“One of the most meaningful experiences in my life was the day that we actually switched on our first white LED....at 1/10 of 1 watt and when we switched it on, I remember like it were yesterday, saying to my technician—’Good God! A child could read with the light of a single diode!’ ”

Dr Dave Irvine-Halliday, founder of Light up the World
Measuring Electricity

Electricity makes our lives easier, but it can seem like a mysterious force. Measuring electricity is confusing because we cannot see it. We are familiar with terms such as watt, volt, and amp, but we do not have a clear understanding of these terms. We buy a 60-watt lightbulb, a tool that needs 120 volts, or a vacuum cleaner that uses 8.8 amps, and don’t think about what those units mean.

Using the flow of water as an analogy can make electricity easier to understand. The flow of electrons in a circuit is similar to water flowing through a hose. If you could look into a hose at a given point, you would see a certain amount of water passing that point each second.

The amount of water depends on how much pressure is being applied—how hard the water is being pushed. It also depends on the diameter of the hose. The harder the pressure and the larger the diameter of the hose, the more water passes each second. The flow of electrons through a wire depends on the electrical pressure pushing the electrons and on the cross-sectional area of the wire.

Voltage

The pressure that pushes electrons in a circuit is called voltage. Using the water analogy, if a tank of water were suspended one meter above the ground with a ten-centimeter pipe coming out of the bottom, the water pressure would be similar to the force of a shower. If the same water tank were suspended 10 meters above the ground, the force of the water would be much greater, possibly enough to hurt you.

Voltage (V) is a measure of the pressure applied to electrons to make them move. It is a measure of the strength of the current in a circuit and is measured in volts (V). Just as the 10-meter tank applies greater pressure than the 1-meter tank, a 10-volt power supply (such as a battery) would apply greater pressure than a 1-volt power supply.

AA batteries are 1.5-volt; they apply a small amount of voltage or pressure for lighting small flashlight bulbs. A car usually has a 12-volt battery—it applies more voltage to push current through circuits to operate the radio or defroster. The voltage of typical wall outlets is 120 volts—a dangerous amount of voltage. An electric clothes dryer is usually wired at 240 volts—a very dangerous voltage.

Current

The flow of electrons can be compared to the flow of water. The water current is the number of molecules flowing past a fixed point; electrical current is the number of electrons flowing past a fixed point. Electrical current (I) is defined as electrons flowing between two points having a difference in voltage. Current is measured in amperes or amps (A). One ampere is $6.25 \times 10^{18}$ electrons per second passing through a circuit.

With water, as the diameter of the pipe increases, so does the amount of water that can flow through it. With electricity, conducting wires take the place of the pipe. As the cross-sectional area of the wire increases, so does the amount of electric current (number of electrons) that can flow through it.
Resistance

Resistance (R) is a property that slows the flow of electrons. Using the water analogy, resistance is anything that slows water flow, a smaller pipe or fins on the inside of a pipe.

In electrical terms, the resistance of a conducting wire depends on the metal the wire is made of and its diameter. Copper, aluminum, and silver—metals used in conducting wires—have different resistance.

Resistance is measured in units called ohms (Ω). There are devices called resistors, with set resistances, that can be placed in circuits to reduce or control the current flow.

Any device placed in a circuit to do work is called a load. The lightbulb in a flashlight is a load. A television plugged into a wall outlet is also a load. Every load has built-in resistance.

Ohm’s Law

George Ohm, a German physicist, discovered that in many materials, especially metals, the current that flows through a material is proportional to the voltage.

In the substances he tested, he found that if he doubled the voltage, the current also doubled. If he reduced the voltage by half, the current dropped by half. The resistance of the material remained the same.

This relationship is called Ohm’s Law, and can be written in a simple formula. If you know any two of the measurements, you can calculate the third using the following formula:

\[
voltage = current \times resistance
\]

or

\[
v = i \times R \quad \text{or} \quad V = A \times \Omega
\]

Electrical Power

Power (P) is a measure of the rate of doing work or the rate at which energy is converted. Electrical power is the rate at which electricity is produced or consumed. Using the water analogy, electric power is the combination of the water pressure (voltage) and the rate of flow (current) that results in the ability to do work.

A large pipe carries more water (current) than a small pipe. Water at a height of 10 meters has much greater force (voltage) than at a height of one meter. The power of water flowing through a 1-centimeter pipe from a height of one meter is much less than water through a 10-centimeter pipe from 10 meters.

Electrical power is defined as the amount of electric current flowing due to an applied voltage. It is the amount of electricity required to start or operate a load for one second. Electrical power is measured in watts (W). The formula is:

\[
\text{power} = \text{voltage} \times \text{current}
\]

or

\[
P = V \times I \quad \text{or} \quad W = V \times A
\]
Measuring Current and Voltage

- To measure current, you need to *force* all the current to go into your current measuring device (multi-meter). So no other path can be available for the current to take.
- To measure voltage, also known as the potential difference, you simply need to measure the potential energy on either side of the device you want to measure.
AC vs DC

- **Direct Current (DC)**
  - Current you get from any battery

- **Alternating Current (AC)**
  - Current in the wall plug
  - Changes from positive to negative 60 times per second (60 Hertz)
Anatomy of an LED

Figure 1-4 – Anatomy of a plastic 5mm diameter (T1 3/4) LED.
Light Emitting Diodes

- What is a diode?
  - A two terminal electronic device made of a solid material that allows current (a flow of charge) to flow in only one particular direction
  - Light Emitting Diodes give off light when this current flows
  - For white LEDs useful for general lighting applications, the solid material that makes up the LED is called Gallium Nitride (GaN)
    - Other color LEDs use different materials

- Before getting into what a diode is, first let’s explore a couple of questions:
  - What is GaN?
  - Where does it come from?
Gallium Nitride (GaN)

- Quick chemistry crash-course!
  - Gallium (Ga): Group 3 → 3 electrons in outer shell
  - Nitrogen (N): Group 5 → 5 electrons in outer shell
  - Remember: Materials are happiest and most stable when they have 8 electrons in their outer shell
How is the GaN LED Produced?

