101
Assembly

ENGR 3410 – Computer Architecture

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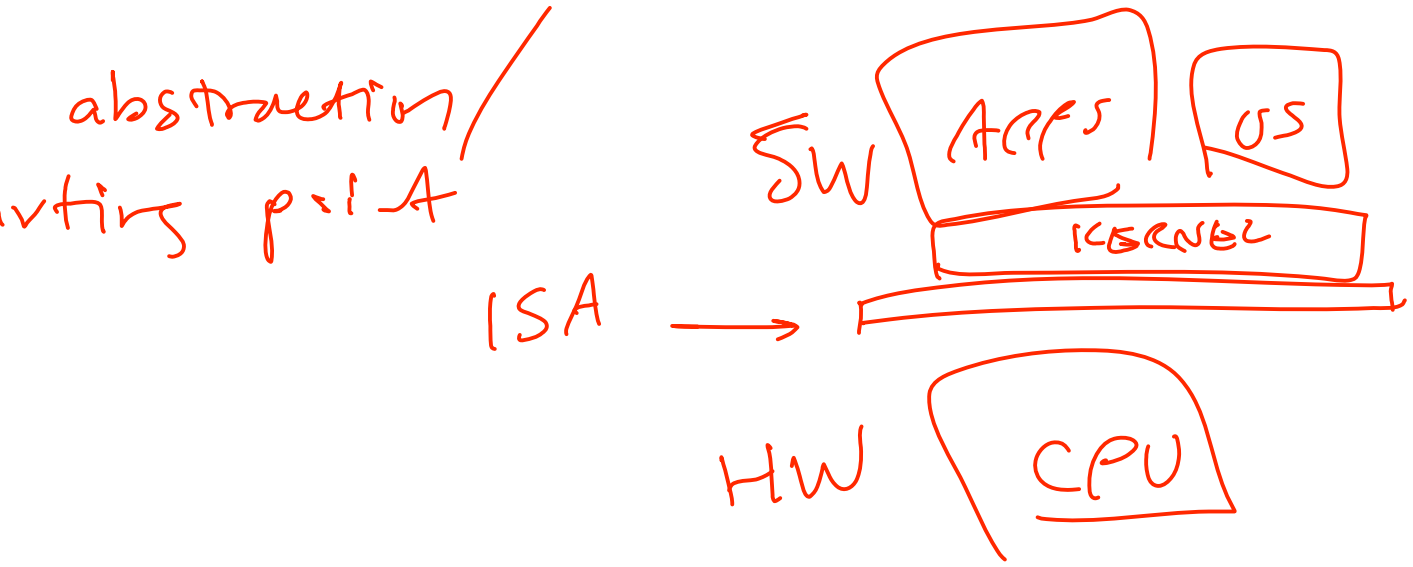
What is assembly?

- one step above machine code.
- very processor-dependent
- hard to use
- can be fast

Why are we learning assembly now?

- see steps of CPU operation
- running assembly is our end goal
  DESIGN.
- good abstraction/
  starting point



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

- Not 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>
```

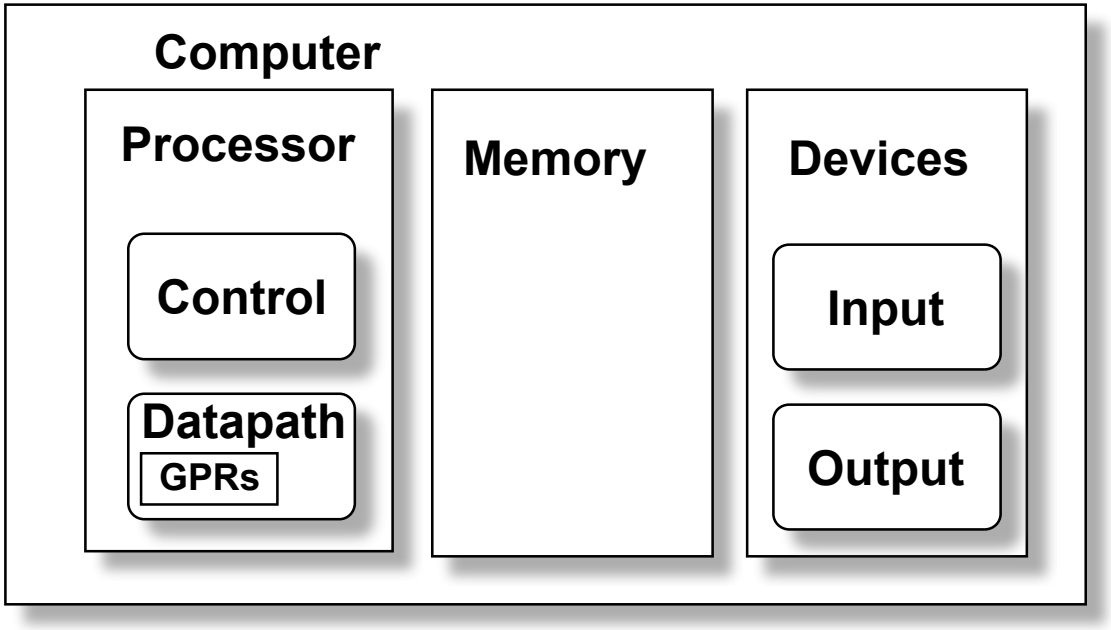
- Simple format: easy to implement in hardware

- More complex: `A = B + C + D - E`

```
add a, b, c
add a, a, d
sub a, a, 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)

