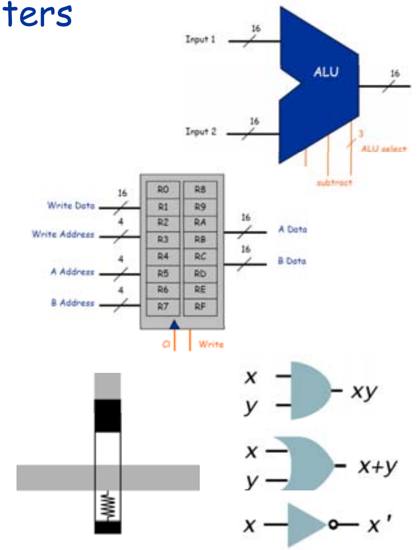
Virtual machines

Abstractions for computers

High-Level Language	Level 5
Assembly Language	Level 4
Operating System	Level 3
Instruction Set Architecture	Level 2
Microarchitecture	Level 1
Digital Logic	**Level 0**



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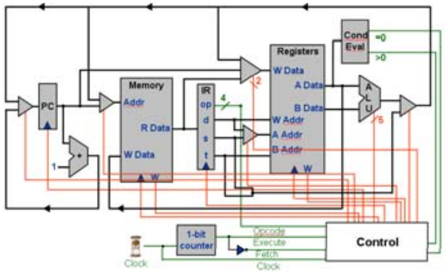

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	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Format 1	opcode				dest d				source s				source t			
Format 2	opcode				dest d				addr							

#	Operation	Fmt	Pseudocode
0:	halt	1	exit(0)
1:	add	1	R[d] ← R[s] + R[t]
2:	subtract	1	R[d] ← R[s] - R[t]
3:	and	1	R[d] ← R[s] & R[t]
4:	xor	1	R[d] ← R[s] ^ R[t]
5:	shift left	1	R[d] ← R[s] << R[t]
6:	shift right	1	R[d] ← R[s] >> R[t]
7:	load addr	2	R[d] ← addr
8:	load	2	R[d] ← mem[addr]
9:	store	2	mem[addr] ← R[d]
A:	load indirect	1	R[d] ← mem[R[t]]
B:	store indirect	1	mem[R[t]] ← R[d]
C:	branch zero	2	if (R[d] == 0) pc ← addr
D:	branch positive	2	if (R[d] > 0) pc ← addr
E:	jump register	1	pc ← R[t]
F:	jump and link	2	R[d] ← pc; pc ← addr

```
10: C020

20: 7101
21: 7A00
22: 7C00

23: 8DFF
24: CD29
25: 12AC
26: BD02
27: 1CC1
28: C023

29: FF2B
2A: 0000
```

Problems with programming using machine code

- Difficult to remember instructions
- Difficult to remember variables
- Hard to calculate addresses/relocate variables or functions
- Need to handle instruction encoding (e.g. jr Rt)

Table B.1 ARM instruction decode table.

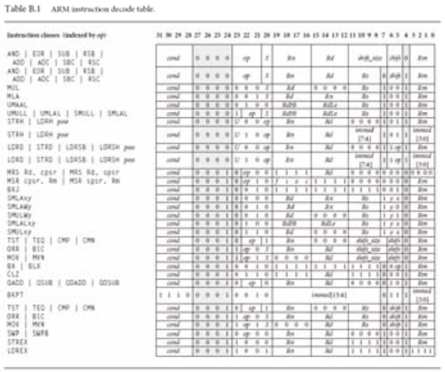
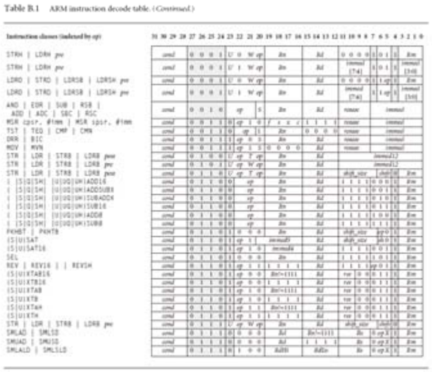


Table B.1 ARM instruction decode table. (Continued)



