101
Assembly

ENGR 3410 – Computer Architecture

Mark L. Chang

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What is assembly?

Language (low-level)

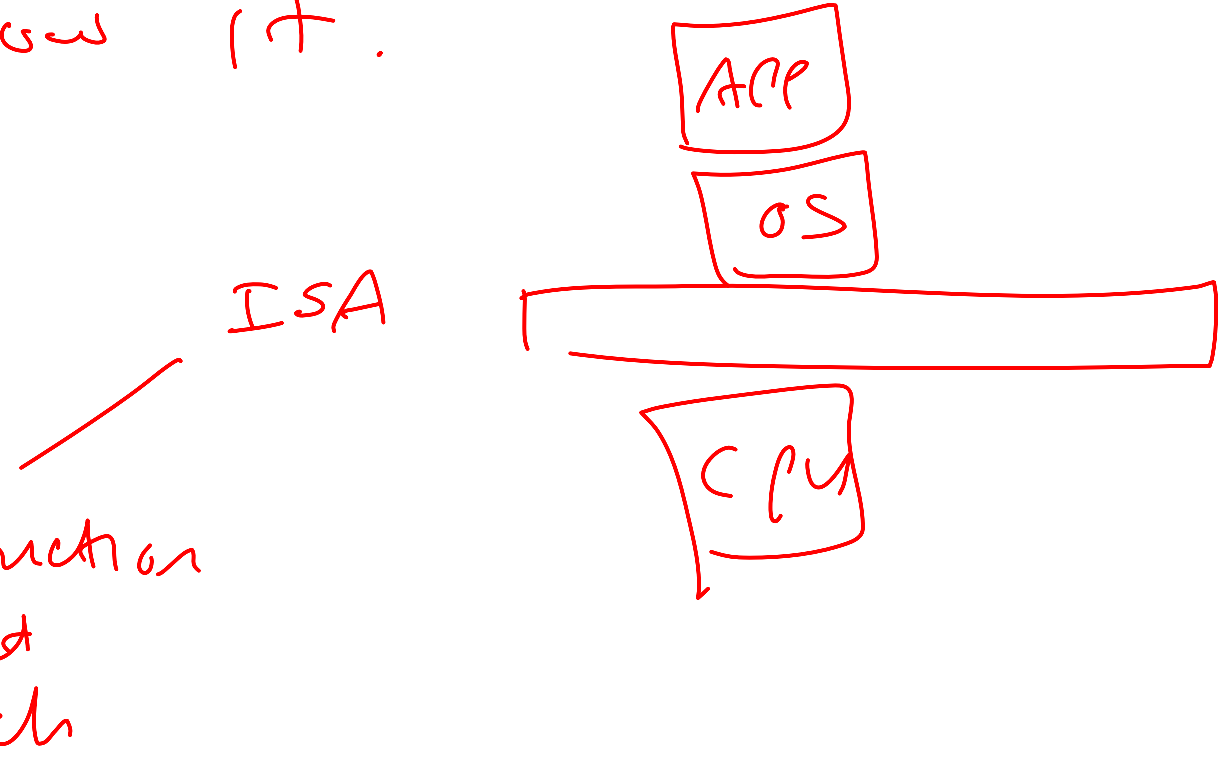
Text representation of CPU instructions

Painful to debug

→ Close to hardware :)

Why are we learning assembly now?

- helps us figure out cpu (what it does)
- You know it.



