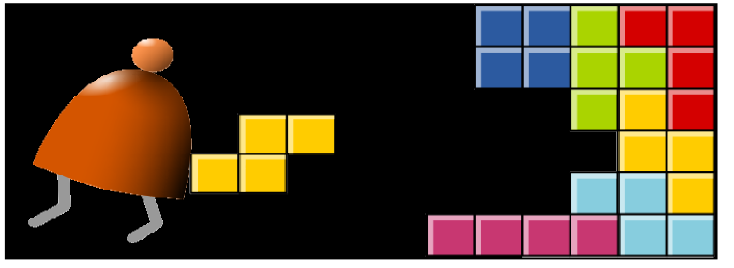
Introduction:
From Nand to Tetris



Building a Modern Computer From First Principles

www.nand2tetris.org

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.

Some course details

- 12 projects, can be done by pairs
- Hardware projects are done and simulated in HDL
  (Hardware Description Language)
- Software projects can be done in any language of your choice
  (we recommend Java)
- Projects methodology:
  - Design (API) + test materials are given
  - Implementation done by students
- Tools: simulators, tutorials, test scripts
- Book
- Q&A policy
- Course grade.

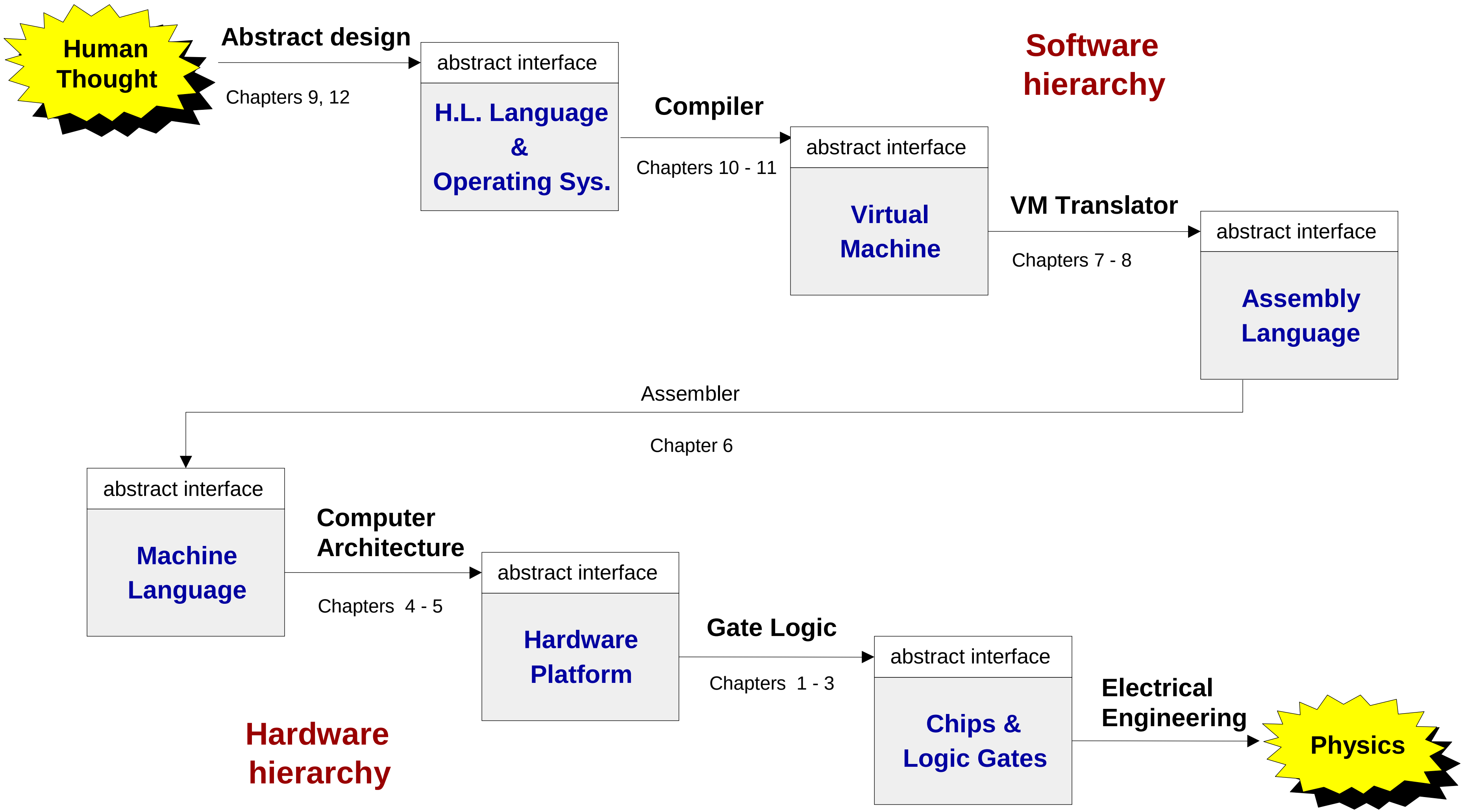
Demo

Pong, 1985

Pong, 2011

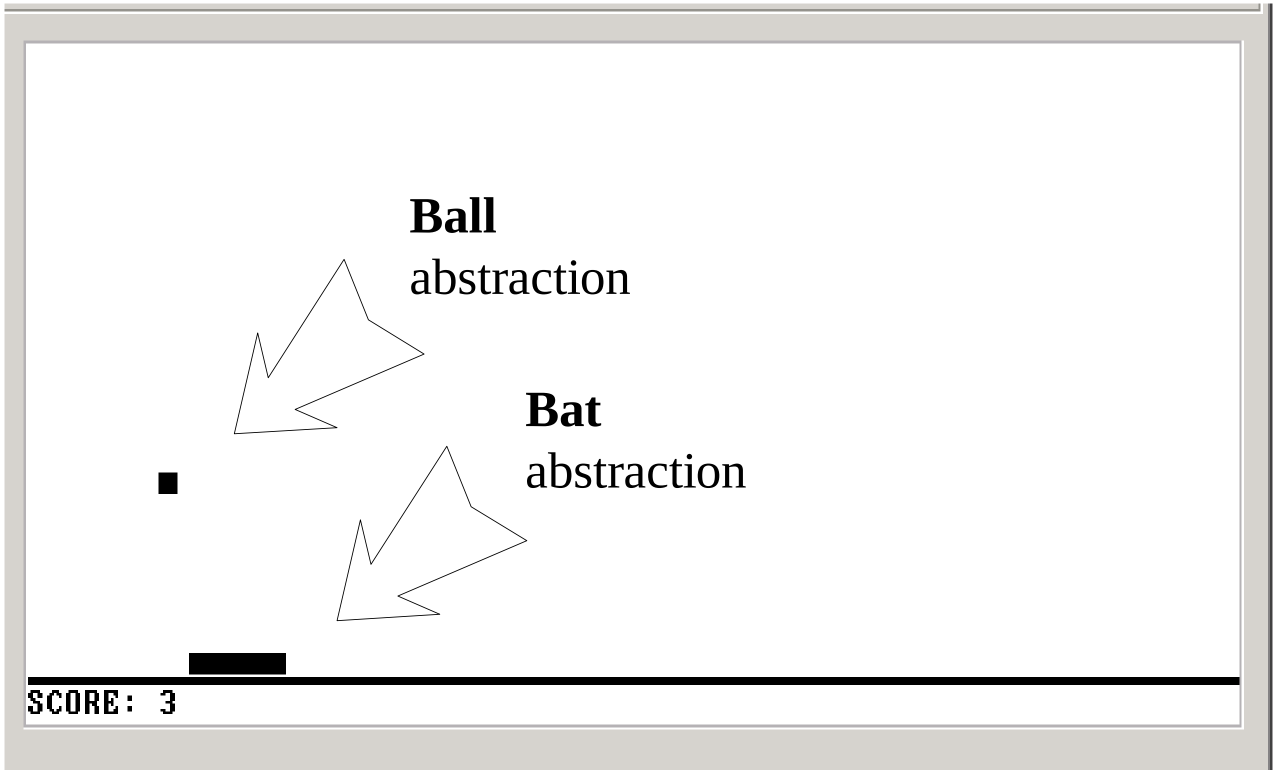
Pong, on our computer

Course theme and structure

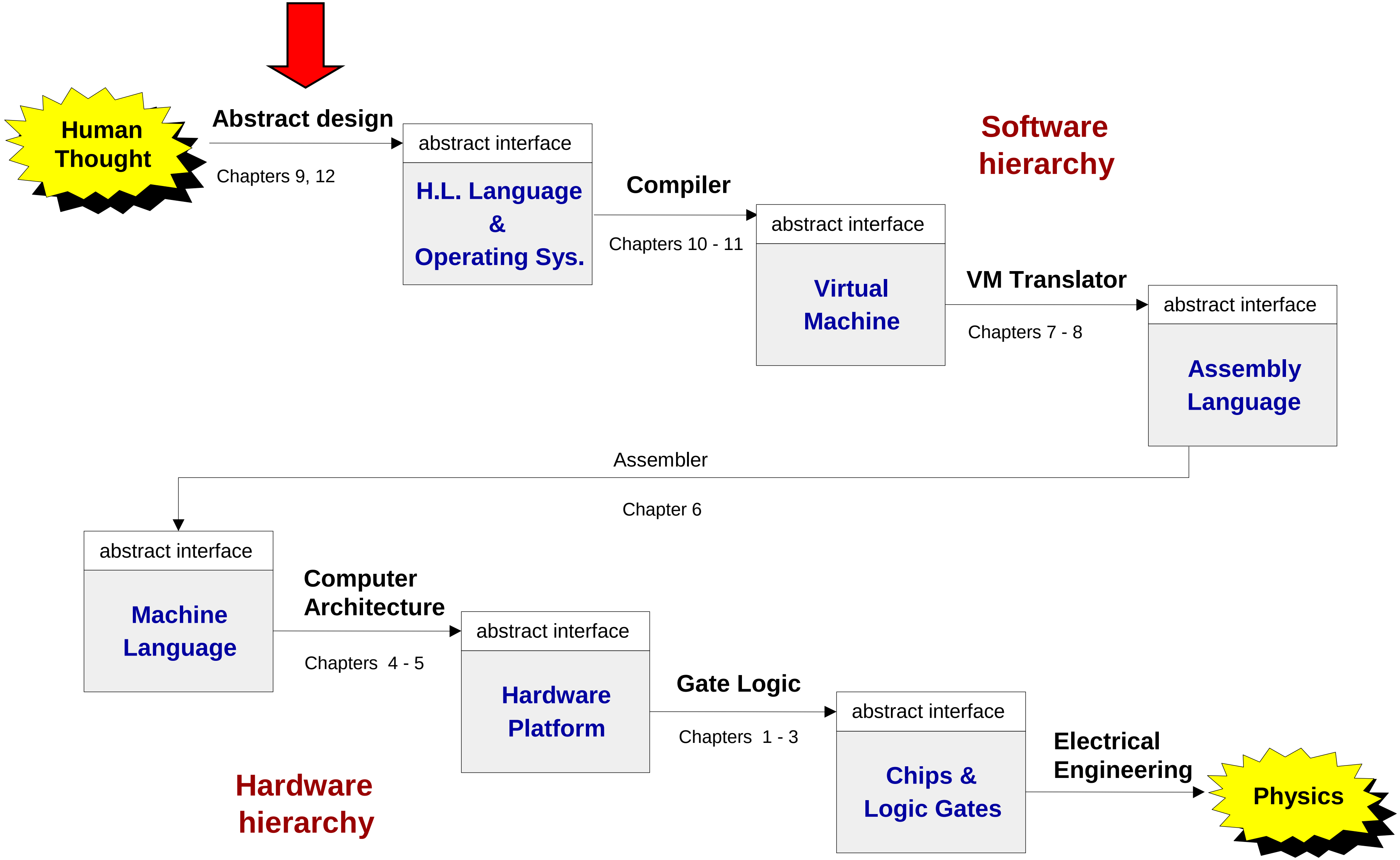


(Abstraction–implementation paradigm)

Application level: Pong (example app)



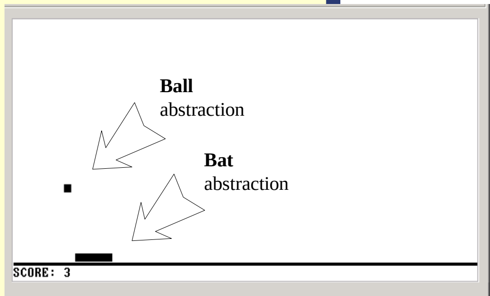
The big picture



High-level programming (our very own Jack language)

