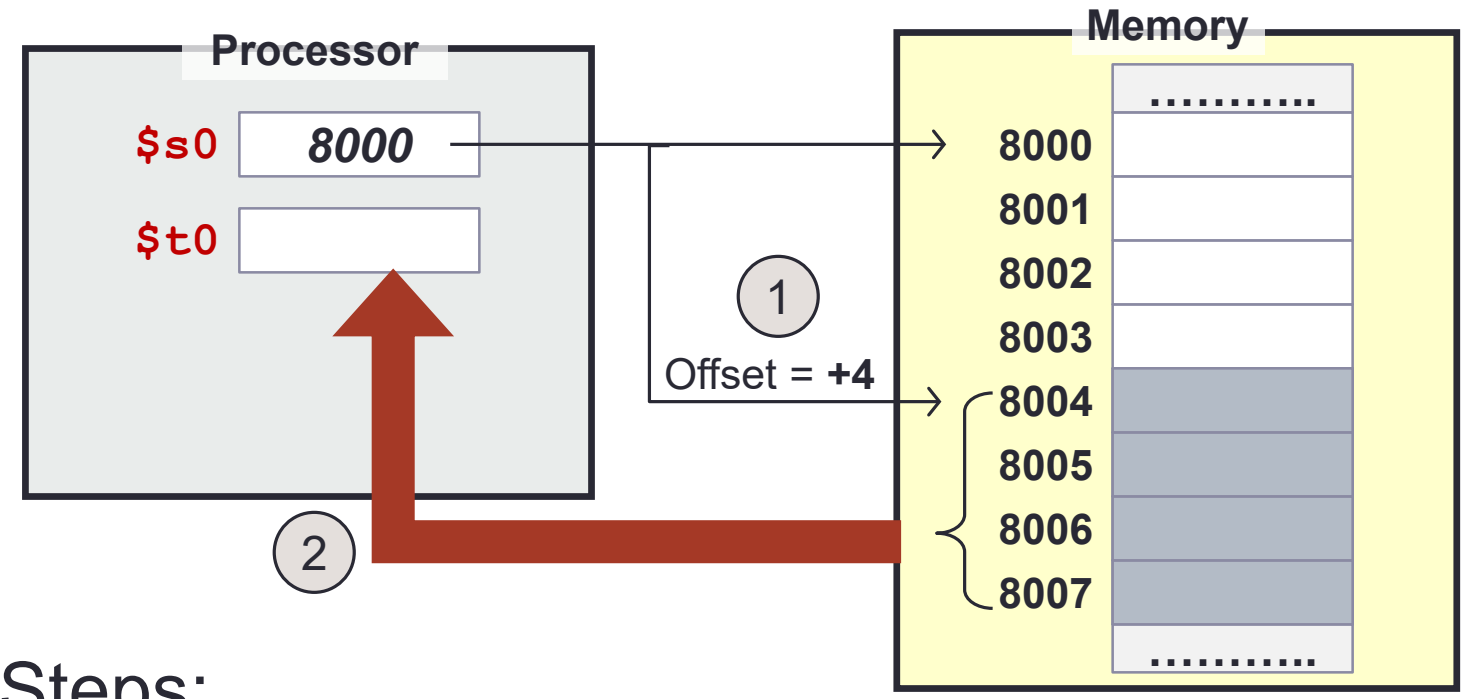
- MIPS is a load-store register architecture
  - 32 registers, each 32-bit (4 bytes) long
  - Each word contains 32 bits (4 bytes)
  - Memory addresses are 32-bit long Why?

Answer: So that they fit into registers

Name	Examples	Comments
32 registers	$s0-$s7, $t0-$t9, $zero, $a0-$a3, $v0-$v1, $gp, $fp, $sp, $ra, $at	Fast processor storage for data. In MIPS, data must be in registers to perform arithmetic.
2^{30} memory words	**Mem[0],** **Mem[4],** …, **Mem[4294967292]**	Accessed only by data transfer instructions. MIPS uses **byte addresses**, so consecutive words differ by 4. Memory holds data structures, such as arrays, and spilled registers, such as those saved on procedure calls.