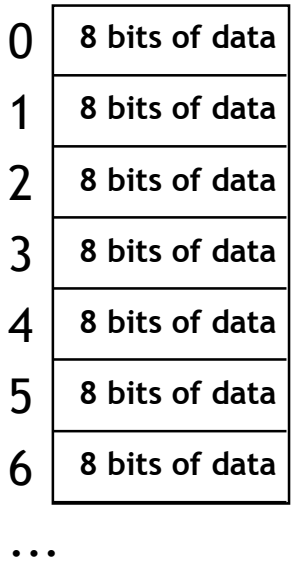
Mathematic: add, sub, mult, div	`add $t0, $t1, $t2  # t0 = t1+t2`
Unsigned (changes overflow condition)	`addu $t0, $t1, $t2 # t0 = t1+t2`
Immediate (one input a constant)	`addi $t0, $t1, 100 # t0 = t1+100`
Logical: and, or, nor, xor	`and $t0, $t1, $t2  # t0 = t1&t2`
Immediate	`andi $t0, $t1, 7   # t0 = 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:

```
andi  $t1, $t0, 0x00000070
srl   $t1, $t1, 4
```

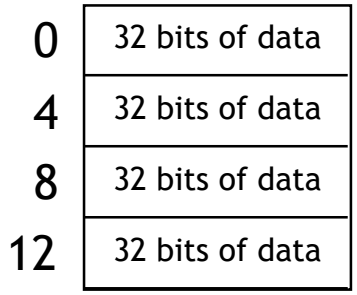
Memory Organization

- 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.



Our registers hold 32 bits of data

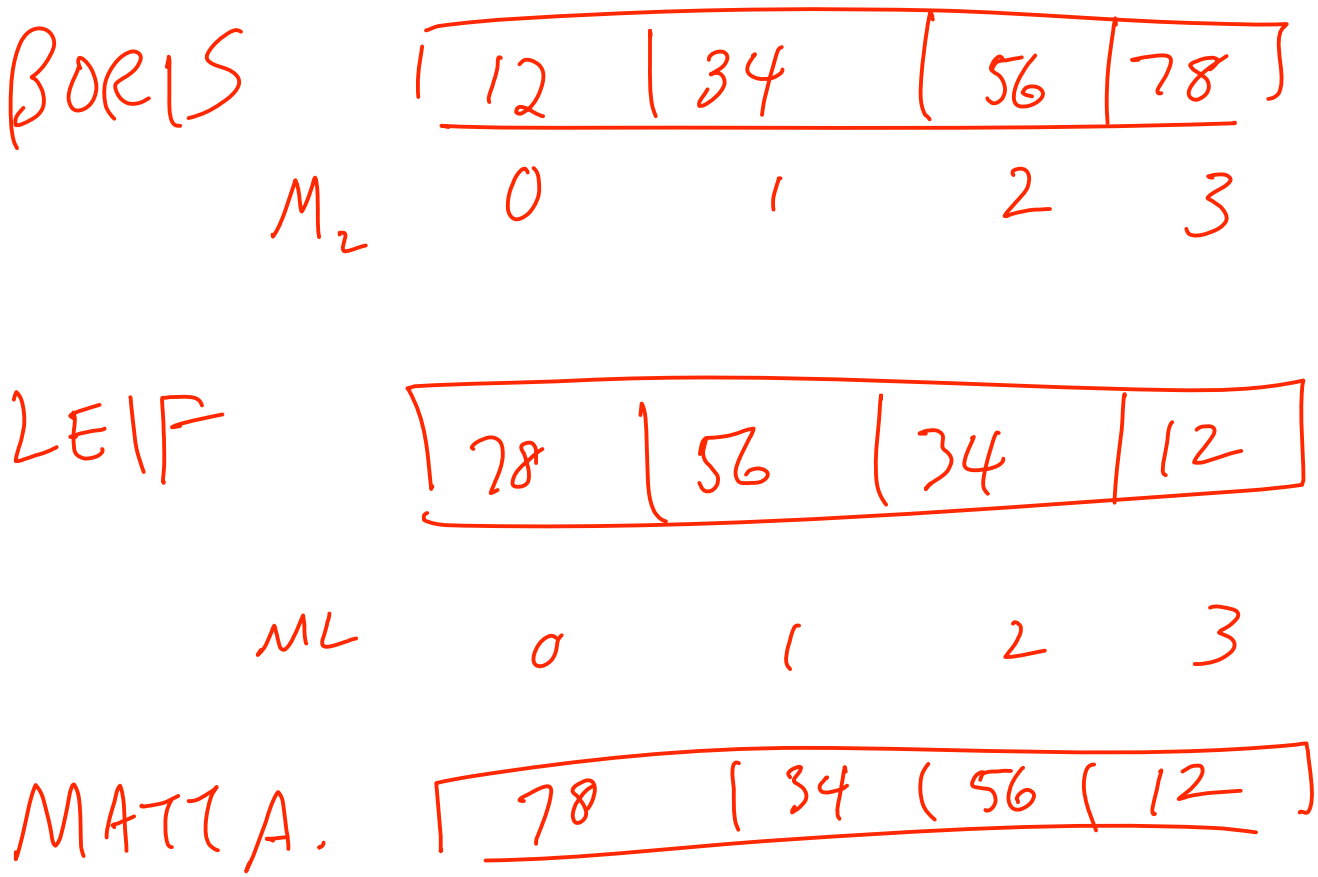
- 2^{32} bytes with byte addresses from 0 to $2^{32}-1$
- 2^{30} words with byte addresses 0, 4, 8, ... $2^{32}-4$
- Words are aligned

  i.e., what are the least 2 significant bits of a word address?