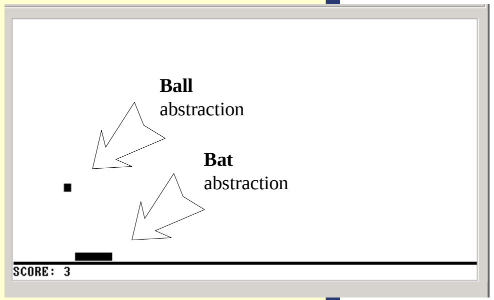
```
/** A Graphic Bat for a Pong Game */
class Bat {
    field int x, y;            // screen location of the bat's top-left corner
    field int width, height;   // bat's width & height

    // 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

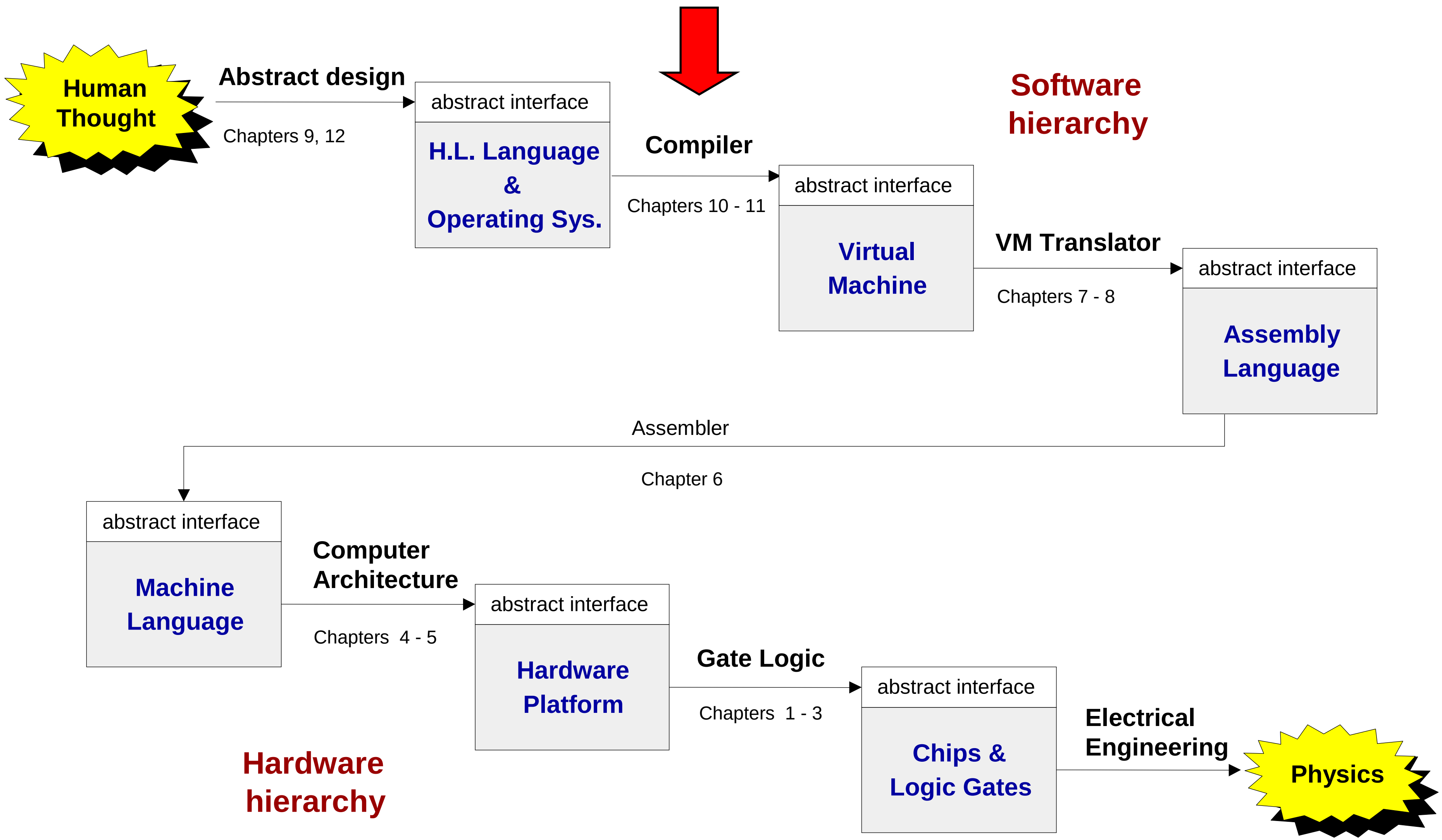


Operating system level (our very own Jack OS)

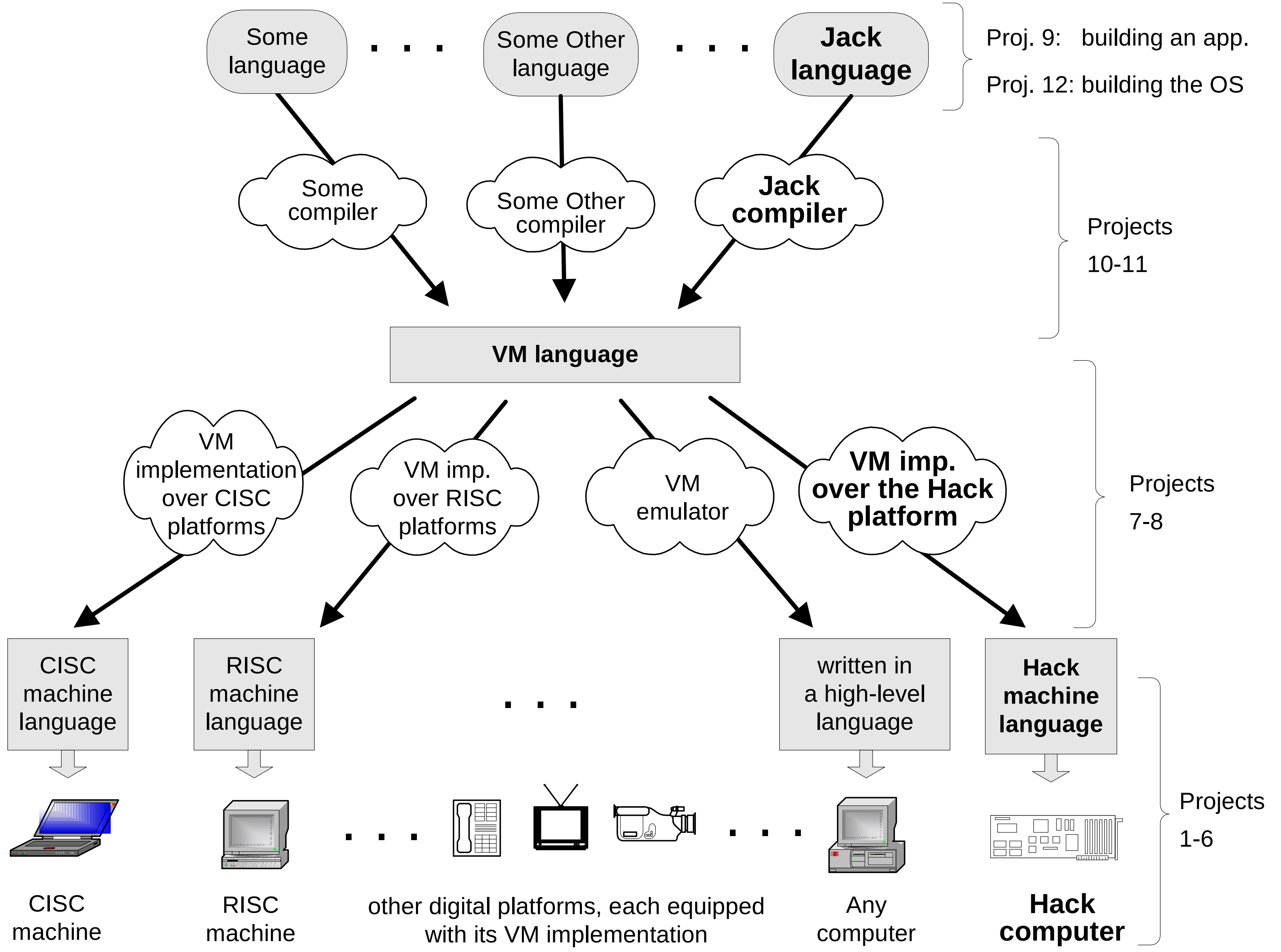
```
/** An OS-level screen driver that abstracts the computer's physical screen */
class Screen {
     static boolean currentColor;  // the current color