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Layer	Level
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```
A       DUP    32

        lda    R1, 1
        lda    RA, A
        lda    RC, 0

read    ld     RD, 0xFF
        bz     RD, exit
        add    R2, RA, RC
        sti    RD, R2
        add    RC, RC, R1
        bz     R0, read

exit    jl     RF, printr
        hlt
```

TOY assembly

Introduction to Computer Science · Robert Sedgewick and Kevin Wayne · Copyright © 2005 · http://www.cs.Princeton.EDU/IntroCS

TOY assembly

Not mapping to instruction

- Data directives
- A DW n: initialize a variable A as n
- B DUP n: reserve n words (n is decimal)
- Support two types of literals, decimal and hexadecimal (0x)
- Label begins with a letter
- Comment begins with ;
- Case insensitive
- Program starts with the first instruction it meets

- Some tricks to handle the starting address 0x10

opcode	mnemonic	syntax
0	hlt	hlt
1	add	add rd, rs, rt
2	sub	sub rd, rs, rt
3	and	and rd, rs, rt
4	xor	xor rd, rs, rt
5	shl	shl rd, rs, rt
6	shr	shr rd, rs, rt
7	lda	lda rd, addr
8	ld	ld rd, addr
9	st	st rd, addr
A	ldi	ldi rd, rt
B	sti	sti rd, rt
C	bz	bz rd, addr
D	bp	bp rd, addr
E	jr	jr rd (rt)
F	jl	jl rd, addr

Assembler

Assembler's task:

- Convert mnemonic operation codes to their machine language equivalents
- Convert symbolic operands to their equivalent machine addresses
- Build machine instructions in proper format
- Convert data constants into internal machine representations (data formats)
- Write object program and the assembly listing

Forward Reference

Definition

- A reference to a label that is defined later in the program

Solution

- Two passes
  - First pass: scan the source program for label definition, address accumulation, and address assignment
  - Second pass: perform most of the actual instruction translation

---

Assembly version of REVERSE

```
int A[32];           A      DUP    32             10: C020

                            lda    R1, 1          20: 7101
                            lda    RA, A          21: 7A00
i=0;                        lda    RC, 0          22: 7C00
Do {
  RD=stdin;          read   ld     RD, 0xFF       23: 8DFF
  if (RD==0) break;         bz     RD, exit       24: CD29
                            add    R2, RA, RC     25: 12AC
  A[i]=RD;                  sti    RD, R2         26: BD02
  i=i+1;                    add    RC, RC, R1     27: 1CC1
} while (1);                bz     R0, read       28: C023

printr();            exit   jl     RF, printr     29: FF2B
                            hlt                   2A: 0000
```

Assembly version of REVERSE

```
printr()             ; print reverse
{                    ; array address (RA)
  do {               ; number of elements (RC)
    i=i-1;           printr  sub   RC, RC, R1      2B: 2CC1
                             add   R2, RA, RC      2C: 12AC
                             ldi   RD, R2          2D: AD02
    print A[i];              st    RD, 0xFF        2E: 9DFF
  } while (i>=0);            bp    RC, printr      2F: DC2B
                             bz    RC, printr      30: CC2B
  return;            return  jr    RF              31: EF00
}
```

toyasm < reverse.asm > reverse.toy

Function Call: A Failed Attempt

Goal: x × y × z.

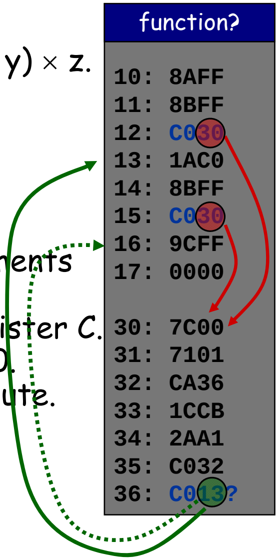
- Need two multiplications: x × y, (x × y) × z.
  - ✐ Solution 1: write multiply code 2 times.
  - ✐ Solution 2: write a TOY function.

A failed attempt:

- Write multiply loop at 30-36.
- Calling program agrees to store arguments in registers A and B.
- Function agrees to leave result in register C.
- Call function with jump absolute to 30.
- Return from function with jump absolute.

Reason for failure.

- ✐ Need to return to a VARIABLE memory address.

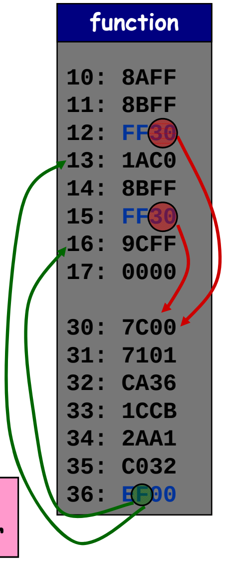

function?