Endianness

- How do we write numbers?

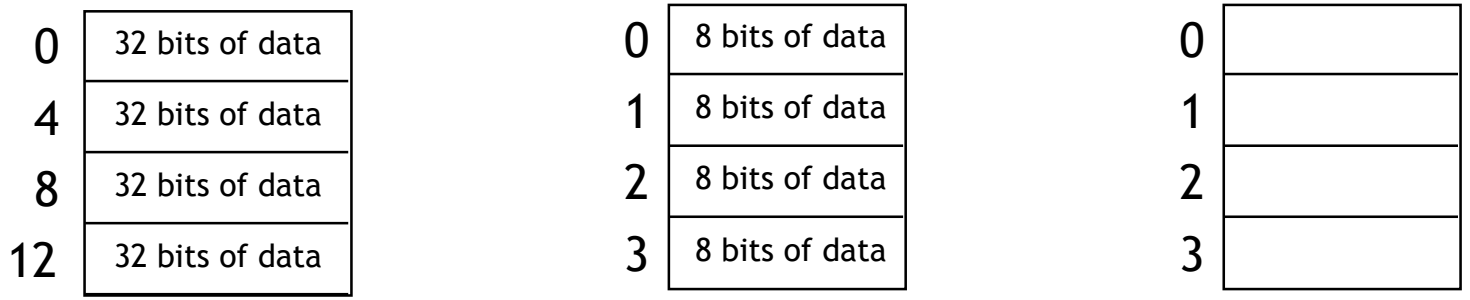
0x 12 34 56 78



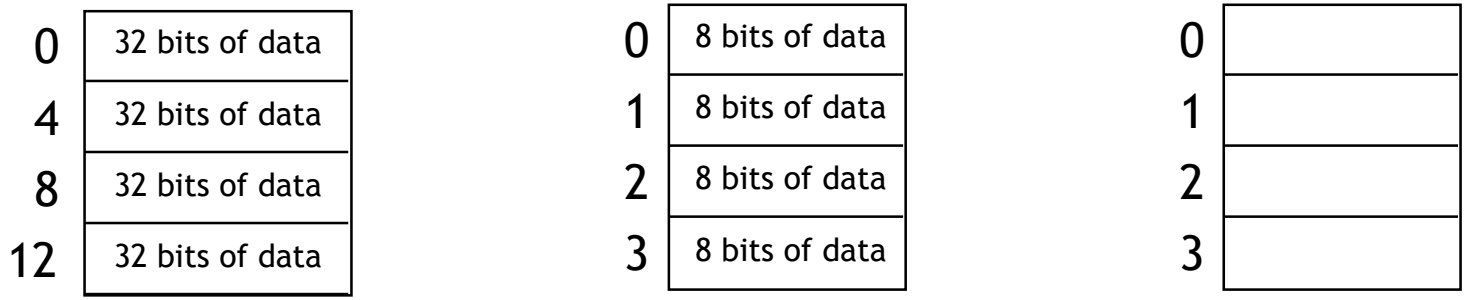
Must establish a convention for the order of digits to represent numbers

Endianness

- In memory, what is the order of a 32-bit word?

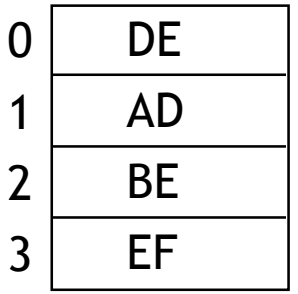


Store the 32-bit word: 0xDEADBEEF

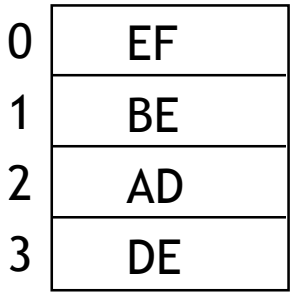


Big and Little Endian

- Big Endian – "Big End" in (first)
  - Motorola 68000
  - Sun SPARC
  - PowerPC G5
  - *Networks*

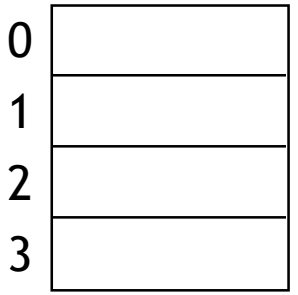


- Little Endian – "Little End" in (first)
  - Intel x86
  - MOS Tech 6502
    - Atari 2600, Apple][, Commodore 64, NES



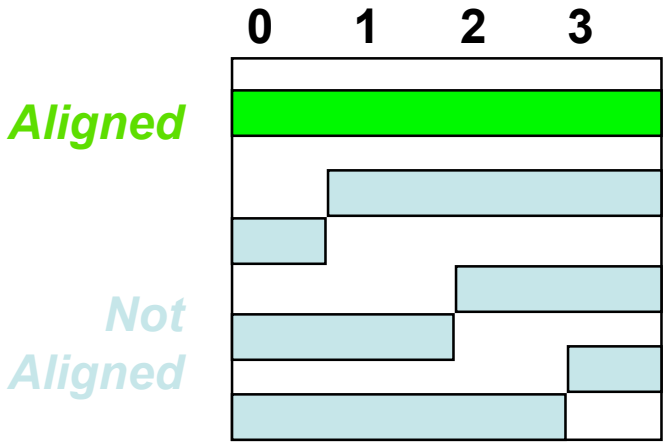
- Bi-Endian – switchable endianness
  - ARM, IBM PowerPC (most)

