Assembly Language

Readings: Chapter 2 (2.1-2.6, 2.8, 2.9, 2.13, 2.15), Appendix A.10

Assembly language

- Simple, regular instructions – building blocks of C & 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

<u>Not</u> our goal to teach complete assembly/machine language programming

- Floating point
- Procedure calls
- Stacks & local variables

MIPS Assembly Language

The basic instructions have four components:

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

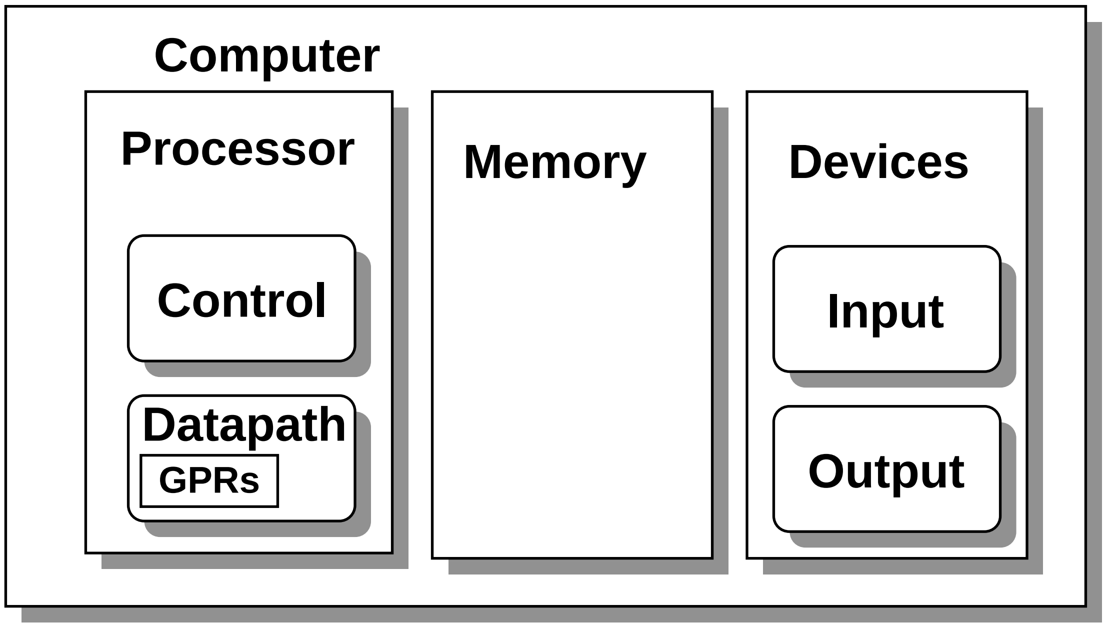
```
add <dst>, <src1>, <src2>      # <dst> = <src1> + <src2>
sub <dst>, <src1>, <src2>      # <dst> = <src1> - <src2>
```

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 (64MB+)



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:

```
srli $tK, $t0, 4
andi $t1, $tK, 7_10
```

0xxx,...
0000,.xxx
0000 0111

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.

0	**8 bits of data**
1	**8 bits of data**
2	**8 bits of data**
3	**8 bits of data**
4	**8 bits of data**
5	**8 bits of data**
6	**8 bits of data**
...	

Memory Organization (cont.)

Bytes are nice, but most data items use larger "words"

For MIPS, a word is 32 bits or 4 bytes.

0	**32 bits of data**
4	**32 bits of data**
8	**32 bits of data**
12	**32 bits of data**
	...

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

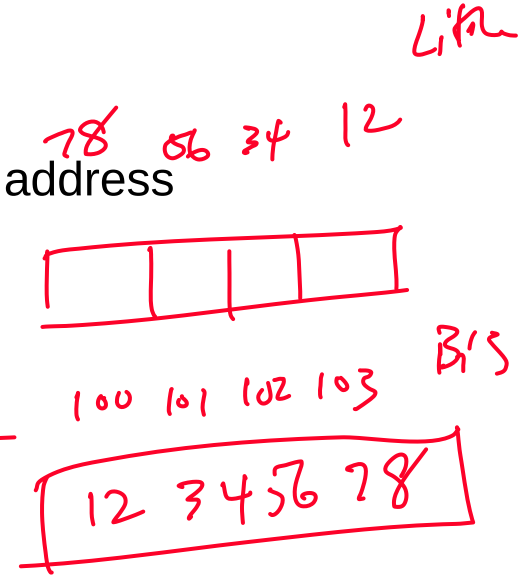
(xx00 = Big End of word)