     // 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;
         }
     }
}
```



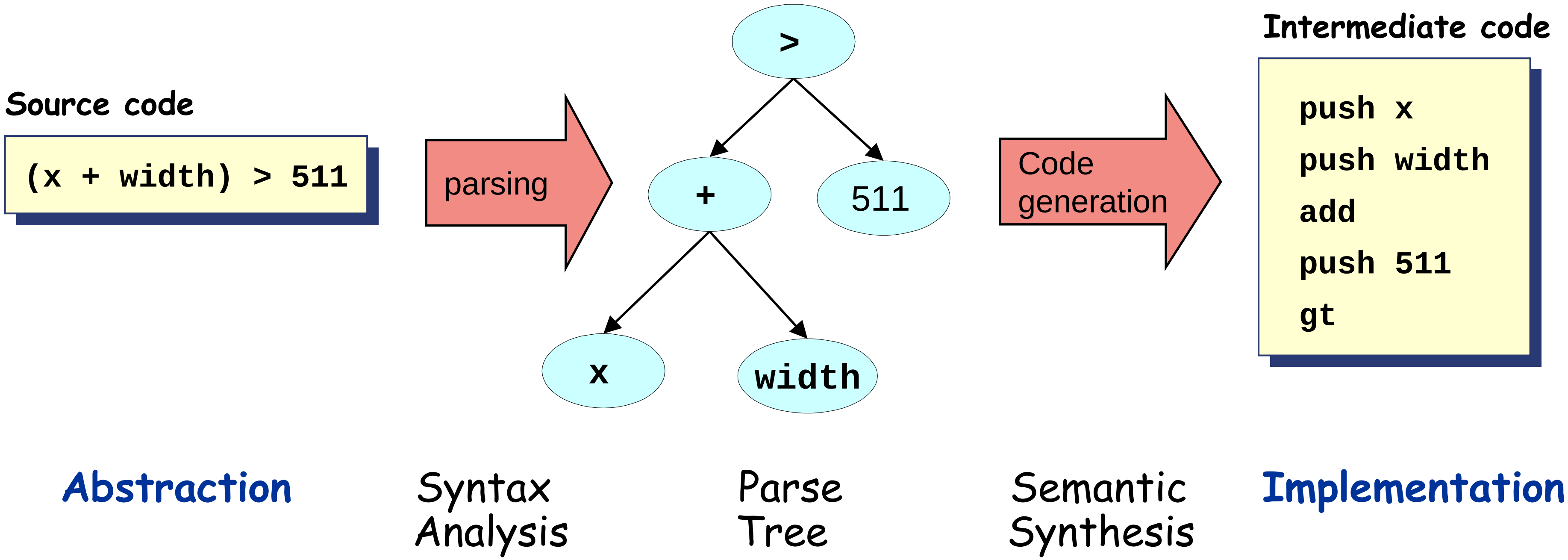
The big picture



A modern compilation model



Compilation 101



