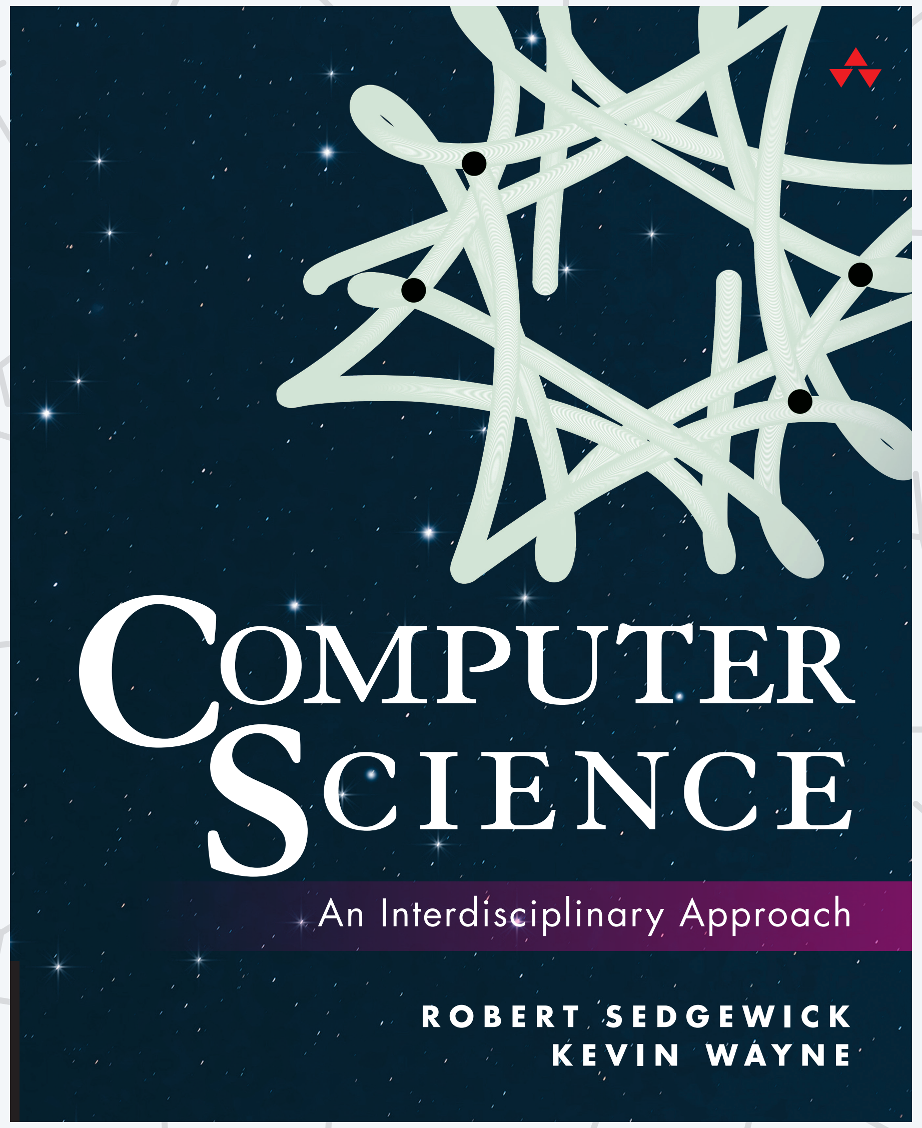

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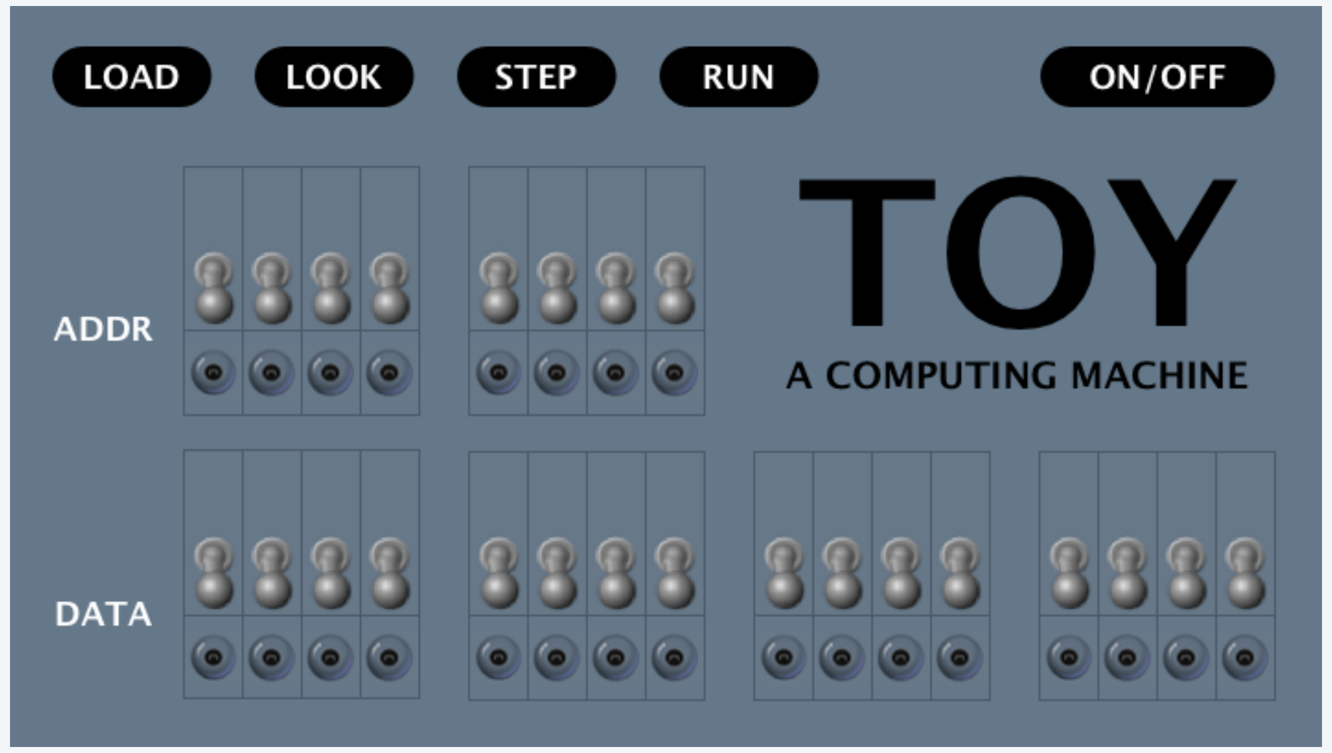
6. TOY Machine II

- *conditionals and loops*
- *input and output*
- *arrays*
- *von Neumann architecture*
- *TOY emulator*

Machine language programming in TOY

TOY machine.

- Arithmetic logic unit (ALU).
- Memory and registers.
- Program counter (PC) and instruction register (IR).
- Lights and switches.



TOY programming.

- Move data between memory and registers.
- Arithmetic/logic operations.

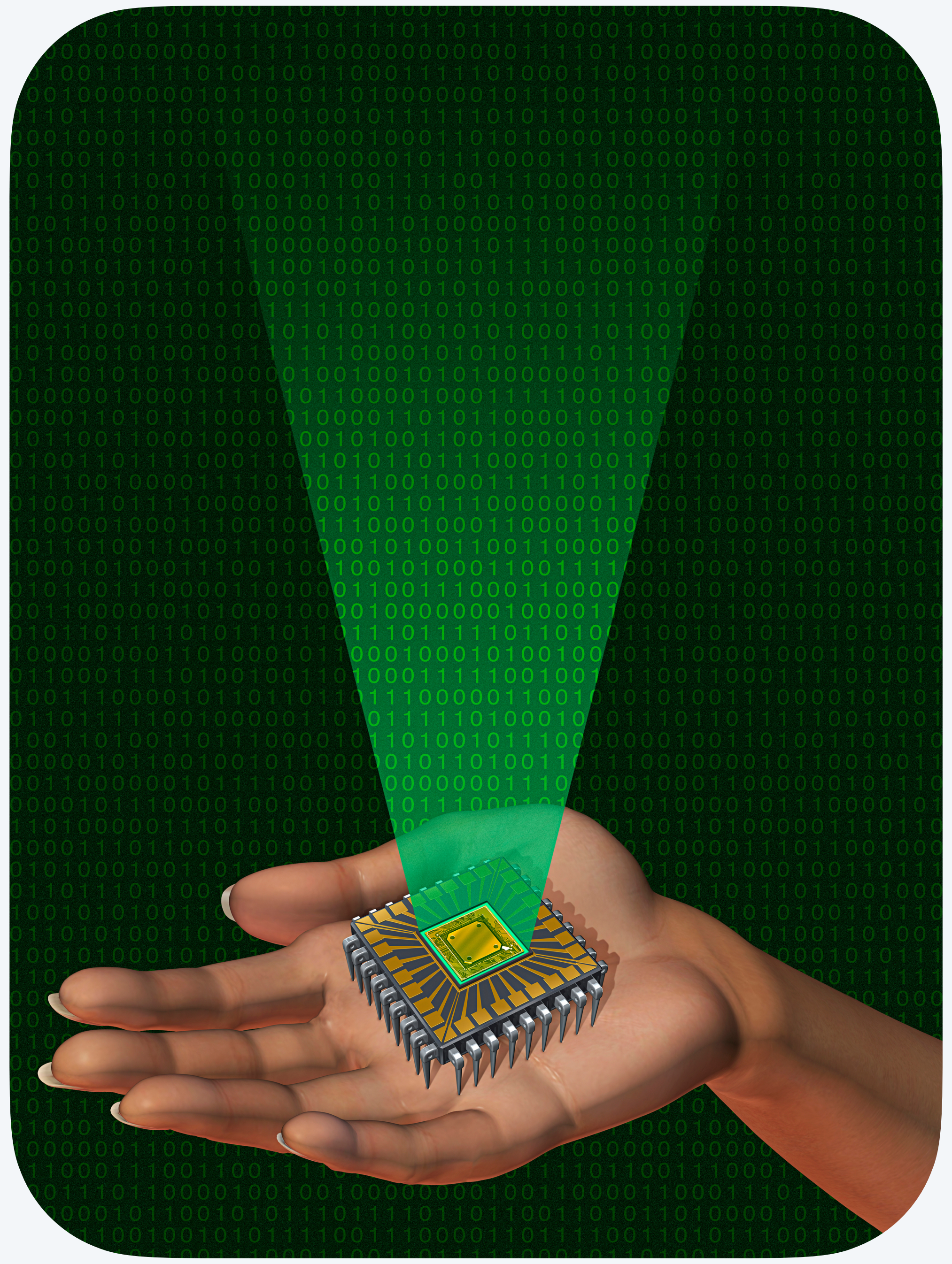
last lecture

- Conditionals and loops.
- Arrays.
- Standard input and output.

this lecture

- Functions.
- Linked structures.

see textbook



Review: your first TOY program

Add two integers.

- Load operands from memory into two registers.
- Add the two registers.
- Store the result in memory.

MEMORY

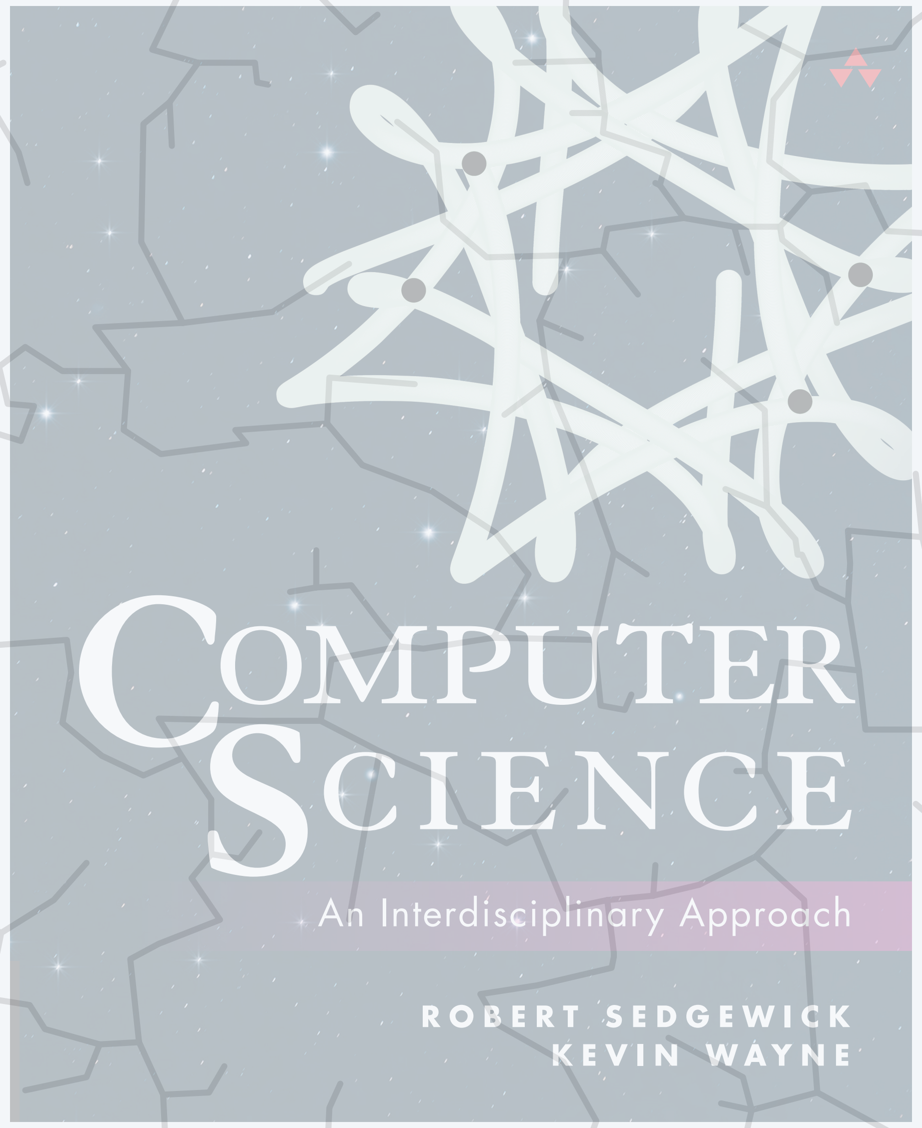
```
 ⋮    ⋮
10: 8A15   R[A] = M[15]
11: 8B16   R[B] = M[16]
12: 1CAB   R[C] = R[A] + R[B]
13: 9C17   M[17] = R[C]
14: 0000   halt
15: 0008   input 1
16: 0005   input 2
17: 0000   output
 ⋮    ⋮
```

REGISTERS

```
  ⋮      ⋮
R[A]   0000
R[B]   0000
R[C]   0000
  ⋮      ⋮
```

PC

10



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6. TOY MACHINE II

- *conditionals and loops*
- *input and output*
- *arrays*
- *von Neumann architecture*
- *TOY emulator*

Conditionals and loops

To control the flow of instruction execution.

