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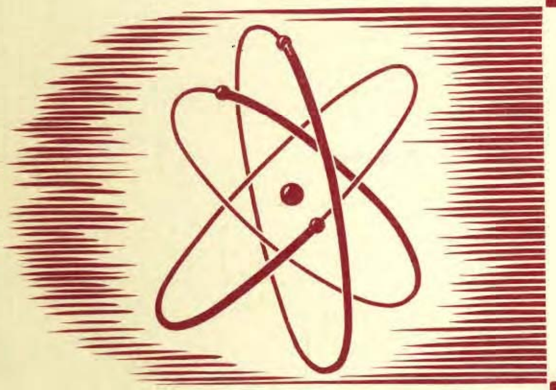
ELECTRONICS in IBM



Discovery of Electricity

Modern Concept of Matter

The Diode ✦ The Triode

Multi-Element Tubes

Electron Tube Oscillators

IBM Applications

Electronic Calculators ✦ The SSEC

and the new Electronic Data-Processing Machine

G. P. LOVELL
ENDICOTT, N.Y.

1954 MAR 17 AM 10 14

ELECTRONICS IN IBM - ERRATA SHEET

WEEKS
SUSPENSE
FILE

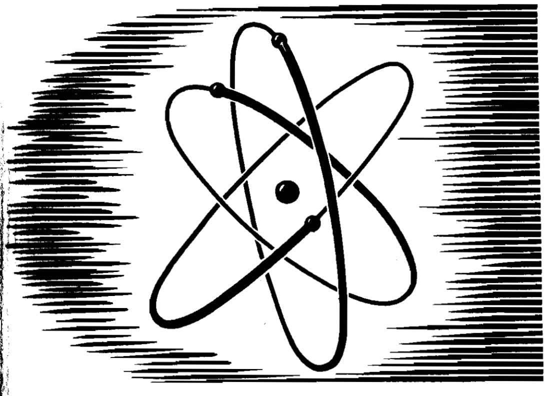
Copies of "Electronics in IBM" were printed and available at the time that new plans were being made for public release of information on the new Electronic Data-Processing Machines. The rapid progress of events brought about changes which affected the accuracy of the information in this booklet and made it necessary that the booklet be withdrawn from release at that time. It is now believed that the need for this booklet on electronics has passed but rather than destroy the existing copies, it was considered advisable to offer the Customer Engineering Manager an opportunity to request a quantity of existing booklets as long as the supply is available.

A number of minor revisions could be made, however, the major points of correction are as follows:

1. To eliminate any inaccurate statements in Chapter VII on the Electronic Time System, pages 55 and 56 have been removed.
2. Chapter IX on Selective Sequence Electronic Calculator should be re-stated in the past tense as this machine has now been removed from IBM, World Headquarters.
3. Chapter X would require, because of the rapid development, minor revisions in regard to size and speeds of various units. The proper name for the Type 701 is now the Electronic Data-Processing Machines and because of its applications and design, it is not considered to be a calculator which is commercially available.

It is recognized that while on some points of electronic theory, there may be differences of opinion, we believe that those differences will not destroy the value of this booklet to you.

ELECTRONICS in IBM



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INTERNATIONAL BUSINESS MACHINES CORPORATION

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preface

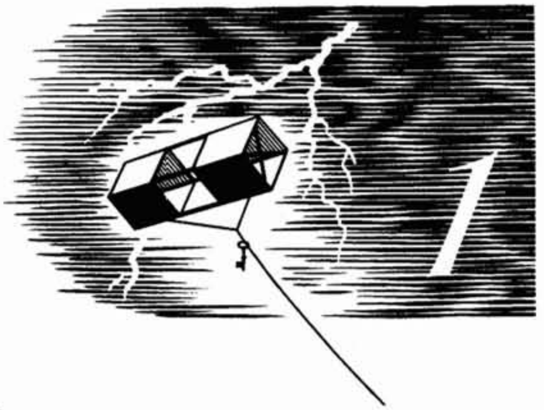
MANY PEOPLE are genuinely interested in learning about the fascinating science of electronics. Unfortunately, their path of learning may run into obstacles of terminology and technicality. The usual book on the subject is not easy to understand; frequently written for groups with special objectives, the material is often highly technical and fails to meet the needs of those looking for general information applicable to their particular problem.

This booklet tries to avoid the criticism implied in the old adage that textbooks are all too often written by experts for other experts. This is a technical booklet on a technical subject, but the approach is mainly one of generating interest.

The opening chapter gives historical background, tracing the development of electrical theory and introducing associated terms. Later chapters show the application of electronics to IBM accounting machines and calculators, a subject of particular interest to all customer engineers.

It is hoped that the simplified mathematics and graphs, the generous illustrations and straightforward text throughout the booklet will combine to give a clearer picture of the basic principles of electronics, as well as a practical understanding of the application of electronics to IBM products.

contents



the DISCOVERY of electricity

Contributions of an Ancient Greek and Queen Elizabeth's physician; of Benjamin Franklin and other great pioneers in science—French, Italian, Danish, German, English and American

ONE of the "seven wise men of Greece" was Thales of Miletus, who lived on the shores of the Mediterranean Sea almost 2600 years ago. Thales discovered many of the principles on which plane and solid geometry are based; he wrote theorems so well that they are still taught in school today. He also discovered and named electricity, although he did not know it at the time.

Thales was curious about a piece of amber he found washed up on the Mediterranean shore. Amber is resin that dropped from trees thousands of years ago and gradually became as hard as rock. Thales discovered that if he rubbed the amber briskly it would attract bits of lint from his robes. Since he could not readily explain why the amber possessed this characteristic, he probably thought the amber was inhabited by some type of god or spirit.[1] How could he know he had caused a concentration of negative electricity to be accumulated on the amber, or that negative electricity could attract neutral particles?

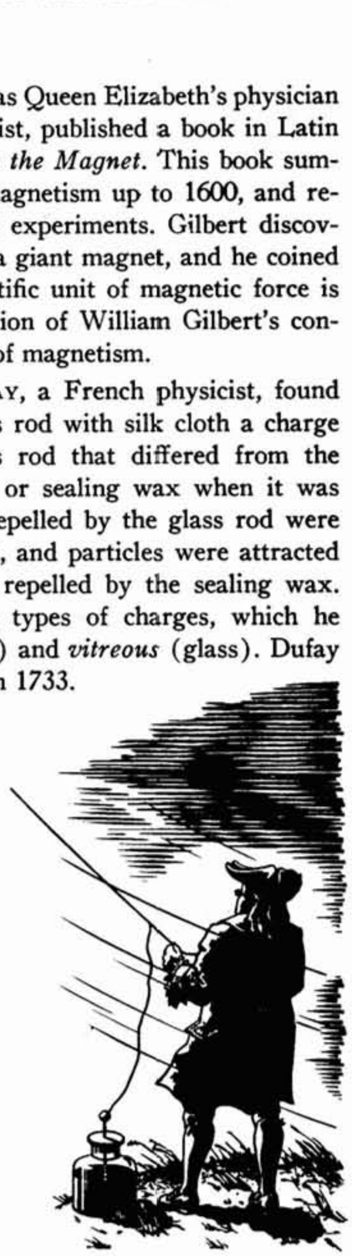
The Greek word for amber is *electron*. Today we use Thales' word for amber to apply to the smallest known particle of electricity.

Thales had also studied another stone, a lump of iron oxide from Magnesia, in Thessaly. He found that this *magnes* stone had the ability to attract iron and other pieces of the same mineral.[2] Since Thales was a philosopher, he was content merely to write about the electron and magnes stones without attempting to put them to any practical use.

WILLIAM GILBERT, who was Queen Elizabeth's physician and also a remarkable scientist, published a book in Latin called *De Magnete* or *About the Magnet*. This book summarized the knowledge of magnetism up to 1600, and reports some of Gilbert's own experiments. Gilbert discovered that the Earth itself is a giant magnet, and he coined the word *electric*. The scientific unit of magnetic force is called the *gilbert* in recognition of William Gilbert's contributions to the knowledge of magnetism.

CHARLES FRANCOIS DUFAY, a French physicist, found that when he rubbed a glass rod with silk cloth a charge was developed on the glass rod that differed from the charge developed on amber or sealing wax when it was rubbed with fur. Particles repelled by the glass rod were attracted by the sealing wax, and particles were attracted by the glass rod that were repelled by the sealing wax. Dufay thus recognized two types of charges, which he called *resinous* (sealing wax) and *vitreous* (glass). Dufay performed his experiments in 1733.

BENJAMIN FRANKLIN in 1747 introduced the terms *positive* and *negative* to distinguish the two types of electric charges. He stated that if a glass rod were rubbed by silk, a positive charge was developed on the rod; if sealing wax were rubbed with fur, a negative charge appeared on the sealing wax. By conducting electric charges down a wet string from a kite flown in a thunderstorm, he proved that lightning was an electrical phenomenon.



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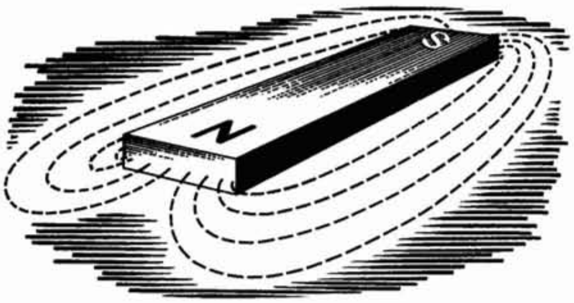
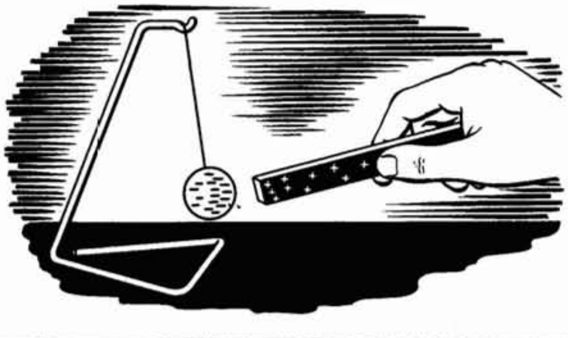
[1] Today, amber furnishes a valuable clue to the life forms of prehistoric times. The dripping resin sometimes imprisoned small reptiles and insects, preserving them intact for hundreds of centuries. It is now believed that many of the folk tales about djinns and demons imprisoned in bottles originated when prehistoric men found pieces of amber containing fossilized, small-life forms.

[2] This mineral is now called *lodestone*, or leading stone, because it was widely used in compasses in the middle ages. Our word *magnet* is derived from *magnes* stone.

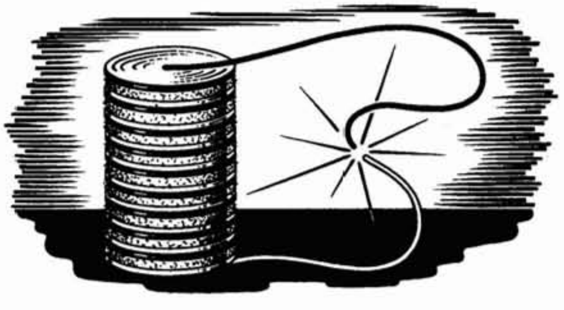


Benjamin Franklin was a brilliant man, but he devised a theory that has caused great confusion and taken more than a hundred years to straighten out. Franklin believed that electricity existed as an invisible "fluid" that was a part of all matter, and that more than the normal amount in a body resulted in a positive electrical charge, and less than the normal amount constituted a negative charge. Thus, he thought, the "electric fluid" always flowed from a positive body to a negative body. His theory has since been replaced by the electron theory, but there is still a tendency to trace electric circuits from positive to negative. In this book, to avoid confusion, the flow of electricity will always be considered to be from negative to positive.

CHARLES AUGUSTIN COULOMB, the French physicist who invented the torsion balance, tells in his *Electrical Papers* published in 1789 how he used this type of scale to measure the attraction and repulsion of electric charges. Coulomb found that a positively-charged body would attract a negatively-charged body, but would repel another positively-charged body. Two negatively-charged bodies likewise repelled each other. *Unlike charges attract each other, while like charges repel each other.* He also discovered that the force between two small charges is directly proportional to the product of the strength of the charges, and varies inversely with the square of the distance between them. Thus, if the distance between two unlike charges were increased from one inch to two inches, the force of attraction would be only one-fourth as great. Coulomb invented the method of determining the size of electric charges, and the practical unit of charge is now called the *coulomb*.[3]



ALESSANDRO VOLTA, an Italian professor of physics, is credited with the invention of the chemical battery. About 1800 Volta made a pile of alternating discs of copper, zinc and cloth soaked in salt water. Where the metals touched the wet cloth, a tiny electric potential was developed, and the cumulative effect of many such potentials in series enabled Volta to draw a spark when he connected the ends of his pile. Volta thus built the first electric battery in recorded history, and in commemoration of his achievement, the unit of electric potential is now called the *volt*.



HANS CHRISTIAN OERSTED of Denmark discovered in 1820 that an electric current would affect a magnetic compass needle. By experiments he was able to show that a magnetic field was developed around a wire when an electric current flowed through it. This discovery opened the path for the invention of the electromagnet. Oersted is remembered by the *oersted,* the scientific unit for magnetic field intensity.

ANDRE MARIE AMPERE, a Frenchman, proved five years later (1825) that the magnetic field around a wire was directly proportional to the electric current flowing through the wire. The unit of current, the *ampere,* takes its name from him. A current of *one ampere* flows in a conductor if a charge of *one coulomb* passes a given point in the time of *one second.* Thus, an ampere is a rate of electric flow of one coulomb per second.

GEORGE SIMON OHM, a German physicist, first published the relation between voltage, current and resistance in 1826. This principle has since been named Ohm's law after its discoverer. Ohm proved that the magnitude of an electric current through a conductor depended upon the electric potential causing the current and the resistance or impedance of the wire. The unit of electrical resistance has since been named the *ohm.* Ohm's discovery that the electrical potential in volts is numerically equal to the product of the current in amperes and the resistance in ohms, is the foundation of modern electrical engineering.

The resistance of a substance is its property of retarding or stopping current flow; this property is measured in ohms. The Greek letter omega (Ω) is used as an abbreviation.

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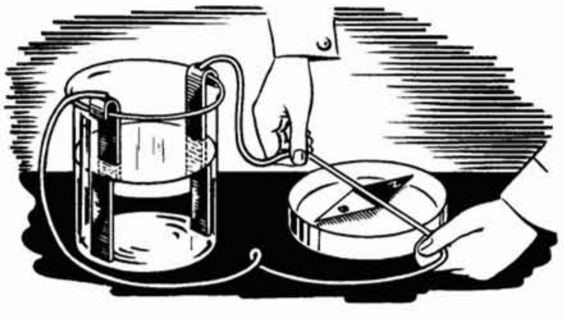
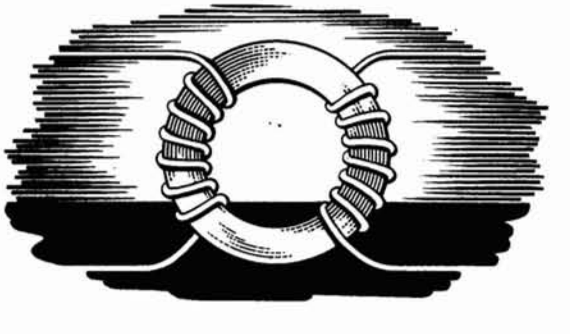
[3] A coulomb has been shown to equal 6,240,000,000,000,000,000 electrons.