```
10:  8AFF
11:  8BFF
12:  C030
13:  1AC0
14:  8BFF
15:  C030
16:  9CFF
17:  0000

30:  7C00
31:  7101
32:  CA36
33:  1CCB
34:  2AA1
35:  C032
36:  C013?
```

Multiplication Function

Calling convention.

- Jump to line 30.
- Store a and b in registers A and B.
- Return address in register F.
- Put result c = a × b in register C.
- Register 1 is scratch.
- Overwrites registers A and B.



function

```
10: 8AFF
11: 8BFF
12: FF30
13: 1AC0
14: 8BFF
15: FF30
16: 9CFF
17: 0000

30: 7C00
31: 7101
32: CA36
33: 1CCB
34: 2AA1
35: C032
36: EF00
```

function.toy

```
30: 7C00   R[C] ← 00
31: 7101   R[1] ← 01
32: CA36   if (R[A] == 0) goto 36
33: 1CCB   R[C] += R[B]
34: 2AA1   R[A]--
35: C032   goto 32
36: EF00   pc ← R[F]
```

return

opcode E
jump register

Multiplication Function Call

Client program to compute x × y × z.

- Read x, y, z from standard input.
- Note: PC is incremented before instruction is executed.
  - value stored in register F is correct return address

opcode F
jump and link

function.toy (cont)

```
10: 8AFF   read R[A]              x
11: 8BFF   read R[B]              y
12: FF30   R[F] ← pc; goto 30     x * y
13: 1AC0   R[A] ← R[C]            (x * y)
14: 8BFF   read R[B]              z
15: FF30   R[F] ← pc; goto 30     (x * y) * z
16: 9CFF   write R[C]
17: 0000   halt
```

R[F] ← 13

R[F] ← 16

Function Call: One Solution

Contract between calling program and function:

- Calling program stores function parameters in specific registers.
- Calling program stores return address in a specific register.
  - jump-and-link
- Calling program sets PC to address of function.
- Function stores return value in specific register.
- Function sets PC to return address when finished.
  - jump register

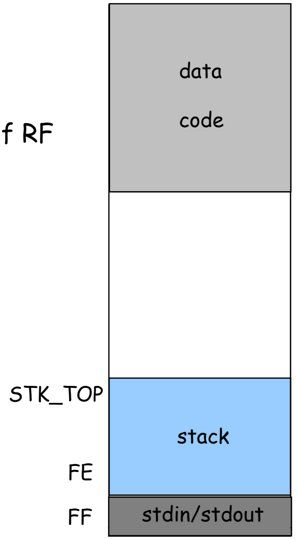
What if you want a function to call another function?

- Use a different register for return address.
- More general: store return addresses on a stack.

---

stack

```
STK_TOP     DW     0xFF

; these procedures will use R8, R9
; assume return address is in RE, instead of RF
; it is the only exception

