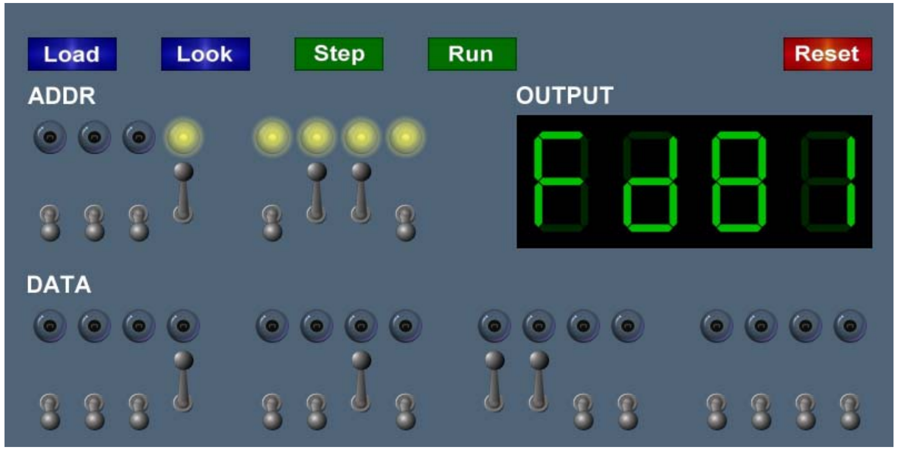
The TOY Machine



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Basic Characteristics of TOY Machine

TOY is a general-purpose computer.

- Sufficient power to perform ANY computation.
- Limited only by amount of memory and time.

Stored-program computer. (von Neumann memo, 1944)

- Data and instructions encoded in binary.
- Data and instructions stored in SAME memory.

John von Neumann

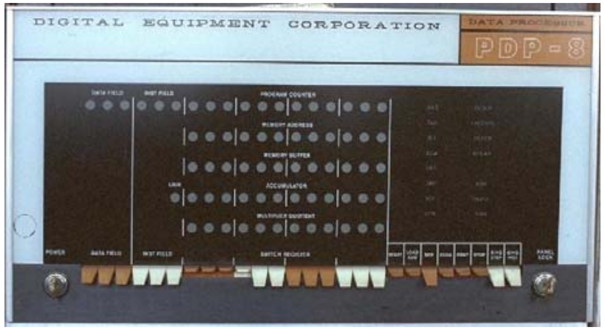
Maurice Wilkes (left)
EDSAC (right)

All modern computers are general-purpose computers and have same (von Neumann/Princeton) architecture.

What is TOY?

An imaginary machine similar to:

- Ancient computers. (PDP-8, world's first commercially successful minicomputer. 1960s)
    - 12-bit words
    - 2K words of memory
    - Used in Apollo project



What is TOY?

An imaginary machine similar to:

- Ancient computers.
- Today's microprocessors.

Pentium Celeron

What is TOY?

An imaginary machine similar to:

- Ancient computers.
- Today's microprocessors.

Why study TOY?

- Machine language programming.
  - how do high-level programs relate to computer?
  - a favor of assembly programming
- Computer architecture.
  - how is a computer put together?
  - how does it work?
- Optimized for understandability, not cost or performance.

Inside the Box

Switches. Input data and programs.

Lights. View data.

Memory.

- Stores data and programs.
- 256 "words." (16 bits each)
- Special word for stdin / stdout.

Program counter (PC).

- An extra 8-bit register.
- Keeps track of next instruction to be executed.

Registers.

- Fastest form of storage.
- Scratch space during computation.
- 16 registers. (16 bits each)
- Register 0 is always 0.

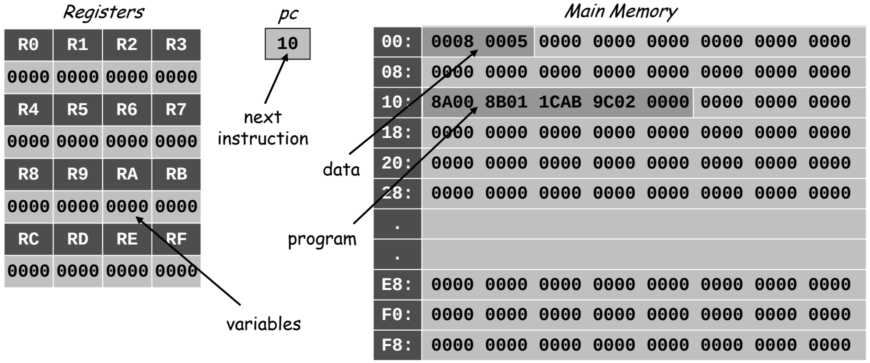
Arithmetic-logic unit (ALU). Manipulate data stored in registers.

