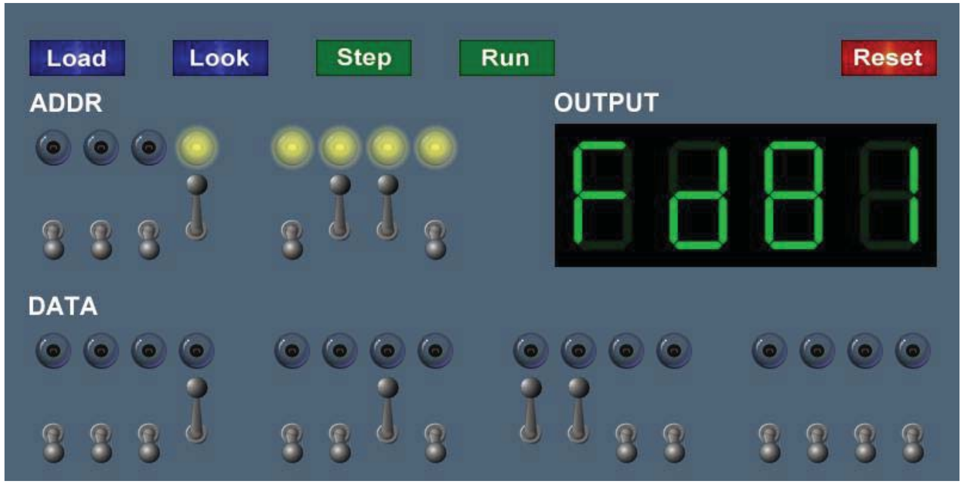
The TOY Machine



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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.

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

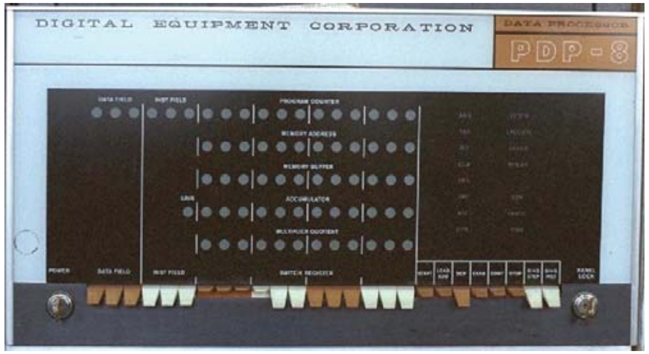
John von Neumann

Maurice Wilkes (left)
EDSAC (right)

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:

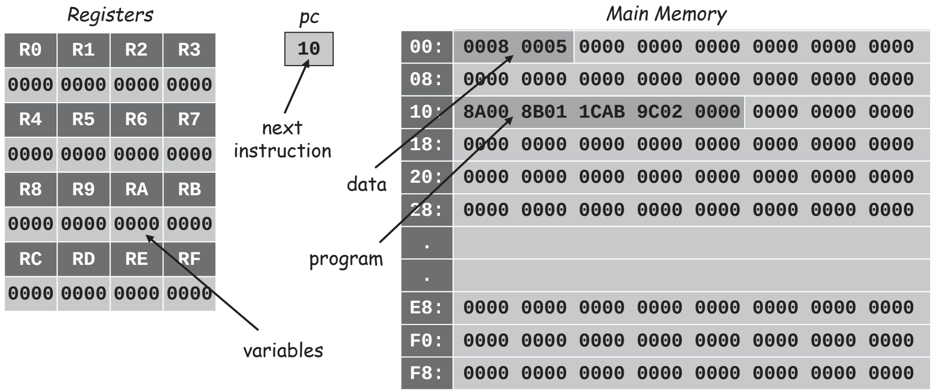
- Ancient computers.
- Today's microprocessors.

Pentium Celeron

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

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

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.

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

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.