2.1 Memory Instruction: **Load Word**

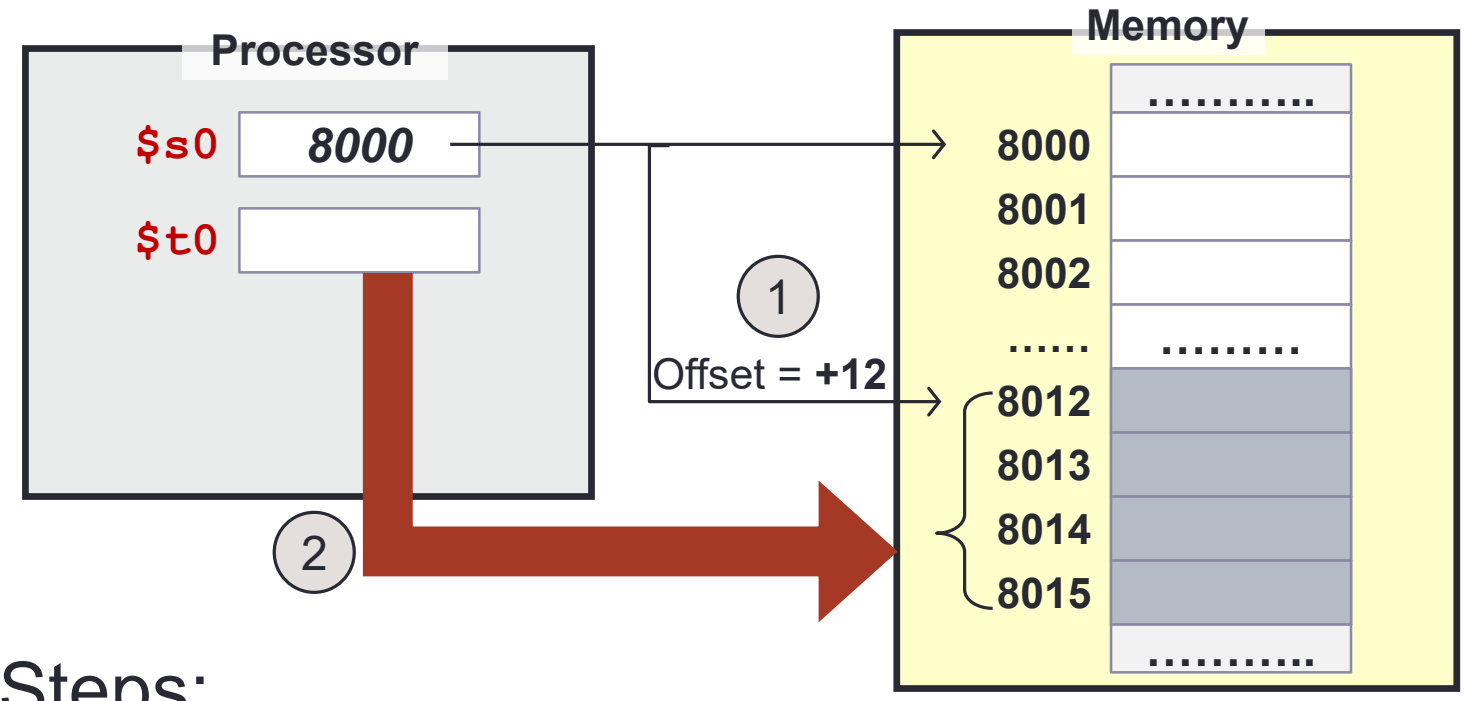
- Example: `lw $t0, 4($s0)`



- Steps:
  1. Memory Address = `$s0` + 4 = 8000 + 4 = **8004**
  2. Memory word at `Mem[8004]` is loaded into `$t0`

2.2 Memory Instruction: **Store Word**

- Example: `sw $t0, 12($s0)`



- Steps:
  1. Memory Address = `$s0` + 12 = 8000 + 12 = **8012**
  2. Content of `$t0` is stored into word at **`Mem[8012]`**

2.3 **Load** and **Store** Instructions

- Only **`load`** and **`store`** instructions can access data in memory.
- Example: Each array element occupies a word.

