

EE 16B Lecture Notes

Transistors as a Switch

February 17, 2016

To contextualize why discussing the hardware elements and circuitry that will come up in the next few lectures, one can look up any teardown of any consumer electronics and look into the operating board. Though you aren't expected to understand most of it, you are expected to recognize some components. And even though the next few lectures will dive into the math of all of this, it's important to take away the intuition and big picture of how the math fits into modern electronics. When you look at a teardown, we realize that not all of the electronics fit inside neat, modular, "black boxes" as "chips". All these other components, that Professor Maharbiz references as "parked cars" show the nonidealities of the digital zeroes and ones within the integrated circuits.

From a conceptual standpoint, it is important to understand that **resistors model dissipation** and capacitors model **energy storage**.

Resistors model heat loss. They dissipate heat and can model many of the universes other dissipative mechanisms.

Capacitors model energy as a result of separation. In electronic capacitors, energy is stored as a separation of charge. The example presented in lecture is the energy stored by loading fluid into a bucket held up high. This has implications for the reality of electronics. Capacitive coupling is a key concern for sensitive measurements. Any two separate pieces of metal act as a capacitor. Thus capacitors exist everywhere, and as a result that means **any** functions within a circuit experience a time delay. When you prompt any changes in the circuit, the capacitors will resist change because it takes a finite amount of time to "unload".

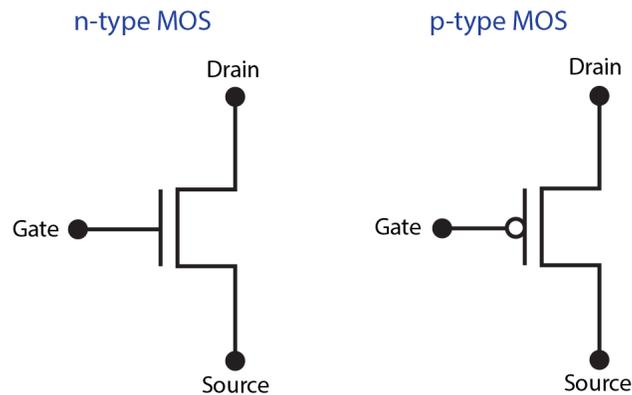
The concept of resistors and capacitors do not solely exist in electronics! They can be modeled in fluids, thermodynamics, and more!

This lecture introduces the concept of transistors and how we use them as switches.

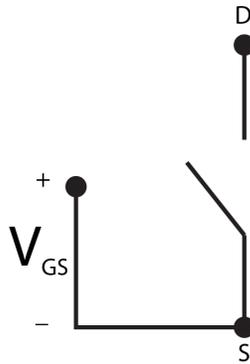
Since much (but definitely not all) of our world's electronics exist in digital circuits and we use zeroes and ones to govern these, we must ask, why do we use zeroes and ones? Why binary as the gradation and not base 10? The main reason we use zeroes and ones is that the voltages used to express zeroes and ones are voltages that exist in our analog world. However, it is easy for us to tell "there" and "not there". Thus, by operating in binary, the electronics are robust and resistant to the disturbances that occur due to our analog, chaotic world.

So, since we use binary, switches become very important and act as building blocks of integrated circuits. We use transistors as these switches.

This provides a very high abstraction level description of how transistors work. We can essentially treat them as switches controlled by an input voltage (the gate voltage). For simplicities sake, we consider the two main types of transistors (there are many many many more types, but we will just look at two for now): n-type metal-oxide-semiconductor (MOS) and p-type MOS. The abbreviations for the three nodes are given by the first letter of the node: G for Gate, D for Drain, and S for Source. The gate essentially acts as a valve on a hose.



We will model the n-type transistor as the following circuit:



in which the switch is:

“on” if $V_{GS} \geq V_{tn}$

“off” if $V_{GS} < V_{tn}$

For a p-type transistor, the same circuit holds, but with the following conditions for the switch:

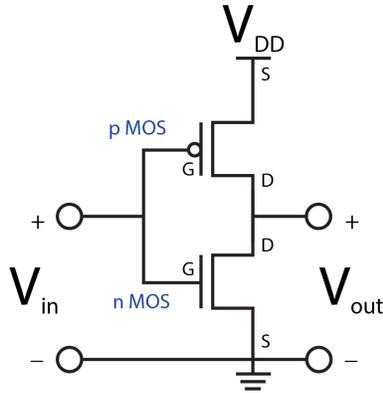
“on” if $V_{SG} \geq V_{tp}$

“off” if $V_{SG} < V_{tp}$

*the t stands for threshold, referring to the threshold voltage that triggers the opening and closing of the switch. V_{tp} = negative threshold voltage. $V_{SG} = -V_{GS}$

As a real-world reference, an example threshold voltage would be $V_{tn} = V_{tp} = 400mV$.

So, let's analyze an example transistor circuit, that consists of a pMOS and nMOS.



Now, let us analyze what happens in the circuit when we input different values for V_{in} .

If $V_{in} = V_{DD}$, then $V_{GS,n} = V_{DD}$ so the n-type transistor is "on" (a short) and $V_{GS,p} = 0$ so the p-type transistor is "off" (an open circuit). This means that V_{out} will be 0.

A similar analysis will yield that when $V_{in} = 0$, then $V_{out} = V_{DD}$.

Input-Output Pairs:

$V_{in} = V_{DD}$, then $V_{out} = 0$

$V_{in} = 0$, then $V_{out} = V_{DD}$

Looking at the input and output pairs, we now realize that this circuit is an inverter.