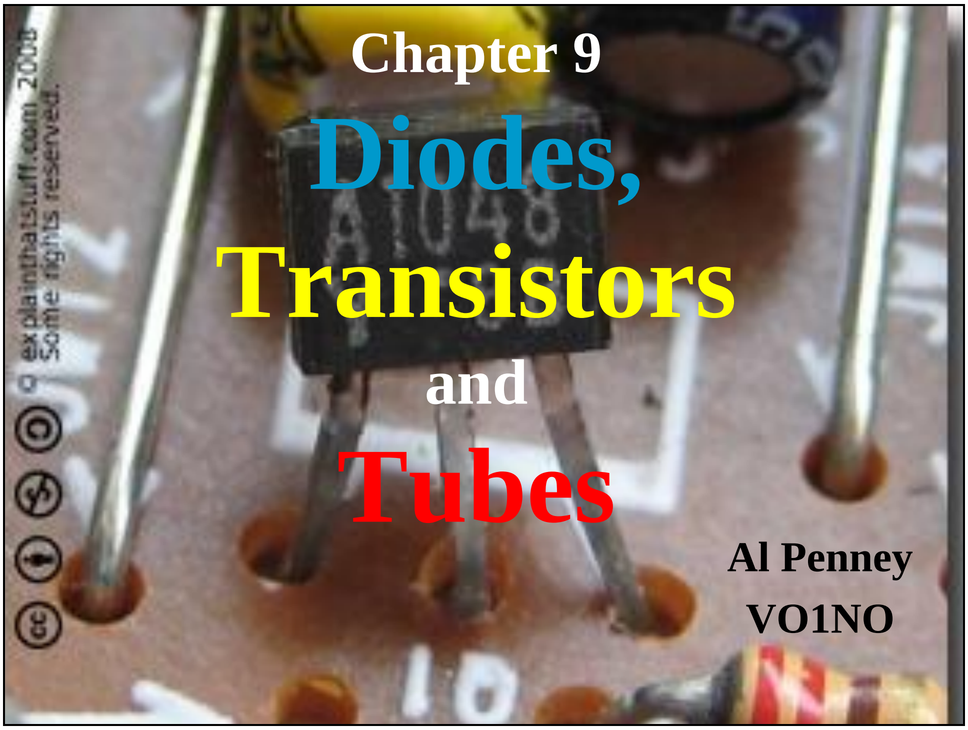


## Chapter 9

# Diodes, Transistors and Tubes

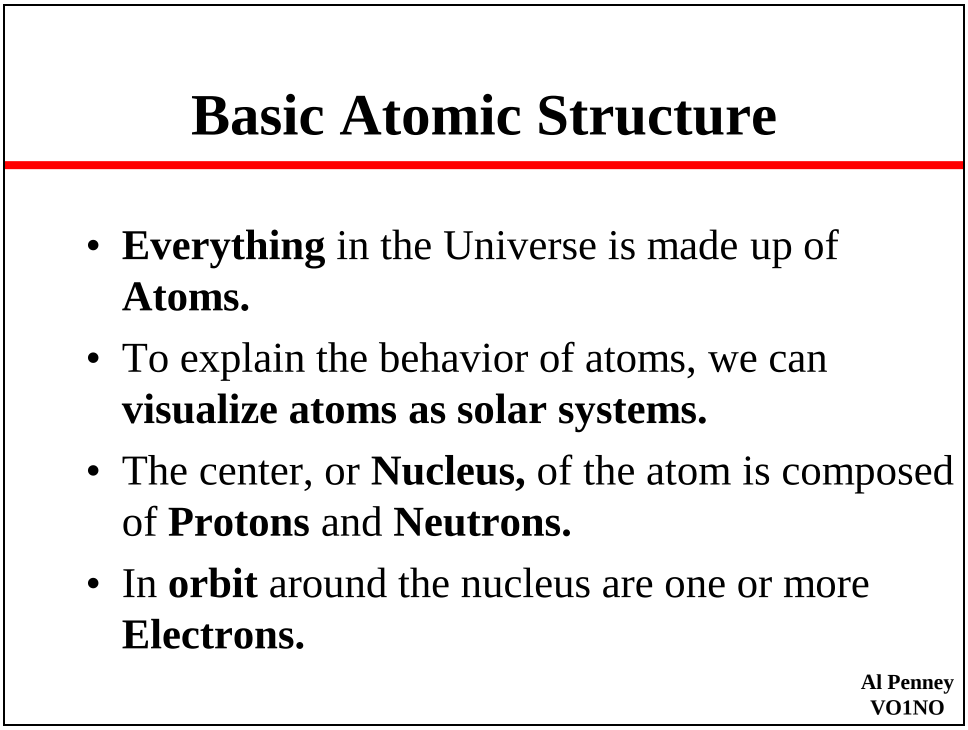
Al Penney
VO1NO

# Objective

On completion, you should:

- Be familiar with the **basics** of **semiconductors** and **vacuum tubes**;
- **Identify** and **name** the parts of each;
- Be able to **compare** semiconductors and tubes; and
- Understand the concept of **amplification**.

**Al Penney**
**VO1NO**



# Basic Atomic Structure

- **Everything** in the Universe is made up of **Atoms.**
- To explain the behavior of atoms, we can **visualize atoms as solar systems.**
- The center, or **Nucleus,** of the atom is composed of **Protons** and **Neutrons.**
- In **orbit** around the nucleus are one or more **Electrons.**

**Al Penney**
**VO1NO**

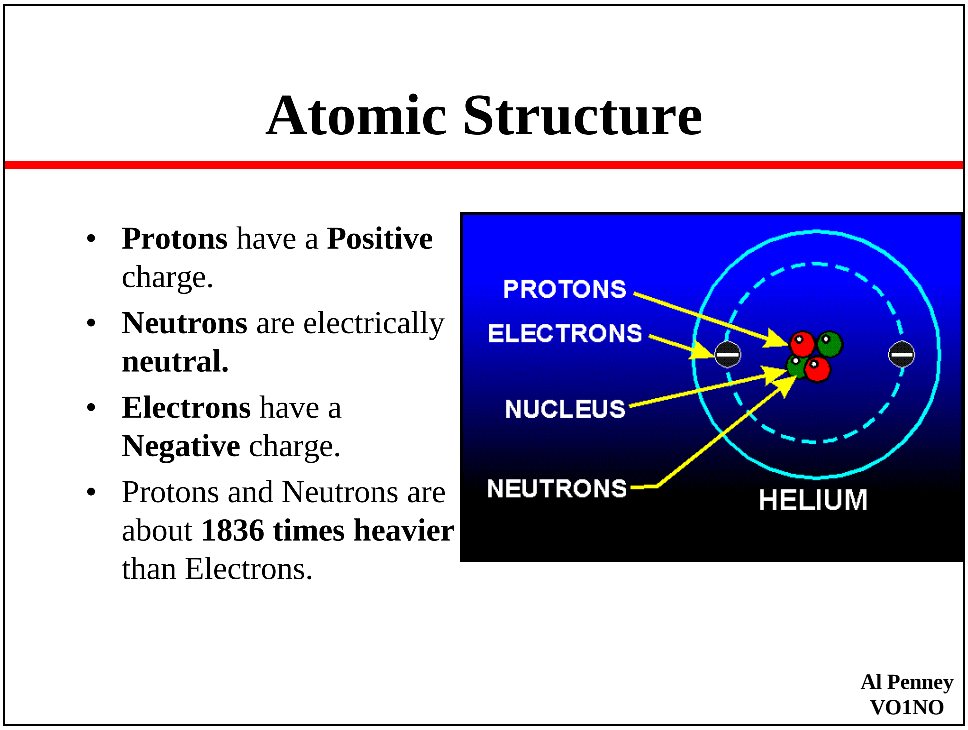
The **atom** is a basic unit of matter that consists of a dense central nucleus surrounded by a cloud of negatively charged electrons.  The atomic nucleus contains a mix of positively charged protons and electrically neutral neutrons (except in the case of hydrogen-1, which is the only stable nuclide with no neutrons).  The electrons of an atom are bound to the nucleus by the electromagnetic force.  Likewise, a group of atoms can remain bound to each other by chemical bonds based on the same force, forming a molecule. An atom containing an equal number of protons and electrons is electrically neutral, otherwise it is positively or negatively charged and is known as an ion. An atom is classified according to the number of protons and neutrons in its nucleus: the number of protons determines the chemical element, and the number of neutrons determines the isotope of the element.

Chemical atoms, which in science now carry the simple name of "atom," are minuscule objects with diameters of a few tenths of a nanometer and tiny masses proportional to the volume implied by these dimensions. Atoms can only be observed individually using special instruments such as the scanning tunneling microscope.  Over 99.94% of an atom's mass is concentrated in the nucleus,] with protons and neutrons having roughly equal mass. Each element has at least one isotope with an unstable nucleus that can undergo radioactive decay. This can result in a transmutation that changes the number of protons or neutrons in a nucleus. Electrons that are bound to atoms possess a set of stable energy levels, or orbitals, and can undergo transitions between them by absorbing or emitting photons that match the energy differences between the levels. The electrons determine the chemical properties of an element, and strongly influence an atom's magnetic properties. The principles of quantum mechanics have been successfully used to model the observed properties of the atom.

**Electron** is the lightest subatomic particle. It is **negatively charged particle.** Its mass is $9.109 \times 10^{-31}$ kg which is only **1/1,840 the mass of a proton**. An electron is therefore considered to be mass less in comparison with proton and neutron and is not included in calculating atomic mass of an atom. **The electron was discovered in 1897 by British Physicist J.J. Thomson** during his investigations of cathode rays.

**Proton** is a subatomic particle **with a positive charge**. It has a mass of $1.67262 \times 10^{-27}$ kg which is 1,836 times of the mass of an electron. When the number of proton is equal to the number of electrons orbiting in nucleus we say that the atom is electrically neutral. **The discovery of the proton is credited to Ernest Rutherford**, who proved that the nucleus of the hydrogen atom (i.e. a proton) is present in the nuclei of all other atoms in the **year 1917**. Based on the conclusions drawn from the gold-foil experiment, Rutherford is also credited with the discovery of the atomic nucleus.

**Neutron** is subatomic particle. Neutron **does not have any charge,** that is, it is neutral. Its mass is $1.67493 \times 10^{-27}$ kg, **greater than that of a proton and electron**. Neutrons and protons are commonly called nucleons. The neutron **was discovered in 1932 by the English physicist James Chadwick.**



# Atomic Structure

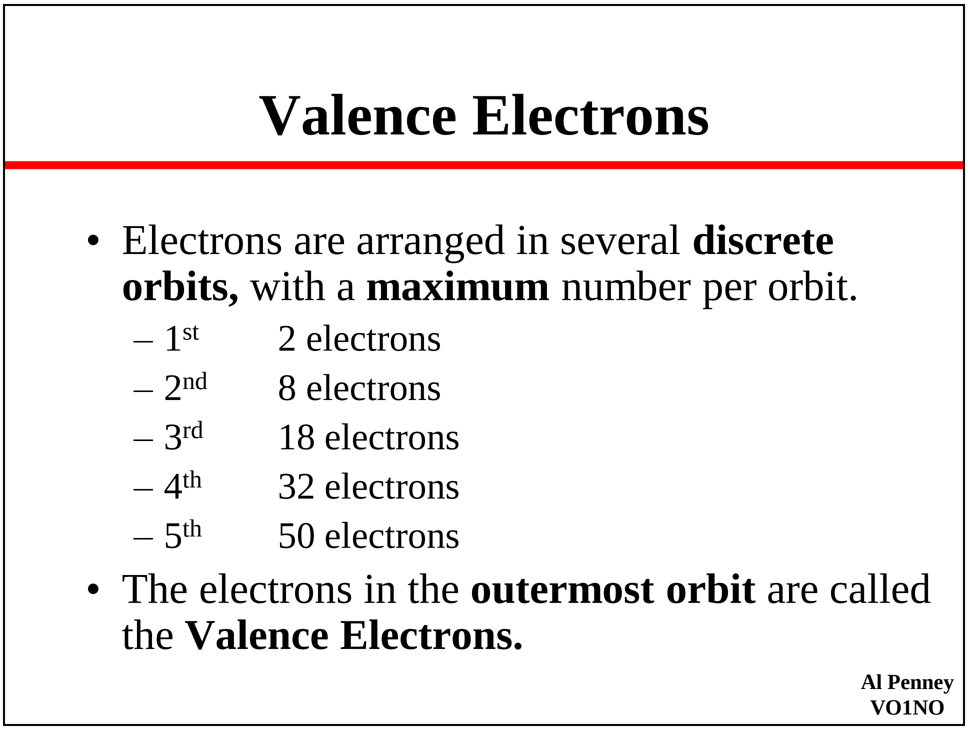
- **Protons** have a **Positive** charge.
- **Neutrons** are electrically **neutral.**
- **Electrons** have a **Negative** charge.
- Protons and Neutrons are about **1836 times heavier** than Electrons.

**Al Penney**
**VO1NO**

Electron is the lightest subatomic particle. It is negatively charged particle. Its mass is 9.109 × 10−31 kg which is only 1/1,840 the mass of a proton. An electron is therefore considered to be mass less in comparison with proton and neutron and is not included in calculating atomic mass of an atom. The electron was discovered in 1897 by British Physicist J.J. Thomson during his investigations of cathode rays.

Proton is a subatomic particle with a positive charge. It has a mass of 1.67262 × 10−27 kg which is 1,836 times of the mass of an electron. When the number of proton is equal to the number of electrons orbiting in nucleus we say that the atom is electrically neutral. Discovered in 1919/1920 by New Zealand physicist Ernest Rutherford, the ‘father of nuclear physics”.

Neutron is subatomic particle. Neutron does not have any charge, that is, it is neutral. Its mass is 1.67493 × 10−27 kg, greater than that of a proton and electron. Neutrons and protons are commonly called nucleons. The neutron was discovered in 1932 by the English physicist James Chadwick.



# Valence Electrons

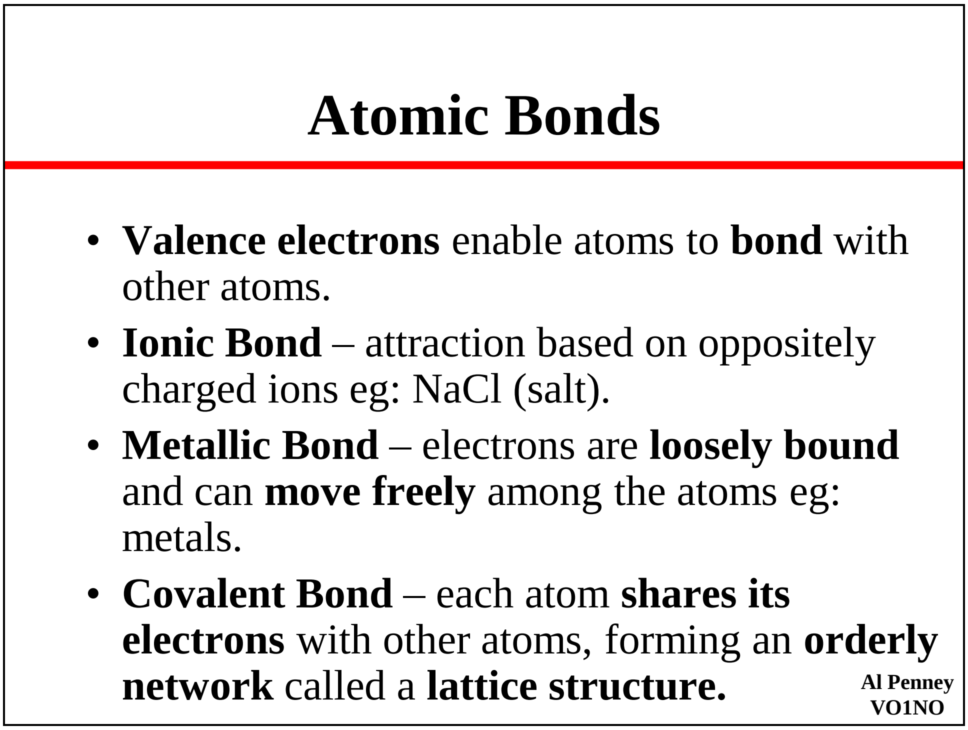
- Electrons are arranged in several **discrete orbits,** with a **maximum** number per orbit.
    - 1st 2 electrons
    - 2nd 8 electrons
    - 3rd 18 electrons
    - 4th 32 electrons
    - 5th 50 electrons
- The electrons in the **outermost orbit** are called the **Valence Electrons.**

**Al Penney**
**VO1NO**

In chemistry and physics, a **valence electron** is an outer shell electron that is associated with an atom, and **that can participate in the formation of a chemical bond if the outer shell is not closed**; in a single covalent bond, both atoms in the bond contribute one valence electron in order to form a shared pair. The presence of valence electrons can determine the element's chemical properties, such as its valence—whether it may bond with other elements and, if so, how readily and with how many. For a main group element, a valence electron can exist only in the outermost electron shell; in a transition metal, a valence electron can also be in an inner shell.

**An atom with a closed shell of valence electrons (corresponding to an electron configuration $s^2p^6$) tends to be chemically inert**. Atoms with one or two valence electrons more than a closed shell are highly reactive due to the relatively low energy to remove the extra valence electrons to form a positive ion. An atom with one or two electrons less than a closed shell is reactive due to its tendency either to gain the missing valence electrons and form a negative ion, or else to share valence electrons and form a covalent bond.

Similar to an electron in an inner shell, a valence electron has the ability to absorb or release energy in the form of a photon. An energy gain can trigger an electron to move (jump) to an outer shell; this is known as atomic excitation. Or the electron can even break free from its associated atom's valence shell; this is ionization to form a positive ion. When an electron loses energy (thereby causing a photon to be emitted), then it can move to an inner shell which is not fully occupied.



# Atomic Bonds

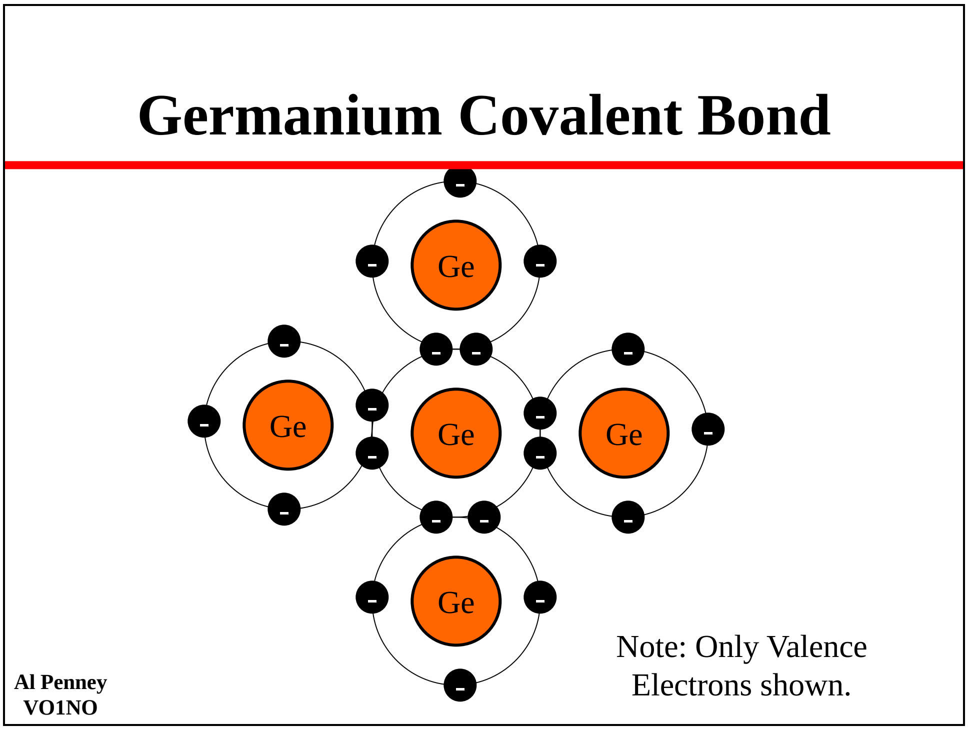
- **Valence electrons** enable atoms to **bond** with other atoms.
- **Ionic Bond** – attraction based on oppositely charged ions eg: NaCl (salt).
- **Metallic Bond** – electrons are **loosely bound** and can **move freely** among the atoms eg: metals.
- **Covalent Bond** – each atom **shares its electrons** with other atoms, forming an **orderly network** called a **lattice structure.**

**Al Penney**
**VO1NO**

**Ionic bonding** involves a transfer of an electron, so one atom gains an electron while one atom loses an electron. One of the resulting ions carries a negative charge (anion), and the other ion carries a positive charge (cation). Because opposite charges attract, the atoms bond together to form a molecule.

**Metallic bonds** are a metal, and share outer bonds with atoms in a solid. Each atom gives off a positive charge by shedding its outer electrons, and the negatively charges electrons hold the metal atoms together.

The **covalent bond** involves the sharing of electrons between two atoms. The pair of shared electrons forms a new orbit that extends around the nuclei of both atoms, producing a molecule.



# Germanium Covalent Bond

Note: Only Valence Electrons shown.

**Al Penney**
**VO1NO**

## Covalent bonding in germanium

The outermost orbit of germanium has only four electrons. Germanium atom needs four more electrons to become most stable. Germanium atom forms four covalent bonds with the four neighboring atoms. In covalent bonding each valence electron is shared by two atoms. When germanium atoms comes close to each other each valence electron of atom is shared with the neighboring atom and each valence electron of neighboring atom is shared with this atom. Likewise each atom will share four valence electrons with the four neighboring atoms and four neighboring atoms will share each valence electron with this atom. Therefore, total eight electrons are shared.

# Conductivity of Materials

- **Conductivity** is a measure of a material's **ability to conduct electricity.**
- Good **Conductors** have a large number of **free electrons.**
- **Insulators** have atomic structures where the **electrons are tightly bound,** and **cannot** be used to **conduct electricity.**

**Al Penney**
**VO1NO**

In a conductor, electric current can flow freely, in an insulator it cannot. Metals such as copper typify conductors, while most non-metallic solids are said to be good insulators, having extremely high resistance to the flow of charge through them. "Conductor" implies that the outer electrons of the atoms are loosely bound and free to move through the material. Most atoms hold on to their electrons tightly and are insulators. In copper, the valence electrons are essentially free and strongly repel each other. Any external influence which moves one of them will cause a repulsion of other electrons which propagates, "domino fashion" through the conductor.

Simply stated, most metals are good electrical conductors, most nonmetals are not. Metals are also generally good heat conductors while nonmetals are not.

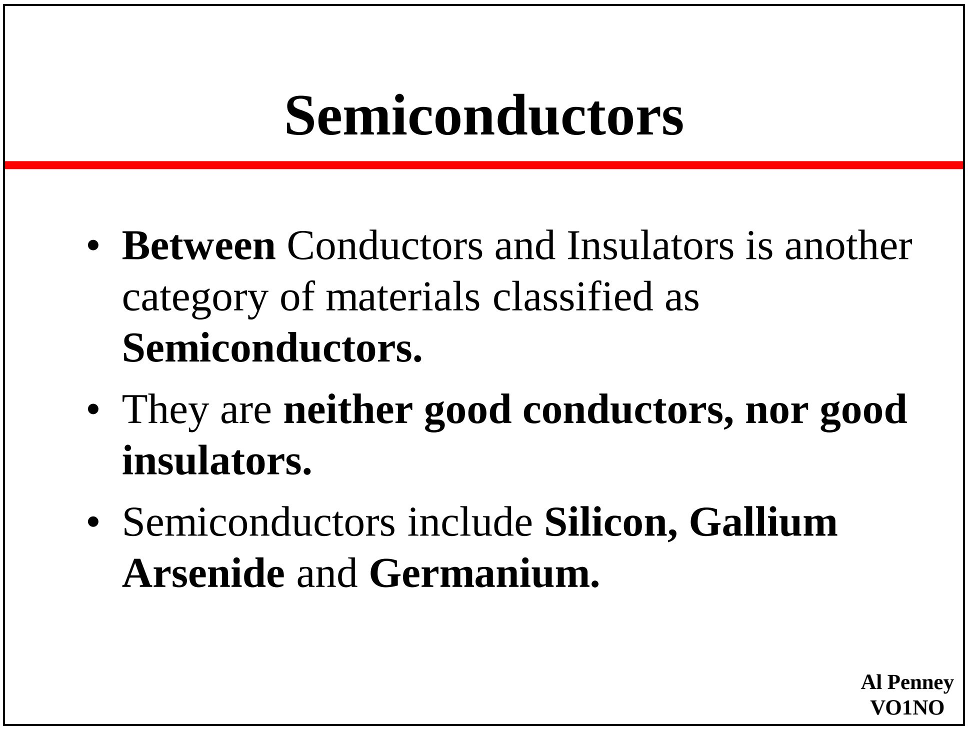
# Conductors

- **Metals** are good conductors.
- They include:
  - **Copper**
  - **Aluminum**
  - **Silver**
  - **Gold**

# Insulators

- **Insulators** include:
  - **Plastics**
  - **Rubber**
  - **Dry Wood**
  - **Porcelain**
  - **Dry Air**

**Al Penney**
**VO1NO**



# Semiconductors

- **Between** Conductors and Insulators is another category of materials classified as **Semiconductors.**
- They are **neither good conductors, nor good insulators.**
- Semiconductors include **Silicon, Gallium Arsenide** and **Germanium.**

**Al Penney**
**VO1NO**

A **semiconductor** material has an electrical conductivity value falling between that of a conductor, such as metallic copper, and an insulator, such as glass. **Its resistance falls as its temperature rises; metals are the opposite**. Its conducting properties may be altered in useful ways by introducing impurities ("doping") into the crystal structure. When two differently-doped regions exist in the same crystal, a semiconductor junction is created. The behavior of charge carriers, which include electrons, ions and electron holes, at these junctions is the basis of diodes, transistors and all modern electronics. Some examples of semiconductors are silicon, germanium, gallium arsenide, and elements near the so-called "metalloid staircase" on the periodic table. After silicon, **gallium arsenide** is the second most common semiconductor and is used in laser diodes, solar cells, microwave-frequency integrated circuits and others. Silicon is a critical element for fabricating most electronic circuits.

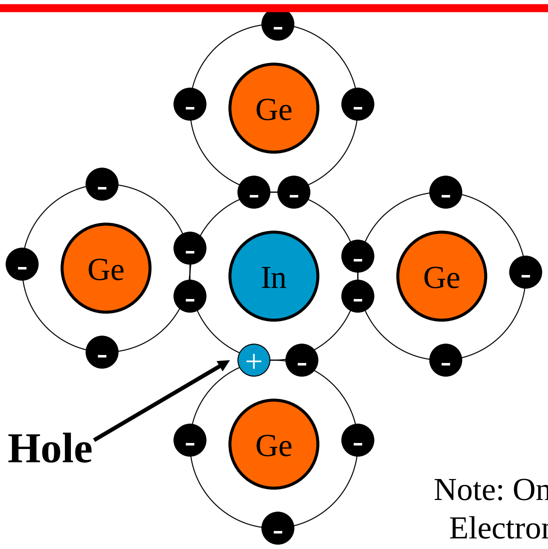
Semiconductor devices can display a range of useful properties, such as passing current more easily in one direction than the other, showing variable resistance, and sensitivity to light or heat. Because the electrical properties of a semiconductor material can be modified by doping, or by the application of electrical fields or light, devices made from semiconductors can be used for amplification, switching, and energy conversion.

# Doping Semiconductors

- Ordinarily, semiconductors are poor conductors.
- When certain **impurities** are added however, their **conductivity improves.**
- The process of **adding impurities** is called **Doping.**
- Depending on the dopant, an **extra electron**, or a **Hole** (“missing” electron) can be added to the lattice structure.

**Al Penney**
**VO1NO**

# Germanium with Indium Doping



Note: Only Valence
Electrons shown.

**Al Penney**
**VO1NO**

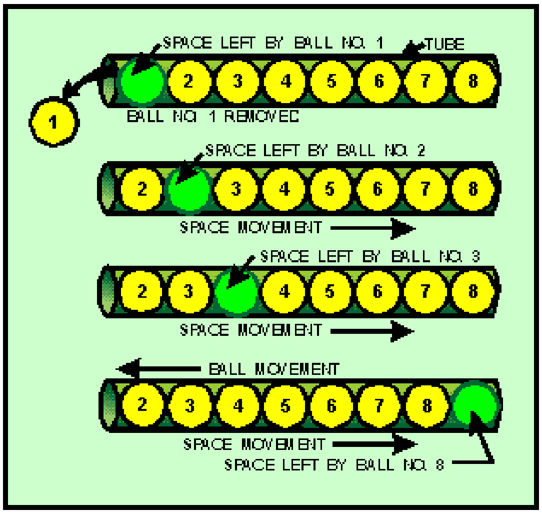
Indium has 3 valence electrons. When germanium is doped with indium, there are 7 electrons in the outermost orbit. Therefore, a “hole”, or missing electron, is created.

# P-Type Material

- The **absence of an electron** creates a **“hole”.**
- The **motion of this hole (Majority Carrier)** will support the **conduction of electricity,** as electrons are displaced to fill the hole.
- Because the conduction of electricity is primarily supported by **positive holes,** substances like this are called **P-Type material.**
- There are still some free electrons available for conducting electricity **(Minority Carrier).**

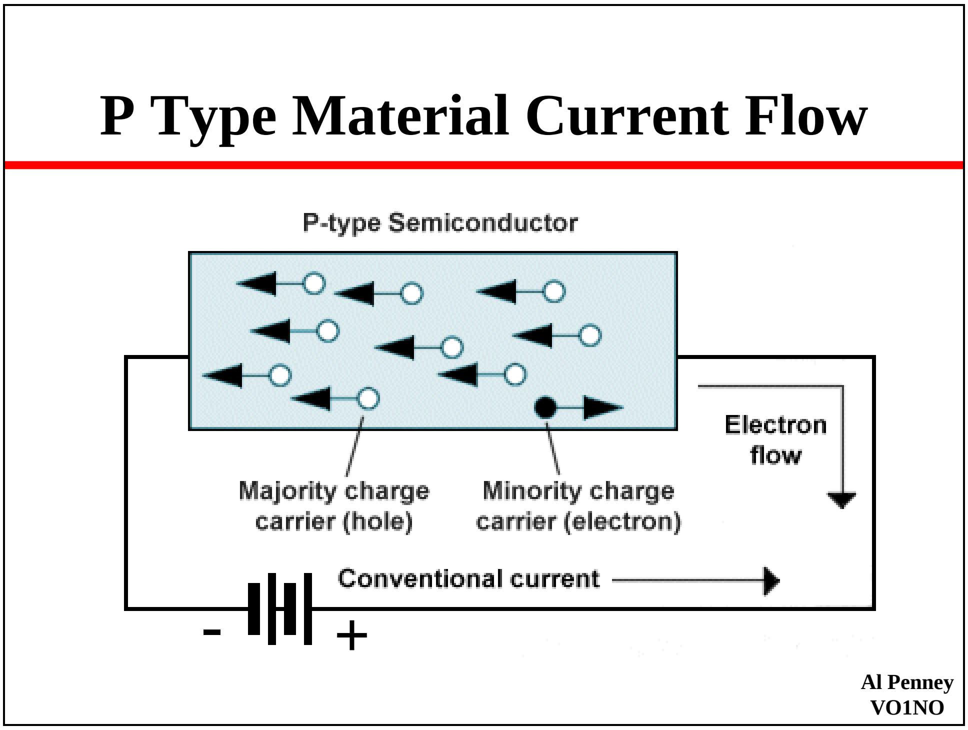
**Al Penney**
**VO1NO**

# Conduction with Holes



**Al Penney**
**VO1NO**

Like the lineup at the liquor store during COVID-19!