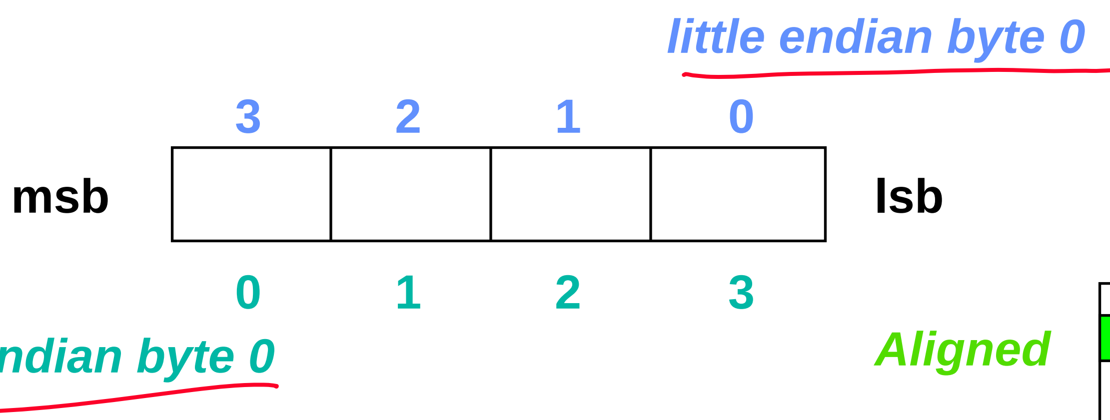
IBM 360/370, Motorola 68k, MIPS, Sparc, HP PA

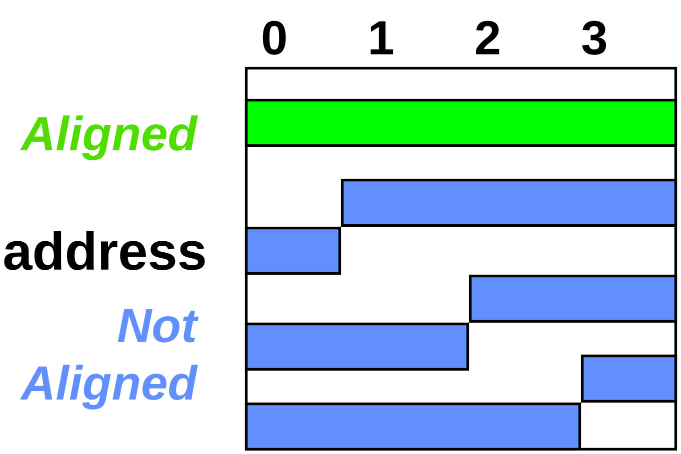
Little Endian: address of least significant byte = word address

(xx00 = Little End of word)

Intel 80x86, DEC Vax, DEC Alpha (Windows NT)