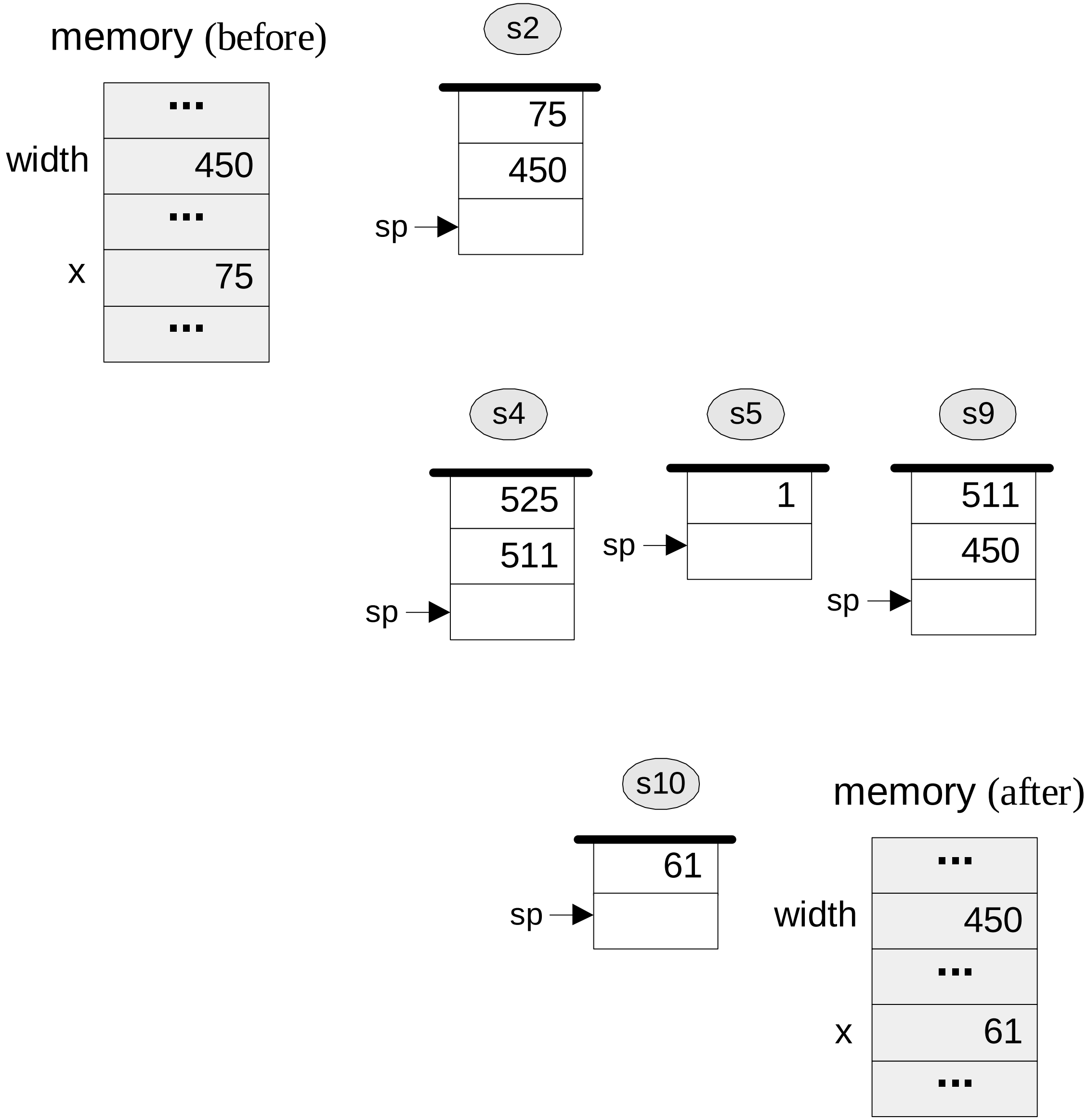
Observations:

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

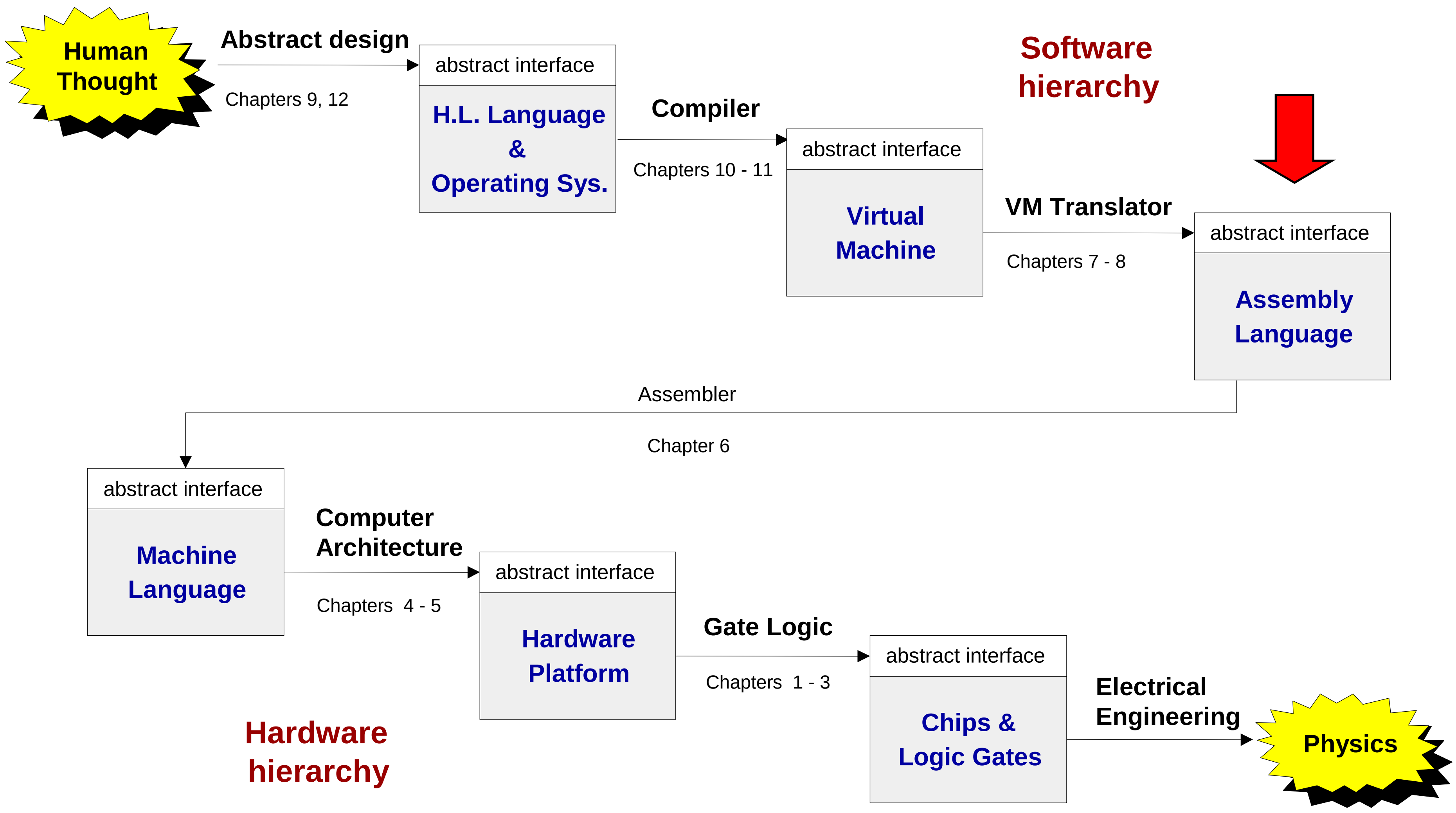
The Virtual Machine (our very own VM, modeled after Java's JVM)

