Digital Electronics: Electronics, Devices and Circuits

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Underlying Concepts

Introduction

- In the coming lectures we will consider how logic gates can be built using electronic circuits
- First, basic concepts concerning electrical circuits and components will be introduced
- This will enable the analysis of linear circuits, i.e., one where superposition applies:
  - If an input $x_1(t)$ gives an output $y_1(t)$, and input $x_2(t)$ gives an output $y_2(t)$, then input $[x_1(t)+x_2(t)]$ gives an output $[y_1(t)+y_2(t)]$

Introduction

- However, logic circuits are non-linear, consequently we will introduce a graphical technique for analysing such circuits
- Semiconductor materials, metal oxide field effect transistors (MOSFET) will be introduced
- Building an NMOS inverter from an n-channel (MOSFET) will be described
- CMOS logic built using MOSFETs will be presented
- Finally, we will look at interfacing to the analogue world

Basic Electricity

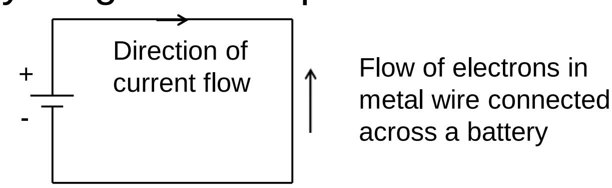
- An electric current is produced when charged particles (e.g., electrons in metals, or electrons and ions in a gas or liquid) move in a definite direction
- In metals, the outer electrons are held loosely by their atoms and are free to move around the fixed positive metal ions
- This free electron motion is random, and so there is no net flow of charge in any direction, i.e., no current flow

Basic Electricity

- If a metal wire is connected across the terminals of a battery, the battery acts as an 'electron pump' and forces the free electrons to drift toward the +ve terminal and in effect flow through the battery
- The drift speed of the free electrons is low, e.g., < 1 mm per second owing to frequent collisions with the metal ions.
- However, they all start drifting together as soon as the battery is applied

Basic Electricity

- The flow of electrons in one direction is known as an electric current and reveals itself by making the metal warmer and by deflecting a nearby magnetic compass



- Before electrons were discovered it was imagined that the flow of current was due to positively charged particles flowing out of +ve toward –ve battery terminal

Basic Electricity

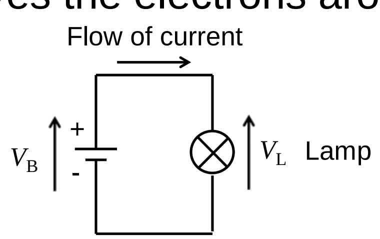
- Note that 'conventional' current flow is still defined as flowing from the +ve toward the –ve battery terminal (i.e., the opposite way to the flow of the electrons in the metal)!
- A huge number of charged particles (electrons in the case of metals) drift past each point in a circuit per second.
- The unit of charge is the *Coulomb* (C) and one electron has a charge of $1.6*10^{-19}$ C

Basic Electricity

- Thus one C of charge is equivalent to $6.25*10^{18}$ electrons
- When one C of charge passes a point in a circuit per second, this is defined as a current (I) of 1 *Ampere* (A), i.e., $I = Q/t$, where Q is the charge (C) and t is time in seconds (s), i.e., current is the rate of flow of charge.

Basic Electricity

- In the circuit shown below, it is the battery that supplies the electrical force and energy that drives the electrons around the circuit.



- The electromotive force (emf) V_B of a battery is defined to be 1 *Volt* (V) if it gives 1 *Joule* (J) of electrical energy to each C of charge passing through it.

Basic Electricity

- The lamp in the previous circuit changes most of the electrical energy carried by the free electrons into heat and light
- The potential difference (pd) V_L across the lamp is defined to be 1 *Volt* (V) if it changes 1 *Joule* (J) of electrical energy into other forms of energy (e.g., heat and light) when 1 C of charge passes through it, i.e., $V_L=E/Q$, where E is the energy dissipated (J) and Q is the charge (C)

Basic Electricity

- Note that pd and emf are usually called *voltages* since both are measured in V
- The flow of electric charge in a circuit is analogous to the flow of water in a pipe. Thus a pressure difference is required to make water flow – To move electric charge we consider that a pd is needed, i.e., whenever there is a current flowing between 2 points in a circuit there must be a pd between them