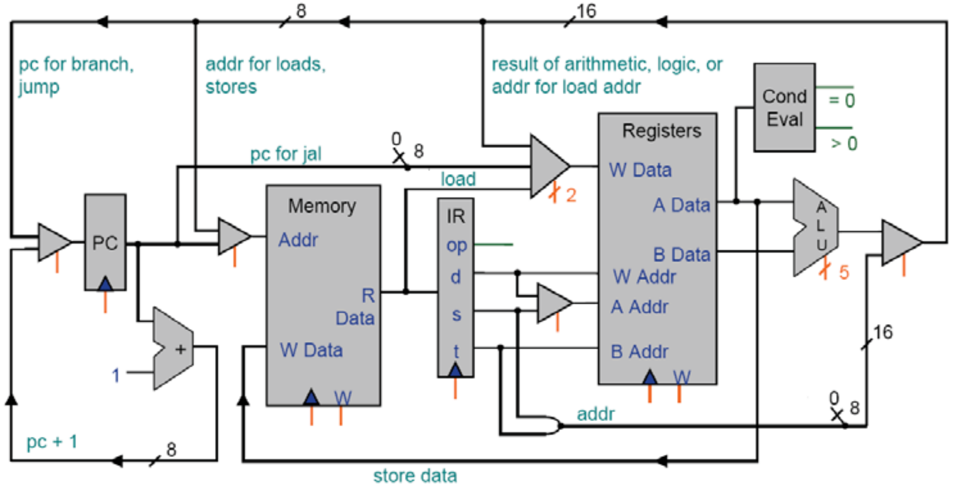
TOY Reference Card

	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							

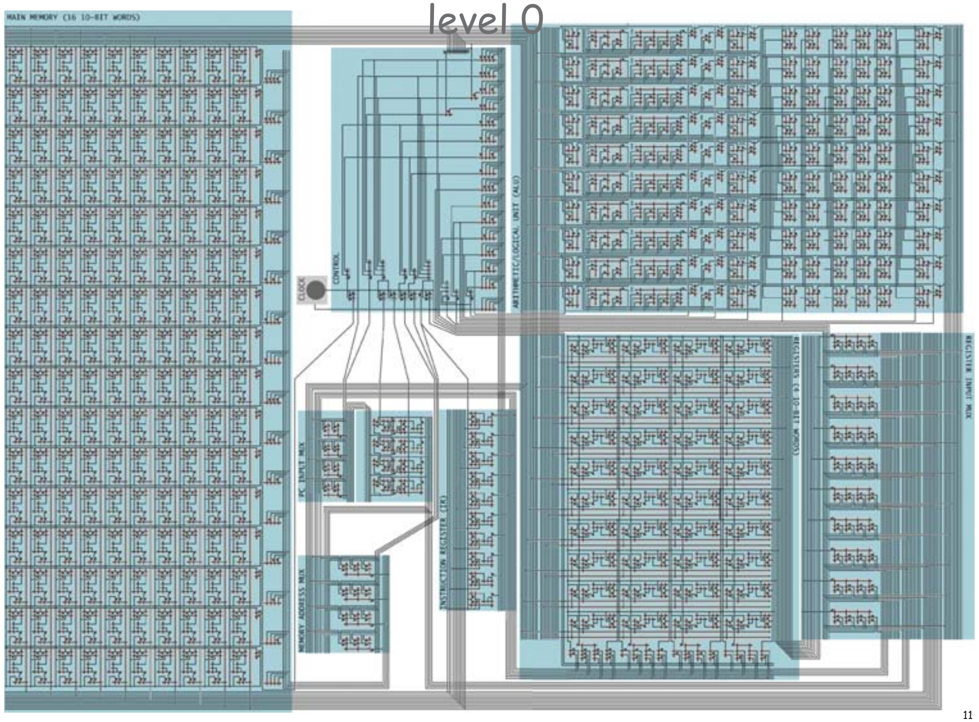
#	Operation	Fmt	Pseudocode
0:	halt	1	`exit(0)`
1:	add	1	`R[d] ← R[s] +  R[t]`
2:	subtract	1	`R[d] ← R[s] -  R[t]`
3:	and	1	`R[d] ← R[s] &  R[t]`
4:	xor	1	`R[d] ← R[s] ^  R[t]`
5:	shift left	1	`R[d] ← R[s] << R[t]`
6:	shift right	1	`R[d] ← R[s] >> R[t]`
7:	load addr	2	`R[d] ← addr`
8:	load	2	`R[d] ← mem[addr]`
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)



level 0



Programming in TOY

Hello, World. Add two numbers.

