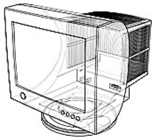
Course overview

Introduction to Computer

Yung-Yu Chuang

*with slides by Nisan & Schocken (*www.nand2tetris.org*)*

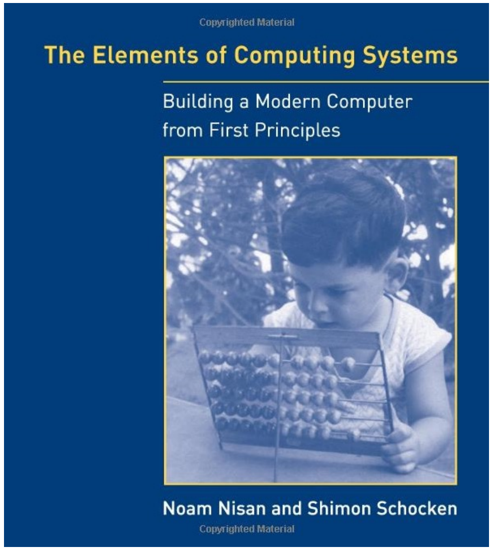
Logistics



- **Meeting time**: 9:10am-12:00pm, Tuesday
- **Instructor**: 莊永裕 Yung-Yu Chuang
- **Webpage**:

  http://www.csie.ntu.edu.tw/~cyy/introcs

Textbook



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The Elements of Computing Systems

Building a Modern Computer from First Principles

Noam Nisan and Shimon Schocken

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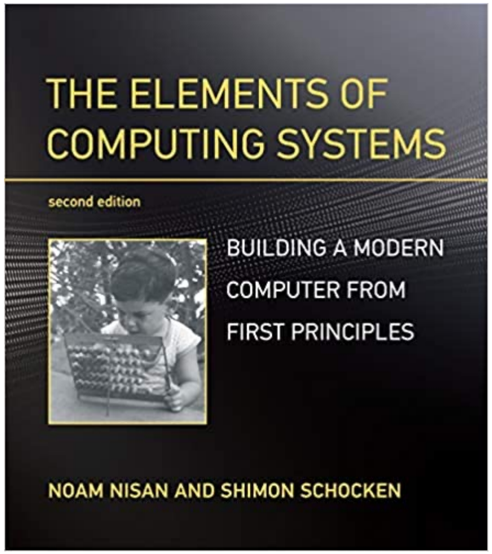


THE ELEMENTS OF COMPUTING SYSTEMS

second edition

BUILDING A MODERN COMPUTER FROM FIRST PRINCIPLES

NOAM NISAN AND SHIMON SCHOCKEN

The Elements of Computing Systems, Noam Nisan, Shimon Schocken, MIT Press

Nand2Tetris on coursera

Nand2Tetris2 on coursera

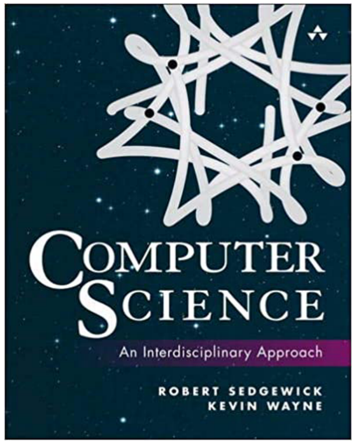
References (TOY)

Princeton's Introduction to CS,

http://www.cs.princeton.edu/introcs/java/60machine/

http://www.cs.princeton.edu/introcs/java/70circuits/

Coursera course

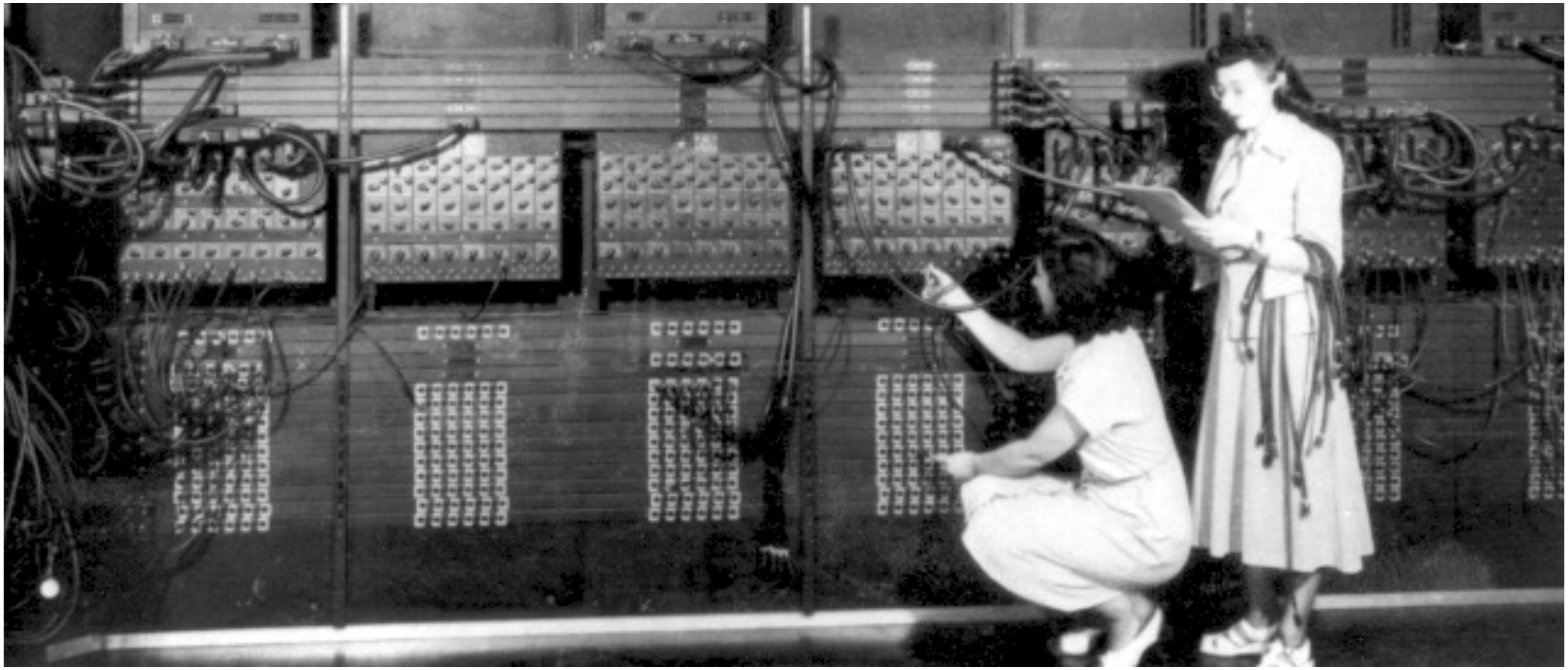


Computer Science: An Interdisciplinary Approach. Robert Sedgewick, Kevin Wayne

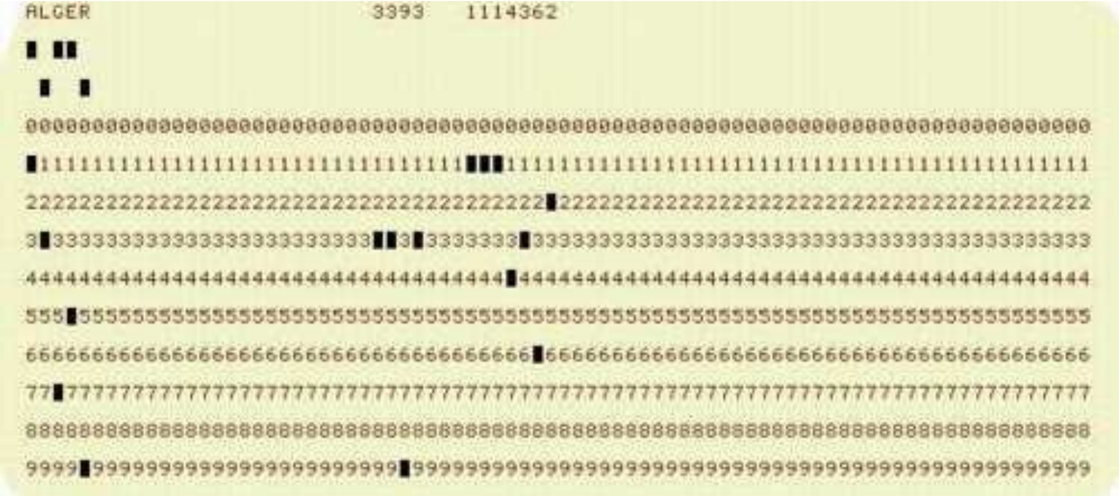
Grading (subject to change)

- Assignments (5 projects+1 homework, 50%) from the accompanying website
- Class participation (5%)
- Midterm quiz (20%)
- Final project (25%)

Early computers



Early programming tools

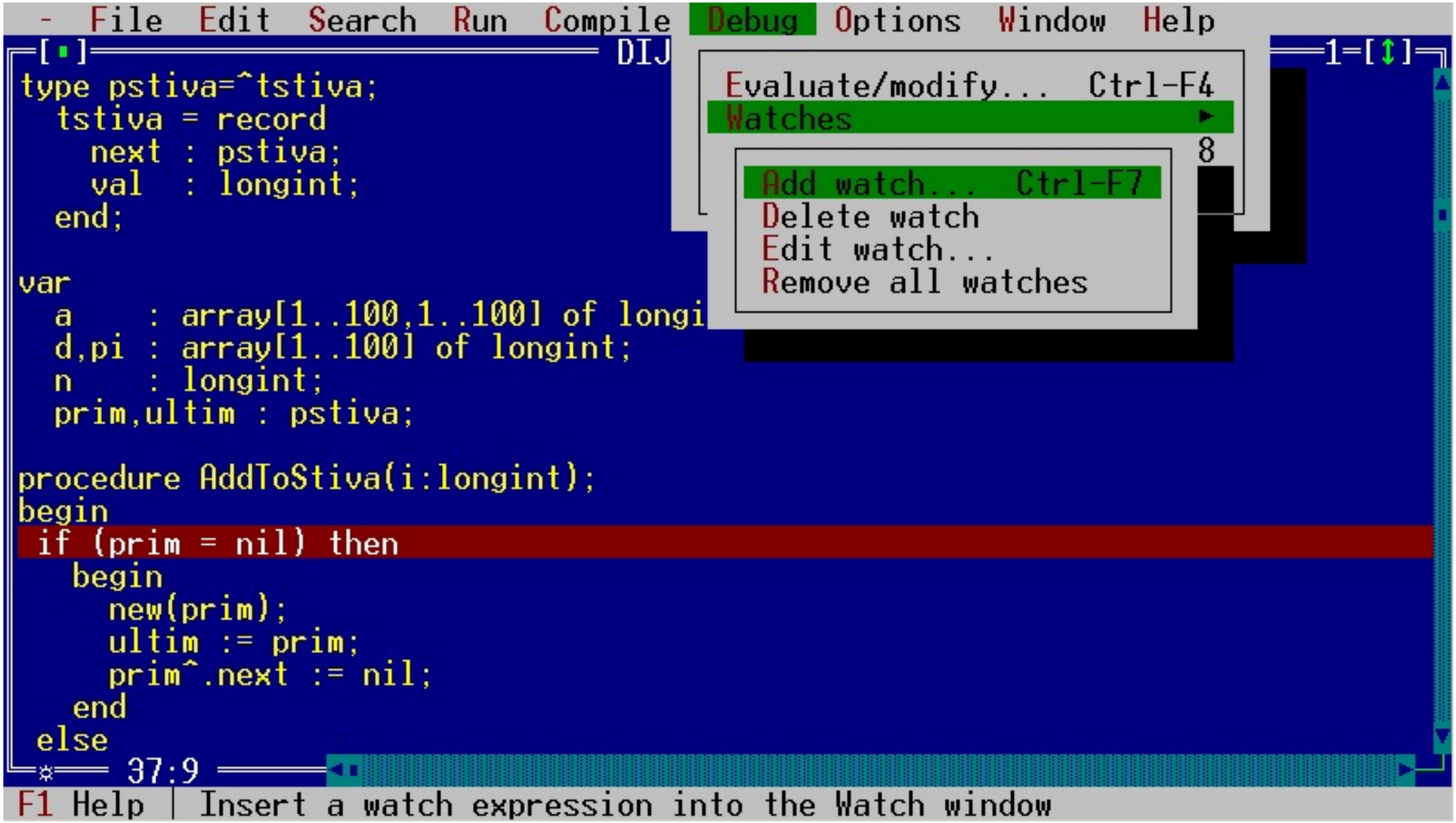


First popular PCs

Early PCs

- Intel 8086 processor
- 768KB memory
- 20MB disk
- Dot-Matrix printer (9-pin)

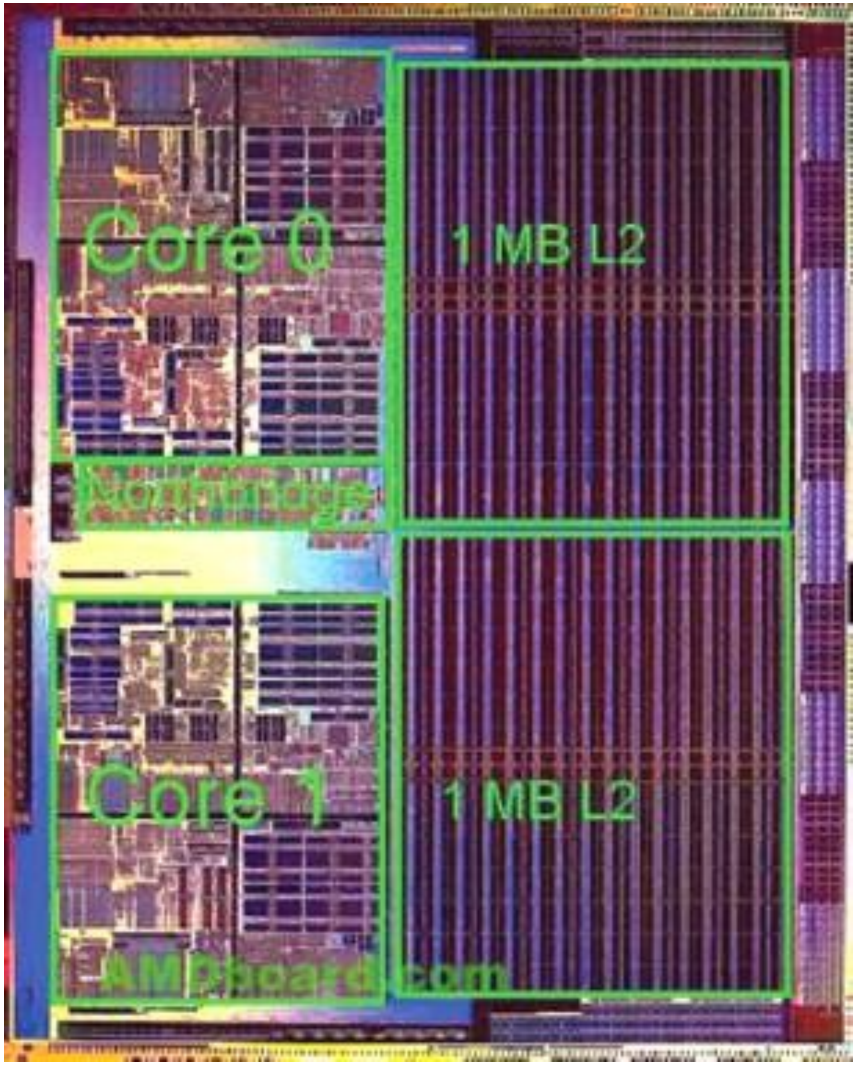
GUI/IDE



```
type pstiva=^tstiva;
  tstiva = record
    next : pstiva;
    val  : longint;
  end;

var
  a     : array[1..100,1..100] of longi
  d,pi  : array[1..100] of longint;
  n     : longint;
  prim,ultim : pstiva;

procedure AddToStiva(i:longint);
begin
 if (prim = nil) then
   begin
     new(prim);
     ultim := prim;
     prim^.next := nil;
   end
 else
```