C Code	MIPS Code

`A[7] = h + A[10];`	`lw $t0, 40($s3)`
	`add $t0, $s2, $t0`
	`sw $t0, 28($s3)`

  - Each array element occupies a word (4 bytes).
  - **`$s3`** contains the **base address** (address of first element, A[0]) of array A. Variable **`h`** is mapped to **`$s2`** .
- Remember arithmetic operands (for **`add`**) are registers, not memory!

2.4 Memory Instructions: Others (1/2)

- Other than load word (**`lw`**) and store word (**`sw`**), there are other variants, example:
  - load byte (**`lb`**)
  - store byte (**`sb`**)
- Similar in format:

```
lb   $t1, 12($s3)
sb   $t2, 13($s3)
```

- Similar in working except that one byte, instead of one word, is loaded or stored
  - Note that the offset no longer needs to be a multiple of 4

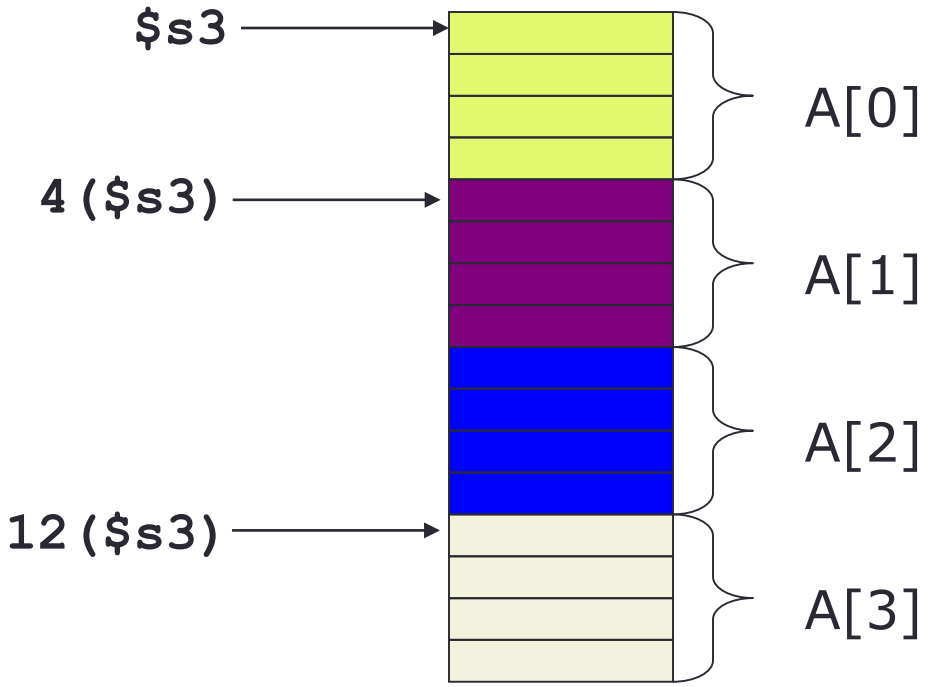
2.4 Memory Instructions: Others (2/2)

- MIPS disallows loading/storing unaligned word using **`lw`**/**`sw`**:
  - Pseudo-Instructions ***unaligned load word*** (**`ulw`**) and ***unaligned store word*** (**`usw`**) are provided for this purpose
- Other memory instructions:
  - **`lh`** and **`sh`**: load halfword and store halfword
  - **`lwl`**, **`lwr`**, **`swl`**, **`swr`**: load word left / right, store word left / right.
  - etc…

2.5 Example: Array (assume 4 bytes per element)

C Statement to translate	Variables Mapping
`A[3] = h + A[1];`	`h` ➔ `$s2` base of `A[]` ➔ `$s3`

```
lw   $t0, 4($s3)
add  $t0, $s2, $t0
sw   $t0, 12($s3)
```



2.6 Common Questions: **Address** vs **Value**

Key concept:

Registers do NOT have types

- A register can hold any 32-bit number:
  - The number has no implicit data type and is interpreted according to the instruction that uses it
- Examples:
  - `add $t2, $t1, $t0`
    - ➔ `$t0` and `$t1` should contain data values
  - `lw $t2, 0($t0)`
    - ➔ `$t0` should contain a memory address