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

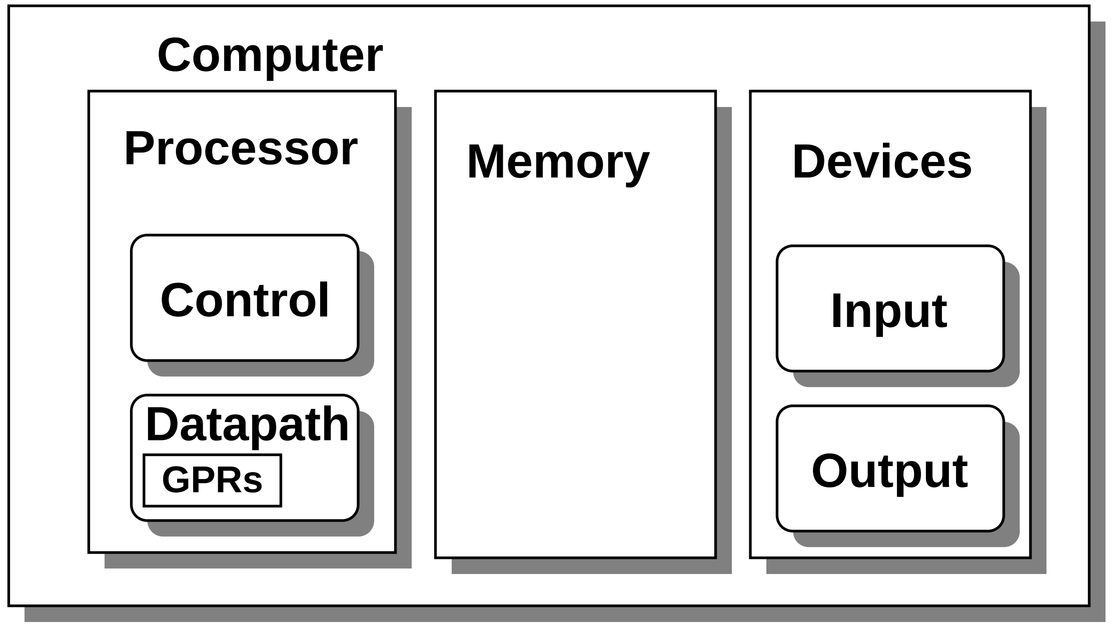
```
add <dst>, <src1>, <src2>     # <dst> = <src1> + <src2>
sub <dst>, <src1>, <src2>     # <dst> = <src1> - <src2>
```

- Simple format: easy to implement in hardware

- More complex: `A = B + C + D – E`

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
Unsigned (changes overflow condition)
Immediate (one input a constant) $\leftarrow$

```
add $t0, $t1, $t2  # t0 = t1+t2
addu $t0, $t1, $t2 # t0 = t1+t2
addi $t0, $t1, 100 # t0 = t1+100
```

Logical: and, or, nor, xor
Immediate

```
and $t0, $t1, $t2  # t0 = t1&t2
andi $t0, $t1, 7   # t0 = t1&b0111
```

Shift: left & right logical, arithmetic
Immediate

```
sllv $t0, $t1, $t2 # t0 = t1<<t2
sll $t0, $t1, 6    # t0 = t1<<6
```

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

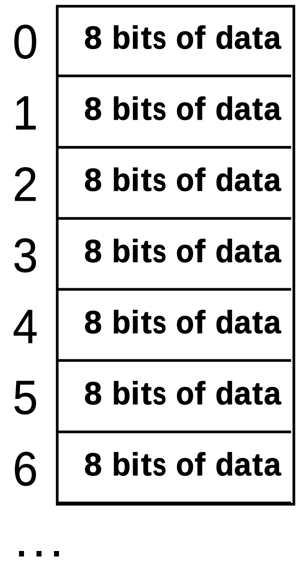
```
srl $t1, $t0, 4
and $t1, $t1, 7
```

000d .. 00111

0x = hex
0b = bin

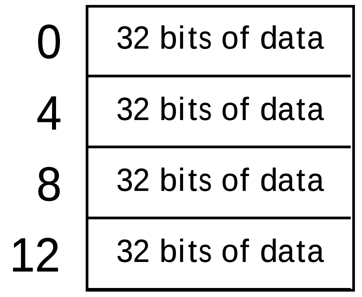
Memory Organization

- 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?