```
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



Low-level programming (on the Hack computer)

For now, ignore all details!

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 the Hack computer)

For now, ignore all details!

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:
...
```

VM translator →

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 the Hack computer)

For now, ignore all details!

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:
...
```

VM translator

Assembly program

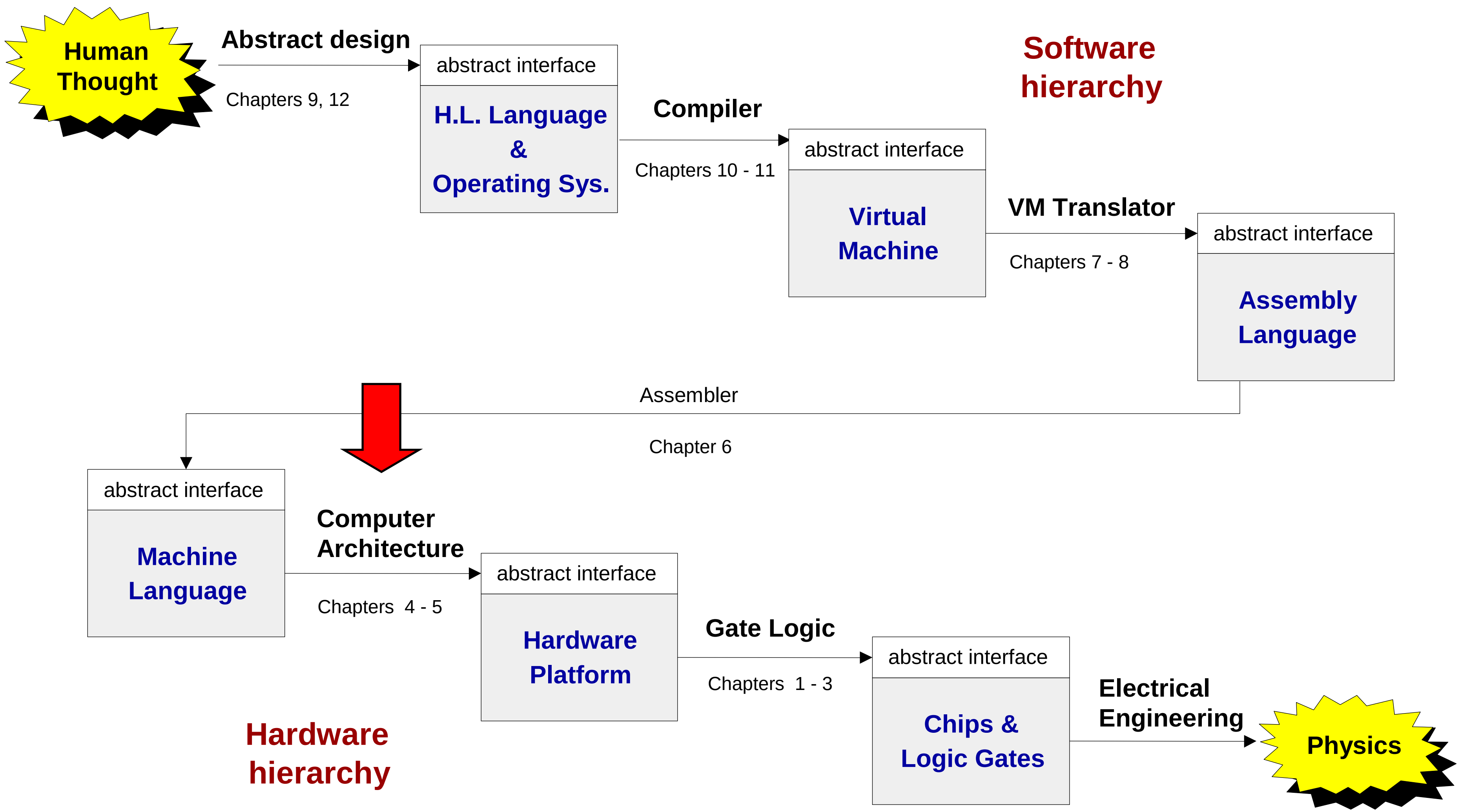
```
// push 511
@511
D=A   // D=511
@SP
A=M
M=D   // *SP=D
@SP
M=M+1 // SP++
```

Assembler

Executable

```
0000000000000000
1110110010001000
```

The big picture



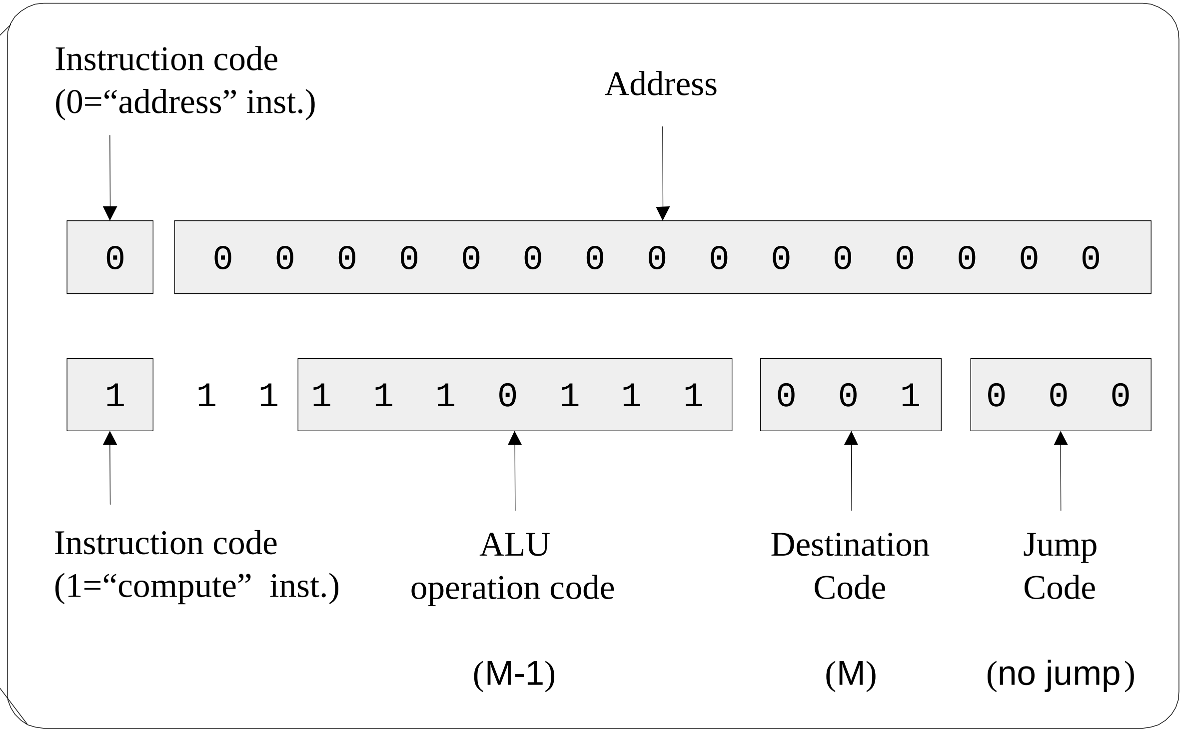
Machine language semantics (our very own Hack platform)

For now, ignore all details!