- Adds 8 + 5 = D.

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

pc
11

Registers

```
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							

A Sample Program

A sample program.

- Adds 8 + 5 = D.

RA	RB	RC
0000	0000	0000

pc
10

Registers

```
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.

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

pc
12

Registers

```
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			

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

pc
10

Registers

```
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							

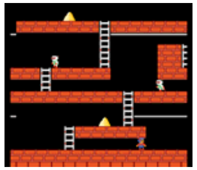
Simulation

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.



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							

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.

Halt

Halt. (opcode 0)

- Stop the machine.

RA	RB	RC
0008	0005	000D

Registers

pc
14

add.toy

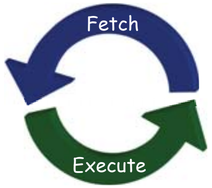
```
00: 0008   8
01: 0005   5

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

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;
}
```

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
```

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
```

loop

multiply.toy

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

Step-By-Step Trace

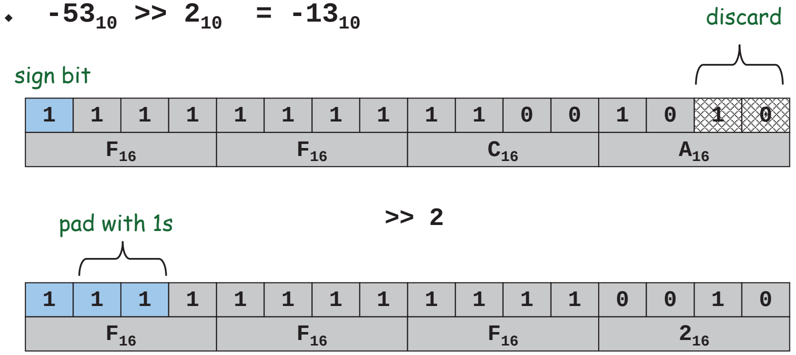
		R1	RA	RB	RC
10: 8A0A	RA ← mem[0A]		0003		
11: 8B0B	RB ← mem[0B]			0009	
12: 8C0D	RC ← mem[0D]				0000
13: 810E	R1 ← mem[0E]	0001			
14: CA18	if (RA == 0) pc ← 18				
15: 1CCB	RC ← RC + RB				0009
16: 2AA1	RA ← RA – R1		0002		
17: C014	pc ← 14				
14: CA18	if (RA == 0) pc ← 18				
15: 1CCB	RC ← RC + RB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

Shift Right (Sign Extension)

Shift right. (opcode 6)

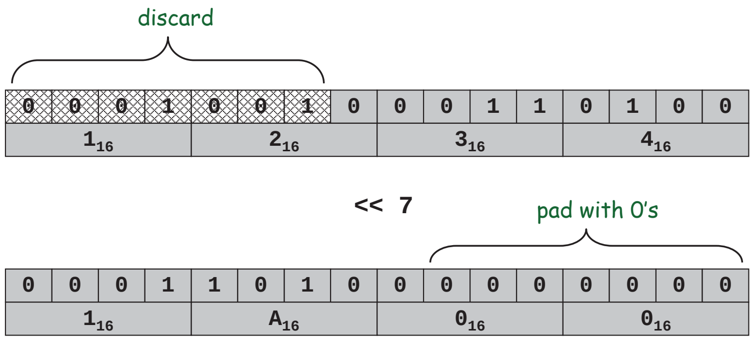
- Move bits to the right, padding with sign bit as needed.
- $FFCA_{16} >> 2_{16} = FFF2_{16}$
- $-53_{10} >> 2_{10} = -13_{10}$