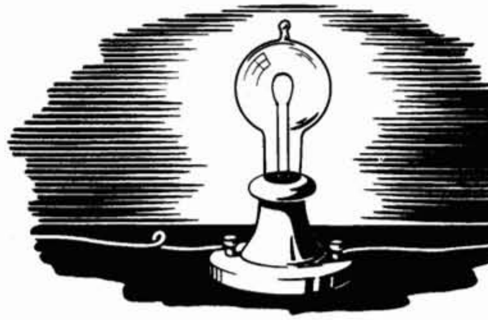
The reciprocal of resistance is called *conductance* and is a measure of how readily a material conducts electric current. The unit of conduction is the *mho* (ohm spelled backwards). As an example, a 10-ohm resistance has a conductance of .1 mho.

JOSEPH HENRY, an American, in 1829 arranged many turns of copper wire on a piece of soft iron shaped like a horseshoe. When electric current was caused to flow through the wire winding, the iron became a powerful magnet that would support many times its own weight. When the circuit to the magnet was opened, a bright electric spark was drawn. Henry showed that when the magnetic field was formed about the wire by an electric current or when it died out with the opening of the circuit, a voltage was *induced* in the copper wire. This voltage tried to keep the current constant. Henry called this phenomenon *self-induction*. Later, Henry arranged two coils of wire on an iron ring, and showed that when the circuit of one coil was made or broken, a momentary surge of voltage was *induced* in the other coil. So the first transformer was the work of Joseph Henry, who prepared the way for the construction of the dynamo and electric motor. The unit of inductance is called the *henry,* and an inductance of one *henry* will induce an electromotive force of one *volt* when the current through it varies at the rate of one *ampere* per second.

MICHAEL FARADAY, an English experimenter, performed the same experiments at about the same time; he is frequently given full credit for the discovery of inductance, although certain refinements are clearly due to Henry. Faraday's important work was on the nature of the effect of one electric charge on another charge when the two are separated by an insulator. In 1837 Michael Faraday rediscovered[4] the effect of varying the type of insulator between charges placed on parallel conducting plates. He found that greater charges could be held when certain materials were used for insulators. Faraday's work on capacitors is an important contribution to the science of electricity, and the unit of capacitance is called the *farad*. A capacitor (or condenser) is rated at one farad if it stores a charge of one coulomb of electricity when a potential of one volt is applied to its plates. In practical electricity, the farad is such a large unit that the millionth part of it, the *microfarad,* is commonly used.



Faraday is also noted for his work in conduction of electricity through liquids. He introduced the terms *electrolyte, electrode, anode, cathode, ion,* etc., which are used in electronic theory today.



THOMAS ALVA EDISON invented the incandescent lamp in 1879. He passed an electric current through a carbon filament that had a fairly high resistance, and found that the current, in overcoming the resistance, heated the filament to white heat. When the filament became heated, it would burn, opening the circuit and rendering the lamp useless; so Edison sealed a filament inside a glass globe and removed as much of the air as he could with the pumps then available. With less oxygen present, the filament could not burn so fast, and would actually give light for several hours. However, particles of the filament were "boiled off" by the heat, and when they condensed on the relatively cool glass globe, they formed a black deposit on the inside of the bulb. We now know that these particles were atoms of carbon. As the black deposit accumulated, the efficiency of the lamp decreased rapidly.

In attempting to prevent the formation of this deposit, Edison sealed an additional metal plate into the globe. He connected this plate to an electric battery through a galvanometer, a device that measures small currents. He discovered that the galvanometer deflected when the positive

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[4] The effect of the dielectric on the capacity of a condenser was discovered by Henry Cavendish in England as early as 1773. However, because Cavendish's chief aim in life seems to have been to avoid the attention of the scientific world, his researches were not published until 1879. So Faraday is given credit for the first published research on capacitance.

battery terminal was connected to the plate, and the negative terminal was connected to the filament. However, he could detect no current when the negative terminal was connected to the plate and the positive terminal was connected to the filament. Edison could not explain the effect with the theories then being used, and because he was busy developing the electric light, he merely noted the effect. This phenomenon of electric current through a vacuum became known as the *Edison effect*. Edison did not see any immediate use for his discovery, and did not develop it further. The Edison effect did interest other experimenters, however, and these men developed our science of electronics.

NIELS BOHR, a Danish physicist, presented in 1913 the theory of matter we use today. Bohr's model of the atom included a positively-charged nucleus surrounded by negatively charged electrons. Robert A. Millikan, formerly of the University of Chicago, obtained the accurate measurement of the charge on the electron: 1.6×10^{-19} coulomb.[5]

All human progress must be built on the foundation laid out by preceding generations. Man has advanced further toward understanding the universe in the last fifty years than he did in the preceding 2500 years. Perhaps a scientist in the year 2000 A.D. will consider our present technology as crude as the early experiments of Franklin and Henry seem to us today.

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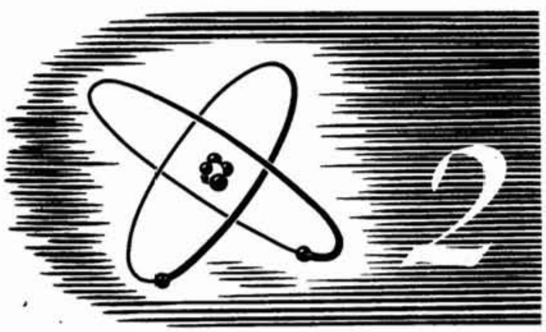
[5] 0.00000000000000000016 coulomb.

the MODERN CONCEPT of matter



Atomic structure and electron theory; application of the theory to electricity, electronics, and the electron tube

TO UNDERSTAND electronics, we must have an understanding of the atomic theory of matter. The building blocks of our universe are the atoms of which all matter is composed. Each atom is made up of electrons, protons and neutrons. No one has ever seen one of these particles, and no one can say with certainty what shapes they take. It is possible that they are merely bundles of energy, with no definite shape at all. However, it will be easier to understand the way atomic particles act if we think of them as very small, springy, rubber balls.

The Bohr Atom

Our present concept of matter is based on the Bohr Atom. In 1913 Niels Bohr, a Danish physicist, devised an atomic model that explains electron behavior so well that with only minor changes it is our atomic model today. Bohr's model of the hydrogen atom (Figure 1) consisted of an *electron* rotating very rapidly in an orbit around a proton, in the manner that the Earth rotates around the Sun. The electron has the smallest possible electrical charge, and is *negative*. The proton is a heavier but smaller particle and has exactly the same charge as the electron, but is positive. Because hydrogen-gas atoms are the lightest atoms in existence, hydrogen atoms consist of one proton and one electron.

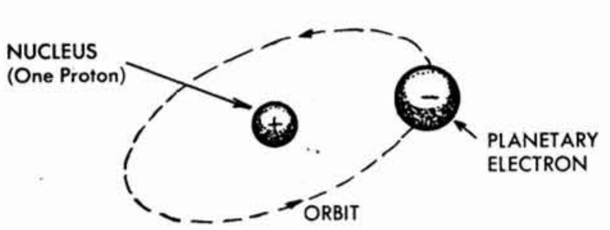


Figure 1. Bohr's Concept of the Hydrogen Atom

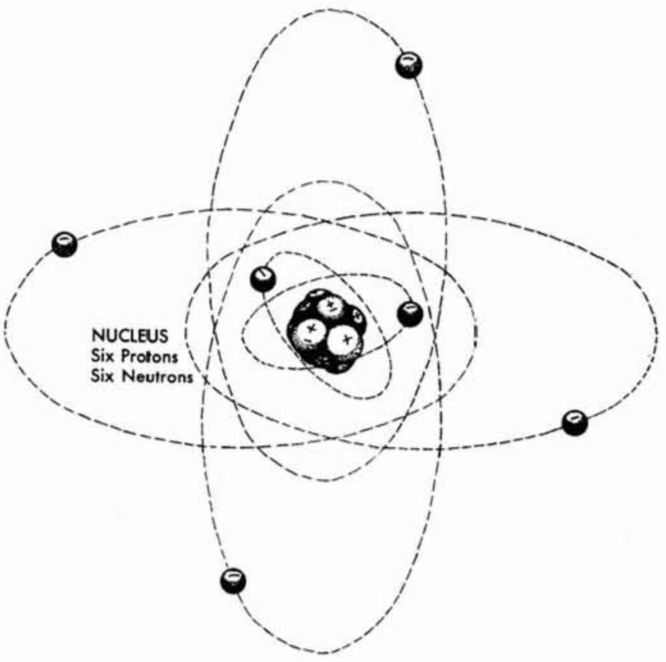


Figure 2. Carbon Atom

Heavier elements have more protons and electrons; also they have atomic particles with mass but no charge. These particles occur in the nucleus and are called ***neutrons***. The neutron has the mass of a proton plus an electron; but the neutron has no charge because the equal positive and negative charges cancel each other. For example, the carbon atom (Figure 2) has six planetary electrons and a nucleus consisting of six protons and six neutrons. A normal atom has as many electrons as it has protons.

As the weight of the material increases, the number of electrons and protons in the atoms of the material increases. One of the most important concepts of the atomic theory is that electrons which revolve about the nucleus are arranged conductor connected to positive terminal, it is attracted to the positive terminal which is collecting electrons. A voltage difference or *gradient* is set up along the conductor. Because there are too many electrons at the negative terminal and too few at the positive pole, the free electrons move toward the positive pole. No single electron moves very far before it enters the structure of an atom that has just lost an electron. The electrons "drift" along the conductor at a speed of only a fraction of an inch per second.

Although the speed of the individual electrons is very slow, the actual speed of electric current is 186,000 miles per second, or about the speed of light. A comparison with a hydraulic system should clarify this statement. In Figure 4 a tank is completely filled with water. If the pump handle is pulled down, the pump will force a pint of water into the tank at point A. Water is virtually incompressible, and a pint of water will instantly be ejected from the pipe at B. However, none of the water injected at A will be in the pint ejected at B. An electric conductor may be thought of as a tank full of electrons. If a conductor 186,000 miles long could be built, one second after a coulomb of electrons was forced into one end, a coulomb of electrons would leave the other end.

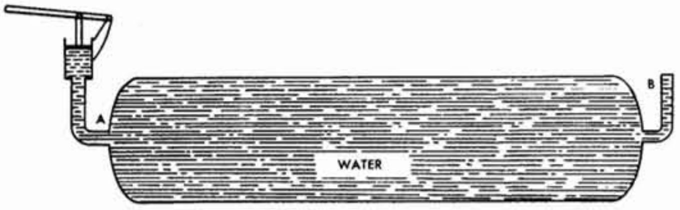


Figure 4. Illustrating Electron Flow

In passing through the conductor, the electrons make numerous collisions with the atomic particles that constitute the material of the conductor. These collisions generate heat and retard the passage of electrons. The property of a material which retards the flow of electrons is called *resistance*. The resistance of a substance to electron flow depends upon the number of free electrons. Most metals have many free electrons. Insulators have almost no free electrons.

Obtaining Electrons

When a substance is heated, the planetary electrons in the substance are speeded up: they move faster and faster about their nuclei. They may move so fast that they are able to break away completely from the surface of the material. This is the method used in obtaining electrons for many vacuum tubes. A metal electrode is heated until electrons are emitted from its surface. This method of obtaining electrons is called *thermionic emission*, indicating that heat has been used to obtain the electrons.

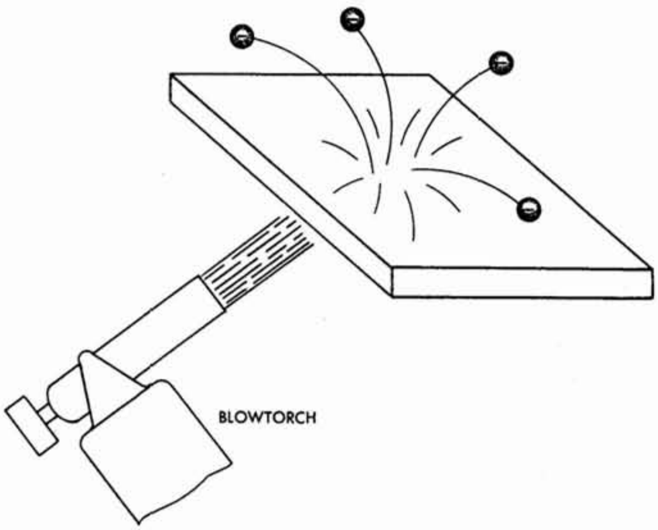


Figure 5. Thermionic Emission

When an electron has been freed from an atom, the net charge on the atom becomes positive, because a negative particle has been removed. An atom with a positive charge is called a *positive ion*. The process of ionization depends upon an atom absorbing sufficient energy in any form to release an electron. Occasionally an electron will enter the outer orbit of an atom that lacks only one or two electrons to fill its outer orbit. The atom will then have a net negative charge and will be a *negative ion*. Because it is easy to remove this electron, negative ions usually exist only a few millionths of a second before an electron is attracted to a more positive atom and the ion becomes a neutral atom.

There are several other ways of obtaining electrons. If an electron, moving at high velocity, strikes a planetary electron of an atom, it may knock this electron from its orbit. This process is called *secondary emission* and is the re-

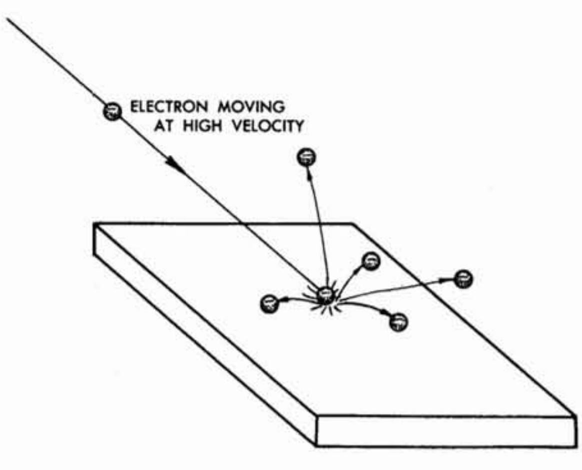


Figure 6. Secondary Emission

moval of electrons from a substance by bombardment with other electrons. Sufficient energy is imparted to the electron by impact to enable it to overcome the surface barrier of the substance and be emitted from the substance.