0 3 6 1

1 6 3 0

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

Endianness

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

BIG

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

0	8 bits of data
1	8 bits of data
2	8 bits of data
3	8 bits of data

0	DE
1	AD
2	BE
3	EF

Store the 32-bit word: 0x$\underline{\text{DE}}$ADBEEF

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

0	8 bits of data
1	8 bits of data
2	8 bits of data
3	8 bits of data

0	EF
1	BE
2	AD
3	DE

LITTLE

Big and Little Endian

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

0	DE
1	AD
2	BE
3	EF

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

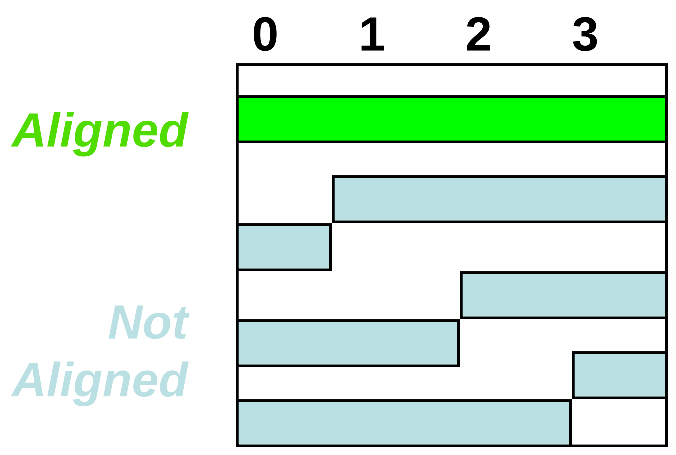
0	EF
1	BE
2	AD
3	DE

- Bi-Endian – switchable endianness
  - ARM, IBM PowerPC (most)
- Middle-Endian
  - PDP-11