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

Data Storage

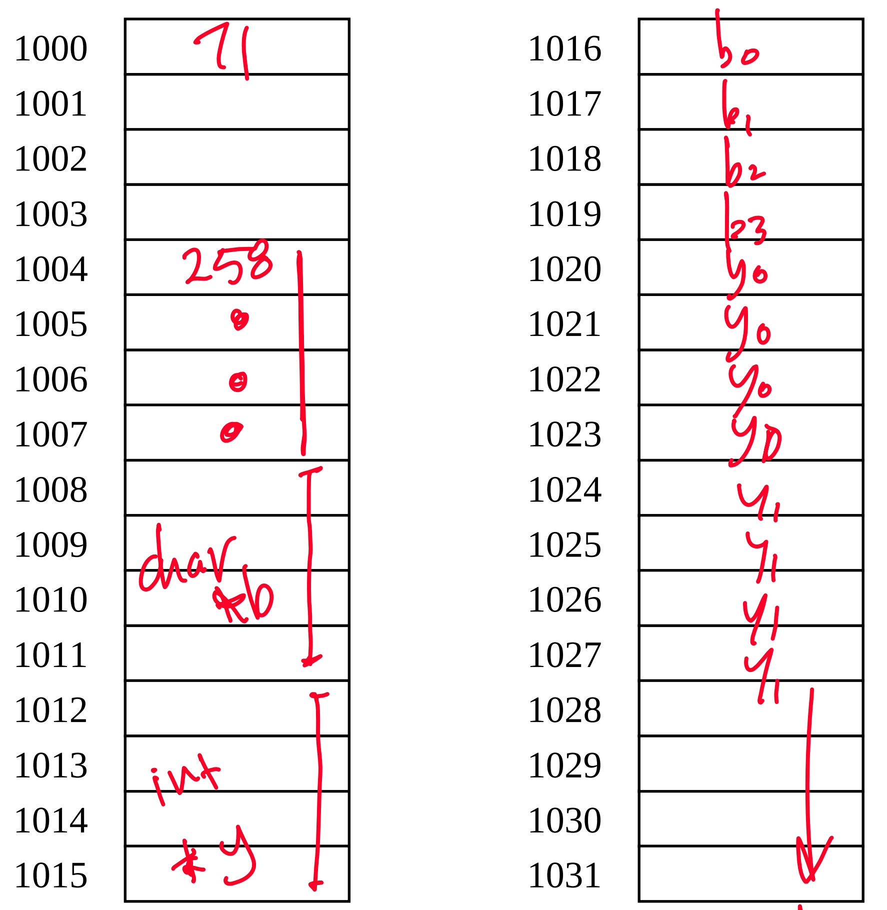
Characters: 8 bits (byte)

Integers: 32 bits (word)

Array: Sequence of locations

Pointer: Address

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



Loads & Stores

Loads & Stores move data between memory and registers

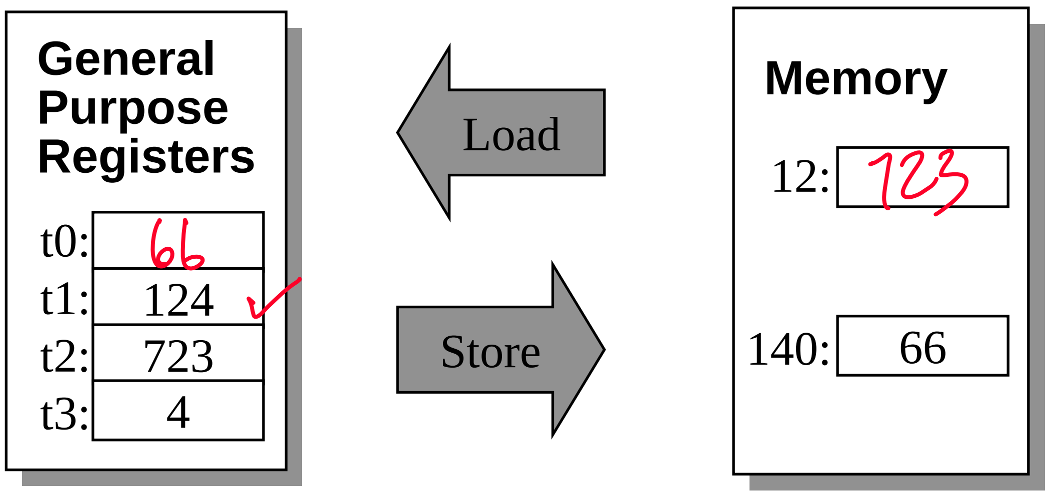
All operations on registers, but too small to hold all data

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

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

lw $t0, $t1
add $t1, $t1, 4
lw $t?, $t1

lw $t0, 0($t1)
lw $t?, 4($t1)
8($t1)
12($t1)