Standard input, standard output. Interact with outside world.

Machine "Core" Dump

Machine contents at a particular place and time.

- Record of what program has done.
- Completely determines what machine will do.



Registers

R0	R1	R2	R3
0000	0000	0000	0000
R4	R5	R6	R7
0000	0000	0000	0000
R8	R9	RA	RB
0000	0000	0000	0000
RC	RD	RE	RF
0000	0000	0000	0000

pc

10

Main Memory

```
00: 0008 0005 0000 0000 0000 0000 0000 0000
08: 0000 0000 0000 0000 0000 0000 0000 0000
10: 8A00 8B01 1CAB 9C02 0000 0000 0000 0000
18: 0000 0000 0000 0000 0000 0000 0000 0000
20: 0000 0000 0000 0000 0000 0000 0000 0000
28: 0000 0000 0000 0000 0000 0000 0000 0000
 .
 .
E8: 0000 0000 0000 0000 0000 0000 0000 0000
F0: 0000 0000 0000 0000 0000 0000 0000 0000
F8: 0000 0000 0000 0000 0000 0000 0000 0000
```

Program and Data

Program: Sequence of instructions.

16 instruction types:

- 16-bit word (interpreted one way).
- Changes contents of registers, memory, and
  PC in specified, well-defined ways.

Data:

- 16-bit word (interpreted other way).

Program counter (PC):

- Stores memory address of "next instruction."
- TOY usually starts at address 10.

Instructions

0:	halt
1:	add
2:	subtract
3:	and
4:	xor
5:	shift left
6:	shift right
7:	load address
8:	load
9:	store
A:	load indirect
B:	store indirect
C:	branch zero
D:	branch positive
E:	jump register
F:	jump and link

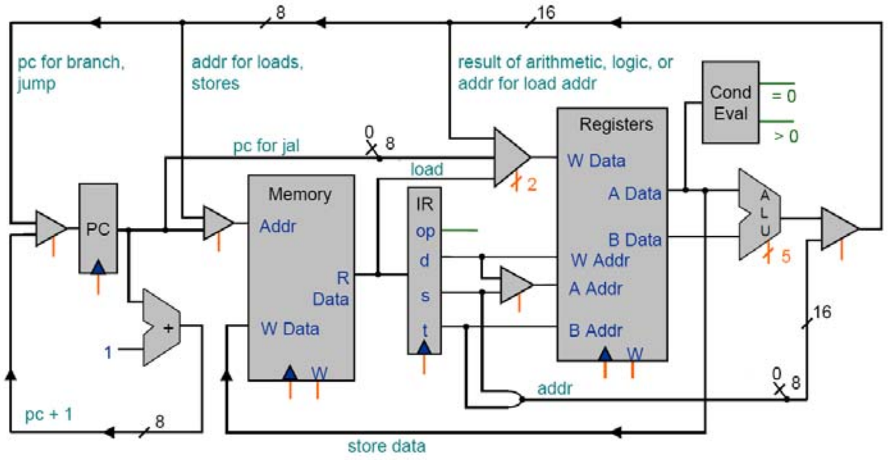
TOY Reference Card

	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`

Register 0 always 0.
Loads from `mem[FF]` from stdin.
Stores to `mem[FF]` to stdout.

TOY Architecture (level 1)



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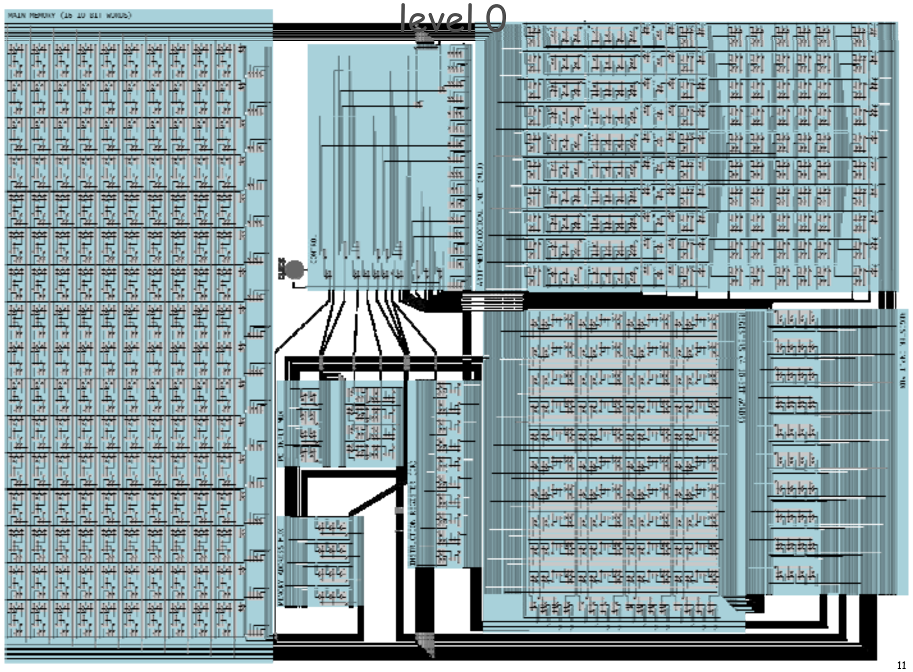
level 0



