Assembly Language

Readings: 2.1-2.7, 2.9-2.10, 2.14
Green reference card, A.10

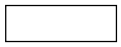
Assembly language
- Simple, regular instructions – building blocks of C, Java & other languages
- Typically one-to-one mapping to machine language

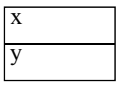
Our goal
- Understand the basics of assembly language
- Help figure out what the processor needs to be able to do

Not our goal to teach complete assembly/machine language programming
- Floating point
- Procedure calls
- Stacks & local variables

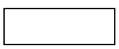
Aside: C/C++ Primer

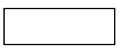
```
struct coord { int x, y; }; /* Declares a type                */
struct coord start;         /* Object with two slots, x and y  */
start.x = 1;                /* For objects "." accesses a slot */
struct coord *myLoc;        /* "*" is a pointer to objects     */
myLoc = &start;             /* "&" returns thing's location    */
myLoc->y = 2;               /* "->" is "*" plus "."            */
```

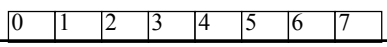





```
int scores[8];              /* 8 ints, from 0..7 */
scores[1]=5;                /* Access locations in array */
int *index = scores;        /* Points to scores[0] */
index++;                    /* Next scores location */
(*index)++;                 /* "*" works in arays as well */
index = &(scores[3]);       /* Points to scores[3] */
*index = 9;
```







MIPS Assembly Language

The basic instructions have four components:

- Operator name
- Destination
- 1st operand
- 2nd operand

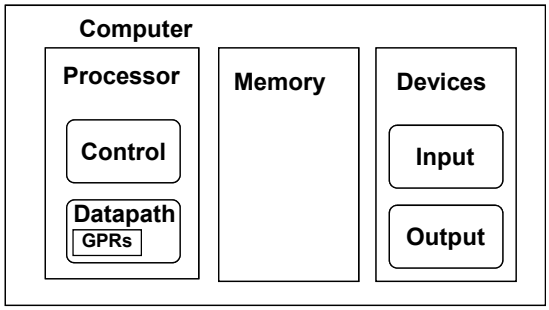
```
add <dst>, <src1>, <src2>     # <dst> = <src1> + <src2>
sub <dst>, <src1>, <src2>     # <dst> = <src1> - <src2>
```

Simple format: easy to implement in hardware

More complex: `A = B + C + D – E`

Operands & Storage

For speed, CPU has 32 general-purpose registers for storing most operands
For capacity, computer has large memory (4GB+)



Load/store operation moves information between registers and main memory
All other operations work on registers

Registers

32 registers for operands

Register	Name	Function	Comment
$0	$zero	Always 0	No-op on write
$1	$at	Reserved for assembler	Don't use it!
$2-3	$v0-v1	Function return	
$4-7	$a0-a3	Function call parameters	
$8-15	$t0-t7	Volatile temporaries	Not saved on call
$16-23	$s0-s7	Temporaries (saved across calls)	Saved on call
$24-25	$t8-t9	Volatile temporaries	Not saved on call
$26-27	$k0-k1	Reserved kernel/OS	Don't use them
$28	$gp	Pointer to global data area	
$29	$sp	Stack pointer	
$30	$fp	Frame pointer	
$31	$ra	Function return address	

Basic Operations

(Note: just subset of all instructions)

Mathematic: add, sub, mult, div
```
add $t0, $t1, $t2  # t0 = t1+t2
```
Unsigned (changes overflow condition)
```
addu $t0, $t1, $t2 # t0 = t1+t2
```
Immediate (one input a constant)
```
addi $t0, $t1, 100 # t0 = t1+100
```

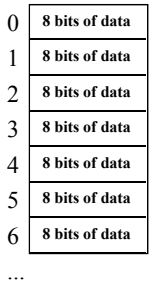
Logical: and, or, nor, xor
```
and $t0, $t1, $t2  # t0 = t1&t2
```
Immediate
```
andi $t0, $t1, 7   # t0 = t1&b0111
```

Shift: left & right logical, arithmetic
```
sllv $t0, $t1, $t2 # t0 = t1<<t2
```
Immediate
```
sll $t0, $t1, 6    # t0 = t1<<6
```

Example: Take bits 6-4 of $t0 and make them bits 2-0 of $t1, zeros otherwise:

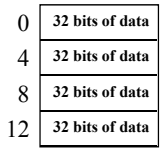
Memory Organization

Viewed as a large, single-dimension array, with an address.
A memory address is an index into the array
"Byte addressing" means that the index points to a byte of memory.