Certain substances exhibit the property of being able to emit electrons when wave energy such as light waves, infrared rays and ultra-violet rays strike them. Energy from the light rays is imparted to the electrons of these substances, allowing them to overcome their surface barriers. This property is called *photoelectric emission.*

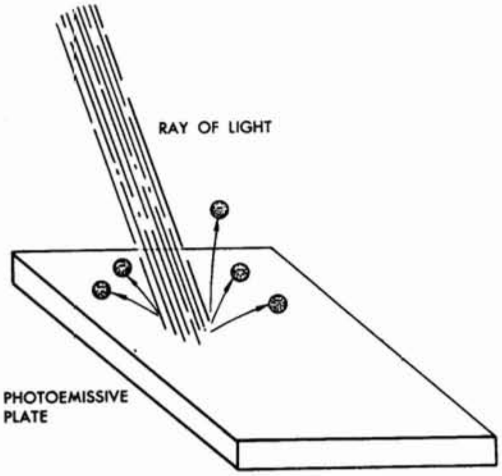


Figure 7. Photoelectric Emission

Another type of emission is shown by minerals such as radium and uranium. They are known as radioactive elements. These atoms are quite unstable and are constantly throwing off electrons and other particles. When the electrons are thrown off, the uranium atom becomes a simple atom of another element. The natural emission of electrons by radioactive substances because of the distintegration of the atoms is called *radioactive emission.*

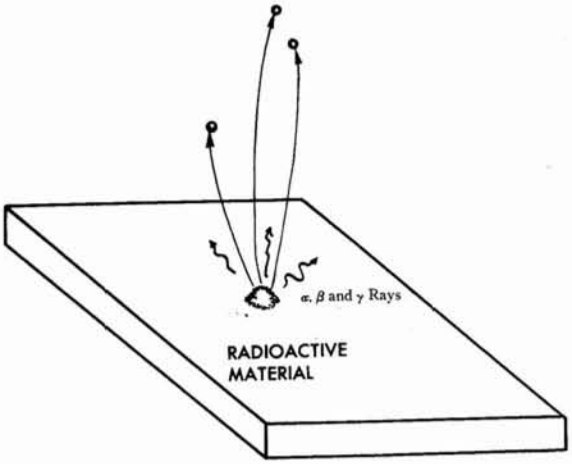


Figure 8. Radioactive Emission

It is possible to obtain electrons from some substances by the application of a very high potential difference, without the application of heat, light or any other form of energy. The negative electrons are so strongly attracted by a positively-charged body near them that they are literally dragged from their orbits. This method of obtaining electrons is called *high-field emission.*

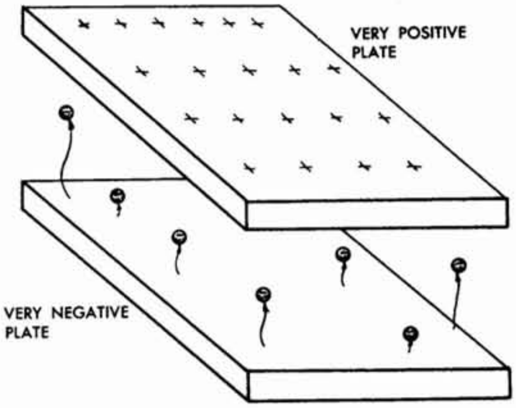


Figure 9. High-Field Emission

Because of differences in their atomic structure, various substances require different amounts of energy to remove electrons. Some atoms hold their electrons much more forcibly than do others. The measure of work necessary to remove an electron from a substance is known as the *work function* of that substance.

The Emitting Electrode

Most of the electronic tubes we use today obtain electrons by thermionic emission. Every electron tube has an electrode known as a *cathode* which emits electrons. In thermionic tubes the cathode is heated by an electric current. In some tubes the current flows through a filament, heating it to red heat and causing it to emit electrons. In this type of tube the filament functions as the cathode and is *directly heated.* In other tubes a cylinder coated with the oxides of calcium, barium or strontium is heated by a coil of wire wound inside it, called the heater. This type of cathode is *indirectly heated.* The directly-heated cathodes are more efficient, less expensive to construct, and heat more quickly when the filament current is applied. The indirectly-heated cathode's advantage is that its entire surface is at the same potential. Alternating current may be used to heat the cathode without interference in the tube circuit.

The materials generally used for the filament of the directly-heated cathodes are tungsten or thoriated-tungsten. Tungsten has a high melting point and long life. It is tough and will withstand bombardment by ions. Thoriated-tungsten is pure tungsten impregnated with a very small amount of thorium oxide and carbon; it is considerably more efficient than pure tungsten, because the thorium has more free electrons than pure tungsten.

The vast majority of small tubes used in radio receiving sets use neither pure tungsten nor thoriated-tungsten cathodes, because of the high temperatures required to produce emission. The tubes used in home radio sets generally employ the oxide-coated indirectly-heated cathodes. Large types of tubes use tungsten or thoriated-tungsten filaments where high power must be handled.

When an electron is removed from the cathode, it leaves on the cathode a small positive charge, known as the positive image. The attraction between this positive image and the electron tends to draw the electron back to the cathode. If the electron is emitted from the cathode with sufficient velocity, it may overcome this positive attraction and remain in the space about the cathode. When many electrons are emitted, they form a negative space charge about the cathode.

When an electron, moving with considerable velocity, strikes an atom of gas, it may knock an electron free from the outer orbit of the atom. The atom with an electron removed from its orbit is now a positive ion, and if the cathode has a negative charge, this ion will be attracted to the cathode. Because the ion has almost all of the weight of the atom, the ion will cause damage to the cathode if it strikes the cathode with high velocity. So it is desirable to remove as much of the air as possible from electron tubes. Certain tubes, however, are designed to be operated with gas atoms present. Provision must be made in these tubes to prevent damage of the cathode by these heavy ions. Because tungsten can withstand ion bombardment, it is frequently employed as a cathode in gas-filled tubes.

Relative Potentials

In electronic circuits, the movement of electrons through vacuum or gas is controlled by charges of electricity on metal plates or electrodes placed in the electronic tubes. The potential or magnitude of charge of the electrode is a determining factor in predicting how the circuit will operate. The charges on the electrodes may be positive or negative; the electrodes may be deficient in electrons, or they may have surplus electrons. To have some reference for comparing charges, the Earth is considered to be at a zero reference potential. Some point in the electronic circuit, frequently the metal box or *chassis* on which the tubes and other components are mounted, is also called *ground,* and is often connected to earth. This point is designated as ground potential by the symbol

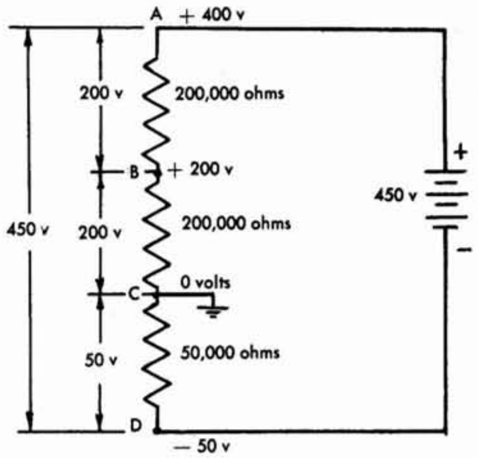


Figure 10. Voltage Divider

The magnitude of voltage at any point in the circuit is given in relation to ground potential.

Figure 10 shows a voltage-divider network similar to many used in electronic devices. A DC power supply, represented by a battery, supplies a series circuit consisting of three resistors with a total resistance of 450,000 ohms. Using Ohm's law:

$$\text{Current} = \frac{\text{Voltage}}{\text{Resistance}}$$

the current through the resistors is

$$\text{Current} = \frac{450 \text{ volts}}{450{,}000 \text{ ohms}}$$

$$\begin{aligned}\text{Current} &= .001 \text{ ampere}\\ &= 1 \text{ milliampere}\end{aligned}$$

The one-milliampere current consists of electrons moving from the negative pole of the power supply to point D, through the three resistors to point A, and back to the positive pole of the power supply. As the electrons move through the resistors, they cause *voltage drops* proportional to the resistance they overcome. The voltage drop across each resistor may be calculated by rearranging Ohm's law,

$$\text{Voltage} = \text{Current} \times \text{Resistance}$$

from which it is seen that 200 volts are developed across each 200,000-ohm resistor, and 50 volts are developed across the 50,000-ohm resistor.

Point C is grounded, and becomes the reference potential in the circuit. Since point D is 50 volts more negative than point C, point D is at a potential of −50 volts. Similarly, point B is at a potential of +200 volts, and point A is at a potential of 400 volts above ground potential. So it is possible to obtain several voltages of either positive or negative polarity from a single power supply. This principle is extremely valuable in electronic circuits.

Electrons in Motion

Inductors and capacitors perform important functions in electronic circuits. These elements affect electrical circuits somewhat as *inertia* affects mechanical devices. Inductors and capacitors play an important part in electrical and electronic circuits, because they prevent instantaneous changes of current or voltage in their circuits. In Figure 11 three circuits are shown. Figure 11A is a simple circuit containing a battery, a switch, and a resistor. No current flows until the switch is closed. The moment the switch is closed, the current rises from zero to a value which can be determined by Ohm's law, and remains indefinitely at this value.

In Figure 11B a capacitor has been added to the series circuit. At the instant the switch is closed, the capacitor has no charge. The battery voltage causes electrons to flow from the negative terminal to the lower plate of the capacitor; these electrons repel electrons from the upper plate which flow through resistor R and the switch to the positive terminal of the battery. At the instant the switch is closed, the capacitor presents no *reactance* to electron flow, and the current is limited only by the resistor. A moment later, as electrons begin to accumulate on the lower plate of the capacitor, fewer electrons leave the negative terminal of the battery. The current decreases slowly to zero as the capacitor charges to the voltage of the battery. The rate at which the capacitor charges is determined by the size of the series resistor and the size of the capacitor. The larger the resistor or the capacitor, the slower the capacitor charges. A convenient measure of the time required to charge a capacitor through a resistor is called the *time constant,* and is obtained by multiplying the capacitance in farads by the series resistance in ohms. The time constant of a capacitive circuit is the time in seconds required to charge the capacitor to 63.2 percent of its final value. For example, if the capacitor in Figure 11B is ten microfarads and the resistance is one megohm (1,000,000 ohms),

(Time Constant)

$$TC = 1{,}000{,}000 \text{ ohms} \times .000010 \text{ farad}$$
$$TC = 10 \text{ seconds}$$

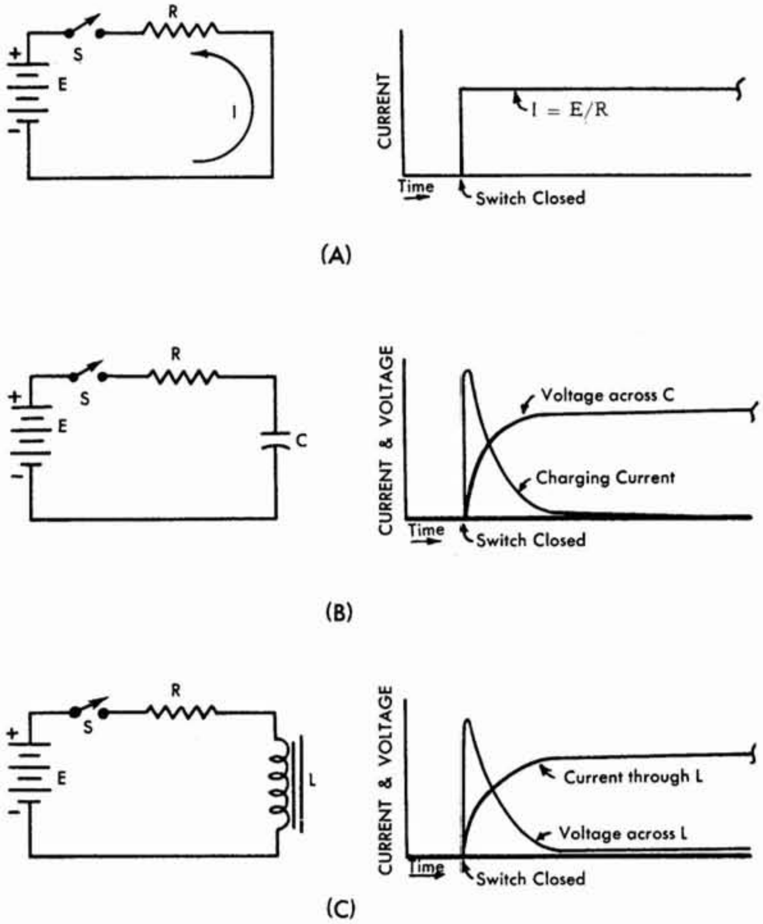


Figure 11. Transient Circuits

Thus, if the battery potential is 100 volts, the capacitor would charge to a potential of 63.2 volts in ten seconds.[1] Note that the rise of voltage is *not* linear, and that the voltage at any other time is *not* proportional to the time constant. In most electronic circuits the time constants will be a fraction of a second.

In Figure 11C an inductor has been connected in series with the resistor, switch and battery. An inductor has large reactance to a *change* in current, although the resistance to a steady direct current is quite small. At the instant the switch is closed, the current tries to increase as it did in Figure 11A. However, the sudden change in current is opposed by the inductor which has high *reactance* to a change in current. Only a trickle of current can pass through the circuit immediately after the switch is closed. The current increases gradually, overcoming the reactance, until the current is limited only by the resistance and the ohmic resistance of the wire of which the inductor is wound. The time constant for an inductive circuit is the time required for the current to rise to 63.2 percent of its final value; this time is obtained by dividing the circuit inductance in henrys by the resistance in ohms. For example, if the inductance is 10 henrys and the resistance is 10 ohms,

$$\text{(Time Constant) TC} = \frac{10\text{ henrys}}{10\text{ ohms}}$$

$$\text{TC} = 1\text{ second}$$

If the battery potential is 100 volts, the current through the circuit would be 6.32 amperes at the end of one second. Usually the inductance is much smaller and the resistance much larger, resulting in smaller time constants.

Inductors have the property of opposing any *change* in current. Figure 12A shows a characteristic of an inductive circuit. Current from the 10-volt battery flows through the switch and the inductor. Assume the inductor is rated at 10 henrys and has a DC resistance of 10 ohms. The current would reach a value of one ampere after the switch had been closed for some time. If the switch were now transferred *instantaneously* to its other position, the inductor would oppose any change of current and would momentarily force a current of one ampere through the resistor R (Figure 12B). If R has a resistance of 100 ohms, a potential of 100 volts will be developed momentarily across it. If R equals 10,000 ohms, a potential of 10,000 volts will be developed across it. However, if R equals 100,000 ohms, the coil will generally break down before 100,000 volts can be developed across the resistor. The high voltage takes the form of an impulse, following the curve shown in Figure 12C. Impulses developed in this manner are called *transients*.