Code semantics, as interpreted by the Hack hardware platform

Code syntax

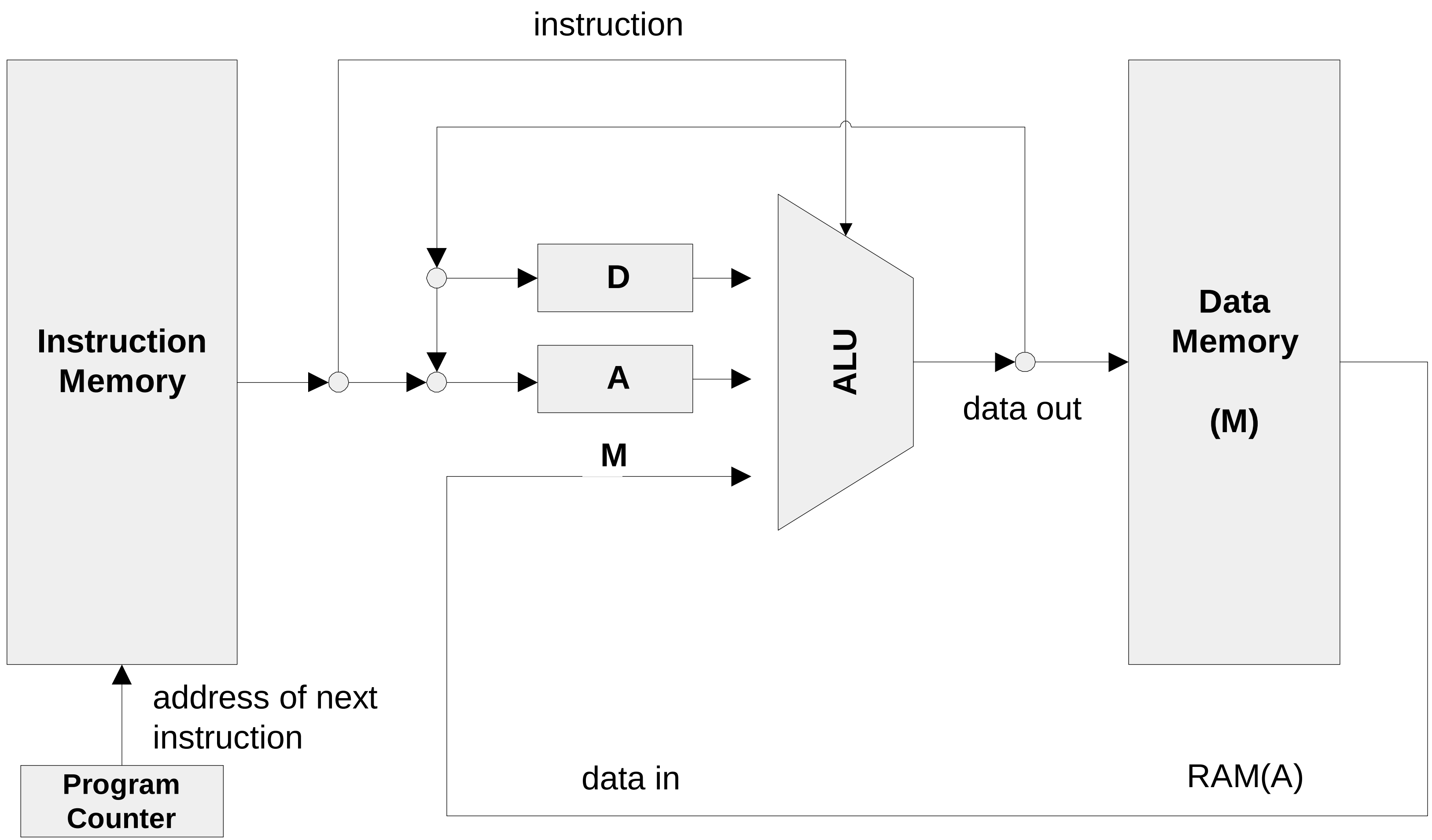
```
0000000000000000    @0
1111110111001000    M=M-1
```



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

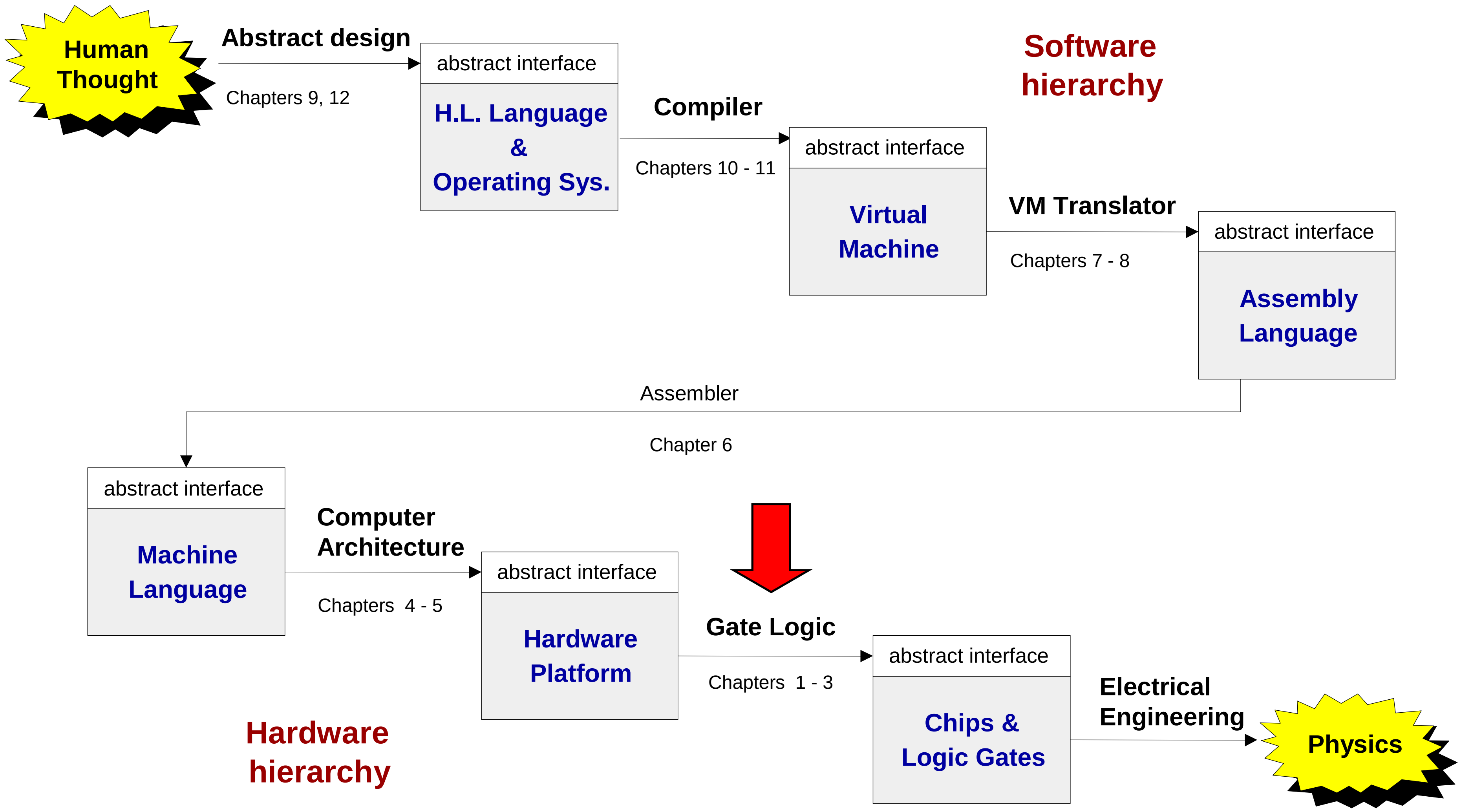
Computer architecture (Hack platform, approx.)

For now, ignore all details!