Memory Organization (cont.)

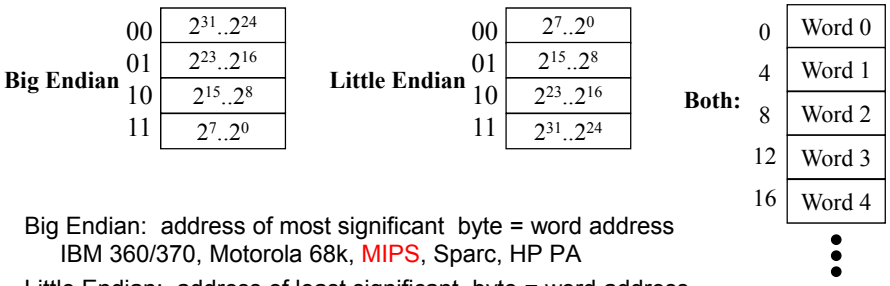
Bytes are nice, but most data items use larger "words"
For MIPS, a word is 32 bits or 4 bytes.



Registers hold 32 bits of data

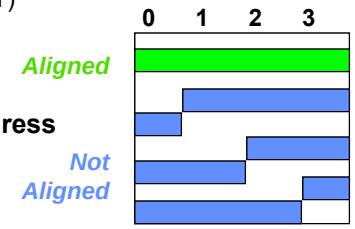
2^{32} bytes with byte addresses from 0 to 2^{32}-1
2^{30} words with byte addresses 0, 4, 8, ... 2^{32}-4
Words are aligned
i.e., what are the least 2 significant bits of a word address?

Addressing Objects: Endianess and Alignment



Big Endian: address of most significant byte = word address
IBM 360/370, Motorola 68k, MIPS, Sparc, HP PA

Little Endian: address of least significant byte = word address
Intel 80x86, DEC Vax, DEC Alpha (Windows NT)



Alignment: require that objects fall on address that is multiple of their size.

Data Storage

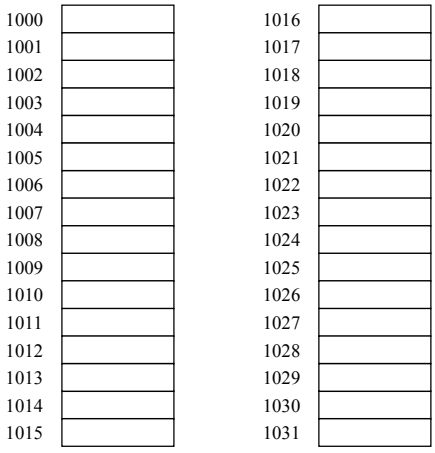
Characters: 8 bits (byte)

Integers: 32 bits (word)

Array: Sequence of locations

Pointer: Address

```
char a = 'G'; // ASCII 71
int x = 258;
char *b;
int *y;
b = new char[4];
y = new int[10];
```



(Note: real compilers place local variables (the "stack") from beginng of memory, new'ed structures (the "heap") from end. We ignore that here for simplicity)

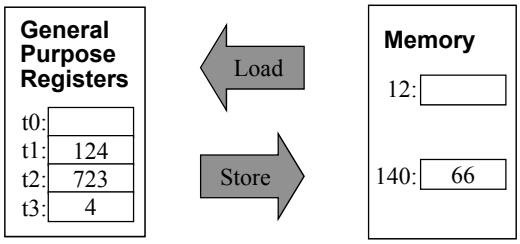
Loads & Stores

Loads & Stores move data between memory and registers

All operations on registers, but too small to hold all data

```
lw $t0, 16($t1)  # $t0 = Memory[$t1+16]

sw $t2, 8($t3)   # Memory[$t3+8] = $t2
```



Note: lbu & sb load & store bytes

Addressing Example

The address of the start of a character array is stored in $t0. Write assembly to load the following characters

$t1 = Array[0]

$t2 = Array[1]

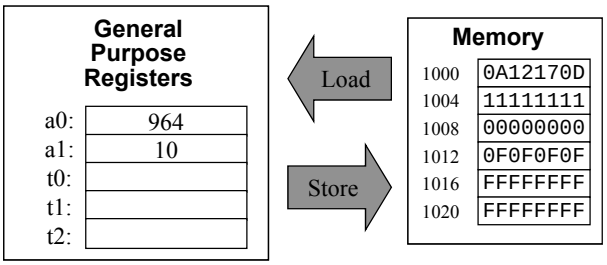
$t3 = Array[2]