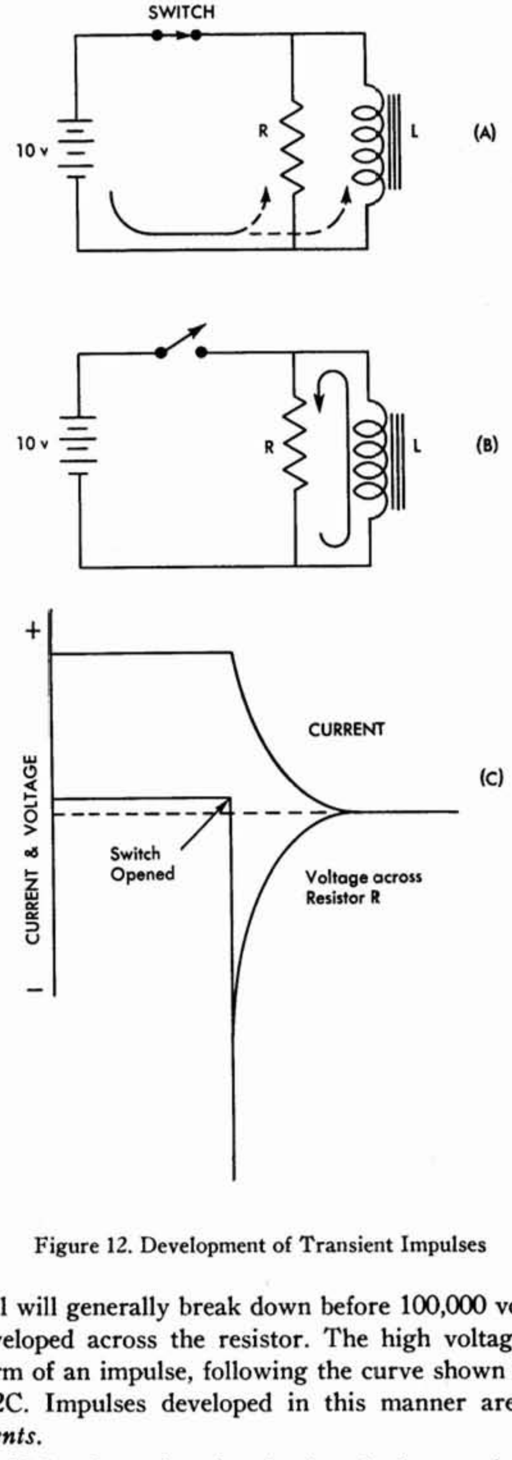


Figure 12. Development of Transient Impulses

The high-voltage impulse developed when an inductive circuit is broken is useful in some applications. The fuel in an automobile engine is ignited at just the right instant by a spark developed in this manner. In electric and electronic accounting machines, however, the transient impulses developed when inductive circuits are made or broken can cause undesirable effects. Circuits to decrease the effect of transient voltages are discussed in Chapter 7.

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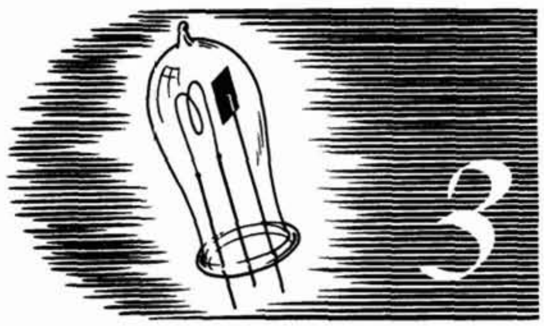
[1] In the next 10 seconds, the capacitor would gain an additional charge of 63.2 percent of the difference between its charge at the end of 10 seconds and its final value. In this 10-second period, the capacitor would gain an additional charge of 63.2 percent of 36.8 volts (100 — 63.2), or 23.25 volts. The potential at the end of 20 seconds would be 63.2 volts plus 23.25 volts, or 86.45 volts. At the end of 30 seconds, the potential is 86.45 + 63.2 (100 — 86.45) = 91.8 volts. The voltage approaches the supply voltage in ever-decreasing increments.



the DIODE

Edison's discovery that electric current could be passed through a vacuum opened a new science of vacuum and then gas-filled tubes. Theory of vacuum, gas and crystal diodes

IN 1883 Thomas Edison discovered that an electric current could be passed through a vacuum. Because this effect seemed to have no practical value then, Edison merely noted the effect and did not study it further. Other scientists took up the study, and the science of electronics was built on their efforts. These men worked under a great handicap, because electrical engineering was in its infancy, and the existing theories of electricity and matter broke down completely when applied to the conduction of electric charges through gas or space.

With our present knowledge of electronics, the *Edison effect* is now easier to explain. When the filament is heated to incandescence, the electrons of the atoms of the filament are speeded up in their orbits until the centrifugal force overcomes the attraction of the nucleus. These negatively-charged electrons then fly out of their orbits and out of the filament. In an ordinary electric lamp, the electrons remain in the vicinity of the filament, but when another electrode is sealed in the bulb and given a positive charge, the negative electrons will be attracted to the electrode. This transfer of electrons is a flow of current through the vacuum of the lamp.

Every electron tube has at least two electrodes: a *cathode,* or emitter of electrons, and an *anode,* or electron collector. The simplest form of tube, using only a cathode and an anode, is called a *diode* (*di* = two). The anode is frequently called the "plate."

The Vacuum Diode

Figure 13 shows the circuit required to demonstrate the Edison effect. A small battery, labeled A, applies current to heat the filament. The larger battery, labeled B, is connected with the polarity shown, between the cathode or filament and the anode. A milliammeter is inserted in series with the battery to measure current through the battery and the tube. When the filament is heated, electrons are emitted from its surface. These electrons are all negatively charged. The anode has a positive charge from the B battery. Because unlike charges attract, the positive anode potential will attract the negative electrons. The electrons travel across the vacuum of the tube and strike the anode. Here they enter the outer orbits of the atoms of which the plate is composed, dislodging other electrons which travel through the wire in the direction shown, to the positive side of the B battery. Simultaneously, electrons leave the negative side of the B battery and move to the filament. These electrons take the place of the electrons that have been emitted and eventually are heated and emitted into the vacuum. This flow of electrons through the circuit causes the milliammeter to be deflected.

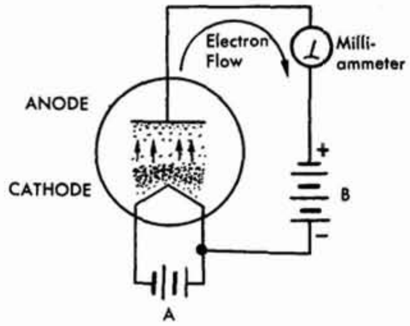


Figure 13. Circuit Demonstrating the Edison Effect

Operating characteristics of the diode depend on the number of electrons available. The cathode's degree of heat has a considerable effect on the number of electrons emitted. Figure 14 shows graphically the emission of electrons from tungsten at different temperatures. Until the cathode is heated to 3200°F., no electrons are emitted. Once emission starts, it increases very rapidly with rise in temperature. As the heat of the cathode increases, the velocity of the

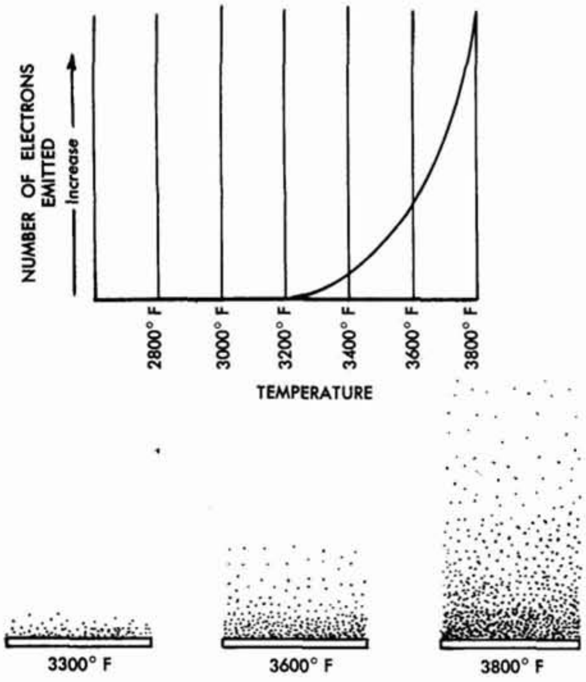


Figure 14. Variation of Emission with Temperature

electrons being emitted increases; so the electrons travel farther from the cathode when they are emitted. For any standard vacuum tube there is a specified heater or filament voltage. This voltage causes a current that heats the filament to the proper operating temperature. When the heater reaches operating temperature, the rate of electron emission becomes stable over a period of time; that is, every second approximately the same number of electrons will be emitted. In the usual vacuum tube, more electrons are emitted than ever reach the plate. Some of these electrons cluster near the cathode and form a negative space charge. This negative space charge acts as a barrier to other electrons being emitted and forces some of them back to the cathode. The space charge acts as a reservoir for electrons to be attracted to the plate.

Figure 15 shows the characteristic anode current versus anode voltage curve for a diode. When a low positive potential is applied to the plate of the diode, a small electron current will flow. When more voltage is applied, the attraction for electrons is greater, and more current results. This will continue up to the point where all of the electrons emitted by the cathode are attracted to the anode. This point is known as the *saturation point*. At this value of anode voltage all the negative space charge is overcome, and electrons are attracted to the anode as fast as they are emitted. The anode current cannot exceed this value.

The B battery has been connected between the cathode and the anode. So an electric field exists between the cathode and the anode in much the same manner as between the plates of a capacitor. When an electron enters this electric field, it is accelerated by the attraction of the positive anode. Energy is imparted to the electron to cause it to overcome the negative space charge, to move through the vacuum and to strike the anode. When the electron strikes the anode,

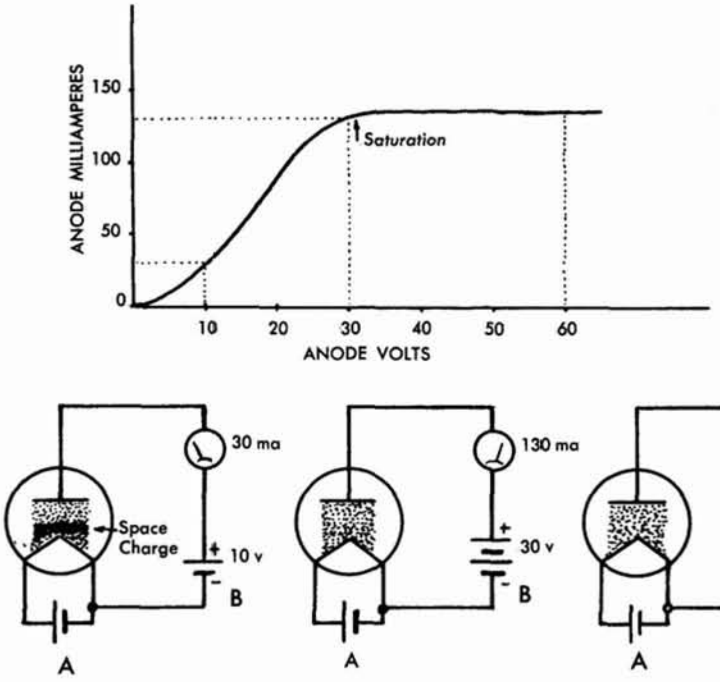
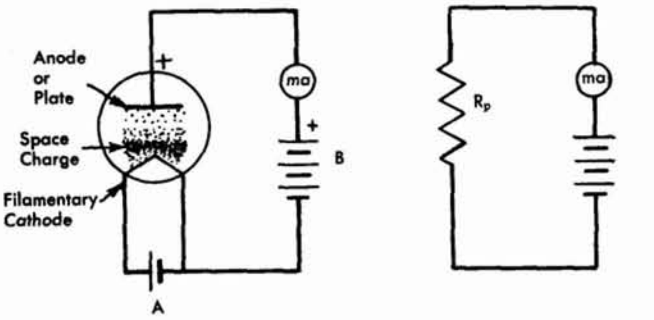


Figure 15. Variation of Anode Current with Applied Voltage



(A) DIODE CIRCUIT (B) EQUIVALENT CIRCUIT

Figure 16. Diode Circuit

its kinetic or moving energy is transformed into heat energy. Provision must be made in all electronic tubes to radiate the heat caused by the electrons striking the anode.

Because work has to be done on the electrons to move them from the cathode to the anode, the electron tube acts much like a resistor in the circuit. We might call this resistor the *plate* or *anode impedance* of the tube. Figure 16B shows an equivalent circuit in which the vacuum tube is replaced by a resistor R_p. The current in the circuit is determined by the magnitude of voltage of the B battery and the resistance of R_p. In Figure 16A the current is determined by the magnitude of the B battery and the anode impedance of the vacuum tube.

Figure 17 shows a circuit identical to the circuit of Figure 13, with the exception that the polarity of the B battery has been reversed. When electrons are emitted from the cathode, they face an anode more negative than the cathode from which they came. The negative charge on the anode repels the electrons, driving them back toward the cathode. No electron current can flow from the anode to the cathode, because no electrons are emitted by the anode. For this reason the diode is known as a *unilateral impedance*: it allows electron flow in one direction only. If the voltage applied between cathode and anode is made too great in the inverse (or back) direction, the voltage may arc across the vacuum of the tube. Electrons are then dragged from the anode by high-field emission, and the tube may be damaged. The maximum safe reverse voltage that may be applied across a tube is called the ***peak inverse voltage***. The unilateral characteristic allows the diode to be used for purposes of *rectification* or changing alternating current into direct current.

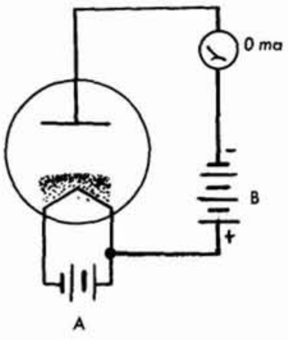


Figure 17. No Current Flows When Anode Is Negative

A direct current (DC) is one in which the polarity or the direction of electron flow is always the same, and the rate of flow is practically constant. A storage battery or dry cell has a direct-current output. Alternating current (AC) changes polarity at regular intervals, building up from zero to a maximum voltage in one direction and returning to zero, then going to a maximum voltage in the other direction and returning to zero. This is known as one cycle, and is repeated indefinitely. Common house-current supply is described as 110-volt 60-cycle power. This means that 60 complete cycles occur every second, and the voltage reverses 120 times every second.

In Figure 18 an alternating-current generator has been substituted for the B battery. When a diode is connected in series with this generator, electrons can flow in the circuit only on those half-cycles when the anode is positive in relation to the cathode. On the alternate half-cycles, no current can flow, for no electrons can move from the anode to the cathode. So the generator causes a series of pulses of direct current to flow in the anode circuit. To obtain a direct voltage, this current must be developed across a load. In Figure 19 a resistor R_L has been placed in the anode circuit. On the half-cycles when current flows, a voltage proportional to the current will be developed across the resistor R_L. Across the terminals of this resistor, a pulsating DC voltage is developed. *Half-wave rectification* of the alternating current has been accomplished.