Note: lbu & sb load & store bytes

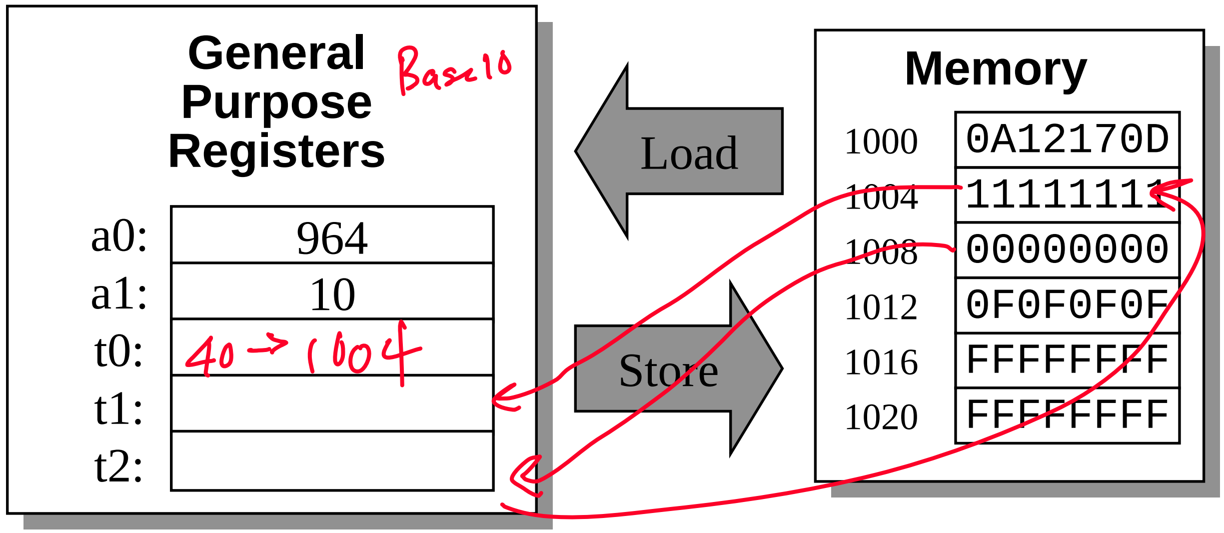
Array Example

lw $dst, val($reg)

v(0)

```