; push RF into stack
push    lda     R8, 1
        ld      R9, STK_TOP
        sub     R9, R9, R8
        st      R9, STK_TOP
        sti     RF, R9
        jr      RE
```

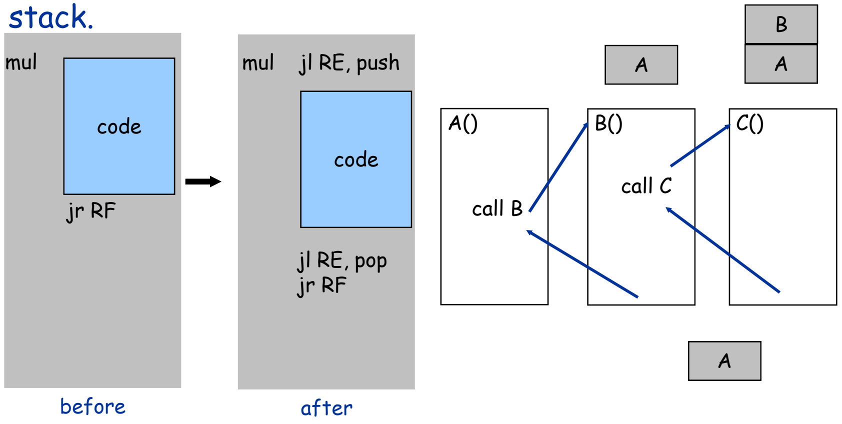


stack

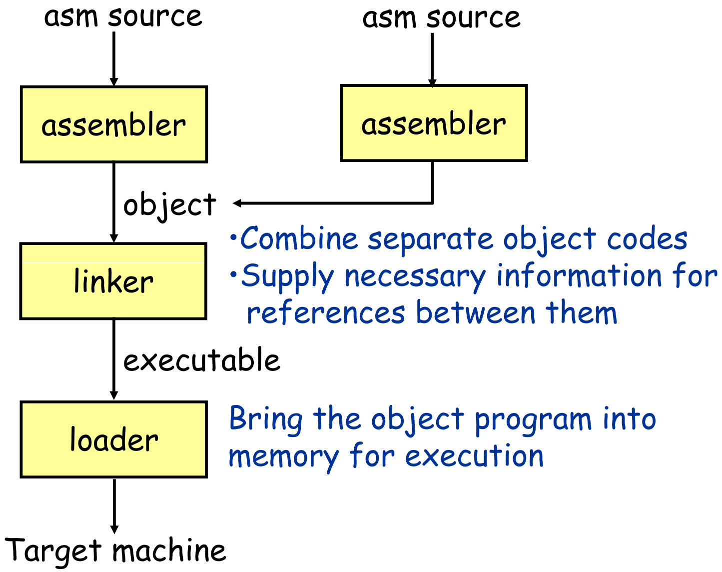
```
; pop and return [top] to RF
pop     lda     R8, 0xFF
        ld      R9, STK_TOP
        sub     R8, R8, R9
        bz      R8, popexit
        ldi     RF, R9
        lda     R8, 1
        add     R9, R9, R8
        st      R9, STK_TOP
popexit jr      RE

; the size of the stack, the result is in R9
stksize lda     R8, 0xFF
        ld      R9, STK_TOP
        sub     R9, R8, R9
        jr      RE
```

Procedure prototype

With a stack, the procedure prototype is changed. It allows us to have a deeper call graph by using the stack.



Assembly programming flow



asm source

asm source

assembler

assembler

object

linker

- Combine separate object codes
- Supply necessary information for references between them

executable

loader

Bring the object program into memory for execution

Target machine

Linking

Many programs will need multiply. Since multiply will be used by many applications, could we make multiply a library?

Toyasm has an option to generate an object file so that it can be later linked with other object files.

That is why we need linking. Write a subroutine mul3 which multiplies three numbers in RA, RB, RC together and place the result in RD.
Three files:

- stack.obj: implementation of stack, needed for procedure
- mul.obj: implementation of multiplication.
- multest.obj: main program and procedure of mul3

`toylink multest.obj mul.obj stack.obj > multest.toy`

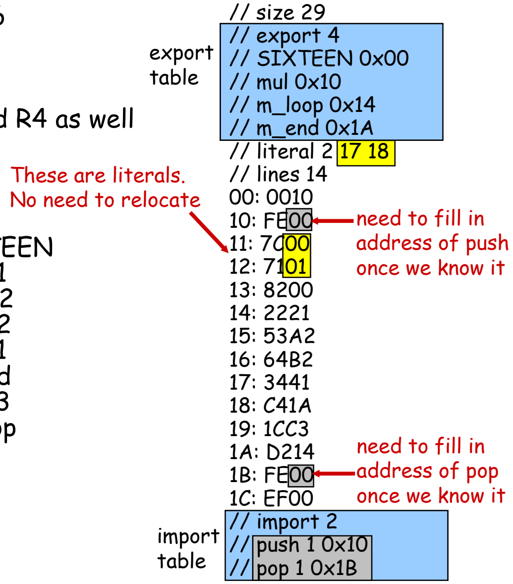
object file (multest.asm)