- Test a register's value.
- Change the PC, depending on the value.

opcode	instruction	pseudocode
C	*branch if zero*	`if (R[d] == 0) PC = addr`
D	*branch if positive*	`if (R[d] > 0) PC = addr`

Ex 1. Typical `if` statement.

```
14:  ...
15:  DA17   if (R[A] > 0) goto 17
16:  2A0A   R[A] = -R[A]
17:  ...
```

skips line 16 if R[A] > 0

replace R[A] with absolute value of R[A]

```
if (a <= 0) {
   a = -a;
}
```

replace a with |a|

Conditionals and loops

To control the flow of instruction execution

- Test a register's value.
- Change the PC, depending on the value.

opcode	instruction	pseudocode
C	*branch if zero*	`if (R[d] == 0) PC = addr`
D	*branch if positive*	`if (R[d] > 0)  PC = addr`

Ex 2. Typical `while` loop.

```
12:  ...
13:  CA18   if (R[A] == 0) goto 18
14:  ...
15:  7101   R[1] = 1
16:  2AA1   R[A] = R[A] - 1
17:  C013   goto 13
18:  ...
```

skip lines 14 to 17 if R[A] *is* 0

load address

goto line 13 (R[0] *is always* 0)

line 14 is repeated R[A] times (assuming R[A] is non-negative)

```
while (a != 0) {
   ...
   a--;
}
```

repeat a times

Multiplication

Goal. Compute product of two positive integers: $c = a \times b$.

Algorithm. Initialize $c = 0$; then, add b to c, a times.

opcode	instruction	pseudocode
C	*branch if zero*	`if (R[d] == 0) PC = addr`
D	*branch if positive*	`if (R[d] > 0) PC = addr`

```
10:  8A1A   R[A] = M[1A]
11:  8B1B   R[B] = M[1B]
12:  7C00   R[C] = 0
13:  CA18   if (R[A] == 0) goto 18
14:  1CCB   R[C] = R[C] + R[B]
15:  7101   R[1] = 1
16:  2AA1   R[A] = R[A] - 1
17:  C013   goto 13
18:  9C1A   M[1C] = R[C]
19:  0000   halt
1A:  0007   input a
1B:  0009   input b
1C:  0000   output c = a * b
```

loop template from previous slide

input and output

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

multiplication: c = a × b
(via repeated addition)

TOY II: quiz 1

Upon termination, which value is stored in R[A] **?**

A. 0000

B. 7FFF

C. FFFF

D. Infinite loop

```
10: 7A00    R[A] = 0
11: 7101    R[1] = 1            ← R[1] is always 1
12: 1AA1    R[A] = R[A] + 1
13: C012    goto 12             ← R[0] is always 0
14: 0000    halt
```

TOY II: quiz 2

Upon termination, which value is stored in `R[B]` ?

A. 0000

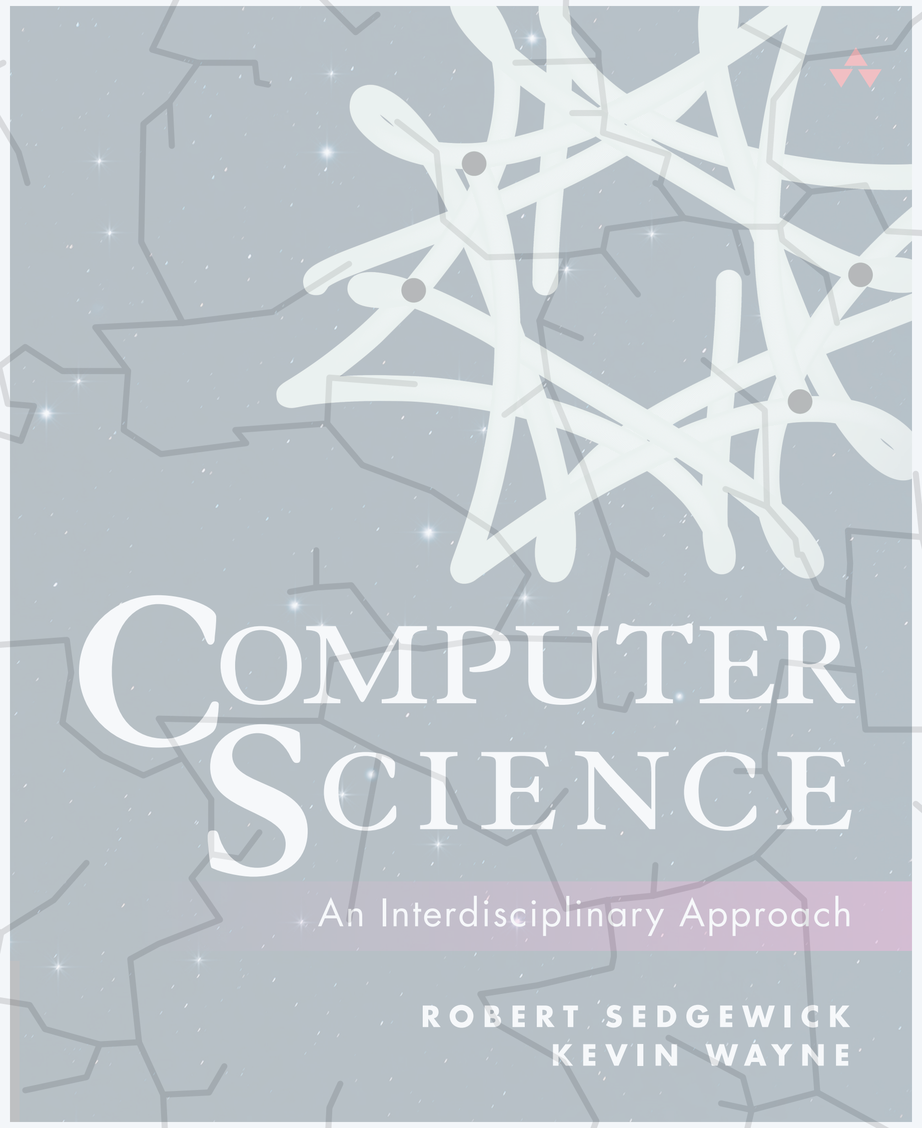
B. 0010

C. 0016

D. 1020

E. 8000

```
10: 7101   R[1] = 1
11: 7A04   R[A] = 4₁₀
12: 7B01   R[B] = 1
13: 2AA1   R[A] = R[A] - 1
14: 1BBB   R[B] = R[B] + R[B]
15: DA13   if (R[A] > 0) goto 13
16: 0000   halt
```



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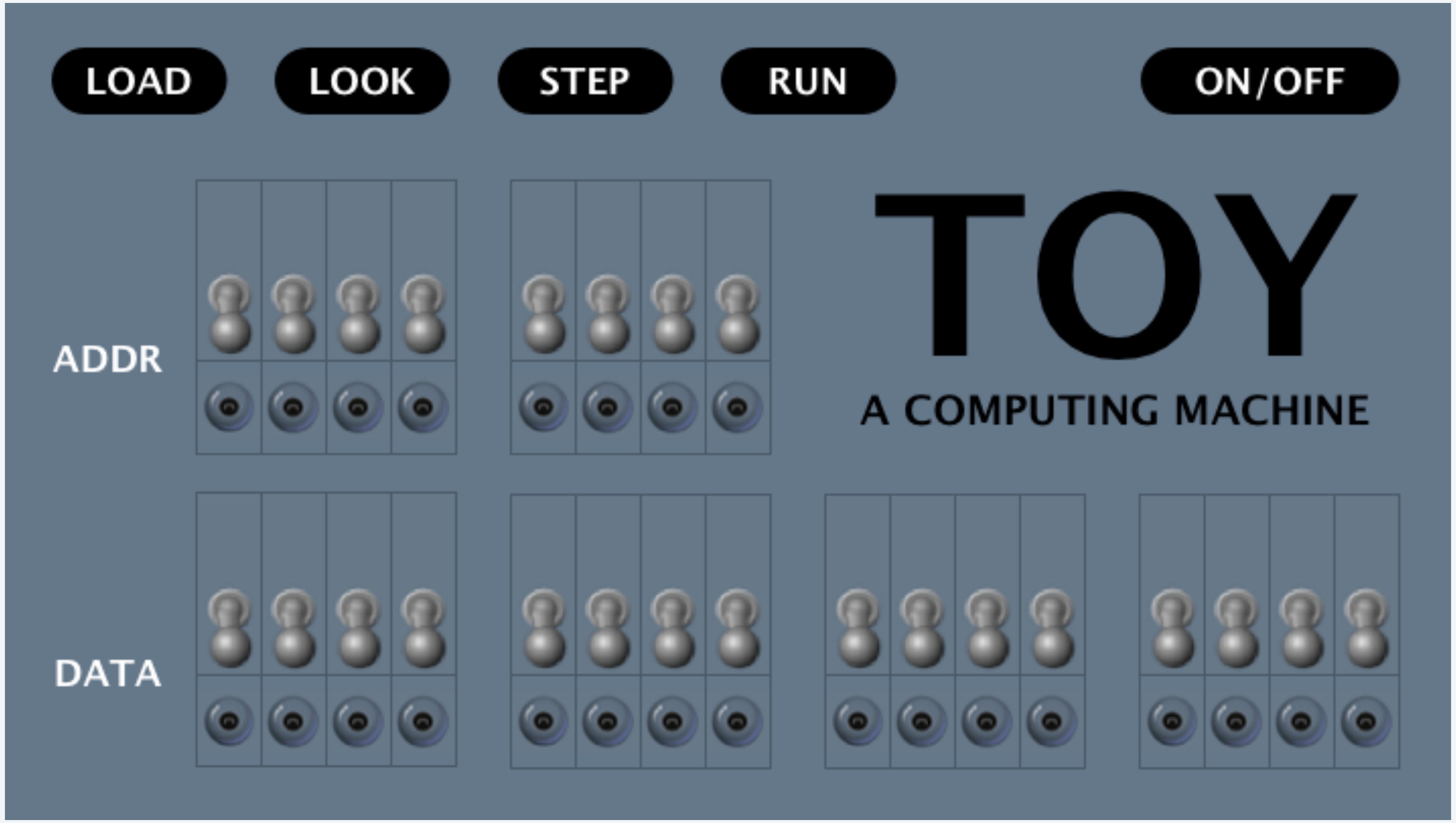
6. TOY Machine II