- Middle-Endian
  - PDP-11



Word Alignment

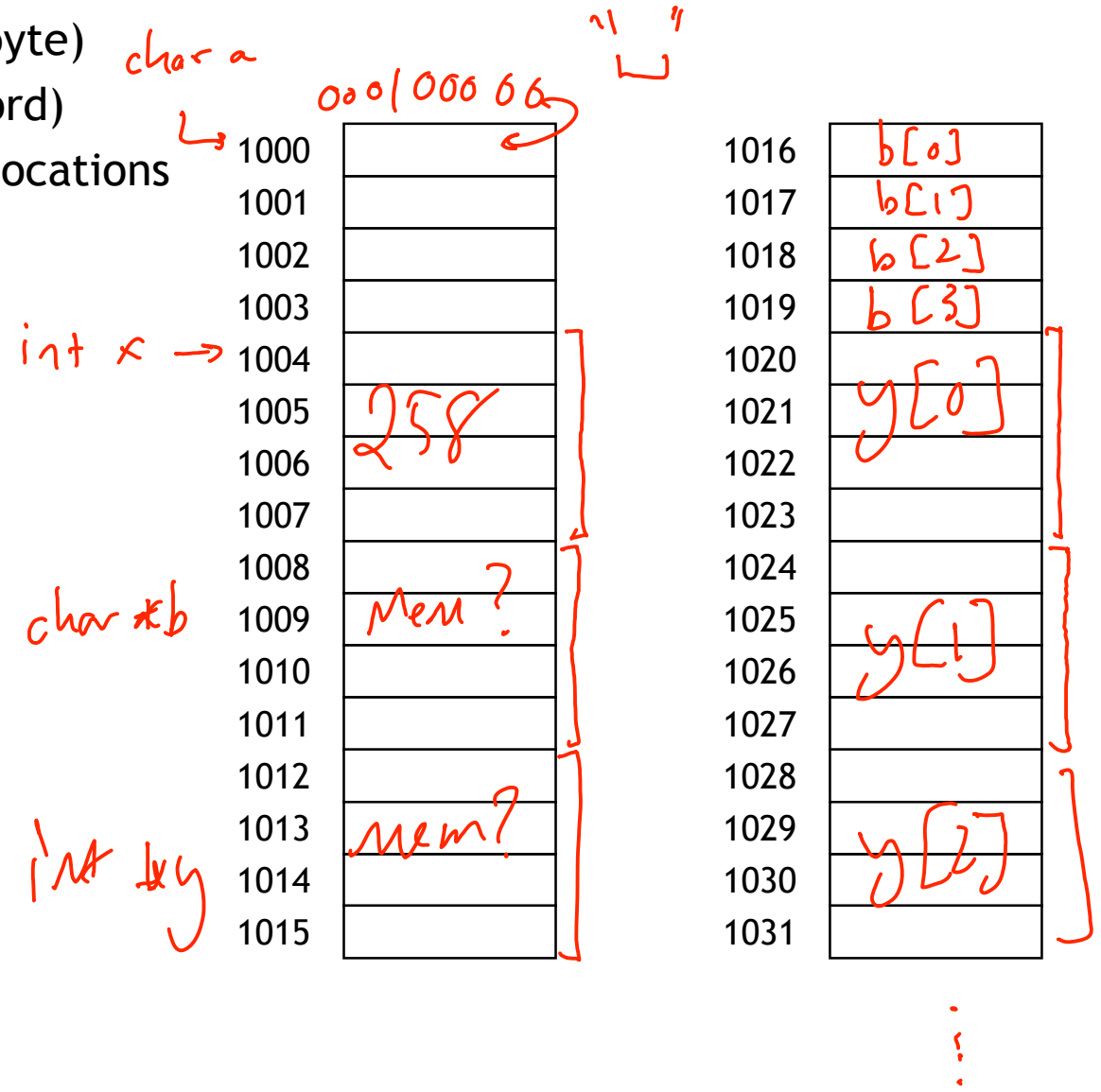
- Require that objects fall on an address that is a multiple of their size



Data Storage

- Characters: 8 bits (byte)
- Integers: 32 bits (word)
- Array: Sequence of locations
- Pointer: Address

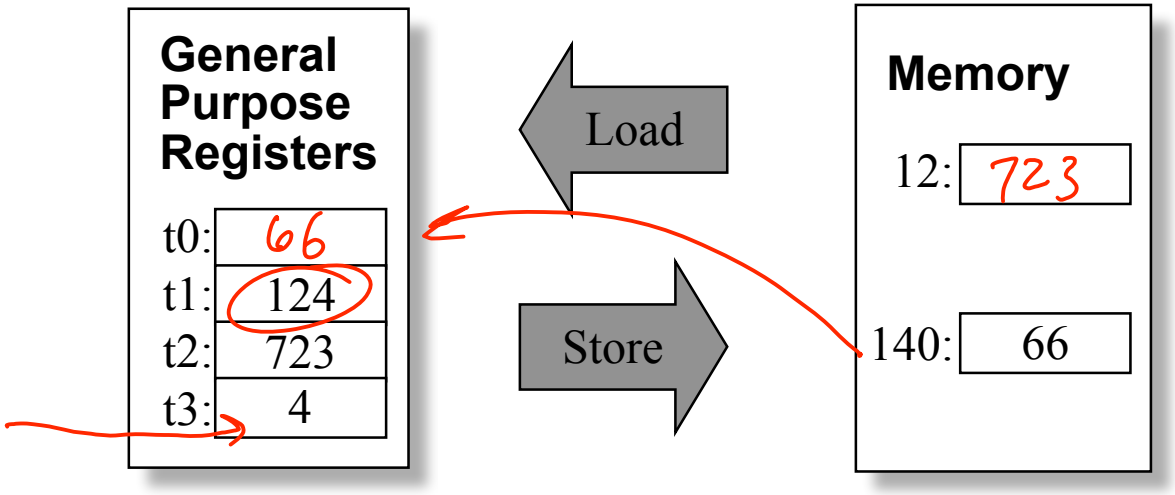
```
char a = 'G';
int x = 258;
char *b;
int *y;
b = new char[4];
y = new int[10];
```