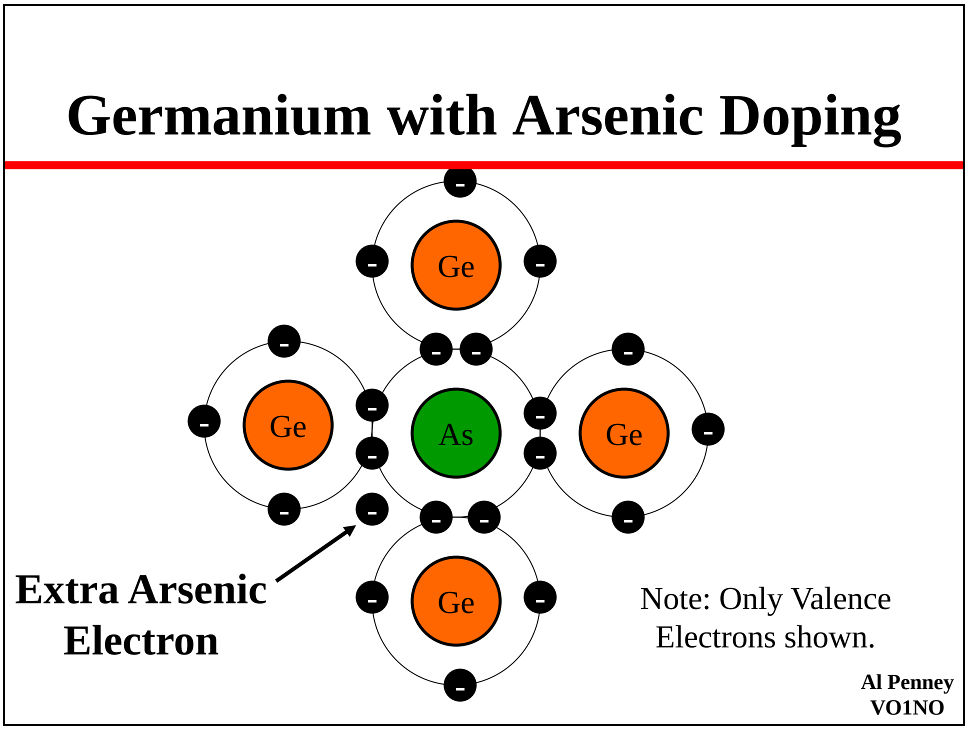
# P Type Material Current Flow

Al Penney
VO1NO

Current Flow in the P-Type Material

Current flow through the P-type material is illustrated in figure 1-16. Conduction in the P material is by positive holes, instead of negative electrons. A hole moves from the positive terminal of the P material to the negative terminal. Electrons from the external circuit enter the negative terminal of the material and fill holes in the vicinity of this terminal. At the positive terminal, electrons are removed from the covalent bonds, thus creating new holes. This process continues as the steady stream of holes (hole current) moves toward the negative terminal.

Notice in both N-type and P-type materials, current flow in the external circuit consists of electrons moving out of the negative terminal of the battery and into the positive terminal of the battery. Hole flow, on the other hand, only exists within the material itself.



## Germanium with Arsenic Doping

**Extra Arsenic Electron**

Note: Only Valence Electrons shown.

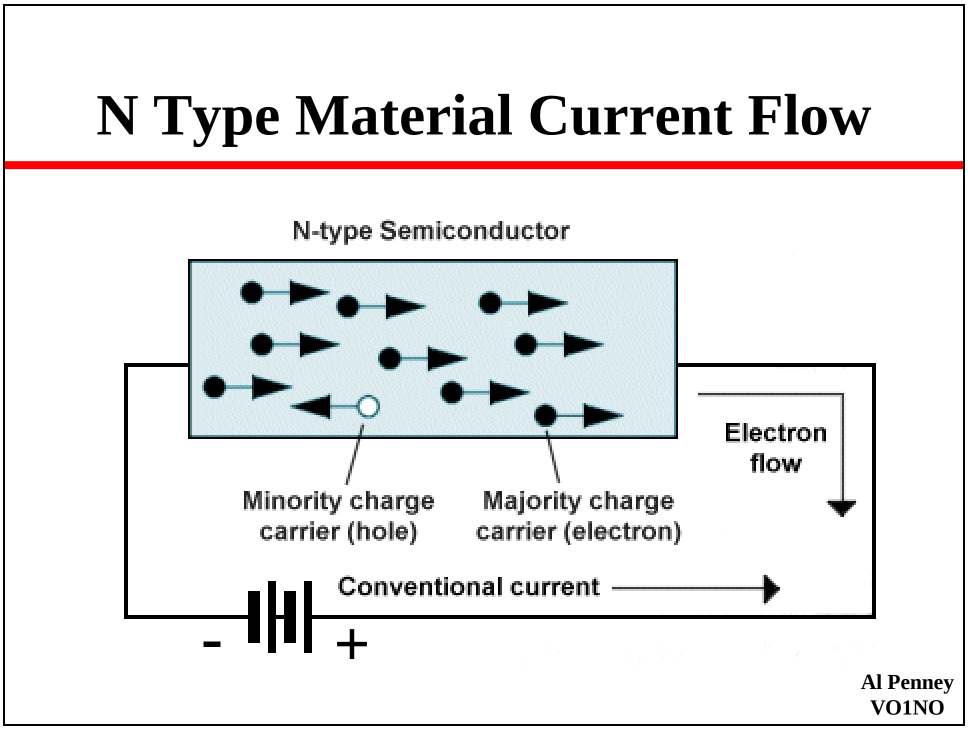
**Al Penney**
**VO1NO**

Arsenic has 5 electrons in its outermost orbit.

# N-Type Material

- Because there are **“extra” electrons** that are not part of the covalent bonds, conduction of electricity is primarily through the **movement of these electrons (Majority Carriers).**
- Because **electrons** have a **negative charge,** these substances are called **N-Type**.
- There are still some holes available in N-Type material **(Minority Carriers).**

**Al Penney**
**VO1NO**



# N Type Material Current Flow

Al Penney
VO1NO

Current Flow in the N-Type Material

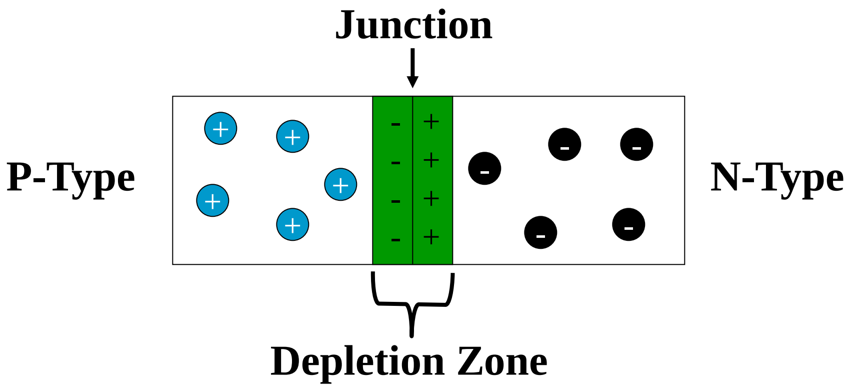
Conduction in the N-type semiconductor, or crystal, is similar to conduction in a copper wire. That is, with voltage applied across the material, electrons will move through the crystal just as current would flow in a copper wire. This is shown in figure 1-15. The positive potential of the battery will attract the free electrons in the crystal. These electrons will leave the crystal and flow into the positive terminal of the battery. As an electron leaves the crystal, an electron from the negative terminal of the battery will enter the crystal, thus completing the current path. Therefore, the majority current carriers in the N-type material (electrons) are repelled by the negative side of the battery and move through the crystal toward the positive side of the battery.

# P-N Junction

- When P-type and N-type material are placed together, **electrons** and **holes** near the boundary **recombine.**
- This creates a region with **negatively charged atoms in the P-type** material, and **positively charged atoms in the N-type material.**
- This is called the **Depletion Zone,** because there is a lack of holes and electrons.
- It is very thin – approximately 0.01 mm thick.

**Al Penney**
**VO1NO**

# Junction Barrier



Junction

P-Type

N-Type

Depletion Zone

Al Penney
VO1NO

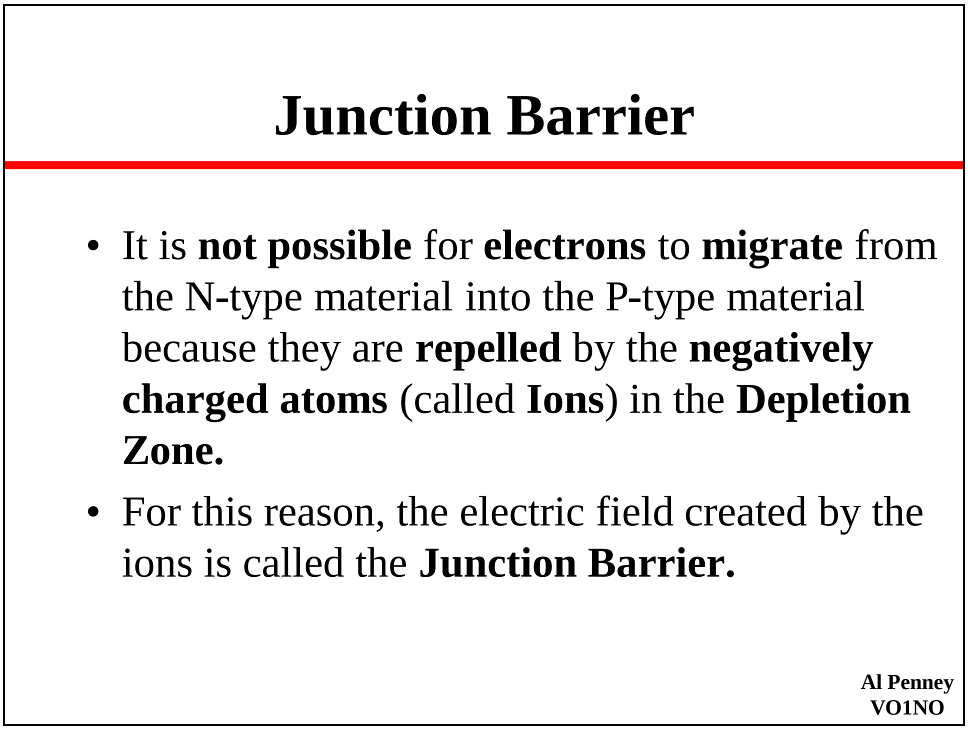
When the N-type semiconductor and P-type semiconductor materials are first joined together a very large density gradient exists between both sides of the PN junction. The result is that some of the free electrons from the donor impurity atoms begin to migrate across this newly formed junction to fill up the holes in the P-type material producing negative ions.

However, because the electrons have moved across the PN junction from the N-type silicon to the P-type silicon, they leave behind positively charged donor ions ( $N_D$ ) on the negative side and now the holes from the acceptor impurity migrate across the junction in the opposite direction into the region where there are large numbers of free electrons.

As a result, the charge density of the P-type along the junction is filled with negatively charged acceptor ions ( $N_A$ ), and the charge density of the N-type along the junction becomes positive. This charge transfer of electrons and holes across the PN junction is known as **diffusion**. The width of these P and N layers depends on how heavily each side is doped with acceptor density $N_A$, and donor density $N_D$, respectively.

This process continues back and forth until the number of electrons which have crossed the junction have a large enough electrical charge to repel or prevent any more charge carriers from crossing over the junction. Eventually a state of equilibrium (electrically neutral situation) will occur producing a “potential barrier” zone around the area of the junction as the donor atoms repel the holes and the acceptor atoms repel the electrons.

Since no free charge carriers can rest in a position where there is a potential barrier, the regions on either sides of the junction now become completely depleted of any more free carriers in comparison to the N and P type materials further away from the junction. This area around the **PN Junction** is now called the **Depletion Layer**.



# Junction Barrier

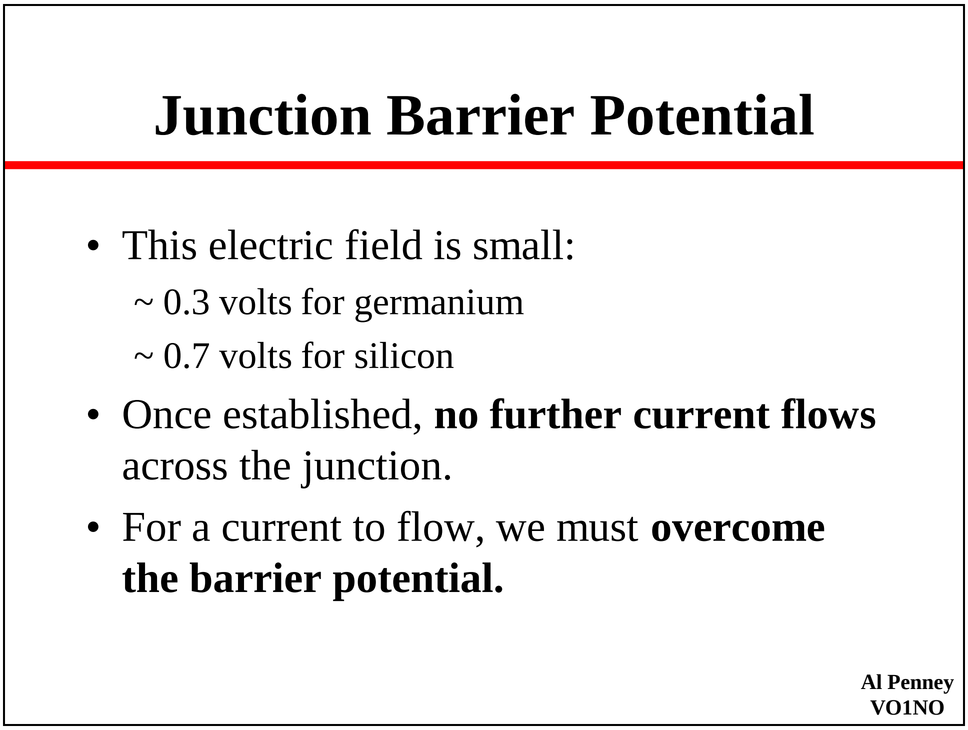
- It is **not possible** for **electrons** to **migrate** from the N-type material into the P-type material because they are **repelled** by the **negatively charged atoms** (called **Ions**) in the **Depletion Zone.**
- For this reason, the electric field created by the ions is called the **Junction Barrier.**

**Al Penney**
**VO1NO**

A suitable positive voltage (forward bias) applied between the two ends of the PN junction can supply the free electrons and holes with the extra energy. The external voltage required to overcome this potential barrier that now exists is very much dependent upon the type of semiconductor material used and its actual temperature.

Typically at room temperature the voltage across the depletion layer for silicon is about 0.6 – 0.7 volts and for germanium is about 0.3 – 0.35 volts. This potential barrier will always exist even if the device is not connected to any external power source, as seen in diodes.

The significance of this built-in potential across the junction, is that it opposes both the flow of holes and electrons across the junction and is why it is called the potential barrier. In practice, a **PN junction** is formed within a single crystal of material rather than just simply joining or fusing together two separate pieces.



# Junction Barrier Potential

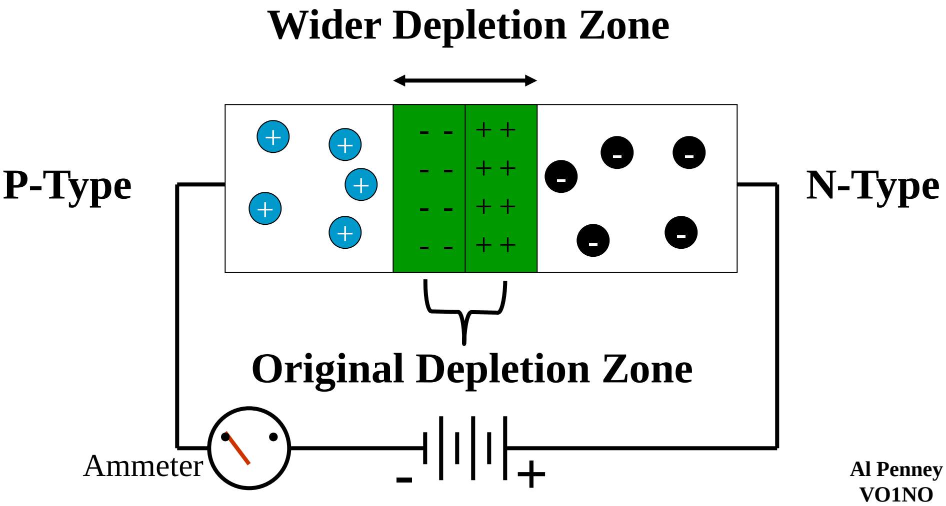
- This electric field is small:
  - ~ 0.3 volts for germanium
  - ~ 0.7 volts for silicon
- Once established, **no further current flows** across the junction.
- For a current to flow, we must **overcome the barrier potential.**

**Al Penney**
**VO1NO**

After joining p-type and n-type semiconductors, electrons from the n region near the p–n interface tend to diffuse into the p region. As electrons diffuse, they leave positively charged ions (donors) in the n region. Likewise, holes from the p-type region near the p–n interface begin to diffuse into the n-type region, leaving fixed ions (acceptors) with negative charge. The regions nearby the p–n interfaces lose their neutrality and become charged, forming the space charge region or depletion layer.

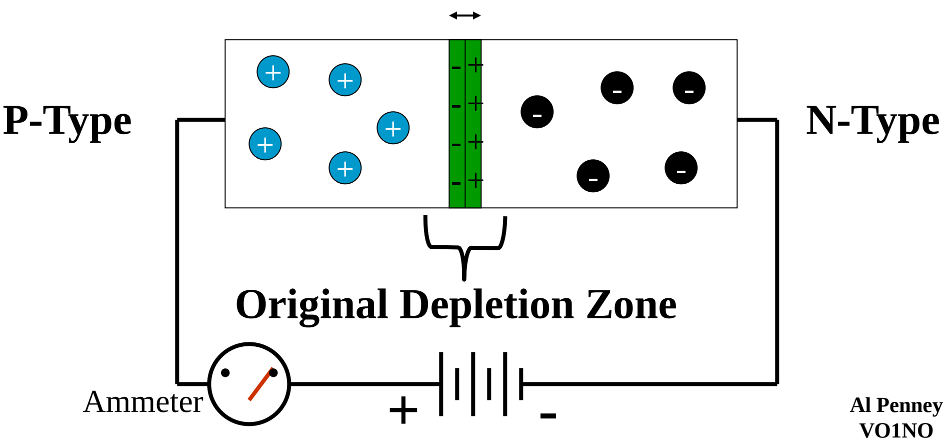
The electric field created by the space charge region opposes the diffusion process for both electrons and holes. There are two concurrent phenomena: the diffusion process that tends to generate more space charge, and the electric field generated by the space charge that tends to counteract the diffusion. The carrier concentration profile at equilibrium is shown in figure A with blue and red lines. Also shown are the two counterbalancing phenomena that establish equilibrium.

# Reverse-Biased Junction Barrier



Al Penney
VO1NO

# Forward-Biased Junction Barrier



Narrower Depletion Zone

P-Type

N-Type

Original Depletion Zone

Ammeter

+

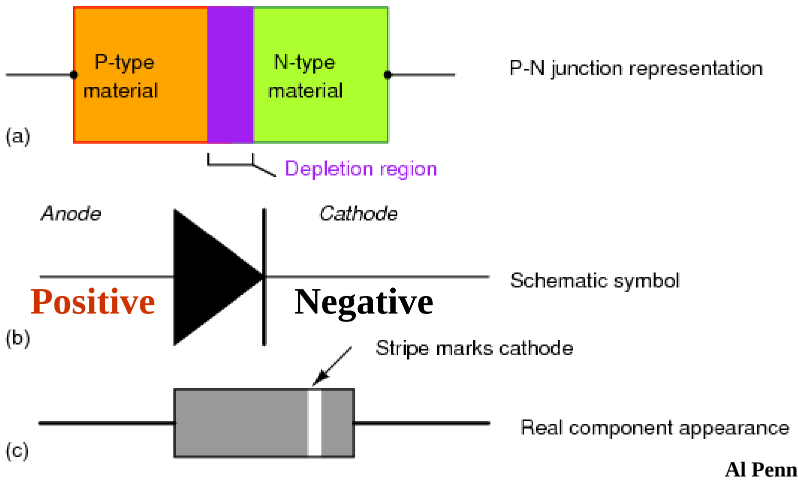
-

**Al Penney**
**VO1NO**

# Diodes

- A **PN junction** allows current to flow in **one direction** only.
- This forms a **diode**.
- Used to **rectify AC** and **demodulate AM** transmissions among other things.

# Diode Symbol



(a)

P-type material

N-type material

Depletion region

P-N junction representation

(b)

*Anode*

*Cathode*

**Positive**

**Negative**

Schematic symbol

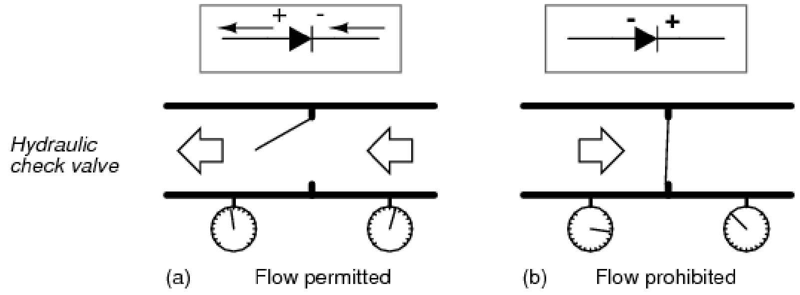
Stripe marks cathode

(c)

Real component appearance

**Al Penney**
**VO1NO**

# Valve Equivalent of Diodes

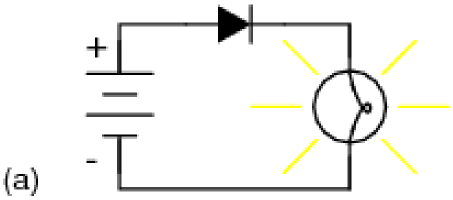


**Note: This illustrates electron flow, not conventional current**

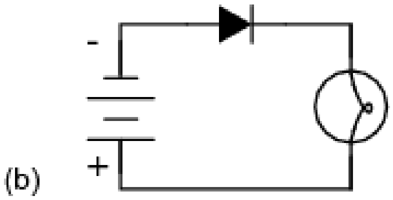
Hydraulic check valve analogy: (a) Current flow permitted. (b) Current flow prohibited.

Check valves are essentially pressure-operated devices: they open and allow flow if the pressure across them is of the correct “polarity” to open the gate (in the analogy shown, greater fluid pressure on the right than on the left). If the pressure is of the opposite “polarity,” the pressure difference across the check valve will close and hold the gate so that no flow occurs.

# Biasing

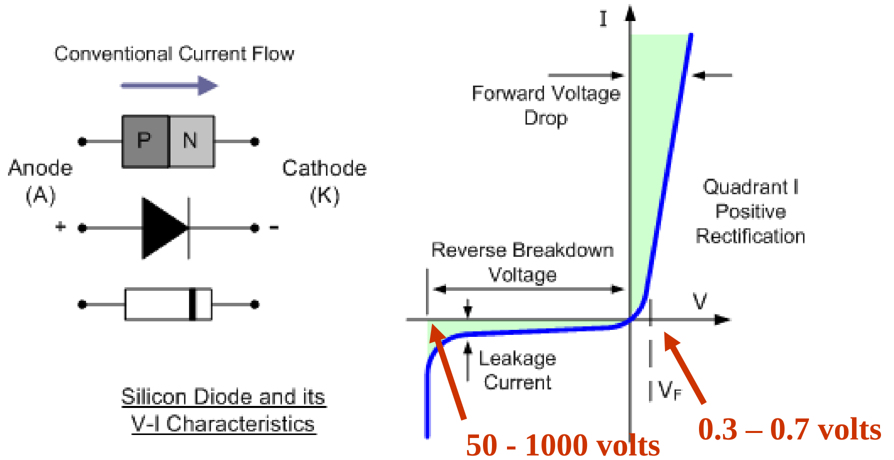


**Forward Biased**



**Reverse Biased**

# Diode Voltages



**50 - 1000 volts or more.**

**0.3 – 0.7 volts**

**Al Penney**
**VO1NO**

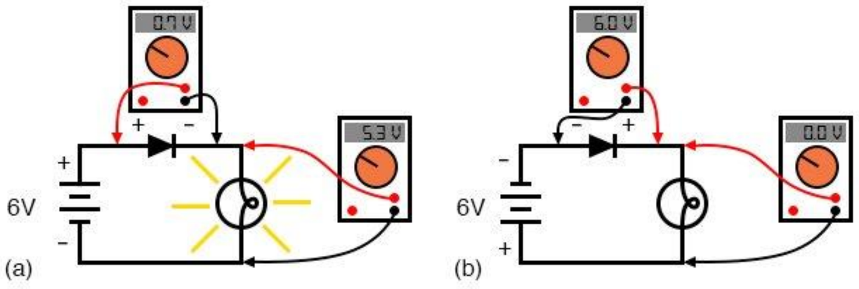
•Germanium Signal Diodes - These have a low reverse resistance value giving a lower forward volt drop across the junction, typically only about 0.2-0.3v, but have a higher forward resistance value because of their small junction area.

•

•Silicon Signal Diodes - These have a very high value of reverse resistance and give a forward volt drop of about 0.6-0.7v across the junction. They have fairly low values of forward resistance giving them high peak values of forward current and reverse voltage.

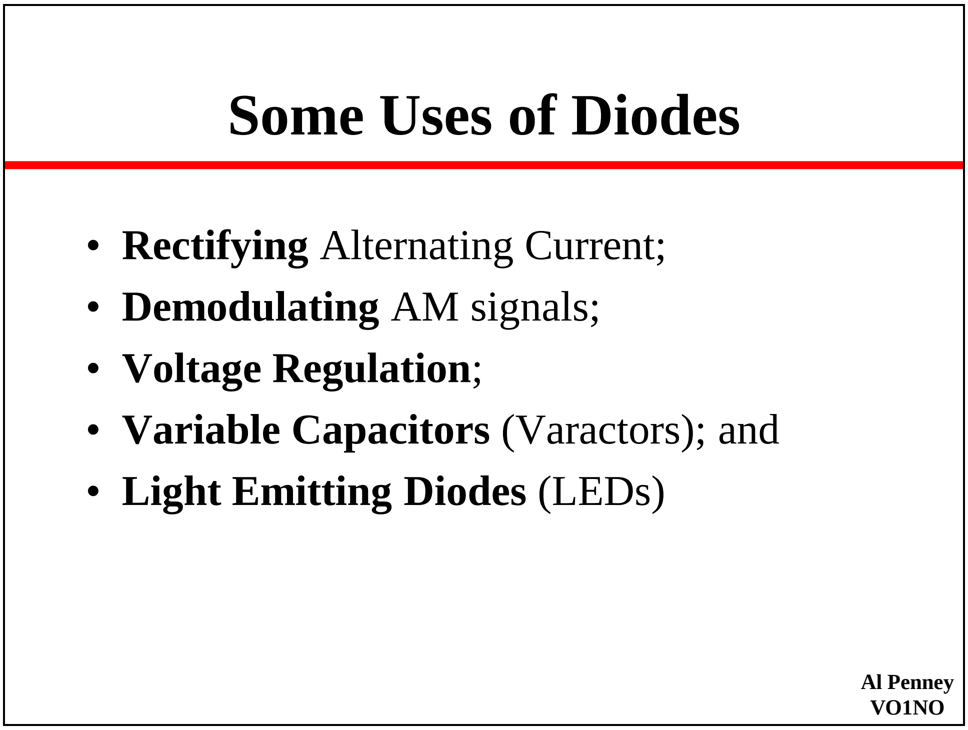
•At very large reverse bias, beyond the peak inverse voltage or PIV, a process called reverse breakdown occurs that causes a large increase in current (i.e., a large number of electrons and holes are created at, and move away from the p–n junction) that usually damages the device permanently. The avalanche diode is deliberately designed for use in the avalanche region.

# Diode Voltage Drop



Like check valves, diodes are essentially “pressure” operated (voltage-operated) devices. The essential difference between forward-bias and reverse-bias is the polarity of the voltage dropped across the diode. Let’s take a closer look at the simple battery-diode-lamp circuit shown earlier, this time investigating voltage drops across the various components in the figure below.

A forward-biased diode conducts current and drops a small voltage across it, leaving most of the battery voltage dropped across the lamp. If the battery’s polarity is reversed, the diode becomes reverse-biased, and drops *all* of the battery’s voltage leaving none for the lamp. If we consider the diode to be a self-actuating switch (closed in the forward-bias mode and open in the reverse-bias mode), this behavior makes sense. The most substantial difference is that the diode drops a lot more voltage when conducting than the average mechanical switch (0.7 volts versus tens of millivolts).



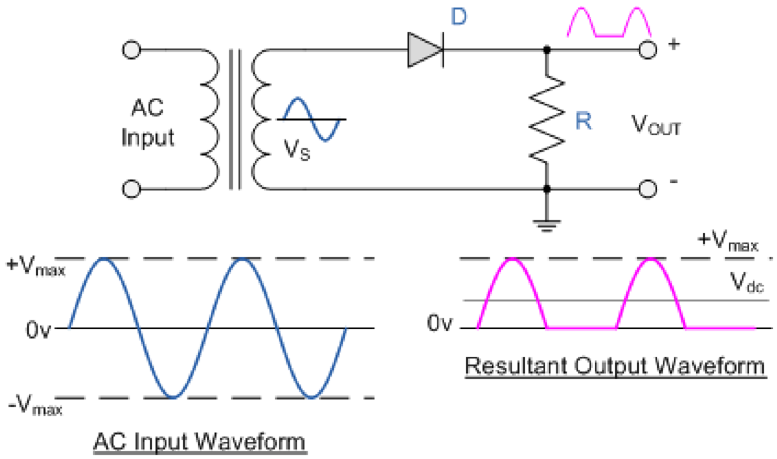
# Some Uses of Diodes

- **Rectifying** Alternating Current;
- **Demodulating** AM signals;
- **Voltage Regulation**;
- **Variable Capacitors** (Varactors); and
- **Light Emitting Diodes** (LEDs)

**Al Penney**
**VO1NO**

The most common function of a diode is to allow an electric current to pass in one direction (called the diode's *forward* direction), while blocking it in the opposite direction (the *reverse* direction). As such, the diode can be viewed as an electronic version of a check valve. This unidirectional behavior is called rectification, and is used to convert alternating current (ac) to direct current (dc). Forms of rectifiers, diodes can be used for such tasks as extracting modulation from radio signals in radio receivers.