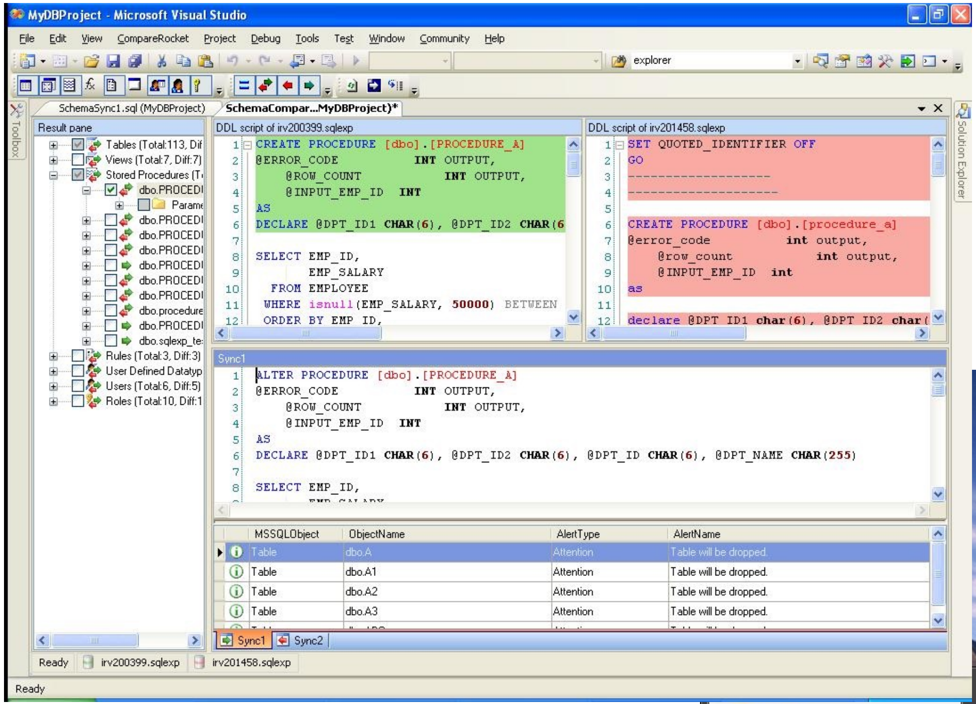
F1 Help │ Insert a watch expression into the Watch window

More advanced architectures



- Pipeline
- SIMD
- Multi-core
- Cache

More advanced software



DDL script of irv200399.sqlexp

```
CREATE PROCEDURE [dbo].[PROCEDURE_A]
@ERROR_CODE                INT OUTPUT,
    @ROW_COUNT              INT OUTPUT,
    @INPUT_EMP_ID   INT
AS
DECLARE @DPT_ID1 CHAR(6), @DPT_ID2 CHAR(6

SELECT EMP_ID,
       EMP_SALARY
  FROM EMPLOYEE
 WHERE isnull(EMP_SALARY, 50000) BETWEEN
 ORDER BY EMP_ID,
```

DDL script of irv201458.sqlexp

```
SET QUOTED_IDENTIFIER OFF
GO
--------------------
--------------------

CREATE PROCEDURE [dbo].[procedure_a]
@error_code           int output,
    @row_count              int output,
    @INPUT_EMP_ID   int
as

declare @DPT_ID1 char(6), @DPT_ID2 char(
```

Sync1

```
ALTER PROCEDURE [dbo].[PROCEDURE_A]
@ERROR_CODE                INT OUTPUT,
    @ROW_COUNT              INT OUTPUT,
    @INPUT_EMP_ID   INT
AS
DECLARE @DPT_ID1 CHAR(6), @DPT_ID2 CHAR(6), @DPT_ID CHAR(6), @DPT_NAME CHAR(255)

SELECT EMP_ID,
```

MSSQLObject	ObjectName	AlertType	AlertName
Table	dbo.A	Attention	Table will be dropped.
Table	dbo.A1	Attention	Table will be dropped.
Table	dbo.A2	Attention	Table will be dropped.
Table	dbo.A3	Attention	Table will be dropped.

More “computers” around us

My computers

Desktop
(Intel Core i7-6700
3.4GHz, GTX960)

MacBook Pro
(Intel Core i5, 2.3GHz)

Surface Pro 4
(Intel i5-6300 2.4GHz)

iPhone 11
Pro (A13,
ARMv8.3-A)

The downside

- “*Once upon a time, every computer specialist had a gestalt understanding of how computers worked*. … As modern computer technologies have become increasingly more complex, this clarity is all but lost.” Quoted from the textbook

How is it done?

```
// First Example in Programming 101
class Main {
  function void main () {
    do Output.printString("Hello World");
    do Output.println(); // New line
    return;
  }
}
```

Main secret of computer science

implementation

Don’t worry about the “how”

Only about the “what”

abstraction

what our programming
language promises to do

- Extremely complicated system
- Information hiding

Main secret of computer science

Don’t worry about the “how”

But, someone has to, for example, you.

Goal of the course

“The best way to understand how computers work is to build one from scratch.” Quoted from the textbook

The course at a glance

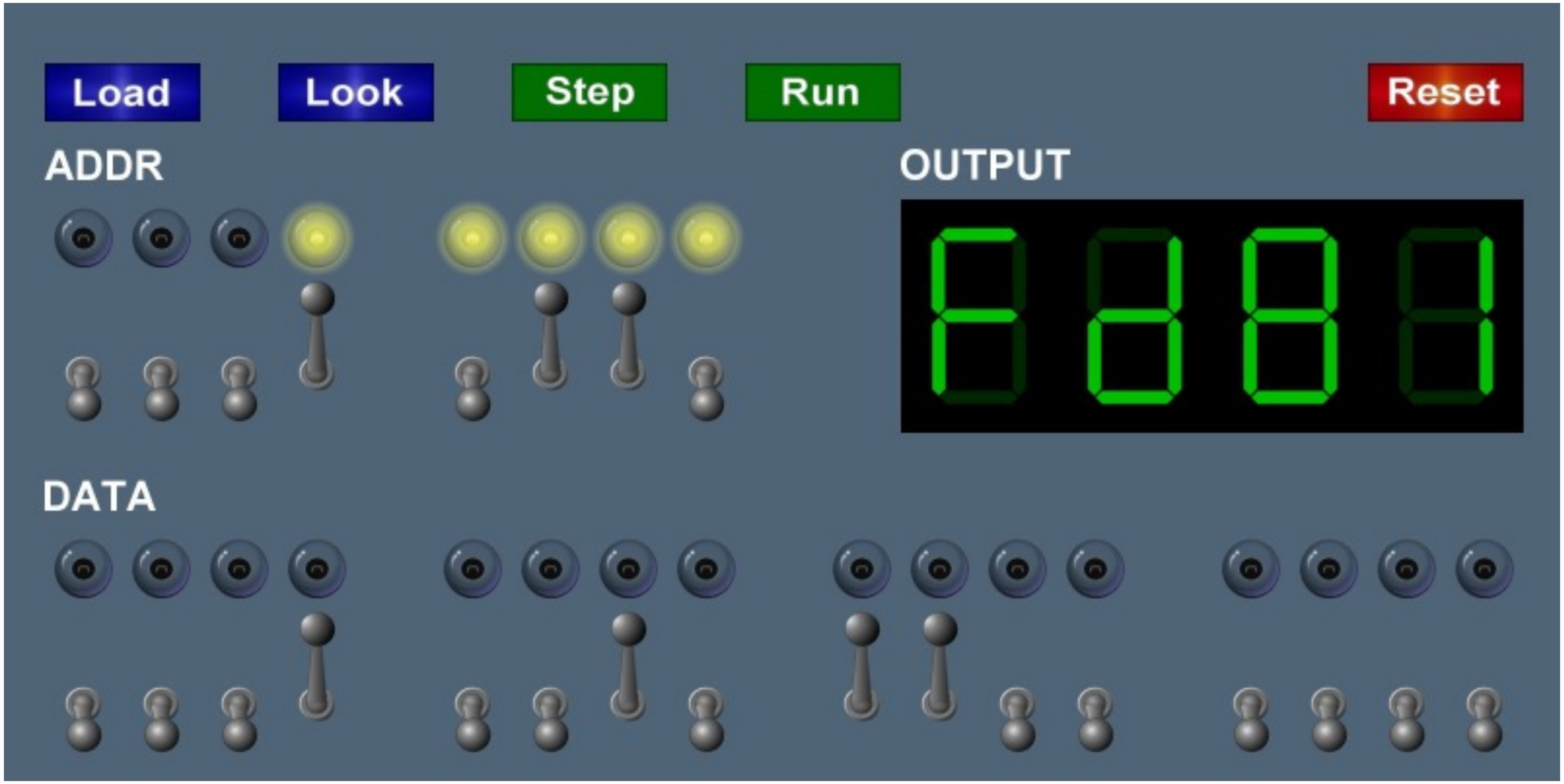
Objectives:

- Understand how hardware and software systems are built and how they work together
- Learn how to break complex problems into simpler ones
- Learn how large scale development projects are planned and executed
- Have fun

Methodology:

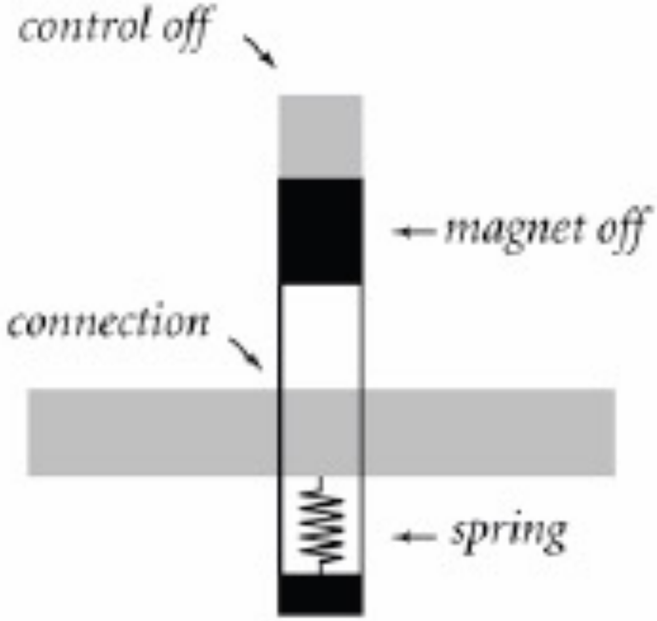
- Build a complete, general-purpose and working computer system
- Play and experiment with this computer, at any level of interest