$t4 = Array[k] // Assume the value of k is in $a0

Array Example

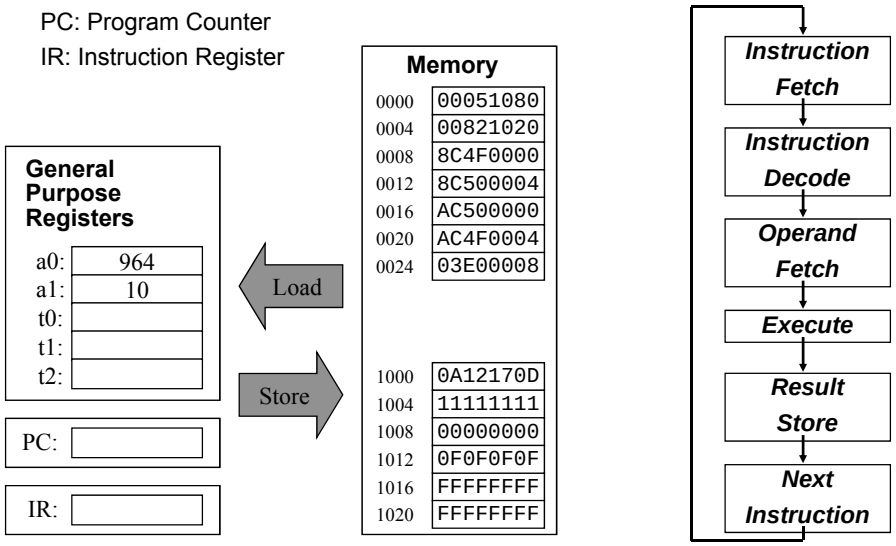
```
/* Swap the kth and (k+1)th element of an array */
swap(int v[], int k) {
      int temp = v[k];
      v[k] = v[k+1];
      v[k+1] = temp;
}

# Assume v in $a0, k in $a1
```



Execution Cycle Example

PC: Program Counter
IR: Instruction Register



Control Flow

Jumps – GOTO different next instruction

```
j BAR                # go to instruction labeled with "BAR" tag
jr $ra               # go to address in $ra: PC = value of $ra
```

Branches – GOTO different next instruction if condition is true

2 register: beq (==), bne (!=)

```
beq $t0, $t1, FOO        # if $t0 == $t1 GOTO FOO: PC = FOO
```

1 register: bgez (>=0), bgtz (>0), blez (<=0), bltz (<0)

```
bgez $t0, FOO    # if $t0 >= 0 GOTO FOO: PC = FOO
```

```
if (a == b)
   a = a + 3;
else
   b = b + 7;
c = a + b;
```

```
# $a0 = a, $a1 = b, $a2 = c
     bne   $a0, $a1, ELSEIF     # branch if a!=b
     addi  $a0, $a0, 3;         # a = a + 3
     j DONE;                    # avoid else
ELSEIF:
     addi  $a1, $a1, 7;         # b = b + 7
DONE:
     add   $a2, $a0, $a1;       # c = a + b
```


Loop Example

Compute the sum of the values 0…N-1

```
int sum = 0;
for (int I = 0; I != N; I++) {
        sum += I;
}
```

```
                        # $t0 = N, $t1 = sum, $t2 = I
```

Comparison Operators

For logic, want to set a register TRUE (1) / FALSE(0) based on condition

```
   slt $t0, $t1, $t2     # if ($t1 < $t2) $t0 = 1 else $t0 = 0;
```

```
if (a >= b)
    c = a + b;           # $t0 = a, $t1 = b, $t2 = c
a = a + c;
```


String toUpper

Convert a string to all upper case

```
    char *index = string;
    while (*index != 0) { /* C strings end in 0 */
        if (*index >= 'a' && *index <= 'z')
            *index = *index +('A' - 'a');
        index++;
    }
```

```
# $t0=index, $t2='a', $t3='z', $t4='A'-'a', Memory[100]=string
```

Machine Language vs. Assembly Language

Assembly Language
- mnemonics for easy reading
- labels instead of fixed addresses
- Easier for programmers
- Almost 1-to-1 with machine language