Programming in TOY

Hello, World. Add two numbers.

- Adds 8 + 5 = D.

A Sample Program

A sample program.

- Adds 8 + 5 = D.

RA	RB	RC
0000	0000	0000

Registers

pc
10

```
00: 0008    8            add.toy
01: 0005    5

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9CFF    mem[FF] ← RC
14: 0000    halt
```

Memory

Since PC = 10, machine interprets 8A00 as an instruction.

Load

Load. (opcode 8)

- Loads the contents of some memory location into a register.
- **8A00** means load the contents of memory cell **00** into register **A**.

RA	RB	RC
0000	0000	0000

Registers

pc
10

```
00: 0008    8            add.toy
01: 0005    5

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9CFF    mem[FF] ← RC
14: 0000    halt
```

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
8_{16}				A_{16}				00_{16}							
opcode				dest d				addr							

Load

Load. (opcode 8)

- Loads the contents of some memory location into a register.
- **8B01** means load the contents of memory cell **01** into register **B**.

RA	RB	RC
0008	0000	0000

Registers

pc
11

```
00: 0008    8            add.toy
01: 0005    5

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9CFF    mem[FF] ← RC
14: 0000    halt
```

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	0	1	0	1	1	0	0	0	0	0	0	0	1
8_{16}				B_{16}				01_{16}							
opcode				dest d				addr							

Add

Add. (opcode 1)

- Add contents of two registers and store sum in a third.
- **1CAB** adds the contents of registers **A** and **B** and put the result into register **C**.

RA	RB	RC
0008	0005	0000

Registers

pc
12

```
00: 0008    8            add.toy
01: 0005    5

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9CFF    mem[FF] ← RC
14: 0000    halt
```

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	1	1	1	0	0	1	0	1	0	1	0	1	1
1_{16}				C_{16}				A_{16}				B_{16}			
opcode				dest d				source s				source t			

Store

Store. (opcode 9)

- Stores the contents of some register into a memory cell.
- **9CFF** means store the contents of register **C** into memory cell **FF** (stdout).

RA	RB	RC
0008	0005	000D

Registers

pc
13

add.toy

```
00: 0008    8
01: 0005    5

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9CFF    mem[FF] ← RC
14: 0000    halt
```

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
1	0	0	1	1	1	0	0	0	0	0	0	0	0	1	0
9_{16}				C_{16}				02_{16}							
opcode				dest d				addr							

Halt

Halt. (opcode 0)

- Stop the machine.

RA	RB	RC
0008	0005	000D

Registers

pc
14

add.toy

```
00: 0008    8
01: 0005    5

10: 8A00    RA ← mem[00]
11: 8B01    RB ← mem[01]
12: 1CAB    RC ← RA + RB
13: 9CFF    mem[FF] ← RC
14: 0000    halt
```

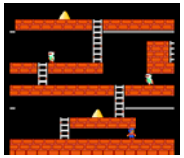
Simulation

Consequences of simulation.

- Test out new machine or microprocessor using simulator.
  - cheaper and faster than building actual machine
- Easy to add new functionality to simulator.
  - trace, single-step, breakpoint debugging
  - simulator more useful than TOY itself
- Reuse software from old machines.

Ancient programs still running on modern computers.

- Lode Runner on Apple IIe.
- Gameboy simulator on PCs.



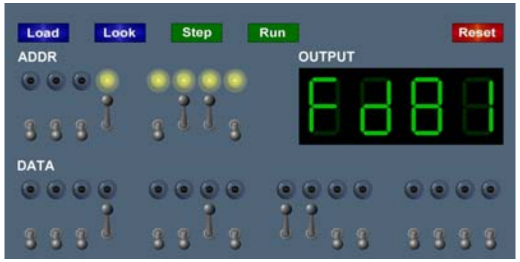
Interfacing with the TOY Machine

To enter a program or data:

- Set 8 memory address switches.
- Set 16 data switches.
- Press LOAD.
  - data written into addressed word of memory

To view the results of a program:

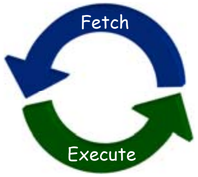
- Set 8 memory address switches.
- Press LOOK: contents of addressed word appears in lights.