TOY machine

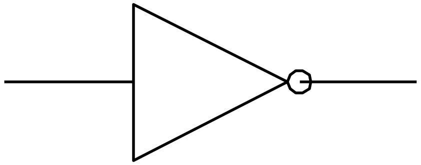


TOY machine

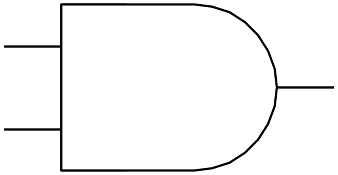
- Starting from a simple construct



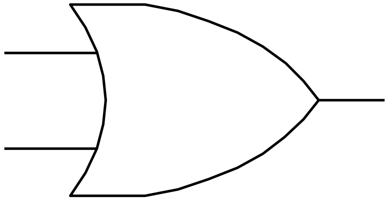
Logic gates



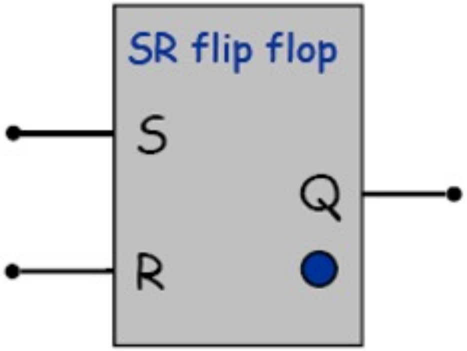
NOT



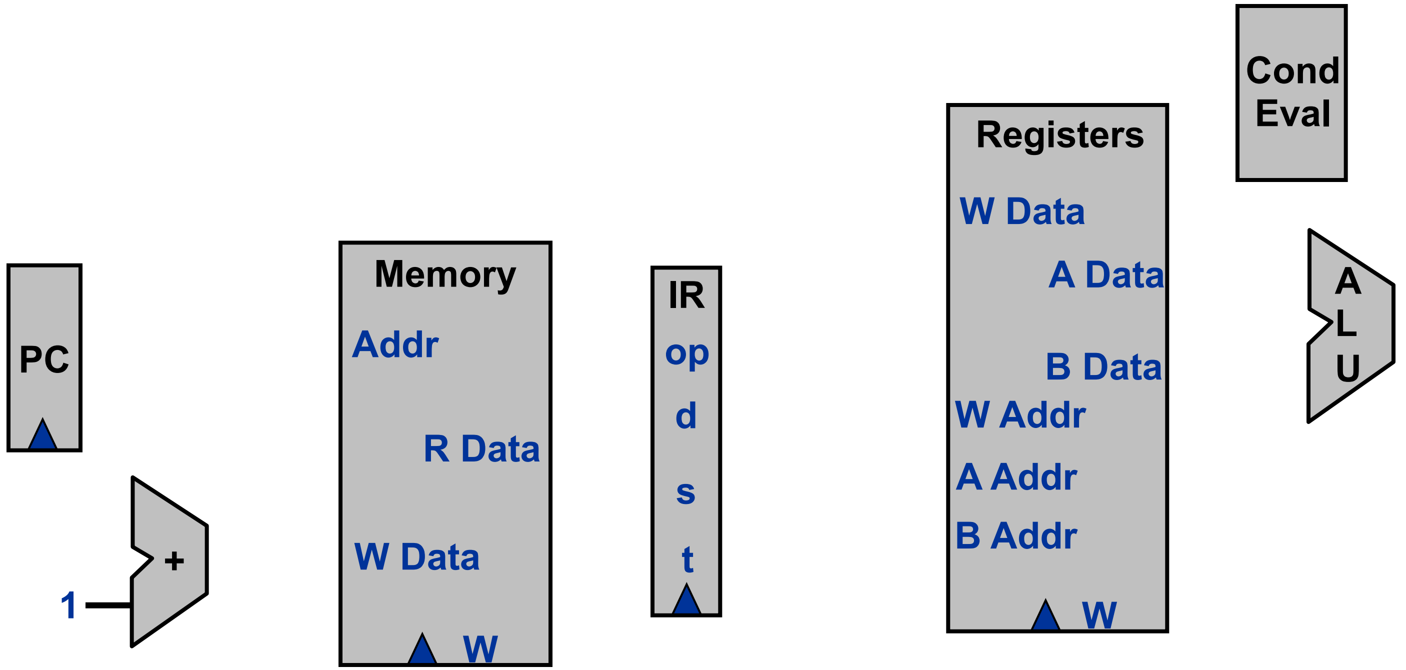
AND



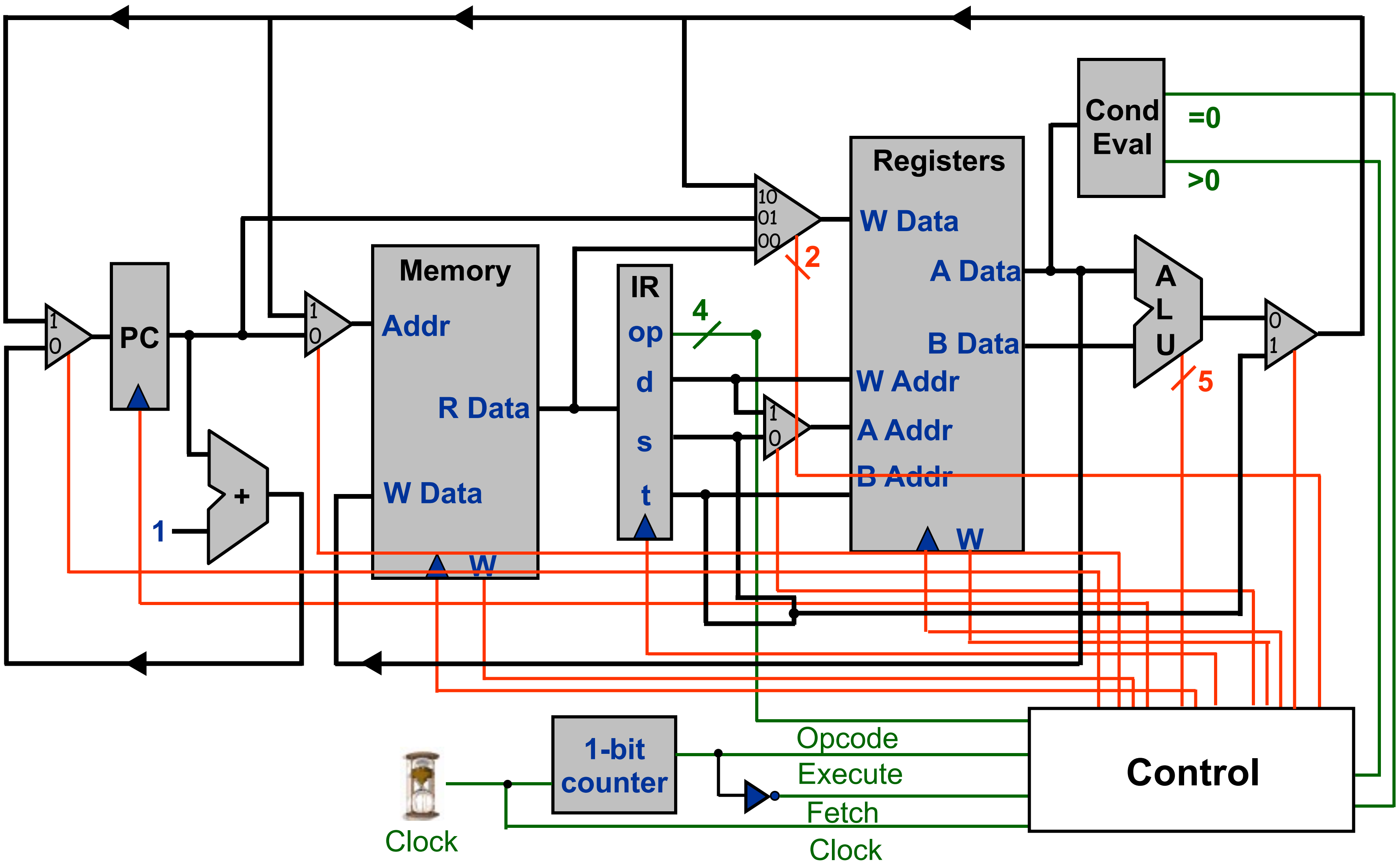
OR



Components

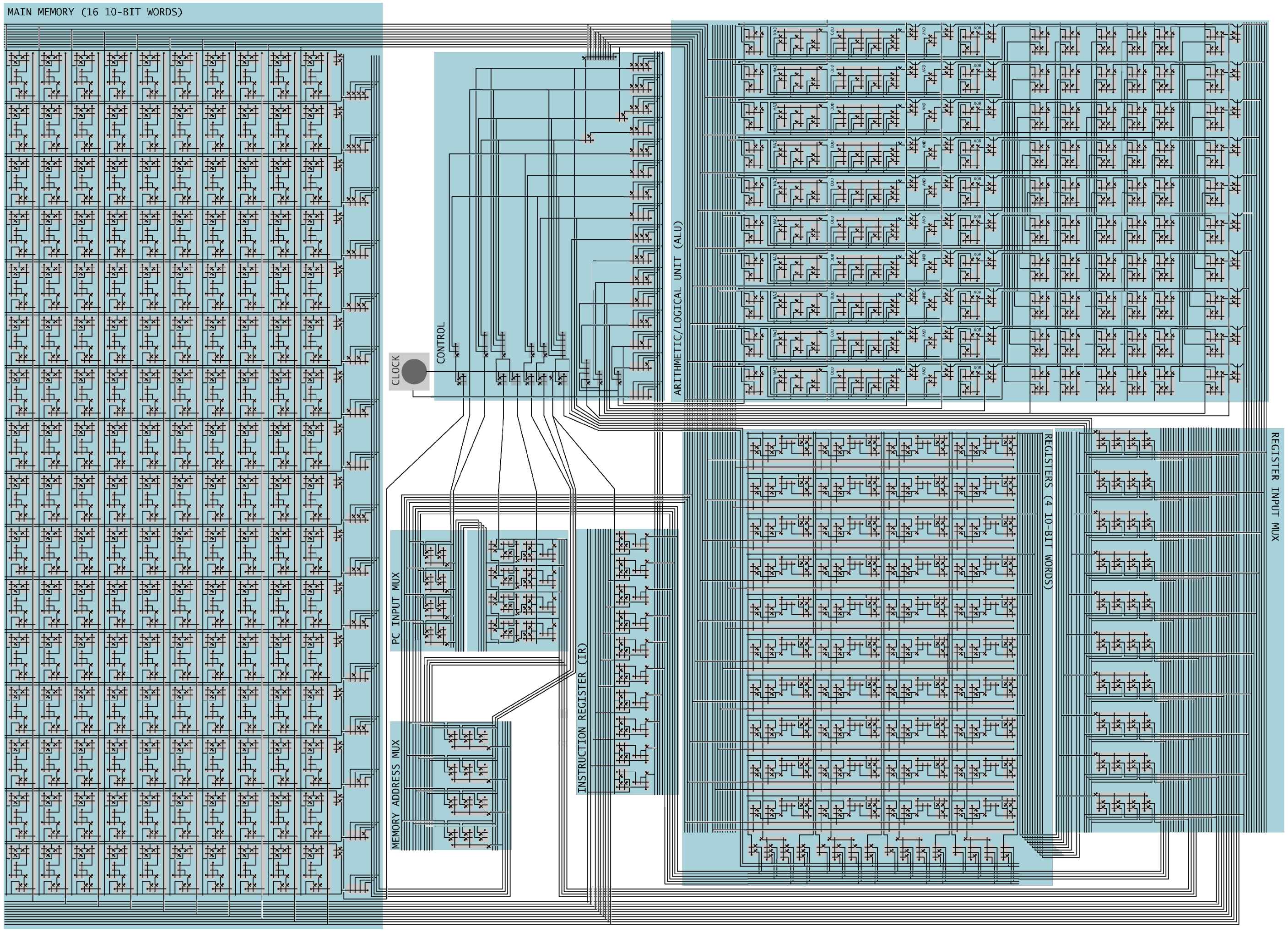

PC
1
+
Memory
Addr
R Data
W Data
W
IR
op
d
s
t
Registers
W Data
A Data
B Data
W Addr
A Addr
B Addr
W
Cond
Eval
A
L
U

Toy machine


Cond
Eval
=0
>0
Registers
W Data
A Data
B Data
W Addr
A Addr
B Addr
W
10
01
00
2
A
L
U
5
0
1
Memory
Addr
R Data
W Data
W
IR
op
d
s
t
4
PC
1
0
+
1
1-bit
counter
Opcode
Execute
Fetch
Clock
Control
Clock

TOY machine

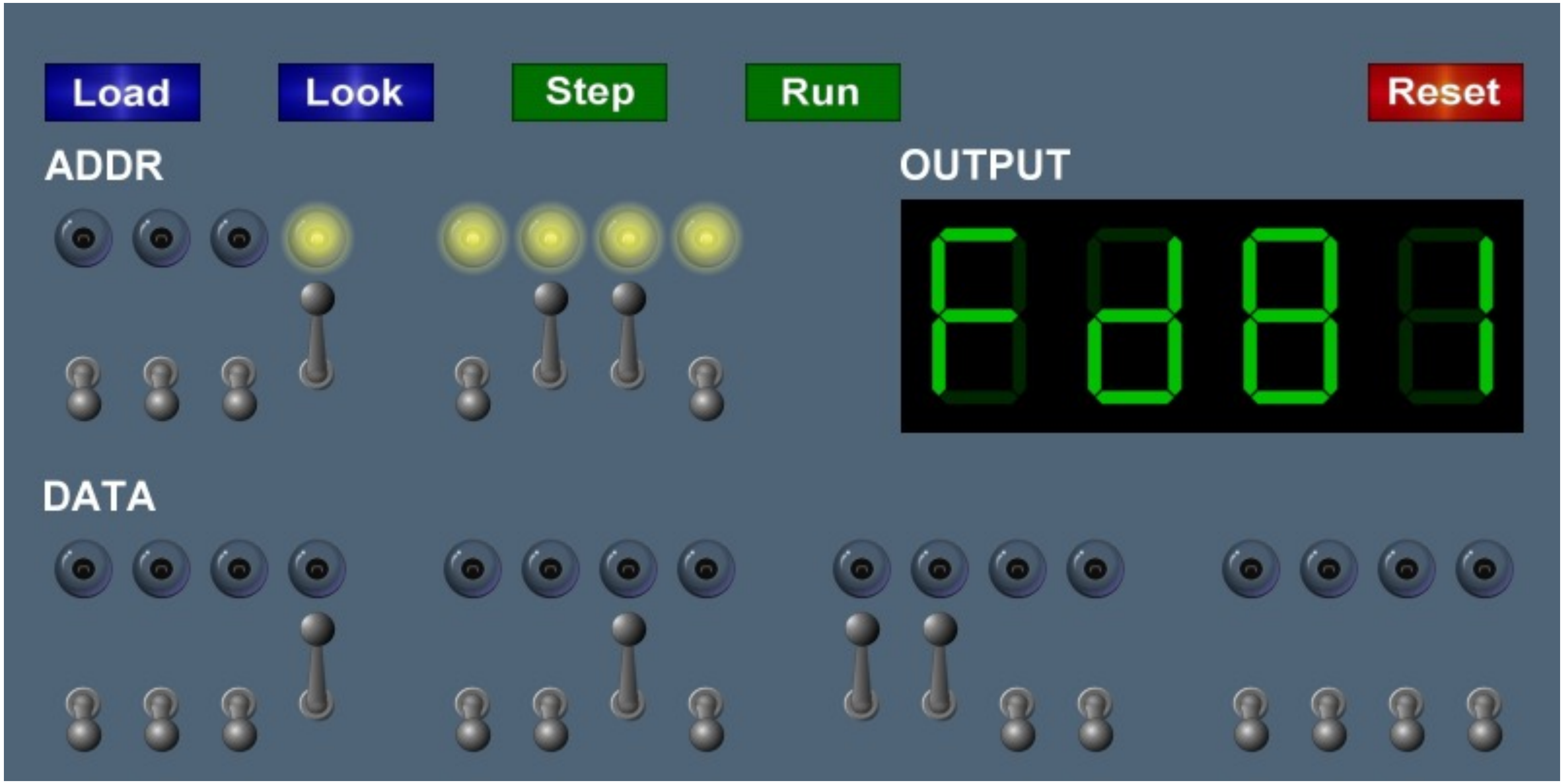
- Almost as good as any computers


MAIN MEMORY (16 10-BIT WORDS)
CLOCK
CONTROL
ARITHMETIC/LOGICAL UNIT (ALU)
REGISTERS (4 10-BIT WORDS)
REGISTER INPUT MUX
PC INPUT MUX
MEMORY ADDRESS MUX
INSTRUCTION REGISTER (IR)

TOY machine

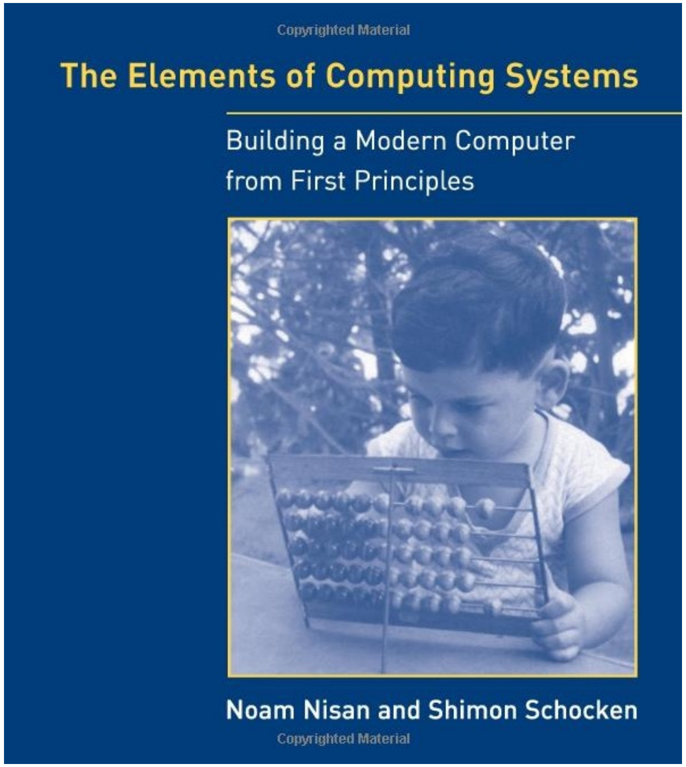
```
int A[32];            A      DUP    32              10: C020

                             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
```

TOY machine



From NAND to Tetris

- The elements of computing systems
- Courses
- Software
- Cool stuffs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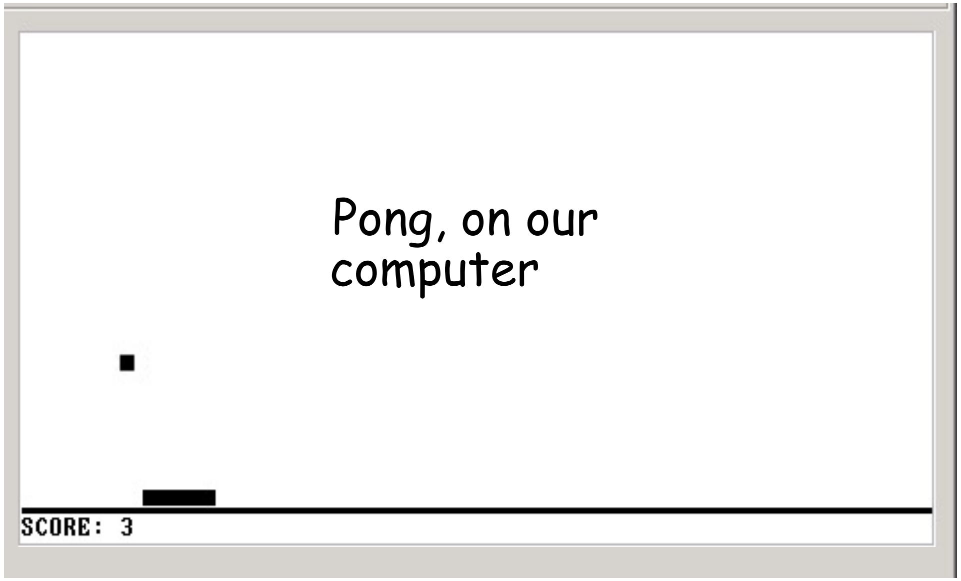
Pong on the Hack computer