/* 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

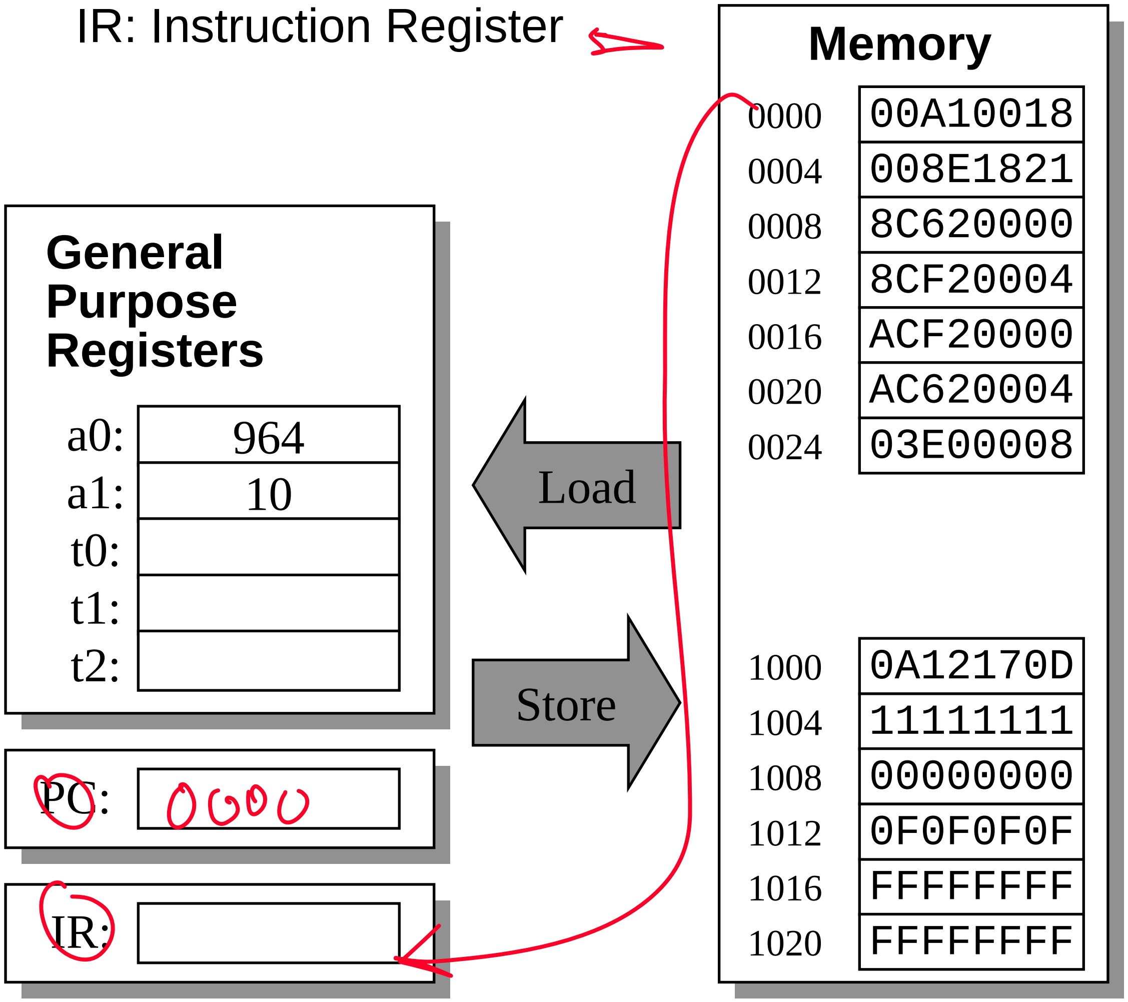


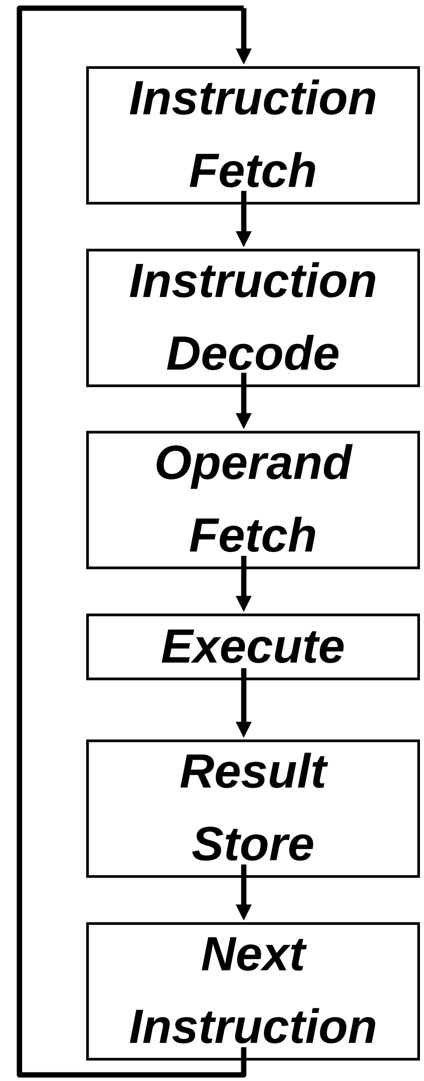