Using the TOY Machine: Run

To run the program:

- Set 8 memory address switches to address of first instruction.
- Press LOOK to set PC to first instruction.
- Press RUN button to repeat fetch-execute cycle until halt opcode.



Branch in TOY

To harness the power of TOY, need loops and conditionals.

- Manipulate PC to control program flow.

Branch if zero. (opcode C)

- Changes PC depending of value of some register.
- Used to implement: `for`, `while`, `if-else`.

Branch if positive. (opcode D)

- Analogous.

An Example: Multiplication

Multiply.

- No direct support in TOY hardware.
- Load in integers a and b, and store c = a × b.
- Brute-force algorithm:
  - initialize c = 0
  - add b to c, a times

```
int a = 3;
int b = 9;
int c = 0;

while (a != 0) {
   c = c + b;
   a = a - 1;
}
```

Java

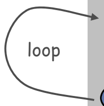
Issues ignored: slow, overflow, negative numbers.

Multiply

```
int a = 3;
int b = 9;
int c = 0;

while (a != 0) {
   c = c + b;
   a = a - 1;
}
```

Multiply

```
0A: 0003   3  ← inputs
0B: 0009   9
0C: 0000   0  ← output

0D: 0000   0  ← constants
0E: 0001   1

10: 8A0A   RA ← mem[0A]             a
11: 8B0B   RB ← mem[0B]             b
12: 8C0D   RC ← mem[0D]             c = 0

13: 810E   R1 ← mem[0E]             always 1

14: CA18   if (RA == 0) pc ← 18     while (a != 0) {
15: 1CCB   RC ← RC + RB                c = c + b
16: 2AA1   RA ← RA - R1                a = a - 1
17: C014   pc ← 14                  }

18: 9CFF   mem[FF] ← RC
19: 0000   halt
```



multiply.toy

Step-By-Step Trace

		R1	RA	RB	RC
10: 8A0A	RA ← mem[0A]		0003		
11: 8B0B	RB ← mem[0B]			0009	
12: 8C0D	RC ← mem[0D]				0000
13: 810E	R1 ← mem[0E]	0001			
14: CA18	if (RA == 0) pc ← 18				
15: 1CCB	RC ← RC + RB				0009
16: 2AA1	RA ← RA - R1		0002		
17: C014	pc ← 14				
14: CA18	if (RA == 0) pc ← 18				
15: 1CCB	RC ← RC + RB				0012
16: 2AA1	RA ← RA - R1		0001		
17: C014	pc ← 14				
14: CA18	if (RA == 0) pc ← 18				
15: 1CCB	RC ← RC + RB				001B
16: 2AA1	RA ← RA - R1		0000		
17: C014	pc ← 14				
14: CA18	if (RA == 0) pc ← 18				
18: 9CFF	mem[FF] ← RC				
19: 0000	halt				

multiply.toy

An Efficient Multiplication Algorithm

Inefficient multiply.

- Brute force multiplication algorithm loops **a** times.
- In worst case, 65,535 additions!

"Grade-school" multiplication.

- Always 16 additions to multiply 16-bit integers.

Decimal

```
        1 2 3 4
      * 1 5 1 2
        2 4 6 8
      1 2 3 4
    6 1 7 0
  1 2 3 4
0 1 8 6 5 8 0 8
```

Binary

```
        1 0 1 1
      * 1 1 0 1
        1 0 1 1
      0 0 0 0
    1 0 1 1
  1 0 1 1
1 0 0 0 1 1 1 1
```

Binary Multiplication

Grade school binary multiplication algorithm to compute c = a × b.

- Initialize c = 0.
- Loop over i bits of b.
  - if b_i = 0, do nothing ⬅ b_i = i^{th} bit of b
  - if b_i = 1, shift a left i bits and add to c

```
        1 0 1 1     a
      * 1 1 0 1     b
        1 0 1 1     a << 0
      0 0 0 0
    1 0 1 1         a << 2
  1 0 1 1           a << 3
1 0 0 0 1 1 1 1     c
```

Implement with built-in TOY shift instructions.