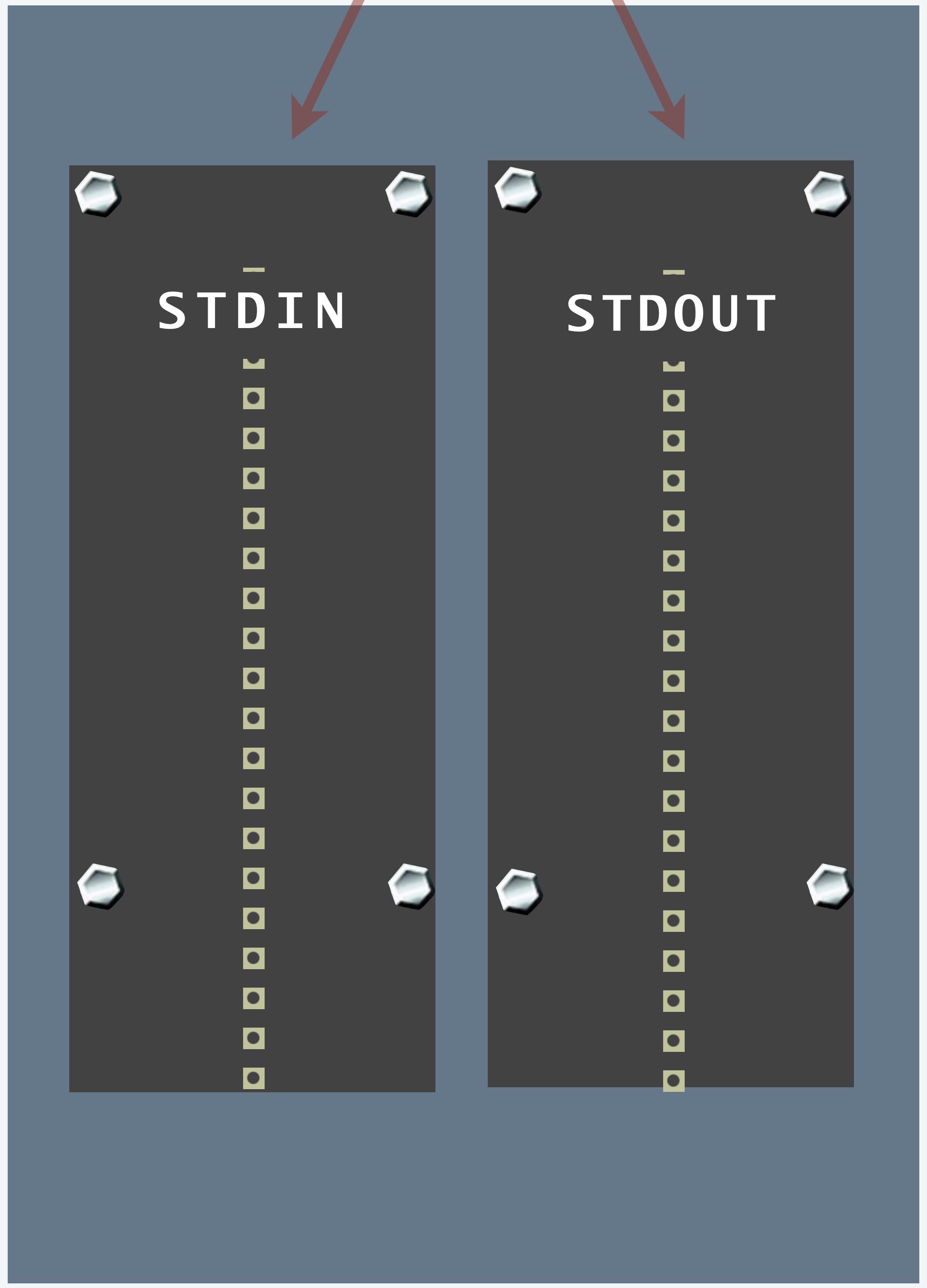
- conditionals and loops
- *input and output*
- arrays
- von Neumann architecture
- TOY emulator

Standard input and output

An immediate problem. Can't address real-world problems with just switches and lights for I/O.

bolt I/O devices to the side of machine





Standard input and output

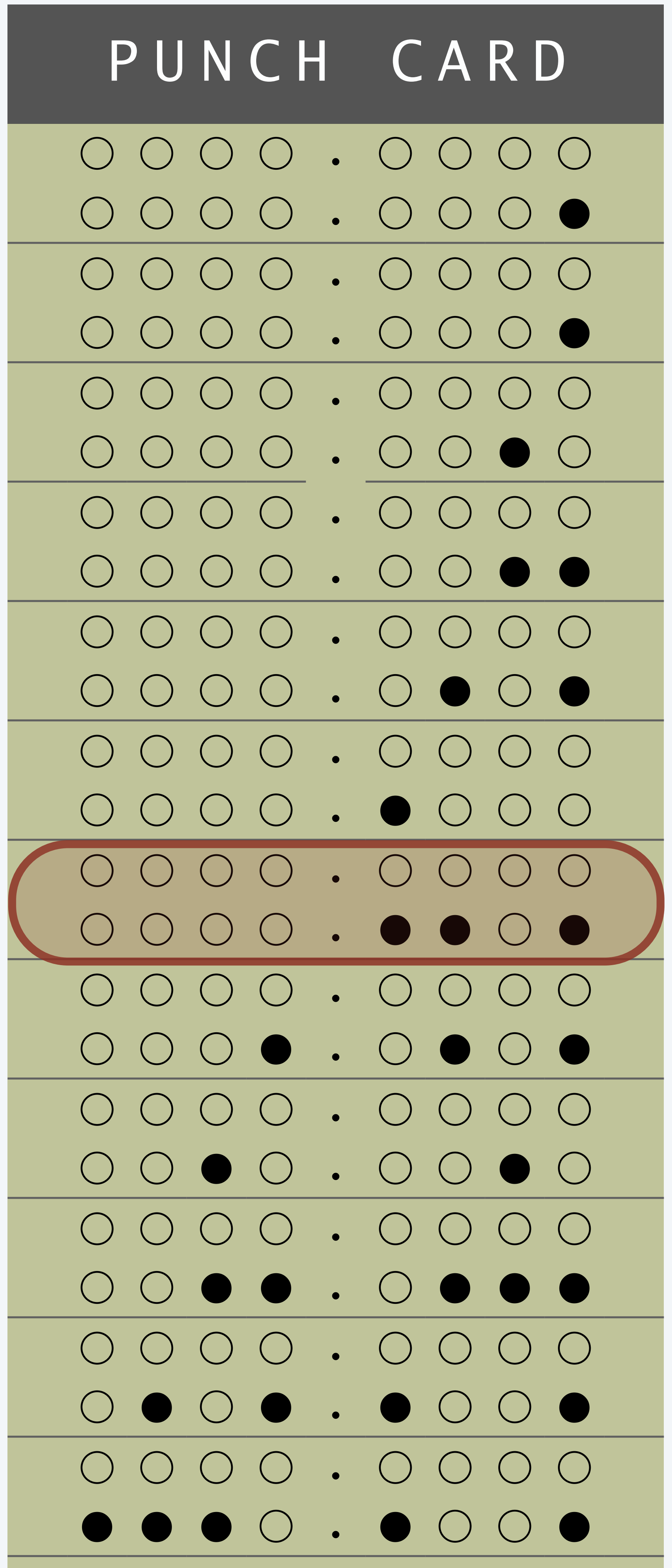
Punched paper tape.

- Encode each 16-bit word in two 8-bit rows.
- To *write* a word, punch a hole for each 1.
- To *read* a word, shine a light behind the tape and sense the holes.

TOY mechanism.

- Connect hardware to memory address `FF`.
- To write the contents of a register to stdout, store to `M[FF]`.
- To read from stdin into a register, load from `M[FF]`.

two 8-bit rows



0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1

16-bit word

Standard input and output: absolute value

Goal. Read integers from standard input (stop on 0000); write absolute value to standard output.

opcode	operation	pseudocode
8	*load*	R[d] = M[addr]
9	*store*	M[addr] = R[d]

```
10: 8AFF   Read R[A] from stdin
11: CA16   if (R[A] == 0) goto 16
12: DA14   if (R[A] >  0) goto 14
13: 2A0A   R[A] = -R[A]
14: 9AFF   write R[A] to stdout
15: C010   goto 10
16: 0000   halt
```

read from standard input (since address is FF)

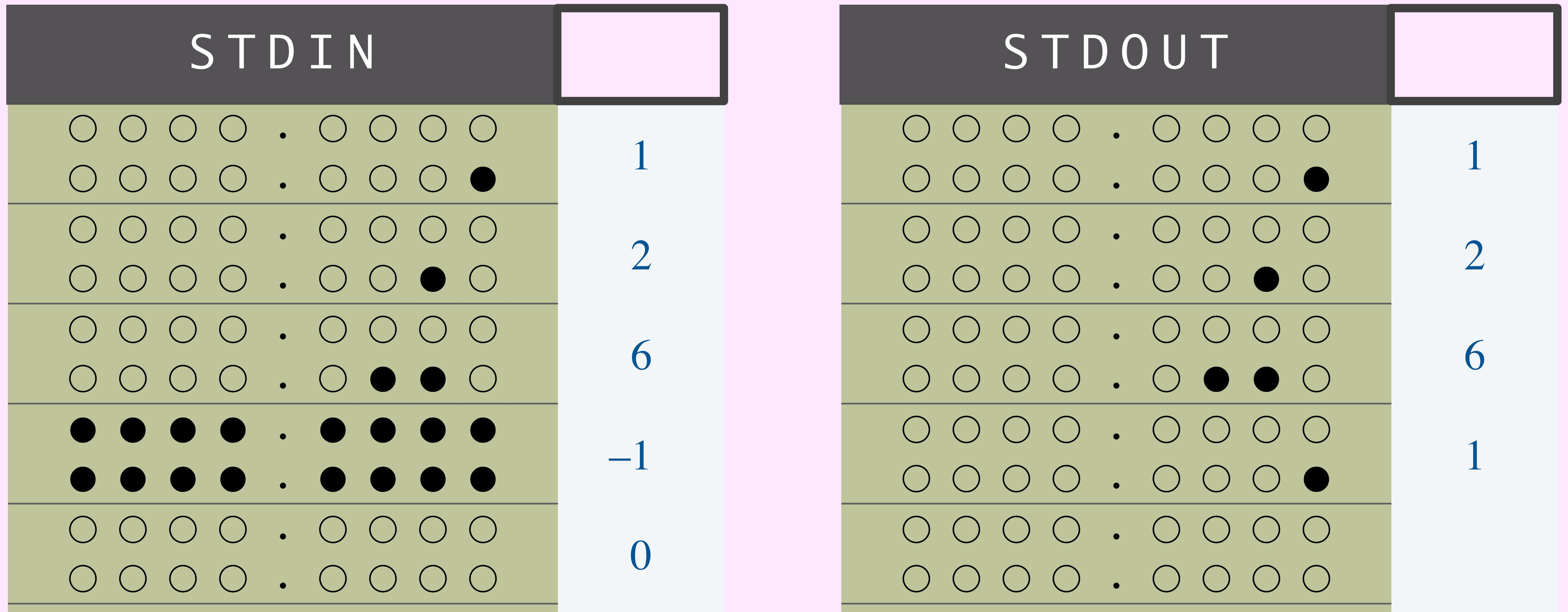
write to standard output (since address is FF)

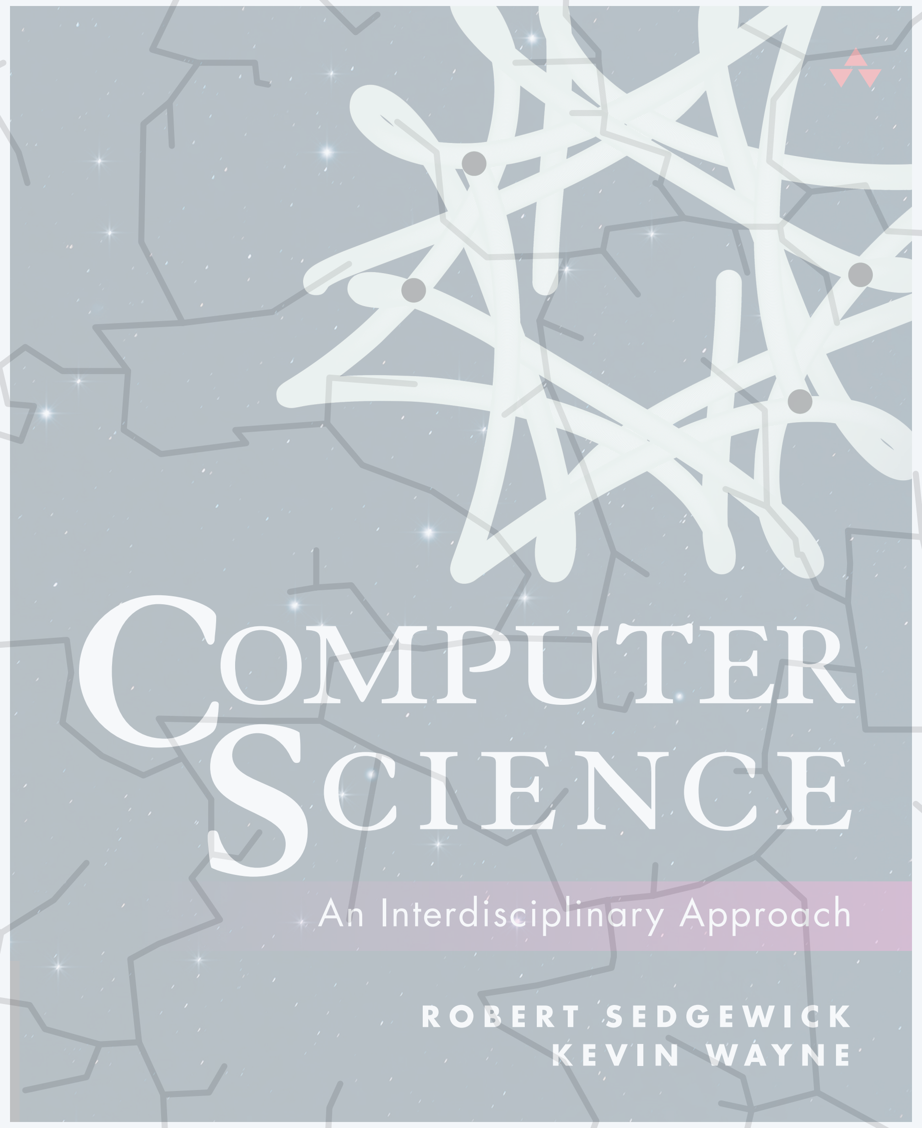
```
while (true) {
   a = StdIn.readInt();
   if (a == 0) break;
   if (a <= 0) a = -a;
   StdOut.println(a);
}
```

Standard input and output trace

Goal. Read integers from standard input (stop on 0000);
write absolute value to standard output.

```
10: 8AFF    Read R[A] from stdin
11: CA16    if (R[A] == 0) goto 16
12: DA14    if (R[A] >  0) goto 14
13: 2A0A    R[A] = -R[A]
14: 9AFF    write R[A] to stdout
15: C010    goto 10
16: 0000    halt
```





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6. TOY Machine II

- conditionals and loops
- input and output
- arrays
- von Neumann architecture
- TOY emulator

TOY II: quiz 3

Upon termination, which value is stored in `R[C]` ?

opcode	operation	pseudocode
7	*load address*	`R[d] = addr`
8	*load*	`R[d] = M[addr]`
A	*load indirect*	`R[d] = M[R[t]]`

A. `000A`

B. `0011`

C. `8B12`

D. `AC0A`

```
10: 7A11    R[A] = 11         ← load address
11: 8B12    R[B] = M[12]      ← load
12: AC0A    R[C] = M[R[A]]    ← load indirect
13: 0000    halt
```

REGISTERS

⋮	⋮
R[A]	0 0 0 0
R[B]	0 0 0 0
R[C]	0 0 0 0
⋮	⋮

PC

1 0

Arrays

To implement an array:

- Keep array elements contiguous in memory, say, starting at 80.
- Access array element i at M[80 + i]. using load/store indirect.

