Great Ideas in Computing Hardware

1. All data processed by computers—including the instructions used to create computer programs—can be represented using collections of individual binary digits, or bits.

2. The amazing complexity of modern computers arises largely from the use of extremely simple components replicated on a massive scale.

3. The best way to manage the complexity of modern computers is to define a hierarchy of virtual machines, each of which hides at least some of the complexity of the underlying layers.

A VERY BIG IDEA:

…that information could be quantified

A Symbolic Analysis of Relay and Switching Circuits (1937)

A VERY BIG IDEA:

the binary paradigm
...a rather small but very important word:

**BIT**: a unit of information derived from a choice between two equally probable alternatives or ‘events’

*etymology: abbreviation of ‘binary digit’*

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Switching Circuits

The SERIES Circuit
Exercise: Controlling Room Lights

- Suppose you have a room with one light that you want to control from two switches at opposite ends of the room. How would you implement this functionality with switches?

The XOR Circuit

- If you want to implement a bit inside a computer, you need to come up with a mechanism that:
  - Can exist in either of two states.
  - Allows other parts of the computer to read the state.
  - Allows other parts of the computer to write the state.

- Conceptually, these capabilities are captured by a hardware unit called a flip-flop, which can exist in either an off or an on state:

Implementing Bits
Implementing Switches in Silicon

- In modern computers, switches are usually implemented in chips made based on a **semiconductor**, which is simply a material (typically some form of silicon) that is conducting in some circumstances and insulating in others.
- One of the most common components in today’s computers is the **field-effect transistor (or FET)**, which you can implement in semiconductor using a structure that looks like this:

  ![Field-effect transistor diagram]

- Field-effect transistors come in two types. In a **n-type FET**, the presence of a charge on the gate allows current to flow across the transistor as a whole. In a **p-type FET**, a charge on the gate inhibits the current flow.

Logic Gates

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOT</td>
<td>![NOT symbol]</td>
<td>![NOT truth table]</td>
</tr>
<tr>
<td>AND</td>
<td>![AND symbol]</td>
<td>![AND truth table]</td>
</tr>
<tr>
<td>OR</td>
<td>![OR symbol]</td>
<td>![OR truth table]</td>
</tr>
<tr>
<td>NAND</td>
<td>![NAND symbol]</td>
<td>![NAND truth table]</td>
</tr>
<tr>
<td>XOR</td>
<td>![XOR symbol]</td>
<td>![XOR truth table]</td>
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</tbody>
</table>

Chip Fabrication

The manufacture of a semiconductor chip begins with a crystal of extremely pure silicon. The silicon itself is extracted from beach sand and then grown into a cylindrical ingot in such a way that impurities represent no more than one of a trillion atoms in the crystal.
Chip Fabrication

The silicon ingot is then sliced into individual wafers, which are typically 8-12 inches in diameter and less than a millimeter thick. Each individual wafer is then polished to remove any irregularities in its surface.

Chip Fabrication

The polished wafer is then heated in the presence of oxygen to create a thin layer of silicon dioxide ($\text{SiO}_2$). The $\text{SiO}_2$ layer is nonconducting, and thereby serves to insulate the silicon wafer from the various materials that will be layered above it.

Chip Fabrication

The problem now is to remove just the right parts of the $\text{SiO}_2$ layer to expose the silicon underneath, so that these regions of the chip can be used as transistors. This phase of chip fabrication is accomplished using a process called photolithography.

Chip Fabrication

The first step in the photolithographic process is to coat the insulated wafer with a layer called photoresist, which changes its chemical composition when exposed to light.

Chip Fabrication

The pattern to be inscribed on the chip is taken from an optical template called a mask. The mask looks very much like an old photographic negative, with the transparent regions indicating which parts of the chip surface need to be etched away.

Chip Fabrication

The image on the mask is transferred to the chip surface by shining ultraviolet light through the mask and then using a lens to focus the image on the desired area of the chip.
Chip Fabrication

The same pattern is then created in a new position in other parts of the wafer by repositioning the image. A typical wafer can hold thousands of identical chips, each of which can be etched into the wafer simultaneously.

Chip Fabrication

The exposed photoresist is then removed chemically, exposing the SiO$_2$ layer underneath. A further etching step removes the SiO$_2$ in the exposed areas, revealing the silicon layer. The final step in the etching process is to remove the unexposed photoresist from the wafer.

Chip Fabrication

The next phase in the chip-making process is to introduce new elements into the silicon wafer to make it semiconducting. An ion beam bombards the surface with the doping atoms needed to create $n$-type and $p$-type regions in the exposed silicon wafer.

Chip Fabrication

To complete the fabrication of the chips on the wafer, additional photolithographic steps are used to lay down alternating layers of insulators and conductors. The conductors (typically aluminum and tungsten) create the wiring pattern for each chip.

Chip Fabrication

Once the wiring is complete, diamond saws cut the wafer into the individual chips, which are then encased in plastic, after connecting metallic leads to the appropriate contact positions on the chip.

Chip Fabrication

The individual chips are then tested to make sure that every internal circuit works correctly. Given the complexity and extremely fine tolerances of the manufacturing process, several of the chips on each wafer typically need to be discarded.