0	AD
1	DE
2	BE
3	EF

Word Alignment

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

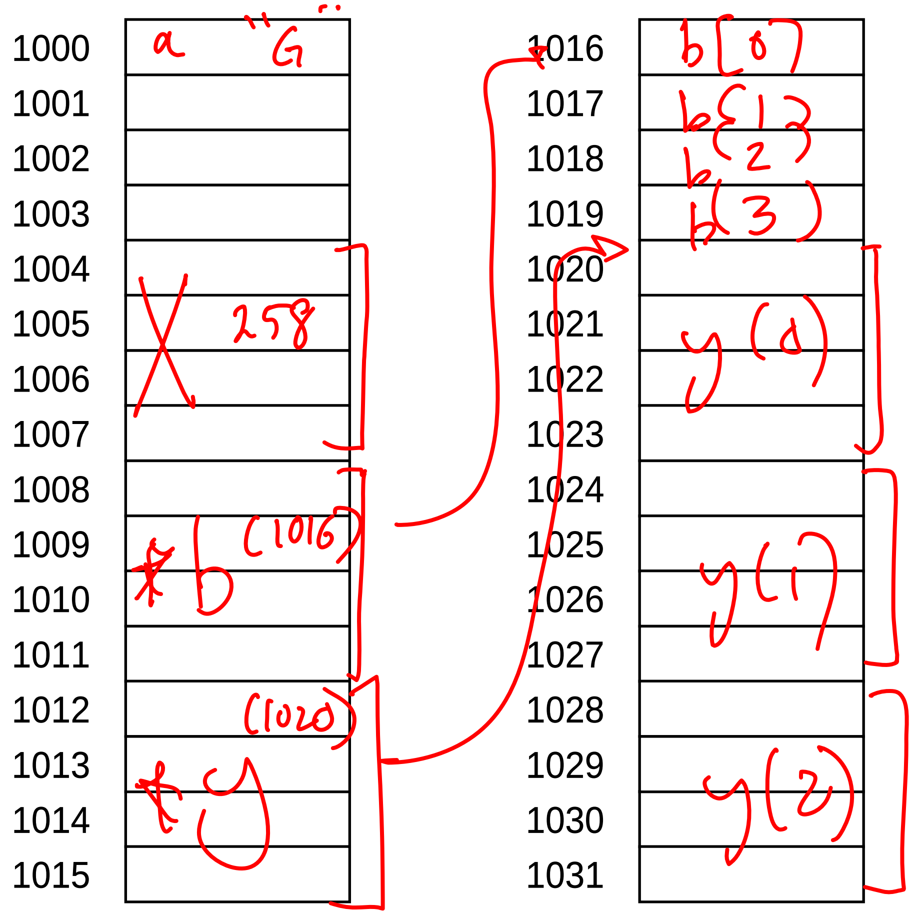


Data Storage

- 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];
```

t= new Char(1)

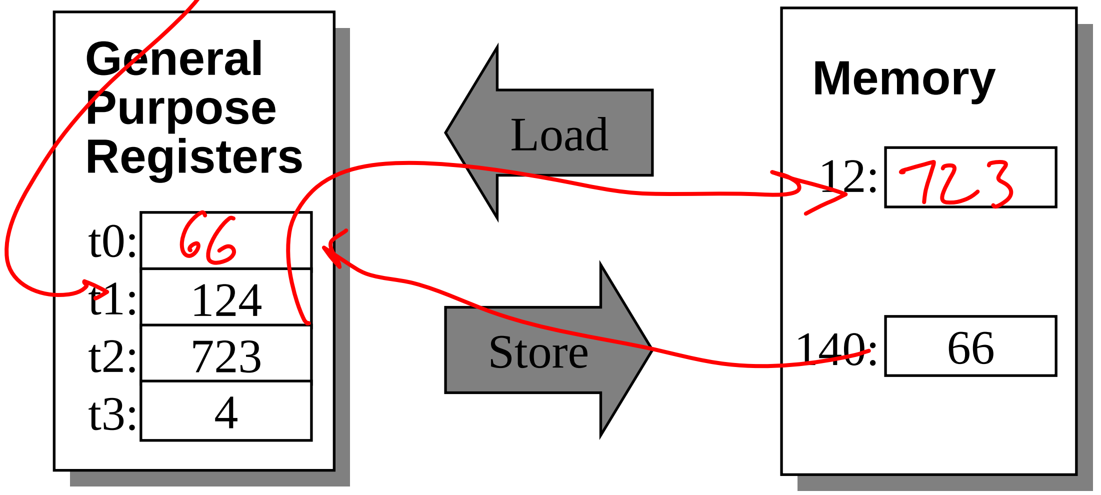


Loads & Stores

- 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
```