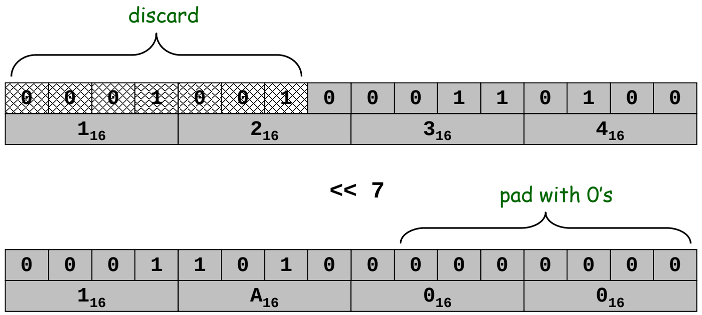
```
int c = 0;
for (int i = 15; i >= 0; i--)
   if (((b >> i) & 1) == 1)
      c = c + (a << i);
```

⬅ b_i = i^{th} bit of b

Shift Left

Shift left. (opcode 5)

- Move bits to the left, padding with zeros as needed.
- 1234_{16} << 7_{16} = $1A00_{16}$



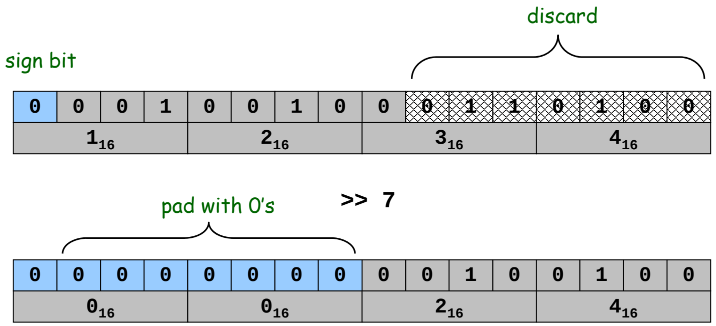
0	0	0	1	0	0	1	0	0	0	1	1	0	1	0	0
1_{16}				2_{16}				3_{16}				4_{16}			

0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0
1_{16}				A_{16}				0_{16}				0_{16}			

Shift Right

Shift right. (opcode 6)

- Move bits to the right, padding with sign bit as needed.
- 1234_{16} >> 7_{16} = 0024_{16}



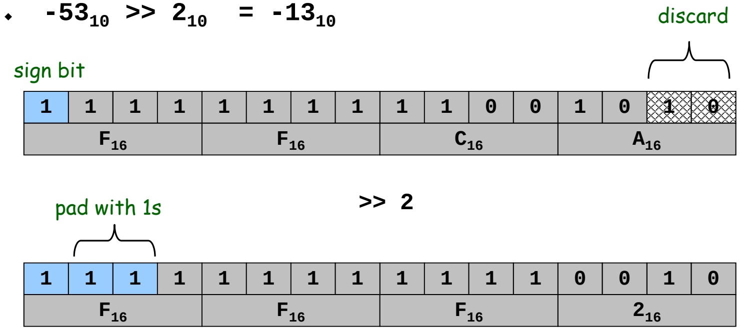
0	0	0	1	0	0	1	0	0	0	1	1	0	1	0	0
1_{16}				2_{16}				3_{16}				4_{16}			

0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
0_{16}				0_{16}				2_{16}				4_{16}			

Shift Right (Sign Extension)

Shift right. (opcode 6)

- Move bits to the right, padding with sign bit as needed.
- $FFCA_{16}$ >> 2_{16} = $FFF2_{16}$
- -53_{10} >> 2_{10} = -13_{10}



1	1	1	1	1	1	1	1	1	1	0	0	1	0	1	0
F_{16}				F_{16}				C_{16}				A_{16}			

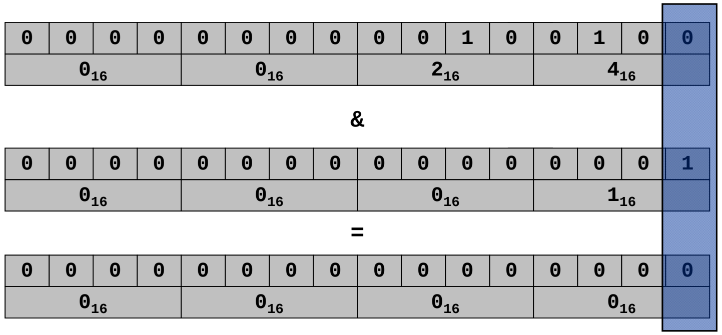
1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0
F_{16}				F_{16}				F_{16}				2_{16}			

Bitwise AND

x	y	AND
0	0	0
0	1	0
1	0	0
1	1	1

Logical AND. (opcode 3)

- Logic operations are BITWISE.
- 0024_{16} & 0001_{16} = 0000_{16}



0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
0_{16}				0_{16}				2_{16}				4_{16}			

&

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0_{16}				0_{16}				0_{16}				1_{16}			

=

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0_{16}				0_{16}				0_{16}				0_{16}			

Shifting and Masking

Shift and mask: get the 7th bit of 1234.