Loads & Stores

- Loads & Stores move data between memory and registers
  - All operations on registers, but too small to hold all data

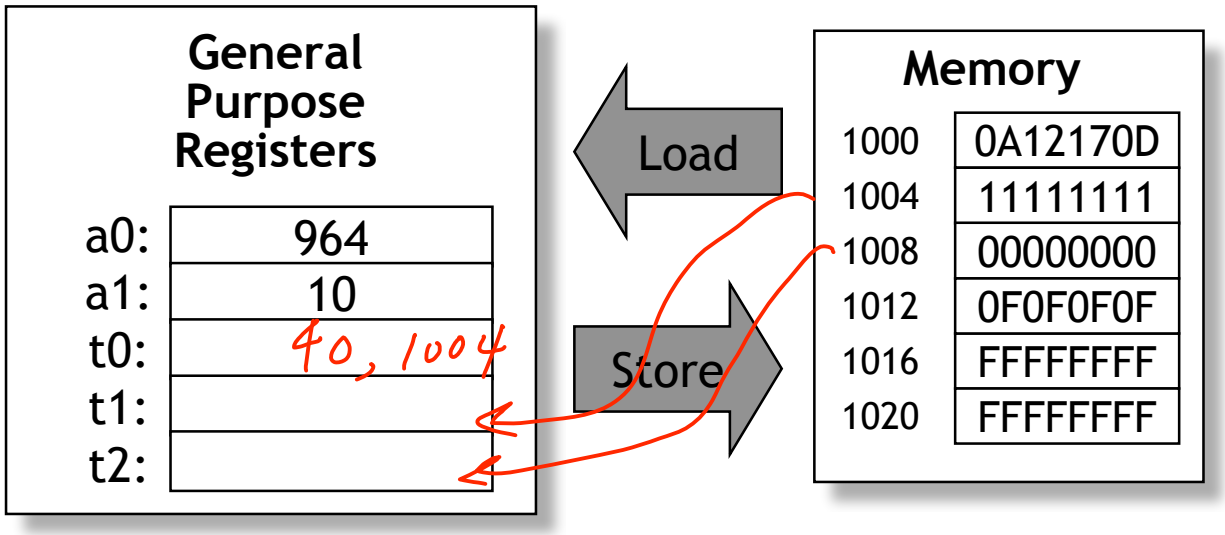
```
lw $t0, 16($t1)        # $t0 = Memory[$t1+16]

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



- Note: lbu & sb load & store bytes

Array Example

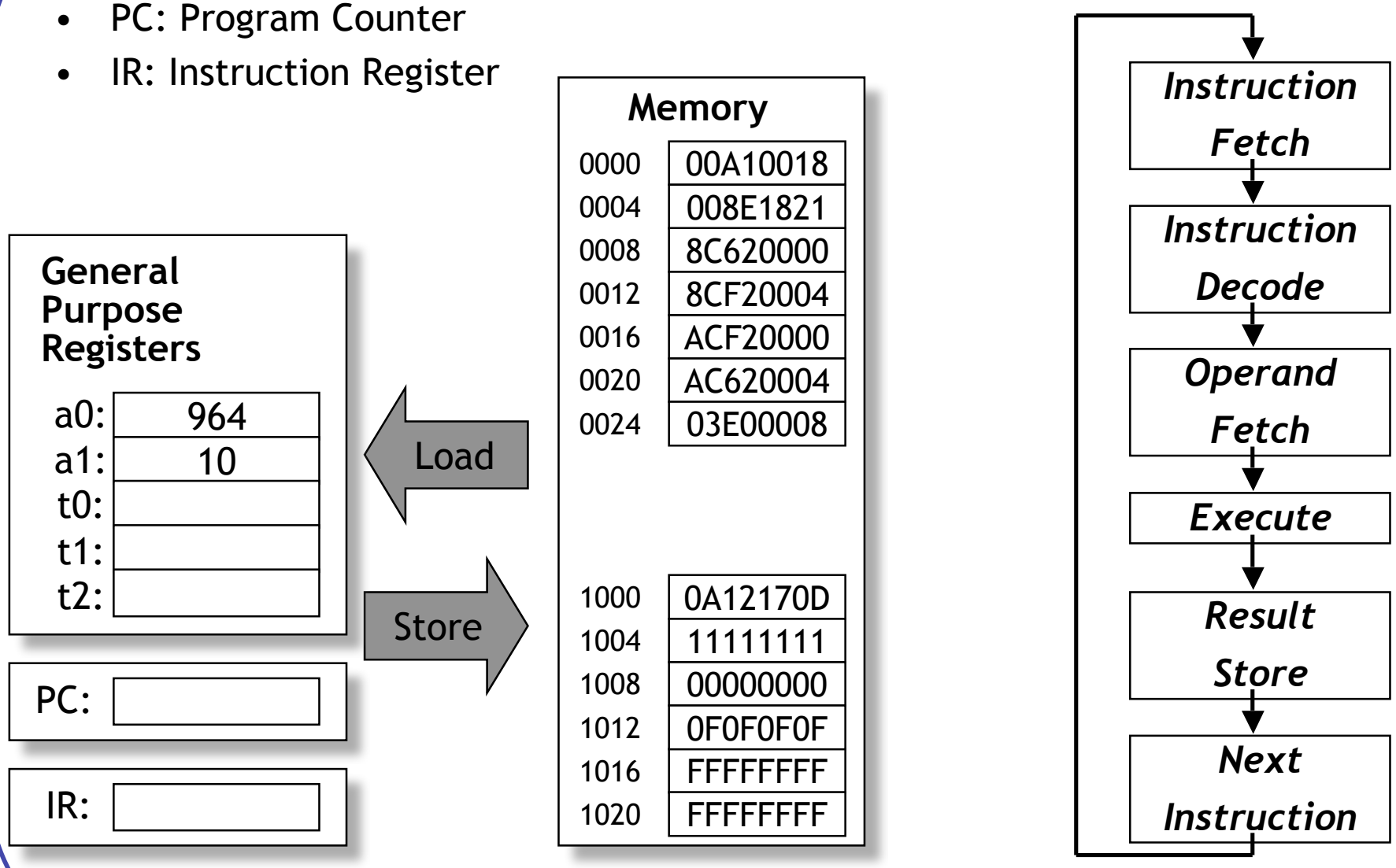
```
/* Swap the kth and (k+1)th element of an array */
swap(int v[], int k)
{
    int temp = v[k];
    v[k] = v[k+1];
    v[k+1] = temp;
}