2.6 Common Questions: **Byte** vs **Word**

Important:

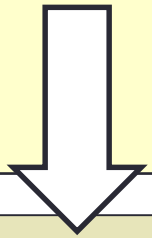
Consecutive word addresses in machines with byte-addressing do not differ by 1

- Common error:
  - Assume that the address of the next word can be found by incrementing the address in a register by 1 instead of by the word size in bytes
- For both `lw` and `sw`:
  - The sum of base address and offset must be a multiple of 4 (i.e. to adhere to word boundary)

2.7 Example: Swapping Elements

C Statement to translate	Variables Mapping

`swap( int v[], int k )`
`{`
`  int temp;`
`  temp = v[k]`
`  v[k] = v[k+1];`
`  v[k+1] = temp;`
`}`
	`k` ➔ `$5`
	Base address of `v[]` ➔ `$4`
	`temp` ➔ `$15`



```
swap:
    sll   $2, $5, 2
    add   $2, $4, $2
    lw    $15, 0($2)
    lw    $16, 4($2)
    sw    $16, 0($2)
    sw    $15, 4($2)
```

Example: k = 3; to swap v[3] with v[4].
Assume base address of v is 2000.

`$5` (k) ← 3
`$4` (base addr. of v) ← 2000

`$2` ← 12
`$2` ← 2012

`$15` ← content of mem. addr. 2012 (v[3])
`$16` ← content of mem. addr. 2016 (v[4])

content of mem. addr. 2012 (v[3]) ← `$16`
content of mem. addr. 2016 (v[4]) ← `$15`

Note: This is simplified and may not be a direct translation of the C code.

Reading

- Instructions: Language of the Computer
  - Read up COD Chapter 2, pages 52-57. (3rd edition)
  - Read up COD Section 2.3 (4th edition)

3. Making Decisions (1/2)

- We cover only sequential execution so far:
  - Instruction is executed in program order
- To perform general computing tasks, we need to:
  - Make decisions
  - Perform iterations (in later section)
- Decisions making in high-level language:
  - `if` and `goto` statements
  - MIPS decision making instructions are similar to `if` statement with a `goto`
    - `goto` is discouraged in high-level languages but necessary in assembly ☺

3. Making Decisions (2/2)

- Decision-making instructions
  - Alter the control flow of the program
  - Change the next instruction to be executed
- Two types of decision-making statements in MIPS
  - **Conditional** (branch)

```
bne $t0, $t1, label
beq $t0, $t1, label
```

  - **Unconditional** (jump)

```
j label
```

- A label is an "anchor" in the assembly code to indicate point of interest, usually as branch target
  - Labels are NOT instructions!

3.1 Conditional Branch: **beq** and **bne**

- Processor follows the branch only when the condition is satisfied (true)
- **`beq $r1, $r2, L1`**
  - Go to statement labeled **`L1`** if the value in register **`$r1`** equals the value in register **`$r2`**
  - **`beq`** is "**branch if equal**"
  - C code: **`if (a == b) goto L1`**
- **`bne $r1, $r2, L1`**
  - Go to statement labeled **`L1`** if the value in register **`$r1`** does not equal the value in register **`$r2`**
  - **`bne`** is "**branch if not equal**"
  - C code: **`if (a != b) goto L1`**

3.2 Unconditional Jump: **j**

- Processor **always** follows the branch
- `j L1`
  - Jump to label `L1` unconditionally
  - C code: `goto L1`
- Technically equivalent to such statement

```
beq $s0, $s0, L1
```

3.3 IF statement (1/2)

C Statement to translate	Variables Mapping

`if (i == j)`
`  f = g + h;`
	`f → $s0`
	`g → $s1`
	`h → $s2`
	`i → $s3`
	`j → $s4`

```
        beq $s3, $s4, L1
        j   Exit
L1:     add $s0, $s1, $s2
Exit:
```

```
        bne $s3, $s4, Exit
        add $s0, $s1, $s2
Exit:
```