```
A       DW      3
B       DW      4
C       DW      5

; calculate A*B*C
main    ld      RA, A
        ld      RB, B
        ld      RC, C
        jl      RF, mul3
        st      RD, 0xFF
        hlt

; RD=RA*RB*RC
; return address is in RF
mul3    jl      RE, push

        lda     RD, 0
        add     RD, RC, R0
        jl      RF, mul
        add     RA, RC, R0
        add     RB, RD, R0
        jl      RF, mul
        add     RD, RC, R0

        jl      RE, pop
        jr      RF
```

---

object file (mul.obj)

```
SIXTEEN     DW      16

; multiply RC=RA*RB
; return address is in RF
; it will modify R2, R3 and R4 as well
mul         jl      RE, push

            lda     RC, 0
            lda     R1, 1
            ld      R2, SIXTEEN
m_loop      sub     R2, R2, R1
            shl     R3, RA, R2
            shr     R4, RB, R2
            and     R4, R4, R1
            bz      R4, m_end
            add     RC, RC, R3
m_end       bp      R2, m_loop

            jl      RE, pop
            jr      RF
```



```
// size 29
// export 4
// SIXTEEN 0x00
// mul 0x10
// m_loop 0x14
// m_end 0x1A
// literal 2 17 18
// lines 14
00: 0010
10: FE00
11: 7C00
12: 7101
13: 8200
14: 2221
15: 53A2
16: 64B2
17: 3441
18: C41A
19: 1CC3
1A: D214
1B: FE00
1C: EF00
// import 2
// push 1 0x10
// pop 1 0x1B
```

export table

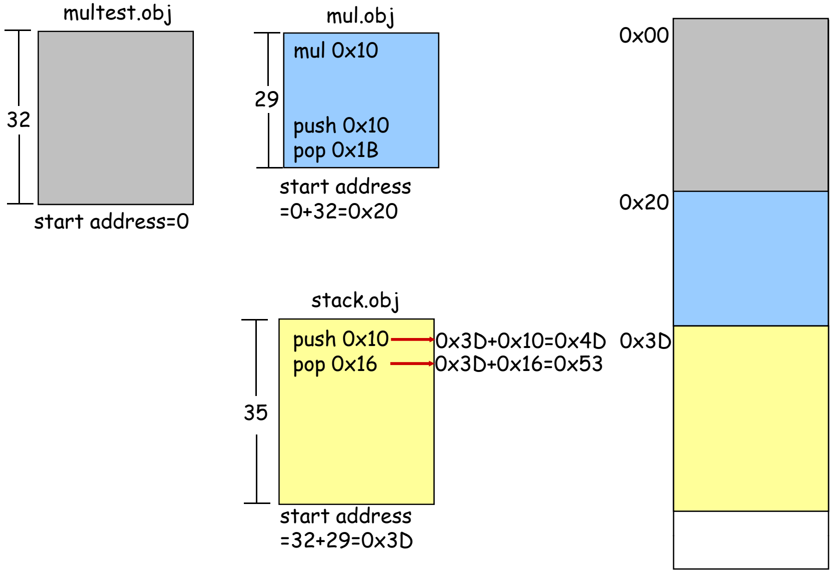
These are literals. No need to relocate

need to fill in address of push once we know it

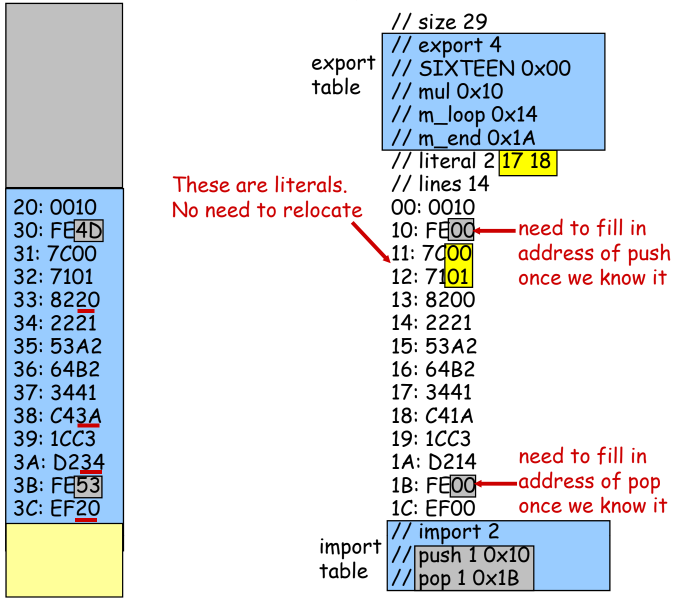
need to fill in address of pop once we know it

import table

Linking



Resolve external symbols