Shift Left

Shift left. (opcode 5)

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

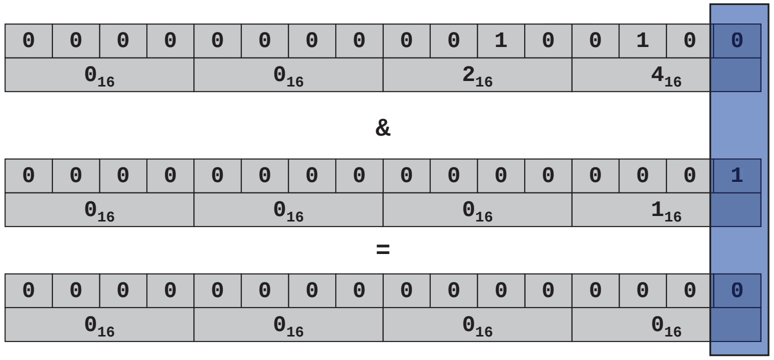


Bitwise AND

Logical AND. (opcode 3)

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

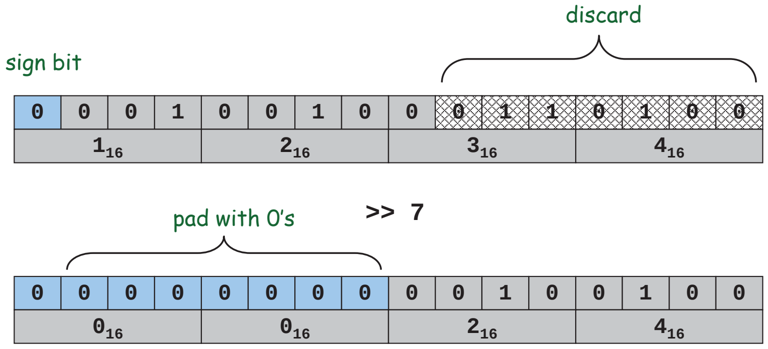
x	y	AND
0	0	0
0	1	0
1	0	0
1	1	1



Shift Right

Shift right. (opcode 6)

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



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

                                     do {
15: 2221    R2 ← R2 -  R1               i--
16: 53A2    R3 ← RA << R2               a << i
17: 64B2    R4 ← RB >> R2               b >> i
18: 3441    R4 ← R4 &  R1               b_i = ith 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
```

loop

branch

Shifting and Masking

Shift and mask: get the 7^{th} 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}			

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
```

Binary Multiplication

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

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.

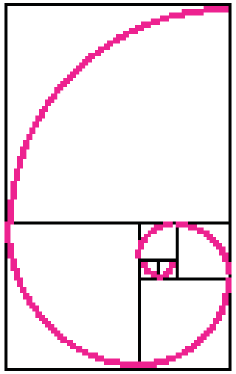
Standard input.

- 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.

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

```
a = 30;
```

Java code

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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```
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.

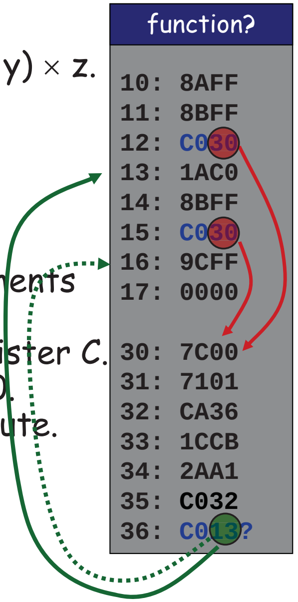
- Need two multiplications: x × y, (x × y) × z.
  - Solution 1: write multiply code 2 times.
  - Solution 2: write a TOY function.