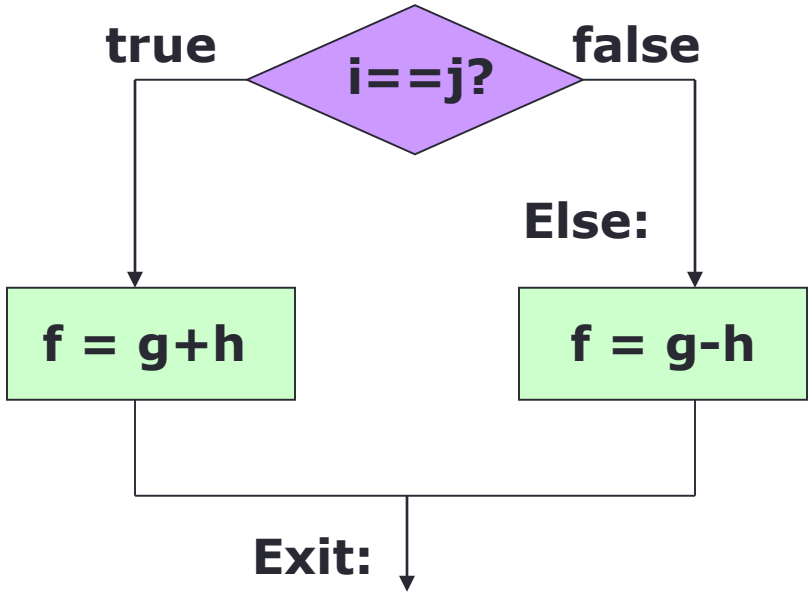
- Two equivalent translations:
  - The one on the right is more efficient
- Common technique: Invert the condition for shorter code

3.3 IF statement (2/2)

C Statement to translate	Variables Mapping

`if (i == j)`
`  f = g + h;`
`else`
`  f = g - h;`
	f → $s0
	g → $s1
	h → $s2
	i → $s3
	j → $s4

```
      bne $s3, $s4, Else
      add $s0, $s1, $s2
      j   Exit
Else: sub $s0, $s1, $s2
Exit:
```



- Question: Rewrite with **beq**?

3.4 Exercise #1: IF statement

MIPS code to translate into C	Variables Mapping

`beq $s1, $s2, Exit`
`add $s0, $zero, $zero`
`Exit:`
	`f` → `$s0`
	`i` → `$s1`
	`j` → `$s2`

- What is the corresponding high-level statement?

```
if (i != j) {
   f = 0;
}
```

4. Loops (1/2)

- C while-loop:

```
while (j == k)
    i = i + 1;
```

- Rewritten with goto

```
Loop:  if (j != k)
          goto Exit;
       i = i+1;
       goto Loop;

Exit:
```

Key concept:

Any form of loop can be written in assembly with the help of conditional branches and jumps.

4. Loops (2/2)

C Statement to translate	Variables Mapping
Loop: if (j != k) goto Exit; i = i+1; goto Loop; Exit:	i ➔ $s3 j ➔ $s4 k ➔ $s5

- What is the corresponding MIPS code?

```
Loop: bne  $s4, $s5, Exit   # if (j!= k) Exit
      addi $s3, $s3, 1
      j    Loop             # repeat loop
Exit:
```

4.1 Exercise #2: FOR loop

- Write the following loop statement in MIPS

C Statement to translate	Variables Mapping
`for ( i=0; i<10; i++)` `  a = a + 5;`	`i` → `$s0` `a` → `$s2`

```
        add  $s0, $zero, $zero
        addi $s1, $zero, 10
Loop:   beq  $s0, $s1, Exit
        addi $s2, $s2, 5
        addi $s0, $s0, 1
        j    Loop
Exit:
```

4.2 Inequalities (1/2)

- We have **`beq`** and **`bne`**, what about branch-if-less-than?
  - There is no real **`blt`** instruction in MIPS
- Use **`slt`** (set on less than) or **`slti`**.

```
slt $t0, $s1, $s2
```

=

```
if ($s1 < $s2)
     $t0 = 1;
else
     $t0 = 0;
```

4.2 Inequalities (2/2)

- To build a "`blt $s1, $s2, L`" instruction:

```
slt $t0, $s1, $s2
bne $t0, $zero, L
```