```
20: 0010
30: FE4D
31: 7C00
32: 7101
33: 8220
34: 2221
35: 53A2
36: 64B2
37: 3441
38: C43A
39: 1CC3
3A: D234
3B: FE53
3C: EF20
```

```
// size 29
// export 4
// SIXTEEN 0x00
// mul 0x10
// m_loop 0x14
// m_end 0x1A
// literal 2 17 18
// lines 14
00: 0010
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1C: EF00
// import 2
// push 1 0x10
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```

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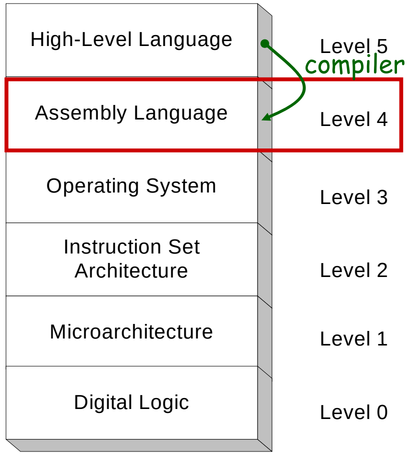
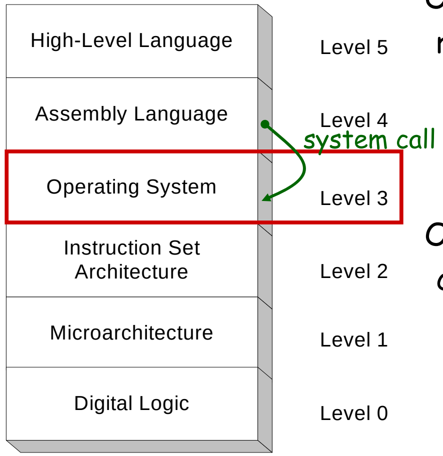


```
A       DUP     32

        lda     R1, 1
        lda     RA, A
        lda     RC, 0

read    ld      RD, 0xFF
        bz      RD, exit
        add     R2, RA, RC
        sti     RD, R2
        add     RC, RC, R1
        bz      R0, read

exit    jl      RF, printr
        hlt
```

Virtual machines

Abstractions for computers



Operating system is a resource allocator

- Managing all resources (memory, I/O, execution)
- Resolving requests for efficient and fair usage

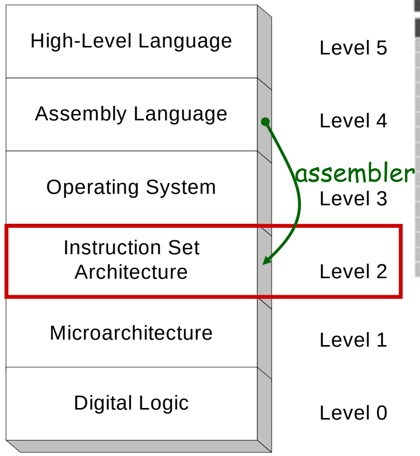
Operating system is a control program

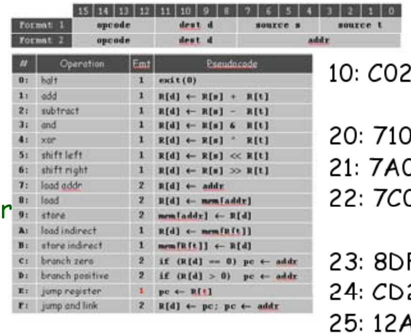
- Controlling execution of programs to prevent errors and improper use of the computer