Goal. Print elements in an array of length $n > 0$ to standard output.

opcode	operation	pseudocode
7	*load address*	`R[d] = addr`
A	*load indirect*	`R[d] = M[R[t]]`
B	*store indirect*	`M[R[t]] = R[d]`

```
10: 7A80   R[A] = 80
11: 7B09   R[B] = 9

12: 7101   R[1] = 1
13: AC0A   R[C] = M[R[A]]
14: 9CFF   write R[C]
15: 1AA1   R[A] = R[A] + 1
16: 2BB1   R[B] = R[B] - 1
17: CB13   if (R[B] > 0) goto 13
18: 0000   halt
```

array starts at R[A] = 80 *and has length* R[B] = 9

load next array element into R[C]

address of next element in array

array of length 9

```
80: C0DE
81: CAFE
82: ABBA
83: 8BAD
84: F00D
85: FACE
86: 1377
87: D1CE
88: C1A0
```

TOY II: quiz 4

Suppose that we execute the same program, but initialize R[A] to 10. What is the result?

A. Prints 0010, 0011, 0012, …, 0018.

B. Prints 7A10, 7B09, 7101, …, 0000. ← *treats the TOY program as data (and prints the program)*

C. Crashes when R[A] is 0013.

D. Infinite loop.

```
10: 7A10    R[A] = 10
11: 7B09    R[B] = 9

12: 7101    R[1] = 1
13: AC0A    R[C] = M[R[A]]
14: 9CFF    write R[C]
15: 1AA1    R[A] = R[A] + 1
16: 2BB1    R[B] = R[B] - 1
17: CB13    if (R[B] > 0) goto 13
18: 0000    halt
```

array now starts at R[A] = 10

Indirection

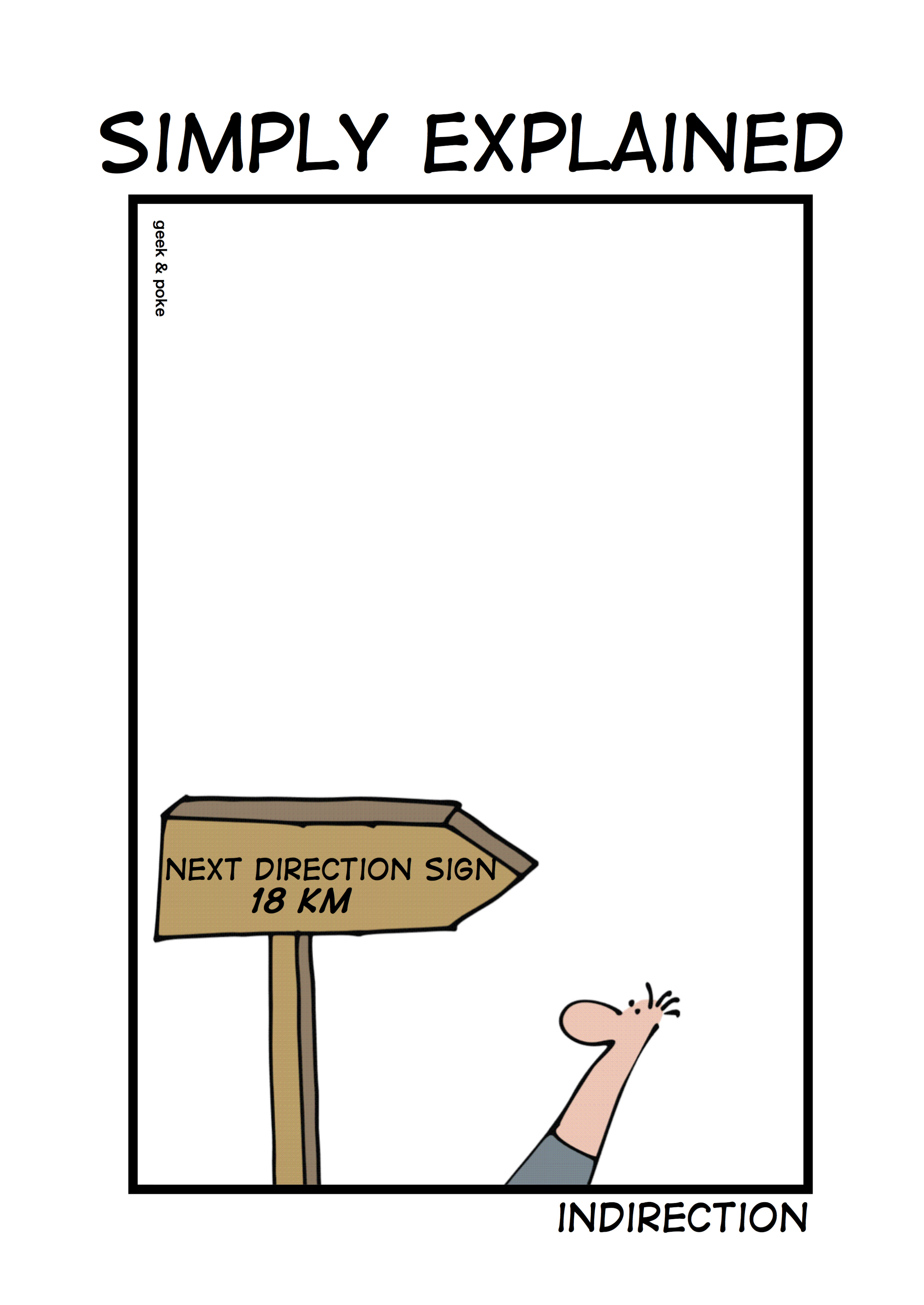
Direct addressing. Specify memory address to access.

Indirect addressing. Specify register containing memory address to access.

Pointer. Variable/register that stores a memory address.

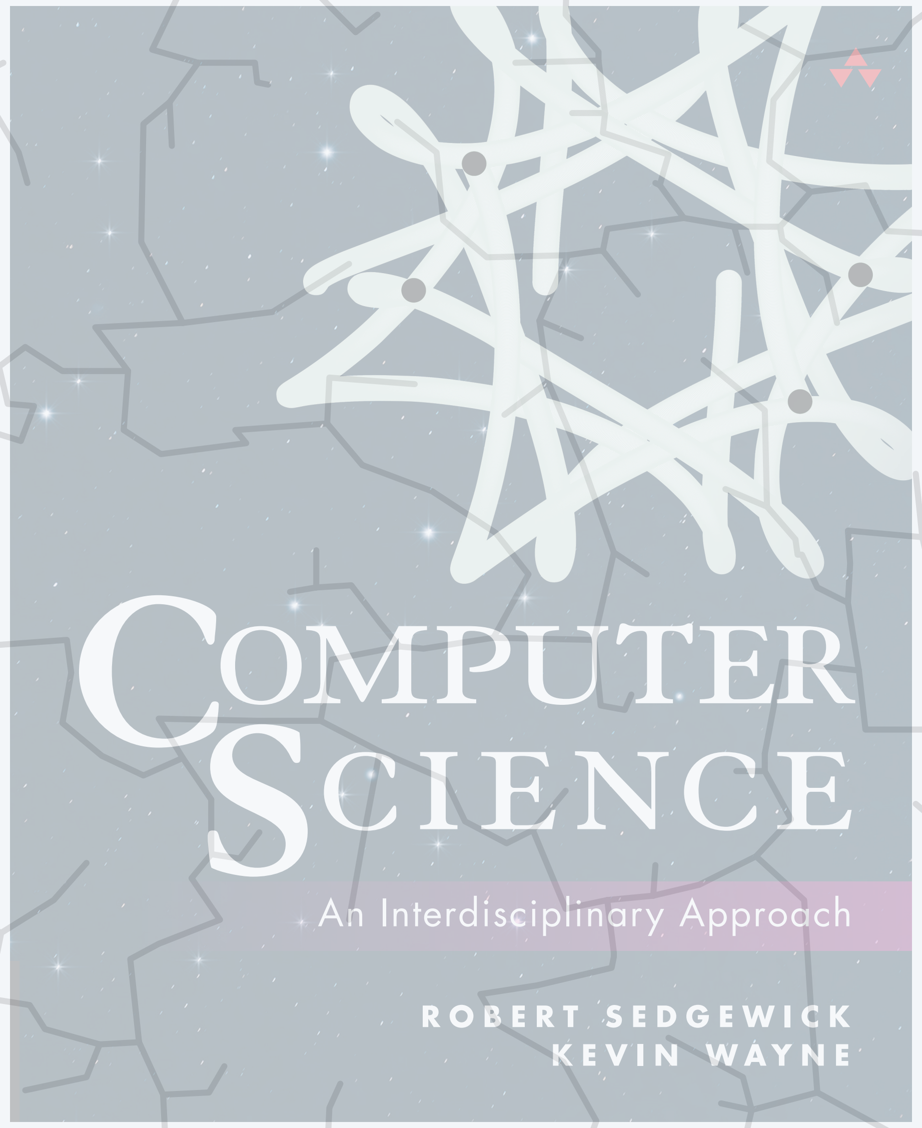
Indirection. Manipulating a value through its memory address.

- TOY arrays.
- Java references.
- C pointers.
- …



" *Any problems in computer science can be solved with another level of indirection.*"

— *attributed to David Wheeler*



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6. TOY Machine II

- conditionals and loops
- input and output
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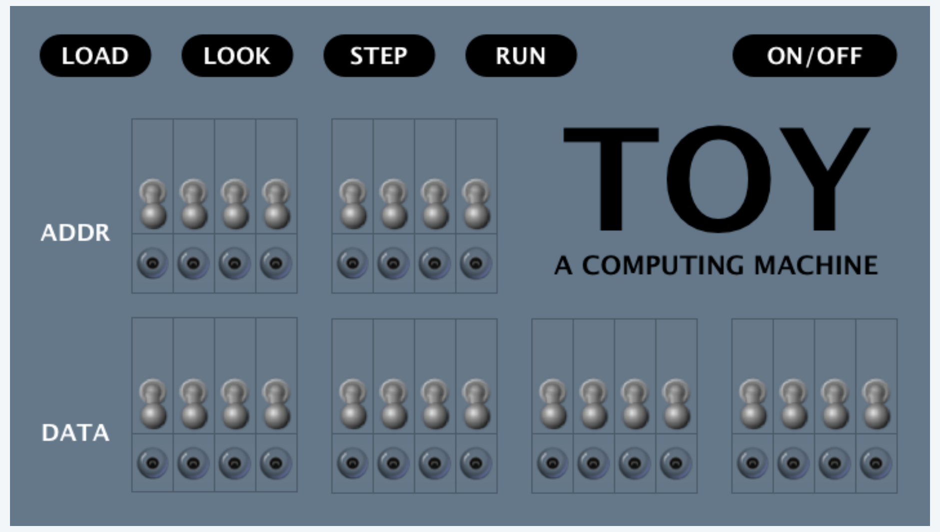
- TOY emulator

TOY vs. your laptop

Two different computing machines.

- Both implement basic data types, conditionals, loops, and other low-level constructs.
- Both can have arrays, functions, linked structures, and other high-level constructs.
- Both have unbounded input and output streams.



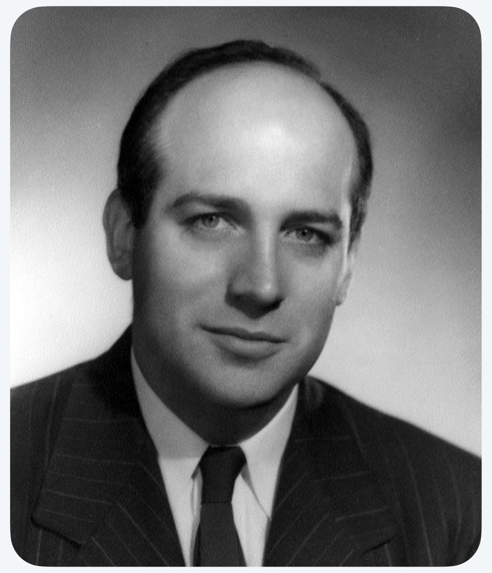
A few key differences.