# Diodes in Half Wave Rectifiers

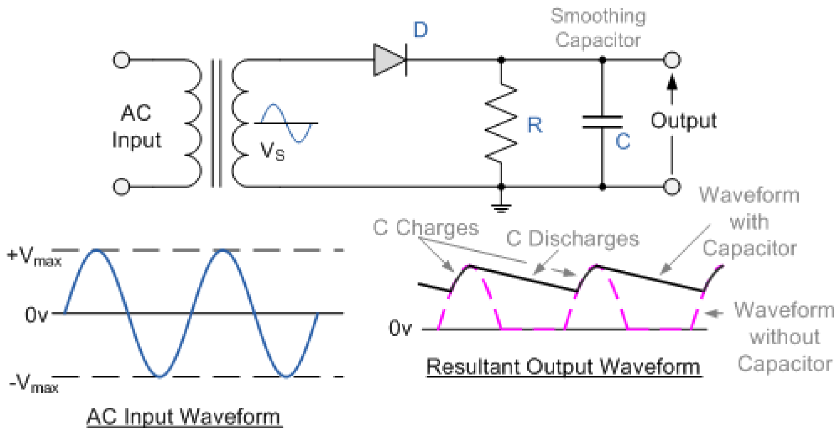


Al Penney
VO1NO

A **rectifier** is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. The process is known as *rectification*, since it "straightens" the direction of current.

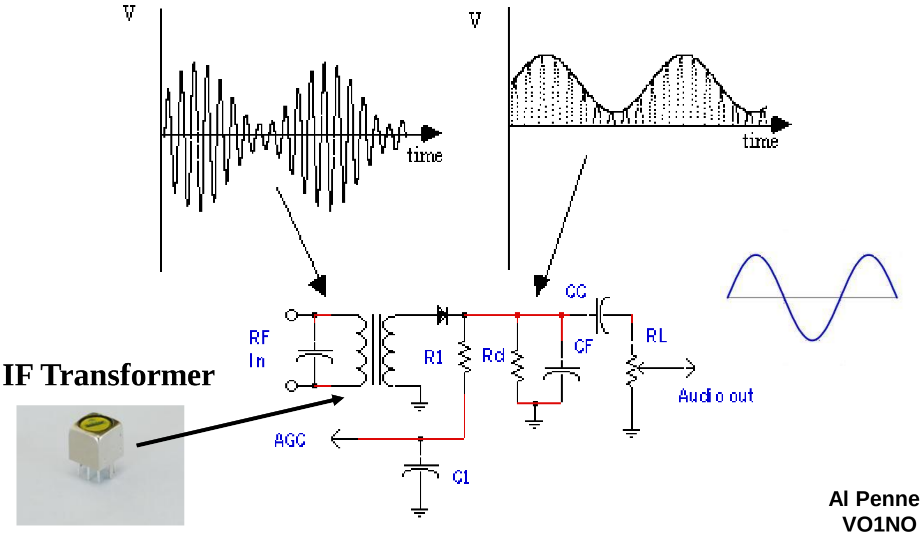
Rectifiers have many uses, but are often found serving as components of DC power supplies and high-voltage direct current power transmission systems. Rectification may serve in roles other than to generate direct current for use as a source of power

# Half Wave Rectifier with a Capacitor



**Al Penney**
**VO1NO**

# AM Demodulation



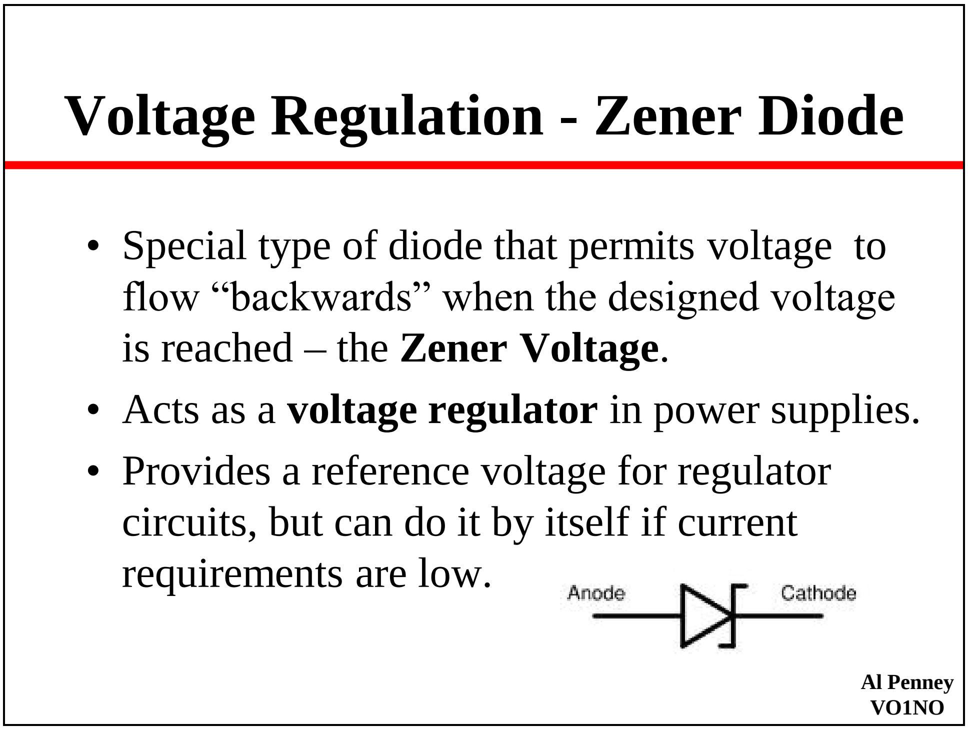
**IF Transformer**

**Al Penney**
**VO1NO**

An ideal diode conducts only during alternate half cycles of the input signal, and during the conducting half cycles the output current is proportional to the input voltage. An AM signal, applied to a diode detector as shown in figure 1, reproduce the modulating (audio) signal by mixing the AM sidebands with the AM carrier. It may be seen from figure 1 that the peak amplitude of each current pulse in the output is proportional to the peak amplitude of the input voltage during that particular conducting half cycle. Thus the peak, and therefore the average, values of the output current pulses follow the amplitude of the input voltage precisely during conducting half cycles and have the same waveform as the modulation envelope. Whether the output voltage would approach the peak or average value of the input voltage depends on the type of filter used in the output. If the filter is a bypass capacitor, and the internal resistance of the rectifier is small in comparison with the load resistance, then output voltage will tend to follow the peaks of the input voltage. Thus, the capacitor, CF, charges essentially to the peak input voltage during the conducting half cycles, but there is not time for appreciable discharge through the high resistance load during the non-conducting half cycles. If the bypass capacitor is too large, the time constant of the discharge will be so large that the detector output will not be able to follow the modulation envelope when the modulation envelope decreases amplitude rapidly.

In addition to detection, a circuit in figure 1 has been added which is called the automatic gain control (AGC). The AGC voltage is the average value of the detector output voltage since R1 and C1 act as a filter to remove the modulating signal as well as the RF from the AGC system. This AGC voltage is therefore proportional to the amplitude of the carrier in a continuous wave system and may be used to automatically control the gain of one or more RF amplifier stages. Thus for samll input signals the RF amplifier will have high gain, but as the magnitude of the input signal increases, the gain of the RF amplifier decreases. This effect tends to keep the detector output relatively constant and prevents overdriving the RF into the saturation or cutoff regions. AGC is effectively and easily applied to a dual-gate MOSFET in the RF stage.


Germanium Diode 1N60
GNU Free Documentation License



# Voltage Regulation - Zener Diode

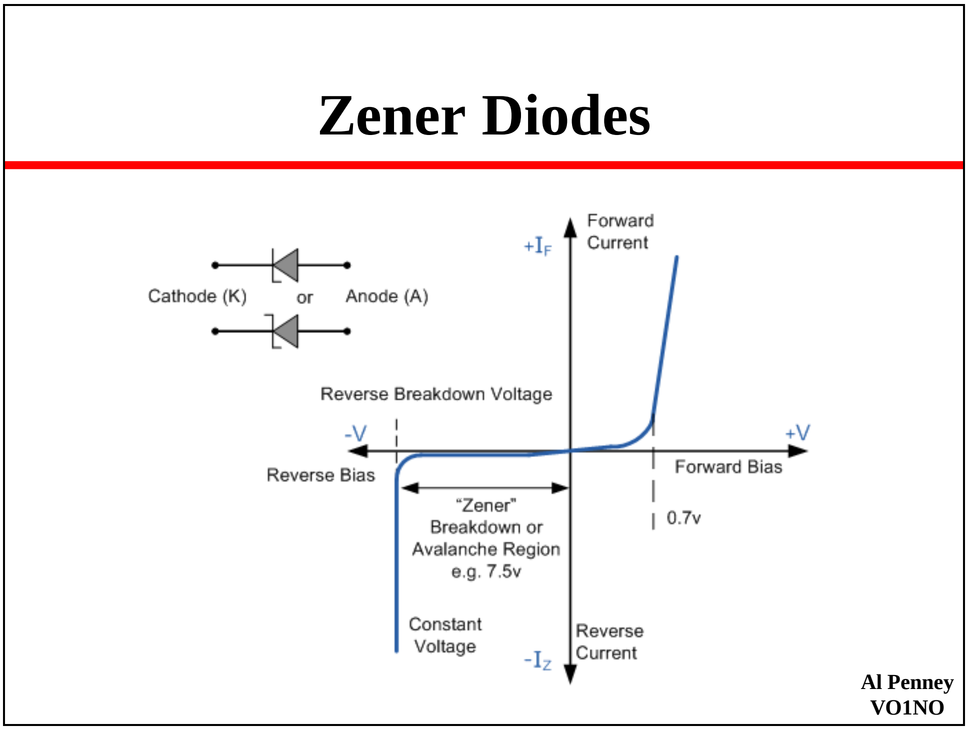
- Special type of diode that permits voltage to flow “backwards” when the designed voltage is reached – the **Zener Voltage**.
- Acts as a **voltage regulator** in power supplies.
- Provides a reference voltage for regulator circuits, but can do it by itself if current requirements are low.

**Al Penney**
**VO1NO**

A **Zener diode** is a special type of diode designed to reliably allow current to flow "backwards" when a certain set reverse voltage, known as the *Zener voltage*, is reached.

Zener diodes are manufactured with a great variety of Zener voltages and some are even variable. Some Zener diodes have a sharp, highly doped p–n junction with a low Zener voltage, in which case the reverse conduction occurs due to electron quantum tunnelling in the short space between p and n regions − this is known as the Zener effect, after Clarence Zener. Diodes with a higher Zener voltage have a more gradual junction and their mode of operation also involves avalanche breakdown. Both breakdown types are present in Zener diodes with the Zener effect predominating at lower voltages and avalanche breakdown at higher voltages.

Zener diodes are widely used in electronic equipment of all kinds and are one of the basic building blocks of electronic circuits. They are used to generate low-power stabilized supply rails from a higher voltage and to provide reference voltages for circuits, especially stabilized power supplies. They are also used to protect circuits from overvoltage, especially electrostatic discharge (ESD).



# Zener Diodes

**Al Penney**
**VO1NO**

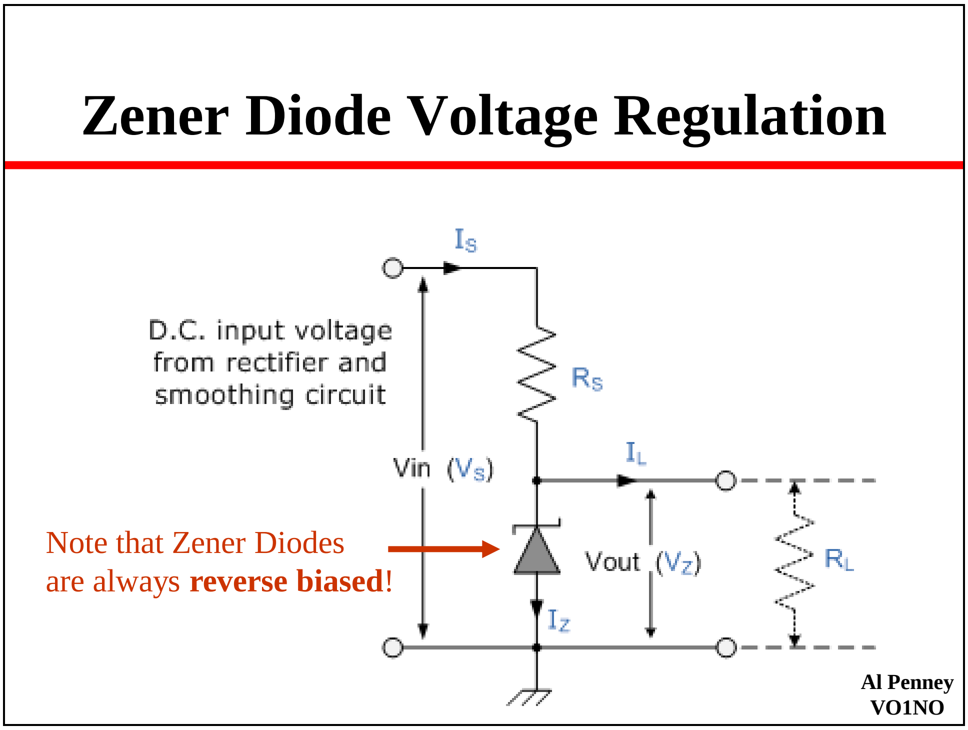
The **Zener diode** behaves just like a normal general-purpose diode consisting of a silicon PN junction and when biased in the forward direction, that is Anode positive with respect to its Cathode, it behaves just like a normal signal diode passing the rated current.

However, unlike a conventional diode that blocks any flow of current through itself when reverse biased, that is the Cathode becomes more positive than the Anode, as soon as the reverse voltage reaches a pre-determined value, the zener diode begins to conduct in the reverse direction.

This is because when the reverse voltage applied across the zener diode exceeds the rated voltage of the device a process called *Avalanche Breakdown* occurs in the semiconductor depletion layer and a current starts to flow through the diode to limit this increase in voltage.

The current now flowing through the zener diode increases dramatically to the maximum circuit value (which is usually limited by a series resistor) and once achieved, this reverse saturation current remains fairly constant over a wide range of reverse voltages. The voltage point at which the voltage across the zener diode becomes stable is called the "zener voltage", ( Vz ) and for zener diodes this voltage can range from less than one volt to a few hundred volts.

The point at which the zener voltage triggers the current to flow through the diode can be very accurately controlled (to less than 1% tolerance) in the doping stage of the diodes semiconductor construction giving the diode a specific *zener breakdown voltage*, ( Vz ) for example, 4.3V or 7.5V. This zener breakdown voltage on the I-V curve is almost a vertical straight line.



# Zener Diode Voltage Regulation

Note that Zener Diodes
are always **reverse biased**!

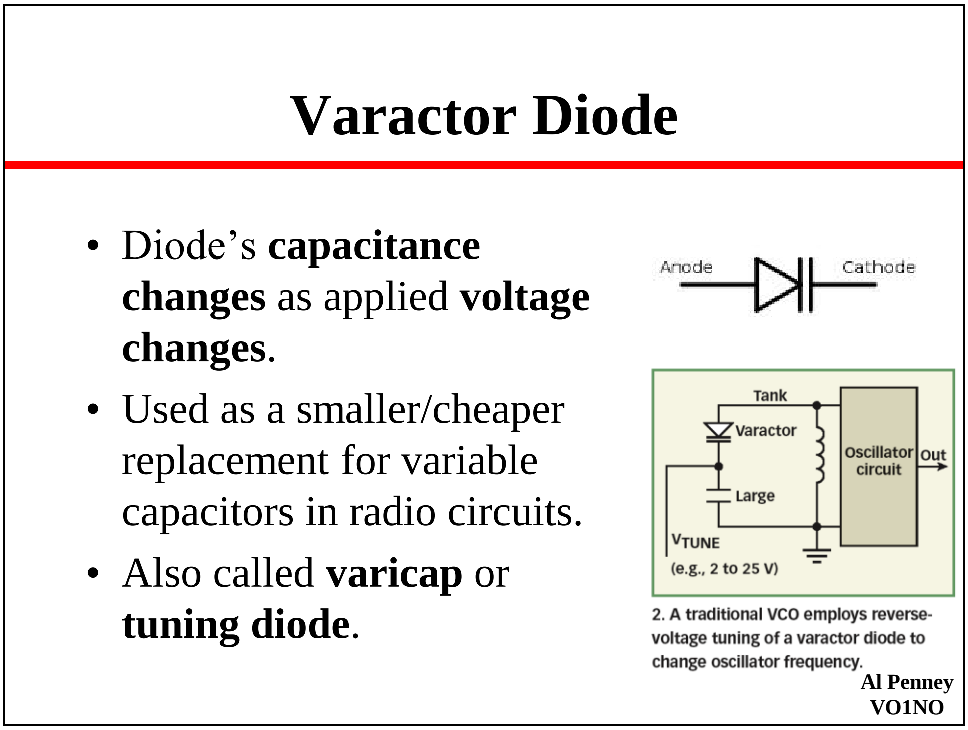
**Al Penney**
**VO1NO**

Resistor, $R_S$ is connected in series with the zener diode to limit the current flow through the diode with the voltage source, $V_S$ being connected across the combination. The stabilised output voltage $V_{out}$ is taken from across the zener diode.

The zener diode is connected with its cathode terminal connected to the positive rail of the DC supply so it is reverse biased and will be operating in its breakdown condition. Resistor $R_S$ is selected so to limit the maximum current flowing in the circuit.

With no load connected to the circuit, the load current will be zero, ( $I_L = 0$ ), and all the circuit current passes through the zener diode which in turn dissipates its maximum power. Also a small value of the series resistor $R_S$ will result in a greater diode current when the load resistance $R_L$ is connected and large as this will increase the power dissipation requirement of the diode so care must be taken when selecting the appropriate value of series resistance so that the zener's maximum power rating is not exceeded under this no-load or high-impedance condition.

The load is connected in parallel with the zener diode, so the voltage across $R_L$ is always the same as the zener voltage, ( $V_R = V_Z$ ). There is a minimum zener current for which the stabilisation of the voltage is effective and the zener current must stay above this value operating under load within its breakdown region at all times. The upper limit of current is of course dependant upon the power rating of the device. The supply voltage $V_S$ must be greater than $V_Z$.



# Varactor Diode

- Diode’s **capacitance changes** as applied **voltage changes**.
- Used as a smaller/cheaper replacement for variable capacitors in radio circuits.
- Also called **varicap** or **tuning diode**.

2. A traditional VCO employs reverse-voltage tuning of a varactor diode to change oscillator frequency.

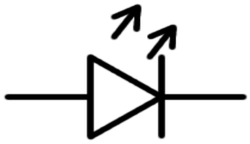
**Al Penney**
**VO1NO**

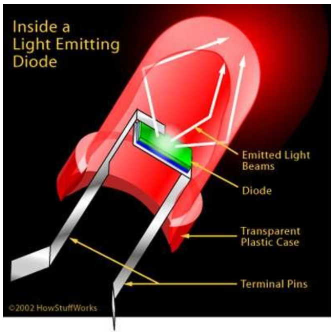
Varicap  or varactor diodes

These are used as voltage-controlled capacitors. These are important in PLL (phase-locked loop) and FLL (frequency-locked loop) circuits, allowing tuning circuits, such as those in television receivers, to lock quickly. They also enabled tunable oscillators in early discrete tuning of radios, where a cheap and stable, but fixed-frequency, crystal oscillator provided the reference frequency for a voltage-controlled oscillator.

# Light Emitting Diode (LED)

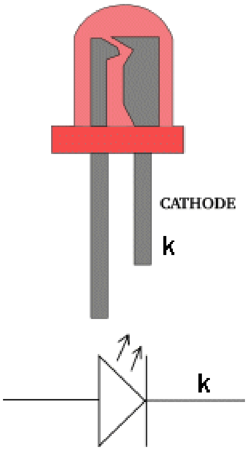
- When forward biased, LEDs emit red, yellow, green or white light depending on composition of the diode.





A **light-emitting diode** (**LED**) is a semiconductor light source that emits light when current flows through it. Electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons. The color of the light (corresponding to the energy of the photons) is determined by the energy required for electrons to cross the band gap of the semiconductor. White light is obtained by using multiple semiconductors or a layer of light-emitting phosphor on the semiconductor device.

# Light Emitting Diode (LED)



**Al Penney**
**VO1NO**

Appearing as practical electronic components in 1962, the earliest LEDs emitted low-intensity infrared (IR) light. Infrared LEDs are used in remote-control circuits, such as those used with a wide variety of consumer electronics. The first visible-light LEDs were of low intensity and limited to red. Modern LEDs are available across the visible, ultraviolet (UV), and infrared wavelengths, with high light output.

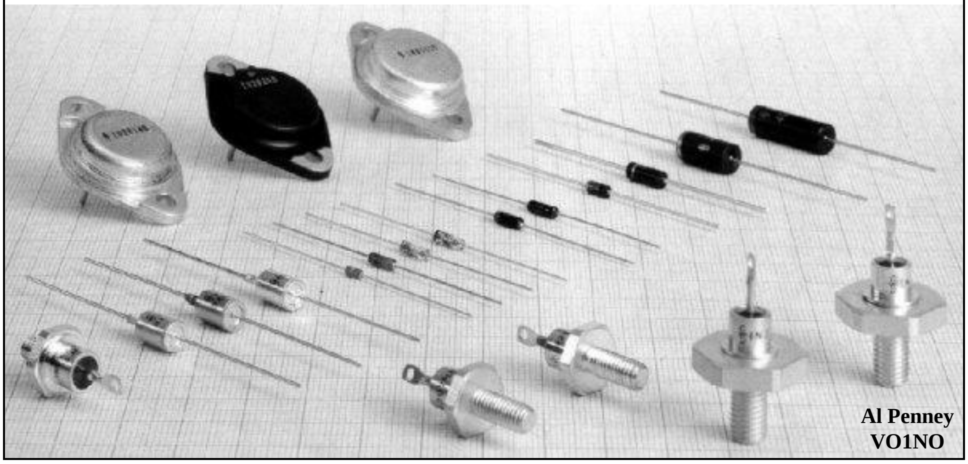
Early LEDs were often used as indicator lamps, replacing small incandescent bulbs, and in seven-segment displays. Recent developments have produced high-output white light LEDs suitable for room and outdoor area lighting. LEDs have led to new displays and sensors, while their high switching rates are useful in advanced communications technology.

LEDs have many advantages over incandescent light sources, including lower energy consumption, longer lifetime, improved physical robustness, smaller size, and faster switching. LEDs are used in applications as diverse as aviation lighting, automotive headlamps, advertising, general lighting, traffic signals, camera flashes, lighted wallpaper, horticultural grow lights, and medical devices.

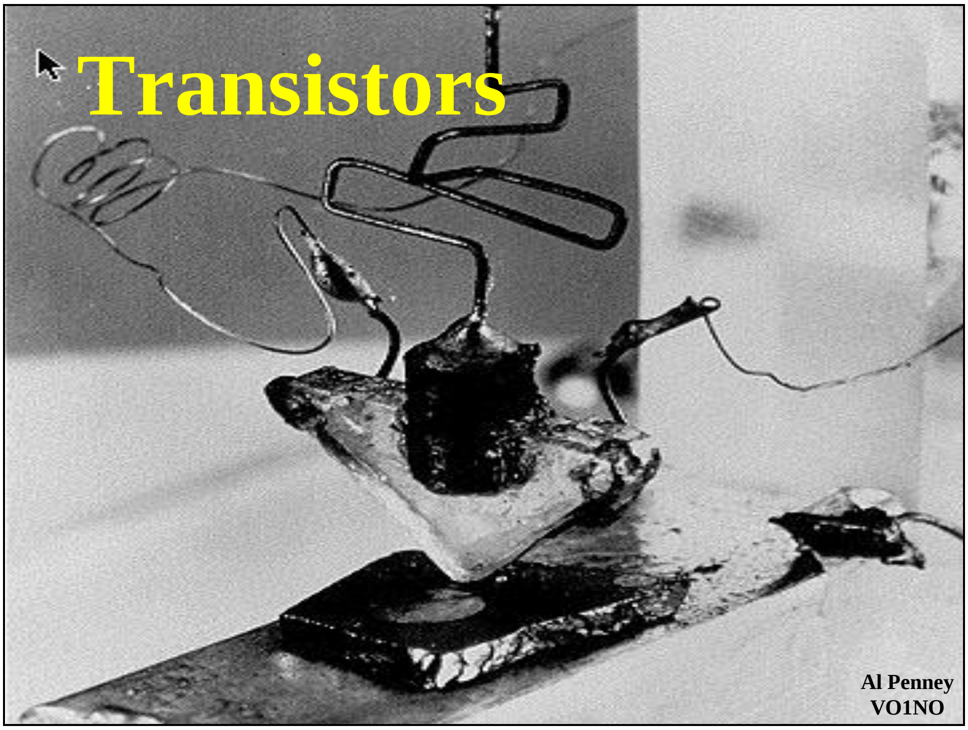
**Types of Diode**

**Al Penney**
**VO1NO**

# Questions?

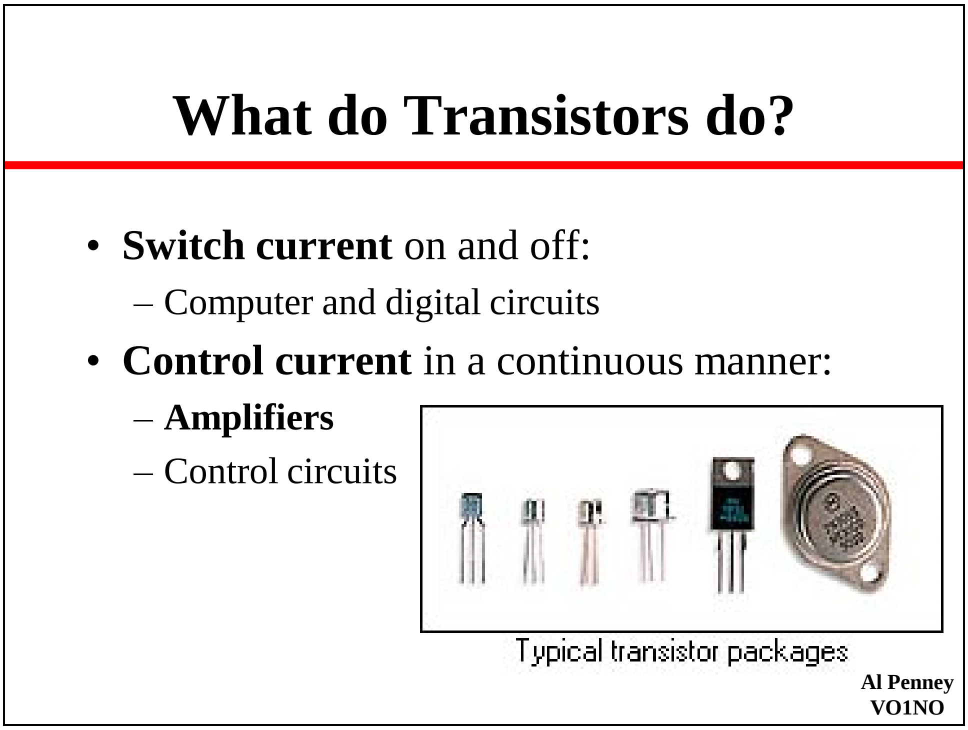


Al Penney
VO1NO



# Transistors

Al Penney
VO1NO



# What do Transistors do?

- **Switch current** on and off:
  - Computer and digital circuits
- **Control current** in a continuous manner:
  - **Amplifiers**
  - Control circuits

Typical transistor packages

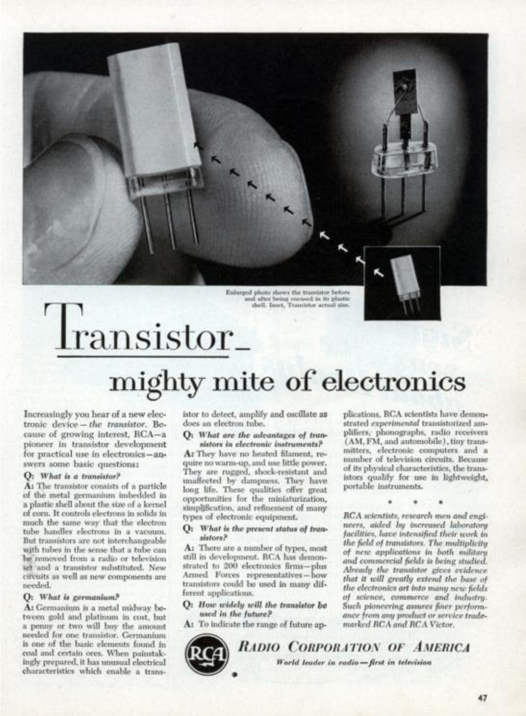
**Al Penney**
**VO1NO**

Transistors are at the very core of today's electronics technology. The development of the bipolar transistor or bipolar junction transistor, BJT, has resulted in many changes to the world.

The introduction of the bipolar transistor has enabled many technologies we take for granted today: everything from portable transistor radios, through to mobile phones, and computers, remote operation, the functionality we take for granted in current day automobiles, etc . . . . All these and many more everyday items have all been made possible by the invention of the transistor.

Transistors **amplify current**, for example they can be used to amplify the small output current from a logic IC so that it can operate a lamp, relay or other high current device. In many circuits a resistor is used to convert the changing current to a changing voltage, so the transistor is being used to **amplify voltage**.

A transistor may be used as a **switch** (either fully on with maximum current, or fully off with no current) and as an **amplifier** (always partly on).



Enlarged photo shows the transistor before and after being encased in its plastic shell. Inset, Transistor actual size.

# Transistor—
## mighty mite of electronics

Increasingly you hear of a new electronic device—*the transistor*. Because of growing interest, RCA—a pioneer in transistor development for practical use in electronics—answers some basic questions:

**Q:** ***What is a transistor?***

**A:** The transistor consists of a particle of the metal germanium imbedded in a plastic shell about the size of a kernel of corn. It controls electrons in solids in much the same way that the electron tube handles electrons in a vacuum. But transistors are not interchangeable with tubes in the sense that a tube can be removed from a radio or television set and a transistor substituted. New circuits as well as new components are needed.

**Q:** ***What is germanium?***

**A:** Germanium is a metal midway between gold and platinum in cost, but a penny or two will buy the amount needed for one transistor. Germanium is one of the basic elements found in coal and certain ores. When painstakingly prepared, it has unusual electrical characteristics which enable a transistor to detect, amplify and oscillate as does an electron tube.

**Q:** ***What are the advantages of transistors in electronic instruments?***

**A:** They have no heated filament, require no warm-up, and use little power. They are rugged, shock-resistant and unaffected by dampness. They have long life. These qualities offer great opportunities for the miniaturization, simplification, and refinement of many types of electronic equipment.

**Q:** ***What is the present status of transistors?***

**A:** There are a number of types, most still in development. RCA has demonstrated to 200 electronics firms—plus Armed Forces representatives—how transistors could be used in many different applications.

**Q:** ***How widely will the transistor be used in the future?***

**A:** To indicate the range of future applications, RCA scientists have demonstrated *experimental* transistorized amplifiers, phonographs, radio receivers (AM, FM, and automobile), tiny transmitters, electronic computers and a number of television circuits. Because of its physical characteristics, the transistors qualify for use in lightweight, portable instruments.