- GaN doesn’t exist naturally
- So to produce GaN for LEDs, we start with a very large, air-tight ‘tin-can’ chamber
- A vacuum is created inside the ‘tin can’ by sucking out all the air
- Gallium atoms and Nitrogen atoms are introduced into the chamber with Ga and N ‘guns’
- GaN forms when the Ga and N atoms mix
- Molecular Beam Epitaxy (MBE) or Metal-Organic Chemical Vapor Epitaxy (MOCVD) are the technical names for the techniques used for LED production
GaN Material

- Solid GaN forms as a regular crystal lattice of material, with the Ga and N atoms sharing 8 electrons between them → therefore it’s a stable solid.
Air Bubbles and Water Drops

- Consider two pipes sealed at both ends:
  - Bottom pipe completely filled with water
  - Top pipe contains no water--completely filled with air
  - When pipes are tilted, there is no movement or flow of water
  - Now consider the same pipes, but this time we will remove a drop of water from the bottom pipe and place in the top pipe:
  - Bottom pipe: Can think of it as water moving down, but easier and more intuitive to think of it as an air drop moving up
What is a Diode? Part I

- Now the question that remains is: What is a diode?
- Let’s start the answer by looking at the GaN material previously described.
- Do you think this material will allow current to flow through it?
  - For current to flow, a free carrier of charge, like a free electron, is needed.
  - So the answer is no, while this material has electrons, the electrons are used to bond the atoms together and are not free to move.
What is a Diode? Part I

- What if a Ga atom is replaced with a Silicon (Si) atom?
- Remember, Si is in Group 4
  - So Si has 4 electrons in its outer shell
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What is a Diode? Part I

- What if a Ga atom is replaced with a Silicon (Si) atom?
- Remember, Si is in Group 4
  - So Si has 4 electrons in its outer shell
- Do you think this material will allow current to flow?
  - Yes, now there is a free electron that is free to move and carry charge
- GaN ‘doped’ with Si is known as N-type since the carriers of charge are electrons--which have a Negative charge
What is a Diode? Part II

- What if a Ga atom is replaced with a Magnesium (Mg) atom?
- Remember, Mg is in Group 2
  - So Mg has 2 electrons in its outer shell
What is a Diode? Part II

- What if a Ga atom is replaced with a Magnesium (Mg) atom?
- Remember, Mg is in Group 2
  - So Mg has 2 electrons in its outer shell
What is a Diode? Part II

- What if a Ga atom is replaced with a Magnesium (Mg) atom?
- Remember, Mg is in Group 2
  - So Mg has 2 electrons in its outer shell
  - Note that there is a missing electron when the Mg atom takes the place of a Ga atom
- Do you think this material will allow current to flow?
  - Yes, the missing electron, also known as a ‘hole’ is free to move and carry charge
Air Bubbles and Water Drops Revisited

- Consider two pipes sealed at both ends:
  - Bottom pipe completely filled with water (anology to electrons)
  - Top pipe contains no water (electrons)--completely filled with air
  - When pipes are tilted, there is no flow of water (current)
  - Now consider the same pipes, but this time we will remove a drop of water (an electron) from the bottom pipe and place it in the top pipe:
  - Bottom pipe: Can think of it as water moving down, but easier and more intuitive to think of it as an air drop (hole) moving up

Analogy Credit: Prof JP Colinge, UC Davis
What is a Diode? Part II

- What if a Ga atom is replaced with a Magnesium (Mg) atom?
- Remember, Mg is in Group 2
  - So Si has 2 electrons in its outer shell
- Do you think this material will allow current to flow?
  - Yes, now there is a free electron that is free to move and carry charge
- GaN ‘doped’ with Mg is known as P-type since the carriers of charge are ‘holes’--which have an effectively positive charge

P-type GaN
What is a Diode?
Answer: A PN Junction

- N-type material has negatively charged free electrons able to carry charge
- P-type material has positively charged free ‘holes’ able to carry charge
- When a p-material is brought into contact with a n-material, the resulting device is called a PN junction, which is a type of diode
- What’s so special about a PN junction?
What is a Diode?
Answer: A PN Junction

- What is a diode?
  - A PN junction is a type of diode, which is a two terminal electronic device made of a solid material that allows current (a flow of charge) to flow in only one particular direction

- If we connect the positive end of the battery to N material
  - No current flow
What is a Diode?

Answer: A PN Junction

- What is a diode?
  - A PN junction is a type of diode, which is a two terminal electronic device made of a solid material that allows current (a flow of charge) to flow in only one particular direction.

- If we connect the positive end of the battery to N side
  - No current flow

- Now, if we connect the positive end of the battery to P side
  - Current flows, light emitted when electrons and holes meet.
The Circuit
Demonstration
Group Composition

- Group 1: Marion, Deyette, Atif, Daniel
- Group 2: Kimberlyn, Jamie, Andrew, Tucker
- Group 3: Dee, Scott, Jordan, Tony
- Group 4: Jeff, James, Corey
- Group 5: Robert, Aymen, Pong, Todd