- Performance: 1Hz vs. 3.5 GHz.
- Memory: 512 bytes vs. 32GB.
- Input/output devices: display, keyboard, trackpad, speakers, webcam, …

An early computer

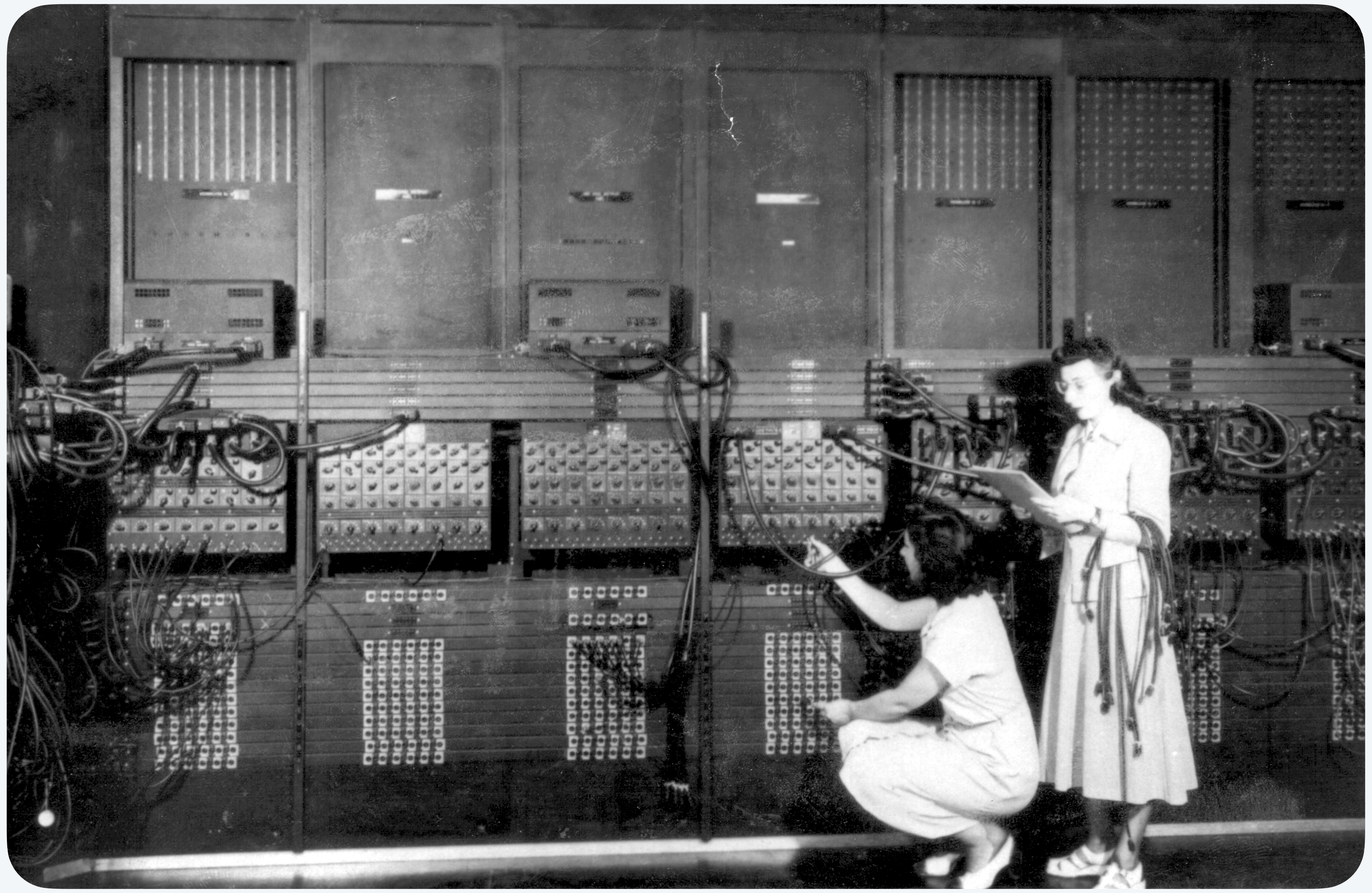
Electronic Numerical Integrator and Calculator (ENIAC).

- First widely-known general-purpose electronic computer.
- "Programmable", but no memory.
- Programming: change switches and cable connections.
- Data: enter numbers using punch cards.



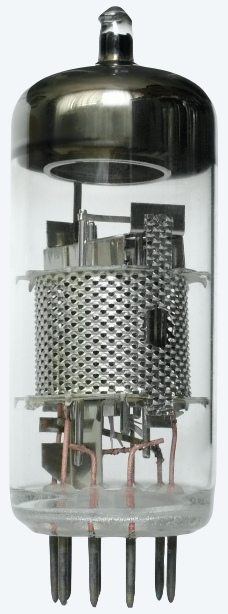
J. Presper Eckert

John W. Mauchly



two programmers "programming" the ENIAC (1946)

facts and figures
30 *tons*
$30 \times 50 \times 8.5$ *feet*
17,468 *vacuum tubes*
300 *multiply/sec*

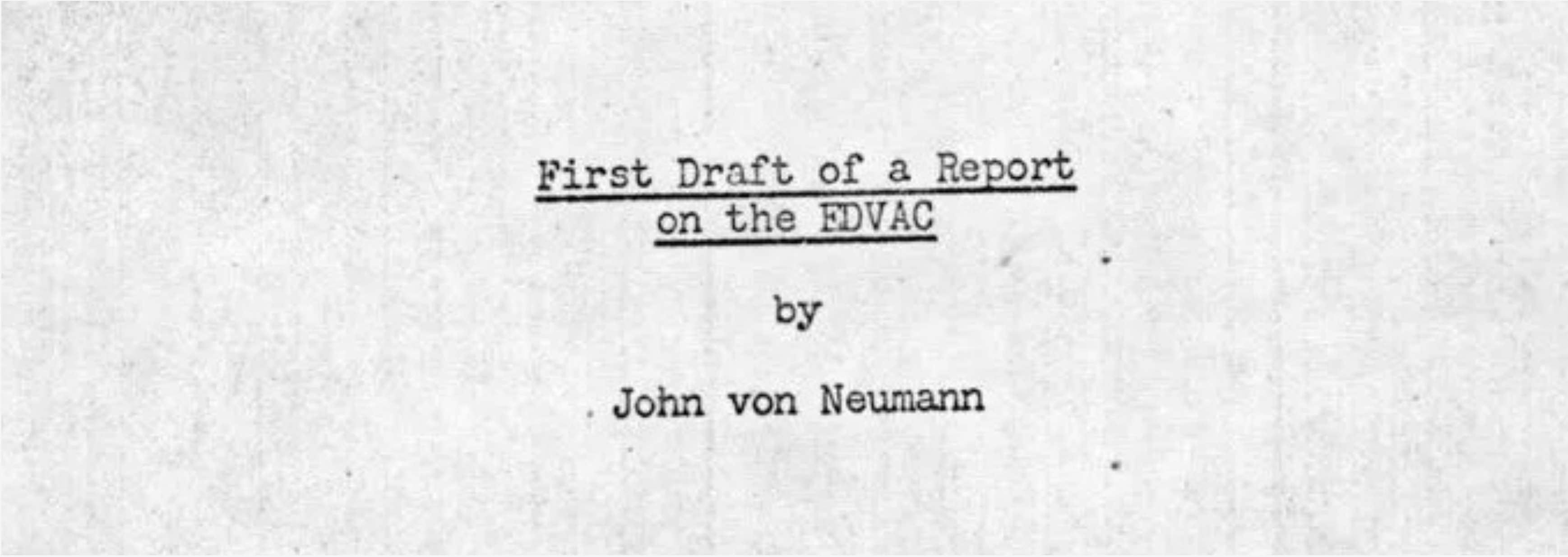


one bit
(vacuum tube)

Von Neumann architecture

First Draft of a Report on the EDVAC (1945).

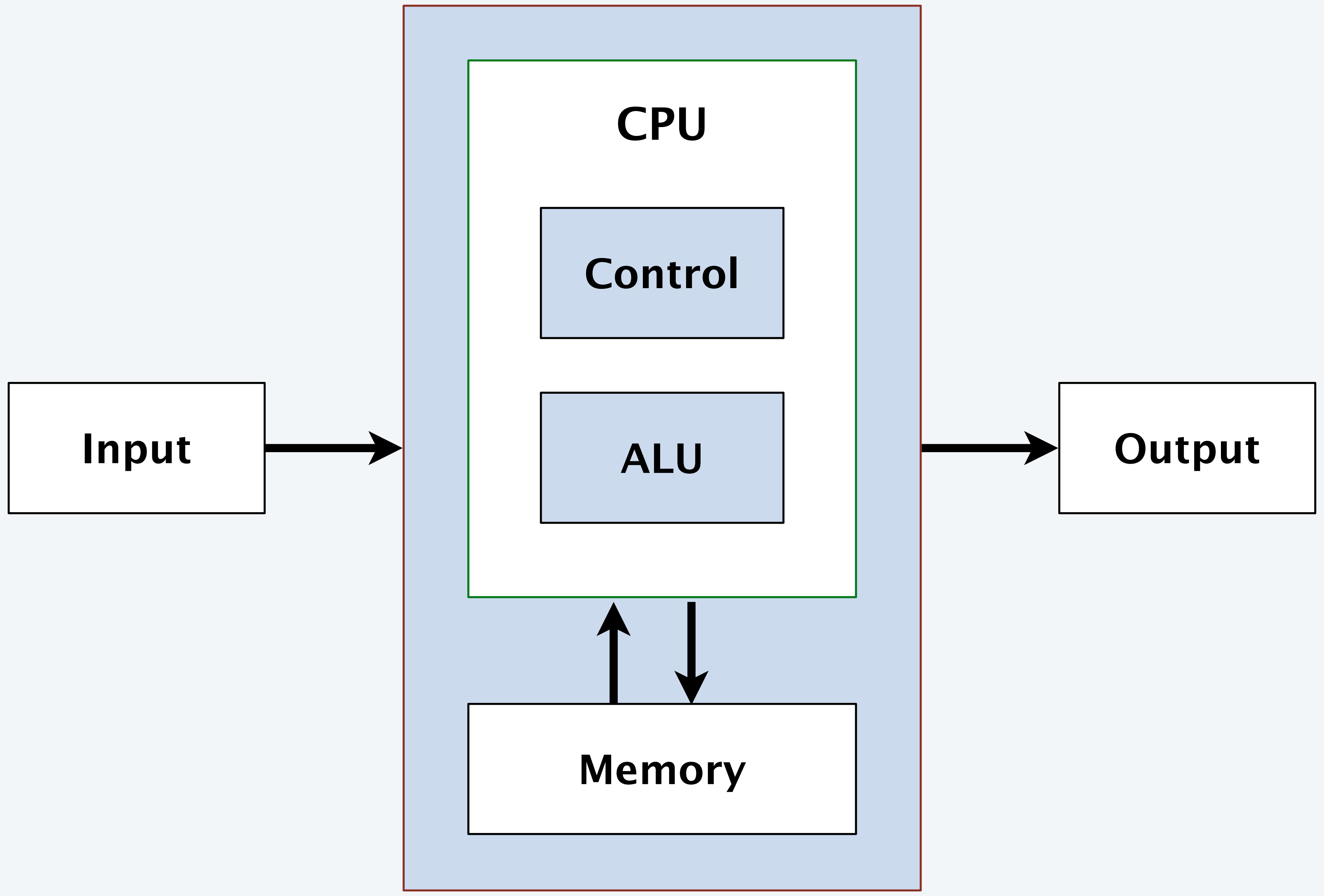
- Brilliant summation of a stored-program machine.
- Written by John von Neumann on a train.
- Based upon EDVAC design of Eckert-Mauchly; influenced by Turing.



First Draft of a Report
on the EDVAC

by

John von Neumann



Keys elements.

- Data and instructions encoded in binary.
- Store both data and instructions in same computer memory.
- ALU, control, memory, registers, and input/output.

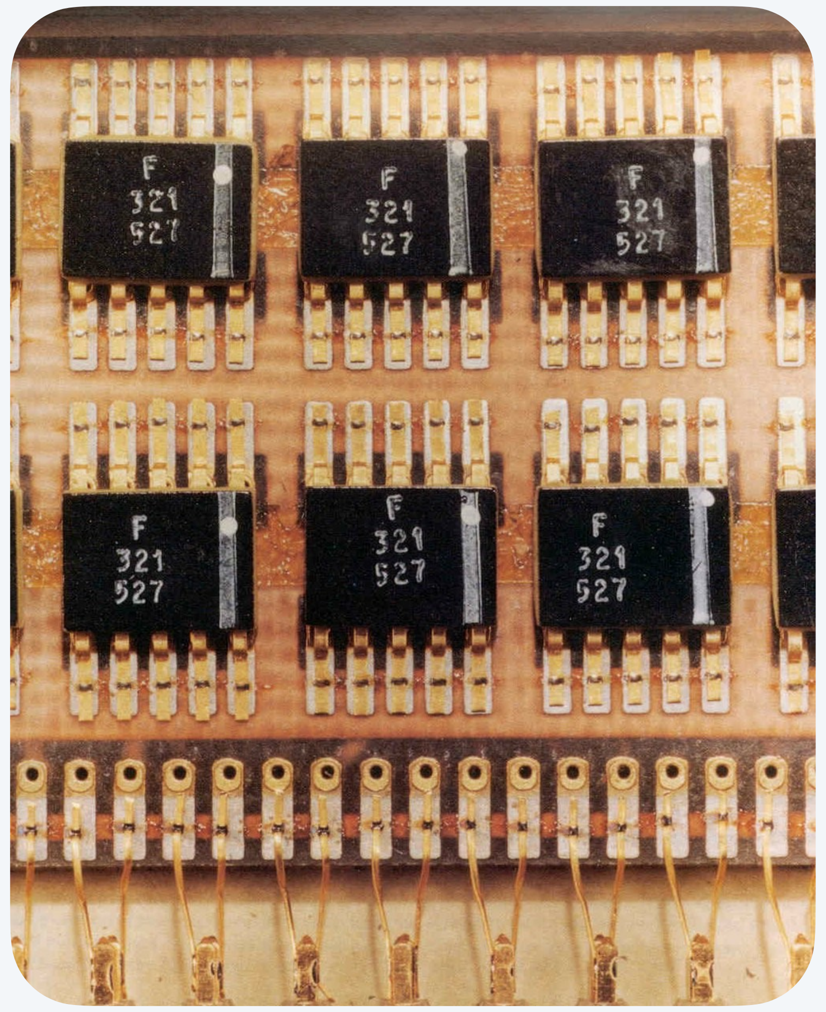
Apollo Guidance Computer

Apollo Guidance Computer. For guidance, navigation, and control of the spacecraft.