```
sll $t0, $a1, 2
add $t0, $t0, $a0
lw  $t1, 0($t0)      // get v[k]
lw  $t2, 4($t0)      // get v[k+1]
sw  $t2, 0($t0)
sw  $t1, 4($t0)
```

Execution Cycle Example

PC: Program Counter

IR: Instruction Register





Control Flow

Jumps – GOTO different next instruction

```
j 25                  # go to 100: PC = 25*4 (instructions are 32-bit)
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 1…N-1

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

```
add $t1, $zero, $zero
add $t2, $2, $2

beq $t0, $t2, END

j Loop
```

```
# $t0 = N, $t1 = sum, $t2 = I
        add  $t1, $zero, $zero
        add  $t2, $zero, $zero
Loop:   add  $t1, $t1, $t2
        addi $t2, $t2, 1
        beq  $t2, $t0, END      bne $t0, $t2, Loop
        j    Loop
END:
```

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;
a = a + c;
```

```
# $t0 = a, $t1 = b, $t2 = c
```

```
addi $t4, $zero, 1        a>=b
                          a<b
slt $t3, $t0, $t1         // (a<b)?
beq $t3, $t4, Foo
bne $t3, $zero, Foo
add $t2, $t0, $t1         // c=a+b
Foo: add $t0, $t0, $t2    // 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:
```

jmplicit

Notes:

Jumps are pseudo-absolute:

[31:26]

PC = { PC[31:28], 26-bit unsigned-Address, "00" }

Branches are PC-relative:

PC = PC + 4 + 4*(16-bit signed Address)

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

<table>
<tr><td>31</td><td>30</td><td>29</td><td>28</td><td>27</td><td>26</td><td>25</td><td>24</td><td>23</td><td>22</td><td>21</td><td>20</td><td>19</td><td>18</td><td>17</td><td>16</td><td>15</td><td>14</td><td>13</td><td>12</td><td>11</td><td>10</td><td>09</td><td>08</td><td>07</td><td>06</td><td>05</td><td>04</td><td>03</td><td>02</td><td>01</td><td>00</td></tr>
<tr><td colspan="6">OP</td><td colspan="5">RS</td><td colspan="5">RT</td><td colspan="5">RD</td><td colspan="5">SHAMT</td><td colspan="6">FUNCT</td></tr>
</table>

(OP = 0,16-20)

Immediate (I-type) instructions

<table>
<tr><td>31</td><td>30</td><td>29</td><td>28</td><td>27</td><td>26</td><td>25</td><td>24</td><td>23</td><td>22</td><td>21</td><td>20</td><td>19</td><td>18</td><td>17</td><td>16</td><td>15</td><td>14</td><td>13</td><td>12</td><td>11</td><td>10</td><td>09</td><td>08</td><td>07</td><td>06</td><td>05</td><td>04</td><td>03</td><td>02</td><td>01</td><td>00</td></tr>
<tr><td colspan="6">OP</td><td colspan="5">RS</td><td colspan="5">RT</td><td colspan="16">16 bit Address/Immediate</td></tr>
</table>

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