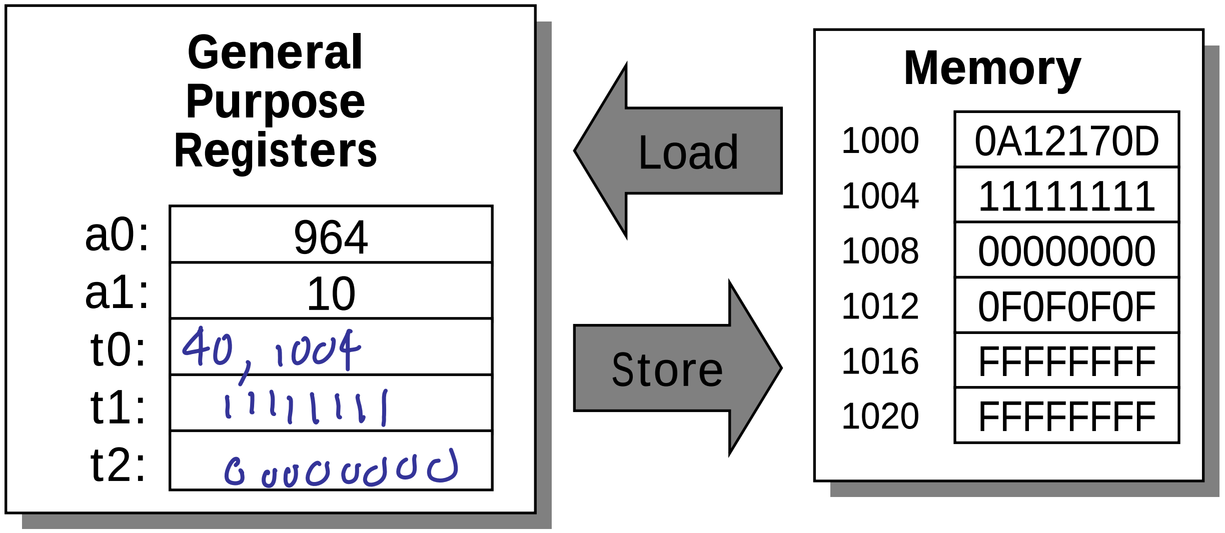


- Note: lbu & sb load & store bytes

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
```