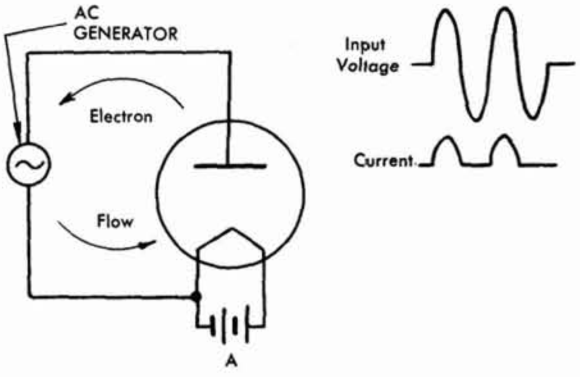


Figure 18. Principle of Rectification

The pulsating DC voltage may be improved by adding a capacitor in parallel with the resistor. On the half-cycles when the tube conducts, the capacitor is charged, and on the half-cycles when the tube prevents the flow of current,

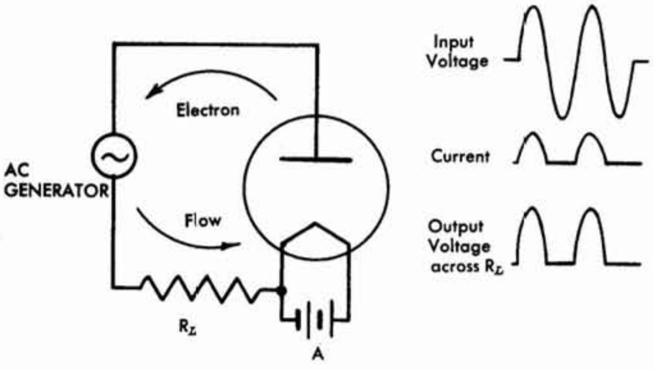


Figure 19. Half-Wave Rectifier

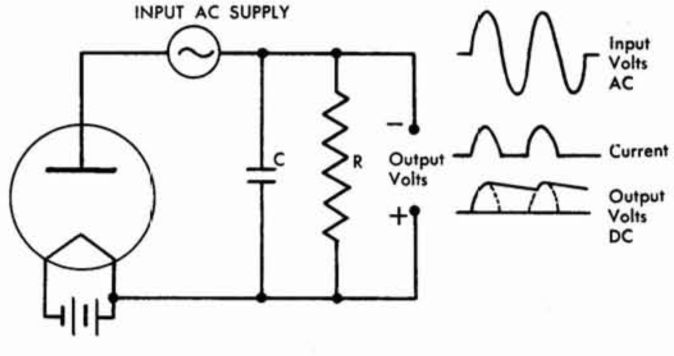


Figure 20. Half-Wave Rectifier with Capacitor Filter

the capacitor discharges and provides current to the output circuit. Figure 20 shows this circuit; the output voltage is a DC voltage. Some "ripple" remains on the DC voltage, but by proper filtering it is possible to eliminate virtually all this ripple. Note the polarity of the rectifier output voltage.

Much higher efficiency may be obtained by employing *full-wave rectification.* A smoother flow of current will result from making the pulsations come closer together. Full-wave rectification requires the use of two diodes. One conducts during the first half of the alternating cycle, and the other conducts during the second half of the cycle. By utilizing the full AC wave, the output voltage contains twice as many pulsations per second and is easier to smooth.

Figure 21 shows a typical full-wave rectifier. For simplicity, the filaments are shown heated by batteries, although in practice they are heated by alternating currents supplied by a separate transformer winding. When an AC voltage is applied to the primary of the transformer, it induces a voltage in the secondary that has the same wave shape. By making a center-tap to the transformer secondary, it is possible to obtain from the secondary two voltages that are 180 degrees out of phase. At the instant when the voltage at point A is at positive maximum in relation to point C, the potential at point B is a maximum in the negative direction in relation to point C. When the cycle reverses, point A reaches maximum negative, and point B is maximum positive in relation to point C. Every half-cycle the anode of one of the tubes will be positive, and electrons can flow from the cathode to that anode, through half of the transformer winding and through R_L back to the cathode. Note that the flow of electrons through R_L is always from point C to point D. The resultant current form

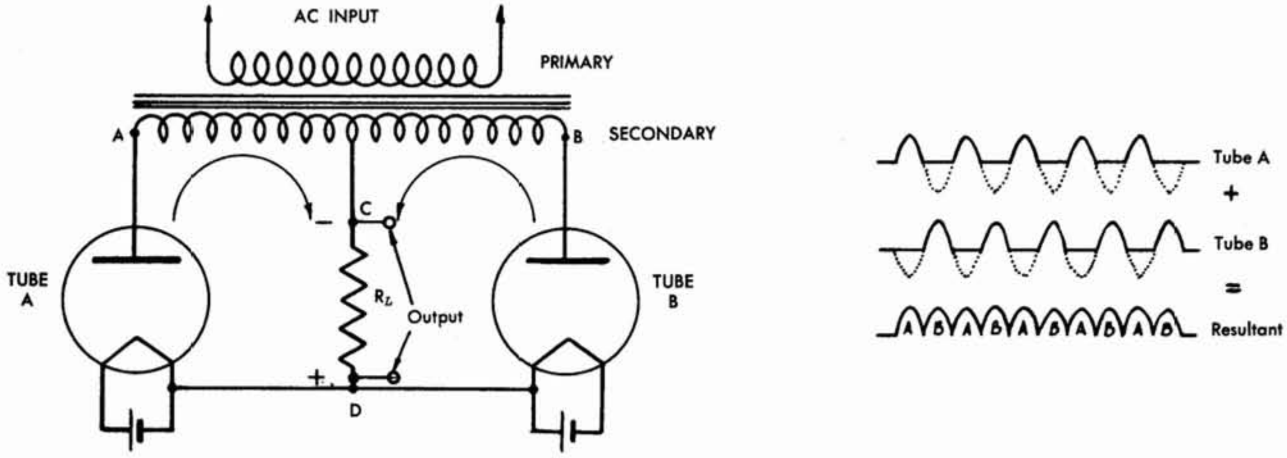


Figure 21. Full-Wave Rectifier

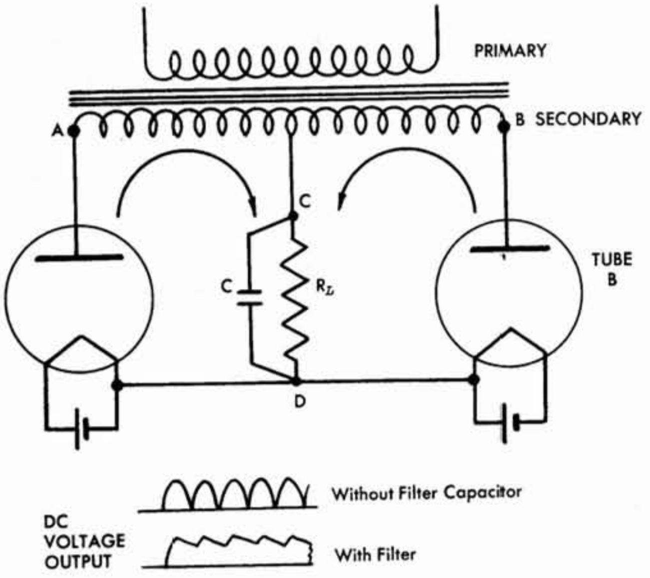


Figure 22. Full-Wave Rectifier and Filter

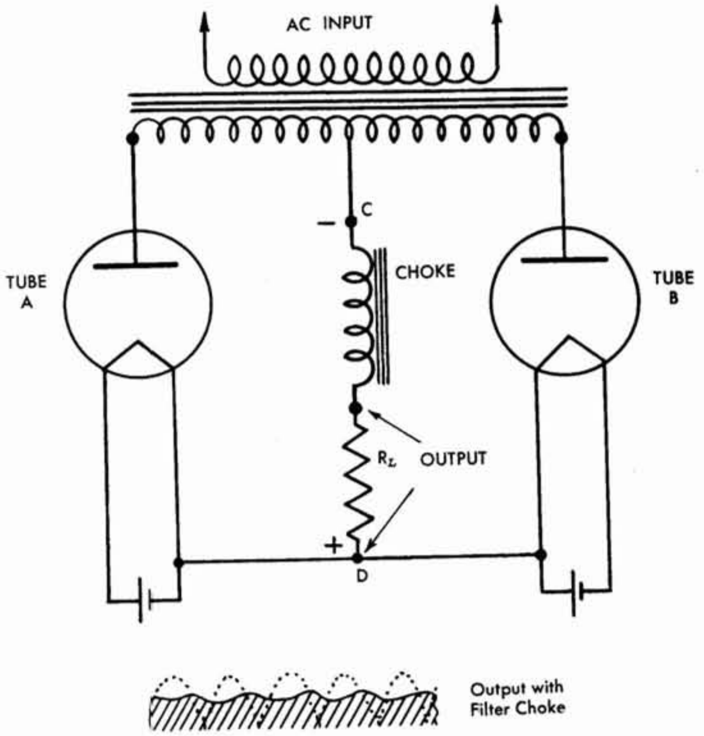


Figure 23. Choke Filter

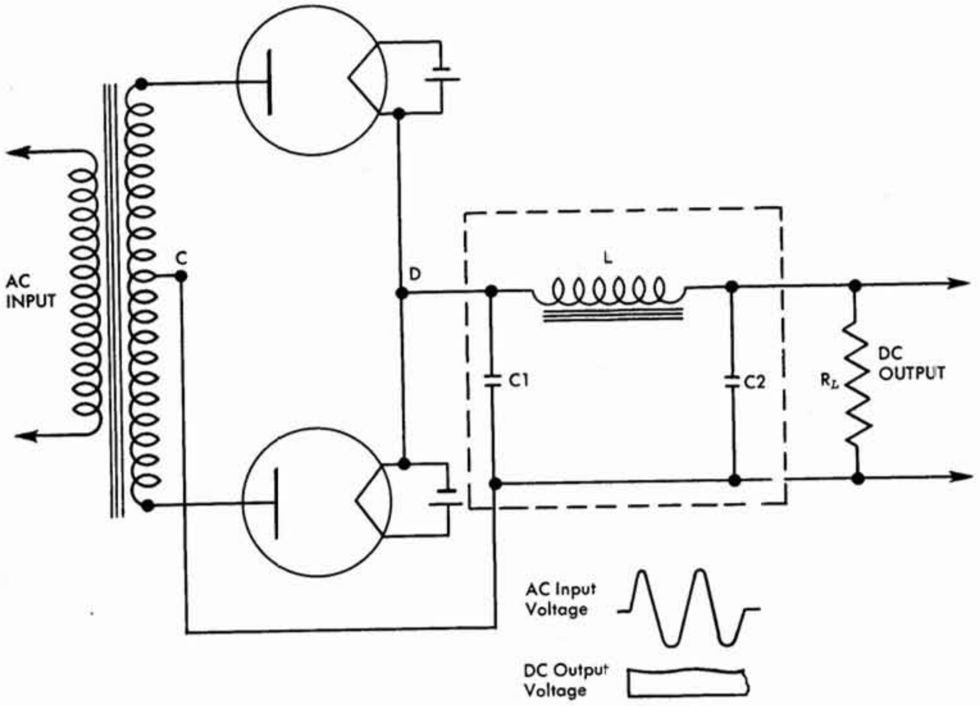


Figure 24. DC Power Supply

is much smoother, even without filtering, and when a capacitor is connected in parallel with the load as in Figure 22, a reasonably smooth DC potential is obtained. The output of the full-wave rectifier requires much less filtering to make it suitable for a given application.

The filtering action can be further improved by inserting an inductance in series with the load. An inductance tends to oppose any change in current. If the current starts to decrease through an inductor, the inductor will generate a voltage that tends to keep the current constant. The current will be smoothed by this effect, and inductors are thus utilized in filter circuits.

Figure 23 shows the effect of a series inductor or choke coil on the rectified AC. Note that the DC output is lower but much smoother than the tube output without the choke coil. Also note that the peaks of the ripple on this DC occur between the peaks of the pulsations when the tubes conduct. Usually inductors and capacitors are used together in filtering a power supply. Figure 24 shows a typical filter circuit. A choke coil is placed in series with the load, while two capacitors are connected in parallel with the load. The DC output has now been made very smooth. This circuit is sometimes called a π (pi) filter because of its form.

The filter circuit of Figure 24 is called a *capacitor-input* circuit, because capacitor C1 is the first element connected to the cathode. If capacitor C1 were removed from the diagram, the circuit would be a *choke-input filter*. A capacitor-input circuit has the advantage of higher output voltage; when a greater load is connected to the rectifier, however, the voltage drops rapidly. The change of output voltage with load is called *regulation,* and capacitor-input filters have poor regulation. Choke-input filters have lower output voltages, but much better regulation; the voltage will remain constant over a wider range of loads.

The Gas Diode

In the design and manufacture of vacuum diodes it is desirable to remove as much air as possible from the tubes. Gas diodes, on the other hand, have a minute amount of gas deliberately introduced into the tube. Gas tubes can be classified as cold-cathode gas tubes, gas-filled thermionic tubes, and mercury-arc pool-type rectifiers.

THE COLD-CATHODE DIODE

The cold-cathode type is used in voltage regulator circuits for small power supplies and as small indicator lamps. The term "cold cathode" derives from the fact that no heat is applied to the cathode. Instead, the electrons are obtained by high-field emission. Two small electrodes are sealed into a glass tube that has introduced into it a small amount of neon, xenon, or some other inert gas. Inert gas is used because it will not combine chemically with the electrodes. The electrodes are coated with metals of low work function such as cerium, or partially-reduced oxides of barium and strontium. When a potential is applied between the two electrodes, a few electrons are emitted from the negative electrode by high-field emission. These electrons are attracted to the positive electrode, but on their way they strike atoms of gas, knocking additional electrons from the outer orbits of these atoms. The emitted electrons and the atomic electrons constitute the current flow through the tube to the positive electrode, while the gas ions move toward the negative electrode. When the ions strike the negative electrode they impart energy to release additional electrons.

Once ionization has been started, less voltage is required to maintain the electron flow through the tube. Some of the electrons enter the outer orbits of gas atoms; but instead of colliding with the electrons in these orbits, they repel these electrons, forcing them to jump to a different orbit or energy level within the atom without repelling them hard enough to free them from the atom. When the original electron has been removed, the atomic electron drops back to its original orbit; in doing so it gives up the energy absorbed when forced out of its orbit. This energy is released in the form of light. Neon gives a reddish-orange light, argon gives a bluish light, and carbon dioxide a white light, The light produced serves no purpose in the electronic circuits; but it has opened up the additional field of electronic lighting units such as neon-tube lights and fluorescent lamps.

The most useful characteristic of the cold-cathode gas diode is that once ionization has occurred, the potential drop across the tube remains essentially constant. The VR-105 type diode requires 137 volts applied to its electrodes to cause ionization. Once ionization potential has been reached, however, the voltage drop across the tube decreases to 105 volts and remains constant as long as ionization continues. This makes cold-cathode diodes very useful in power supplies where it is desired to maintain a constant voltage. The cold-cathode diode is connected in parallel with the load, and the voltage drop across the diode and the load will be held constant.