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




```
sll $t0, $a1, 2
add $t0, $t0, $a0
lw  $t1, 0($t0)
lw  $t2, 4($t0)
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;
}
```

```
# $t0 = N, $t1 = sum, $t2 = I
        add  $t1, $zero, $zero
        add  $t2, $zero, $zero
TOP:
        beq  $t0, $t2, DONE
        add  $t1, $t1, $t2
        addi $t2, $t2, 1
        j    TOP

DONE:
```

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;
```

tmp = (a<b) →

```
# $t0 = a, $t1 = b, $t2 = c
slt  $t3, $t0, $t1
bne  $t3, $zero, LATER
add  $t2, $t0, $t1

LATER:
     add  $t0, $t0, $t2
```

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
    lw  $t0, 100($zero)
LOOP: lb  $t1, 0($t0)
    beq $t1, $zero, END
    slt $t12, $t1, $t2
    bne $t12, $zero, NEXT
    slt $t13, $t3, $t1
    bne $t13, $zero, NEXT
    add $t1, $t1, $t4
    sb  $t1, 0($t0)
NEXT:
    addi $t0, $t0, 1
    j   LOOP
END:
```

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)

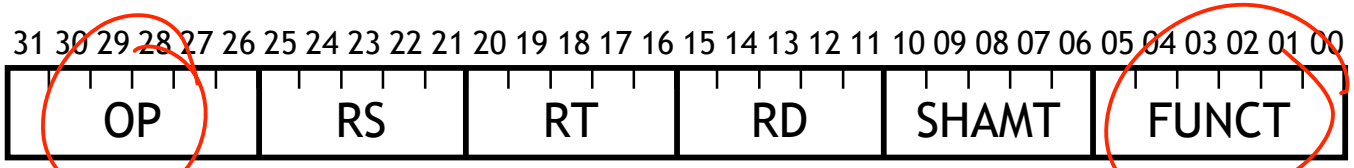
Instruction Types

- 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;
```

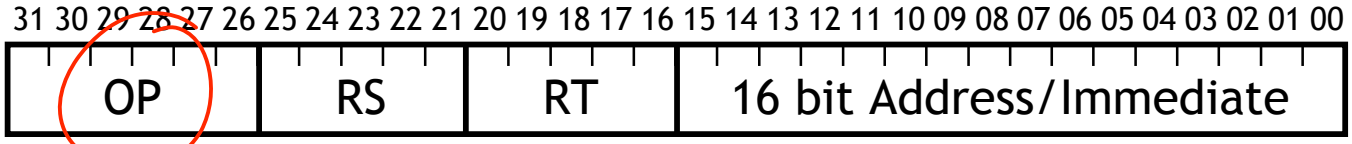
Instruction Formats