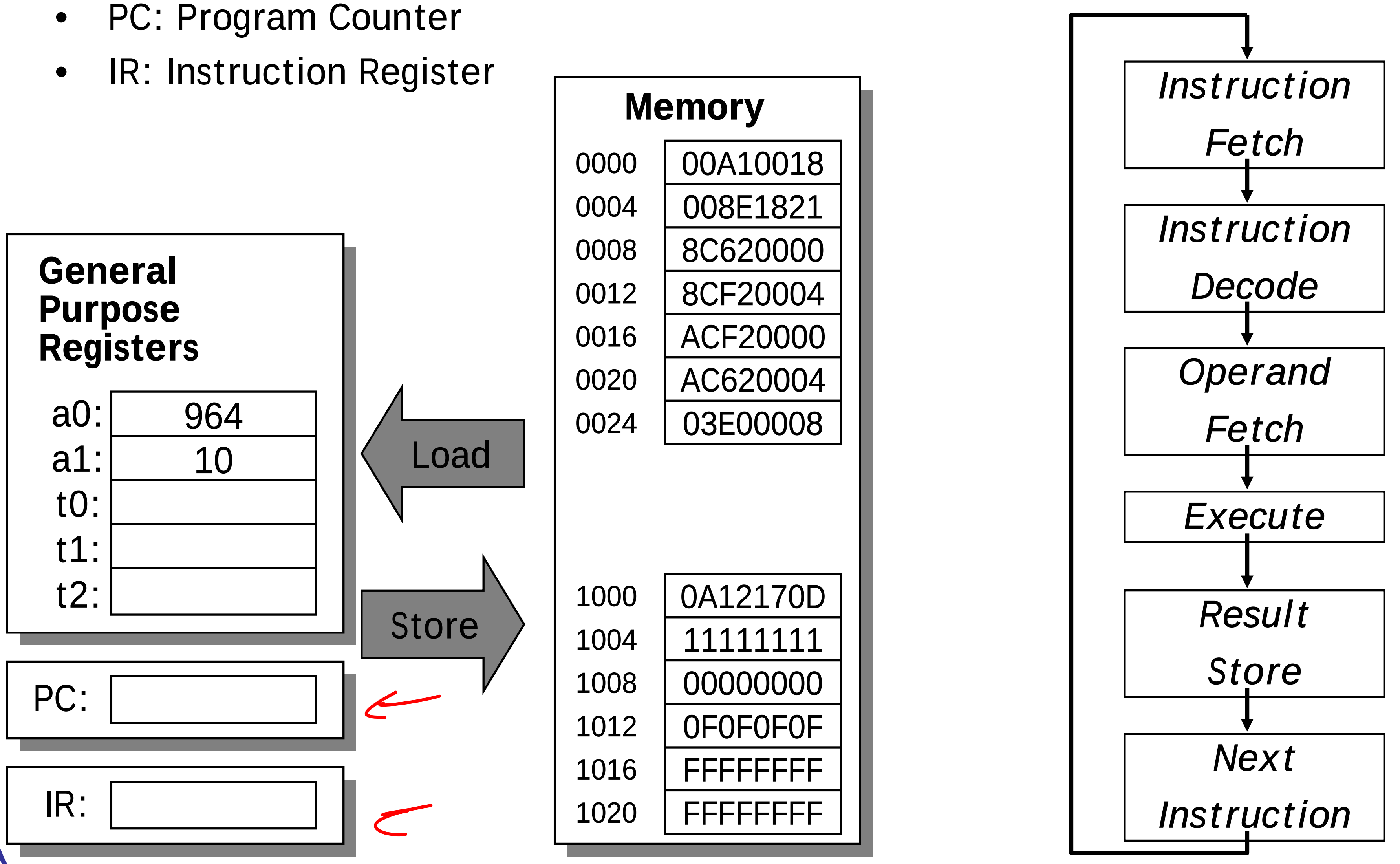
a0:	964
a1:	10
t0:	40, 1004
t1:	11111111
t2:	00000000

1000	0A12170D
1004	11111111
1008	00000000
1012	0F0F0F0F
1016	FFFFFFFF
1020	FFFFFFFF