THE THERMIONIC GAS DIODE

The same principles apply to thermionic diodes. Electrons are here emitted by heating the cathode. When a positive potential is placed on the anode, the electrons are attracted to the anode and on their way strike atoms of gas, knocking additional electrons from the outer orbits of these atoms. These electrons contribute to the electron flow, and enable the gas diode to carry much heavier currents than the vacuum diode is capable of carrying. The atoms relieved of electrons become positive ions and are attracted to the cathode. On their way they may collide with other atoms, releasing more electrons. Each electron passing through the gas can result in the transfer of many electrons. When the ions strike the cathode, they release more electrons. When they attract enough electrons to fill their outer orbit, they cease to be ions and again become gas atoms. The gas diode has its chief application in power rectifiers.

The mercury-arc pool-type rectifier is used where extremely high currents must be rectified. These devices are found primarily where high power must be rectified.

THE PHOTOCELL

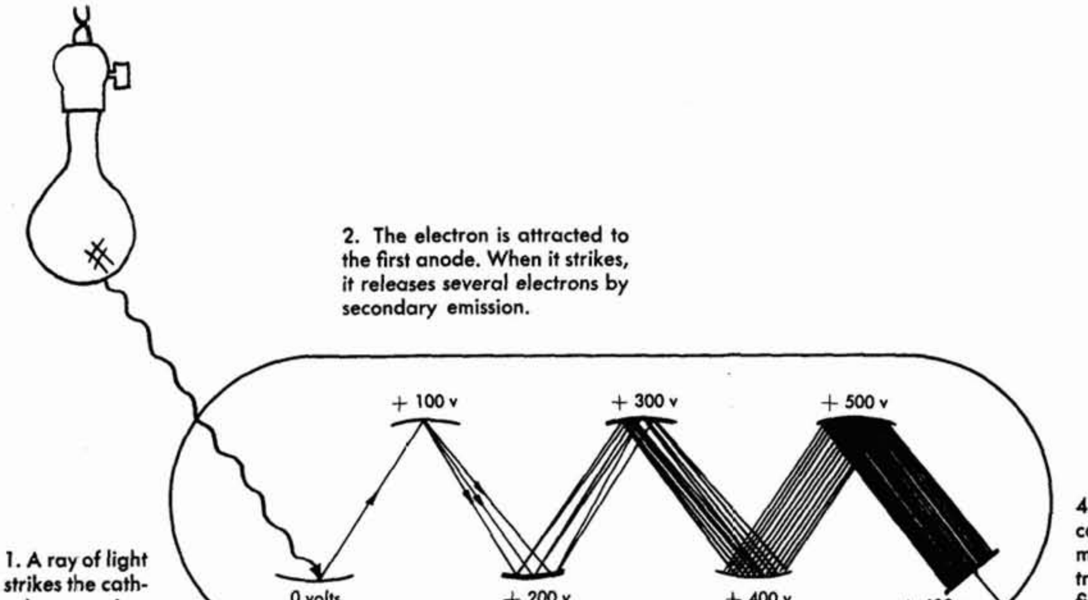
Another type of diode is the photoelectric cell. There are three types of photoelectric cells: photovoltaic cells, photoconductive cells, and photoemissive cells. The photovoltaic cell generates a voltage between its electrodes when light reaches it. The photoconductive cell varies its resistance in accordance with the light intensity it receives.

Photoemissive cells are composed of a cathode made of an element such as cesium which emits electrons when struck by light rays. As long as no light strikes the cesium, no electrons will be emitted; but when light energy strikes the cesium, electrons will be emitted and attracted to a positively-charged anode. The electron flow is very small and generally cannot be used directly. An amplifier is therefore employed to magnify the cell output so that it can control other devices.

Sometimes an *electron multiplier* is built into a photoelectric cell. Figure 25 shows the principle of the electron multiplier. When light strikes the cathode, the emitted electrons are attracted to the first anode. When they strike this anode, they release other electrons by secondary emission. This process continues as the secondary electrons are attracted to the second anode, where secondary emission again occurs. One type of tube employs a photoelectric cathode and nine anodes, called *dynodes*. For every electron leaving the cathode, about 2,000,000 electrons reach the final electrode.

Certain types of photocells contain a small amount of inert gas. A considerable increase in sensitivity—or current produced for a given amount of light striking the cathode—can be accomplished. The emitted electrons collide with gas atoms and cause ionization. Ionization results in more emission and higher anode current. It is possible to obtain up to ten times as much anode current by including gas in the cell. If a higher *gas amplification* is attempted, the positive ions strike the cathode with such force that they may damage it.

Photocells are widely used in burglar alarms. A beam of light is focused upon the photoelectric cell. As long as the beam remains focused on the cell, the amplifier and relays of the alarm system are inoperative. When an intruder interrupts the beam of light, the photocell stops conducting.



2. The electron is attracted to the first anode. When it strikes, it releases several electrons by secondary emission.

1. A ray of light strikes the cathode, causing emission of an electron.

3. These electrons are attracted to the second anode where they each free several electrons.

4. The process continues until millions of electrons reach the final anode.

Figure 25. Photocell with Dynode Amplifier

The amplifier magnifies this tiny change in photoelectric cell current and sounds an alarm.

The sound track on a motion-picture film is a series of light and dark areas on the edge of the film. The sound track passes between a bright lamp and a photoelectric cell, and the variations in current produced by the cell are amplified and sent to the loudspeakers behind the screen.

IBM uses photoelectric cells in the traffic recorder, and for control of machines used in the factory.

The Crystal Diode

In the early days of radio development, radio receiving sets used a detector made by clamping a small piece of metallic crystal (usually lead sulfide) in a small cup or receptacle. A flexible wire "cat whisker" was held in light contact with a sensitive spot on the crystal. This constituted a crystal-diode rectifier. The development of the vacuum-tube diode caused crystal detectors to become obsolete in commercial sets; however, because the crystal-diode rectifier was superior in certain respects to the vacuum-tube diode, considerable research has been made on this device. Now it is re-appearing in television detection circuits.

The most widely used substances for crystal diodes are crystaline germanium and silicon. A crystal is pressed into a holder, and the exposed surface is ground and polished to a bright finish. The crystal is assembled in its carriage with a cat whisker of platinum or tungsten pressing lightly on the polished surface. A high current is sent through the assembly momentarily to heat the cat whisker and weld the whisker to the crystal. The welded unit is mechanically stable, and does not require further adjustment.

The crystal rectifier utilizes the principle that, at the junction between the cat whisker and the crystal, electrons can flow more readily in one direction than in the other. The germanium rectifier acts as a unilateral impedance, offering low resistance to electron flow from the crystal to the whisker, and high resistance to electron flow in the opposite direction. The silicon rectifier acts in exactly the opposite manner. The crystal diode is not as effective as the vacuum-tube diode, because a few electrons may move in the reverse direction, cancelling the effect of an equal number of electrons moving in the forward direction. Because the crystal diode does not require a heated cathode, there is no *thermionic* noise added into its anode circuit; this is important when the circuit is handling very small currents and voltages.

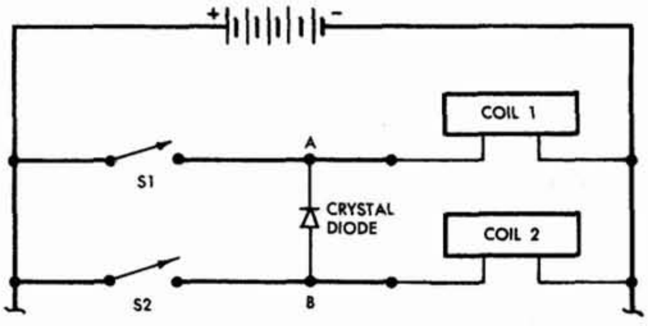
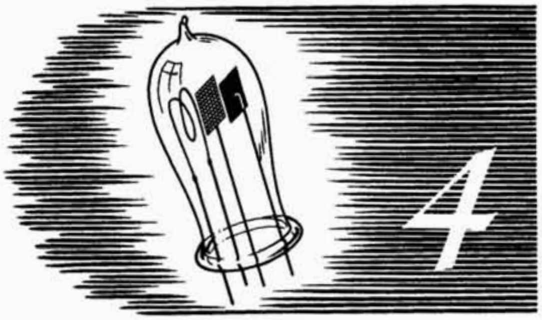


Figure 26. Crystal-Diode Switching Circuit

Germanium-crystal rectifiers are finding wide use in IBM machines as polarity traps. They offer low resistance to a current in the proper circuit but act as a high impedance to any current in a "back" circuit. Figure 26 shows a simple example. Switch S1 is designed to energize coil 1, but switch S2 should energize both coil 1 and coil 2. The crystal diode is thus connected in the manner shown. When switch S1 is closed, electrons can flow from the negative terminal of the power supply through coil 1 and switch S1 to the positive power-supply terminal. Electrons trying to pass from the negative terminal through coil 2 find a very high resistance between points B and A, and coil 2 would not be energized. If switch S1 is opened and switch 2 is closed, electrons flow from the negative terminal through coil 2 and switch 2 to the positive terminal. Electrons can also flow through coil 1, the crystal diode, and switch S2 to the positive terminal, because the diode presents a very low resistance to electrons moving from point A to point B.



the TRIODE

DeForest's invention of the wire-mesh grid was the key to modern electronics, unlocking doors to radio, television, long-distance telephony, talking pictures, and electronic calculators

AN AMERICAN named Lee DeForest made the basic invention of modern electronics in 1906. Between the cathode and the anode of a vacuum diode, DeForest placed a third element formed of wire mesh. This element, which he called a *grid,* made possible the control of the electrons flowing from the cathode to the anode. From this invention the entire electronics industry has been developed. Because this device has three elements, it is called a *triode* (*tri* = three).

The Vacuum Triode

In the triode, the cathode is surrounded by a small wire-mesh element called a grid. The function of the grid is easily visualized by comparison with a Venetian blind. Figure 27A shows a Venetian blind set so that the sunlight can readily enter the window. This is the condition in a vacuum triode when the grid structure is at cathode potential or positive in relation to the cathode. Electrons leaving the cathode are able to penetrate the holes in the wire mesh

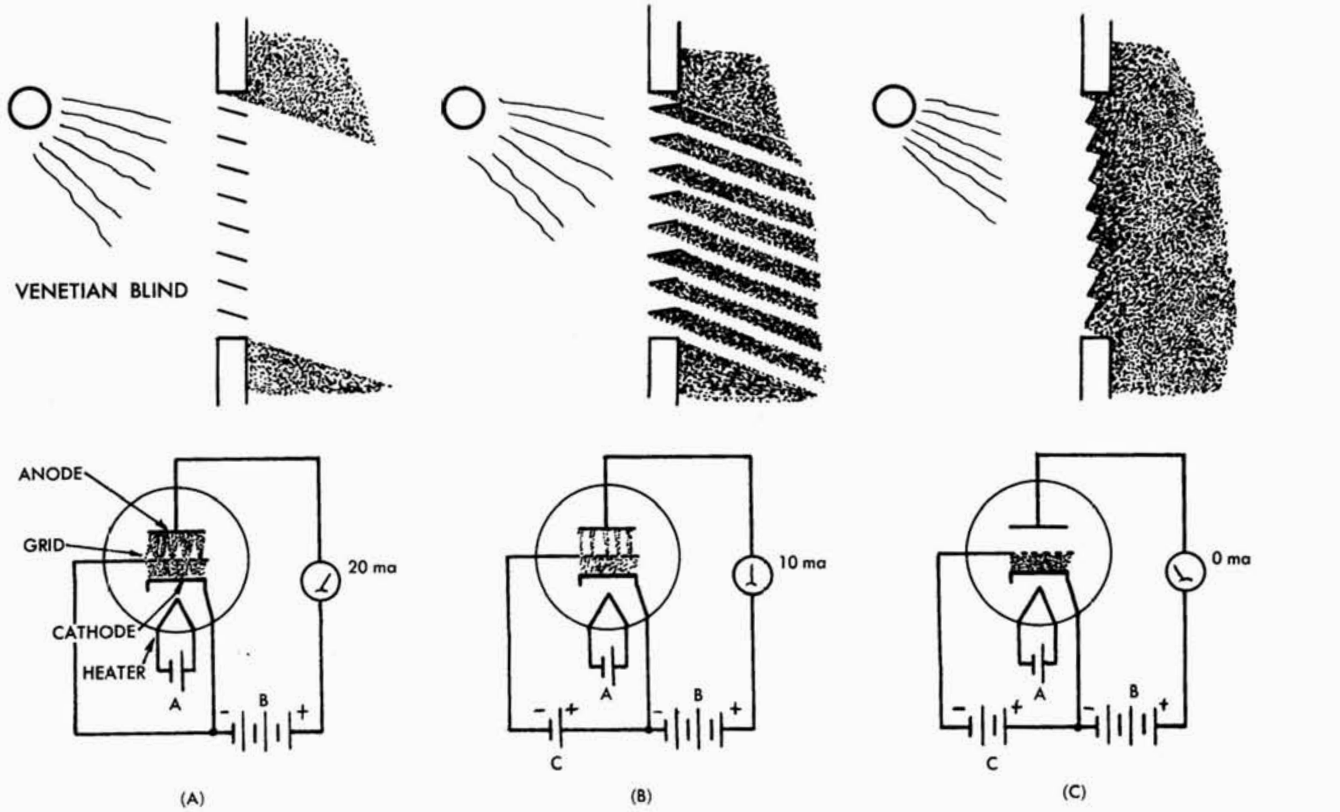


Figure 27. Control-Grid Principle

and reach the anode, resulting in anode current. In Figure 27B, the Venetian blind has been turned to partially exclude the sunlight. In the vacuum triode, when the grid is made negative in relation to the cathode, electrons leaving the cathode face a field more negative than the surface they have just left; so some are forced back to the cathode, and fewer electrons penetrate the holes in the grid and reach the anode.

Figure 27C shows the triode action when the grid has been made still more negative in relation to the cathode. When closed, the Venetian blind shuts out all the sunlight. When the grid is made very negative in relation to the cathode, no electrons can penetrate its high negative field, and the anode current is zero. This condition is called *cutoff*. Thus, the grid is capable of controlling the electron stream. The intensity of the electron stream may be varied from the full capacity of the tube (saturation) to cutoff. The vacuum triode operates on the flow of electrons much as a faucet controls the flow of water. The British call the vacuum triode a "valve" for this reason.

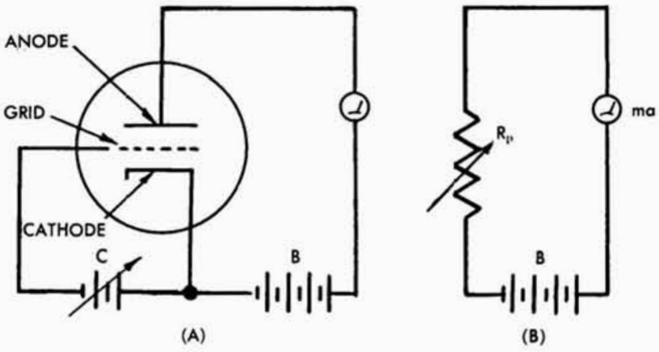


Figure 28. Triode Circuit

The grid of the triode is capable of controlling the electron flow through the tube. This function might be accomplished in a direct-current circuit without electronic tubes by employing a variable resistor in place of the triode. Figure 28 shows an equivalent circuit when the resistor R_p replaces the vacuum triode. When the value of R_p is made small, the current through the circuit is increased; but if R_p is made very large, the current through the circuit may be decreased to a small trickle. If R_p were made infinitely large, no current would flow through the circuit. The vacuum triode can take the place of the variable resistor and can vary the magnitude of anode current much faster than it is possible to vary the resistor R_p.