Basic Electricity

- What is the power dissipated (P_L) in the lamp in the previous circuit?
- $P_L = E/t$ (J/s). Previously we have, $E = QV_L$, and so, $P_L = QV_L/t$ (W) .
- Now substitute $Q = It$ from before to give, $P_L = It\,V_L/t = IV_L$ (W) , an expression that hopefully is familiar

Basic Electricity

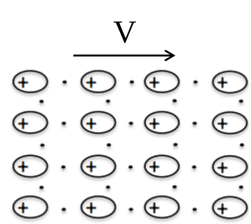
- So far, we have only considered metallic conductors where the charge is carried by ‘free’ electrons in the metal lattice.
- We will now consider the electrical properties of some other materials, specifically, *insulators* and *semiconductors*

Basic Materials

- The electrical properties of materials are central to understanding the operation of electronic devices
- Their functionality depends upon our ability to control properties such as their current-voltage characteristics
- Whether a material is a conductor or insulator depends upon how strongly bound the outer valence electrons are to their atomic cores

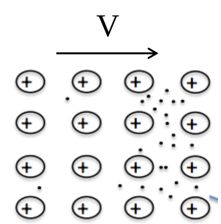
Insulators

- Consider a crystalline insulator, e.g., diamond
- Electrons are strongly bound and unable to move
- When a voltage difference is applied, the crystal will distort a bit, but no charge (i.e., electrons) will flow until breakdown occurs



Conductors

- Consider a metal conductor, e.g., copper
- Electrons are weakly bound and free to move
- When a voltage difference is applied, the crystal will distort a bit, but charge (i.e., electrons) will flow



Semiconductors

- Since there are many free electrons in a metal, it is difficult to control its electrical properties
- Consequently, what we need is a material with a low electron density, i.e., a semiconductor, e.g., Silicon
- By carefully controlling the electron density we can create a whole range of electronic devices

Semiconductors

- We can create *n*-type silicon (Group 4) by doping with arsenic (Group V) that donates an additional electron
- This electron is free to move around the silicon lattice
- Owing to its negative charge, the resulting semiconductor is known as *n-type*

Semiconductors

- Similarly we can create *p*-type silicon (Group 4) by doping with Boron (Group 3) that accepts an additional electron
- This leaves a *hole* (i.e., absence of a valence electron) in the lattice
- This hole is free to move in the lattice – actually it is the electrons in the lattice that do the shifting, but the net result is that the hole is shuffled from atom to atom.
- The free hole has a positive charge, hence this semiconductor is *p-type*

Semiconductors

- The Metal Oxide Semiconductor Field Effect Transistor (MOSFET) devices that are used to implement virtually all digital logic circuits are fabricated from *n* and *p* type silicon
- Later on, we will see how MOSFETs can be used to implement digital logic circuits

Circuit Theory

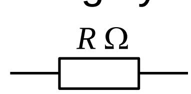
- Electrical engineers have an alternative (but essentially equivalent) view concerning pd.
- That is, conductors, to a greater or lesser extent, oppose the flow of current. This ‘opposition’ is quantified in terms of *resistance* (R). Thus the greater is the resistance, the larger is the potential difference measured across the conductor (for a given current).

Circuit Theory

- The *resistance* (R) of a conductor is defined as $R=V/I$, where V is the pd across the conductor and I is the current through the conductor.
- This is know as *Ohms Law* and is usually expressed as $V=IR$, where resistance is defined to be in Ohms (Ω).
- So for an *ohmic* (i.e., linear) conductor, plotting I against V yields a straight line through the origin

Circuit Theory

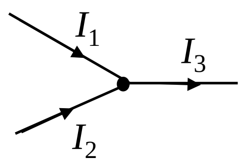
- Conductors made to have a specific value of resistance are known as *resistors*.
- They have the following symbol in an electrical circuit:



- Analogy:
  - The flow of electric charges can be compared with the flow of water in a pipe.
  - A pressure (voltage) difference is needed to make water (charges) flow in a pipe (conductor).