Machine language
- Completely numeric representation
- format CPU actually uses

```
SWAP:
    sll   $2, $5, 2                                  000000 00000 00101 00010 00010 000000
    add   $2, $4, $2     // Compute address of v[k]  000000 00100 00010 00010 00000 100000
    lw    $15, 0($2)     // get v[k]                 100011 00010 01111 00000 00000 000000
    lw    $16, 4($2)     // get v[k+1]               100011 00010 10000 00000 00000 000100
    sw    $16, 0($2)     // save new value to v[k]   101011 00010 10000 00000 00000 000000
    sw    $15, 4($2)     // save new value to v[k+1] 101011 00010 01111 00000 00000 000100
    jr    $31            // return from subroutine   000000 11111 00000 00000 00000 001000
```


Labels

Labels specify the address of the corresponding instruction
- Programmer doesn't have to count line numbers
- Insertion of instructions doesn't require changing entire code

```
# $t0 = N, $t1 = sum, $t2 = I
   add   $t1, $zero, $zero   # sum = 0
   add   $t2, $zero, $zero   # I = 0
TOP:
   bne   $t0, $t2, END       # I!=N
   add   $t1, $t1, $t2       # sum += I
   addi  $t2, $t2, 1         # I++
   j     TOP                 # next iteration
END:
```

Notes:
- Jumps are pseudo-absolute:
  - PC = { PC[31:28], 26-bit unsigned-Address, "00" }
- Branches are PC-relative:
  - PC = PC + 4 + 4*(16-bit signed Address)

Labels Example

Given the format for branches and jumps, compute the value of the labels in the code below.

Jumps: PC = { PC[31:28], LABEL_VAL, “00” }

Branches: PC = PC + 4 + 4*(LABEL_VAL)

```
# Program starts at address 100
        lw      $t0, 100($zero)
LOOP:
        lbu     $t5, 0($t0)
        beq     $t5, $zero, END
        slt     $t6, $t5, $t2
        bne     $t6, $zero, NEXT
        slt     $t6, $t3, $t5
        bne     $t6, $zero, NEXT
        add     $t5, $t5, $t4
        sb      $t5, 0($t0)
NEXT:
        addi    $t0, $t0, 1
        j       LOOP
END:
```


Instruction Types

Can group instructions by # of operands

3-register

2-register

1-register

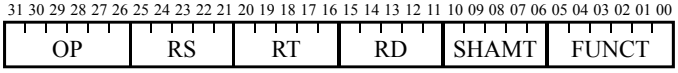
0-register

```
add   $t0, $t1, $t2      # t0 = t1+t2
addi  $t0, $t1, 100      # t0 = t1+100
and   $t0, $t1, $t2      # t0 = t1&t2
andi  $t0, $t1, 7        # t0 = t1&b0111
sllv  $t0, $t1, $t2      # t0 = t1<<t2
sll   $t0, $t1, 6        # t0 = t1<<6
lw    $t0, 12($t1)       # $t0 = Memory[$t1+10]
sw    $t2, 8($t3)        # Memory[$t3+10] = $t2
j     25                 # go to 100 - PC = 25*4 (instr are 32-bit)
jr    $ra                # go to address in $ra - PC = value of $ra
beq   $t0, $t1, FOO      # if $t0 == $t1 GOTO FOO - PC = FOO
bgez  $t0, FOO           # if $t0 >= 0 GOTO FOO - PC = FOO
slt   $t0, $t1, $t2      # if ($t1 < $t2) $t0 = 1 else $t0 = 0;
```

Instruction Formats

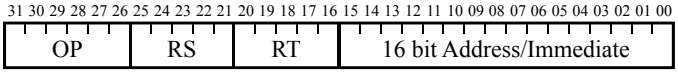
All instructions encoded in 32 bits (operation + operands/immediates)

Register (R-type) instructions



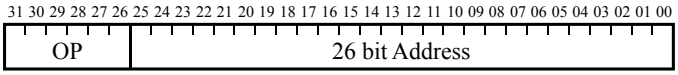
(OP = 0,16-20)

Immediate (I-type) instructions



(OP = any but 0,2,3,16-20)

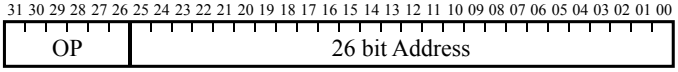
Jump (J-type) instructions



(OP = 2,3)