Pong, 1985

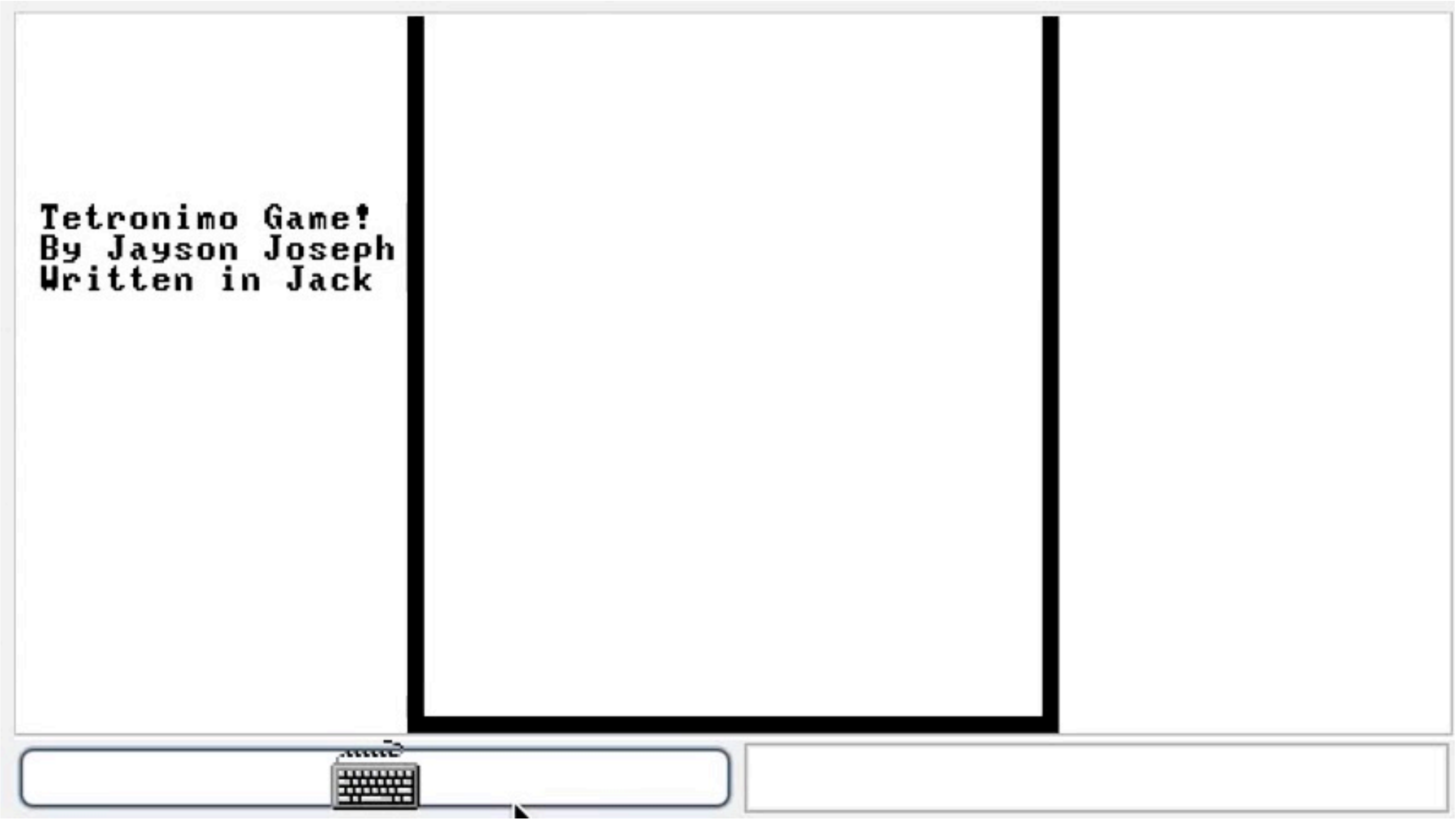
Pong, 2011



SCORE: 3

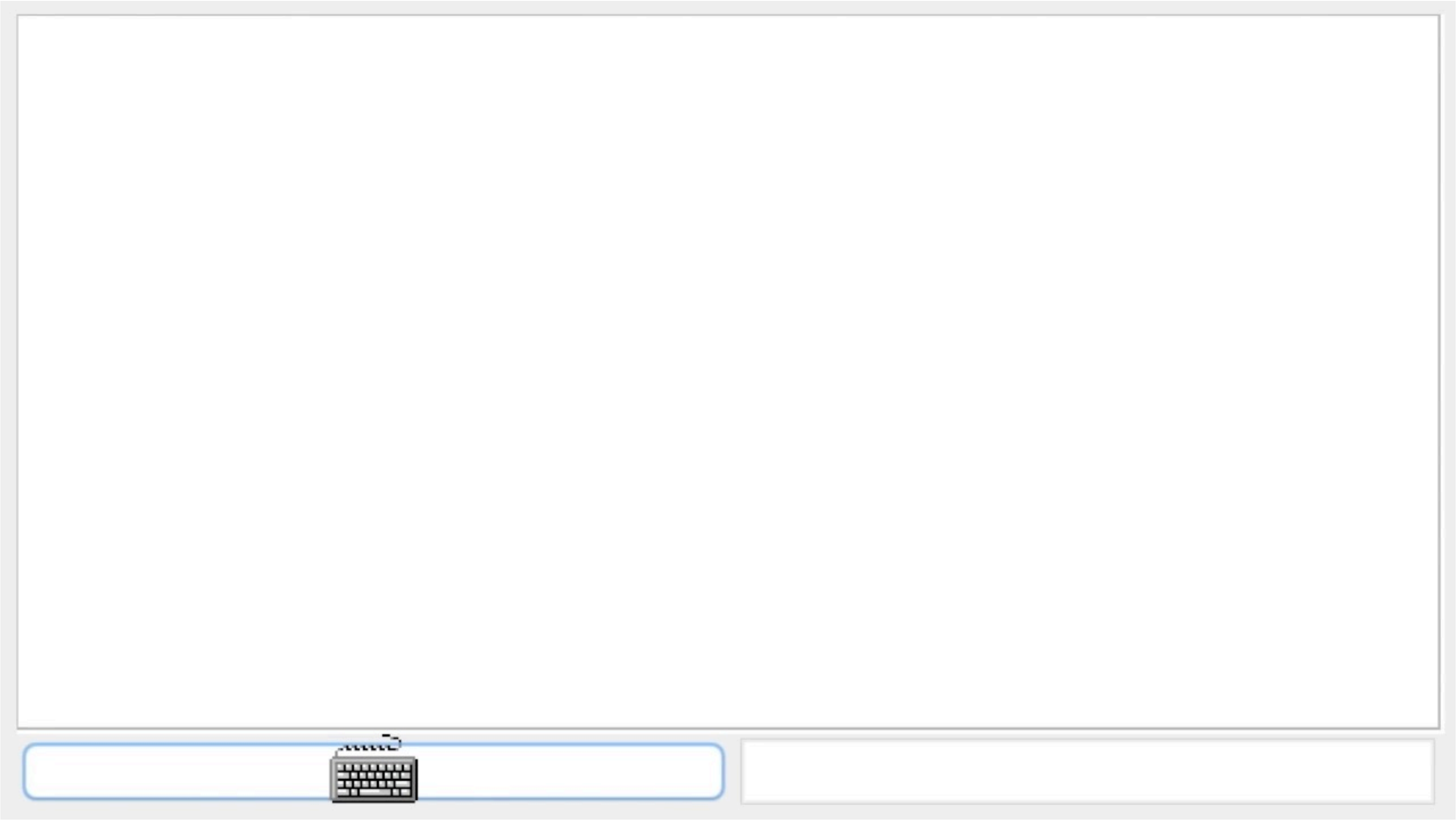
Pong, on our computer

Sample projects

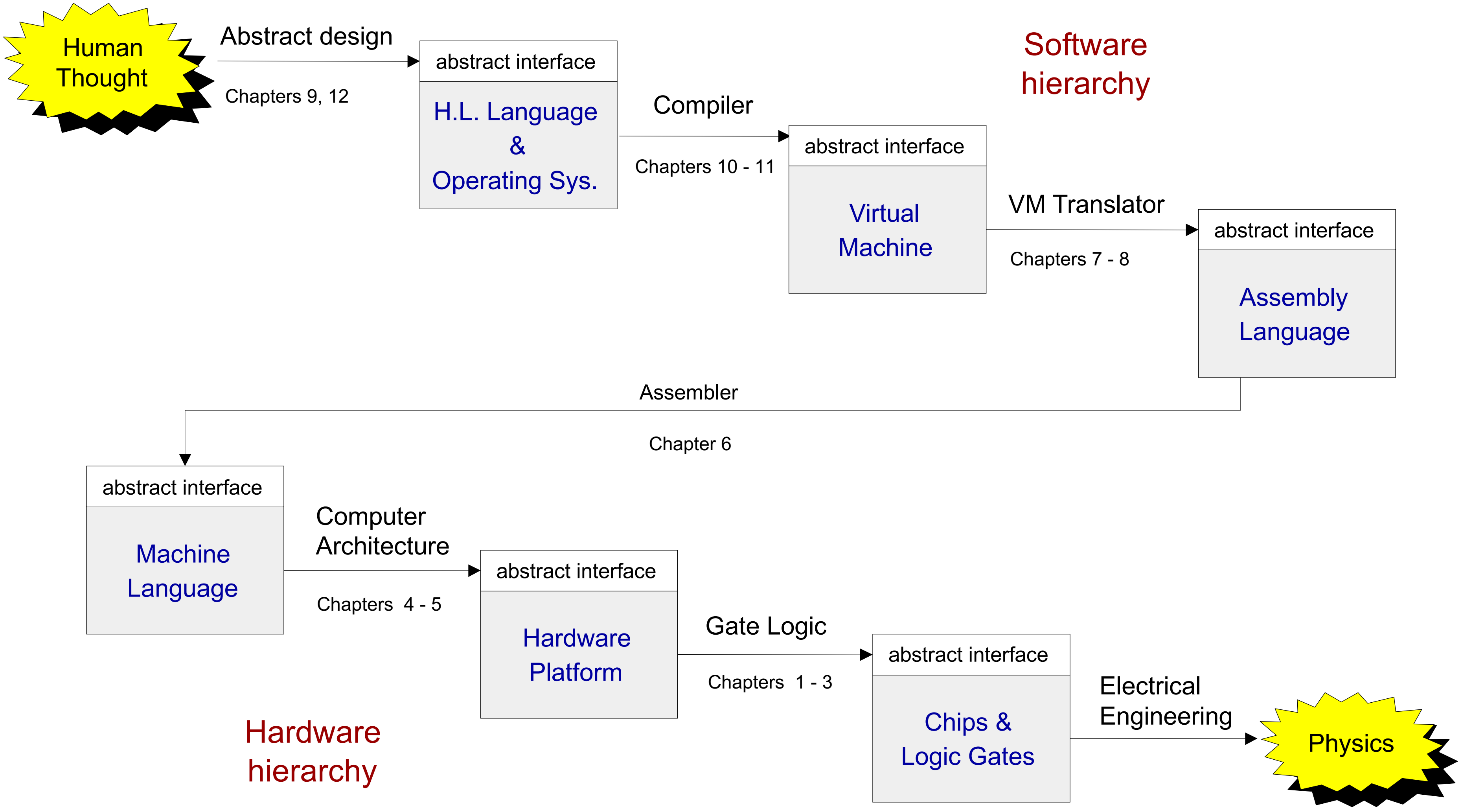


Tetronimo Game!
By Jayson Joseph
Written in Jack

Sample projects

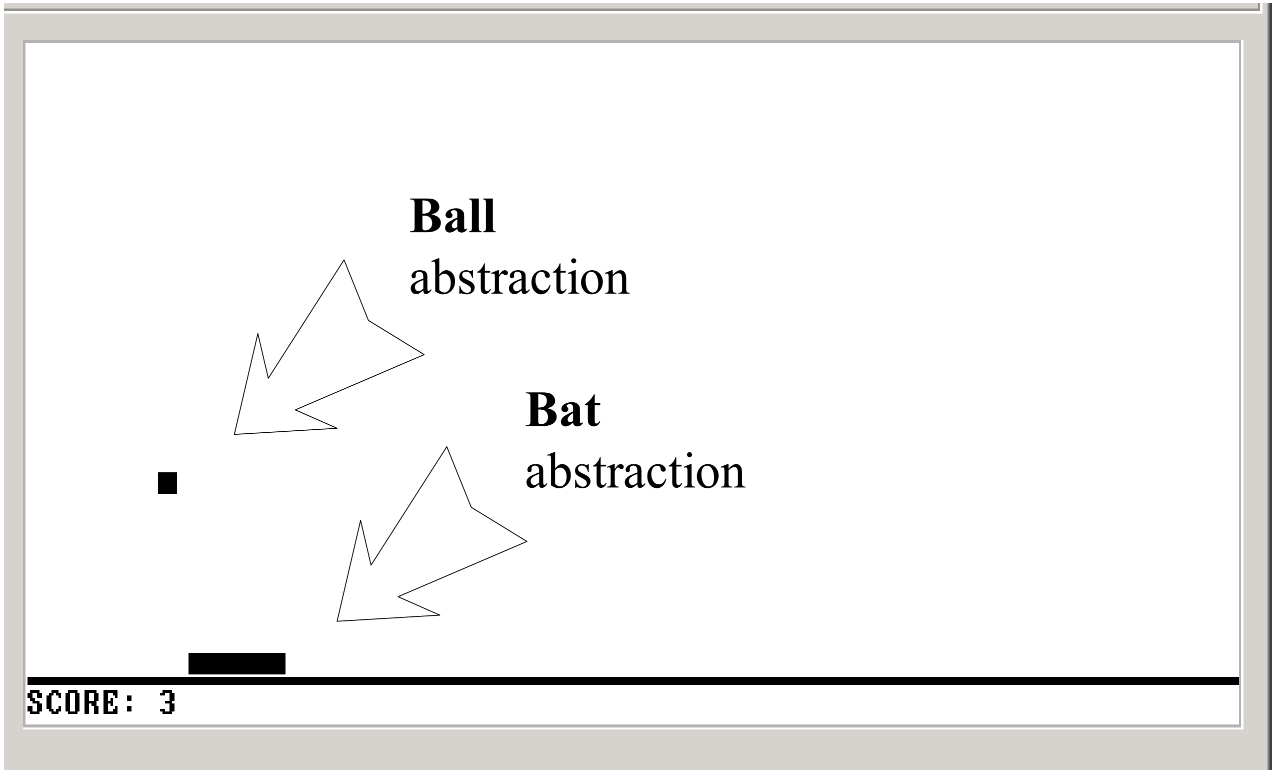


Theme and structure of the book



(Abstraction–implementation paradigm)