• • •

*RCA scientists, research men and engineers, aided by increased laboratory facilities, have intensified their work in the field of transistors. The multiplicity of new applications in both military and commercial fields is being studied. Already the transistor gives evidence that it will greatly extend the base of the electronics art into many new fields of science, commerce and industry. Such pioneering assures finer performance from any product or service trademarked RCA and RCA Victor.*

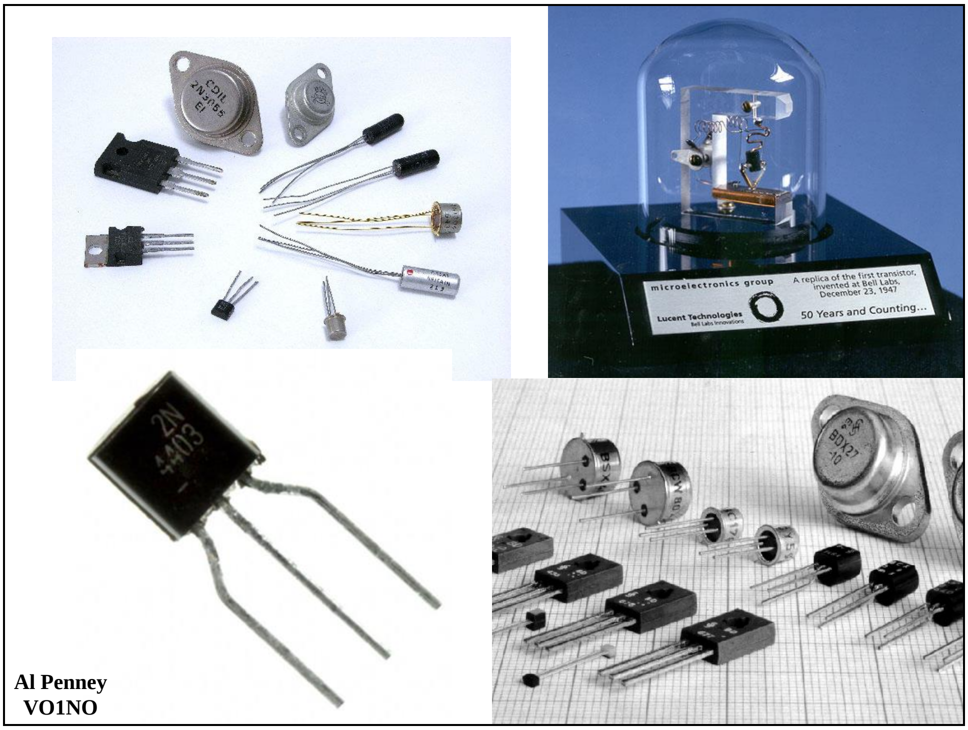
RADIO CORPORATION OF AMERICA

*World leader in radio—first in television*

47

**Al Penney**
**VO1NO**

From November 17, 1947, to December 23, 1947, John Bardeen and Walter Brattain at AT&T's Bell Labs in Murray Hill, New Jersey of the United States performed experiments and observed that when two gold point contacts were applied to a crystal of germanium, a signal was produced with the output power greater than the input. Solid State Physics Group leader William Shockley saw the potential in this, and over the next few months worked to greatly expand the knowledge of semiconductors. The term *transistor* was coined by John R. Pierce as a contraction of the term *transresistance*. According to Lillian Hoddeson and Vicki Daitch, authors of a biography of John Bardeen, Shockley had proposed that Bell Labs' first patent for a transistor should be based on the field-effect and that he be named as the inventor. Having unearthed Lilienfeld’s patents that went into obscurity years earlier, lawyers at Bell Labs advised against Shockley's proposal because the idea of a field-effect transistor that used an electric field as a "grid" was not new. Instead, what Bardeen, Brattain, and Shockley invented in 1947 was the first point-contact transistor. In acknowledgement of this accomplishment, Shockley, Bardeen, and Brattain were jointly awarded the 1956 Nobel Prize in Physics "for their researches on semiconductors and their discovery of the transistor effect".



**Al Penney**
**VO1NO**

## Inventing the Transistor

Scientists in the 1920s proposed building amplifiers from semiconductors. But they didn’t understand the materials well enough to actually do it. In 1939, William Shockley at AT&T’s Bell Labs revived the idea as a way to replace vacuum tubes.

Under Shockley’s direction, John Bardeen and Walter Brattain demonstrated in 1947 the first semiconductor amplifier: the point-contact transistor, with two metal points in contact with a sliver of germanium. In 1948, Shockley invented the more robust junction transistor, built in 1951.

The three shared the 1956 Nobel Prize in Physics for their inventions.

## How Bardeen and Brattain's Transistor Worked

Bardeen and Brattain’s transistor consisted of a sliver of germanium with two closely spaced gold point contacts held in place by a plastic wedge. They selected germanium material that had been treated to contain an excess of electrons, called N-type. When they caused an electric current to flow through one contact (called the emitter) it induced a scarcity of electrons in a thin layer (changing it locally to P-type) near the germanium surface. This changed the amount of current that could flow through the collector contact. A small change in the current through the emitter caused a larger change in the collector current. They had created a current amplifier.

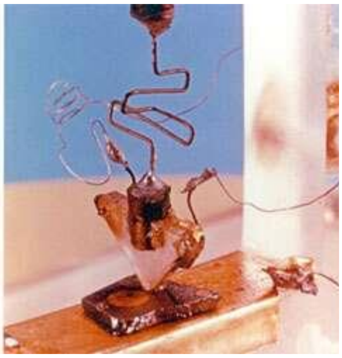
### Transistors Take Off

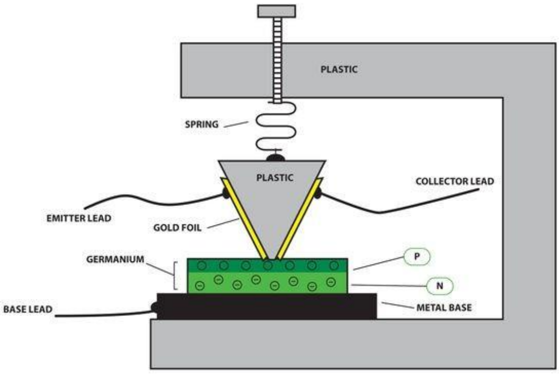
AT&T, which had invented the transistor, licensed the technology in 1952. It hoped to benefit from others' improvements.

Transistors swiftly left the lab and entered the marketplace. Although costlier than vacuum tubes, they were ideal when portability and battery operation were important. The 1952 Sonotone hearing aid was America's first transistorized consumer product. AT&T also used transistor amplifiers in its long distance telephone system. They soon appeared as switches, beginning with an experimental computer at Manchester University in 1953.

As prices dropped, uses multiplied. By 1960, most new computers were transistorized.

# The First Transistor!

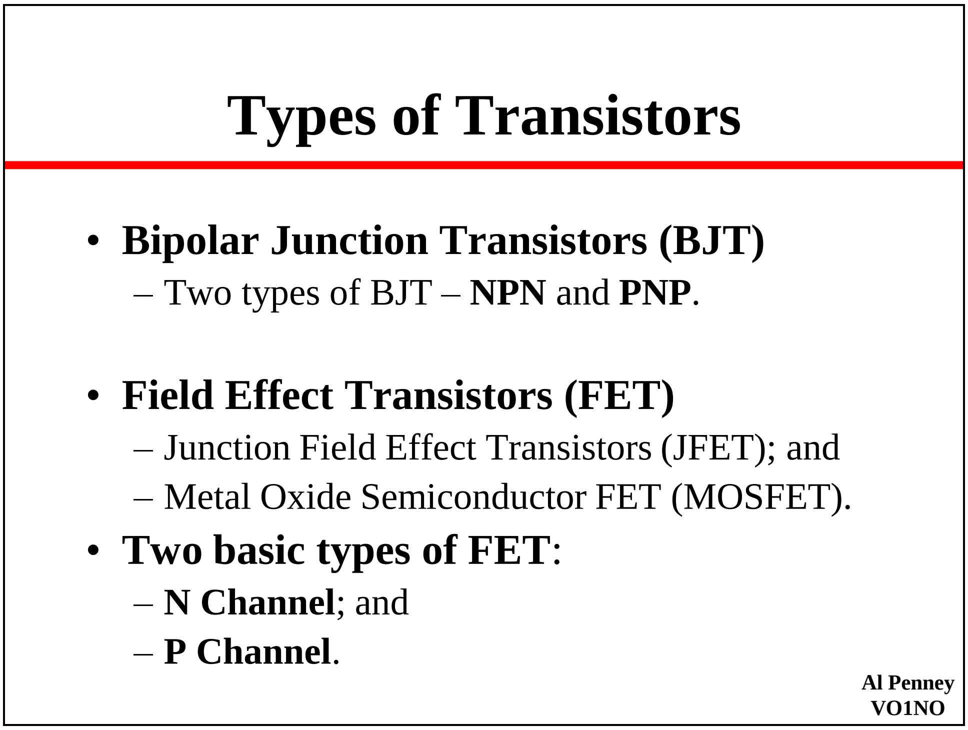




Al Penney
VO1NO

### How Bardeen and Brattain's Transistor Worked

Bardeen and Brattain’s transistor consisted of a sliver of germanium with two closely spaced gold point contacts held in place by a plastic wedge. They selected germanium material that had been treated to contain an excess of electrons, called N-type. When they caused an electric current to flow through one contact (called the emitter) it induced a scarcity of electrons in a thin layer (changing it locally to P-type) near the germanium surface. This changed the amount of current that could flow through the collector contact. A small change in the current through the emitter caused a larger change in the collector current. They had created a current amplifier.



## Types of Transistors

- **Bipolar Junction Transistors (BJT)**
  - – Two types of BJT – **NPN** and **PNP**.

- **Field Effect Transistors (FET)**
  - – Junction Field Effect Transistors (JFET); and
  - – Metal Oxide Semiconductor FET (MOSFET).
- **Two basic types of FET**:
  - – **N Channel**; and
  - – **P Channel**.

**Al Penney**
**VO1NO**

**Bipolar transistor definition:**

A bipolar transistor is a semiconductor device consisting of three areas either P-type or N-type - an area of one type is sandwiched between areas of the other. The transistor fundamentally amplifies current but it can be connected in circuits designed to amplify voltage or power.

A bipolar transistor needs to be differentiated from a field effect transistor. A bipolar junction transistor, BJT, gains its name from the fact that it uses both holes and electrons in its operation. Field effect transistors are unipolar devices using one or either type of charge carrier.

A bipolar transistor, or more exactly a bipolar junction transistor, BJT, has two PN diode junctions which are back to back. The bipolar transistor has three terminals, named the emitter, base and collector.

The transistor amplifies current - bipolar transistors are current devices, unlike thermionic valves vacuum tubes, and FETs which are voltage devices. The current flowing in the base circuit affects the current flowing between the collector and the emitter.

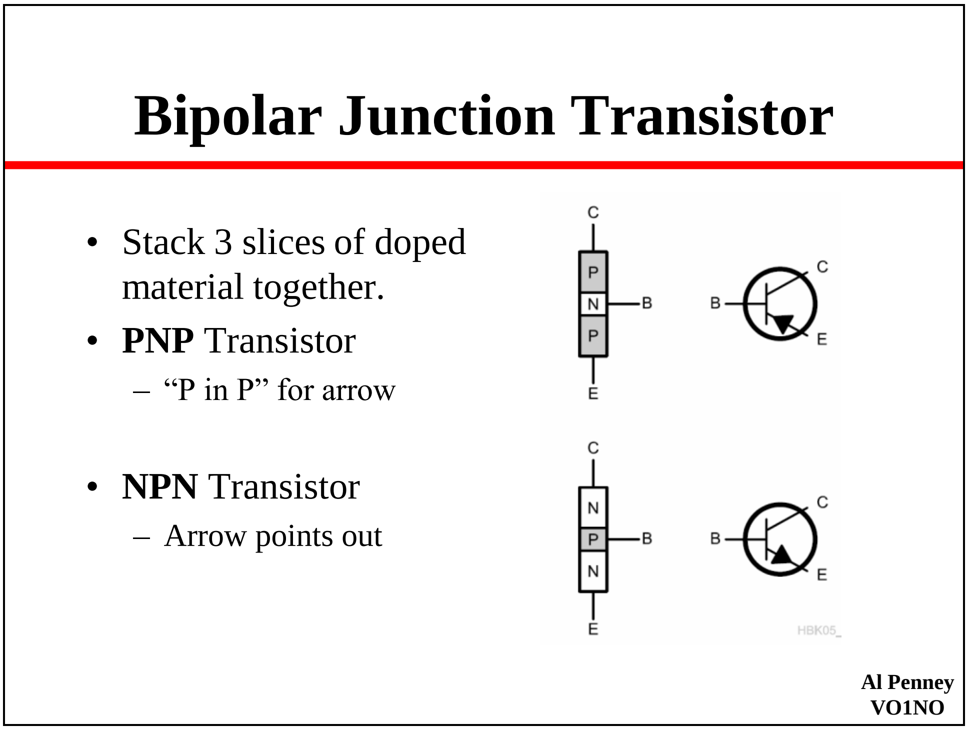
There are two types of standard (bipolar junction) transistors, **NPN** and **PNP**. The letters refer to the layers of semiconductor material used to make the transistor. Most transistors used today are NPN because this is the easiest type to make from silicon. If you are new to electronics it is best to start by learning how to use NPN transistors.

The leads are labelled **base** (B), **collector** (C) and **emitter** (E). These terms refer to the internal operation of a transistor but they are not much help in understanding how a transistor is used, so just treat them as labels.

A *field-effect transistor (FET)* consists of a channel of N- or P-type semiconductor material through which current can flow, with a different material (laid across a section of the channel) controlling the conductivity of the channel.

In addition to bipolar junction transistors, there are **field-effect transistors** which are usually referred to as **FET**s. There are two basic classes of FETs – the Junction Field Effect Transistor (JFET), and the Metal Oxide Semiconductor Field Effect Transistor (MOSFET), sometimes called the Insulated Gate Field Effect Transistor (IGFET).

All FETS have two basic types – **N Channel**, and **P Channel**.



## Bipolar Junction Transistor

- Stack 3 slices of doped material together.
- **PNP** Transistor
  - “P in P” for arrow
- **NPN** Transistor
  - Arrow points out

**Al Penney**
**VO1NO**

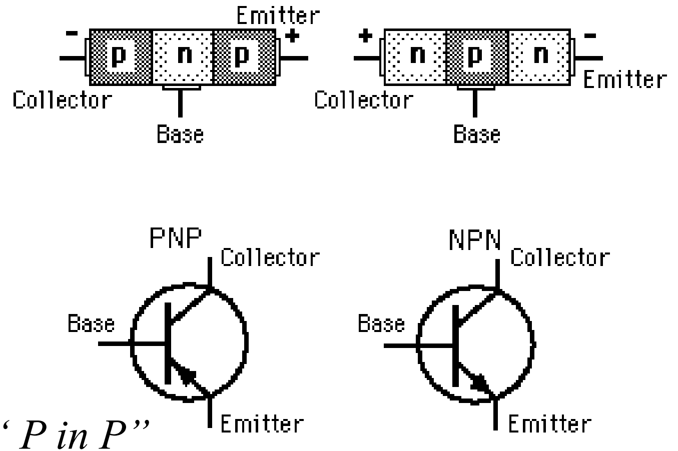
### Basic transistor structure

The transistor is a three terminal device and consists of three distinct layers. Two of them are doped to give one type of semiconductor and the there is the opposite type, i.e. two may be n-type and one p-type, or two may be p-type and one may be n-type.. They are arranged so that the two similar layers of the transistor sandwich the layer of the opposite type. As a result these semiconductor devices are designated as either PNP transistors or NPN transistors according to the way they are made up.

In the diode tutorials we saw that simple diodes are made up from two pieces of semiconductor material to form a simple pn-junction and we also learnt about their properties and characteristics. If we now join together two individual signal diodes back-to-back, this will give us two PN-junctions connected together in series that share a common **P** or **N** terminal. The fusion of these two diodes produces a three layer, two junction, three terminal device forming the basis of a **Bipolar Junction Transistor**, or **BJT** for short.

Transistors are three terminal active devices made from different semiconductor materials that can act as either an insulator or a conductor by the application of a small signal voltage. The transistor’s ability to change between these two states enables it to have two basic functions: “switching” (digital electronics) or “amplification” (analogue electronics).

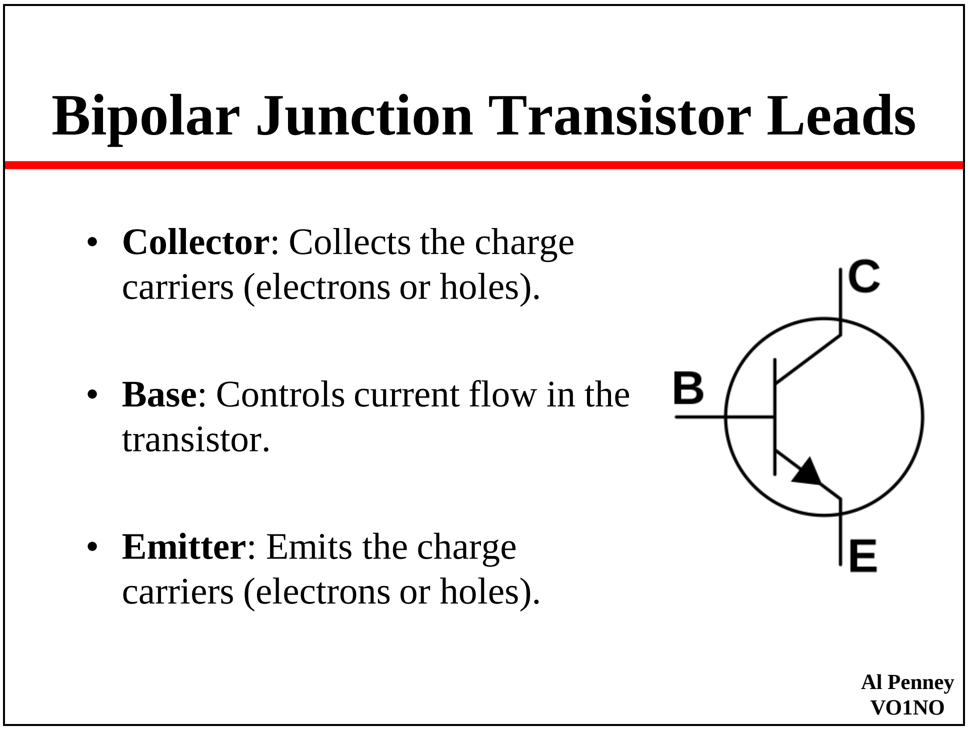
# Bipolar Junction Transistors



*" P in P"*

Copyright: GSU

**Al Penney**
**VO1NO**



# Bipolar Junction Transistor Leads

- **Collector**: Collects the charge carriers (electrons or holes).
- **Base**: Controls current flow in the transistor.
- **Emitter**: Emits the charge carriers (electrons or holes).

Al Penney
VO1NO

The names for the three electrodes widely used but their meanings are not always understood:

•***Base:*** The base of the transistor gains its name from the fact that in early transistors, this electrode formed the base for the whole device. The earliest point contact transistors had two point contacts placed onto the base material. This base material formed the base connection . . . and the name stuck.

•***Emitter:*** The emitter gains its name from the fact that it emits the charge carriers.

•***Collector:*** The collector gains its name from the fact that it collects the charge carriers.

For the operation of the transistor, it is essential that the base region is very thin. In today's transistors the base may typically be only about 1µm across. It is the fact that the base region of the transistor is thin that is the key to the operation of the device

Emitter

•The bottom lead of the above shown structure can be understood as **Emitter**.

•This has a **moderate size** and is **heavily doped** as its main function is to **supply** a number of **majority carriers**, i.e. either electrons or holes.

•As this emits electrons, it is called as an Emitter.

•This is simply indicated with the letter **E**.

Base

•The middle material in the above figure is the **Base**.

•This is **thin** and **lightly doped**.

•Its main function is to **pass** the majority carriers from the emitter to the collector.

•This is indicated by the letter **B**.

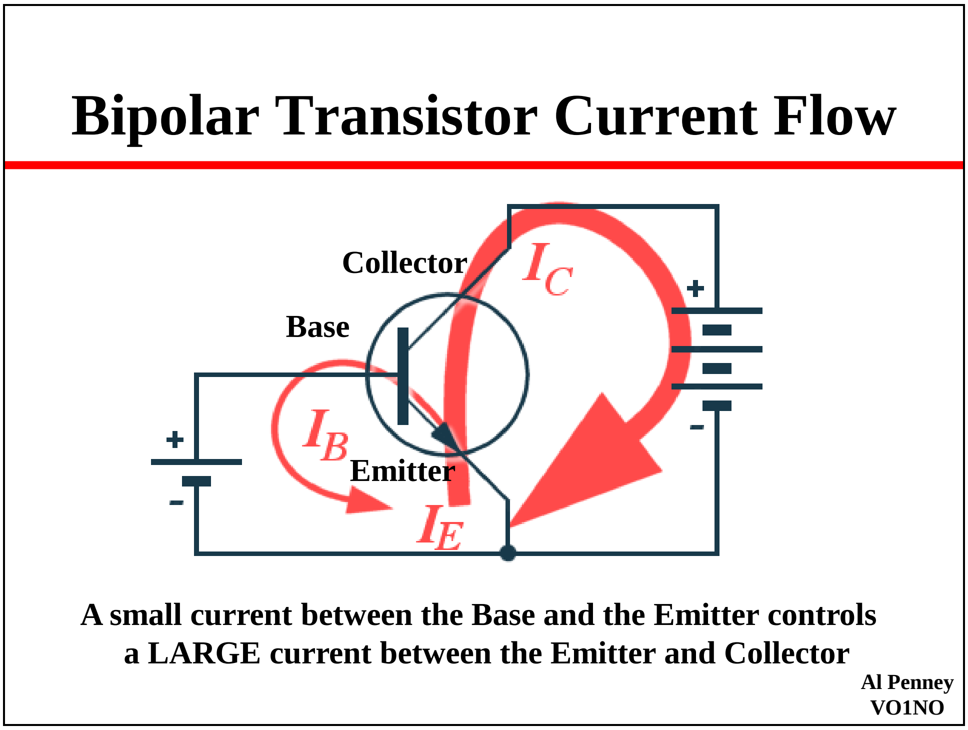
Collector

•The top lead in the above figure can be understood as a **Collector**.

•Its name implies its function of **collecting the carriers**.

•This is **a bit larger** in size than emitter and base. It is **moderately doped**.

•This is indicated by the letter **C**.



# Bipolar Transistor Current Flow

**A small current between the Base and the Emitter controls a LARGE current between the Emitter and Collector**

**Al Penney**
**VO1NO**

Bipolar Transistors are current regulating devices that control the amount of current flowing through them from the Emitter to the Collector terminals in proportion to the amount of biasing voltage applied to their Base terminal, thus acting like a current-controlled switch. As a small current flowing into the base terminal controls a much larger collector current forming the basis of transistor action.

# Conventional Current Flow

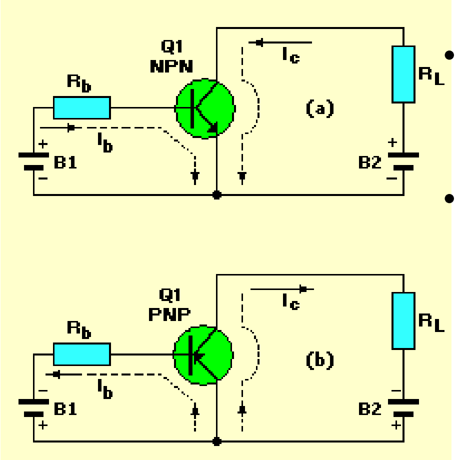


Fig. 3--CURRENT FLOW in transistors: NPN (a), and PNP (b).

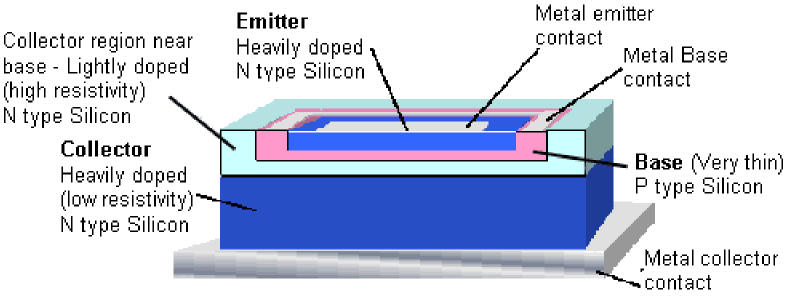
- Note that this is the **Conventional Current** flow!
- **Electron flow** is in the **opposite** direction!

Al Penney
VO1NO

The principle of operation of the two transistor types PNP and NPN, is exactly the same the only difference being in their biasing and the polarity of the power supply for each type.

The construction and circuit symbols for both the PNP and NPN bipolar transistor are given above with the arrow in the circuit symbol always showing the direction of “conventional current flow” between the base terminal and its emitter terminal. The direction of the arrow always points from the positive P-type region to the negative N-type region for both transistor types, exactly the same as for the standard diode symbol.

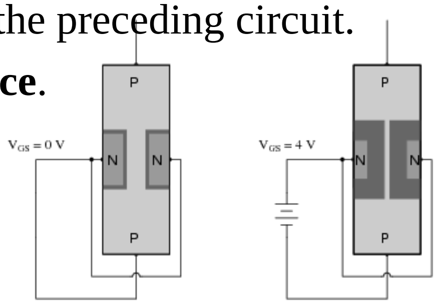
# Modern Bipolar Junction Transistor



**Al Penney**
**VO1NO**

# Field Effect Transistors

- Uses **voltage** (electric field) at the **Gate** to control the flow of current.
- Very **little current** flows through the Gate, so it does not affect the preceding circuit.
- **Very high impedance**.



**Al Penney**
**VO1NO**

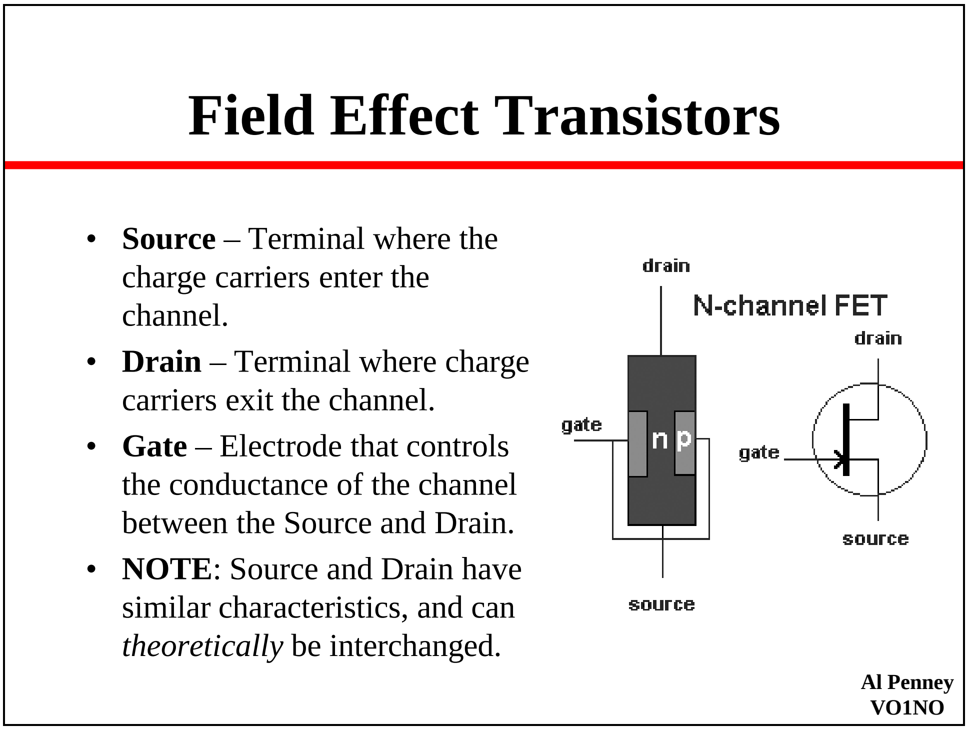
The **field-effect transistor** (FET) is a transistor that uses an electric field to control the shape and hence the conductivity of a channel of one type of charge carrier in a semiconductor material. FETs are unipolar transistors as they involve single-carrier-type operation. The *concept* of the FET predates the bipolar junction transistor (BJT), though it was not physically implemented until *after* BJTs due to the limitations of semiconductor materials and the relative ease of manufacturing BJTs compared to FETs at the time.

The field-effect transistor was first patented by Julius Edgar Lilienfeld in 1926 and by Oskar Heil in 1934, but practical semiconducting devices (the JFET) were developed only much later after the transistor effect was observed and explained by the team of William Shockley at Bell Labs in 1947. The MOSFET, which largely superseded the JFET and had a more profound effect on electronic development, was invented by Dawon Kahng and Martin Atalla in 1960.

The main advantage of the FET is its high input resistance, on the order of 100 MΩ or more. Thus, it is a voltage-controlled device, and shows a high degree of isolation between input and output. It is a unipolar device, depending only on majority current flow. Because base current noise will increase with shaping time, a FET typically produces less noise than a bipolar junction transistor (BJT), and is thus found in noise sensitive electronics such as tuners and low-noise amplifiers for VHF and satellite receivers. It is relatively immune to radiation. It exhibits no offset voltage at zero drain current and hence makes an excellent signal chopper. It typically has better thermal stability than a BJT.

### Disadvantages of FET

It has a relatively low gain-bandwidth product compared to a BJT. The MOSFET has a drawback of being very susceptible to overload voltages, thus requiring special handling during installation. The fragile insulating layer of the MOSFET between the gate and channel makes it vulnerable to electrostatic damage during handling. This is not usually a problem after the device has been installed in a properly designed circuit.



# Field Effect Transistors

- **Source** – Terminal where the charge carriers enter the channel.
- **Drain** – Terminal where charge carriers exit the channel.
- **Gate** – Electrode that controls the conductance of the channel between the Source and Drain.
- **NOTE**: Source and Drain have similar characteristics, and can *theoretically* be interchanged.

**Al Penney**
**VO1NO**

### Field Effect Transistor – the basics

The concept of the field effect transistor is based around the concept that charge on a nearby object can attract charges within a semiconductor channel. It essentially operates using an electric field effect - hence the name.

The FET consists of a semiconductor channel with electrodes at either end referred to as the drain and the source.

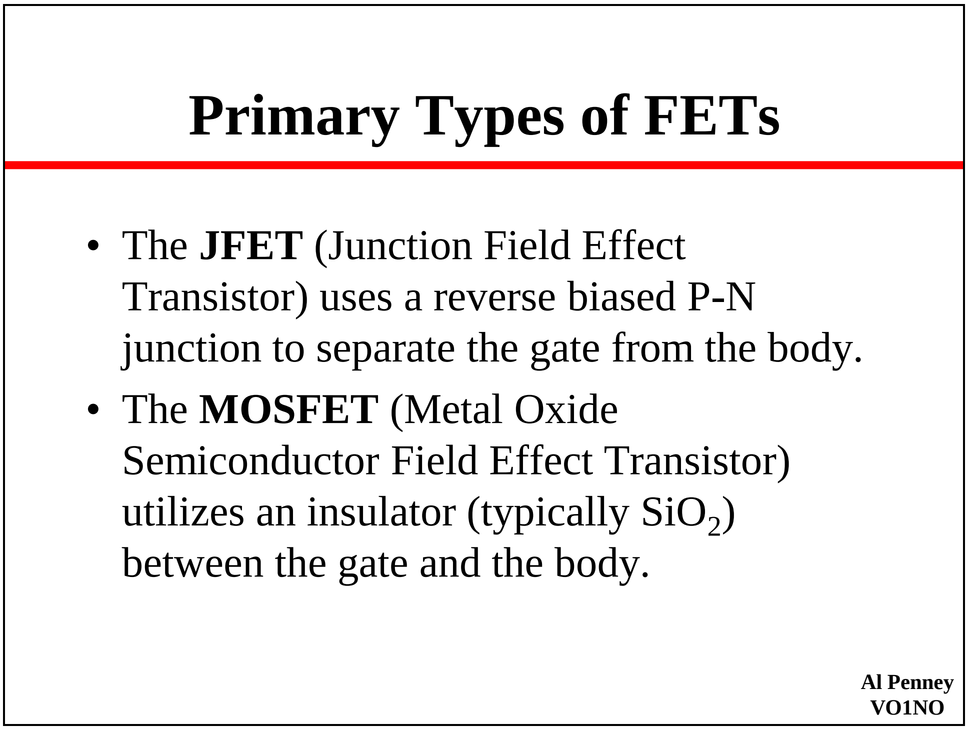
A control electrode called the gate is placed in very close proximity to the channel so that its electric charge is able to affect the channel.

