School of Computer Science

COMP SCI 2000 Computer Systems
Lecture 22

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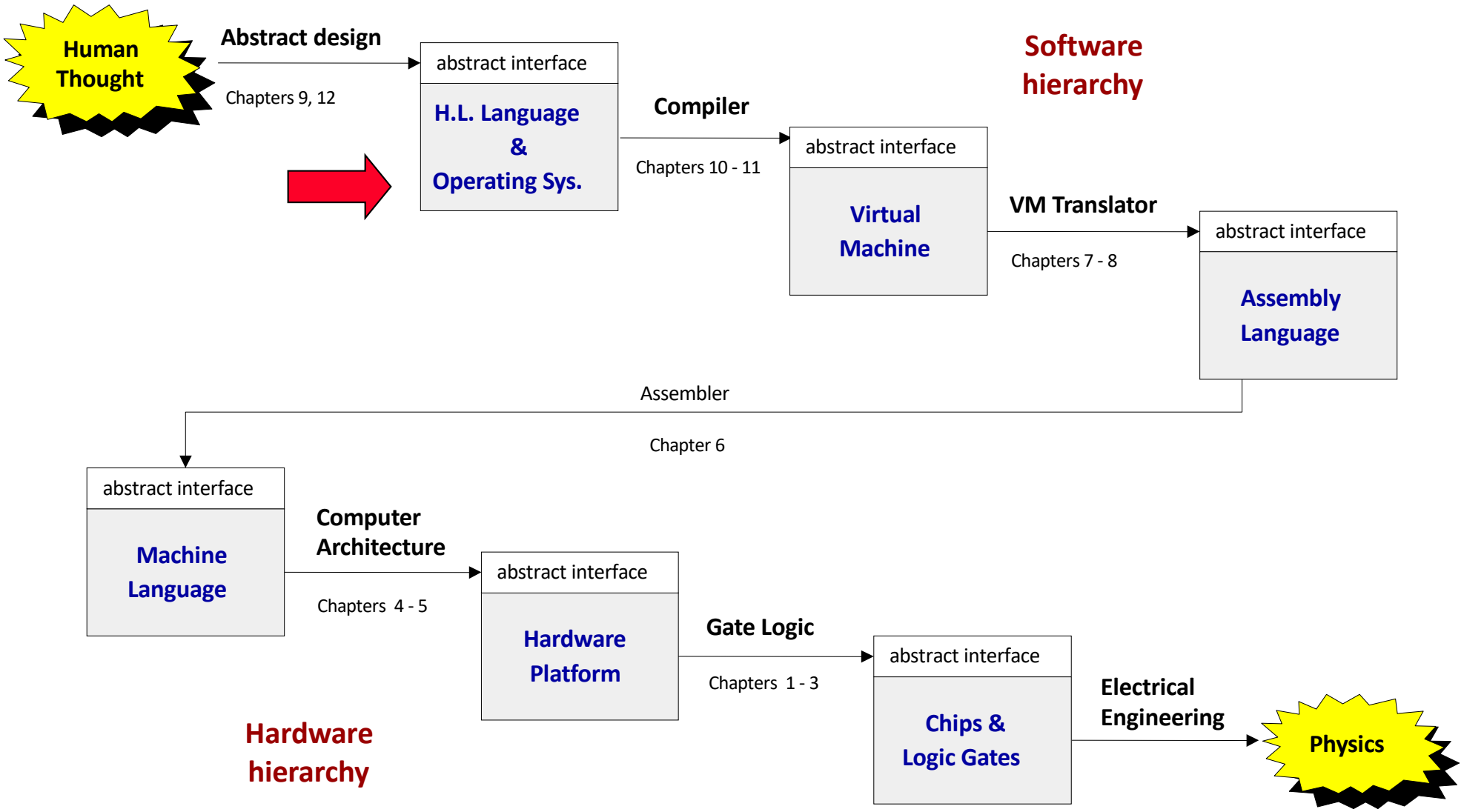
seek LIGHT

Where we are at:



Lecture Plan

- The Operating System
  - Basic libraries
  - Single user system
- More efficient integer arithmetic
  - Multiply
  - Square root