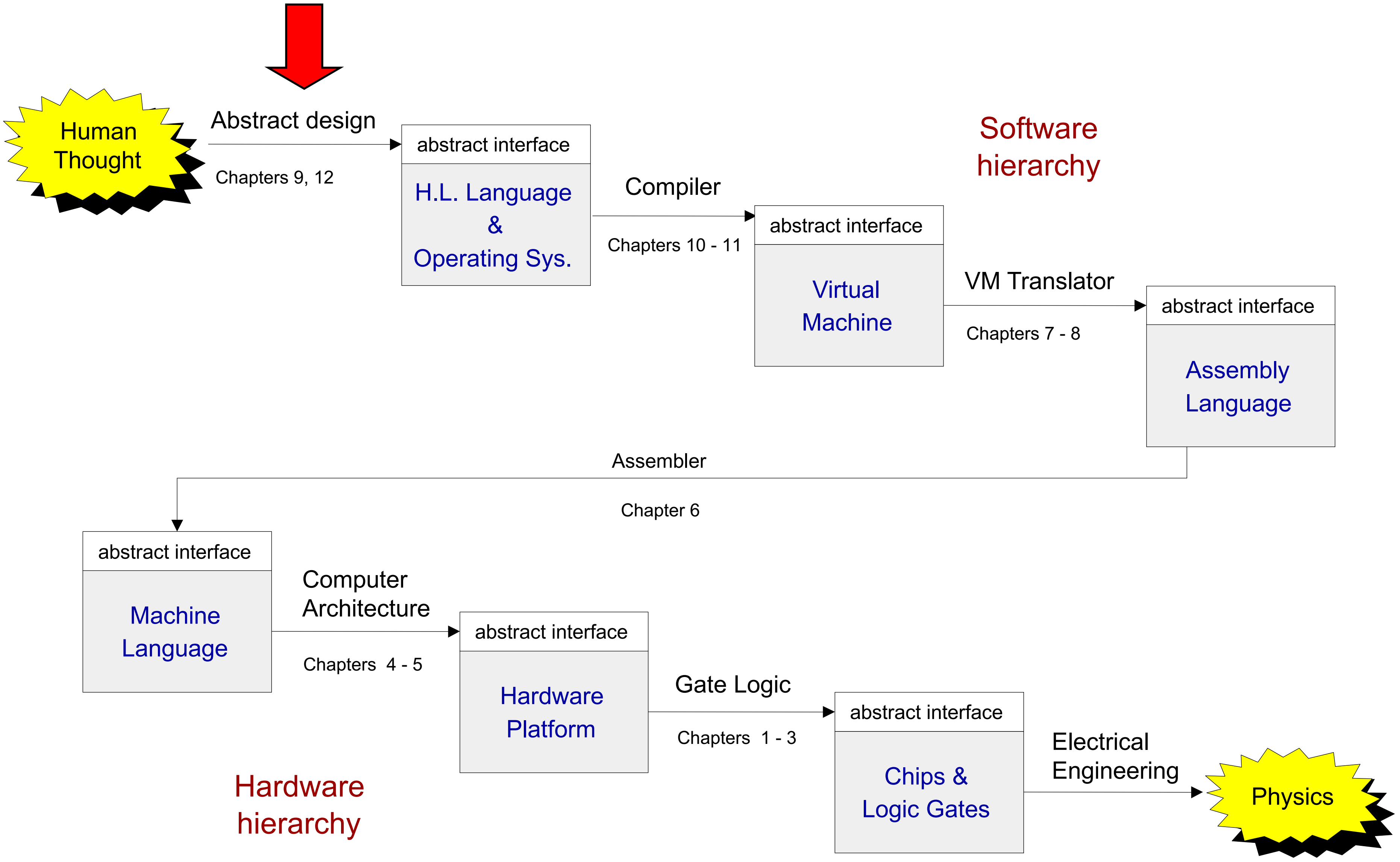
Application level: Pong (an example)



Ball abstraction

Bat abstraction

The big picture



Human Thought

Abstract design

Chapters 9, 12

abstract interface

H.L. Language & Operating Sys.

Compiler

Chapters 10 - 11

abstract interface

Virtual Machine

Software hierarchy

VM Translator

Chapters 7 - 8

abstract interface

Assembly Language

Assembler

Chapter 6

abstract interface

Machine Language

Computer Architecture

Chapters 4 - 5

abstract interface

Hardware Platform

Gate Logic

Chapters 1 - 3

abstract interface

Chips & Logic Gates

Electrical Engineering

Physics

Hardware hierarchy

High-level programming (Jack language)

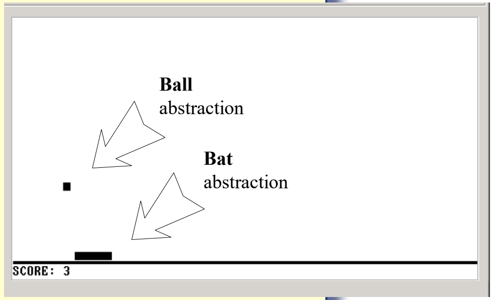
```
/** A Graphic Bat for a Pong Game */
class Bat {
    field int x, y;             // screen location of the bat's top-left corner
    field int width, height;    // bat's width & height

    // The class constructor and most of the class methods are omitted

    /** Draws (color=true) or erases (color=false) the bat */
    method void draw(boolean color) {
       do Screen.setColor(color);
       do Screen.drawRectangle(x,y,x+width,y+height);
       return;
    }

    /** Moves the bat one step (4 pixels) to the right. */
    method void moveR() {
       do draw(false);  // erase the bat at the current location
       let x = x + 4;   // change the bat's X-location
       // but don't go beyond the screen's right border
        if ((x + width) > 511) {
           let x = 511 - width;
       }
       do draw(true);  // re-draw the bat in the new location
       return;
    }
}
```

Typical call to an OS method



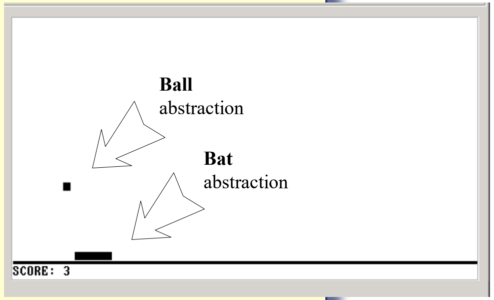
SCORE: 3

Operating system level (Jack OS)

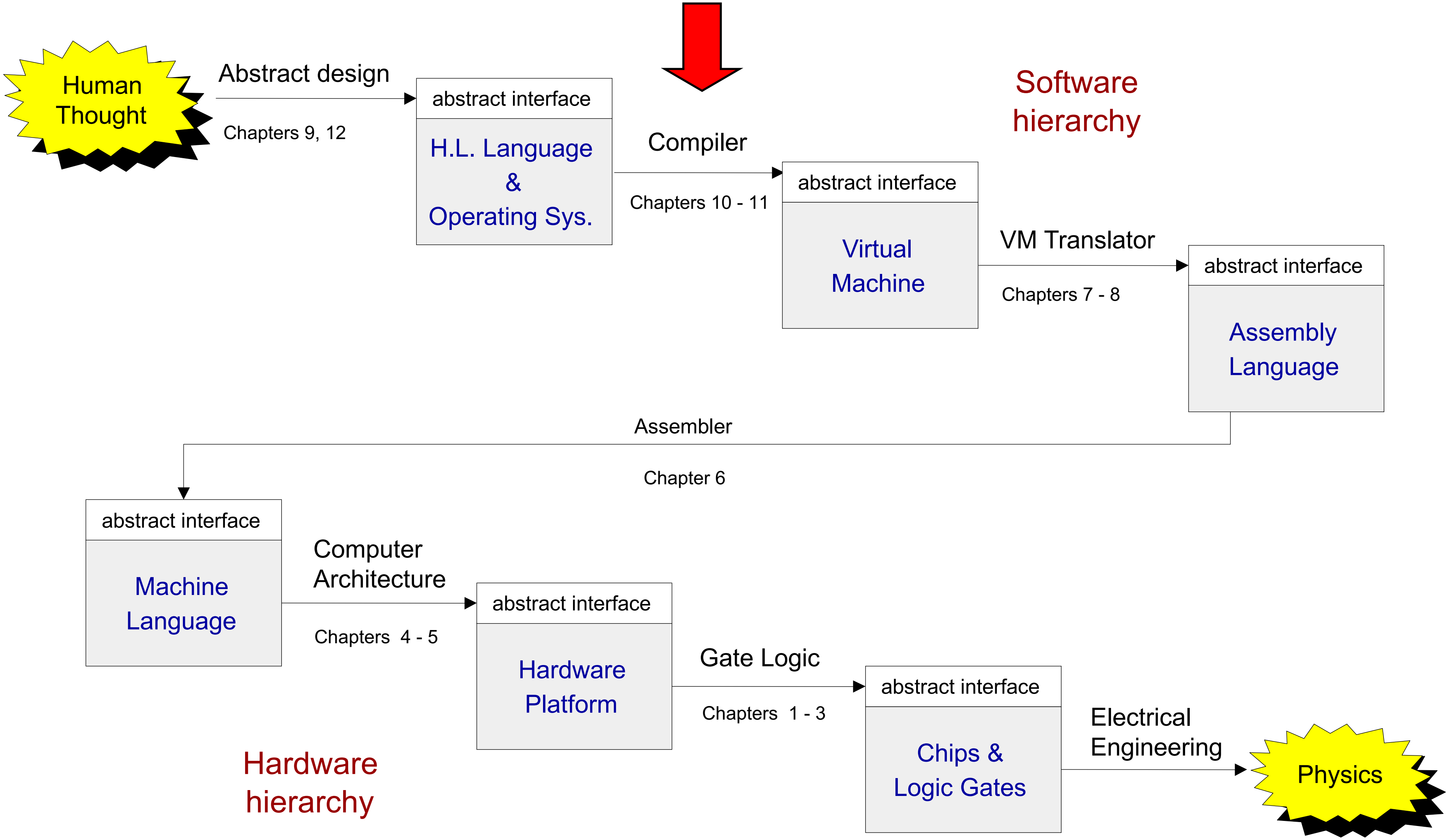
```
/** An OS-level screen driver that abstracts the computer's physical screen */
class Screen {
     static boolean currentColor;  // the current color

     // The Screen class is a collection of methods, each implementing one
     // abstract screen-oriented operation.  Most of this code is omitted.

     /** Draws a rectangle in the current color. */
     // the rectangle's top left corner is anchored at screen location (x0,y0)
     // and its width and length are x1 and y1, respectively.
     function void drawRectangle(int x0, int y0, int x1, int y1) {
         var int x, y;
         let x = x0;
         while (x < x1) {
             let y = y0;
             while(y < y1) {
                do Screen.drawPixel(x,y);
                let y = y+1;
             }
             let x = x+1;
         }
     }
}
```



The big picture



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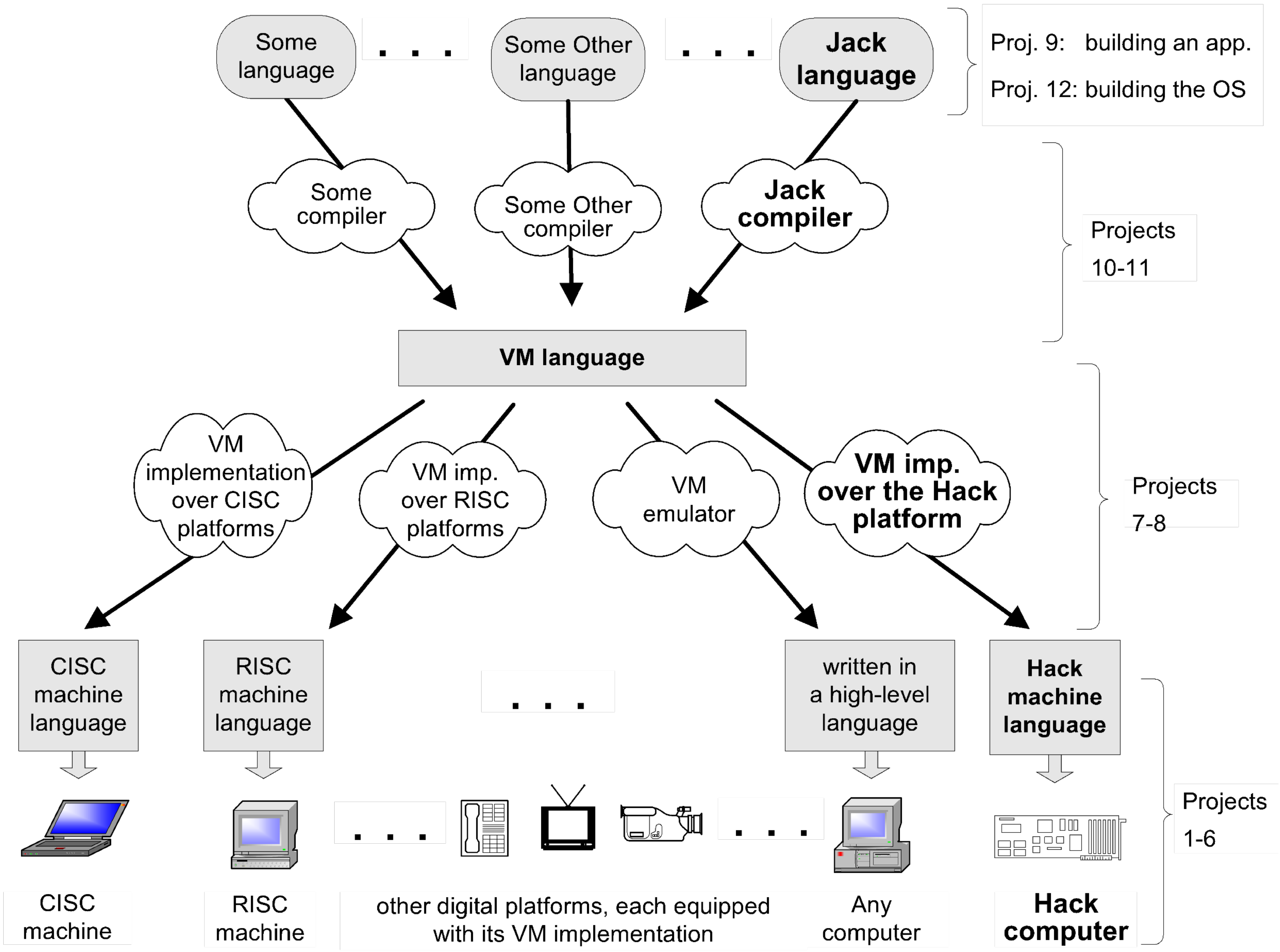
A modern compilation model



Some language

. . .

Some Other language

. . .

Jack language

Proj. 9: building an app.

Proj. 12: building the OS

Some compiler

Some Other compiler

Jack compiler

Projects 10-11

VM language

VM implementation over CISC platforms

VM imp. over RISC platforms

VM emulator

VM imp. over the Hack platform

Projects 7-8

CISC machine language

RISC machine language

. . .

written in a high-level language

Hack machine language

. . .

. . .