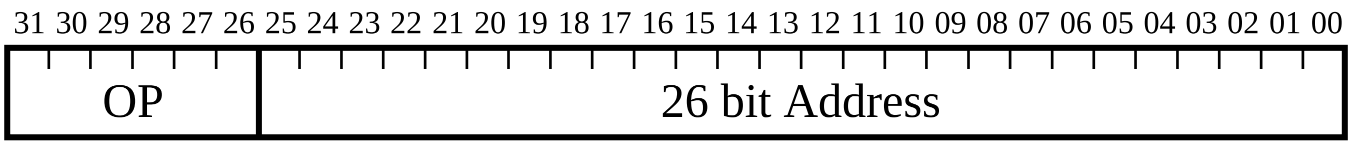
Jump (J-type) instructions

<table>
<tr><td>31</td><td>30</td><td>29</td><td>28</td><td>27</td><td>26</td><td>25</td><td>24</td><td>23</td><td>22</td><td>21</td><td>20</td><td>19</td><td>18</td><td>17</td><td>16</td><td>15</td><td>14</td><td>13</td><td>12</td><td>11</td><td>10</td><td>09</td><td>08</td><td>07</td><td>06</td><td>05</td><td>04</td><td>03</td><td>02</td><td>01</td><td>00</td></tr>
<tr><td colspan="6">OP</td><td colspan="26">26 bit Address</td></tr>
</table>

(OP = 2,3)

J-Type

Used for unconditional jumps



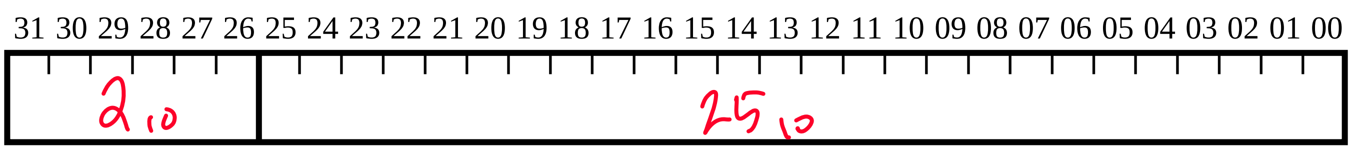
2: j (jump)

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

31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00

OP	RS	RT	16 bit Address/Immediate
	Op1, L/S addr	Op2, Dest, L/S targ	

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

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

31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00

08_{10}	9_{10}	8_{10}	100_{10}

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

31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00

04_{10}	8_{10}	9_{10}	-11_{10}

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

31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01 00

35_{10}	9_{10}	8_{10}	12_{10}

R-Type

Used for 3 register ALU operations

Bits	31 30 29 28 27 26	25 24 23 22 21	20 19 18 17 16	15 14 13 12 11	10 09 08 07 06	05 04 03 02 01 00
Field	OP	RS	RT	RD	SHAMT	FUNCT
	00 (16-20 for FP)	Op1	Op2	Dest	Shift amount (0 for non-shift)	

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

31 30 29 28 27 26	25 24 23 22 21	20 19 18 17 16	15 14 13 12 11	10 09 08 07 06	05 04 03 02 01 00
00	9	10	8	0	32

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

31 30 29 28 27 26	25 24 23 22 21	20 19 18 17 16	15 14 13 12 11	10 09 08 07 06	05 04 03 02 01 00
00	X	9	8	6	60

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

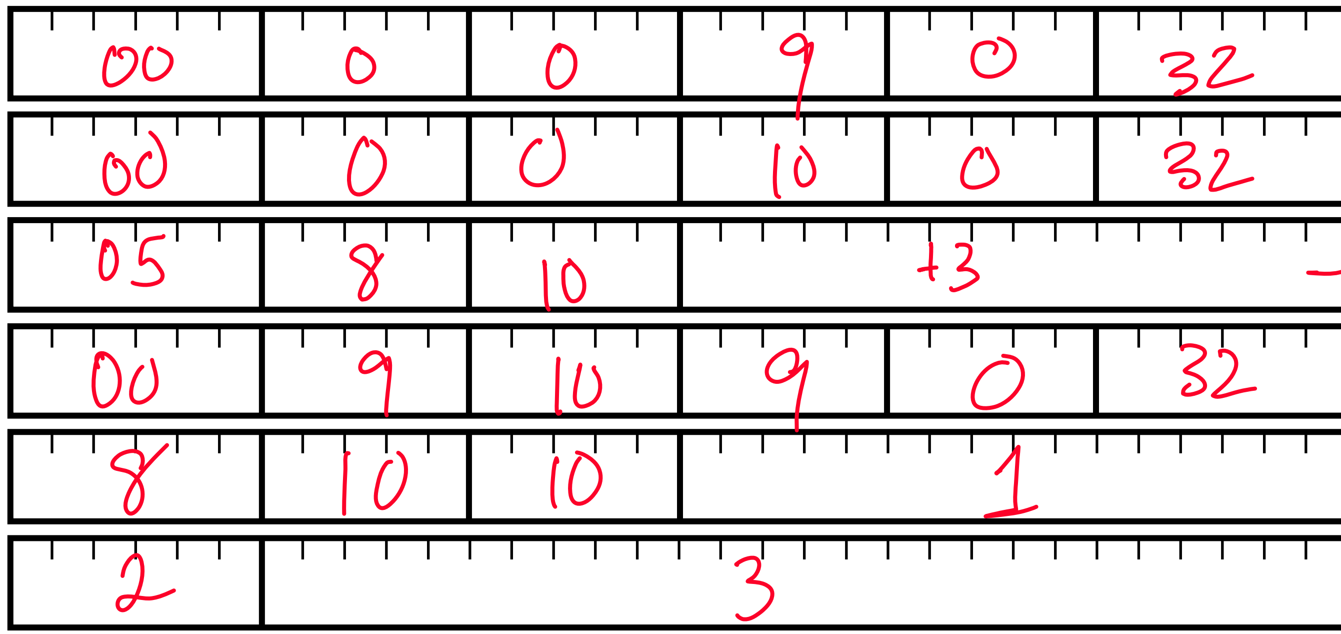
31 30 29 28 27 26	25 24 23 22 21	20 19 18 17 16	15 14 13 12 11	10 09 08 07 06	05 04 03 02 01 00
00	10	9	8	0	4

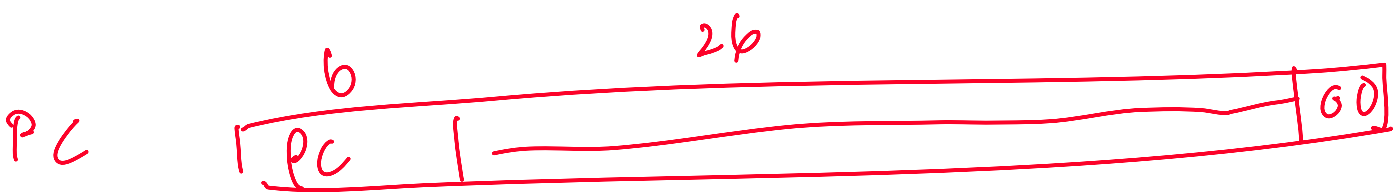
FUNCT	Instruction
00:	sll
02:	srl
03:	sra
04:	sllv
06:	srlv
07:	srav
08:	jr
24:	mult
26:	div
32:	add
33:	addu
34:	sub
35:	subu
36:	and
37:	or
38:	xor
39:	nor
42:	slt

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

1-to-1 mapping

Human readable

Machine Language

32 bits

NOT easy to understand.

Fixed format – easy for machine