- First computer based on silicon integrated circuits.
- Weighed only 70 pounds!
- 1.024 MHz processor speed.
- 4 KB memory.

less powerful than a USB-C charger

Apollo 11
(landed on moon)



integrated circuit

Margaret Hamilton
(lead NASA software engineer)

What does the following program print to standard output?

- **A.** 0000
- **B.** 0088
- **C.** 0088, 0088, 0088, 0088, ...
- **D.** Nothing.

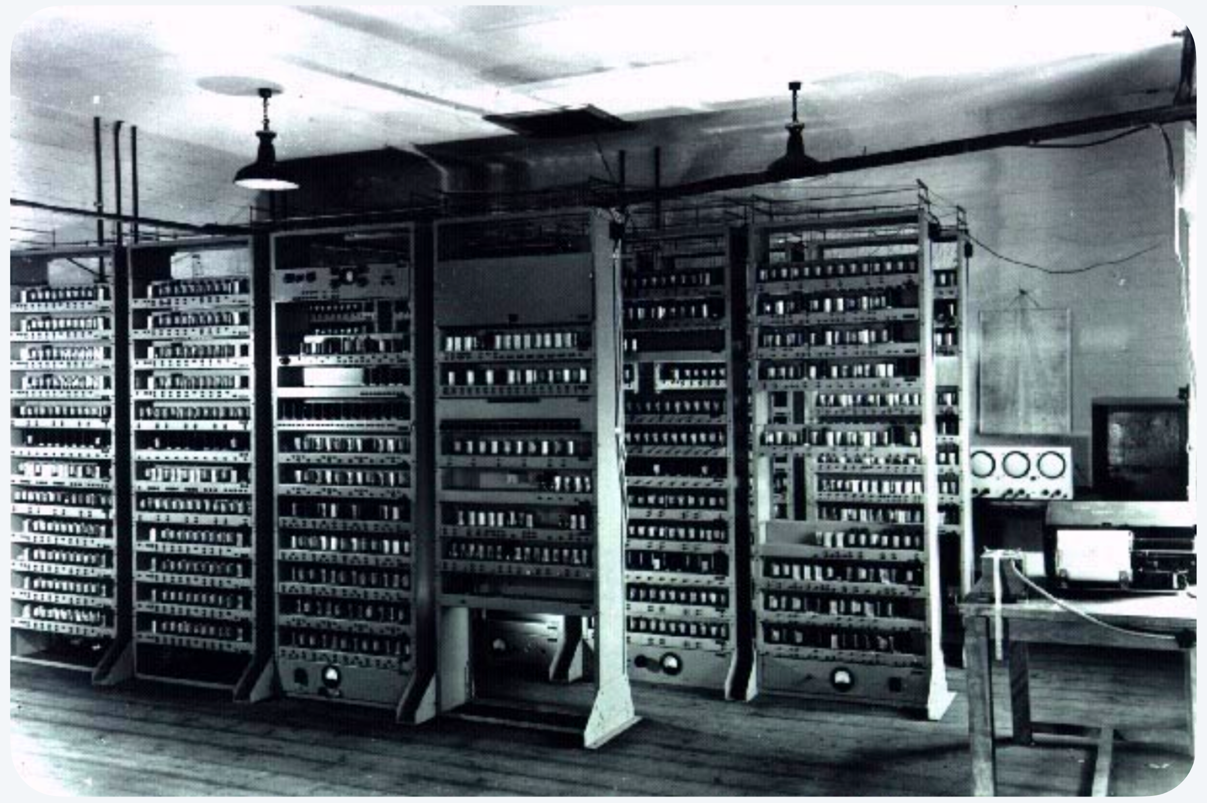
```
10: 7202    R[2] = 2
11: 7A88    R[A] = 88
12: AB16    R[B] = M[16]          ← R[B] stores C017
13: 2BB1    R[B] = R[B] - 2       ← R[B] stores C015
14: BB16    M[16] = R[B]
15: 9AFF    write R[A] to stdout
16: C017    goto 17
17: 0000    halt
```

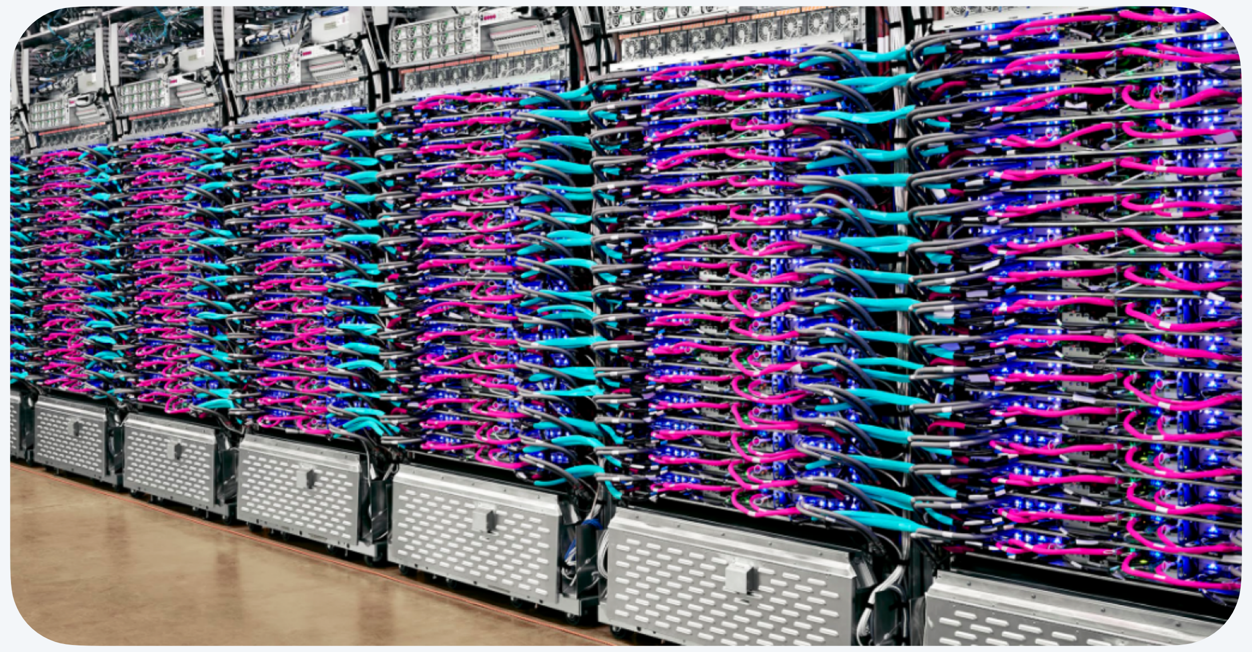
Implications

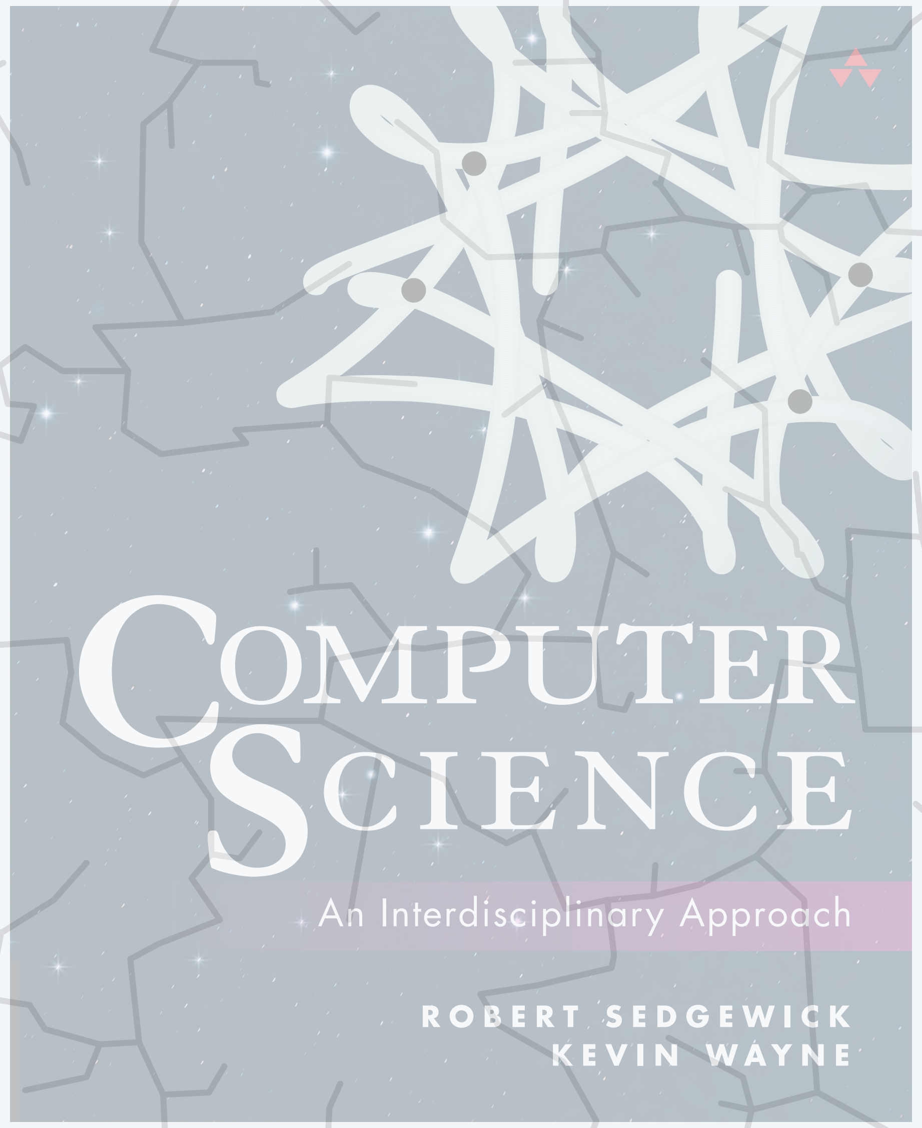
Stored-program (von Neumann) architecture is the basis of nearly all computers since the 1950s.

Practical implications.

- Programming: develop programs without rewiring.
- Download apps: load programs, not just data, into memory.
- Compilers: write programs that take programs as input (and produce programs as output).
- Code-injection attacks: trick program into treating input data as code.







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6. TOY MACHINE II

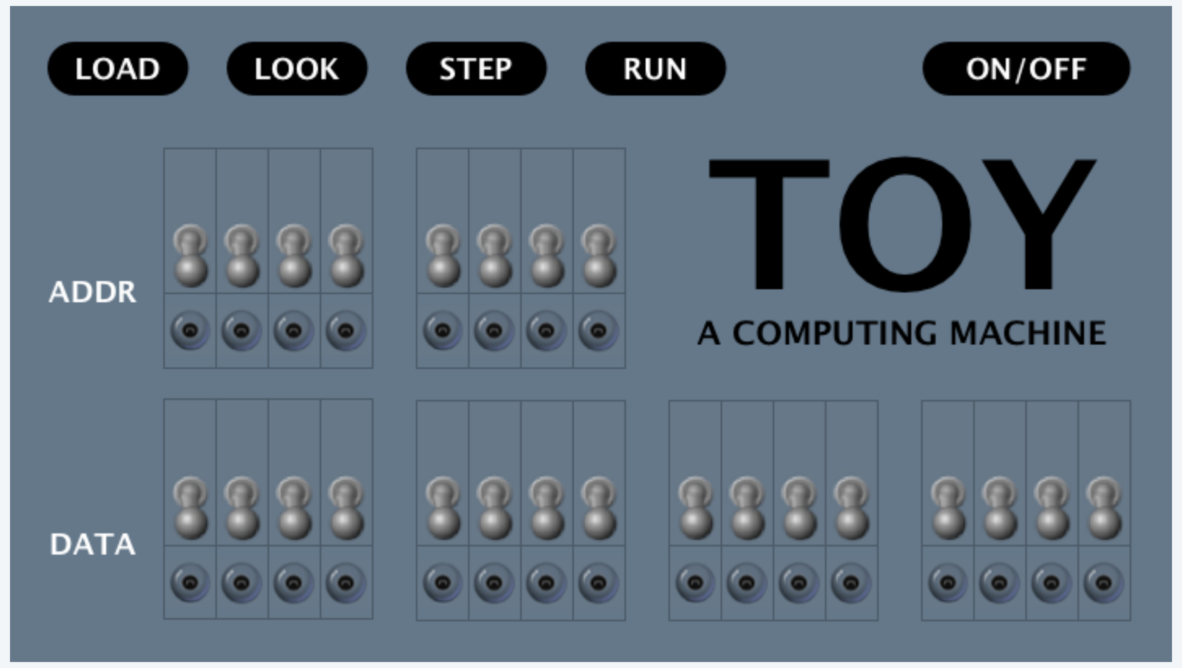
- conditionals and loops
- input and output
- arrays
- von Neumann architecture
- TOY emulator

TOY emulator

Q. How did we debug all our TOY programs?

A. We wrote a Java program to emulate a TOY machine.

Emulator. Hardware or software that enables one computer system to behave like another.



estimated number of Android devices: 1 billion+

estimated number of TOY devices: 1 billion+

Remarks.