- Compute 1234_{16} >> 7_{16} = 0024_{16}.
- Compute 0024_{16} && 1_{16} = 0_{16}.

0	0	0	1	0	0	1	0	0	0	1	1	0	1	0	0
1_{16}				2_{16}				3_{16}				4_{16}			

>> 7

0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
0_{16}				0_{16}				2_{16}				4_{16}			

&

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0_{16}				0_{16}				0_{16}				1_{16}			

=

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0_{16}				0_{16}				0_{16}				0_{16}			

Binary Multiplication

```
int c = 0;
for (int i = 15; i >= 0; i--)
   if (((b >> i) & 1) == 1)
      c = c + (a << i);
```

Binary Multiplication

```
        0A: 0003     3   ⇐    inputs
        0B: 0009     9
        0C: 0000     0   ⇐    output
        0D: 0000     0
        0E: 0001     1   ⇐    constants
        0F: 0010    16

        10: 8A0A    RA ← mem[0A]           a
        11: 8B0B    RB ← mem[0B]           b
        12: 8C0D    RC ← mem[0D]           c = 0
        13: 810E    R1 ← mem[0E]           always 1
        14: 820F    R2 ← mem[0F]           i = 16  ⇐  16 bit words

loop                                       do {
        15: 2221    R2 ← R2 -  R1             i--
        16: 53A2    R3 ← RA << R2             a << i
        17: 64B2    R4 ← RB >> R2             b >> i
branch  18: 3441    R4 ← R4 &  R1             b_i = i^th bit of b
        19: C41B    if (R4 == 0) goto 1B      if b_i is 1
        1A: 1CC3    RC ← RC + R3                 add a << i to sum
        1B: D215    if (R2 > 0) goto 15    } while (i > 0);

        1C: 9CFF    mem[FF] ← RC
```

multiply-fast.toy

Useful TOY "Idioms"

Jump absolute.

- Jump to a fixed memory address.
  - branch if zero with destination
  - register 0 is always 0

```
17: C014   pc ← 14
```

Register assignment.

- No instruction that transfers contents of one register into another.
- Pseudo-instruction that simulates assignment:
  - add with register 0 as one of two source registers

```
17: 1230   R[2] ← R[3]
```

No-op.

- Instruction that does nothing.
- Plays the role of whitespace in C programs.
  - numerous other possibilities!

```
17: 1000   no-op
```

Standard Input and Output: Implications

Standard input and output enable you to:

- Process more information than fits in memory.
- Interact with the computer while it is running.

Standard output.

- Writing to memory location **`FF`** sends one word to TOY stdout.
- **`9AFF`** writes the integer in register **`A`** to stdout.

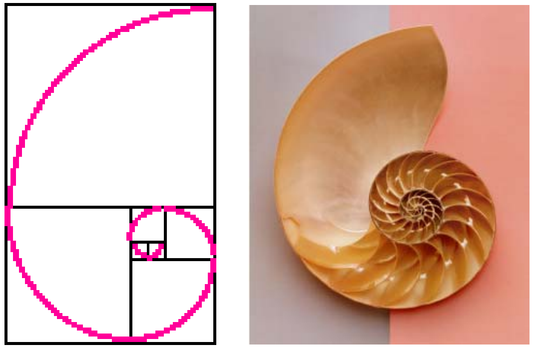
Standard input.

- Loading from memory address **`FF`** loads one word from TOY stdin.
- **`8AFF`** reads in an integer from stdin and store it in register **`A`**.

Fibonacci Numbers

Fibonacci sequence: 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, . . .

$$F_n = \begin{cases} 0 & \text{if } n = 0 \\ 1 & \text{if } n = 1 \\ F_{n-1} + F_{n-2} & \text{otherwise} \end{cases}$$



Reference: http://www.mcs.surrey.ac.uk/Personal/R.Knott/Fibonacci/fibnat.html

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Standard Output

```
00: 0000   0
01: 0001   1

10: 8A00   RA ← mem[00]            a = 0
11: 8B01   RB ← mem[01]            b = 1
                                   do {
12: 9AFF   print RA                   print a
13: 1AAB   RA ← RA + RB               a = a + b
14: 2BAB   RB ← RA - RB               b = a - b
15: DA12   if (RA > 0) goto 12     } while (a > 0)
16: 0000   halt
```

fibonacci.toy

```
0000
0001
0001
0002
0003
0005
0008
000D
0015
0022
0037
0059
0090
00E9
0179
0262
03DB
063D
0A18
1055
1A6D
2AC2
452F
6FF1
```

Standard Input

Ex: read in a sequence of integers and print their sum.