- All instructions encoded in 32 bits (operation + operands/immediates)
- Register (R-type) instructions



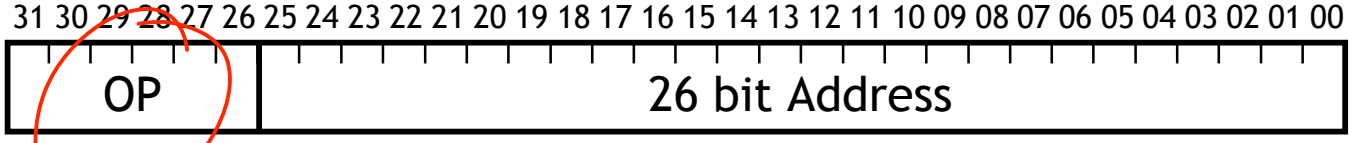
(OP = 0,16-20)

- Immediate (I-type) instructions



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

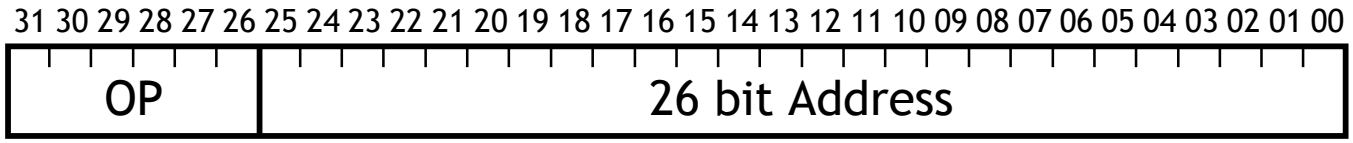
- Jump (J-type) instructions



(OP = 2,3)

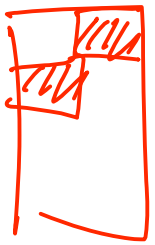
J-Type

- Used for unconditional jumps



2: j (jump)

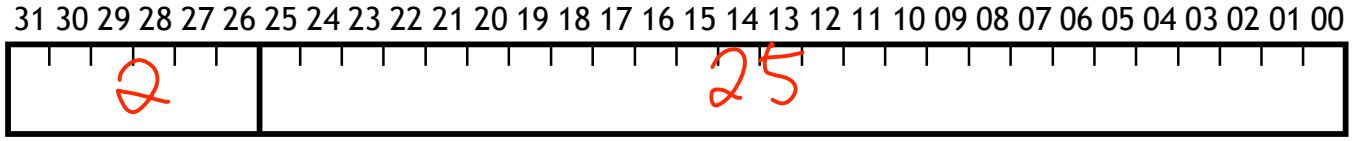
3: jal (jump and link)



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

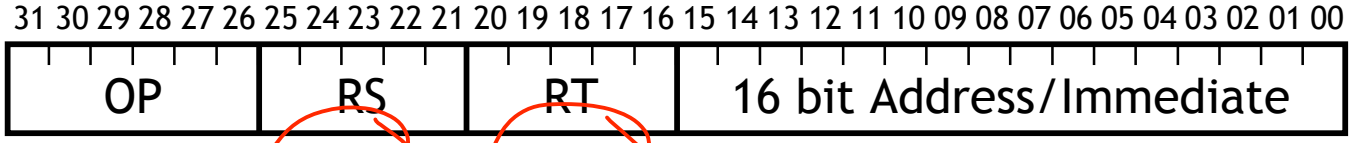
- Example:

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



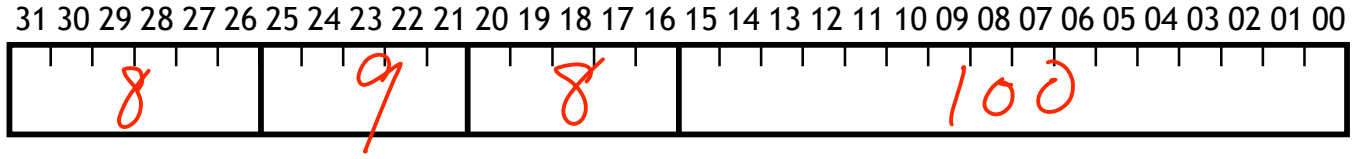
I-Type

- Used for operations with immediate (constant) operand



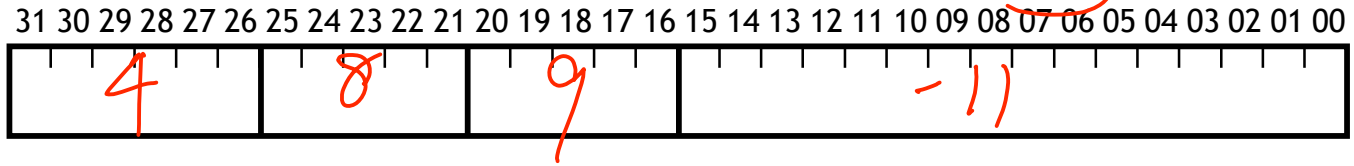
04: beq
05: bne
06: blez
07: bgtz
08: addi
09: addiu
10: slti
11: sltiu
12: andi
13: ori
14: xori
32: lb
35: lw
40: sb
43: sw

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

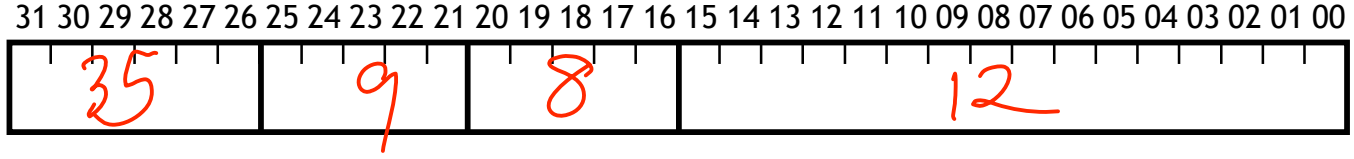



```
beq     $8, $9, -11      # if $8 == $9 GOTO (PC+4+FOO*4)
```

=PC

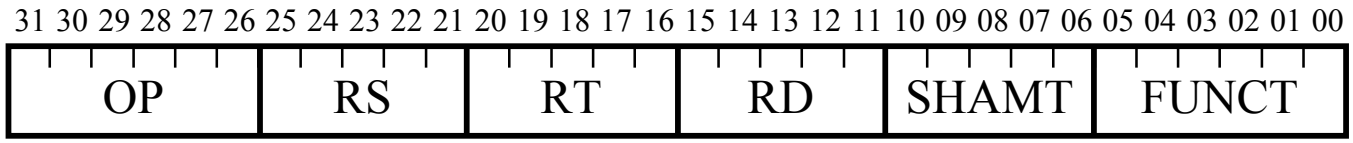