In this way, the gate of the FET controls the flow of carriers (electrons or holes) flowing from the source to drain. It does this by controlling the size and shape of the conductive channel.

The semiconductor channel where the current flow occurs may be either P-type or N-type. This gives rise to two types or categories of FET known as P-Channel and N-Channel FETs.

As it is only the electric field that controls the current flowing in the channel, the device is said to be voltage operated and it has a high input impedance, usually many megohms. This can be a distinct advantage over the bipolar transistor that is current operated and has a much lower input impedance.

One end of the channel is known as the ***source,*** the other end of the channel is called the ***drain,*** and the control mechanism is called the ***gate.*** By applying a voltage to the gate, you control the flow of current from the source to the drain. Leads are attached to the source, drain, and gate. Some FETs include a fourth lead so you can ground part of the FET to the chassis of the circuit. (But don’t confuse these four-legged creatures with *dual-gate MOSFETs,* which also have four leads.



## Primary Types of FETs

- The **JFET** (Junction Field Effect Transistor) uses a reverse biased P-N junction to separate the gate from the body.
- The **MOSFET** (Metal Oxide Semiconductor Field Effect Transistor) utilizes an insulator (typically $SiO_2$) between the gate and the body.

**Al Penney**
**VO1NO**

***Junction FET, JFET:*** The junction FET, or JFET uses a reverse biased diode junction to provide the gate connection. The structure consists of a semiconductor channel which can be either N-type or P-type. A semiconductor diode is then fabricated onto the channel in such a way that the voltage on the diode affects the FET channel.

In operation this is reverse biased and this means that it is effectively isolated from the channel - only the diode reverse current can flow between the two. The JFET is the most basic type of FET, and the one that was first developed. However it still provides excellent service in many areas of electronics.

**The MOSFET is the most widely manufactured device in history. The MOSFET generates annual sales of $295 billion as of 2015. Between 1960 and 2018, an estimated total of 13 sextillion MOS transistors have been manufactured, accounting for at least 99.9% of all transistors. (13 followed by 21 zeros!)**

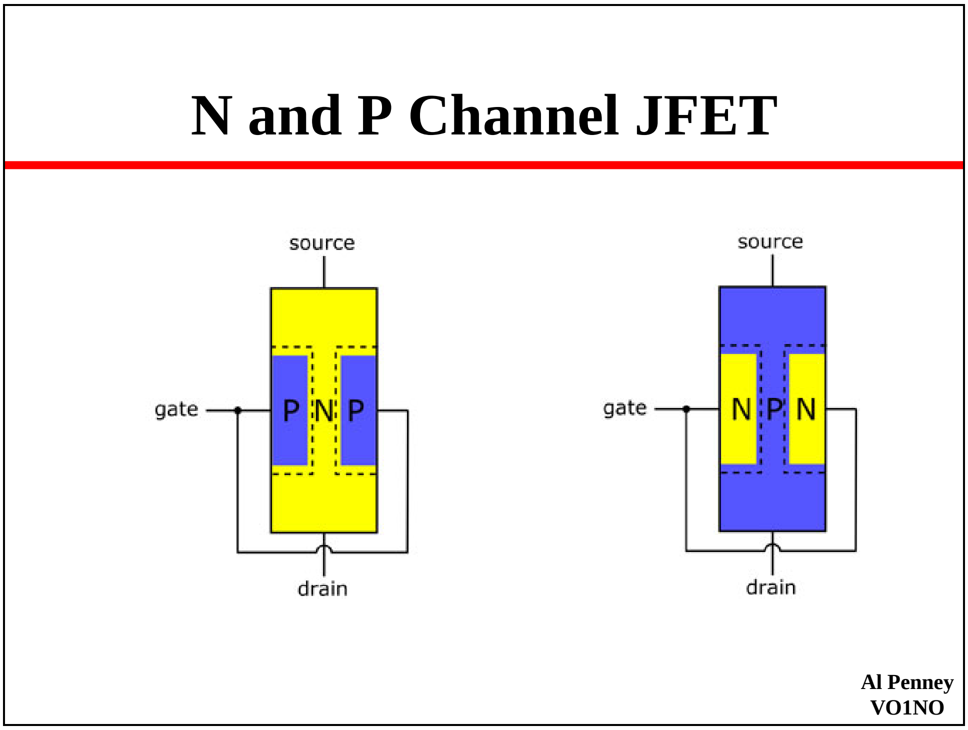
***Insulated Gate FET / Metal Oxide Silicon FET MOSFET:*** The MOSFET uses an insulated layer between the gate and the channel. Typically this is formed from a layer of oxide of the semiconductor.

The name IGFET refers to any type of FET that has an insulated gate. The most common form of IGFET is the silicon MOSFET - Metal Oxide Silicon FET. Here, the gate is made of a layer of metal set down on the silicon oxide which in turn is on the silicon channel. MOSFETs are widely used in many areas of electronics and particularly within integrated circuits.

The key factor of the IGFET / MOSFET is the exceedingly gate high impedance these FETs are able to provide. That said, there will be an associated capacitance and this will reduce the input impedance as the frequency rises.

**Silicon dioxide**, also known as **silica**, is an oxide of silicon with the chemical formula $SiO_2$, most commonly found in nature as quartz and in various living organisms. In many parts of the world, silica is the major constituent of sand.

**The MOSFET is the most widely manufactured device in history. The MOSFET generates annual sales of $295 billion as of 2015. Between 1960 and 2018, an estimated total of 13 sextillion MOS transistors have been manufactured, accounting for at least 99.9% of all transistors. (13 followed by 21 zeros!)**



# N and P Channel JFET

**Al Penney**
**VO1NO**

A *field-effect transistor (FET)* consists of a channel of N- or P-type semiconductor material through which current can flow, with a different material (laid across a section of the channel) controlling the conductivity of the channel.

One end of the channel is known as the *source,* the other end of the channel is called the *drain,* and the control mechanism is called the *gate.* By applying a voltage to the gate, you control the flow of current from the source to the drain. Leads are attached to the source, drain, and gate. Some FETs include a fourth lead so you can ground part of the FET to the chassis of the circuit. (But don’t confuse these four-legged creatures with *dual-gate MOSFETs,* which also have four leads.

One end of the channel is known as the *source,* the other end of the channel is called the *drain,* and the control mechanism is called the *gate.* By applying a voltage to the gate, you control the flow of current from the source to the drain. Leads are attached to the source, drain, and gate. Some FETs include a fourth lead so you can ground part of the FET to the chassis of the circuit. (But don’t confuse these four-legged creatures with *dual-gate MOSFETs,* which also have four leads.)

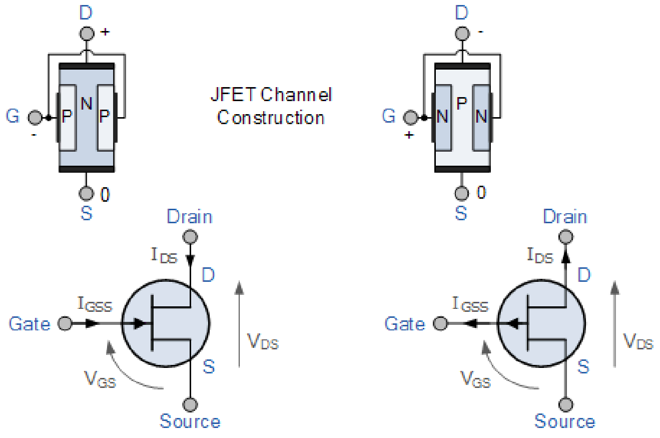
FETs (pronounced “fetts”) come in two flavors — N-channel and P-channel —

depending on the type of semiconductor material (N-type or P-type, respectively) through which current flows. There are two major subtypes of FET: *MOSFET (metal-oxide-semiconductor FET)* and *JFET (junction FET).* Which is which depends on how the gate is constructed — which results, in turn, in different electrical properties and different uses for each type.

FETs (particularly MOSFETs) have become much more popular than bipolar transistors for use in *integrated circuits* (*ICs*), where thousands of transistors work together to perform a task. That's because they're low-power devices whose structure allows thousands of N- and P-channel MOSFETs to be crammed like sardines on a single piece of silicon (that is, semiconductor material).

The magnitude of the current flowing through the channel between the Drain and the Source terminals is controlled by a voltage applied to the Gate terminal, which is a reverse-biased. **In an N-channel JFET this Gate voltage is negative while for a P-channel JFET the Gate voltage is positive**

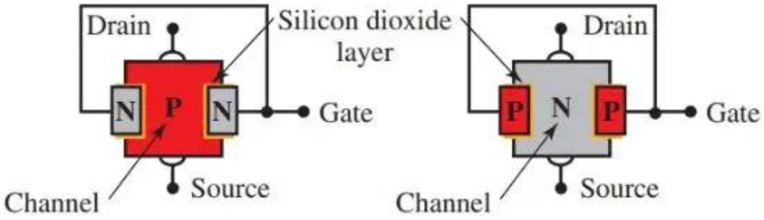
# N and P Channel JFET



N-channel JFET P-channel JFET

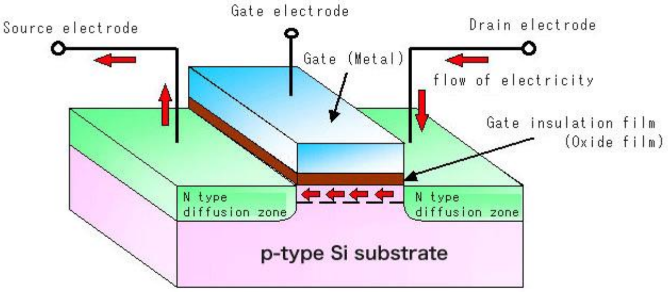
**Al Penney**
**VO1NO**

# N and P Channel MOSFET



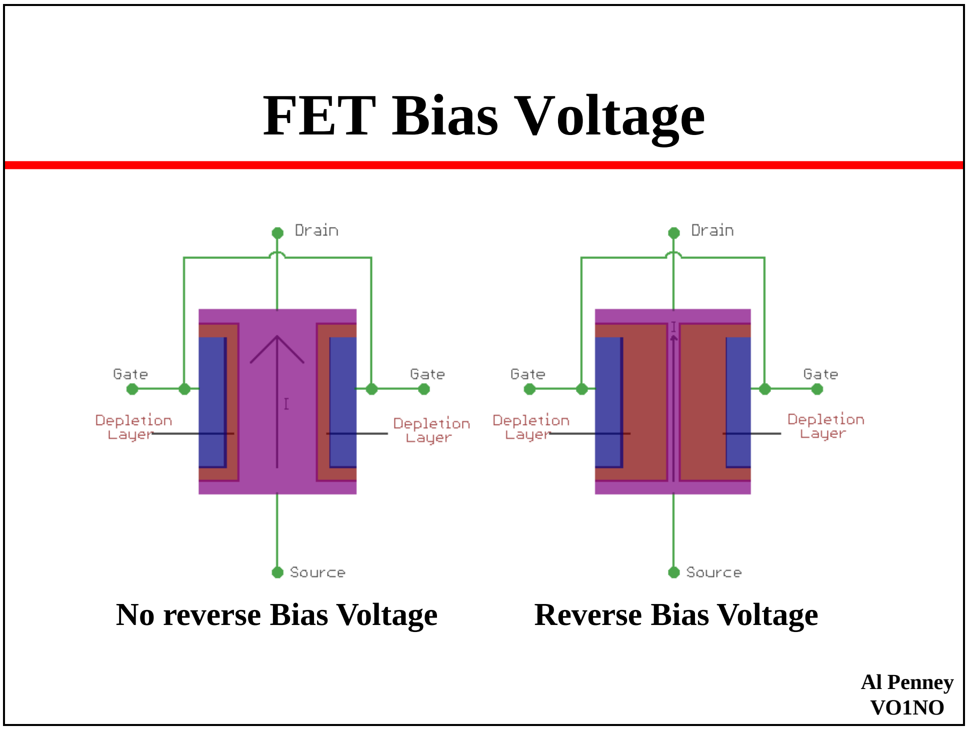
**Al Penney**
**VO1NO**

# MOSFET Construction



Construction of MOSFET

Al Penney
VO1NO



# FET Bias Voltage

No reverse Bias Voltage

Reverse Bias Voltage

Al Penney
VO1NO

## Working of JFET

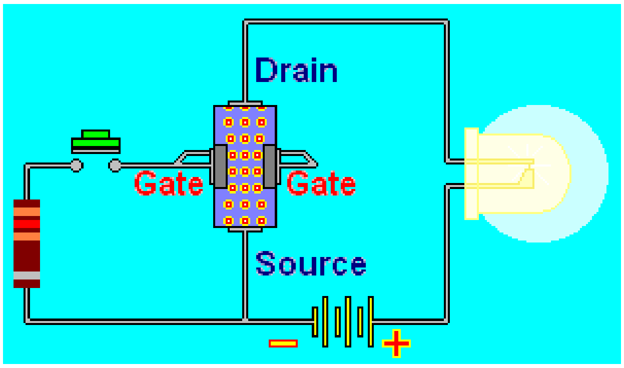
One best example to understand the working of a JFET is to imagine the **garden hose pipe**. Suppose a garden hose is providing a water flow through it. If we squeeze the hose the water flow will be less and at a certain point if we squeeze it completely there will be zero water flow. JFET works exactly in that way. If we interchange the hose with a JFET and the water flow with a current and then construct the current-carrying channel, we could control the current flow.

When there is no voltage across gate and source, the channel becomes a smooth path which is wide open for electrons to flow. But the reverse thing happens when a voltage is applied between gate and source in reverse polarity, that makes the P-N junction reversed biased and makes the channel narrower by increasing the depletion layer and could put the JFET in cut-off or pinch off region.

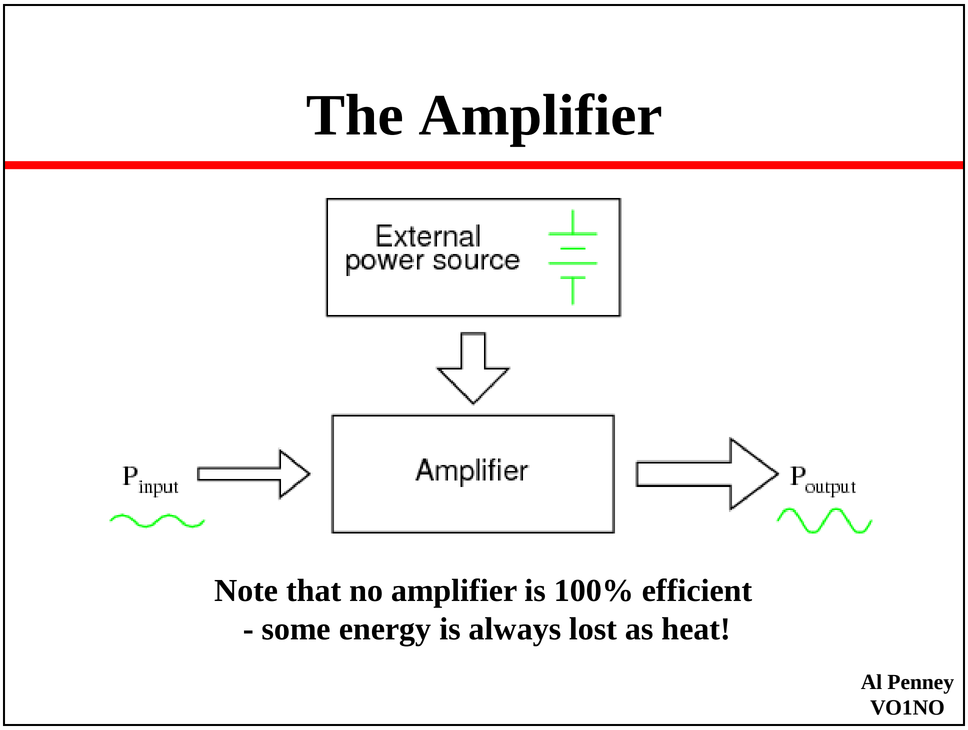
In the above image we can see the **saturation mode and pinch off mode** and we will be able to understand the **depletion layer became wider and the current flow becomes less**.

# Pinch-Off Voltage

- The reverse bias voltage that cuts off conduction completely.



**Al Penney**
**VO1NO**



# The Amplifier

**Note that no amplifier is 100% efficient**
**- some energy is always lost as heat!**

**Al Penney**
**VO1NO**

**Amplifier** is the generic term used to describe a circuit which produces an increased version of its input signal. However, not all amplifier circuits are the same as they are classified according to their circuit configurations and modes of operation.

In “Electronics”, small signal amplifiers are commonly used devices as they have the ability to amplify a relatively small input signal, for example from a *Sensor* such as a photo-device, into a much larger output signal to drive a relay, lamp or loudspeaker for example.

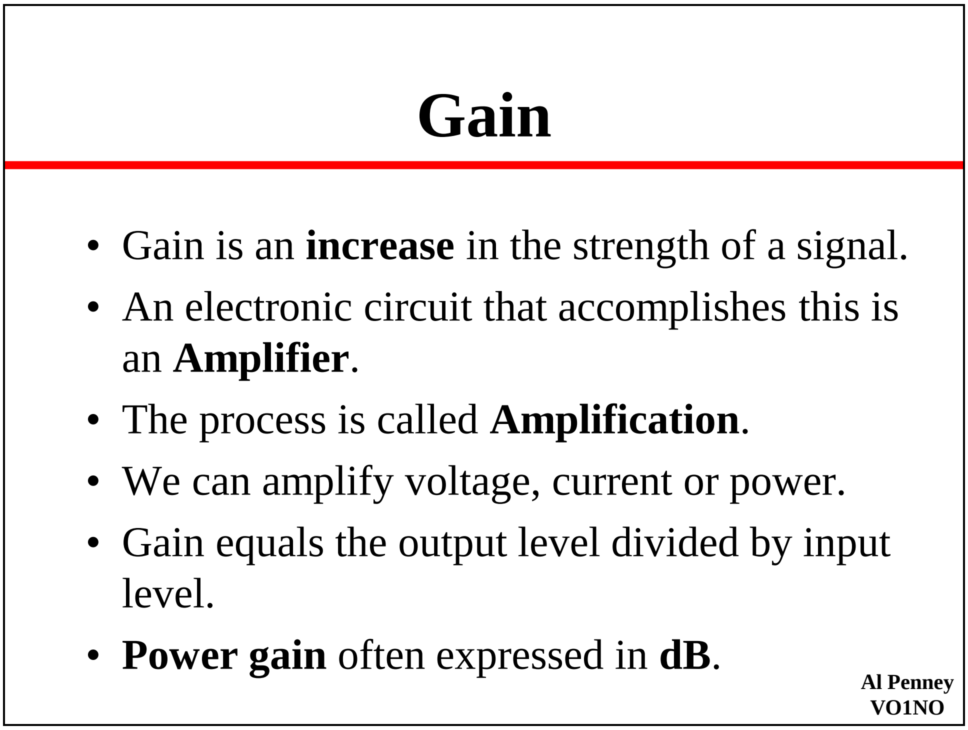
There are many forms of electronic circuits classed as amplifiers, from Operational Amplifiers and Small Signal Amplifiers up to Large Signal and Power Amplifiers. The classification of an amplifier depends upon the size of the signal, large or small, its physical configuration and how it processes the input signal, that is the relationship between input signal and current flowing in the load.

The amplified difference between the input and output signals is known as the Gain of the amplifier. Gain is basically a measure of how much an amplifier “amplifies” the input signal. For example, if we have an input signal of 1 volt and an output of 50 volts, then the gain of the amplifier would be “50”. In other words, the input signal has been increased by a factor of 50. This increase is called **Gain**.

Amplifier gain is simply the ratio of the output divided-by the input. Gain has no units as its a ratio, but in Electronics it is commonly given the symbol “A”, for Amplification. Then the gain of an amplifier is simply calculated as the “output signal divided by the input signal”.

### Amplifier Gain

The introduction to the amplifier gain can be said to be the relationship that exists between the signal measured at the output with the signal measured at the input. There are three different kinds of amplifier gain which can be measured and these are: *Voltage Gain* ( Av ), *Current Gain* ( Ai ) and *Power Gain* ( Ap ) depending upon the quantity being measured.



## Gain

- Gain is an **increase** in the strength of a signal.
- An electronic circuit that accomplishes this is an **Amplifier**.
- The process is called **Amplification**.
- We can amplify voltage, current or power.
- Gain equals the output level divided by input level.
- **Power gain** often expressed in **dB**.

**Al Penney**
**VO1NO**

### The Output Properties of Amplifiers

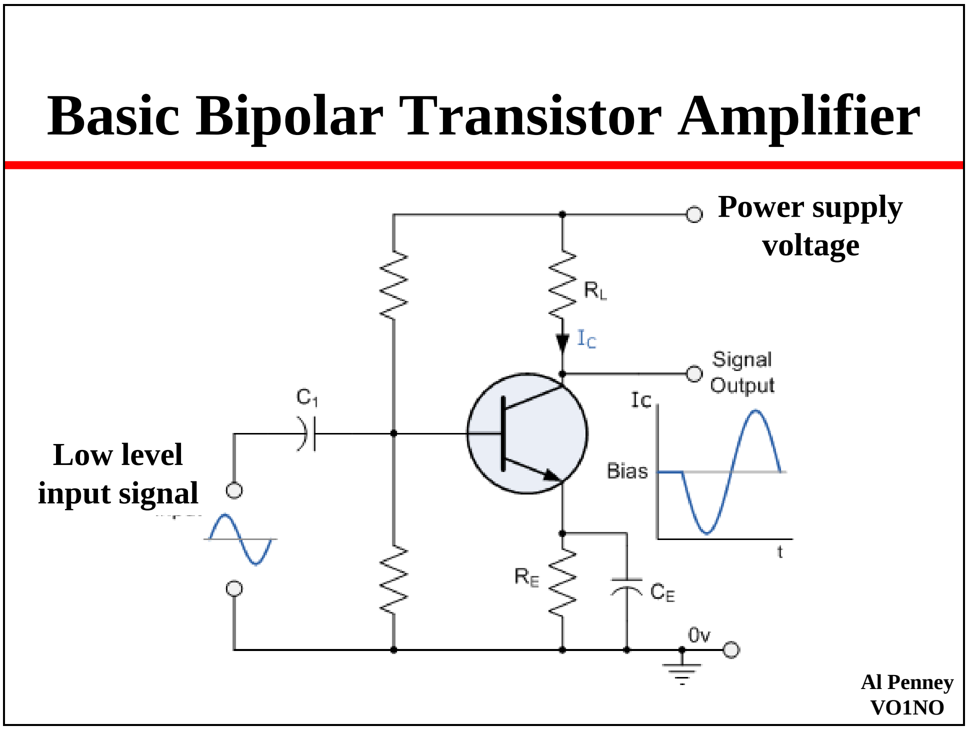
Amplifiers are used to increase the amplitude of a voltage or current, or to increase the amount of power available usually from an AC signal. Whatever the task, there are three categories of amplifier that relate to the properties of their output;

1. Voltage amplifiers.
2. Current amplifiers.
3. Power amplifiers.

The purpose of a voltage amplifier is to make the amplitude of the output voltage waveform greater than that of the input voltage waveform (although the amplitude of the output current may be greater or smaller than that of the input current, this change is less important for the amplifier´s designed purpose).

The purpose of a current amplifier is to make the amplitude of the output current waveform greater than that of the input current waveform (although the amplitude of the output voltage may be greater or smaller than that of the input voltage, this change is less important for the amplifier´s designed purpose).

In a power amplifier, the product of voltage and current (i.e. power = voltage x current) at the output is greater than the product of voltage x current at the input. Note that either voltage or current may be less at the output than at the input. It is the product of the two that is significantly increased.



# Basic Bipolar Transistor Amplifier

Power supply voltage

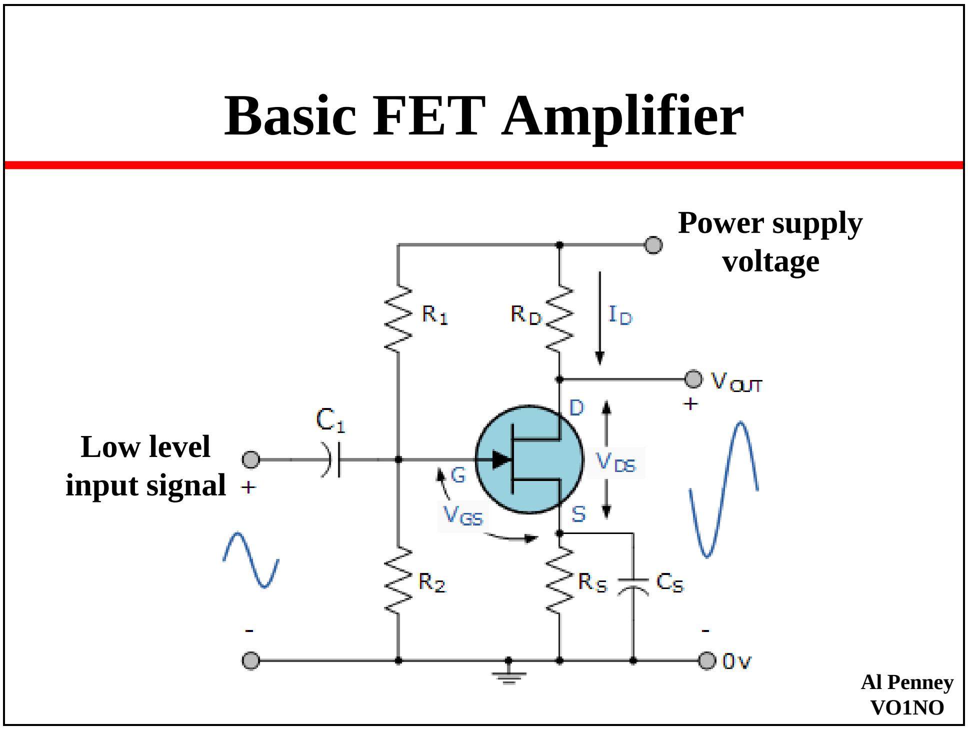
Low level input signal

Al Penney
VO1NO

## Common Emitter Amplifier

The most common amplifier configuration for an NPN transistor is that of the Common Emitter Amplifier circuit

The single stage common emitter amplifier circuit shown above uses what is commonly called “Voltage Divider Biasing”. This type of biasing arrangement uses two resistors as a potential divider network across the supply with their center point supplying the required Base bias voltage to the transistor. Voltage divider biasing is commonly used in the design of bipolar transistor amplifier circuits.



# Basic FET Amplifier

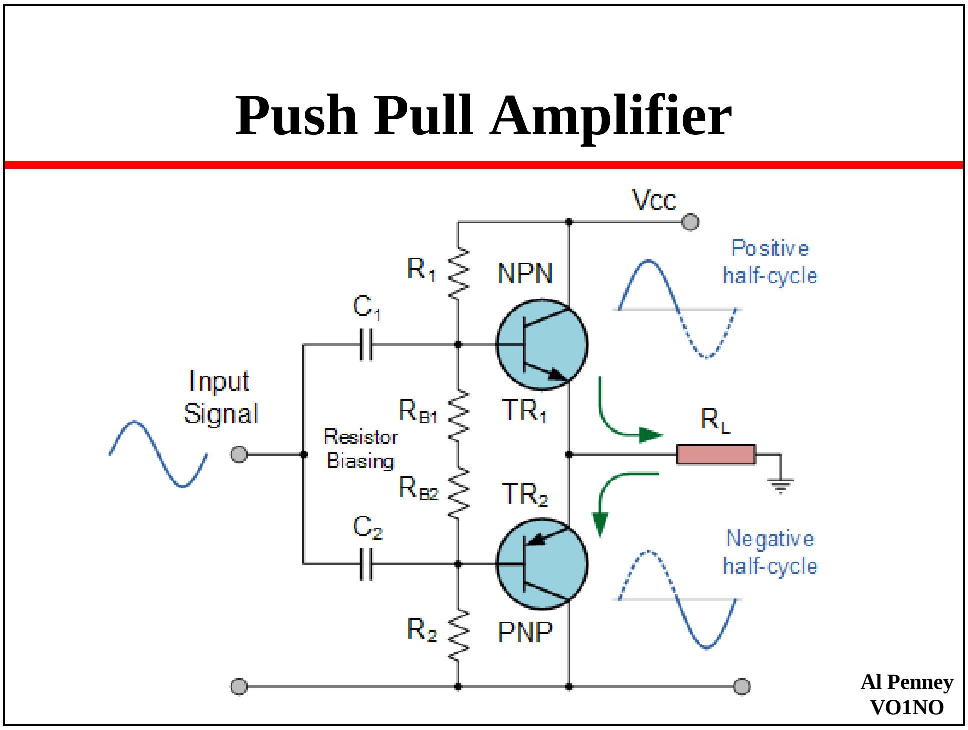
Al Penney
VO1NO

## Common Source JFET Amplifier

Common Source JFET Amplifier uses junction field effect transistors as its main active device offering high input impedance characteristics

The amplifier circuit consists of an N-channel JFET, but the device could also be an equivalent N-channel depletion-mode MOSFET as the circuit diagram would be the same just a change in the FET, connected in a common source configuration. The JFET gate voltage Vg is biased through the potential divider network set up by resistors R1 and R2 and is biased to operate within its saturation region which is equivalent to the active region of the bipolar junction transistor.

Unlike a bipolar transistor circuit, the junction FET takes virtually no input gate current allowing the gate to be treated as an open circuit.