Projects 1-6

CISC machine

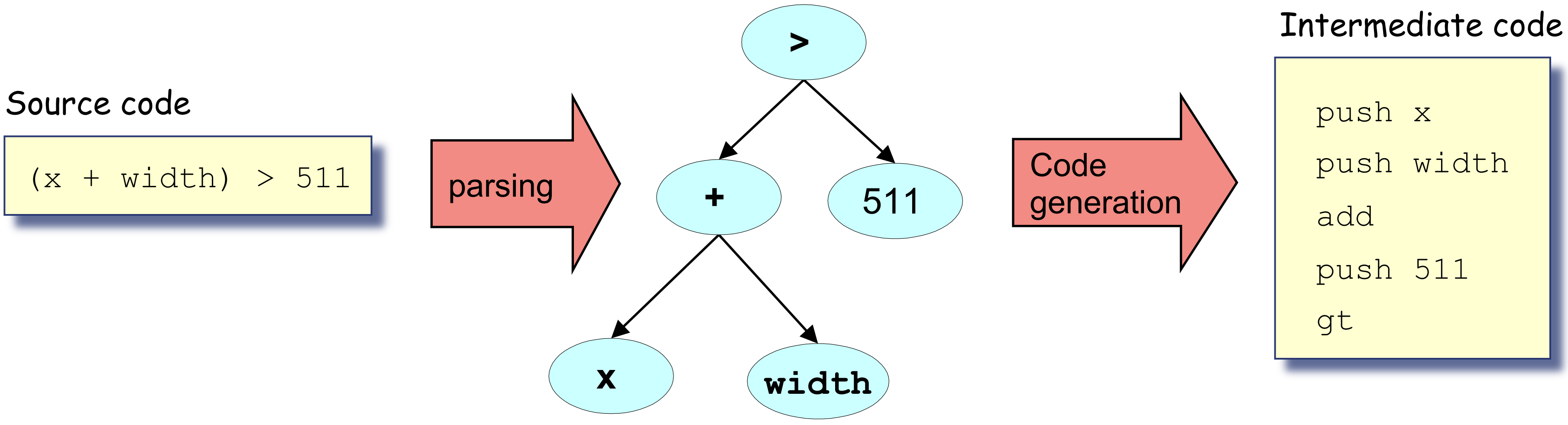
RISC machine

other digital platforms, each equipped with its VM implementation

Any computer

Hack computer

Compilation 101



Source code

```
(x + width) > 511
```

parsing

Code generation

Intermediate code

```
push x
push width
add
push 511
gt
```

Abstraction

Syntax Analysis

Parse Tree

Semantic Synthesis

Implementation

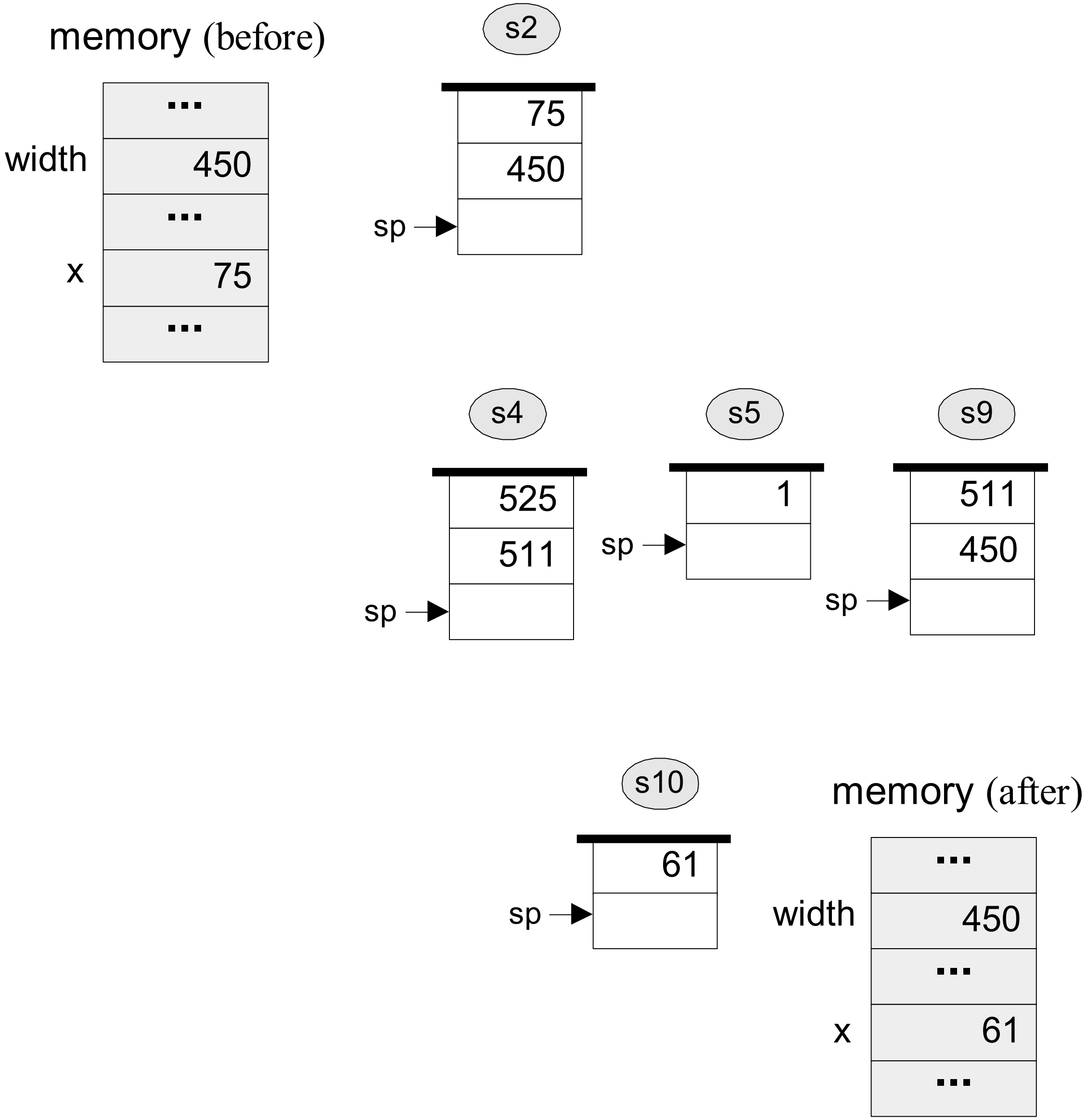
Observations:

- Modularity
- Abstraction / implementation interplay
- The implementation uses abstract services from the level below.

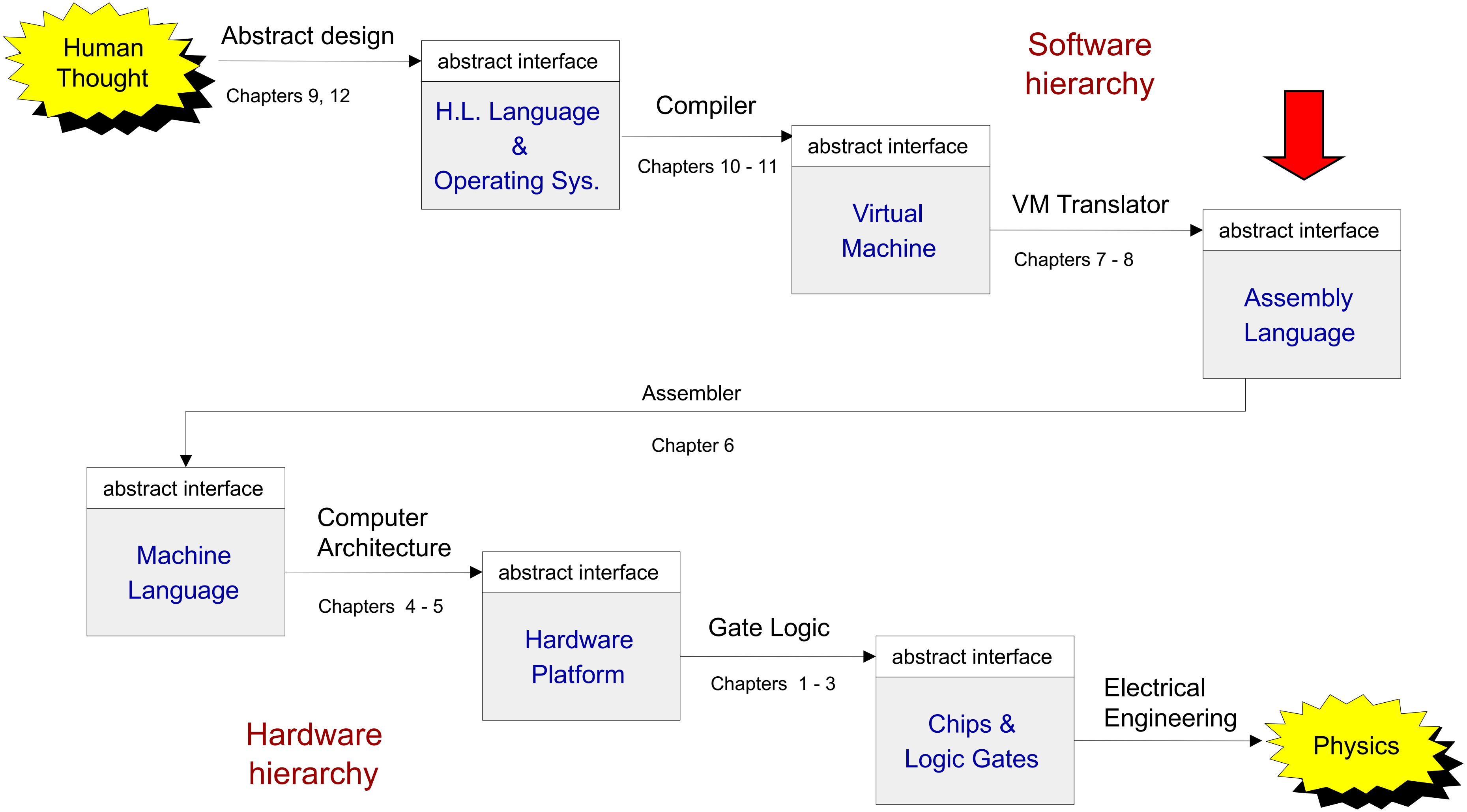
The virtual machine (VM modeled after JVM)

```
if ((x+width)>511) {
   let x=511-width;
}
```

```
// VM implementation
   push x         // s1
   push width     // s2
   add            // s3
   push 511       // s4
   gt             // s5
   if-goto L1     // s6
   goto L2        // s7
L1:
   push 511       // s8
   push width     // s9
   sub            // s10
   pop x          // s11
L2:
...
```



The big picture



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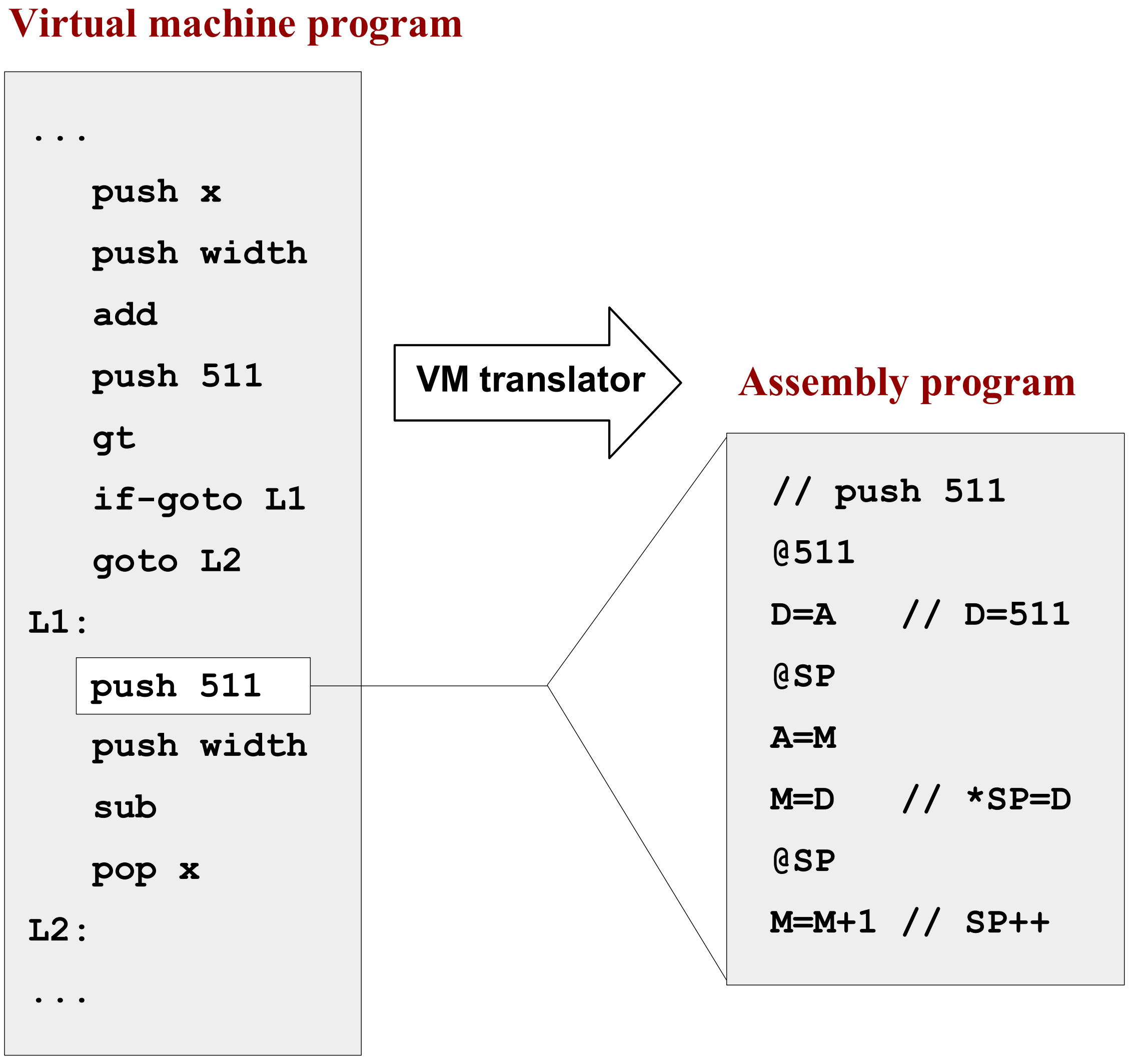
Hardware hierarchy

Low-level programming (on Hack)

Virtual machine program

```
...
   push x
   push width
   add
   push 511
   gt
   if-goto L1
   goto L2
L1:
   push 511
   push width
   sub
   pop x
L2:
...
```

Low-level programming (on Hack)