Jack revisited

```
/** Computes the average of a sequence of integers. */
class Main
{
  function void main()
  {
    var Array a;
    var int length;
    var int i, sum;

    let length = Keyboard.readInt("How many numbers? ");
    let a = Array.new(length); // Constructs the array
    let i = 0;

    while (i < length)
    {
      let a[i] = Keyboard.readInt("Enter the next number: ");
      let sum = sum + a[i];
      let i = i + 1;
    }

    do Output.printString("The average is: ");
    do Output.printInt(sum / length);
    do Output.println();
    return;
  }
}
```

Typical OS functions

Language extensions / standard library

- Mathematical operations (**`abs`**, **`sqrt`**, ...)
- Abstract data types (**`String`**, **`Date`**, ...)
- Output functions (**`printChar`**, **`printString`** ...)
- Input functions (**`readChar`**, **`readLine`** ...)
- Graphics functions (**`drawPixel`**, **`drawCircle`**, ...)
- And more ...

System-oriented services

- Memory management (objects, arrays, ...)
- I/O device drivers
- Mass storage
- File system
- Multi-tasking
- UI management (shell / windows)
- Security
- Communications
- And more ...

The Jack OS

- **`Math:`** Provides basic mathematical operations;
- **`String:`** Implements the **`String`** type and string-related operations;
- **`Array:`** Implements the **`Array`** type and array-related operations;
- **`Output:`** Handles text output to the screen;
- **`Screen:`** Handles graphic output to the screen;
- **`Keyboard:`** Handles user input from the keyboard;
- **`Memory:`** Handles memory operations;
- **`Sys:`** Provides some execution-related services.

A typical OS:

- Is modular and scalable
- Empowers programmers (language extensions)
- Empowers users (file system, GUI, …)
- Closes gaps between software and hardware
- Runs in “protected mode”
- Typically written in some high level language
- Typically grows gradually, assuming more and more functions
- Must be efficient.

Efficiency

We have to implement various operations on *n*-bit binary numbers (n = 16, 32, 64, …).

For example, consider *multiplication*

- Naïve algorithm: to multiply x * y: { for i = 1 … y do sum = sum + x }
  - Run-time is proportional to *y*
  - In a 64-bit system, *y* can be as large as 2^{64}.
  - Multiplications can take years to complete
- Algorithms that operate on *n*-bit inputs can be either:
  - Naïve: run-time is proportional to the *value* of the *n*-bit inputs
  - Good: run-time is proportional to *n*, *the input's size*.

Example I: multiplication

The "steps"

$$
\begin{array}{rrrrrcrr}
 & 1 & 0 & 1 & 1 & = & 1 & 1 \\
 & & 1 & 0 & 1 & = & & 5 \\
\hline
 & 1 & 0 & 1 & 1 & & & \\
0 & 0 & 0 & 0 & & & & \\
1 & 0 & 1 & 1 & & & & \\
\hline
1 & 1 & 0 & 1 & 1 & 1 & = 5 & 5
\end{array}
$$

The algorithm explained (first 4 of 16 iteration)

x:	0	0	0	1	0	1	1	
y:	0	0	0	0	1	0	1	j'th bit of y
	0	0	0	**1**	**0**	**1**	**1**	1
	0	0	**1**	**0**	**1**	**1**	0	0
	0	**1**	**0**	**1**	**1**	0	0	1
	1	**0**	**1**	**1**	0	0	0	0
$x \cdot y$:	0	1	1	0	1	1	1	sum

multiply(x, y):

```
// Where x, y ≥ 0
sum = 0
shiftedX = x
for j = 0...(n−1) do
    if (j-th bit of y) = 1 then
        sum = sum + shiftedX
    shiftedX = shiftedX * 2
```

- Run-time: proportional to n
- Can be implemented in SW or HW
- Division: similar idea.