```
sll  $t0, $a1, 2      ⟶ multiply $a1 by 4.
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



Address	Memory
0000	00A10018
0004	008E1821
0008	8C620000
0012	8CF20004
0016	ACF20000
0020	AC620004
0024	03E00008
1000	0A12170D
1004	11111111
1008	00000000
1012	0F0F0F0F
1016	FFFFFFFF
1020	FFFFFFFF

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, END
   add   $t1, $t1, $t2
   addi  $t2, $t2  1
   j     TOP
END:
```

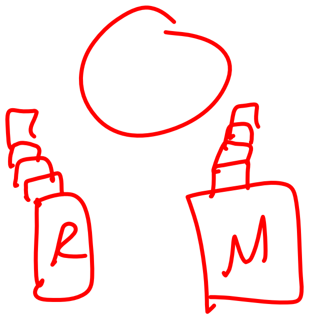
Comparison Operators

- 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
slt $t3, $t0, $t1
bne $t3, $zero, END
add $t2, $t0, $t1
END:
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
```

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[31:2$\overset{8}{6}$], 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

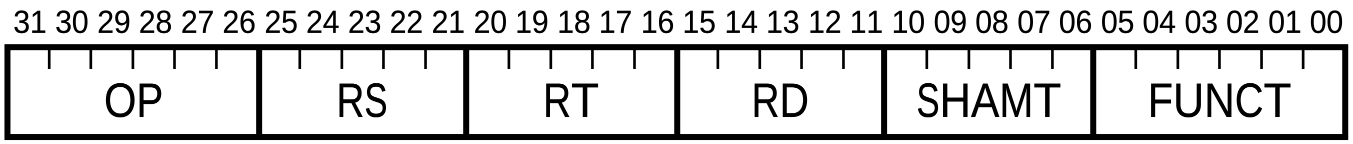
  1-register

  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;
```

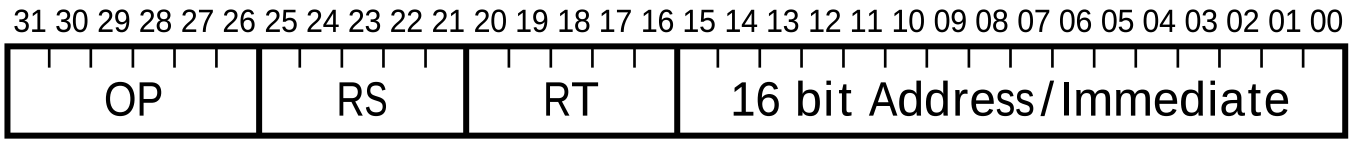
Instruction Formats

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



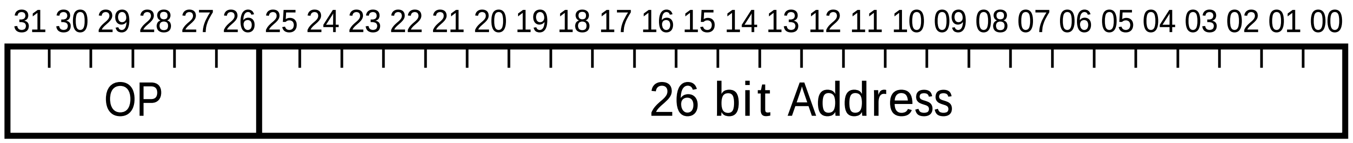
(OP = 0,16-20)

- Immediate (I-type) instructions



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

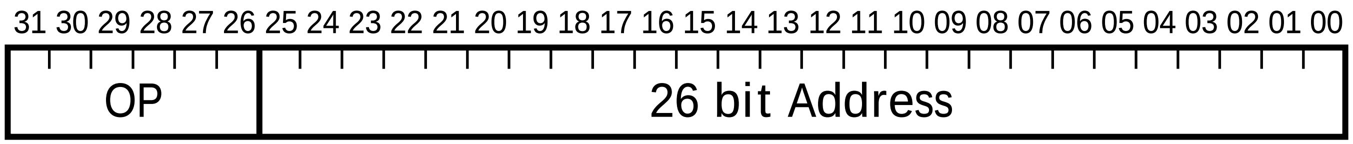
- Jump (J-type) instructions



(OP = 2,3)

J-Type

- Used for unconditional jumps



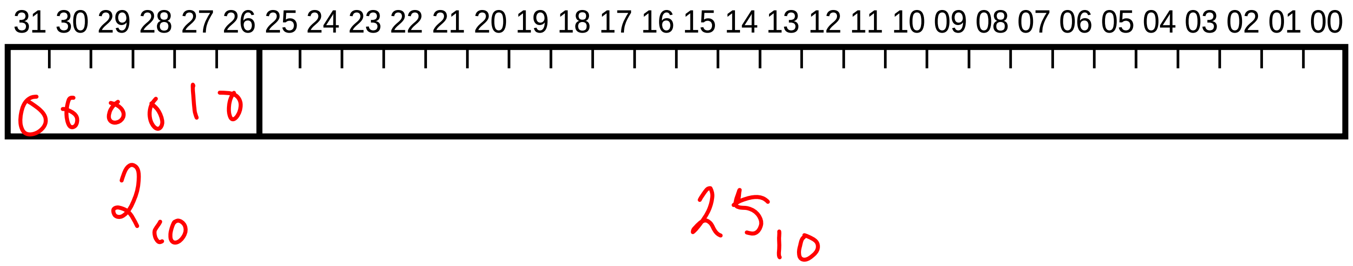
2: j (jump)

3: jal (jump and link)

- Note: top 6 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
8_{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
4_{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

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