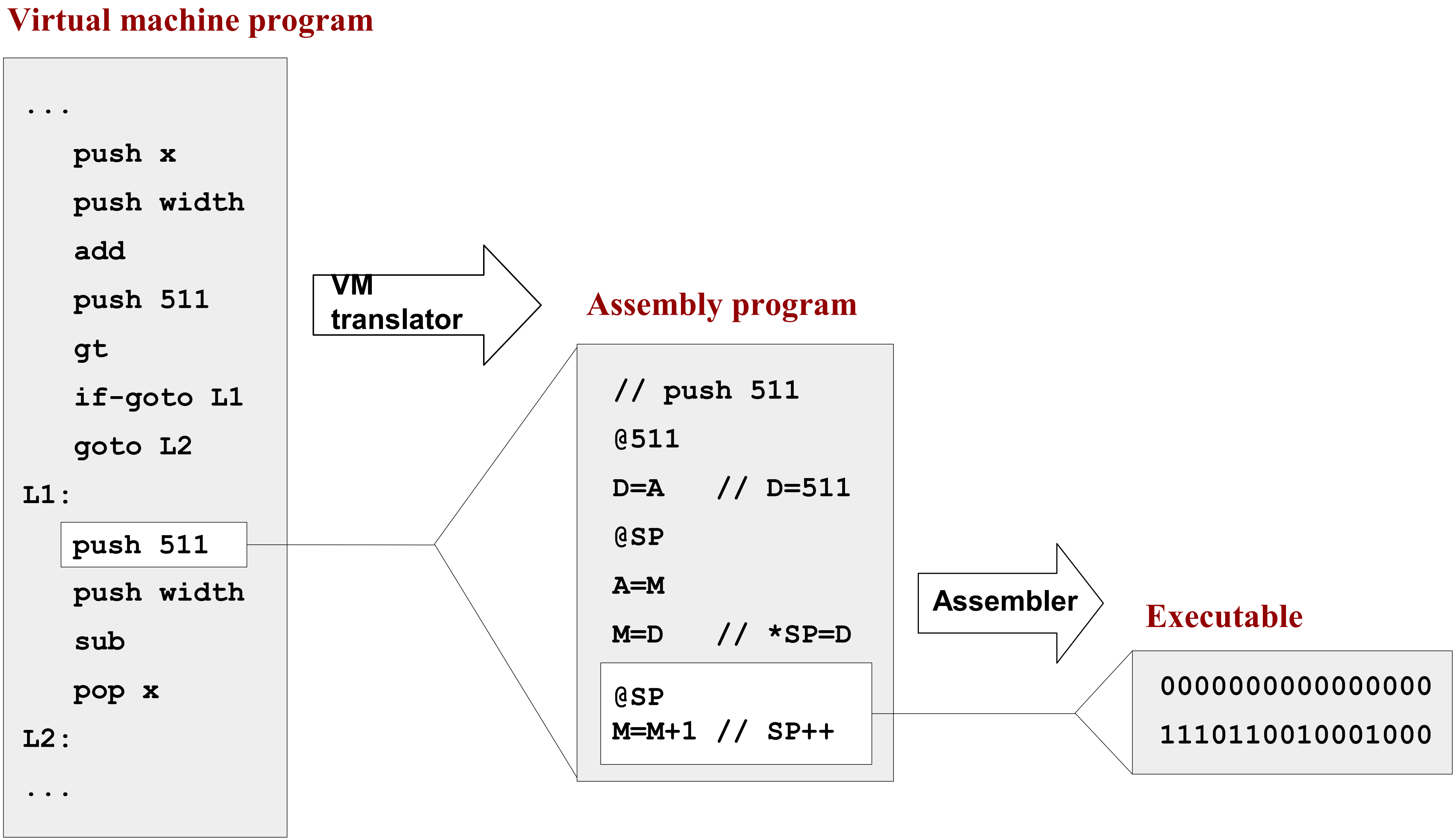
Virtual machine program

```
...
   push x
   push width
   add
   push 511
   gt
   if-goto L1
   goto L2
L1:
   push 511
   push width
   sub
   pop x
L2:
...
```

Assembly program

```
// push 511
@511
D=A    // D=511
@SP
A=M
M=D    // *SP=D
@SP
M=M+1  // SP++
```

Low-level programming (on Hack)



Virtual machine program

```
...
   push x
   push width
   add
   push 511
   gt
   if-goto L1
   goto L2
L1:
   push 511
   push width
   sub
   pop x
L2:
...
```

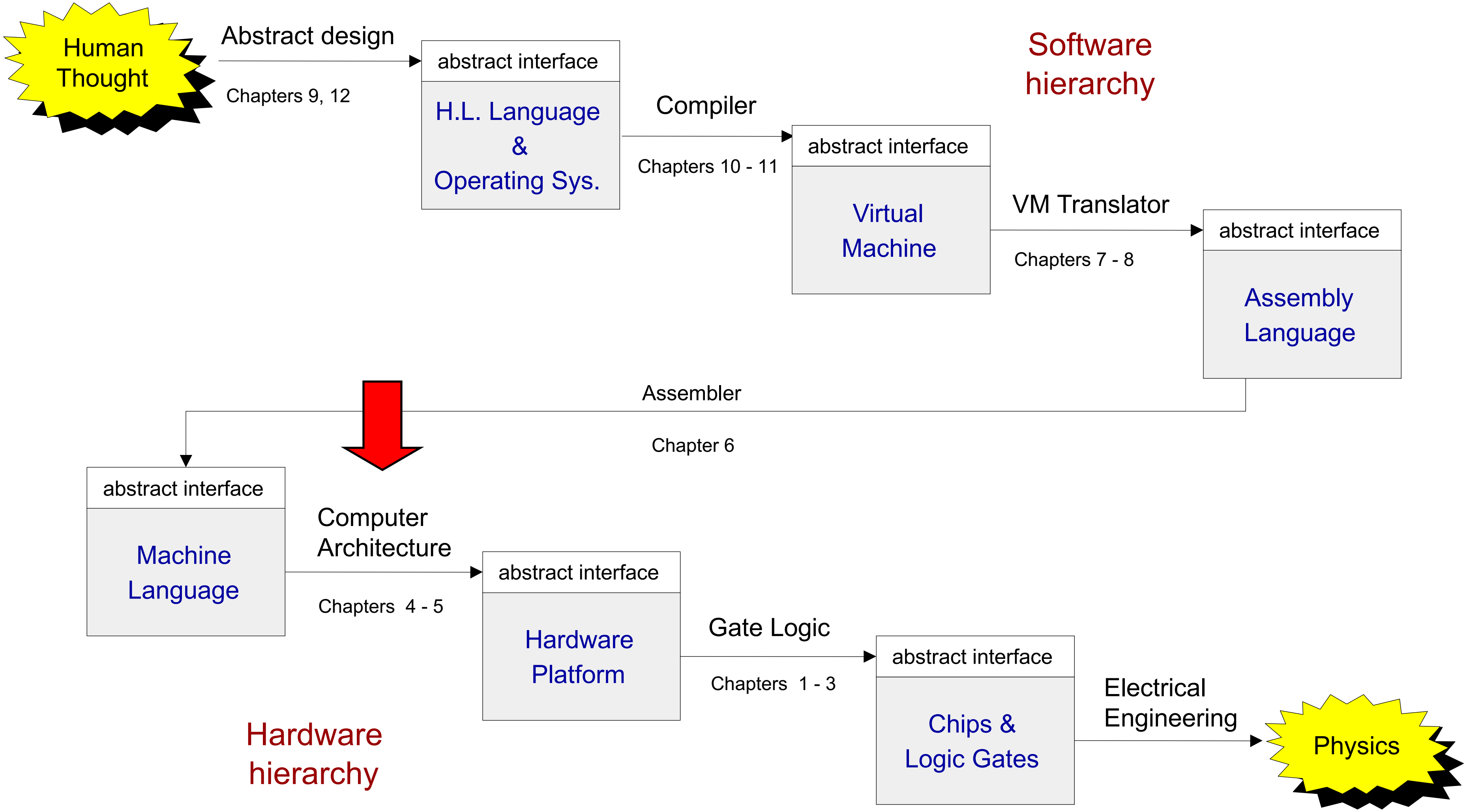
Assembly program

```
// push 511
@511
D=A    // D=511
@SP
A=M
M=D    // *SP=D
@SP
M=M+1  // SP++
```

Executable

```
0000000000000000
1110110010001000
```

The big picture



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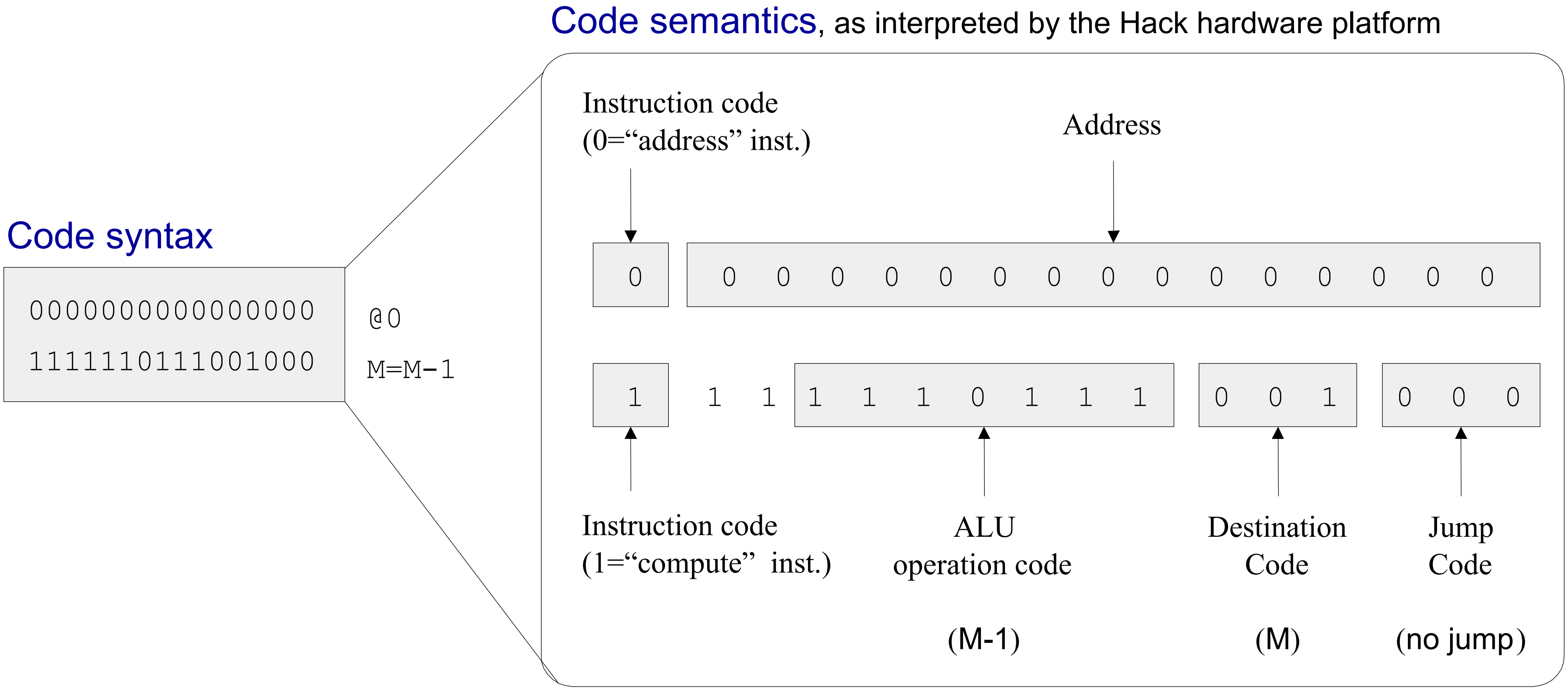
Hardware hierarchy

Machine language semantics (Hack)



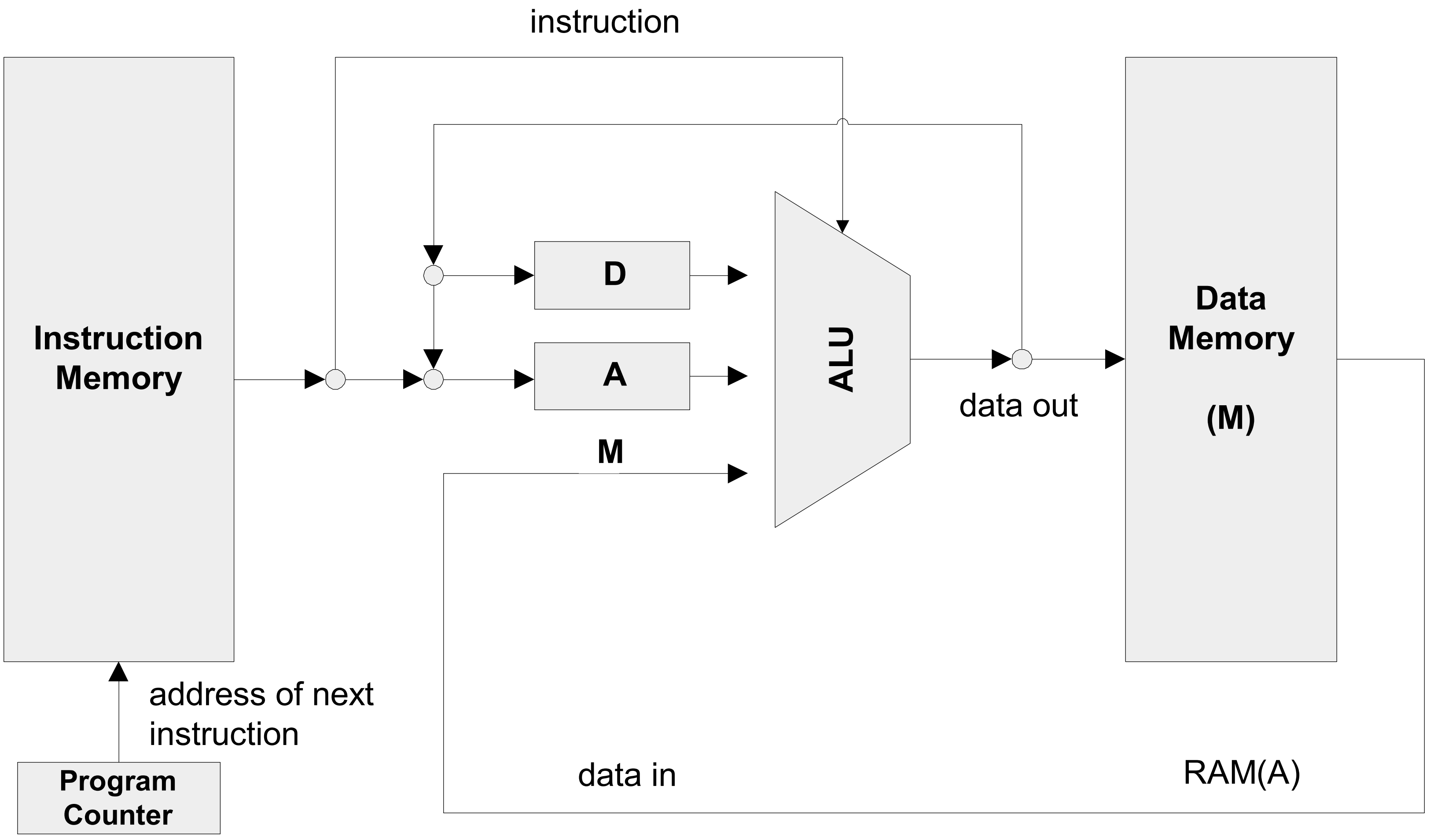
Code syntax

```
0000000000000000    @0
1111110111001000    M=M-1
```