Figure 29 shows the anode characteristic curves for a typical triode. The abscissa of the graph represents the

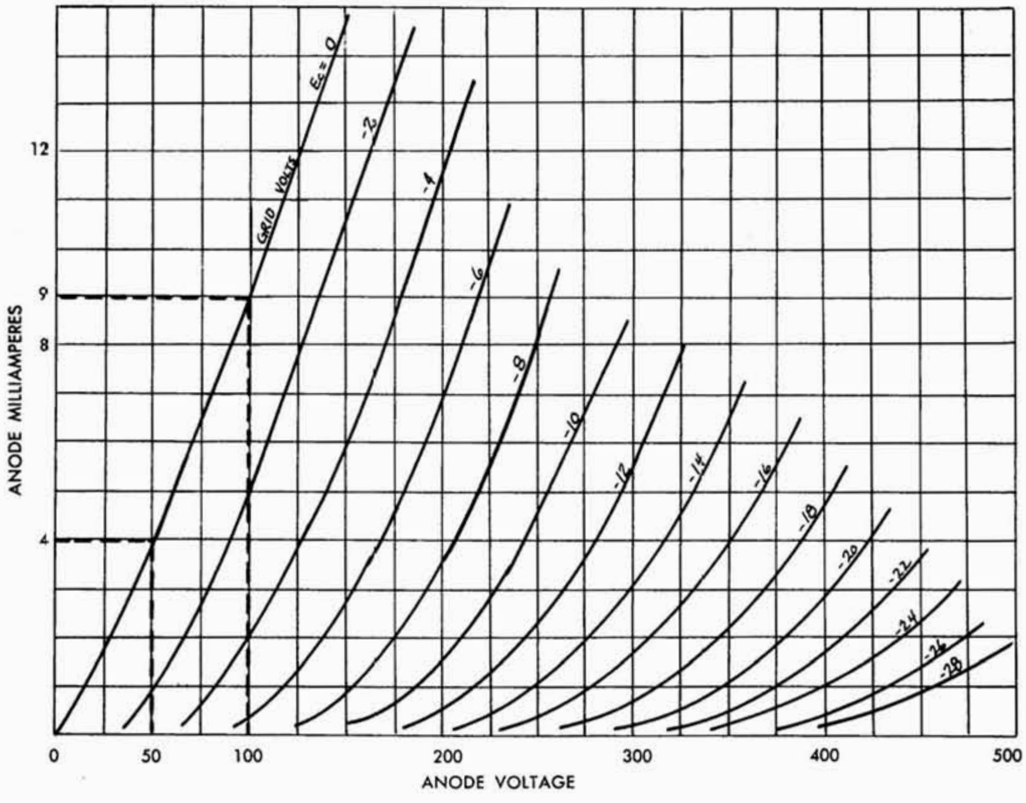


Figure 29. Triode Characteristics

magnitude of anode voltage, while the ordinate axis represents the magnitude of anode current. The curves traced on the graph represent constant grid voltages. For example, if the grid is at cathode potential ($E_c = O$), four milliamperes would flow in the anode circuit when the anode potential is 50 volts in relation to the cathode. If the anode potential is raised to 100 volts, the current increases to 9 milliamperes. Now, a pure resistance would exhibit a proportional rise in current: that is, a resistor that allowed 50 volts to force 4 milliamperes through it should allow 100 volts to cause a current flow of 8 milliamperes. Since the triode obviously decreases its impedance as the anode voltage is increased, the plate resistance is a *non-linear impedance*. Ohm's law does not apply to the calculation of anode resistance. Instead, the anode resistance must be calculated from the relation

$$\text{Anode resistance} = \frac{\text{change in anode potential}}{\text{change produced in anode current}}$$

(grid potential held constant)

In Figure 29, with the control grid at cathode potential,

$$\text{Anode resistance} = \frac{100\text{ volts} - 50\text{ volts}}{9\text{ milliamps} - 4\text{ milliamps}}$$

$$\text{Anode resistance} = \frac{50\text{ volts}}{.005\text{ amp}}$$

$$\text{Anode resistance} = 10{,}000\text{ ohms}$$

The *transconductance* or *mutual conductance*, g_m, of a triode is the rate at which the plate current changes with a change in grid voltage and is measured in mhos.

$$g_m = \frac{\text{change in anode current}}{\text{change in grid voltage}}$$

(anode voltage constant)

In Figure 29 the anode current increases from 5 milliamperes to 9 milliamperes when the grid voltage is changed from -2 volts to 0 volts. The transconductance *at this point of operation* is approximately

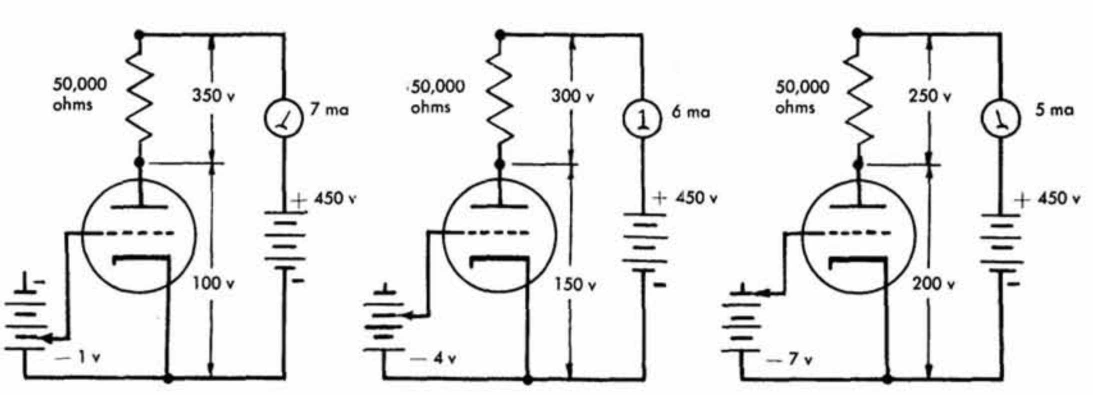
$$g_m = \frac{.004\text{ ampere}}{2\text{ volts}} = .002\text{ mho}$$

$$g_m = 2000\text{ micromhos}$$

Because the anode resistance and transconductance are constant for only a small range of the tube characteristic, the characteristic curves for the proper tube must be consulted whenever a vacuum-tube circuit is considered.

The characteristic that makes the vacuum triode so valuable is that comparatively high voltages, developed across the anode circuit, can be controlled by a small voltage (and virtually no power) applied to the grid. This process is called *amplification*. To obtain amplification, a load must be connected in the anode circuit. Figure 30 helps explain the basic amplifier principle. A constant 450-volt supply is connected across the tube and load resistor in series. Electrons can flow from the negative terminal of the 450-volt supply to the cathode of the triode. The cathode is indirectly heated, and electrons are emitted from the cathode. Some electrons find their way through the holes in the grid, and are attracted to the anode. The electrons flow through the 50,000-ohm resistor to the positive terminal of the power supply. The grid of the triode is connected to a potential of -1 volt in Figure 30A. With the grid at this potential, the DC resistance of the triode is about 14,300 ohms. The 450-volt supply causes a current of 7 milliamperes to flow through the tube and the load resistor in series. This 450-volt potential is divided as follows: 100 volts across the tube resistance, and 350 volts across the load resistor.

The grid potential is changed to -4 volts in Figure 30B. Fewer electrons can get through this more negative grid, and the DC resistance of the tube increases to about



(A) (B) (C)

Figure 30. Principle of Amplification of Static Voltages

25,000 ohms. If the voltage across the tube and load resistor remains at 450 volts, this potential will be developed as 150 volts across the triode and 300 volts across the load resistor. Thus, a three-volt change in grid voltage has caused a 50-volt change in anode voltage.

Figure 30C shows that if the grid is made more negative by another three volts, the current will again be decreased. The DC tube resistance now becomes 40,000 ohms, and the 450-volt supply is divided as 200 volts across the tube and 250 volts across the load resistor. Again, a change in grid voltage of three volts has caused a change in anode potential of 50 volts. Operating the tube at these potentials produces essentially *linear* amplification. The amplification or voltage gain of a triode is the ratio of change in anode potential to change in grid voltage. For this application, a total change of six volts grid potential caused an anode change of 100 volts. Therefore, the voltage gain would be $100/6 = 16.6$. This is another way of saying that the change in anode voltage is 16.6 times the change in grid voltage.

The *amplification factor*, μ, is the measure of the change in anode potential caused by a change in grid voltage *when the anode current is held constant.*

$$\mu \text{ (mu)} = \frac{\text{change in anode voltage}}{\text{change in grid voltage}}$$

(anode current held constant)

For example, in Figure 29, with the grid at cathode potential an anode potential of 100 volts causes an anode current of 9 milliamperes. The same current would flow if the anode potential were raised to 300 volts and the grid potential lowered to -10 volts. Then,

$$\mu = -\left(\frac{300\text{ v} - 100\text{ v}}{-10\text{ v} - 0\text{ v}}\right)$$

$$\mu = -\left(\frac{200\text{ v}}{-10\text{ v}}\right) = -(-20) = 20$$

Mathematically, the amplification factor bears a negative sign indicating that the anode potential decreases μ times the increase in grid potential (anode current constant). To have a positive number for the amplification factor, the minus sign is added before the right-hand side of the equation. It is also possible to show that the amplification factor is numerically equal to the product of g_m and r_p.

$$\mu = g_m \times r_p$$

$$\mu = .002 \times 10{,}000 = 20$$

The amplification factor indicates the maximum gain possible for an amplifier tube. Actually the voltage amplification can never reach the amplification factor in a practical circuit, because the anode current is not held constant.

The circuits of Figure 30 show only three points in the operation of a triode. Figure 31 shows the circuit of Figure 30B with the addition of a sine-wave signal generator in the grid circuit. The signal-generator output is an alternating sine wave that starts from zero, goes to a positive 3 volts, returns to zero, goes to a negative 3 volts, and returns to zero each cycle. When the generator voltage is zero, the -4-volt battery potential is supplied to the grid, and the current and voltage are as in Figure 30B. As the generator voltage increases to $+3$ volts, the instantaneous voltage on the grid decreases to -1 volt (-4 volts $+3$ volts). The circuit now takes the configuration of Figure 30A. The generator cycle continues as the voltage moves through zero to -3 volts. The instantaneous voltage applied to the grid is now -7 volts (-4 volts -3 volts), and the resulting circuit condition is that of Figure 30C. Thus, the currents and voltages in the circuit have been varied between the ex-

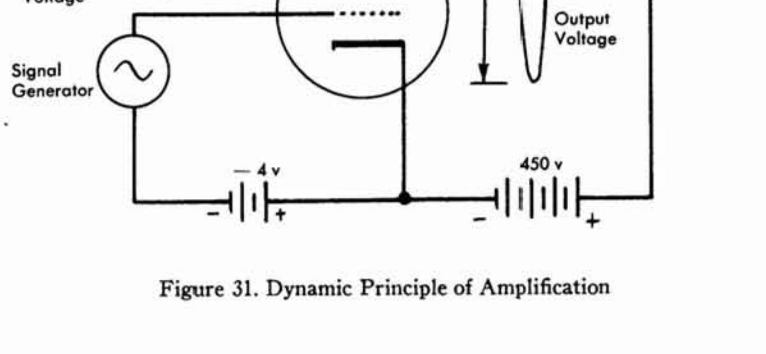


Figure 31. Dynamic Principle of Amplification

treme values of Figure 30A and Figure 30C. The anode potential has varied as the grid voltage was varied—and so is an amplified sine wave. Note that the output sine wave is an inverted replica of the sine wave applied to the grid. The signal undergoes a 180-degree phase shift in passing through the tube.

The grid voltage with no signal was set at a value of -4 volts in relation to the cathode in the preceding example. This value is called the *grid bias* of the tube. When the grid bias is set, and the circuit is *quiescent* (not amplifying a signal), the currents and voltages take steady-state values as in Figure 30B. The grid bias of -4 volts allows the signal to vary as much as four volts in either a positive or a negative direction. If the input signal is greater than four volts, on the positive half-cycles the grid will be driven slightly positive in relation to the cathode. A positive grid will start to attract electrons, grid current will flow, and the signal output may be distorted. The grid has no provision to radiate the heat from the collected electrons and may be damaged. The signal should never exceed the bias where undistorted amplification is desired.

If the amplification obtained by the use of one tube is insufficient, two or more tubes can be connected in *cascade*. Figure 32 shows a *direct-coupled* amplifier using two tubes in series, or cascade. Each of these tubes has a voltage gain of 10. A one-volt input signal is applied across the resistor R_g. This resistor is in series with the grid-bias battery C1, and the input signal adds algebraically to the bias voltage. Across the load resistor R, a ten-volt output signal will be developed by the action of tube 1 in varying the anode current. This ten-volt change is connected *directly* to the grid of tube 2. Tube 2 amplifies the signal voltage across resistor R in the same manner, except that a ten-volt input signal applied to the grid causes a 100-volt output change in voltage to be developed across R_L. An input signal of one volt has been amplified 100 times by the two tubes in cascade. Note that the amplification of several tubes in cascade is the *product* of the individual amplifications.

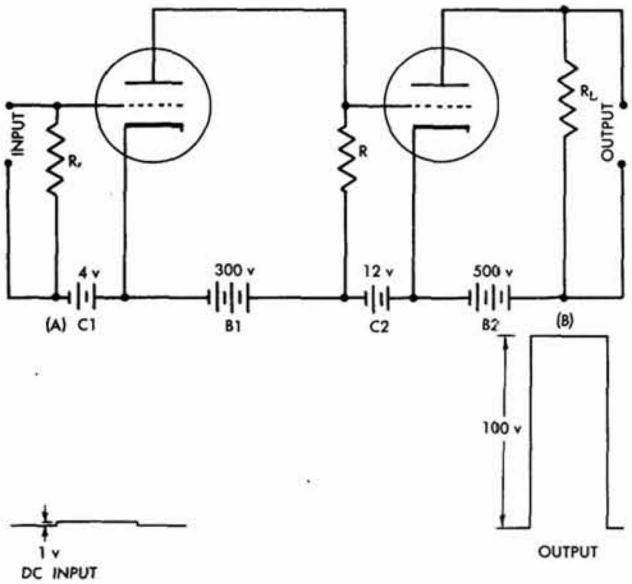


Figure 32. Direct-Coupled Cascade Amplifier

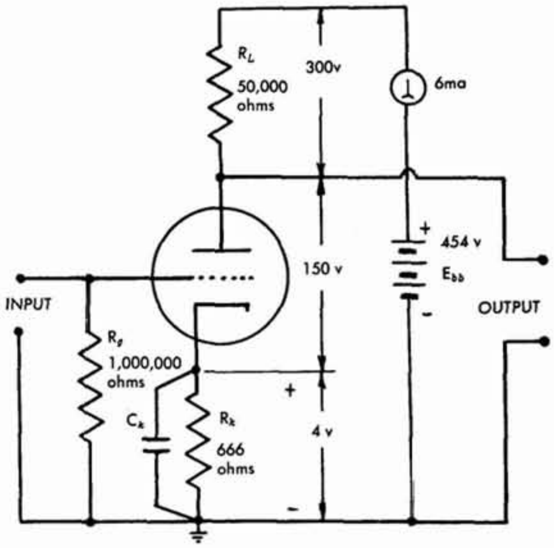


Figure 33. Cathode Bias

A direct-coupled amplifier has the disadvantage of requiring a large power supply. Between points A and B in Figure 32 a total voltage of 816 volts $(4 + 300 + 12 + 500)$ is required. Other types of coupling have been developed that allow simplifications in the power supply.