```
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

0	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

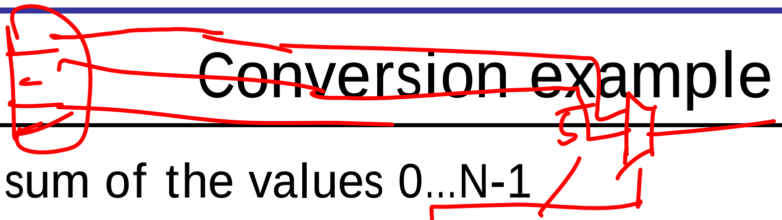
0	?	9	8	6	0

```
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

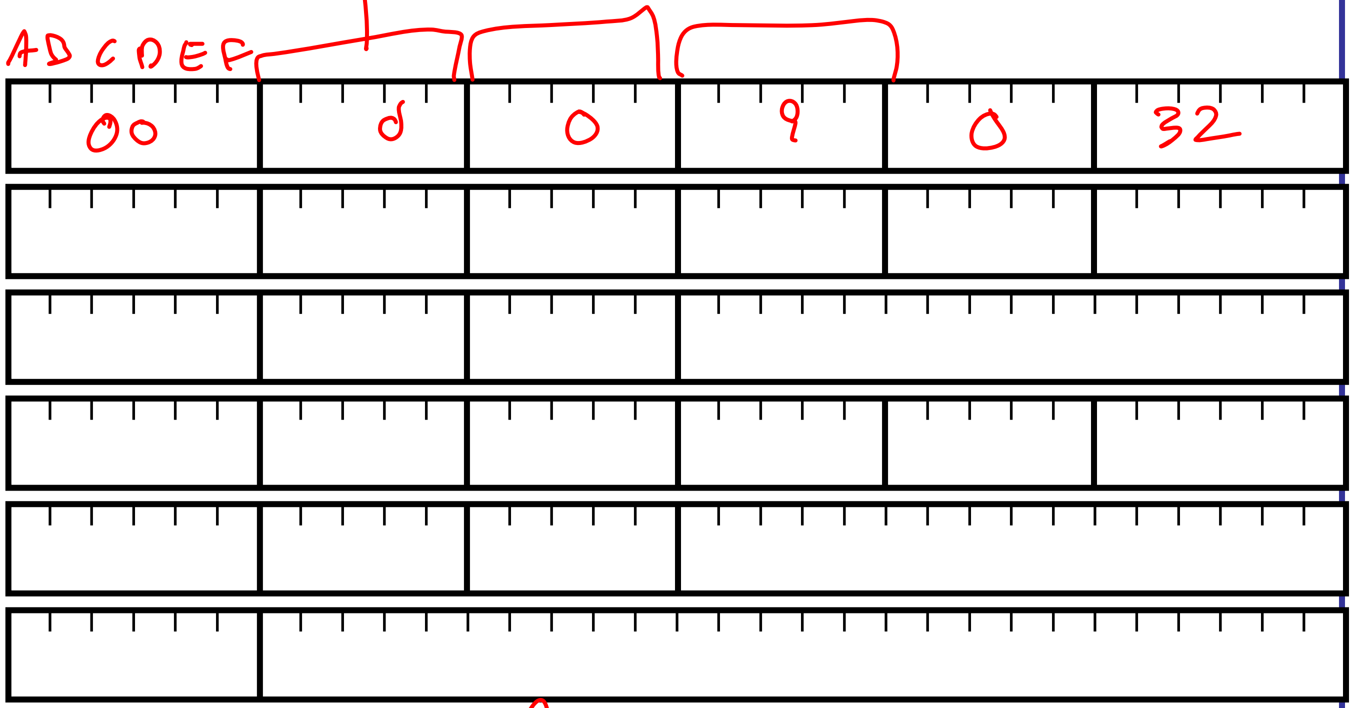
0	10	9	8	0	4

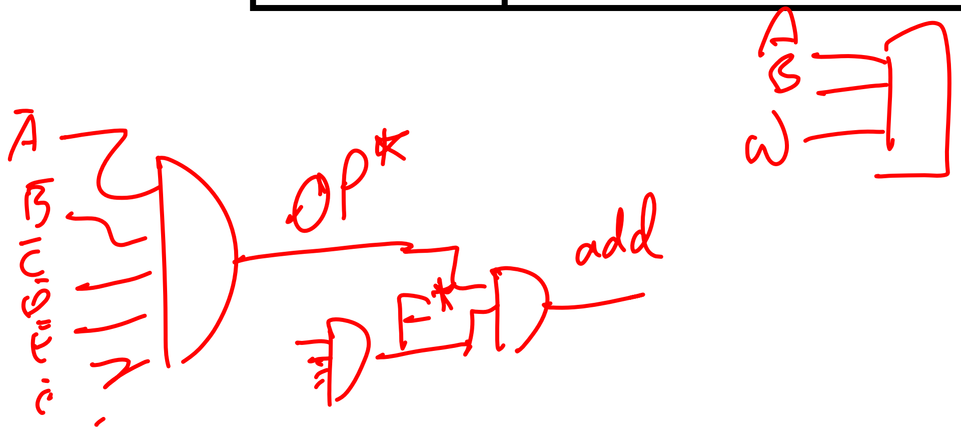
Conversion example



- 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