J-Type

Used for unconditional jumps



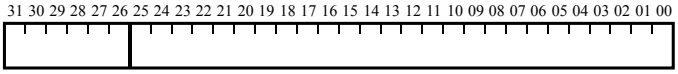
2: j (jump)

3: jal (jump and link)

Note: top 4 bits of jumped-to address come from current PC

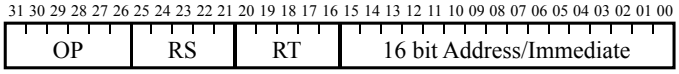
Example:

```
j    25      # go to 100, PC = 25*4 (instr are 32-bit)
```



I-Type

Used for operations with immediate (constant) operand

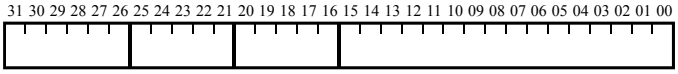


04: beq
05: bne
06: blez
07: bgtz
08: addi
09: addiu
10: slti
11: sltiu
12: andi
13: ori
14: xori
32: lb
35: lw
40: sb
43: sw

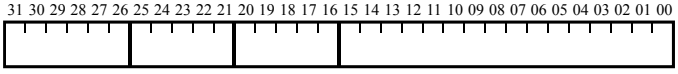
Op1, L/S addr

Op2, Dest, L/S targ

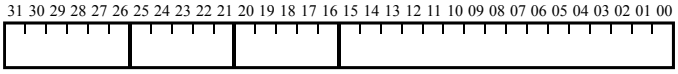
```
addi    $8, $9, 100      # $8 = $9+100
```




```
beq     $8, $9, -11      # if $8 == $9 GOTO (PC+4+FOO*4)
```

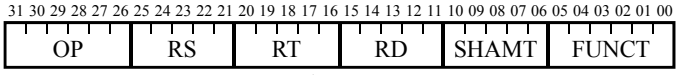



```
lw      $8, 12($9)       # $8 = Memory[$9+12]
```



R-Type

Used for 3 register ALU operations



00 (16-20 for FP)

Op1 (XX for const shift, SHAMT reg for var shift)

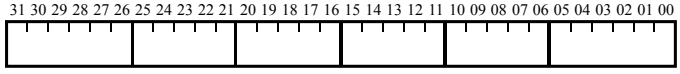
Op2/ Shifted val

Dest

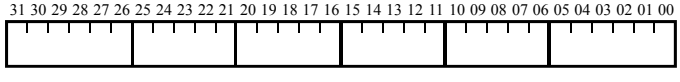
Shift amount (0 for non-shift, 0 for var shift)

00: sll
02: srl
03: sra
04: sllv
06: srlv
07: srav
08: jr
24: mult
26: div
32: add
33: addu
34: sub
35: subu
36: and
37: or
38: xor
39: nor
42: slt
43: sltu

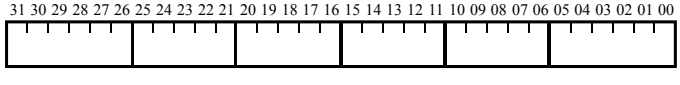
```
add     $8, $9, $10      # $8 = $9+$10
```




```
sll     $8, $9, 6        # $8 = $9<<6
```



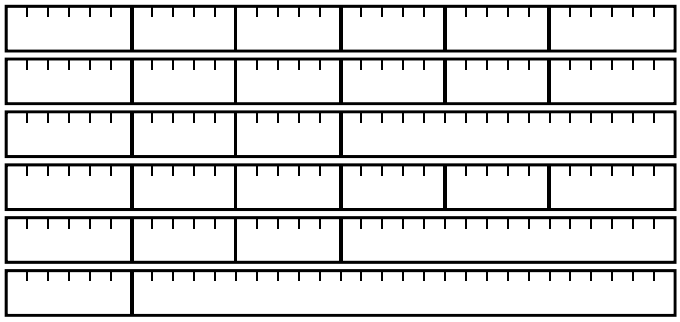

```
sllv    $8, $9, $10      # $8 = $9<<$10
```



Conversion example

Compute the sum of the values 0…N-1

```
004   add   $9, $0, $0
008   add   $10, $0, $0
  TOP:
012   bne   $8, $10, END
016   add   $9, $9, $10
020   addi  $10, $10, 1
024   j     TOP
  END:
028
```



Assembly & Machine Language

Assembly

Machine Language