- In Java, stop reading when EOF.
- In TOY, stop reading when user enters **`0000`**.

```
while(!StdIn.isEmpty()) {
   a = StdIn.readInt();
   sum = sum + a;
}
System.out.println(sum);
```

```
00: 0000   0

10: 8C00   RC <- mem[00]
11: 8AFF   read RA
12: CA15   if (RA == 0) pc ← 15
13: 1CCA   RC ← RC + RA
14: C011   pc ← 11
15: 9CFF   write RC
16: 0000   halt
```

```
00AE
0046
0003
0000
00F7
```

Load Address (a.k.a. Load Constant)

Load address. (opcode 7)

- Loads an 8-bit integer into a register.
- **7A30** means load the value **30** into register **A**.

Applications.

```
a = 30;
```

Java code

- Load a small constant into a register.
- Load a 8-bit memory address into a register.
  - register stores "pointer" to a memory cell

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	1	1	1	1	0	1	0	0	0	1	1	0	0	0	0
7_{16}				A_{16}				3_{16}				0_{16}			
opcode				dest d				addr							

Arrays in TOY

TOY main memory is a giant array.

- Can access memory cell **30** using load and store.
- **8C30** means load **mem[30]** into register **C**.
- Goal: access memory cell **i** where **i** is a variable.

Load indirect. (opcode A)

- **AC06** means load **mem[R6]** into register **C**.

a variable index (like a pointer)

Store indirect. (opcode B)

- **BC06** means store contents of register **C** into **mem[R6]**.

a variable index

```
for (int i = 0; i < N; i++)
   a[i] = StdIn.readInt();

for (int i = 0; i < N; i++)
   System.out.println(a[N-i-1]);
```

Reverse.java

TOY Implementation of Reverse

TOY implementation of reverse.

- Read in a sequence of integers and store in memory **30, 31, 32, …**
- Stop reading if **0000**.
- Print sequence in reverse order.

TOY Implementation of Reverse

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- Read in a sequence of integers and store in memory **30, 31, 32, …**
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```
10: 7101  R1 ← 0001                  constant 1
11: 7A30  RA ← 0030                  a[]
12: 7B00  RB ← 0000                  n

                                     while(true) {
13: 8CFF  read RC                       c = StdIn.readInt();
14: CC19  if (RC == 0) goto 19          if (c == 0) break;
15: 16AB  R6 ← RA + RB                  address of a[n]
16: BC06  mem[R6] ← RC                  a[n] = c;
17: 1BB1  RB ← RB + R1                  n++;
18: C013  goto 13                    }
```

read in the data

TOY Implementation of Reverse

TOY implementation of reverse.

- Read in a sequence of integers and store in memory `30, 31, 32, …`
- ➡ Stop reading if `0000`.
- Print sequence in reverse order.

```
19: CB20  if (RB == 0) goto 20        while (n > 0) {
1A: 16AB  R6 ← RA + RB                   address of a[n]
1B: 2661  R6 ← R6 – R1                   address of a[n-1]
1C: AC06  RC ← mem[R6]                   c = a[n-1];
1D: 9CFF  write RC                       System.out.println(c);
1E: 2BB1  RB ← RB – R1                   n--;
1F: C019  goto 19                     }
20: 0000  halt
```

print in reverse order

Unsafe Code at any Speed

What happens if we make array start at `00` instead of `30`?

- Self modifying program.
- Exploit buffer overrun and run arbitrary code!

```
10: 7101  R1 ← 0001                  constant 1
11: 7A00  RA ← 0000                  a[]
12: 7B00  RB ← 0000                  n

                                     while(true) {
13: 8CFF  read RC                       c = StdIn.readInt();
14: CC19  if (RC == 0) goto 19          if (c == 0) break;
15: 16AB  R6 ← RA + RB                  address of a[n]
16: BC06  mem[R6] ← RC                  a[n] = c;
17: 1BB1  RB ← RB + R1                  n++;
18: C013  goto 13                    }
```

Crazy 8s Input

```
1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1
8888 8810
98FF C011
```

What Can Happen When We Lose Control?