- YOU could write a TOY emulator (ahead).
- We designed TOY by refining this code.
- All computers are designed in this way.

TOY emulator in Java: high-level design

Goal. Write a Java program that emulates the TOY machine.

hex literal (starts with 0x)

```
public class TOYLite {
   public static void main(String[] args) {
      int pc = 0x10;            // program counter
      int[] R = new int[16];    // registers
      int[] M = new int[256];   // main memory

      In in = new In(args[0]);
      for (int i = pc; !in.isEmpty(); i++)
         M[i] = Integer.parseInt(in.readString(), 16);

      while (true) {
         // 1. fetch instruction and increment PC
         // 2. decode instruction
         // 3. execute instruction
      }
   }
}
```

base 16

```
~/cos126/toy> more add.toy
8AFF
8BFF
1CAB
9CFF
0000

~/cos126/toy> java-introcs TOYLite add.toy
0008
0005
000D
```

read R[A] and R[B] from standard input

print R[C] to standard output

takes TOY program as input

emulates TOY program and produces same output

TOY emulator: fetch and increment

Fetch. Get instruction from memory location indexed by PC.

Increment. Increment PC by 1.

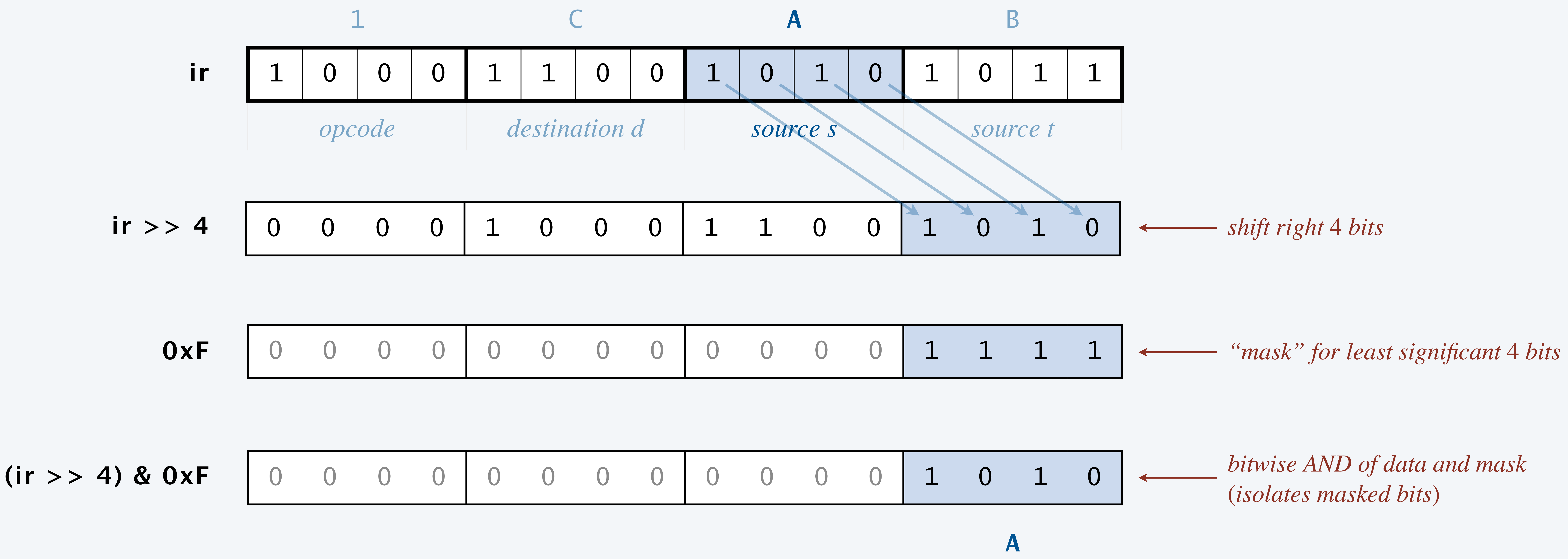
```
int ir = M[pc];     // fetch
pc++;               // increment
```

TOY emulator: decode instruction

Decode. Extract relevant components from instruction register (IR).

- Bitwise operations are the same in Java and TOY.
- Use shift-and-mask technique.

Ex. Extract source s from `1CAB`.



TOY emulator: decode instruction

Decode. Extract relevant components from instruction register (IR).

- Bitwise operations are the same in Java and TOY.
- Use shift-and-mask technique.

```
int ir = M[pc];    // fetch
pc++;              // increment

int op   = (ir >> 12) &  0xF;    // opcode
int d    = (ir >>  8) &  0xF;    // destination d
int s    = (ir >>  4) &  0xF;    // source s
int t    = (ir >>  0) &  0xF;    // source t
int addr = (ir >>  0) & 0xFF;    // address
```

TOY emulator: execute instruction

Execute. Use Java `switch` statement to implement state change for each of 16 instructions.

```
if (op == 0) break;        // halt
```

```
switch (op) {
   case  1:  R[d] = R[s] +  R[t];        break;
   case  2:  R[d] = R[s] -  R[t];        break;
   case  3:  R[d] = R[s] &  R[t];        break;
   case  4:  R[d] = R[s] ^  R[t];        break;
   case  5:  R[d] = R[s] << R[t];        break;
   case  6:  R[d] = R[s] >> R[t];        break;
   case  7:  R[d] = addr;                break;
   case  8:  R[d] = M[addr];             break;
   case  9:  M[addr] = R[d];             break;
   case 10:  R[d] = M[R[t]];             break;
   case 11:  M[R[t]] = R[d];             break;
   case 12:  if (R[d] == 0) pc = addr;   break;
   case 13:  if (R[d] >  0) pc = addr;   break;
   case 14:  pc = R[d];                  break;
   case 15:  R[d] = pc; pc = addr;       break;
}
```

TOY emulator in Java

A few missing details.

- R[0] is always 0000.
- TOY standard input/output.
- 16-bit TOY word vs. 32-bit Java int.
- More flexible TOY program input format.

Full implementation. See booksite.

Implications.

- Can run any TOY program!
- Can develop TOY code on another machine.
- Easy to change TOY design.

```java
public class TOYLite {
   public static void main(String[] args) {
      int pc   = 0x10;              // program counter
      int[] R = new int[16];        // registers
      int[] M = new int[256];       // main memory

      In in = new In(args[0]);
      for (int i = pc; !in.isEmpty(); i++)
         M[i] = Integer.parseInt(in.readString(), 16);

      while (true) {
         int ir = M[pc++];      // fetch
         pc++;                  // increment

         int op   = (ir >> 12) &  0xF;    // opcode
         int d    = (ir >>  8) &  0xF;    // destination d
         int s    = (ir >>  4) &  0xF;    // source s
         int t    = (ir >>  0) &  0xF;    // source t
         int addr = (ir >>  0) & 0xFF;    // address

         if (op == 0) break;
         switch (op) {
            case  1:  R[d] = R[s] +  R[t];        break;
            case  2:  R[d] = R[s] -  R[t];        break;
            case  3:  R[d] = R[s] &  R[t];        break;
            case  4:  R[d] = R[s] ^  R[t];        break;
            case  5:  R[d] = R[s] << R[t];        break;
            case  6:  R[d] = R[s] >> R[t];        break;
            case  7:  R[d] = addr;                break;
            case  8:  R[d] = M[addr];             break;
            case  9:  M[addr] = R[d];             break;
            case 10:  R[d] = M[R[t]];             break;
            case 11:  M[R[t]] = R[d];             break;
            case 12:  if (R[d] == 0) pc = addr;   break;
            case 13:  if (R[d] >  0) pc = addr;   break;
            case 14:  pc = R[d];                  break;
            case 15:  R[d] = pc; pc = addr;       break;
         }
      }
   }
}
```

state

parse input file

fetch, increment

decode instruction

execute instruction

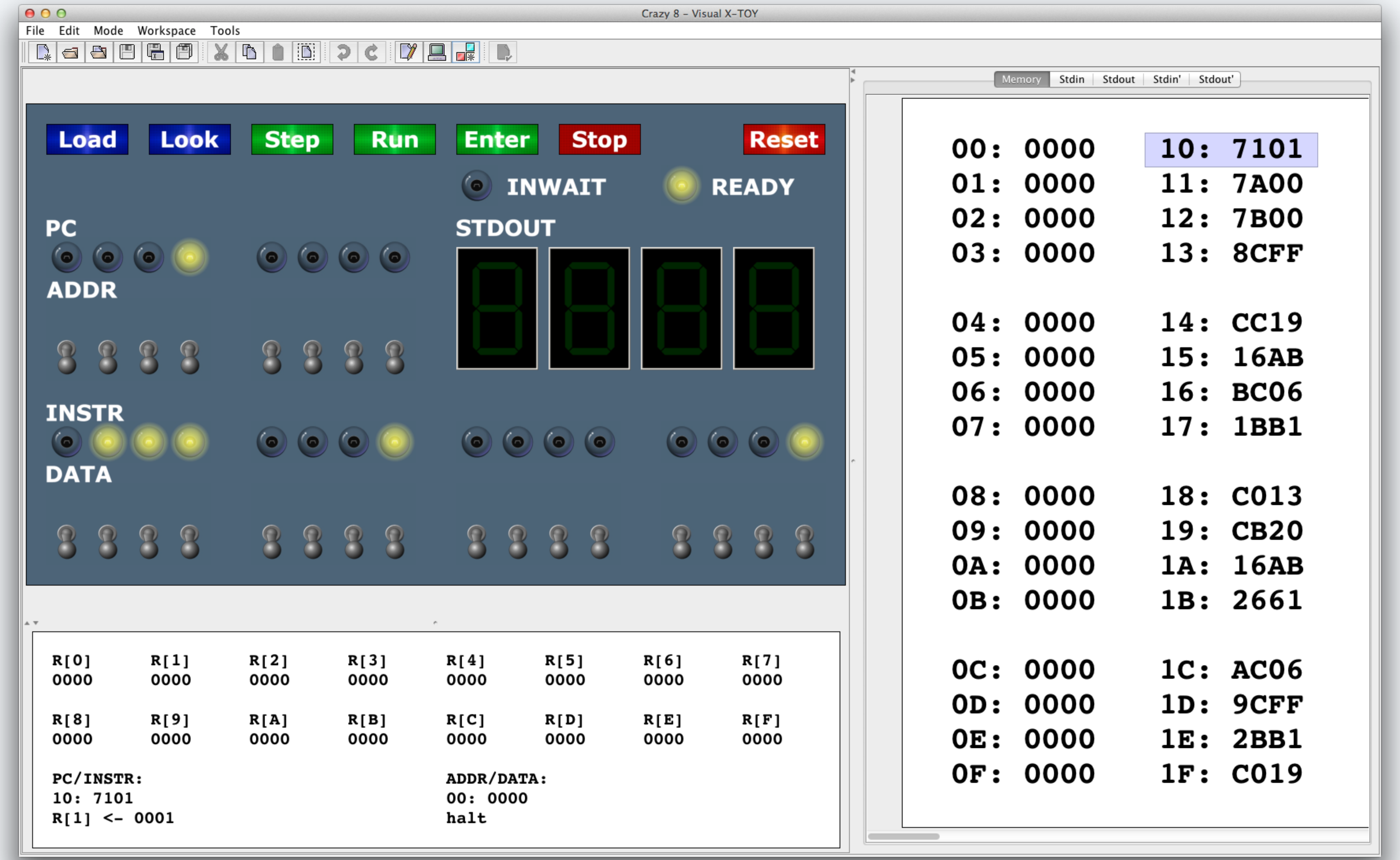
Visual X-TOY

Visual X–TOY. A Java IDE that emulates the TOY machine.

- GUI, text editor, auto-comments, debugger, many other features.
- Written by Brian Tsang ’04 (using Java 1.3). ← *and still works 20 years later!*
- Available on the booksite.
- YOU can develop TOY software. ← *Assignment 8*

Same approach used for all new systems.

- Build simulator and development environment.
- Develop and test software.
- Build and sell hardware.