# Push Pull Amplifier

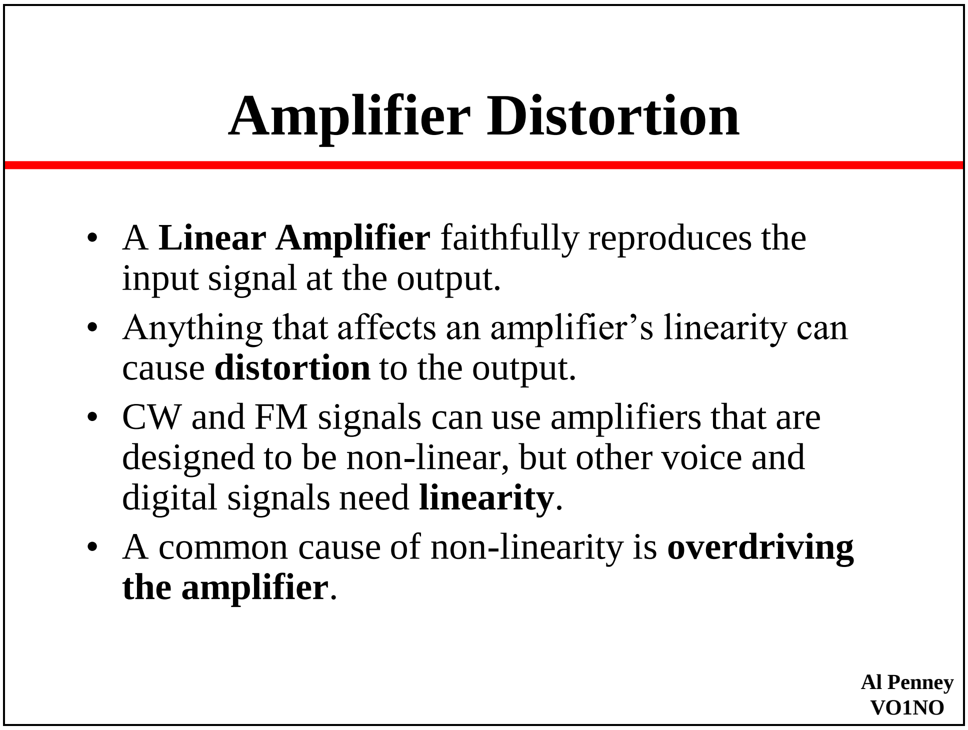
Al Penney
VO1NO

Class-B Amplifiers use two or more transistors biased in such a way so that each transistor only conducts during one half cycle of the input waveform.

To improve the full power efficiency of the previous Class A amplifier by reducing the wasted power in the form of heat, it is possible to design the power amplifier circuit with two transistors in its output stage producing what is commonly termed as a **Class B Amplifier** also known as a **push-pull amplifier** configuration.

Push-pull amplifiers use two “complementary” or matching transistors, one being an NPN-type and the other being a PNP-type with both power transistors receiving the same input signal together that is equal in magnitude, but in opposite phase to each other. This results in one transistor only amplifying one half or 180° of the input waveform cycle while the other transistor amplifies the other half or remaining 180° of the input waveform cycle with the resulting “two-halves” being put back together again at the output terminal.

Then the conduction angle for this type of amplifier circuit is only 180° or 50% of the input signal. This pushing and pulling effect of the alternating half cycles by the transistors gives this type of circuit its amusing “push-pull” name, but are more generally known as the **Class B Amplifier**.



# Amplifier Distortion

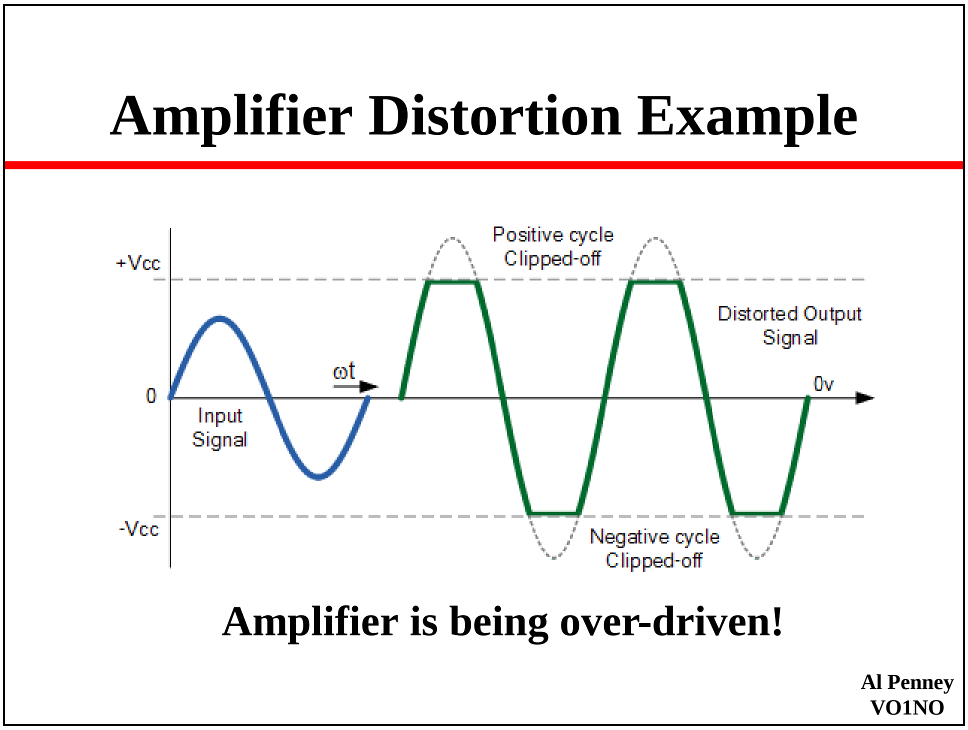
- A **Linear Amplifier** faithfully reproduces the input signal at the output.
- Anything that affects an amplifier’s linearity can cause **distortion** to the output.
- CW and FM signals can use amplifiers that are designed to be non-linear, but other voice and digital signals need **linearity**.
- A common cause of non-linearity is **overdriving the amplifier**.

**Al Penney**
**VO1NO**

**Distortion** of the output signal is the **result of the amplifier operating in an overdriven state**.

Most amplifiers have a range of gain in which they are clean, not distorting very much, then once you turn them up past a certain point, they will be in 'overdrive' and hence distorting.

"Up to eleven", also phrased as "these go to eleven", is an idiom from popular culture, coined in the 1984 film **This Is Spinal Tap**, where guitarist Nigel Tufnel demonstrates an amplifier whose volume knobs are marked from zero to eleven, instead of the usual zero to ten.



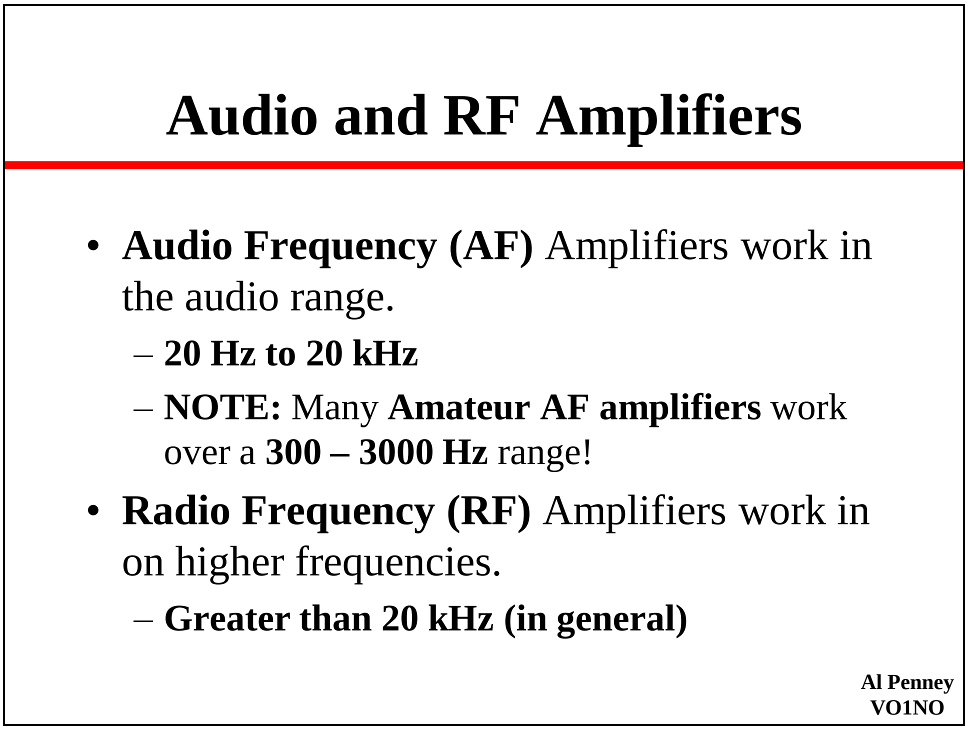
# Amplifier Distortion Example

**Amplifier is being over-driven!**

**Al Penney**
**VO1NO**

Even with the correct biasing voltage level set, it is still possible for the output waveform to become distorted due to a large input signal being amplified by the circuits gain. The output voltage signal becomes clipped in both the positive and negative parts of the waveform an no longer resembles a sine wave, even when the bias is correct. This type of amplitude distortion is called **Clipping** and is the result of "over-driving" the input of the amplifier.

When the input amplitude becomes too large, the clipping becomes substantial and forces the output waveform signal to exceed the power supply voltage rails with the peak (+ve half) and the trough (-ve half) parts of the waveform signal becoming flattened or "Clipped-off". To avoid this the maximum value of the input signal must be limited to a level that will prevent this clipping effect as shown above.



## Audio and RF Amplifiers

- **Audio Frequency (AF)** Amplifiers work in the audio range.
  - **20 Hz to 20 kHz**
  - **NOTE:** Many **Amateur AF amplifiers** work over a **300 – 3000 Hz** range!
- **Radio Frequency (RF)** Amplifiers work in on higher frequencies.
  - **Greater than 20 kHz (in general)**

**Al Penney**
**VO1NO**

### A.F. Amplifiers

Audio frequency amplifiers are used to amplify signals in the range of human hearing, approximately 20Hz to 20kHz, although some Hi-Fi audio amplifiers extend this range up to around 100kHz, whilst other audio amplifiers may restrict the high frequency limit to 15kHz or less.

Audio voltage amplifiers are used to amplify the low level signals from microphones, tape and disk pickups etc. With extra circuitry they also perform functions such as tone correction equalisation of signal levels and mixing from different inputs, they generally have high voltage gain and medium to high output resistance.

Audio power amplifiers are used to receive the amplified input from a series of voltage amplifiers, and then provide sufficient power to drive loudspeakers.

A radio frequency power **amplifier** (**RF** power **amplifier**) is a type of electronic **amplifier** that converts a low-power radio-frequency signal into a higher power signal. Typically, **RF** power **amplifiers** drive the antenna of a transmitter, or amplify weak received signals before demodulation. The frequency at which maximum gain occurs in an **RF amplifier** is made variable by changing the inductance or capacitance of the tuned circuit. In general, they operate at frequencies greater than AF amplifiers, ~20 kHz and higher.

# Transistor Characteristics

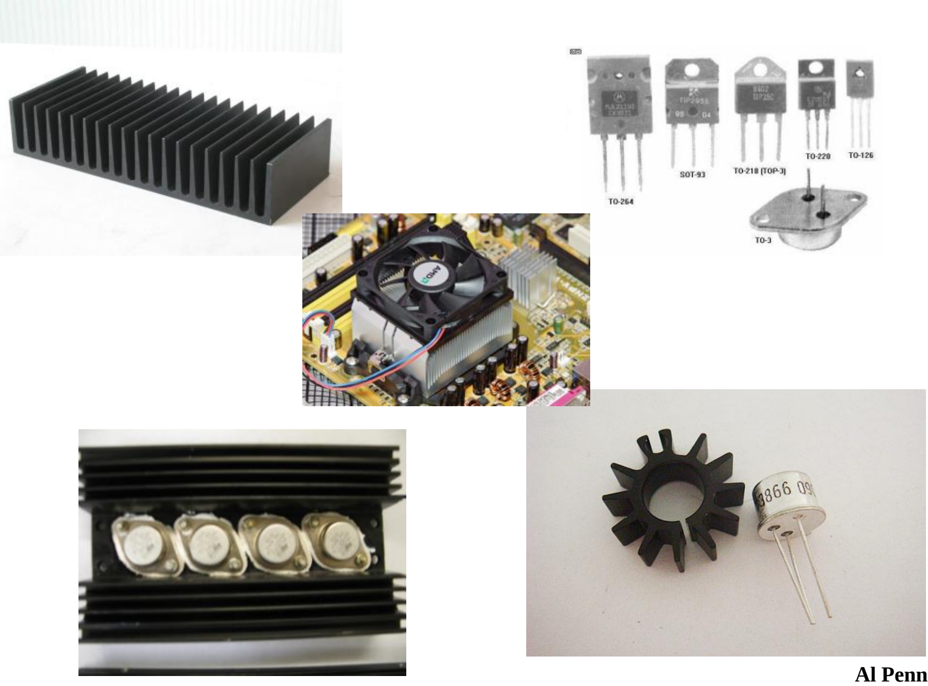
- **Breakdown Voltage** – Max voltage that may be safely applied to the electrodes.
- **Maximum Voltage** – Max operating voltages that may safely be applied to the electrodes.  Usually less than Breakdown Voltage, and never greater.

**Al Penney**
**VO1NO**

# Transistor Characteristics

- **Maximum Current** – Usually refers to the maximum Collector Current, $I_c$
- **Maximum Power** – Maximum amount of power the device can shed in terms of heat.
- Heat is the big enemy of most semiconductor devices!

**Al Penney**
**VO1NO**



**Al Penney**
**VO1NO**

# Integrated Circuits

- Electronic circuits built on a small plate, usually silicon.
- Contains transistors, resistors, capacitors, diodes, and sometimes inductors.
- Newest “chips” have billions of transistors!

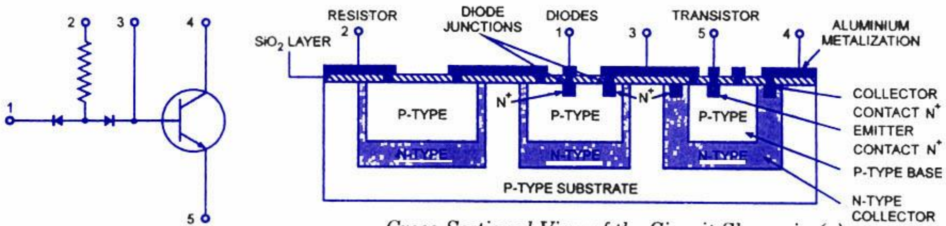
**Al Penney**
**VO1NO**

An **integrated circuit** or **monolithic integrated circuit** (also referred to as an **IC**, a **chip**, or a **microchip**) is a set of electronic circuits on one small plate ("chip") of semiconductor material, normally silicon. This can be made much smaller than a discrete circuit made from independent components.

Integrated circuits are used in virtually all electronic equipment today and have revolutionized the world of electronics, Computers, mobile phones, and other digital home appliances are now inextricable parts of the structure of modern societies, made possible by the low cost of producing integrated circuits.

ICs can be made very compact, having up to several billion transistors and other electronic components in an area the size of a fingernail. The width of each conducting line in a circuit can be made smaller and smaller as the technology advances; in 2008 it dropped below 100 nanometers and in 2013 it is expected to be in the tens of nanometers.[

# Integrated Circuits

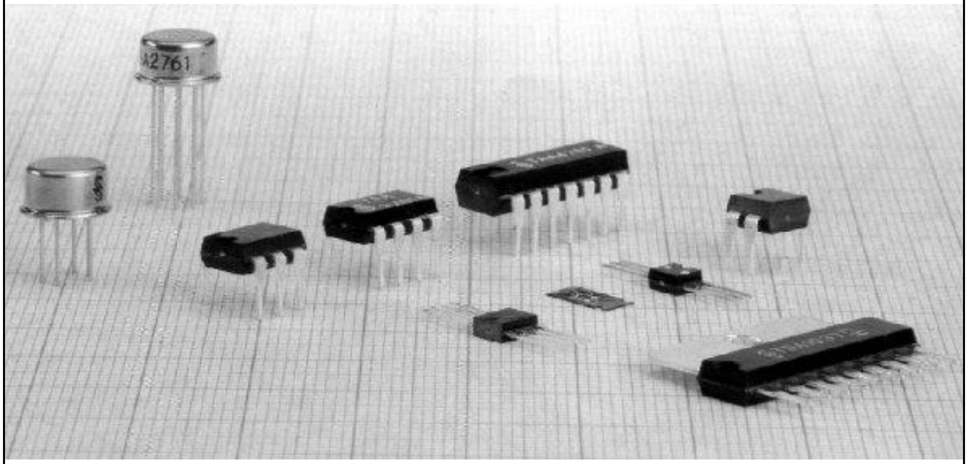


*(a)*

*Cross-Sectional View of the Circuit Shown in (a) When Transformed into a Monolithic Form*

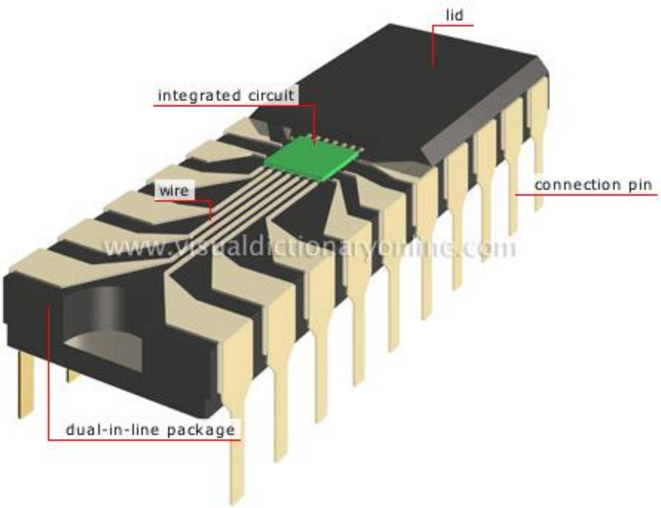
**Al Penney**
**VO1NO**

# Integrated Circuits

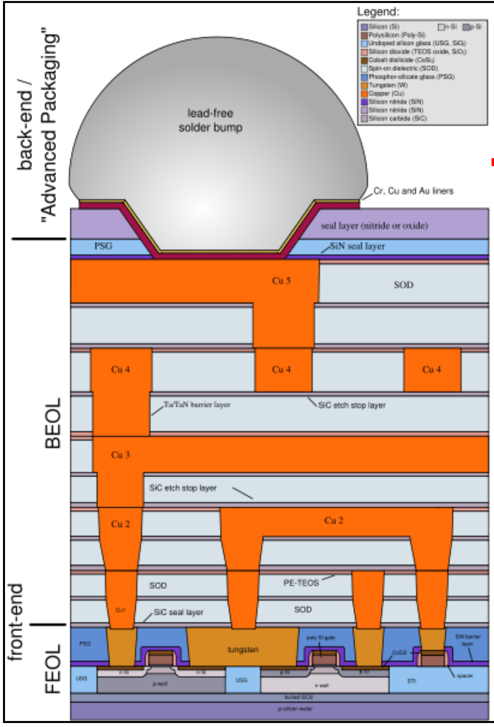


**Al Penney**
**VO1NO**

# Integrated Circuits



**Al Penney**
**VO1NO**



# Integrated Circuits

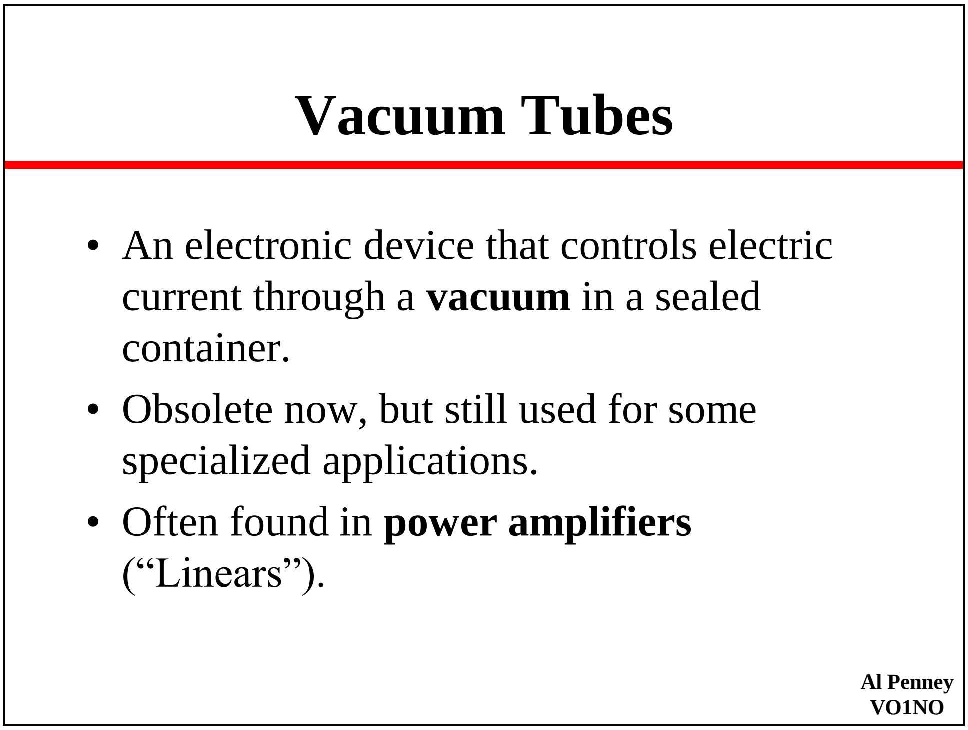
- Cross section of a multi-layer integrated circuit.

**Al Penney**
**VO1NO**

# Advantages of Integrated Circuits

- **Scale** – Millions, even billions of discrete components on a single chip.
- **Cost** – MUCH cheaper than individual components!
- **Reliability** – Manufacturing process is strictly controlled and chips thoroughly tested before leaving the factory.

**Al Penney**
**VO1NO**



# Vacuum Tubes

- An electronic device that controls electric current through a **vacuum** in a sealed container.
- Obsolete now, but still used for some specialized applications.
- Often found in **power amplifiers** (“Linears”).

**Al Penney**
**VO1NO**

In electronics, a **vacuum tube**, **electron tube** (in North America), **tube**, or **thermionic valve** or **valve** (in British English) is a device controlling electric current through a vacuum in a sealed container. The simplest vacuum tube, the diode, contains only two elements; current can only flow in one direction through the device between the two electrodes, as electrons emitted by the hot cathode travel through the tube and are collected by the anode. Addition of a third and additional electrodes allows the current flowing between cathode and anode to be controlled in various ways.[1] The device can be used as an electronic amplifier, a rectifier, an electronically controlled switch, an oscillator, and for other purposes.

Vacuum tubes mostly rely on thermionic emission of electrons from a hot filament or a cathode heated by the filament. Some electron tube devices rely on the properties of a discharge through an ionized gas.

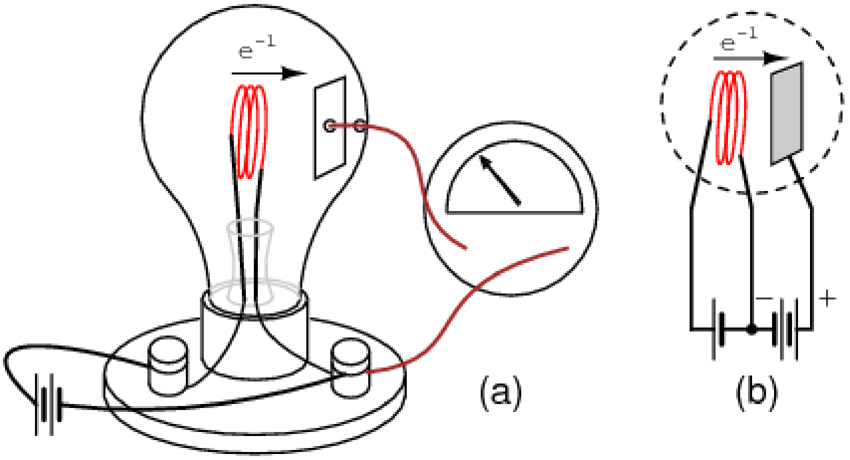
Vacuum tubes were critical to the development of electronic technology, which drove the expansion and commercialization of radio broadcasting, television, radar, sound reinforcement, sound recording and reproduction, large telephone networks, analog and digital computers, and industrial process control. Although some applications had counterparts using earlier technologies such as the spark gap transmitter or mechanical computers, it was the invention of the vacuum tube with three electrodes (called a *triode*) and its capability of electronic amplification that made these technologies widespread and practical.

In most applications, solid-state devices such as transistors and other semiconductor devices have replaced tubes. Solid-state devices last longer and are smaller, more efficient, more reliable, and cheaper than tubes. However, tubes are still manufactured for applications where solid-state devices are impractical.

**Al Penney**
**VO1NO**

Excellent explanation of vacuum tubes:
https://www.allaboutcircuits.com/textbook/semiconductors/chpt-13/introduction-electron-tubes/

# Edison Effect



Al Penney
VO1NO

**Thermionic emission** is the heat-induced flow of charge carriers from a surface or over a potential-energy barrier. This occurs because the thermal energy given to the carrier overcomes the binding potential, also known as work function of the metal. The charge carriers can be electrons or ions, and in older literature are sometimes referred to as "thermions". After emission, a charge will initially be left behind in the emitting region that is equal in magnitude and opposite in sign to the total charge emitted. But if the emitter is connected to a battery, then this charge left behind will be neutralized by charge supplied by the battery, as the emitted charge carriers move away from the emitter, and finally the emitter will be in the same state as it was before emission. The thermionic emission of electrons is also known as *thermal electron emission.*

The classical example of thermionic emission is the emission of electrons from a hot cathode into a vacuum (also known as the **Edison effect**) in a vacuum tube. The hot cathode can be a metal filament, a coated metal filament, or a separate structure of metal or carbides or borides of transition metals. Vacuum emission from metals tends to become significant only for temperatures over 1000 K. The science dealing with this phenomenon has been known as **thermionics**, but this name seems to be gradually falling into disuse.

Thomas Edison, that prolific American inventor, is often credited with the invention of the incandescent lamp. More accurately, it could be said that Edison was the man who perfected the incandescent lamp. Edison's successful design of 1879 was actually preceded by 77 years by the British scientist Sir Humphry Davy, who first demonstrated the principle of using electric current to heat a thin strip of metal (called a "filament") to the point of incandescence (glowing white hot).

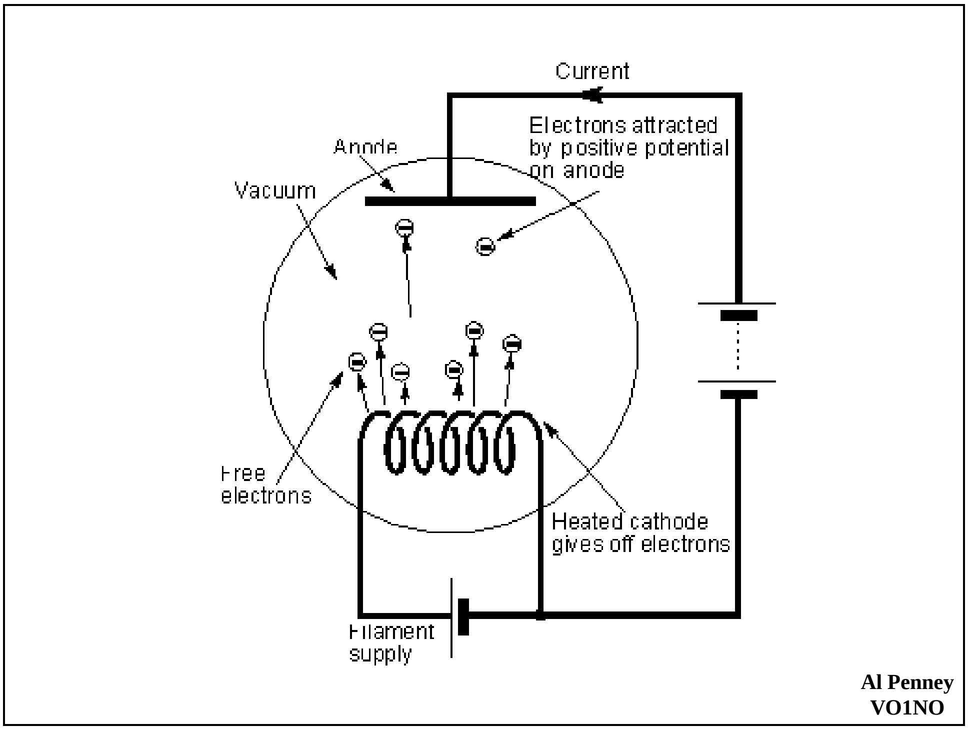
Edison was able to achieve his success by placing his filament (made of carbonized sewing thread) inside of a clear glass bulb from which the air had been forcibly removed. In this vacuum, the filament could glow at white-hot temperatures without being consumed by combustion.

In the course of his experimentation (sometime around 1883), Edison placed a strip of metal inside of an evacuated (vacuum) glass bulb along with the filament. Between this metal strip and one of the filament connections, he attached a sensitive ammeter. What he found was that electrons would flow through the meter whenever the filament was hot but ceased when the filament cooled down.

The white-hot filament in Edison's lamp was liberating free electrons into the vacuum of the lamp, those electrons finding their way to the metal strip, through the galvanometer, and back to the filament. His curiosity piqued, Edison then connected a fairly high-voltage battery in the galvanometer circuit to aid the small current. Sure enough, the presence of the battery created a much larger current from the filament to the metal strip. However, when the battery was turned around, there was little to no current at all!

In effect, what Edison had stumbled upon was a diode! Unfortunately, he saw no practical use for such a device and proceeded with further refinements in his lamp design.

The one-way electron flow of this device (known as the Edison Effect) remained a curiosity until J. A. Fleming experimented with its use in 1895. Fleming marketed his device as a "valve," initiating a whole new area of study in electric circuits. Vacuum tube diodes—Fleming's "valves" being no exception—are not able to handle large amounts of current, and so Fleming's invention was impractical for any application in AC power, only for small electric signals.



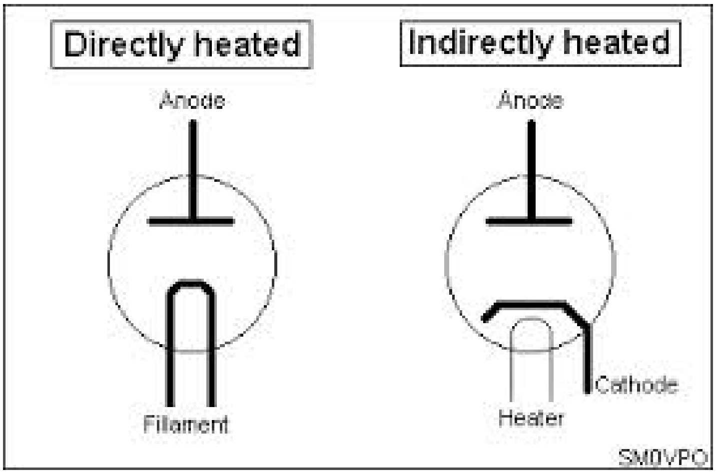
**Al Penney VO1NO**

The electrons flowing between the cathode and the anode form a cloud which is known as the "space charge". It can tend to repel electrons leaving the cathode, but if the potential applied to the anode is sufficiently high then it will be overcome, and electrons will flow toward the anode. In this way the circuit is completed and current flows.

As the potential is increased on the anode, so the current increases until a point is reached where the space change is completely neutralised and the maximum emission from the cathode is reached. At this point the emission can only be increased by increasing the cathode temperature to increase the energy of the electrons and allow further electrons to leave the cathode.

If the anode potential is reversed, and made negative with respect to the cathode it will repel the electrons. **No electrons will be emitted from the anode as it is not hot, and no current flows.** This means that current can only flow in one direction. In other words the device only allows current in one direction, blocking it in the other. In view of this effect, the inventor of the diode vacuum tube, Professor Sir Ambrose Fleming called it an "oscillation valve" in view of its one way action.