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?
```

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.

Multiplication Function

Calling convention.

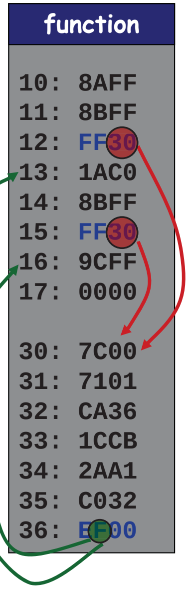
- Jump to line 30.
- Store a and b in registers A and B.
- Return address in register F.
- Put result c = a × b in register C.
- Register 1 is scratch.
- Overwrites registers A and B.

function.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

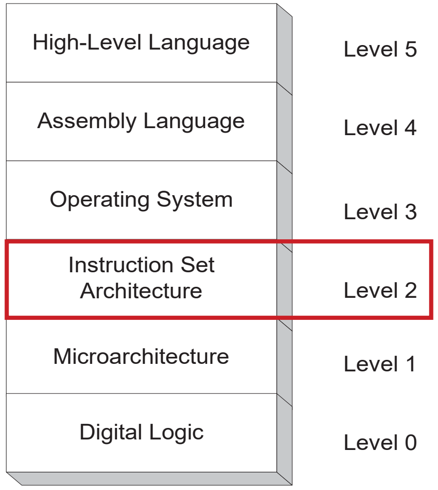


function

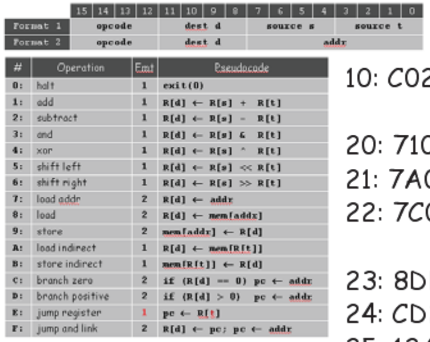
```
10: 8AFF
11: 8BFF
12: FF30
13: 1AC0
14: 8BFF
15: FF30
16: 9CFF
17: 0000

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

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
```

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

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

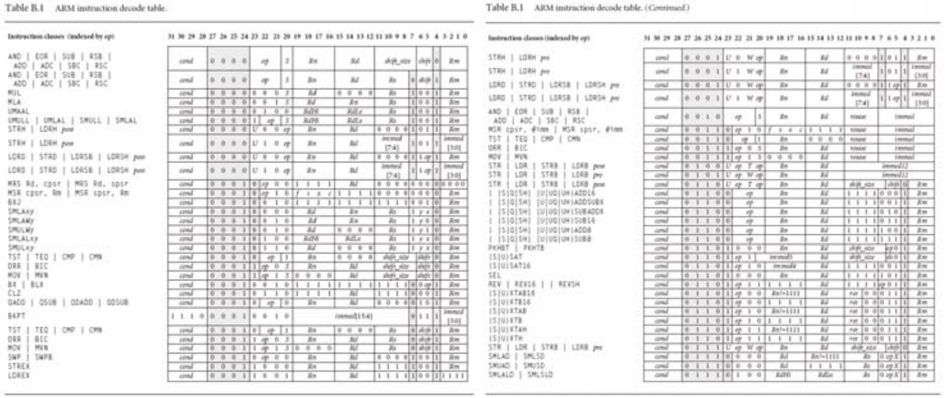
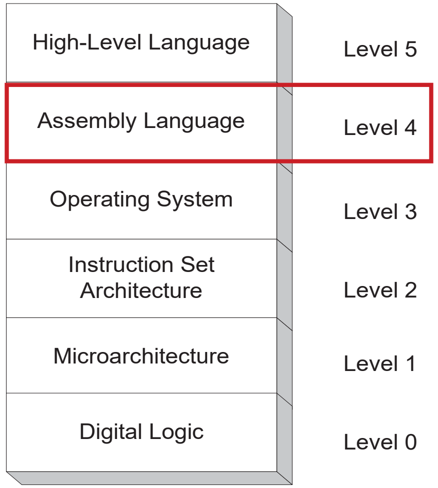


Table B.1 ARM instruction decode table.

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

Virtual machines

Abstractions for computers



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

```
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
```