Backward compatibility

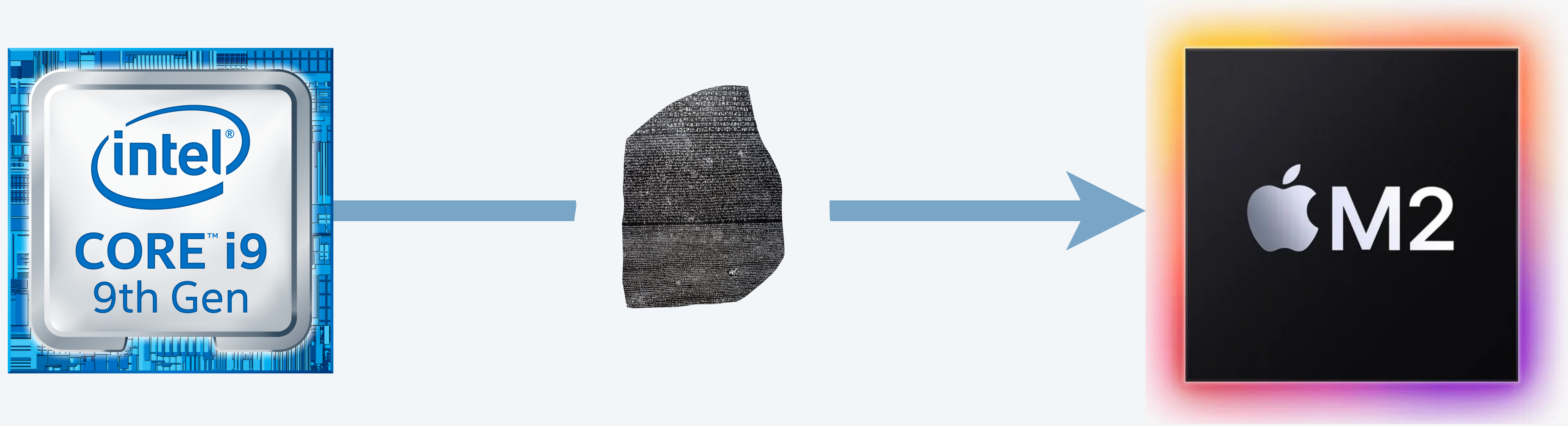
Q. How to run old software on a new machine architecture?

Approach 1. Rewrite it all: time-consuming, expensive, error-prone.

Approach 2. Write an emulator for old computer on the new one.

Ex 1. Pac-Man.

Ex 2. Rosetta 2. ←— *run 64-bit Intel on Apple Silicon*



64-bit Intel

Apple Silicon

Pac-Man 1980s
(arcade machine)

Pac-Man 2020s
(Android phone)

Impact. Old software remains available.

Virtual machines

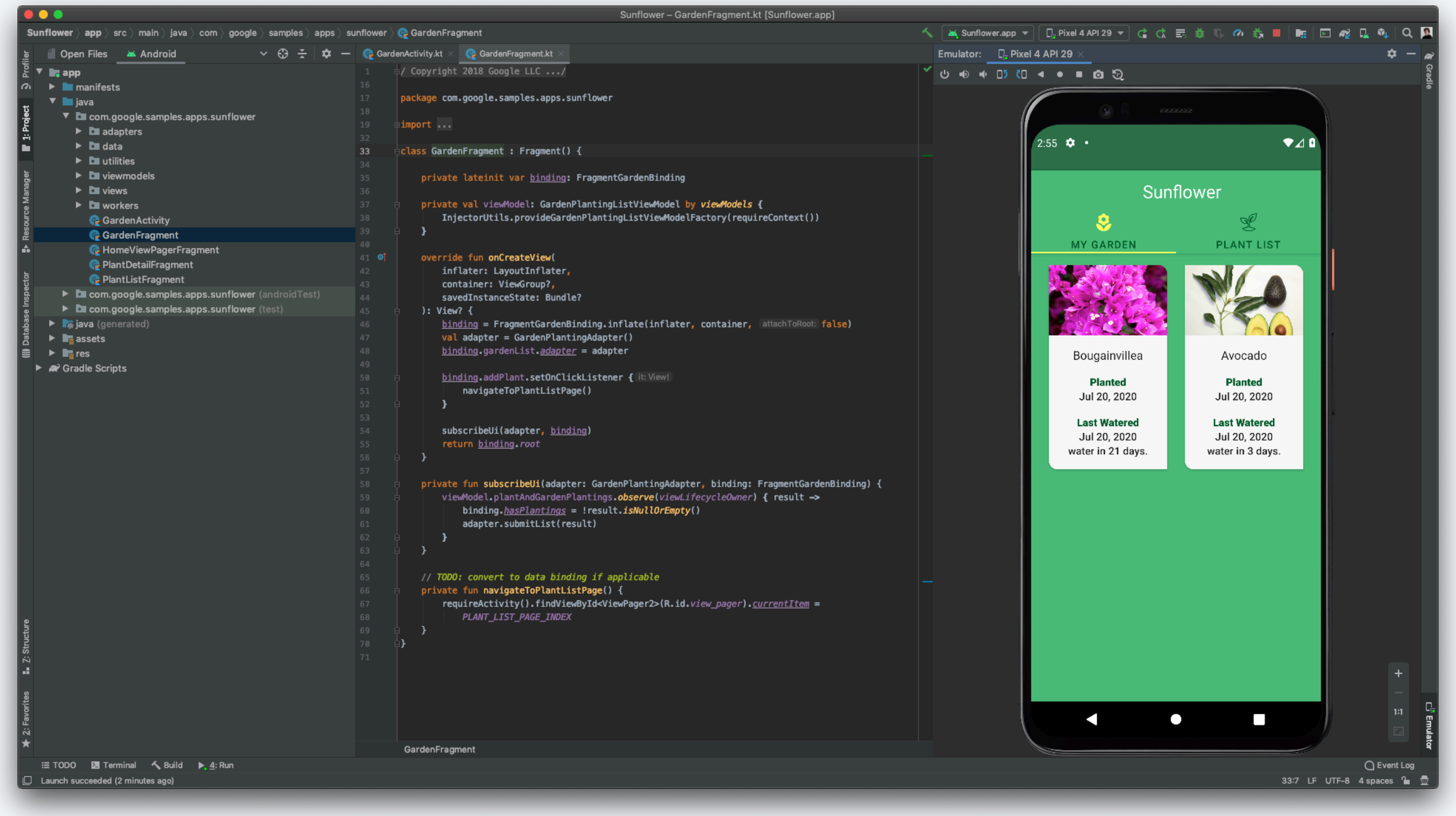
Virtual machine. Software-based emulation of a physical computer.

- Can run/develop software without having physical computer.
- Provides portability, scalability, flexibility, and security.

"write once, run anywhere"

Java virtual machine (JVM). Abstract machine that can execute Java `.class` files.

Mobile app IDEs. Provide emulator for Android, iPhone, Apple watch, …



Cloud computing. Virtual CPU, memory, storage, OS, and network.

Amazon EC2

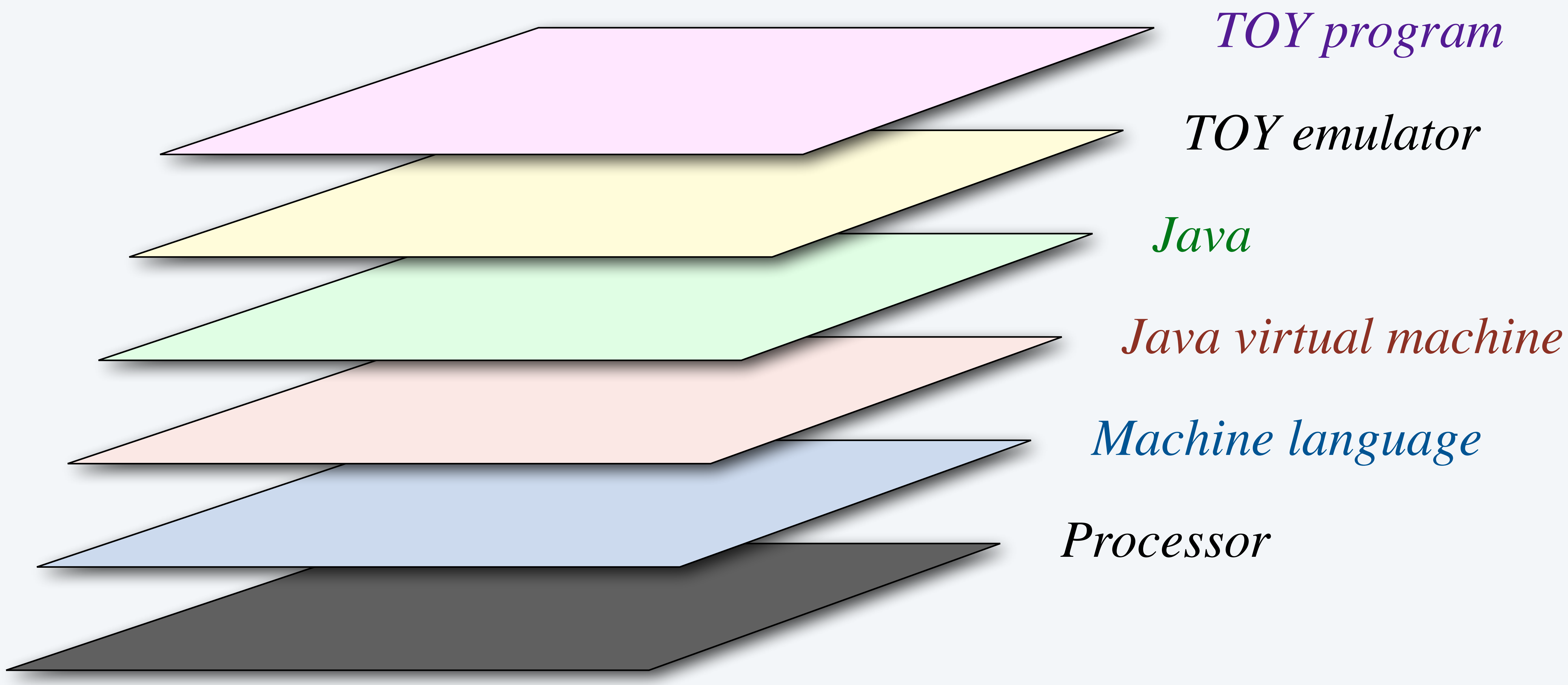
Google CE

Microsoft Azure

Layers of abstraction

Computer systems are built by accumulating layers of abstraction.

Ex. Running a TOY program.



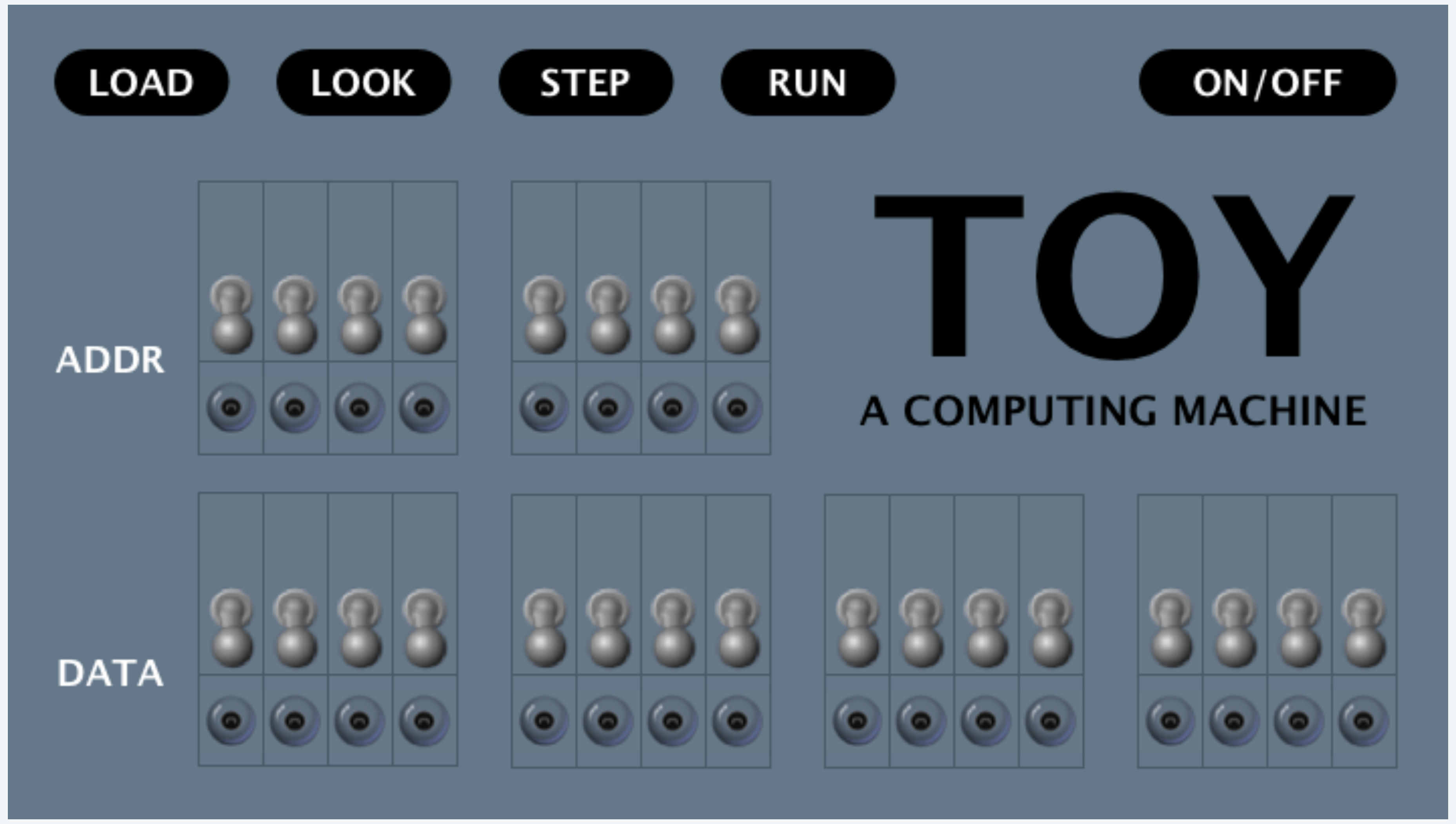
Big ideas

Digital computers. Encode "everything" in binary, including programs and data.

von Neumann machine. Store programs and data in same memory.

Indirection. Manipulate a value through its memory address.

Emulation. Make one system imitate another.



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