Circuit Theory

- Kirchhoff's Current Law – The sum of currents entering a junction (or node) is zero, e.g.,

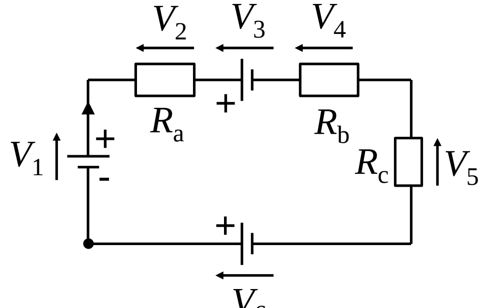


$I_1 + I_2 - I_3 = 0$ or $I_1 + I_2 = I_3$

- That is, what goes into the junction is equal to what comes out of the junction – Think water pipe analogy again!

Circuit Theory

- Kirchhoff's Voltage Law – In any closed loop of an electric circuit the sum of all the voltages in that loop is zero, e.g.,

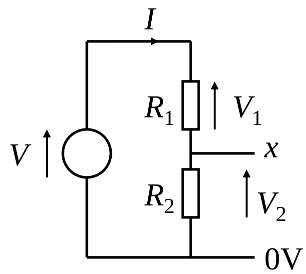


$V_1 - V_2 - V_3 - V_4 - V_5 + V_6 = 0$

- We will now analyse a simple 2 resistor circuit known as a *potential divider*

Potential Divider

- What is the voltage at point x relative to the 0V point?



$$V = V_1 + V_2$$

$$V_1 = IR_1 \qquad V_2 = IR_2$$

$$V = IR_1 + IR_2 = I(R_1 + R_2)$$

$$I = \frac{V}{(R_1 + R_2)}$$

$$V_x = V_2 = \frac{V}{(R_1 + R_2)} R_2 = V\left(\frac{R_2}{R_1 + R_2}\right)$$

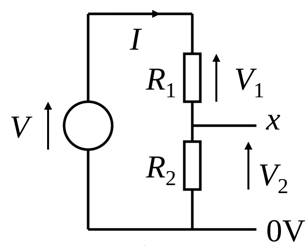
Note: circle represents an ideal voltage source, i.e., a perfect battery

Solving Non-linear circuits

- As mentioned previously, not all electronic devices have linear I-V characteristics, importantly in our case this includes the FETs used to build logic circuits
- Consequently we cannot easily use the algebraic approach applied previously to the potential divider. Instead, we will use a graphical approach
- Firstly though, we will apply the graphical approach to the potential divider example

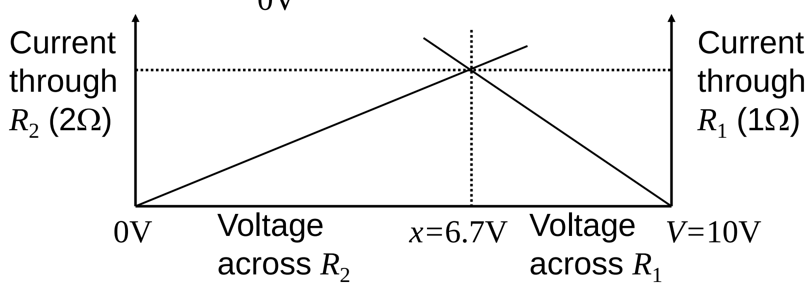
Potential Divider

- How can we do this graphically?



So if V = 10V, R_1 = 1Ω and R_2 = 2Ω

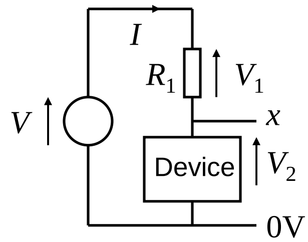
$$V_x = V\left(\frac{R_2}{R_1+R_2}\right) = 10\left(\frac{2}{1+2}\right) = 6.7\text{V}$$



Graphical Approach

- Clearly approach works for a linear circuit.
- How could we apply this if we have a non-linear device, e.g., a transistor in place of R_2?
- What we do is substitute the V-I characteristic of the non-linear device in place of the linear characteristic (a straight line due to Ohm’s Law) used previously for R_2

Graphical Approach



So if V = 10V and R_1 = 1Ω

The voltage at x is aV as shown in the graph