# The Diode



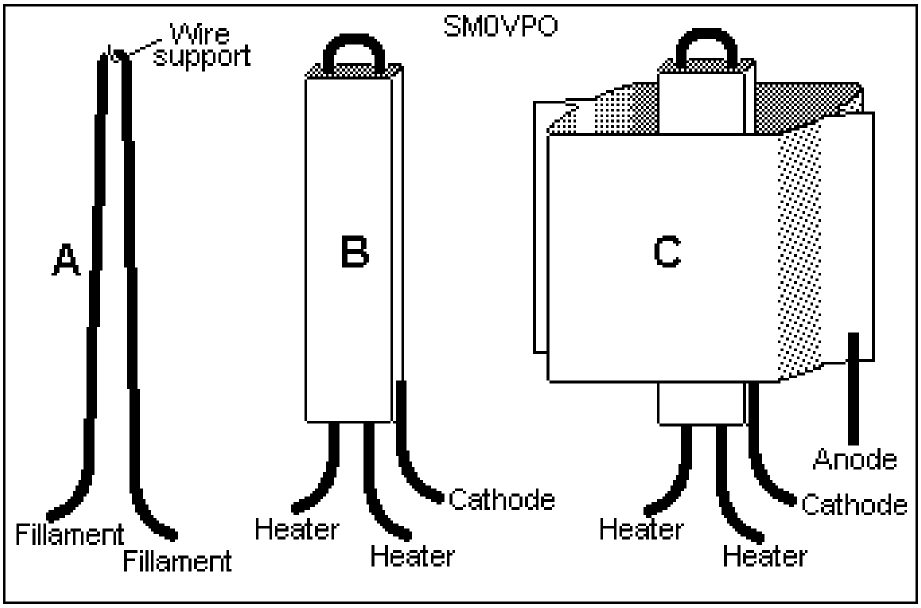
**Al Penney**
**VO1NO**

Basically, when an electrode (CATHODE) is placed in a vacuum, coated with Barium Oxide and heated to several hundred degrees, the electrons on its surface become more agitated and form a cloud around the cathode's surface. From this cloud of electrons it is easy to attract electrons to a positively charged electrode (ANODE). The anode only needs to be placed in the same vacuum as the cathode. Electrons will flow from the heated cathode to the relatively cool anode, but electrons will NOT flow from the anode to the cathode because there is no Barium Oxide coating on the anode and it is too cold. We have formed a DIODE valve. Here are the circuit symbols.

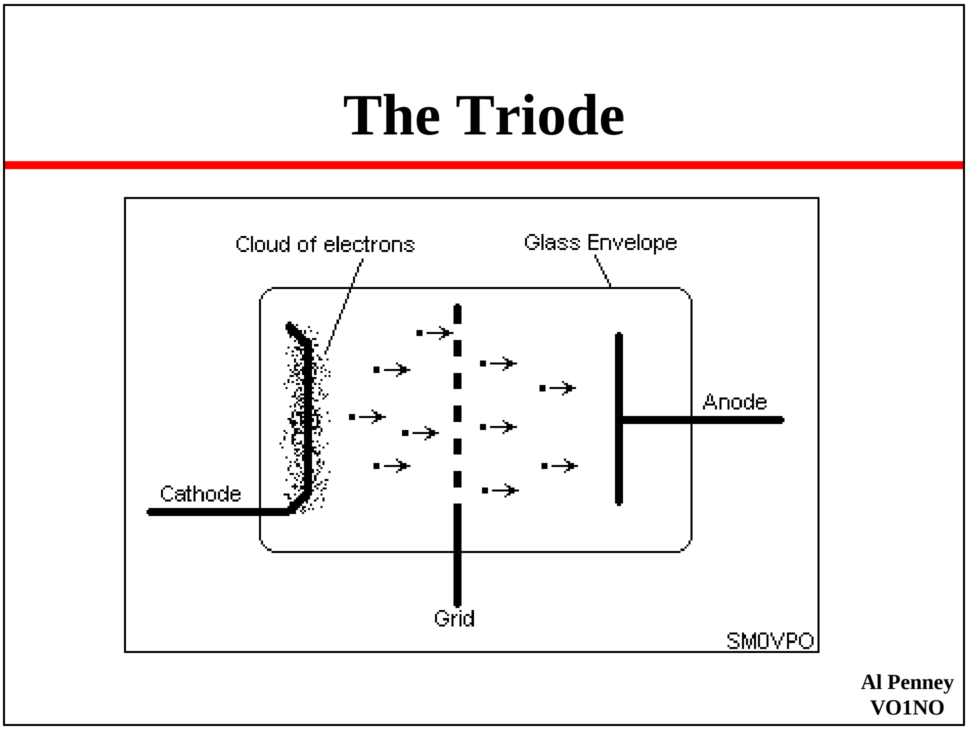
DIRECTLY HEATED
The cathode is a bit of filament wire coated with Barium Oxide and a current is passed through it to make it get hot. One of the two filament terminals is used as the cathode connection. This method of heating a valve cathode was most often used in battery portable equipment and HT rectifier valves. The filament voltage is normally 1.4 volts for battery valves such as 1T4, 1L4, 1S4, DF91, DL91 etc. Directly heated HT rectifier valves commonly used 5 volts to heat them. Early valves used only 2.5 volts for the filament.

A huge disadvantage of a directly heated diode is that current flowing from cathode to anode is added to the filament current. If this current becomes too large then the filament can become too hot and burn out, just like an overloaded torch-bulb.

INDIRECTLY HEATED
The non-coated filament wire is inserted into a Barium Oxide coated metal tube and insulated from it. The filament is only used to heat the cathode tube and so it is normally called the HEATER.



Al Penney
VO1NO



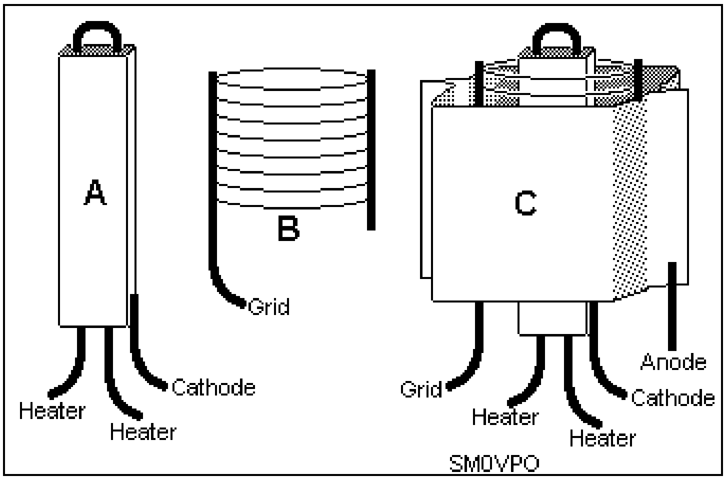
# The Triode

**Al Penney**
**VO1NO**

To make an amplifying device (and to prevent the catastrophic scenario above) we need to regulate the current flowing from the cathode to the anode of a valve. If we insert a wire mesh or GRID between the anode and the cathode we can control the electron flow and so we have created a TRIODE:

This grid is called the CONTROL GRID. With a few hundred volts positive on the ANODE and the negative on the cathode, electrons from the electron cloud around the heated cathode will go coursing their way towards the anode. But the wire mesh/grid is in the way, no problem; they just go through the holes. But if we connect a small negative voltage to the grid (with respect to the cathode) then the wires of the grid will have a field around them that will repel electrons. This field of repulsion will effectively reduce the size of the hole the electrons can pass through, thereby reducing electron flow and the anode current. If the negative voltage on the grid is made even more negative then the field of repulsion around each grid wire can become so wide that they all join up. This will cut the valve off totally and NO electrons can flow from cathode to anode.

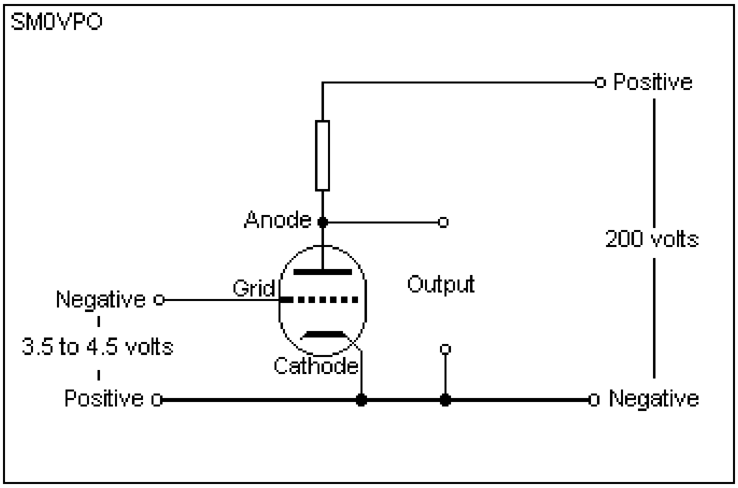
# The Triode



Al Penney
VO1NO

Here is the typical construction of a triode valve. The same cathode (A) is used as for a diode, but a grid (B) is placed around it. The grid is commonly composed of two vertical lengths of wire about 1-2mm Diameter spaced about 1 cm apart. Between these two wires a very thin 'hair-like' wire is wrapped around loosely so that it forms a circular or oval cylinder. The grid wires are spot-welded to the two vertical wires.

# Using the Triode



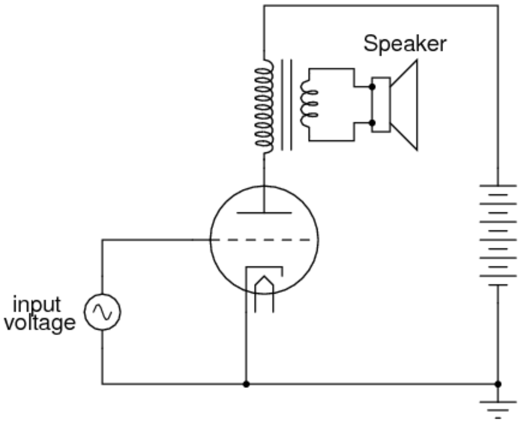
**Al Penney**
**VO1NO**

A typical triode valve will control an anode current by means of varying the voltage on the valve's grid. Typically, the anode will be 2mA (0.002 Amperes) for a grid voltage of 4 volts NEGATIVE (with respect to cathode). If we vary the grid voltage from -3.5 to -4.5 volts the anode current will vary, typically, from 1mA to 3mA.

By varying the grid by 1 volt (-3.5v to -4.5v) the anode current changed from 1mA to 3mA. The CHANGE is 2mA. The 2mA change will give us a 100 volt change across the anode load resistor. One volt signal in = 100 volts of signal out. Voltage amplification factor is therefore 100, and this figure is quite typical for a valve.

Note that there is no current flowing to or from the grid under normal conditions. The grid input impedance is therefore not far from infinity.

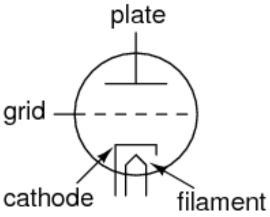
# Triode Audio Amplifier



Al Penney
VO1NO

# Grid Bias

- If we make the grid sufficiently negative, all electrons will be repelled, and none will get through to the Anode.
- This is called **cut-off**.
- That voltage value is called the **cut-off bias**.



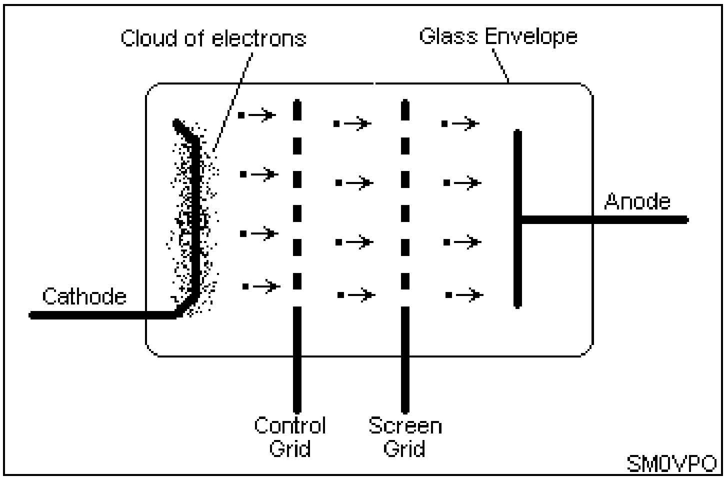
**Al Penney**
**VO1NO**

# Comparison – Transistors and Tubes

| | Transistor | FET | Triode |
|---|---|---|---|
| Input | Emitter | Source | Cathode |
| Output | Collector | Drain | Plate/Anode |
| Control | Base | Gate | Control Grid |

Al Penney
VO1NO

# The Tetrode



Al Penney
VO1NO

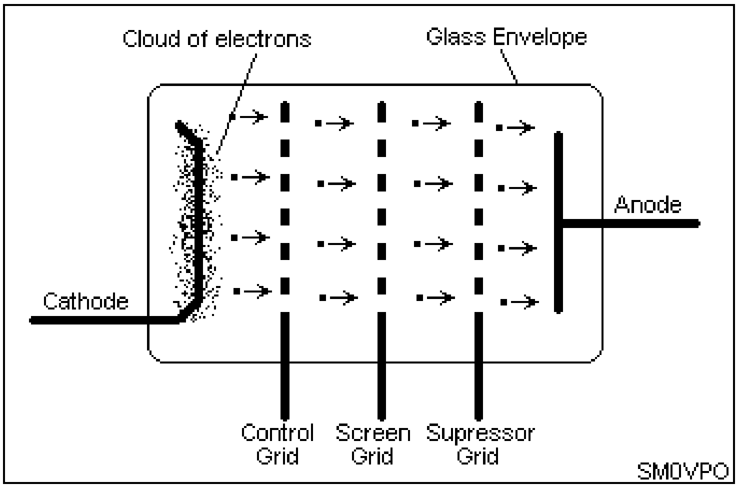
**One of the biggest problems with the triode valve is the small current it will handle. Anode currents of a couple of milli-amperes are of little use for powers above about half a watt. For radio frequency use, the capacitance between the anode and the control grid of a valve can become a problem by providing unwanted feedback. Earlier triode valves used anodes or grids mounted at the top of the glass bulb as an attempt to get the connections as far away from the others as possible.**

Another solution was to insert a second grid between the control grid and the anode. This additional grid was called a SCREEN GRID and a valve with two grids is called a TETRODE.

The valve may still be used exactly as a triode, but a few hundred positive volts are applied to the screen grid, usually about 66% of the anode voltage. Electrons whizzing past the negative control grid are retarded, but immediately after the control grid lies a few hundred positive volts on the screen grid, so the electrons continue their journey with renewed vigour. As they get to the screen grid they will feel the influence of the anode with its higher potential and so the majority will head for that.

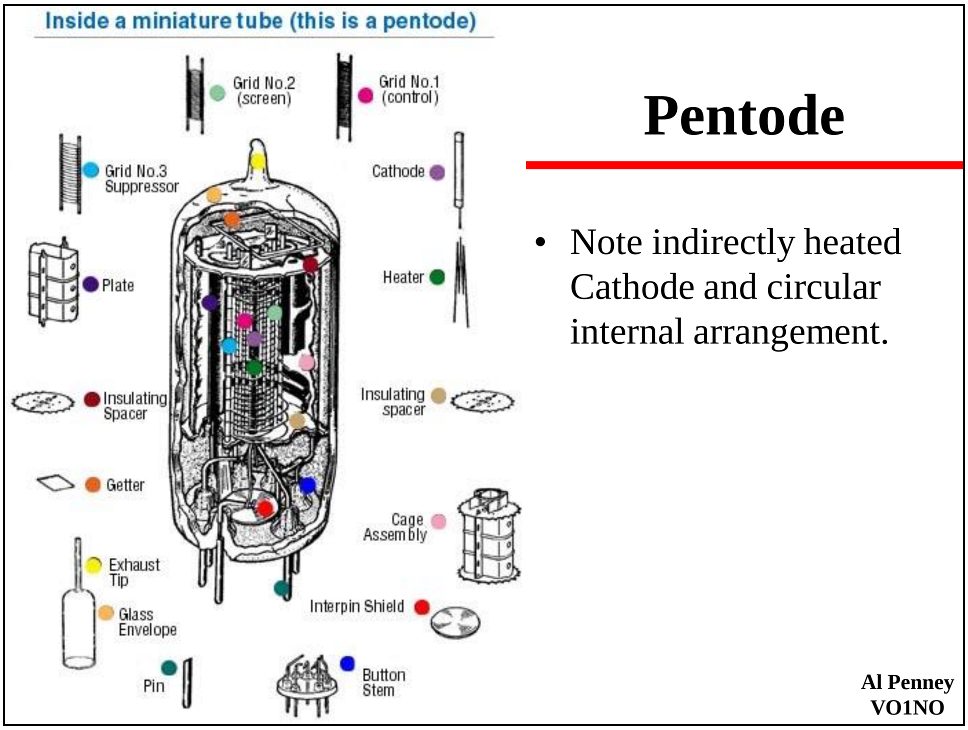
**When the electrons flying through a tetrode hit the anode they can knock electrons off the anode plate due to the impact. Most of these 'liberated' electrons become attracted back to the anode. Some, however, are happy with their freedom and fall under the influence of the screen grid. This is called SECONDARY EMISSION. Secondary emission gives the tetrode characteristic curve a very peculiar non-linear 'kink'.**

# The Pentode



**Al Penney**
**VO1NO**

The solution to the 'kinky' tetrode is the PENTODE, which has yet another grid, the SUPRESSOR GRID (G3). The suppressor grid is normally held at cathode potential so any electrons liberated from the anode are shielded from the screen grid. This way they only feel the attractive force of the positively charges anode, so they go back to the anode where they belong.



# Pentode

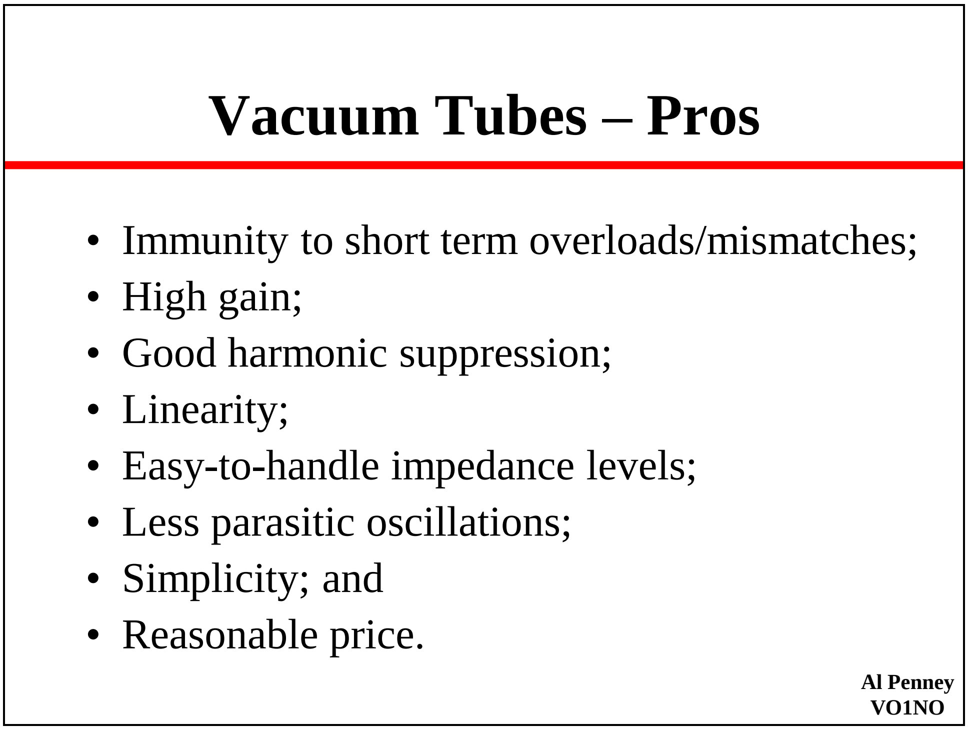
- Note indirectly heated Cathode and circular internal arrangement.

Al Penney
VO1NO

A **getter** is a deposit of reactive material that is placed inside a vacuum system, for the purpose of completing and maintaining the vacuum. When gas molecules strike the getter material, they combine with it chemically or by absorption. Thus the getter removes small amounts of gas from the evacuated space. The getter is usually a coating applied to a surface within the evacuated chamber.

A vacuum is initially created by connecting a closed container to a vacuum pump. After achieving a vacuum, the container can be sealed, or the vacuum pump can be left running. Getters are especially important in sealed systems, such as vacuum tubes, including cathode ray tubes (CRTs) and vacuum insulated panels, which must maintain a vacuum for a long time. This is because the inner surfaces of the container release absorbed gases for a long time after the vacuum is established. The getter continually removes this residual gas as it is produced. Even in systems which are continually evacuated by a vacuum pump, getters are also used to remove residual gas, often to achieve a higher vacuum than the pump could achieve alone. Although it weighs almost nothing and has no moving parts, a getter is itself a vacuum pump.

Getters cannot react permanently with inert gases, though some getters will absorb them in a reversible fashion. Also, hydrogen is usually handled by adsorption rather than reaction.



# Vacuum Tubes – Pros

- Immunity to short term overloads/mismatches;
- High gain;
- Good harmonic suppression;
- Linearity;
- Easy-to-handle impedance levels;
- Less parasitic oscillations;
- Simplicity; and
- Reasonable price.

Al Penney
VO1NO

## Pros for vacuum tube amps for the RF bands

•**High immunity to short-time overloads or mismatches**. This is due to large structures with suffient heat capacity that can absorb temporary power peaks without melting instantly.

•**High gain**. At HF, you can drive a 100W amp with QRP levels with ease. To be honest, modern FETs also have very a high gain nowadays.

•**Good harmonic suppression**. Due to the use of a tuned Pi filter for matching, harmonics are well supressed without any special effort.

•**Linearity**. Tubes, especially when using high anode voltages, tend to be more linear than (at least bipolar) transistors. Overdrive and saturation behavior of tubes is more benevolent than transistor circuitry. With tube amps, you hardly ever need the extensive low-pass filter banks that are a must for transistor amps.

•**Easy-to-handle impedance levels**. While high-power transistors exhibit impedance levels below 1 Ohm in extreme cases, vacuum tubes have impedances in the hundreds of Ohms to a few kOhms range. This makes broadband matching a lot easier.

•**Less parasitic oscillations**. If you obey a few rules of thumb, tube amps not so prone to parasitic oscillations as modern, high ft RF power transistors. Parasitic oscillations killing the gate oxide by overvoltage are one of the most prominent (and very hard to find) causes of DMOS RF power transistor malfunctions.

•**Simplicity**. Tube amps can be built with a lower number of components compared to transistor amps.

•**Price**. Up to a few 100W, there are a lot of surplus tubes on the market, a lot of them from russian manufacturers. DMOS transistors in the hundreds of Watts range are still expensive even today.

# Vacuum Tubes – Cons

- Lethal supply voltages;
- Physical size;
- Limited tube life;
- Arcing;
- Safety hazards; and
- Generates much heat.

**Al Penney**
**VO1NO**

Cons for vacuum tube amps for the RF bands

•**Lethal supply voltages** in the range of a few 100 Volts up to several kV are used. “Lethal” is no joke; if you touch the high voltage side of a tube amp, you are lucky to survive this. Careful component selection, wide safety margins and an “airy” design with long isolation paths is a must, as well as proper screening and safety high voltage power supply design.

•**Physical size**. Compared to semiconductor solutions (up to a certain power level) tube amps seem to be larger and heavier. This does not hold for tens of kilowatts or even more powerful amps; in these power ranges tubes still dominate.

•**Limited tube life**. Depending on the power level used, tubes have lifetimes from a few 100 hours to 10000 hours. The typical “aging” failure mode of a tube is reduced emission (“dull” cathode) or rupture of the filament. Many amateurs tend to run their tubes a lot outside their limits and get away with it (for ICAS service, with additional forced air cooling, and for a limited time only). If, on the contrary, you run your tube amp conservatively and with proper cooling, it could last a lifetime.

•**Arcovers**. This is a spectacular failure mode caused by arcs from cathode to anode or anode to grid. It is normally caused by gas eruptions (originating from the heated cathode, often after prolonged periods of inoperation) that create an ionized plasma in the tube resulting in a straight short and spot-welding tube structures like the (low thermal inertia) grids or the anode material. The energy in the high voltage power supply output stabilization caps (can be 10s of Joules) is dumped into the arc, often evaporizing components in the anode high voltage lines or the grid circuitry, too. Resist the temptation to just use normal glass fuses here; they will melt, but due to the high voltage the arc current flow will not stop. High voltage (microwave oven type or better) glass fuses are a must.

•**Safety Hazards**. Tube designs have very few components, but due to the high voltages used these components are *critical* and the consequences of their failure can be drastic. This mainly applies to capacitors. Their working voltage must be chosen with a wide safety margin (100% minimum), and it must be clear that their loss tangent is low enough so they dont heat up due to the high RF currents flowing thru them (do calculate RF currents and voltages also for mismatched loads !!!).
By all means a punch-thru of the anode high voltage to the antenna output must be prevented. This normally is the job of an output choke. This choke must never blow up in case of a tube arcover, output cap or other failure, and it must be without resonances in the complete frequency range of the amplifier. For a 1.8MHz to 30MHz amp, this is less easy than you might think.
The power supply capacitors are a hazard of its own; the energy stored there can kill even after mains power has been disconnected. Bleeding resistors must make sure that the voltage is down to nonhazardous levels after, say, 30 seconds after power off. These resistors must be either (double) chains of normal resistors or special high voltage, high power resistors. If the high voltage caps are constructed of electrolytic capacitors, voltage equalization resistors are compulsory, too. The same goes for rectifiers made from strings of silicon diodes.
All resistors must be checked not only for their power rating, but also for rated voltage. If it is too high, use a series connection of several resistors.

•Barium Oxide: Barium oxide is an irritant. If it contacts the skin or the eyes or is inhaled it causes pain and redness. However, it is more dangerous when ingested. It can cause nausea and diarrhea, muscle paralysis, cardiac arrhythmia, and can cause death. If ingested, medical attention should be sought immediately.

•Barium oxide should not be released environmentally; it is harmful to aquatic organisms

# Questions?

Al Penney
VO1NO

# Review Question 1

Zener diodes are used as:

- current regulators
- RF detectors
- AF detectors
- voltage regulators

**Al Penney**
**VO1NO**

# Review Question 1

Zener diodes are used as:

- current regulators
- RF detectors
- AF detectors
- voltage regulators

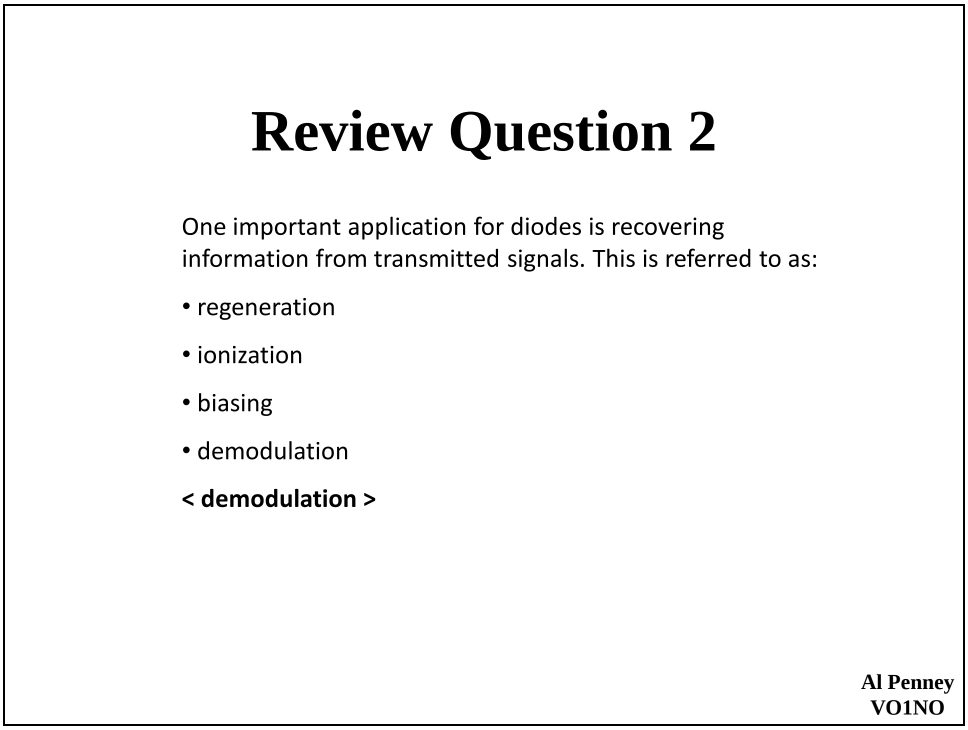
**< voltage regulators >**

# Review Question 2

One important application for diodes is recovering information from transmitted signals. This is referred to as:

- regeneration
- ionization
- biasing
- demodulation

**Al Penney**
**VO1NO**



# Review Question 2

One important application for diodes is recovering information from transmitted signals. This is referred to as:

- regeneration
- ionization
- biasing
- demodulation

**< demodulation >**

**Al Penney**
**VO1NO**

# Review Question 3

The action of changing alternating current to direct current is called:

- rectification
- amplification
- transformation
- modulation

**Al Penney**
**VO1NO**

# Review Question 3

The action of changing alternating current to direct current is called:

- rectification
- amplification
- transformation
- modulation

**< rectification >**

**Al Penney**
**VO1NO**

# Review Question 4

The electrodes of a semi-conductor diode are known as:

- anode and cathode
- gate and source
- collector and base
- cathode and drain

# Review Question 4

The electrodes of a semi-conductor diode are known as:

- anode and cathode
- gate and source
- collector and base
- cathode and drain

**< anode and cathode >**

# Review Question 5

In a semi-conductor diode, electrons flow from:

- cathode to grid
- grid to anode
- cathode to anode
- anode to cathode

**Al Penney**
**VO1NO**

# Review Question 5

In a semi-conductor diode, electrons flow from:

- cathode to grid
- grid to anode
- cathode to anode
- anode to cathode

**< cathode to anode >**

**Al Penney**
**VO1NO**

# Review Question 6

What semi-conductor device glows different colours depending upon its chemical composition?

- A neon bulb
- A vacuum diode
- A light-emitting diode
- A fluorescent bulb

**Al Penney**
**VO1NO**

# Review Question 6

What semi-conductor device glows different colours depending upon its chemical composition?

- A neon bulb
- A vacuum diode
- A light-emitting diode
- A fluorescent bulb

**< A light-emitting diode >**

**Al Penney**
**VO1NO**

# Review Question 7

Voltage regulation is the principal application of the:

- light-emitting diode
- vacuum diode
- Zener diode
- junction diode

**Al Penney**
**VO1NO**

# Review Question 7

Voltage regulation is the principal application of the:

- light-emitting diode
- vacuum diode
- Zener diode
- junction diode

**< Zener diode >**

**Al Penney**
**VO1NO**

# Review Question 8

In order for a diode to conduct, it must be:

- reverse-biased
- forward-biased
- close coupled
- enhanced

# Review Question 8

In order for a diode to conduct, it must be:

- reverse-biased
- forward-biased
- close coupled
- enhanced

**< forward-biased >**

**Al Penney**
**VO1NO**

# Review Question 9

Which component can amplify a small signal using low voltages?

- A multiple-cell battery
- A PNP transistor
- A variable resistor
- An electrolytic capacitor

**Al Penney**
**VO1NO**

# Review Question 9

Which component can amplify a small signal using low voltages?