```
lw      $8, 12($9)       # $8 = Memory[$9+12]
```



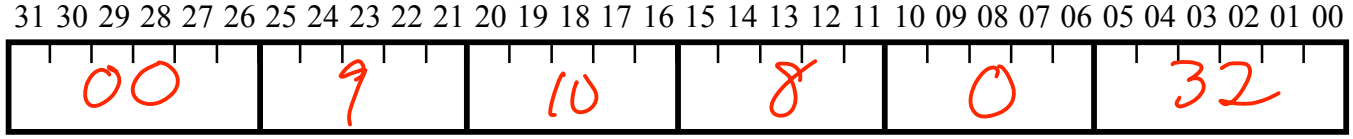
R-Type

- Used for 3 register ALU operations

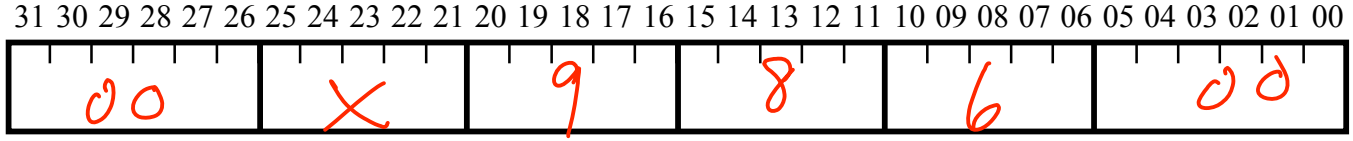


OP	RS	RT	RD	SHAMT	FUNCT
00 (16-20 for FP)	Op1	Op2	Dest	Shift amount (0 for non-shift)	

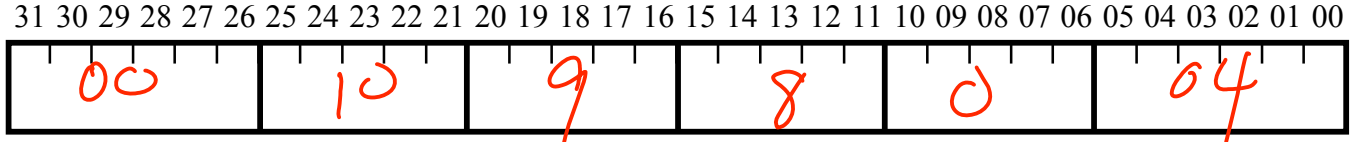
```
add     $8, $9, $10       # $8 = $9+$10
```




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




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



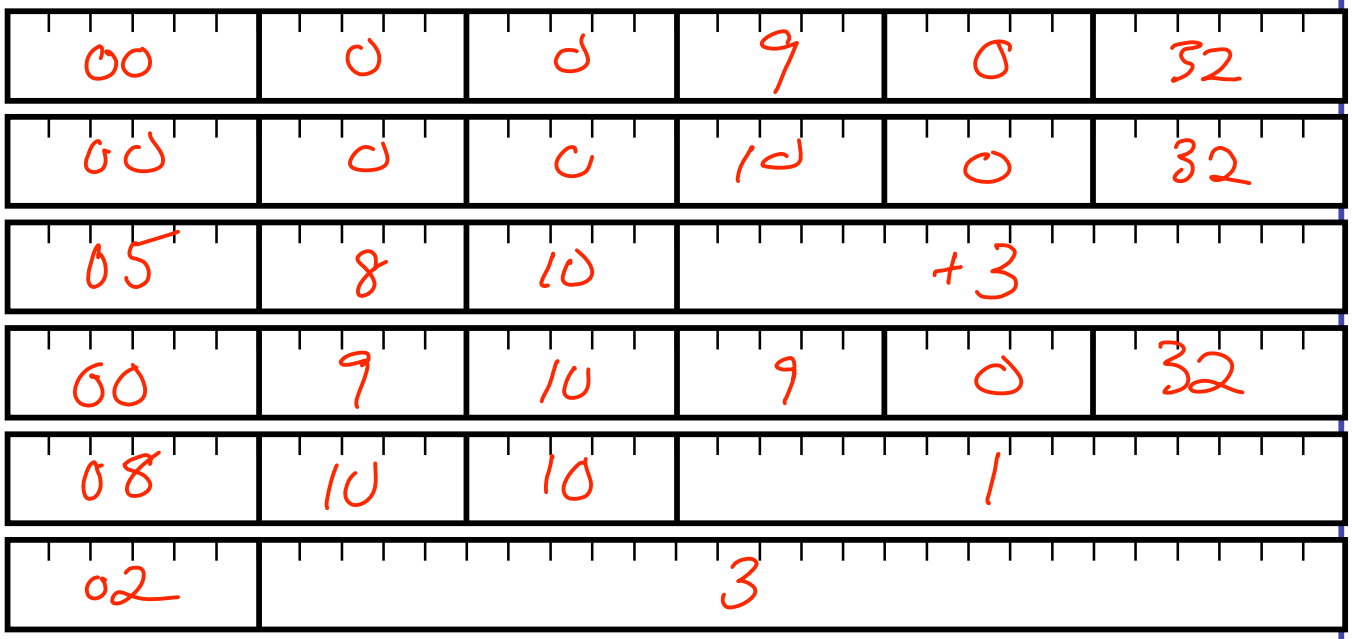
00:	sll
02:	srl
03:	sra
04:	sllv
06:	srlv
07:	srav
08:	jr
24:	mult
26:	div
32:	add
33:	addu
34:	sub
35:	subu
36:	and
37:	or
38:	xor
39:	nor
42:	slt

Conversion example

- Compute the sum of the values 0…N-1

PC = PC + 4 + imm x 4

```
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
  - human readable
  - must be assembled
  - lowest level of abstraction
  - mnemonics for machine code
- Machine Language
  - binary (0/1)

Regular