Code semantics, as interpreted by the Hack hardware platform

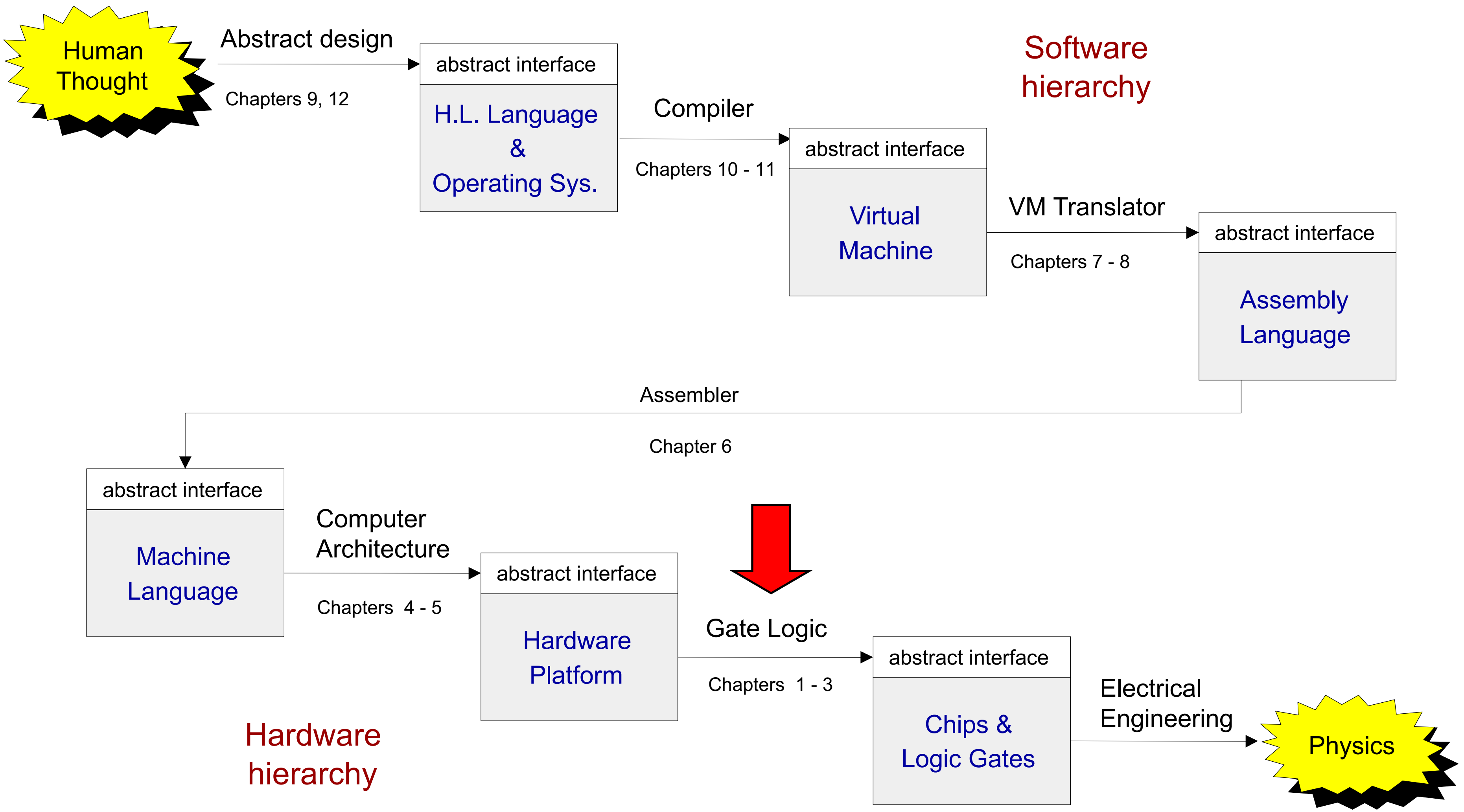
- We need a hardware architecture that realizes this semantics
- The hardware platform should be designed to:
  - Parse instructions, and
  - Execute them.

Computer architecture (Hack)



- A typical Von Neumann machine

The big picture



Human Thought

Abstract design

Chapters 9, 12

abstract interface

H.L. Language & Operating Sys.

Compiler

Chapters 10 - 11

abstract interface

Virtual Machine

Software hierarchy

VM Translator

Chapters 7 - 8

abstract interface

Assembly Language

Assembler

Chapter 6

abstract interface

Machine Language

Computer Architecture

Chapters 4 - 5

abstract interface

Hardware Platform

Gate Logic

Chapters 1 - 3

abstract interface

Chips & Logic Gates

Electrical Engineering

Physics

Hardware hierarchy

Logic design

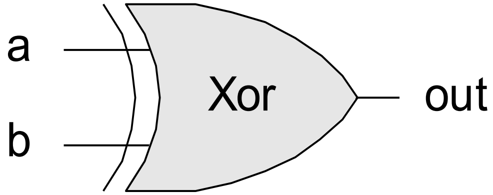
- Combinational logic (leading to an ALU)
- Sequential logic (leading to a RAM)
- Putting the whole thing together (leading to a computer)

Using … gate logic

Gate logic

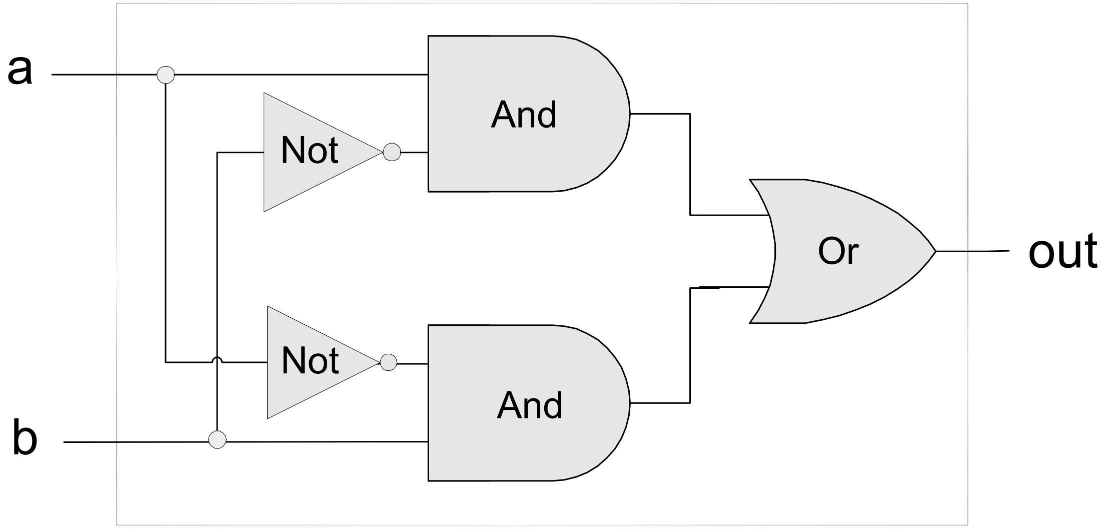
- Hardware platform = inter-connected set of chips
- Chips are made of simpler chips, all the way down to elemantary logic gates
- Logic gate = hardware element that implements a certain Boolean function
- Every chip and gate has an *interface*, specifying WHAT it is doing, and an *implementation*, specifying HOW it is doing it.

Interface

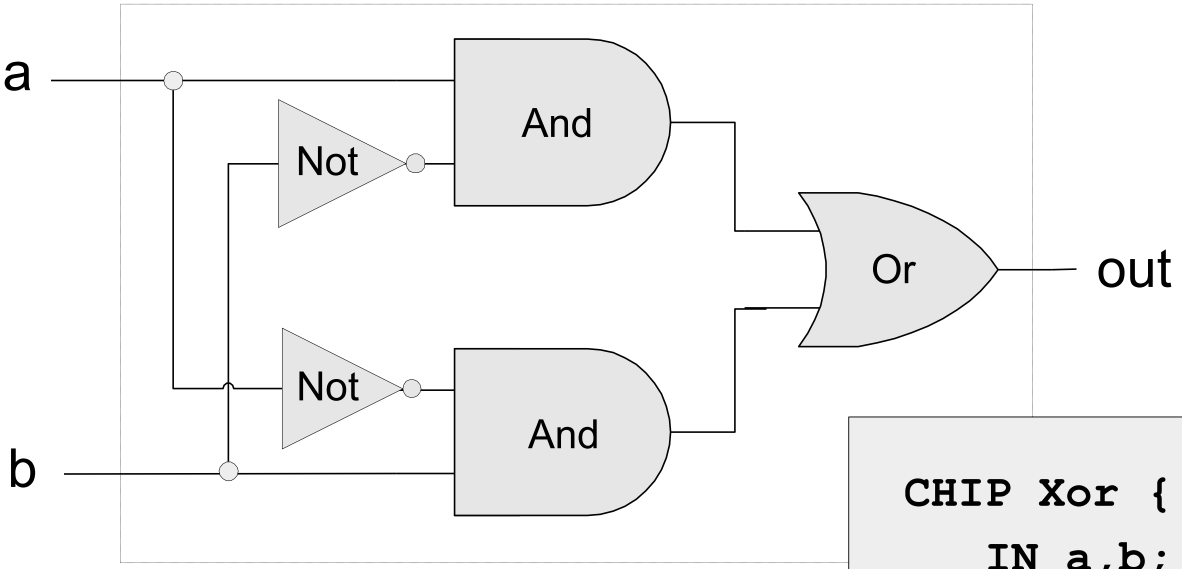


a	b	out
0	0	0
0	1	1
1	0	1
1	1	0

Implementation



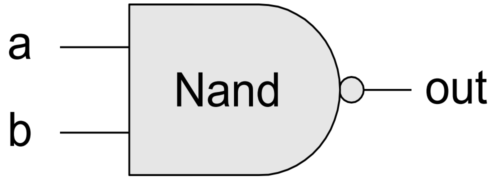
Hardware description language (HDL)



```
CHIP Xor {
   IN a,b;
   OUT out;
   PARTS:
   Not(in=a,out=Nota);
   Not(in=b,out=Notb);
   And(a=a,b=Notb,out=w1);
   And(a=Nota,b=b,out=w2);
   Or(a=w1,b=w2,out=out);
}
```

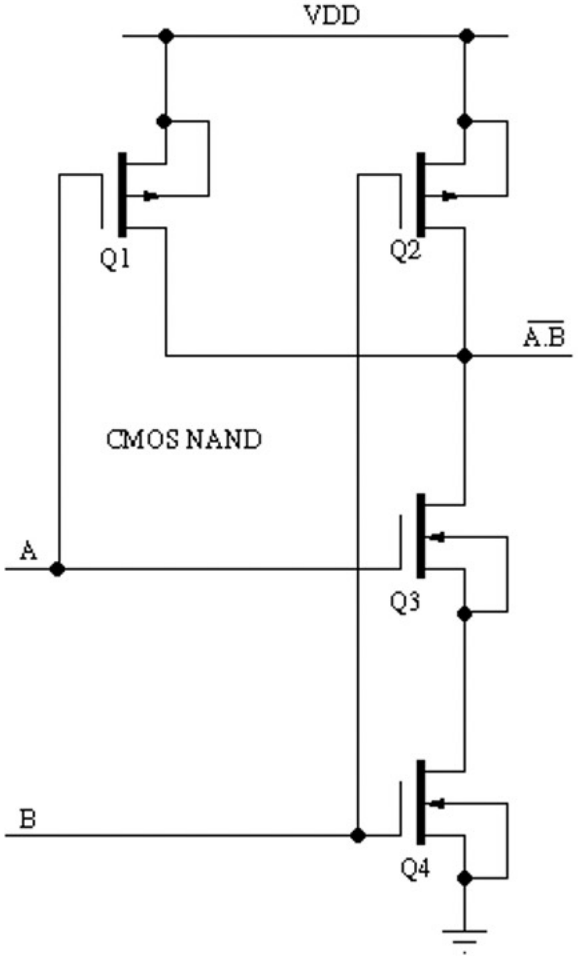
The tour ends:

Interface

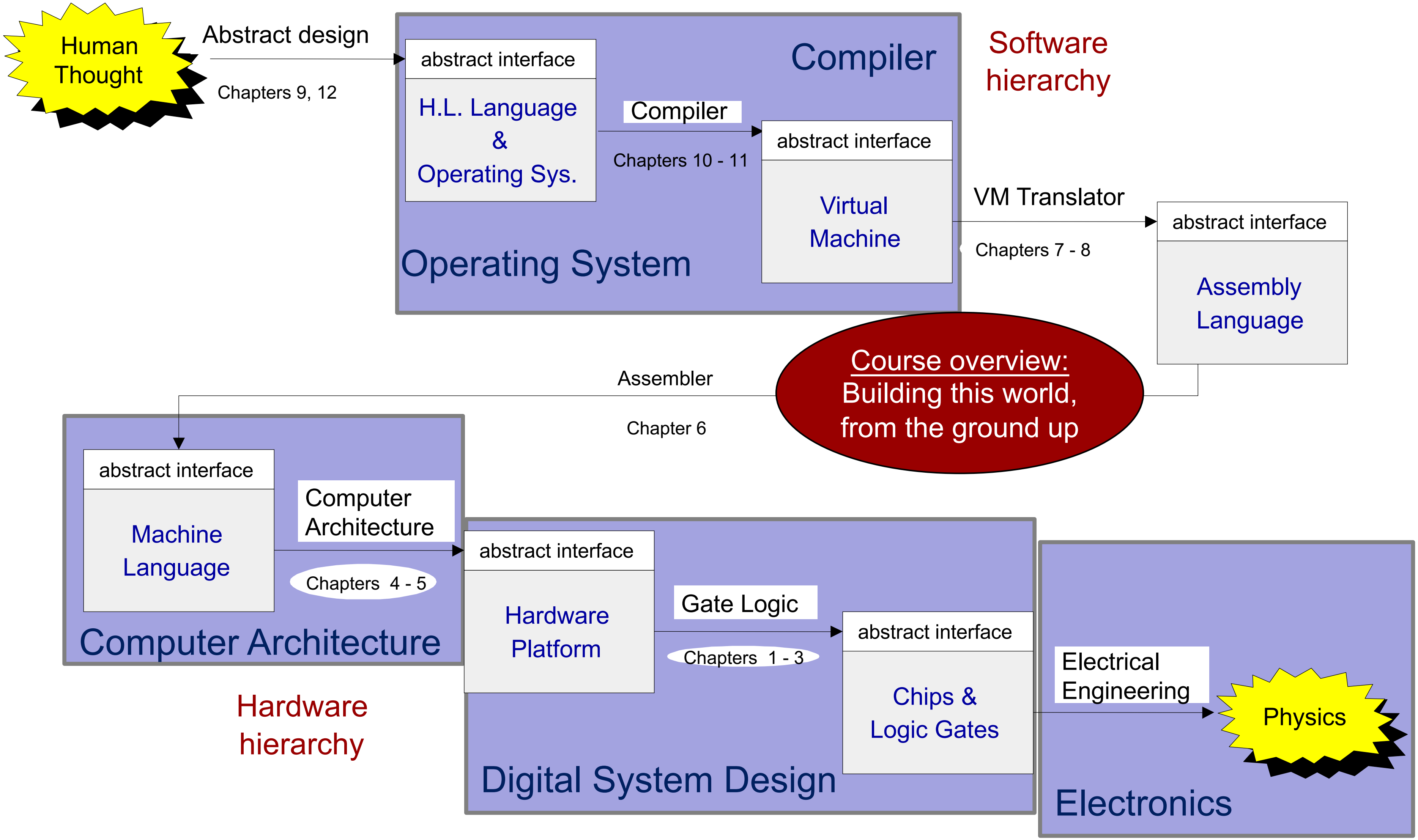


a	b	out
0	0	1
0	1	1
1	0	1
1	1	0

One implementation option (CMOS)



The tour map, revisited



What you will learn

- Number systems
- Combinational logic
- Sequential logic
- Basic principle of computer architecture
- Assembler
- Virtual machine
- High-level language
- Fundamentals of compilers
- Basic operating system
- Application programming

In short