```
#include <stdio.h>
int main(void) {
   char buffer[100];
   scanf("%s", buffer);
   printf("%s\n", buffer);
   return 0;
}
```

unsafe C program

Buffer overrun.

- Array `buffer[]` has size 100.
- User might enter 200 characters.
- Might lose control of machine behavior.
- Majority of viruses and worms caused by similar errors.

Robert Morris Internet Worm.

- Cornell grad student injected worm into Internet in 1988.
- Exploited buffer overrun in finger daemon fingerd.

Function Call: A Failed Attempt

Goal: x × y × z.

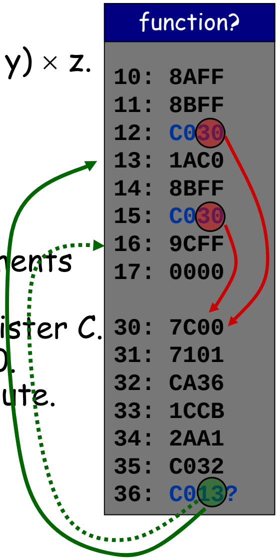
- Need two multiplications: x × y, (x × y) × z.
  - Solution 1: write multiply code 2 times.
  - Solution 2: write a TOY function.

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?

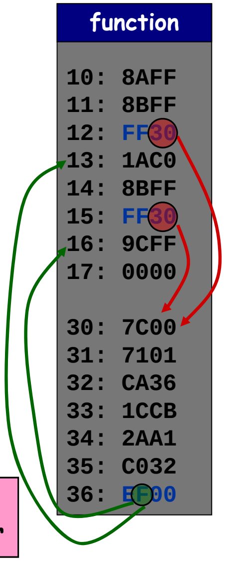
```
10: 8AFF
11: 8BFF
12: C030
13: 1AC0
14: 8BFF
15: C030
16: 9CFF
17: 0000

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:

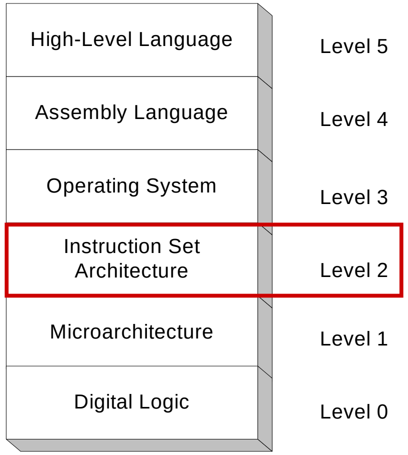
- Calling program stores function parameters in specific registers.
- Calling program stores return address in a specific register.
  - jump-and-link
- Calling program sets PC to address of function.
- Function stores return value in specific register.
- Function sets PC to return address when finished.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

What if you want a function to call another function?

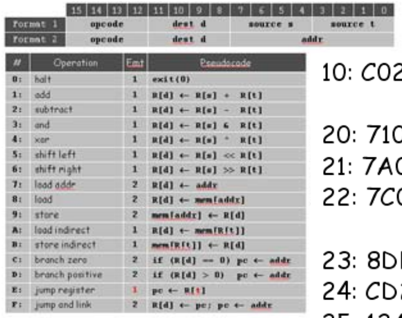
- Use a different register for return address.
- More general: store return addresses on a stack.

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



	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

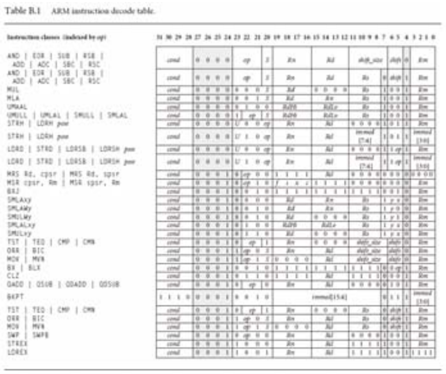


Table B.1 ARM instruction decode table.

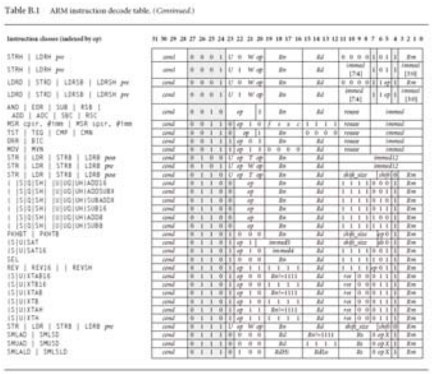
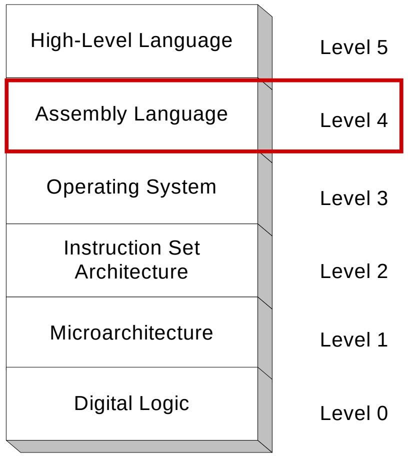


Table B.1 ARM instruction decode table. (Continued)

Virtual machines

Abstractions for computers



```
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
```