- *A typical Von Neumann machine*

The big picture



Logic design

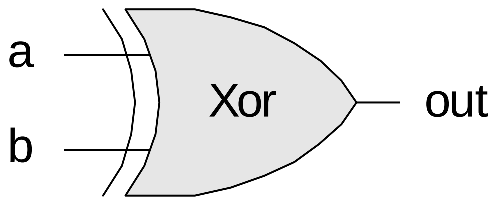
- Combinational logic (leading to an **ALU**)
- Sequential logic (leading to a **RAM**)
- Putting the whole thing together (leading to a **Computer**)

Using … *gate logic.*

Gate logic

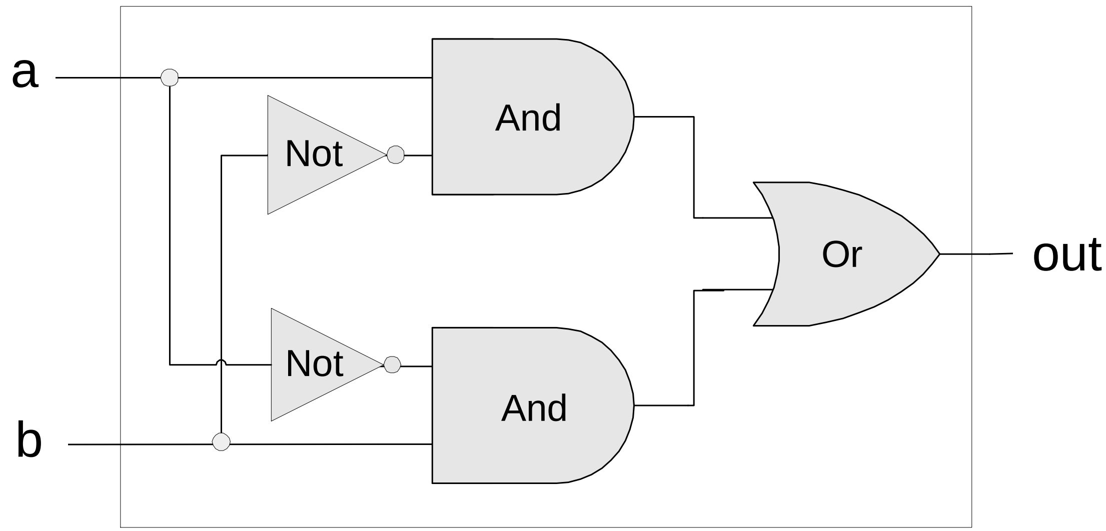
- Hardware platform = inter-connected set of chips
- Chips are made of simpler chips, all the way down to elemantary logic gates
- Logic gate = hardware element that implements a certain Boolean function
- Every chip and gate has an *interface*, specifying WHAT it is doing, and an *implementation*, specifying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

Interface

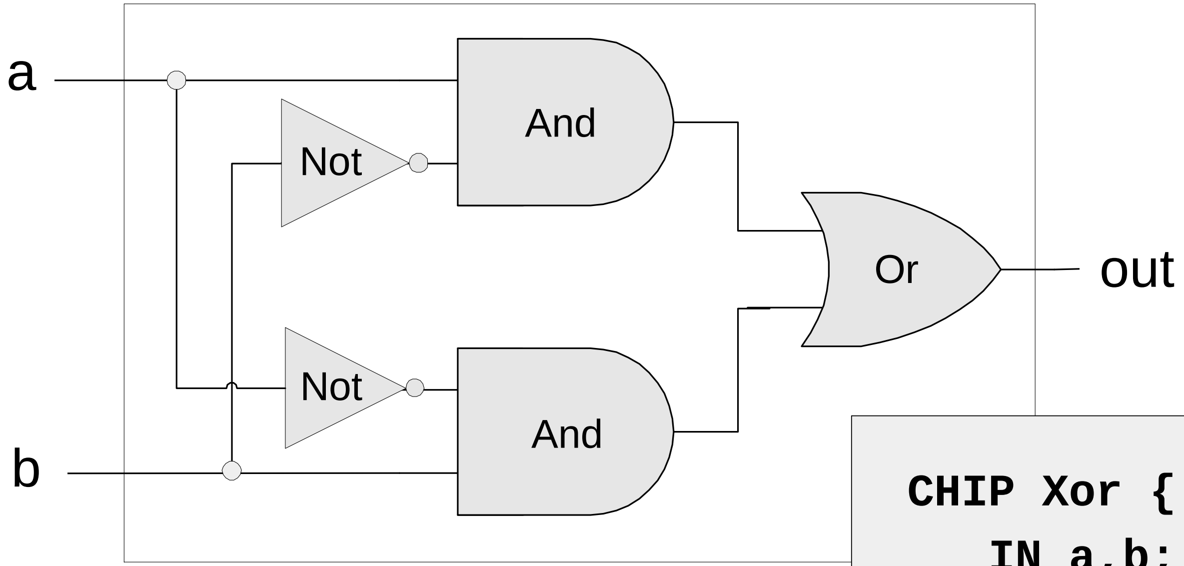


a	b	out
0	0	0
0	1	1
1	0	1
1	1	0

Implementation



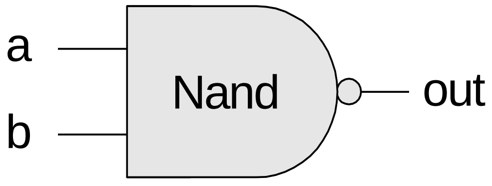
Hardware Description Language (HDL)




```
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);
}
```

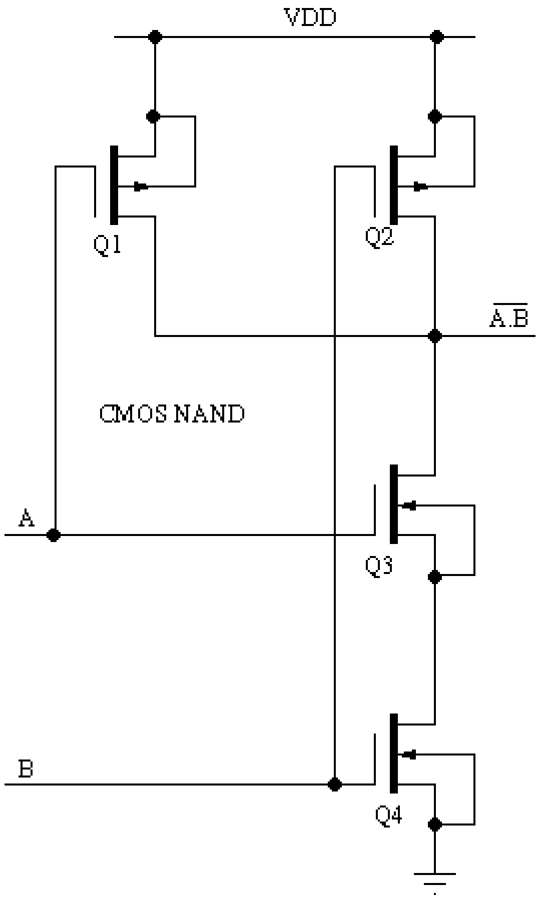
The tour ends:

Interface



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

One implementation option (CMOS)



The tour map, revisited