- A multiple-cell battery
- A PNP transistor
- A variable resistor
- An electrolytic capacitor

**< A PNP transistor >**

**Al Penney**
**VO1NO**

# Review Question 10

The three leads from a PNP transistor are named:

- collector, source and drain
- gate, source and drain
- collector, emitter and base
- drain, base and source

**Al Penney**
**VO1NO**

# Review Question 10

The three leads from a PNP transistor are named:

- collector, source and drain
- gate, source and drain
- collector, emitter and base
- drain, base and source

**< collector, emitter and base >**

**Al Penney**
**VO1NO**

# Review Question 11

If a low level signal is placed at the input to a transistor, a higher level of signal is produced at the output lead. This effect is known as:

- rectification
- amplification
- detection
- modulation

# Review Question 11

If a low level signal is placed at the input to a transistor, a higher level of signal is produced at the output lead. This effect is known as:

- rectification
- amplification
- detection
- modulation

**< amplification >**

**Al Penney**
**VO1NO**

# Review Question 12

A semi-conductor is described as a “general purpose audio NPN device”. This would be:

- a bipolar transistor
- a silicon diode
- a triode
- an audio detector

**Al Penney**
**VO1NO**

# Review Question 12

A semi-conductor is described as a “general purpose audio NPN device”. This would be:

- a bipolar transistor
- a silicon diode
- a triode
- an audio detector

**< a bipolar transistor >**

**Al Penney**
**VO1NO**

# Review Question 13

The two basic types of bipolar transistors are:

- varicap and Zener types
- P and N channel types
- NPN and PNP types
- diode and triode types

**Al Penney**
**VO1NO**

# Review Question 13

The two basic types of bipolar transistors are:

- varicap and Zener types
- P and N channel types
- NPN and PNP types
- diode and triode types

**< NPN and PNP types >**

**Al Penney**
**VO1NO**

# Review Question 14

In a bipolar transistor, the compares closest to the control grid of a triode vacuum tube.

- collector
- base
- emitter
- source

**Al Penney**
**VO1NO**

# Review Question 14

In a bipolar transistor, the compares closest to the control grid of a triode vacuum tube.

- collector
- base
- emitter
- source

**< base >**

**Al Penney**
**VO1NO**

# Review Question 15

In a bipolar transistor, the compares closest to the plate of a triode vacuum tube.

- gate
- emitter
- base
- collector

**Al Penney**
**VO1NO**

# Review Question 15

In a bipolar transistor, the compares closest to the plate of a triode vacuum tube.

- gate
- emitter
- base
- collector

**< collector >**

**Al Penney**
**VO1NO**

# Review Question 16

In a bipolar transistor, the compares closest to the cathode of a triode vacuum tube.

- emitter
- collector
- base
- drain

**Al Penney**
**VO1NO**

# Review Question 16

In a bipolar transistor, the compares closest to the cathode of a triode vacuum tube.

- emitter
- collector
- base
- drain

**< emitter >**

**Al Penney**
**VO1NO**

# Review Question 17

The two basic types of field effect transistors (FET) are:

- inductive and capacitive
- N and P channel
- NPN and PNP
- germanium and silicon

**Al Penney**
**VO1NO**

# Review Question 17

The two basic types of field effect transistors (FET) are:

- inductive and capacitive
- N and P channel
- NPN and PNP
- germanium and silicon

**< N and P channel >**

# Review Question 18

A semi-conductor having its leads labeled gate, drain, and source is best described as a:

- silicon diode
- field-effect transistor
- gated transistor
- bipolar transistor

**Al Penney**
**VO1NO**

# Review Question 18

A semi-conductor having its leads labeled gate, drain, and source is best described as a:

- silicon diode
- field-effect transistor
- gated transistor
- bipolar transistor

**< field-effect transistor >**

**Al Penney**
**VO1NO**

# Review Question 19

In a field effect transistor, the is the terminal that controls the conductance of the channel.

- drain
- source
- collector
- gate

**Al Penney**
**VO1NO**

# Review Question 19

In a field effect transistor, the is the terminal that controls the conductance of the channel.

- drain
- source
- collector
- gate

**< gate >**

**Al Penney**
**VO1NO**

# Review Question 20

If you wish to reduce the current flowing in a field effect transistor, you could:

- decrease the reverse bias voltage
- increase the forward bias voltage
- increase the forward bias gain
- increase the reverse bias voltage

**Al Penney**
**VO1NO**

# Review Question 20

If you wish to reduce the current flowing in a field effect transistor, you could:

- decrease the reverse bias voltage
- increase the forward bias voltage
- increase the forward bias gain
- increase the reverse bias voltage

**< increase the reverse bias voltage >**

**Al Penney**
**VO1NO**

# Review Question 21

The source of a field effect transistor corresponds to the of a bipolar transistor.

- base
- drain
- collector
- emitter

Al Penney
VO1NO

# Review Question 21

The source of a field effect transistor corresponds to the of a bipolar transistor.

- base
- drain
- collector
- emitter

**< emitter >**

**Al Penney**
**VO1NO**

# Review Question 22

The drain of a field effect transistor corresponds to the of a bipolar transistor.

- base
- source
- emitter
- collector

**Al Penney**
**VO1NO**

# Review Question 22

The drain of a field effect transistor corresponds to the of a bipolar transistor.

- base
- source
- emitter
- collector

**< collector >**

**Al Penney**
**VO1NO**

# Review Question 23

Which two elements in a field effect transistor exhibit fairly similar characteristics?

- Source and base
- Source and drain
- Source and gate
- Gate and drain

**Al Penney**
**VO1NO**

# Review Question 23

Which two elements in a field effect transistor exhibit fairly similar characteristics?

- Source and base
- Source and drain
- Source and gate
- Gate and drain

**< Source and drain >**

**Al Penney**
**VO1NO**

# Review Question 24

What is one reason a triode vacuum tube might be used instead of a transistor in a circuit?

- It is much smaller
- It uses lower voltages
- It may be able to handle higher power
- It uses less current

**Al Penney**
**VO1NO**

# Review Question 24

What is one reason a triode vacuum tube might be used instead of a transistor in a circuit?

- It is much smaller
- It uses lower voltages
- It may be able to handle higher power
- It uses less current

**< It may be able to handle higher power >**

**Al Penney**
**VO1NO**

# Review Question 25

Which component can amplify a small signal but must use high voltages?

- A multiple-cell battery
- A vacuum tube
- A transistor
- An electrolytic capacitor

**Al Penney**
**VO1NO**

# Review Question 25

Which component can amplify a small signal but must use high voltages?

- A multiple-cell battery
- A vacuum tube
- A transistor
- An electrolytic capacitor

**< A vacuum tube >**

# Review Question 26

A feature common to triode tubes and transistors is that both:

- convert electrical energy to radio waves
- use heat to cause electron movement
- can amplify signals
- have electrons drifting through a vacuum

**Al Penney**
**VO1NO**

# Review Question 26

A feature common to triode tubes and transistors is that both:

- convert electrical energy to radio waves
- use heat to cause electron movement
- can amplify signals
- have electrons drifting through a vacuum

**< can amplify signals >**

# Review Question 27

In a vacuum tube, the electrode that is operated with the highest positive potential is the:

- plate
- filament (heater)
- cathode
- grid

**Al Penney**
**VO1NO**

# Review Question 27

In a vacuum tube, the electrode that is operated with the highest positive potential is the:

- plate
- filament (heater)
- cathode
- grid

**< plate >**

**Al Penney**
**VO1NO**

# Review Question 28

In a vacuum tube, the electrode that is usually a cylinder of wire mesh is the:

- filament (heater)
- cathode
- plate
- grid

# Review Question 28

In a vacuum tube, the electrode that is usually a cylinder of wire mesh is the:

- filament (heater)
- cathode
- plate
- grid

**< grid >**

# Review Question 29

In a vacuum tube, the element that is furthest away from the plate is the:

- cathode
- filament (heater)
- grid
- emitter

# Review Question 29

In a vacuum tube, the element that is furthest away from the plate is the:

- cathode
- filament (heater)
- grid
- emitter

**< filament (heater) >**

**Al Penney**
**VO1NO**

# Review Question 30

In a vacuum tube, the electrode that emits electrons is the:

- grid
- collector
- plate
- cathode

**Al Penney**
**VO1NO**

# Review Question 30

In a vacuum tube, the electrode that emits electrons is the:

- grid
- collector
- plate
- cathode

**< cathode >**

# Review Question 31

What is inside the envelope of a triode tube?

- A vacuum
- Argon
- Air
- Neon

**Al Penney**
**VO1NO**

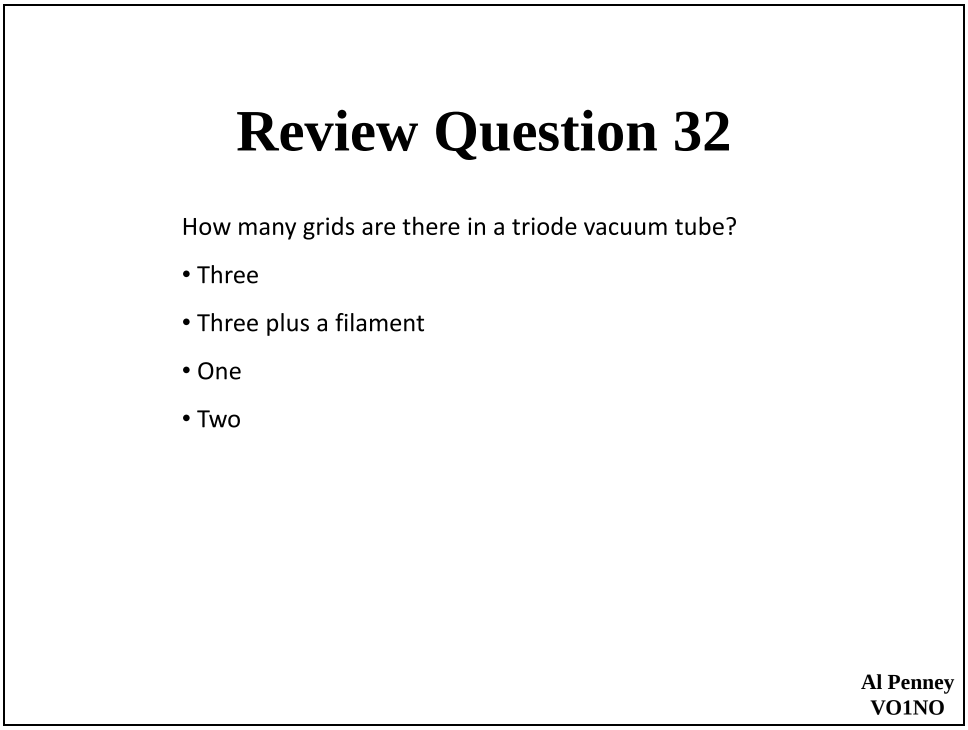
# Review Question 31

What is inside the envelope of a triode tube?

- A vacuum
- Argon
- Air
- Neon

**< A vacuum >**

Al Penney
VO1NO

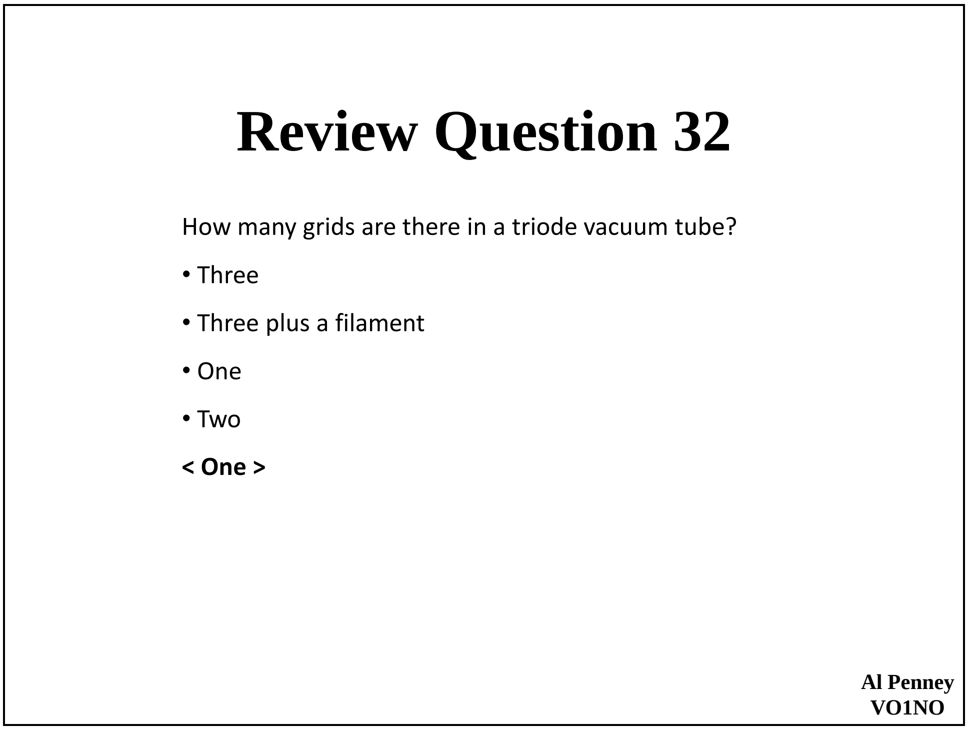


# Review Question 32

How many grids are there in a triode vacuum tube?

- Three
- Three plus a filament
- One
- Two

**Al Penney**
**VO1NO**



# Review Question 32

How many grids are there in a triode vacuum tube?

- Three
- Three plus a filament
- One
- Two

**< One >**

**Al Penney**
**VO1NO**

# Review Question 33

A circuit designed to increase the level of its input signal is called:

- a modulator
- an oscillator
- a receiver
- an amplifier

**Al Penney**
**VO1NO**

# Review Question 33

A circuit designed to increase the level of its input signal is called:

- a modulator
- an oscillator
- a receiver
- an amplifier

**< an amplifier >**

**Al Penney**
**VO1NO**

# Review Question 34

If an amplifier becomes non-linear, the output signal would:

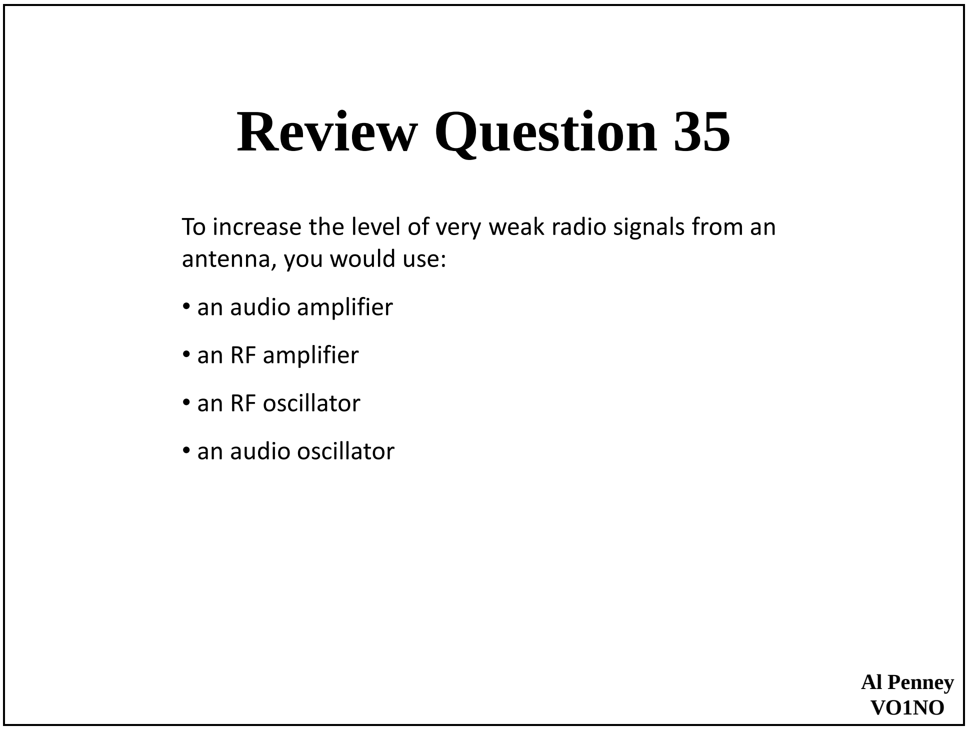
- cause oscillations
- overload the power supply
- become distorted
- be saturated

# Review Question 34

If an amplifier becomes non-linear, the output signal would:

- cause oscillations
- overload the power supply
- become distorted
- be saturated

**< become distorted >**

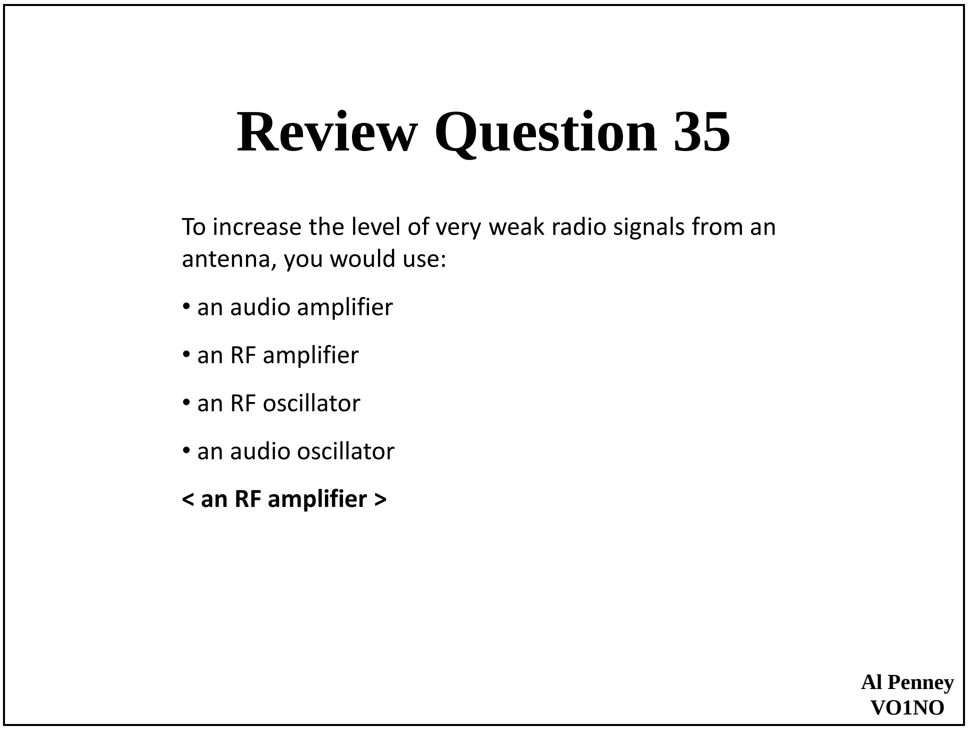


# Review Question 35

To increase the level of very weak radio signals from an antenna, you would use:

- an audio amplifier
- an RF amplifier
- an RF oscillator
- an audio oscillator

**Al Penney**
**VO1NO**



# Review Question 35

To increase the level of very weak radio signals from an antenna, you would use:

- an audio amplifier
- an RF amplifier
- an RF oscillator
- an audio oscillator

**< an RF amplifier >**

**Al Penney**
**VO1NO**

# Review Question 36

To increase the level of very weak signals from a microphone you would use:

- an RF oscillator
- an RF amplifier
- an audio oscillator
- an audio amplifier

Al Penney
VO1NO

# Review Question 36

To increase the level of very weak signals from a microphone you would use:

- an RF oscillator
- an RF amplifier
- an audio oscillator
- an audio amplifier

**< an audio amplifier >**

**Al Penney**
**VO1NO**

# Review Question 37

The range of frequencies to be amplified by a speech amplifier is typically:

- 3 to 300 Hz
- 300 to 1000 Hz
- 40 to 40 000 Hz
- 300 to 3000 Hz

**Al Penney**
**VO1NO**

# Review Question 37

The range of frequencies to be amplified by a speech amplifier is typically:

- 3 to 300 Hz
- 300 to 1000 Hz
- 40 to 40 000 Hz
- 300 to 3000 Hz

**< 300 to 3000 Hz >**

**Al Penney**
**VO1NO**

# Review Question 38

Which of the following is NOT amplified by an amplifier?

- Voltage
- Resistance
- Current
- Power

**Al Penney**
**VO1NO**

# Review Question 38

Which of the following is NOT amplified by an amplifier?

- Voltage
- Resistance
- Current
- Power

**< Resistance >**

**Al Penney**
**VO1NO**

# Review Question 39

The increase in signal level by an amplifier is called:

- modulation
- gain
- attenuation
- amplitude

# Review Question 39

The increase in signal level by an amplifier is called:

- modulation
- gain
- attenuation
- amplitude

**< gain >**

# Review Question 40

A device with gain has the property of:

- modulation
- amplification
- attenuation
- oscillation

**Al Penney**
**VO1NO**

# Review Question 40

A device with gain has the property of:

- modulation
- amplification
- attenuation
- oscillation

**< amplification >**

**Al Penney**
**VO1NO**

# Review Question 41

Amplifiers can amplify:

- voltage, current, or inductance
- voltage, current, or power
- current, power, or inductance
- voltage, power, or inductance

**Al Penney**
**VO1NO**

# Review Question 41

Amplifiers can amplify:

- voltage, current, or inductance
- voltage, current, or power
- current, power, or inductance
- voltage, power, or inductance

**< voltage, current, or power >**

**Al Penney**
**VO1NO**

# Questions?

Al Penney
VO1NO

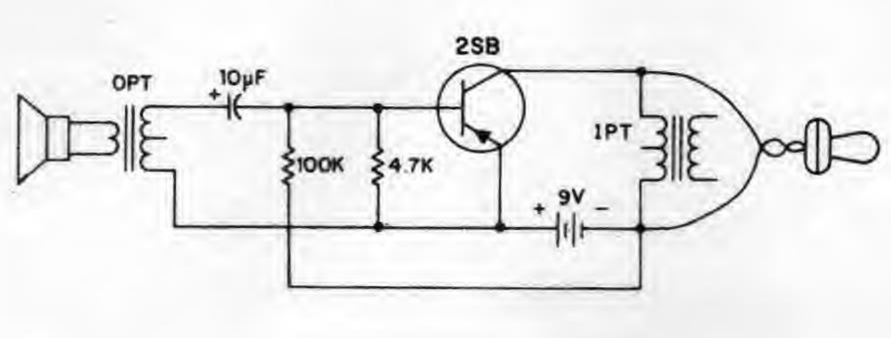
# For Next Class:

- Review Chapter 9 of Basic Study Guide;
- Read Chapter 10 of Basic Study Guide;
- Read RBR-4: https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10650.html
- Read Regulations Handout; and
- Do Practice Tests.

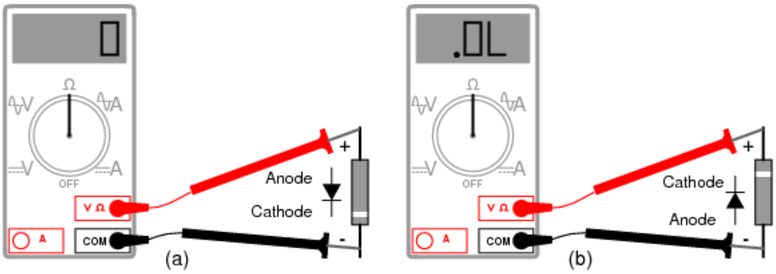
# Questions?

Al Penney
VO1NO

# Simple Audio Amplifier



# Checking Diodes



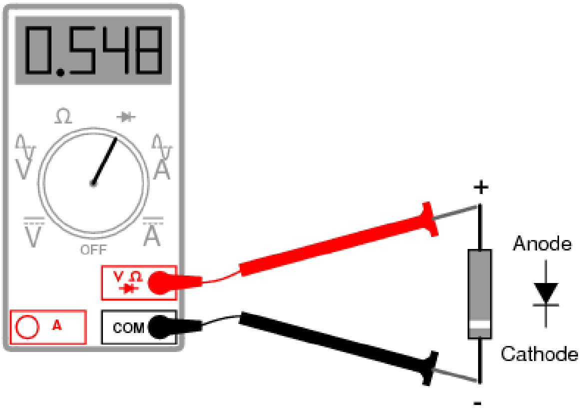
**Al Penney**
**VO1NO**

Being able to determine the polarity (cathode versus anode) and basic functionality of a diode is a very important skill for the electronics hobbyist or technician to have. Since we know that a diode is essentially nothing more than a one-way valve for electricity, it makes sense we should be able to verify its one-way nature using a DC (battery-powered) ohmmeter as in Figure below. Connected one way across the diode, the meter should show a very low resistance at (a). Connected the other way across the diode, it should show a very high resistance at (b) (“OL” on some digital meter models).

Of course, to determine which end of the diode is the cathode and which is the anode, you must know with certainty which test lead of the meter is positive (+) and which is negative (-) when set to the “resistance” or “Ω” function. With most digital multimeters I've seen, the red lead becomes positive and the black lead negative when set to measure resistance, in accordance with standard electronics color-code convention. However, this is not guaranteed for all meters. Many analog multimeters, for example, actually make their black leads positive (+) and their red leads negative (-) when switched to the “resistance” function, because it is easier to manufacture it that way!

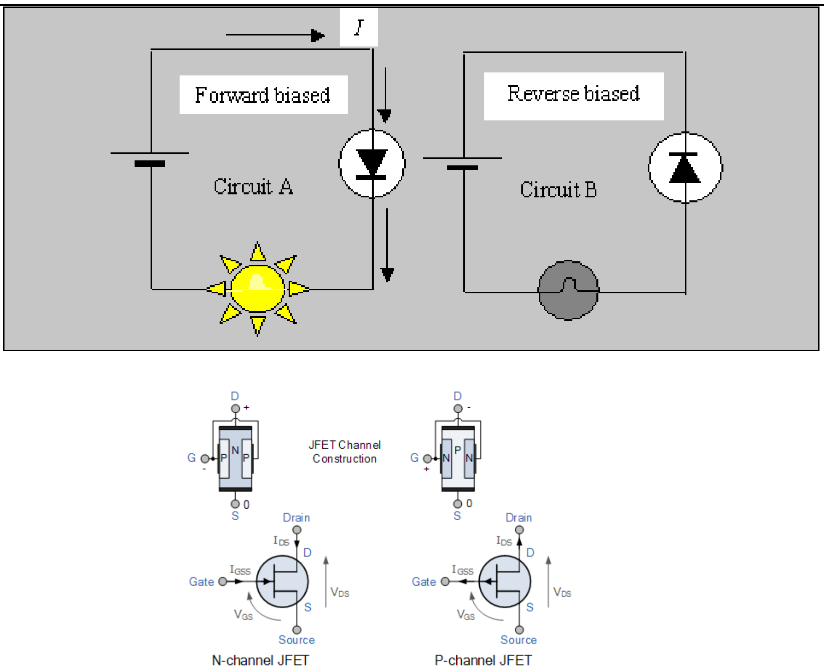
One problem with using an ohmmeter to check a diode is that the readings obtained only have qualitative value, not quantitative. In other words, an ohmmeter only tells you which way the diode conducts; the low-value resistance indication obtained while conducting is useless. If an ohmmeter shows a value of "1.73 ohms" while forward-biasing a diode, that figure of 1.73 Ω doesn't represent any real-world quantity useful to us as technicians or circuit designers. It neither represents the forward voltage drop nor any "bulk" resistance in the semiconductor material of the diode itself, but rather is a figure dependent upon both quantities and will vary substantially with the particular ohmmeter used to take the reading.

# Diode Check Function



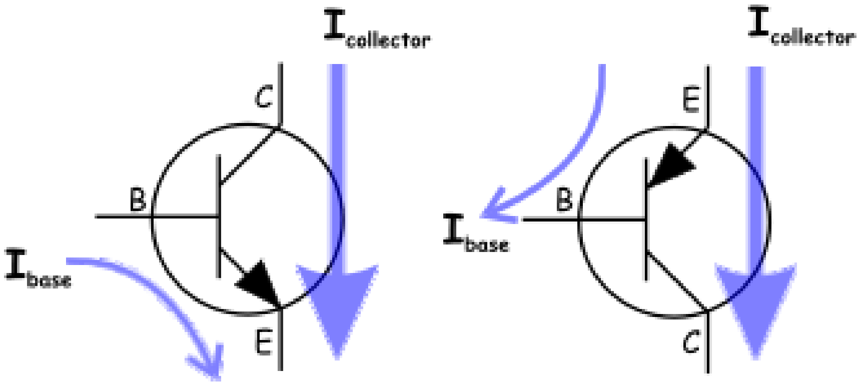
**Al Penney**
**VO1NO**

For this reason, some digital multimeter manufacturers equip their meters with a special “diode check” function which displays the actual forward voltage drop of the diode in volts, rather than a “resistance” figure in ohms. These meters work by forcing a small current through the diode and measuring the voltage dropped between the two test leads.



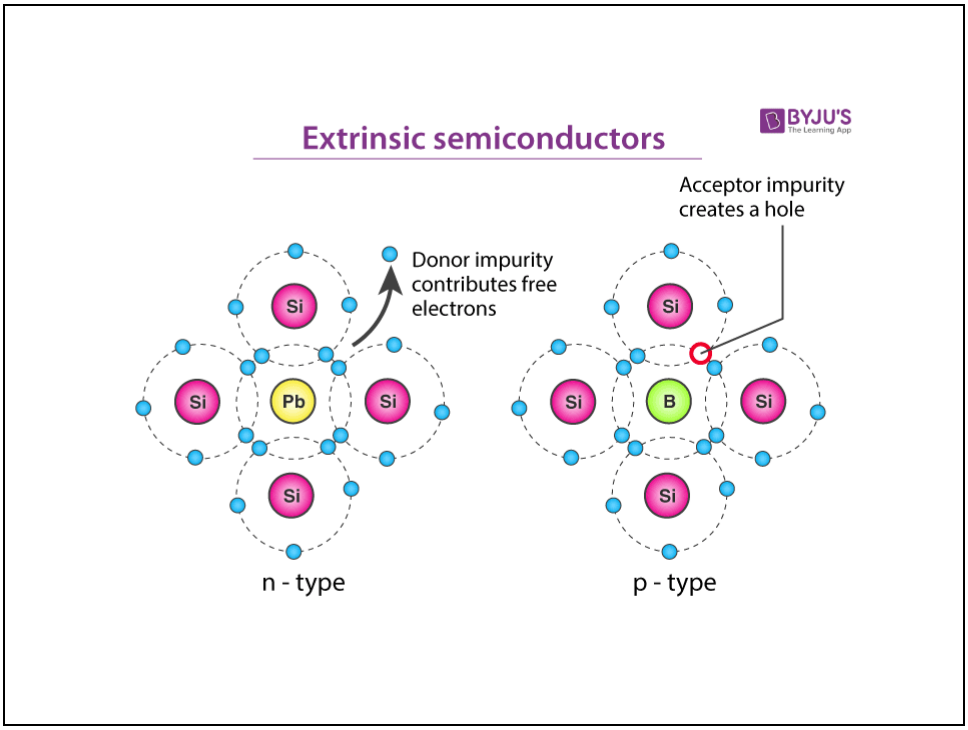
**Al Penney**
**VO1NO**

- In circuit A the diode is **forward-biased** so the current flows and the bulb will light.
- In circuit B the diode is **reverse-biased**, the current will not flow and the bulb will not light



$$I_{collector} = H_{fe} * I_{base}$$

**Al Penney**
**VO1NO**



## Extrinsic semiconductors

Donor impurity contributes free electrons

Acceptor impurity creates a hole

n - type

p - type