==

```
if ($s1 < $s2)
    goto L;
```

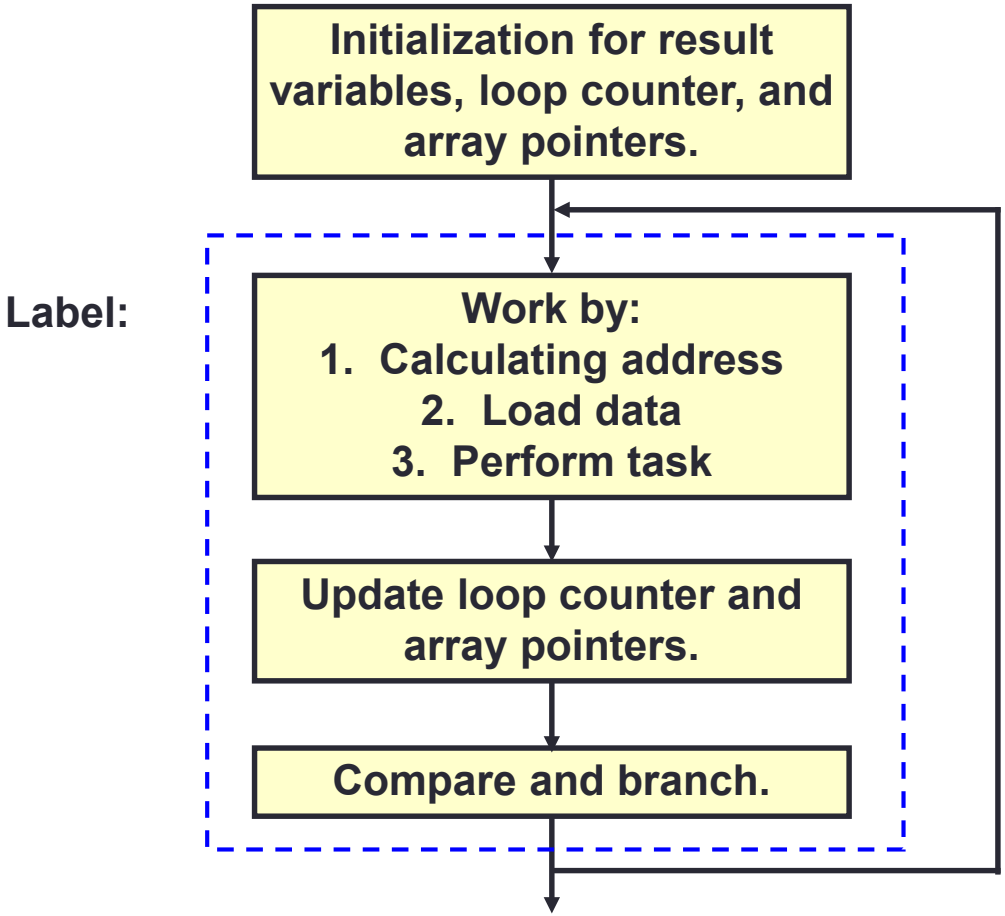
- This is another example of **pseudo-instruction**:
  - Assembler translates (`blt`) instruction in an assembly program into the equivalent MIPS (two) instructions

Reading

- Instructions: Language of the Computer
  - Section 2.6 Instructions for Making Decisions. (3rd edition)
  - Section 2.7 Instructions for Making Decisions. (4th edition)

5. Array and Loop

- Typical example of accessing array elements in a loop:



5. Array and Loop: Question

Count the number of zeros in an Array **A**

- **A** is word array with 40 elements
- Address of A[] ➔ **`$t0`**, Result ➔ **`$t8`**

Simple C Code

```
result = 0;

i = 0;

while ( i < 40 ) {
    if ( A[i] == 0 )
        result++;
    i++;

}
```

- Think about:
  - How to perform the right comparison
  - How to translate A[i] correctly

