EE16B Designing Information Devices and Systems II **Spring 2016**

Lecture Notes: 23

Lecturer: Anant Sahai, Michel Maharbiz
Scribe: Minyoung Huh

23.1 Power in CMOS

We have learned that capacitors are supposed to just store charge. In the ideal case that is true, and there should be no dissipated energy. However, this is not true in the real world. Hence, we are interested in finding out the amount of power dissipated in the CMOS. The amount of energy that is dissipated as heat can cause damage to the hardware.

See the simple circuit on the left in figure 23.1. The output of the inverter is driving this load capacitance. If the input source starts from low to high, the output of the inverter should also start low to high following the curve in figure 23.2 due to the resistance built inside the inverter.

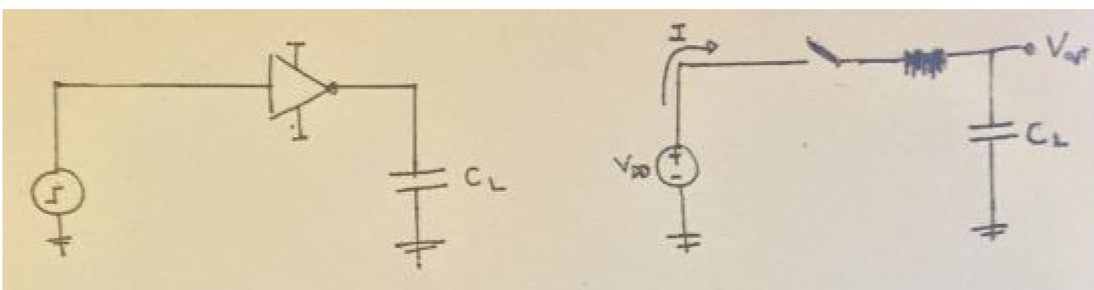

Figure 23.1: Inverting circuit when switched on

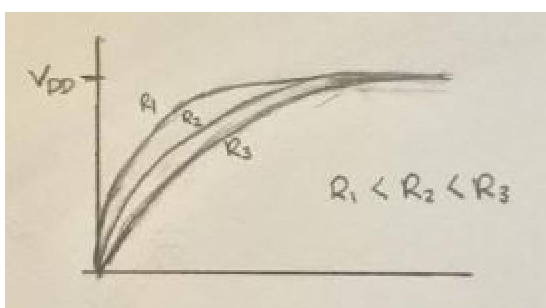

Figure 23.2: Voltage across the capacitor C_L

This circuit, in the ideal case, can be alternatively represented as the circuit on the right in figure 23.1. Using this representation lets find out how much power dissipates in this circuit. How much charge is in the capacitor to have a voltage potential of V_{DD}?

$$Q_{C_L} = C_L V_{DD}$$

The charge in the capacitor originates from the V_{DD}.

Recall the relationship from physics

$$P = IV$$

$$E = V(It) = VQ$$

Plugging in our equation for Q_{C_L}

$$E_{V_{DD}} = C_L V_{DD} V_{DD} = C_L V_{DD}^2$$

The energy that came out of the circuit only depends on the voltage source and the capacitance not from the resistance!

$$E = Pt$$

What must be happening such that the energy does not depend on the resistance? To answer this question we first answer, how does the output of the inverter change as we change the resistance? The curve becomes sharper as seen in figure 23.2. It turns out that P is proportional to $1/R$ and t is proportional to r hence the energy, E, does not depend on the resistance of the circuit. The energy however still dissipates through the resistance.

When $V_{out} = V_{DD}$

$$E_{stored} = \frac{1}{2} C_L V_{DD}^2$$

The E_{stored} is the energy stored in the capacitor. But the total energy pulled out of the source was calculated to be $C_L V_{DD}^2$. Half of the energy is stored in the capacitor and the other half is stored in the resistance.

Let's have the same circuit but with input from low to high. See figure 23.3. What happens to the energy that was stored in the capacitor? We know that the energy of the capacitance converges to 0. The resistor dissipates the energy stored in the capacitor.

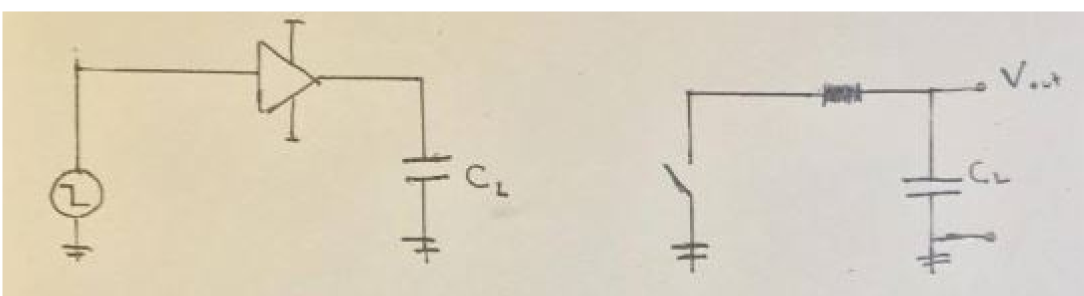

Figure 23.3: Inverting circuit when switched off

We have complete cycle. For any arbitrary binary wave form anytime the inverter goes from low to high, the circuit pull out $C_L V_{DD}^2$ energy from the source as seen in figure 23.4.

$$P = \frac{E}{t}$$

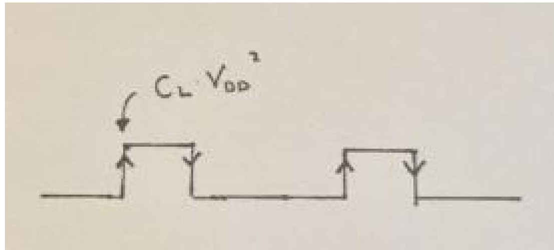

Figure 23.4: Binary wave form

How much energy per time do we dissipate? To answer this question we need to understand about clock speed. The clock speed/frequency is the frequency in which the processor can process an instruction.

For more information on how processor clocks work, refer to the link
`https://en.wikipedia.org/wiki/Clock_rate`.

Each clock tick can be seen as a period in a square wave. Hence we can denote the power dissipated as

$$\alpha_{0\to 1} f(clk) C_L V_{DD}^2$$

Where $\alpha_{0\to 1} f(clk)$ denotes the average clock frequency to go from 0 to 1. To get a processor with lowest power consumption possible we want the V_{DD} to be 0 but then it would be off and none of our circuit would work. It turns out that the resistance in the inverters are related to some function inverse V_{DD}. So if we want to overclock the processor we might want to increase V_{DD}. It turns out most processors are made in the following way. It will try to have the lowest clock frequency as possible to be able to complete any instruction and set the voltage as low as possible.