---

Virtual machines

Abstractions for computers





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Format 1	opcode				dest d				source s				source t			
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4:	xor	1	R[d] ← R[s] ^ R[t]
5:	shift left	1	R[d] ← R[s] << R[t]
6:	shift right	1	R[d] ← R[s] >> R[t]
7:	load addr	2	R[d] ← addr
8:	load	2	R[d] ← mem[addr]
9:	store	2	mem[addr] ← R[d]
A:	load indirect	1	R[d] ← mem[R[t]]
B:	store indirect	1	mem[R[t]] ← R[d]
C:	branch zero	2	if (R[d] == 0) pc ← addr
D:	branch positive	2	if (R[d] > 0) pc ← addr
E:	jump register	1	pc ← R[t]
F:	jump and link	2	R[d] ← pc; pc ← addr

```
10: C020

20: 7101
21: 7A00
22: 7C00

23: 8DFF
24: CD29
25: 12AC
26: BD02
27: 1CC1
28: C023

29: FF2B
2A: 0000
```

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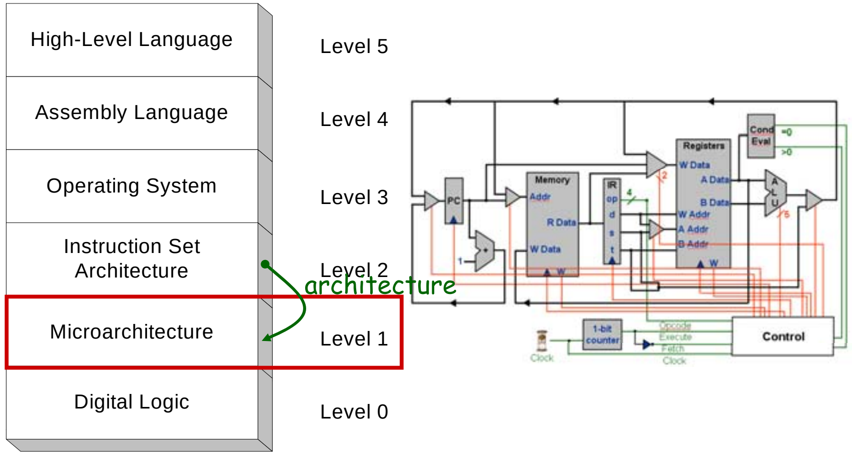

Virtual machines

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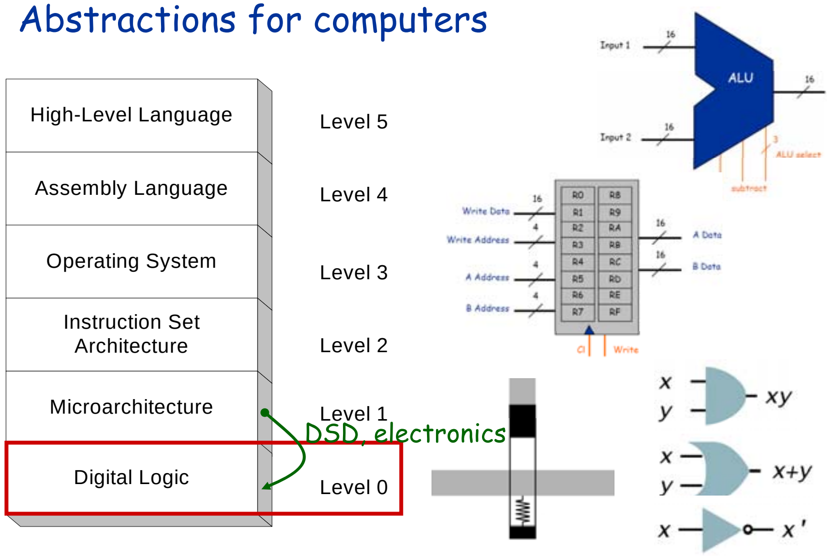

High-Level Language	Level 5
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DSD, electronics

Assignment #2

Assigned: 11/03/2008
Due: 11:59pm 11/16/2008
Part 1 (50%): write a procedure BCD to convert a hexadecimal number into a BCD (Binary-Coded Decimal). The input number is placed in RA. The result should be placed in RB. The return address is in RF. (Hint: you need to implement division)

Part 2 (30%): write a procedure CNT0 to count 0's in an array. The address of the array is placed at RA. The size of the array is specified by RC. The result should be placed in RB. The return address is in RF.

Part 3 (20%): write a program to read a series of numbers specified by the user from stdin until the input is 0x0000. Count the number of 0-bits in the input array and display this number using BCD in stdout.