5. Array and Loop: Version 1.0

Address of A[] ➔ $t0 Result ➔ $t8 i ➔ $t1	Comments
`addi $t8, $zero, 0`	
`addi $t1, $zero, 0`	
`addi $t2, $zero, 40`	`# end point`
`loop: bge $t1, $t2, end`	
`sll $t3, $t1, 2`	`# i * 4`
`add $t4, $t0, $t3`	`# &A[i]`
`lw $t5, 0($t4)`	`# $t3 ← A[i]`
`bne $t5, $zero, skip`	
`addi $t8, $t8, 1`	`# result++`
`skip: addi $t1, $t1, 1`	`# i++`
`j loop`	
`end:`	

5. Array and Loop: Version 2.0

Address of A[] ➔ $t0 Result ➔ $t8 &A[i] ➔ $t1	Comments
addi $t8, $zero, 0	
addi $t1, $t0, 0	# addr of current item
addi $t2, $t0, 160	# &A[40]
loop: bge $t1, $t2, end	# comparing address!
lw $t3, 0($t1)	# $t3 ← A[i]
bne $t3, $zero, skip	
addi $t8, $t8, 1	# result++
skip: addi $t1, $t1, 4	# move to next item
j loop	
end:	

- Use of “pointers” can produce more efficient code!

6.1 Exercise #3: Simple Loop

- Given the following MIPS code:

```
        addi $t1, $zero, 10
        add  $t1, $t1, $t1
        addi $t2, $zero, 10
Loop:   addi $t2, $t2, 10
        addi $t1, $t1, -1
        beq  $t1, $zero, Loop
```

i. How many instructions are executed? **Answer: (a)**

(a) 6 (b) 30 (c) 33 (d) 36 (e) None of the above

ii. What is the final value in `$t2`? **Answer: (b)**

(a) 10 (b) 20 (c) 300 (d) 310 (e) None of the above

6.2 Exercise #4: Simple Loop II

- Given the following MIPS code:

```
        add  $t0, $zero, $zero
        add  $t1, $t0, $t0
        addi $t2, $t1, 4
Again:  add  $t1, $t1, $t0
        addi $t0, $t0, 1
        bne  $t2, $t0, Again
```

i. How many instructions are executed? **Answer: (c)**

(a) 6 (b) 12 (c) 15 (d) 18 (e) None of the above

ii. What is the final value in `$t1`? **Answer: (c)**

(a) 0 (b) 4 (c) 6 (d) 10 (e) None of the above

6.3 Exercise #5: Simple Loop III (1/2)

- Given the following MIPS code accessing a word array of elements in memory with the starting address in **`$t0`**.

```
        addi $t1, $t0, 10
        add  $t2, $zero, $zero
Loop:   ulw  $t3, 0($t1) # ulw: unaligned lw
        add  $t2, $t2, $t3
        addi $t1, $t1, -1
        bne  $t1, $t0, Loop
```

i. How many times is the **`bne`** instruction executed?

(a) 1 (b) 3 (c) 9 (d) 10 (e) 11 **Answer: (d)**

ii. How many times does the **`bne`** instruction actually branch to the label **`Loop`**?

(a) 1 (b) 8 (c) 9 (d) 10 (e) 11 **Answer: (c)**

6.3 Exercise #5: Simple Loop III (2/2)

- Given the following MIPS code accessing a word array of elements in memory with the starting address in **`$t0`**.

```
        addi $t1, $t0, 10
        add  $t2, $zero, $zero
Loop:   ulw  $t3, 0($t1) # ulw: unaligned lw
        add  $t2, $t2, $t3
        addi $t1, $t1, -1
        bne  $t1, $t0, Loop
```

iii. How many instructions are executed?

(a) 6 (b) 12 (c) 41 (d) 42 (e) 46 **Answer: (d)**

iv. How many unique bytes of data are read from the memory?

(a) 4 (b) 10 (c) 11 (d) 13 (e) 40 **Answer: (d)**

Summary: Focus of CS2100

- Basic MIPS programming
  - Arithmetic: among registers only
  - Handling of large constants
  - Memory accesses: load/store
  - Control flow: branch and jump
  - Accessing array elements
  - System calls (covered in labs)
- Things we are not going to cover
  - Support for procedures
  - Linkers, loaders, memory layout
  - Stacks, frames, recursion
  - Interrupts and exceptions

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