Example II: square root

The square root function has two convenient properties:

- It's inverse function is computed easily
- Monotonically increasing

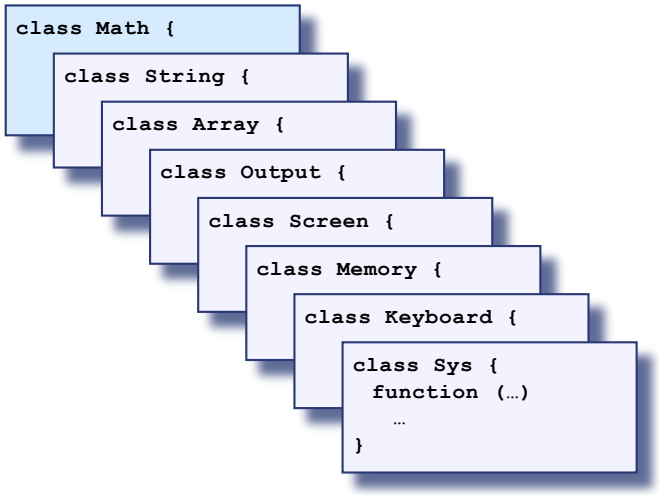
Functions that have these two properties can be computed by binary search:

sqrt(x):

// Compute the integer part of $y = \sqrt{x}$. Strategy:
// Find an integer y such that $y^2 \le x < (y+1)^2$ (for $0 \le x < 2^n$)
// By performing a binary search in the range $0 \ldots 2^{n/2} - 1$.
$y = 0$
for $j = n/2 - 1 \ldots 0$ do
    if $(y + 2^j)^2 \le x$ then $y = y + 2^j$
return y

Number of loop iterations is bounded by n/2, thus the run-time is O(n).

Math operations (in the Jack OS)




```
class Math {

   function void init()

   function int abs(int x)

✓  function int multiply(int x, int y)

✓  function int divide(int x, int y)

   function int min(int x, int y)

   function int max(int x, int y)

✓  function int sqrt(int x)

}
```

The remaining functions are simple to implement.

Perspective

- What we presented can be described as a:
  - mini OS
  - Standard library
- Many classical OS functions are missing
- No separation between user mode and OS mode
- Some algorithms (e.g. multiplication and division) are standard
- Other algorithms (e.g. line- and circle-drawing) can be accelerated with special hardware
- And, by the way, we've just finished building the computer.

Summary

- What have we done in this course?
  - We have seen how to build a computer system from Nand Gates up!
  - You have built
    - Basic gates
    - Sequential Logic
    - Assembler language programs
    - An Assembler
  - You have also studied
    - Boolean arithmetic circuits
    - Machine Language
    - CPU Design
    - Virtual Machines
    - VM-Translators
    - Compilers
    - OS's and High Level Languages

How did it all work?

- When you think about it a simple application written in Jack can translate to moderate number of VM instructions
- And these VM instructions translate into very many assembly language instructions.
- Once assembled these instructions ran on a CPU consisting of many hundreds of nand-gates
  - And memory consisting of over 100,000 gates.
- How did we handle this complexity?
  - Through modular design and
  - Well-designed interfaces
- By itself each component is not too complex
  - Wrap it in an interface and it becomes simpler still!
- These ideas of interfaces and abstraction are at the core of computer science.

Perspective

- Did we build a real machine?
  - Yes! The HDL can be mapped to hardware.
  - The software described would run on top of the machine as specified
- However
  - The Hack machine is designed for simplicity
  - Not for speed and scale
- Modern machines are more complex
  - Bigger word sizes, byte addressable, more complex and flexible instruction sets, more registers
  - Add to this a lot of complexity to speed up the machine
    - Caches, memory management hardware, instruction pipelines, branch prediction, out-of-order instruction issue, multiple cores…
- Most of this extra complexity is designed for extra performance
  - Very often – to make the common case fast
  - Another recurring theme in Computer Science!

Some Final notes

- CS is a science
- What is science?
- Reductionism
- Life science: From Aristo (millions of rules) to Darwin (3 rules) to Watson and Crick (1 rule)
- Computer science: We *knew* in advance that we could build a computer from almost nothing. In this course we actually did it.
- Key lessons:
  - Elegance
  - Clarity
  - Simplicity
  - Playfulness.

a	b	Out
0	0	1
0	1	1
1	0	1
1	1	0