In Figure 33 a resistor labelled R_k has been connected in series with the cathode. The value of this resistor is chosen so that with six milliamperes (the quiescent current) flowing through the resistor, the tube, and the load resistor R_L, the voltage drop across the resistor R_k is four volts—the voltage required for the grid at the quiescent point. By connecting the grid to the negative end of this four-volt drop by means of the resistor R_G (through which no current is flowing), the grid is connected to a point that is four volts negative in relation to the cathode. To make the voltage drops round numbers, the power supply has been increased four volts to 454 volts. So the cathode resistor R_k could be used to obtain grid bias. This arrangement is called *cathode bias*.

Because the current through R_k and the tube changes with changes in signal, the voltage developed across R_k would also vary slightly. For example, a three-volt negative signal, which should decrease the grid potential to -7 volts, should decrease the anode current from 6 to 5 milliamperes, causing the anode potential to increase 50 volts. However, the one-milliampere decrease in anode current causes the drop across R_k to decrease from 4 volts to 3.3 volts; and the three-volt signal added in series (across R_G) brings the grid to only —6.3 volts. The result is that the effective voltage of the signal is decreased, and the amplification is decreased. Similarly, when a positive signal is applied to the grid, the increase in anode current increases the IR drop across R_k, driving the grid more negative and decreasing the amplification. This effect is called degeneration. Where alternating-current sine waves are being amplified (and virtually all wave-shapes can be resolved into a combination of sine-waves), degeneration may be greatly reduced by connecting a large capacitor (C_k = 20 microfarads or so) across R_k. The capacitor charges to the quiescent value (four volts in this example) and discharges slowly enough to maintain the grid-bias voltage when the anode current is momentarily increased or decreased. The degenerative effect is reduced, and the four-volt C battery is replaced by the cathode resistor and capacitor.

Two similar amplifier tubes are coupled in Figure 34. A *coupling capacitor,* C_c, is connected between the anode of tube 1 and the grid of tube 2. This capacitor charges to the quiescent anode potential of tube 1. Once charged, it allows only *changes* in anode potential of tube 1 to reach the grid of tube 2. Therefore, the grid of tube 2 can be run at a low potential in relation to the input circuit, and one power supply can supply voltage for both anodes. The amplifier in Figure 34 will have the same gain as the amplifier in Figure 32, and its power supply is much more simple. However, the direct-coupled amplifier (Figure 32) will amplify changes in DC input, but the capacitor-coupled amplifier only amplifies instantaneous changes in signal, and so cannot maintain a long DC change. Resistance-capacitance coupling (abbreviated RC coupling) is used in a large percentage of electronic amplifiers, because resistors and condensers are inexpensive compared to other types of coupling.

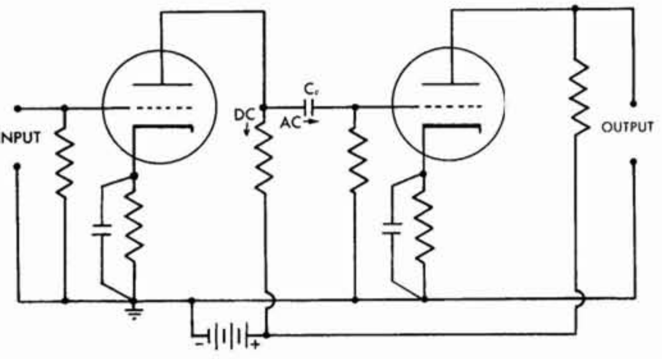


Figure 34. Resistance-Capacitance (RC) Coupled Amplifier

Figure 35 shows how two triode amplifiers may be coupled by means of transformers. Only AC can be transferred from the primary to the secondary of the transformer; hence no coupling capacitors are required. It is possible to obtain a voltage gain of three or four in the transformer, before the signal is applied to the grid of the second tube.

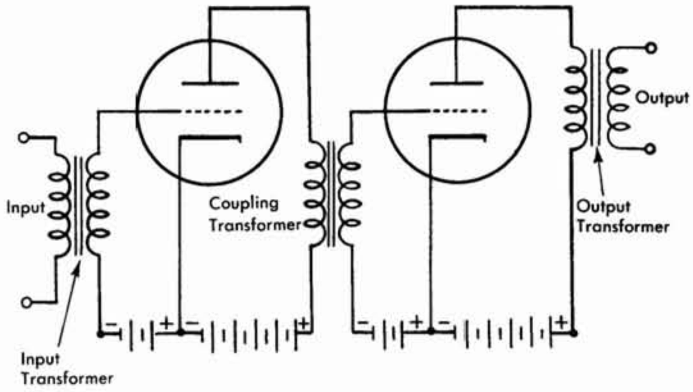


Figure 35. Transformer Coupling

When the B-supply is limited, *impedance coupling* is often used. The load resistor is replaced by an iron-core inductance (L_c in Figure 36) which has high inductance but low resistance. The DC voltage drop across the inductance is dependent on the steady-state current through the tube and the DC resistance of the induction coil. Thus, the vacuum-tube plate voltage will be almost as high as the supply voltage: inductive reactance does not affect direct current. However, any AC signal applied to the grid will cause a change in current through the tube and inductor. Any *change* of current will react with the inductance to produce a voltage across the inductor. In this way the instantaneous plate potential will be the sum of the DC plate voltage and the voltage generated by the change of current through the inductor. Because the voltage generated across the inductor can reach a considerable value, the instantaneous plate voltage may reach a value of several times the plate supply. Impedance coupling has the disadvantage that the inductive reactance varies with frequency; so low-frequency signals will be amplified less than high-frequency signals.

The triode circuits previously mentioned have been designed for voltage amplification. For the amplifier to do useful work, one or more stages of *power amplification* are

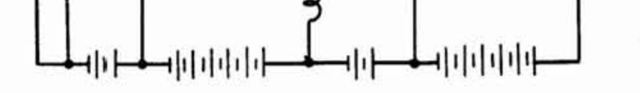


Figure 36. Impedance Coupling

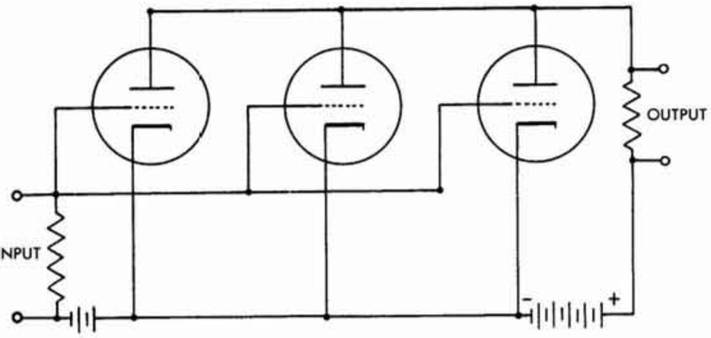


Figure 37. Parallel Triode Connection

generally included in a cascade amplifier. These power amplifiers are driven by the voltage developed by the voltage amplifier. The power amplifier can take the same form as the voltage amplifier, except that a lower plate load allows more current to flow through the anode circuit. Since the power developed is given by the equation,

$$\text{Power} = (\text{Current})^2 \times \text{Resistance}$$

it is important to have a large change in anode current. Frequently two or more vacuum tubes are operated in parallel. In Figure 37 three triodes operated in parallel make it possible for the load to draw three times as much current (and nine times as much power) as a single tube could supply.

Another widely-used power amplifier circuit is the push-pull arrangement of Figure 38, which is similar to the circuit used for a full-wave rectifier. In the push-pull circuit one tube amplifies the positive half of the signal while the other tube amplifies the negative half. The two halves are re-combined in the output transformer. Push-pull amplifiers tend to cancel even harmonic distortion[1] caused by the tubes, and are generally more efficient than parallel-tube arrangements.

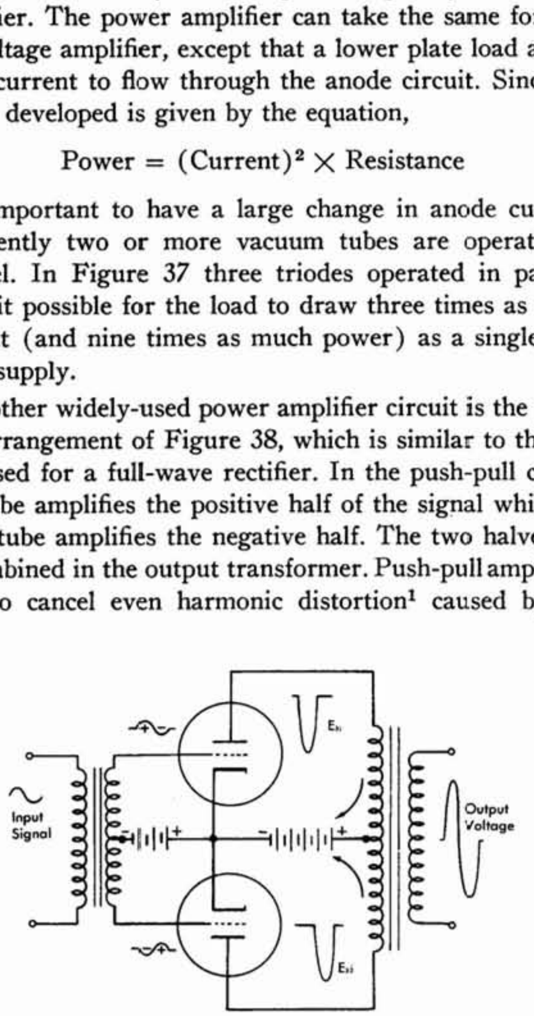


Figure 38. Push-Pull Operation of Triodes (Class B)

Amplifiers are frequently classified by the bias and grid-current conditions of the tubes. In *class A* operation the grid is always negative in relation to the cathode. The anode current never goes to zero, and the grid voltage never becomes positive. As long as the variations in anode current never exceed these limits, the output will be an almost exact reproduction of the input signal. Since the grid of the class A amplifier is never positive in relation to the cathode, no electrons should ever flow from cathode to grid. The over-all efficiency of the class A amplifier is poor, because only a small part of the tube's output capacity can be utilized.

To obtain a higher efficiency and increased power output, the quiescent grid bias of the tube may be set at cutoff. When no signal is applied to the grid, no anode current flows; if a signal is applied, anode current flows only for the positive half of the alternating signal, when the grid is driven less negative. When the tube is biased at cutoff, it is being operated as a *class B* amplifier. Generally, to amplify both halves of the signal, two class B amplifiers are operated in a push-pull circuit.

The maximum efficiency of amplification can be obtained by *class C* operation. The grid is biased beyond the cutoff point so that anode current flows for less than half the applied signal. The resulting wave is naturally much distorted from the input; but this does not prevent use of this type of operation, because the load in the output circuit is usually a resonant circuit. A resonant circuit tuned to the frequency of the signal restores the missing portion of the wave so that the final wave form is only slightly distorted. Class C operation could never be used in an amplifier for speech or music, but it is useful in amplifying radio-frequency waves.[2]

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[1] Harmonic distortion is introduced because the tube characteristics are not linear. In effect, if the tube is amplifying a signal of 100 cycles per second, traces of 200, 300, 400, 500, etc., cycles-per-second frequencies could be detected in the output. Push-pull amplifiers tend to cancel the even harmonics—200, 400, etc., in this example. This is desirable in an amplifier for speech or music, since the ear is more tolerant of odd harmonics.

[2] Amplifiers are frequently classified by the type of wave they are designed to amplify. An *audio* amplifier is designed to amplify waves in the range of frequencies that are heard by human ears—from 20 to 20,000 cycles per second. *Radio-frequency* amplifiers are used for frequencies above this range. *Video* amplifiers are used to amplify signals from about 60 cycles to 4 megacycles, with substantially uniform gain—a requirement for the transmission of television intelligence.

The following chart shows the operating conditions for the various classes.

	Portion of the Cycle during which plate current flows	Biased
Class A	100%	Halfway between cutoff and saturation
Class AB	Greater than 50% Less than 100%	Slightly above cutoff
Class B	50%	At cutoff
Class C	Less than 50%	Below cutoff

Note: To show that grid current does not flow during any part of the cycle, the subscript 1 may be added to the letter or letters of the class designation. The subscript 2 is used to show that grid current flows during part of the cycle. For example, class AB_1 signifies that the tube is operated slightly above cutoff, plate current flows less than 100% but more than 50% of the time, and the grid is never driven positive.

When very small signals are amplified millions of times by a cascade amplifier, it is important that tube noise be kept as low as possible in the earlier stages of the amplifier to prevent it from masking the signal. Vacuum tubes are inherently noisy. Traces of gas in a tube may cause noise: the gas atoms are ionized by collision with electrons and attracted to the cathode where they liberate little bursts of electrons. Noise due to faulty tube construction may cause trouble. If any of the elements are not properly insulated, noise may be generated by leakage currents between elements. If the elements are not properly braced, they may vibrate, causing the tube to amplify mechanical shocks, or be microphonic.

Another type of noise in vacuum tubes is called "shot noise" or *Schottky effect* and is due to the random emission or arrival of electrons. If electrons were emitted from the cathode at an absolutely constant rate, there would be no shot noise. Instead, they appear to be emitted in bundles, and they arrive at the anode in bunches. The small variations from steady current caused by the arrival of electrons in groups causes the anode current to vary at a random rate, producing noise.

Noise is also generated by the random motion of the electrons in the grid resistors of the earlier stages. The tiny variations in voltage across the grid resistor of the first stage are amplified by the entire cascade. For this reason, the smallest signal that can be amplified must be greater than the electron noise in the first stage. The comparative magnitude of desired signal and electron noise is called the *signal-to-noise* ratio.

Vacuum triodes are finding wide use in electronic calculators. In applications of this type use is made of the fact that the triode has two well-defined states. With the grid at cathode potential, electrons flow through the vacuum, and the tube conducts. If the grid is made sufficiently negative, no electrons can reach the anode, and the tube is cut off. Because the anode potential is quite different under these conditions, the anode voltage indicates whether the tube is conducting or not conducting. The manner in which electron tubes can be caused to do arithmetic will be explained in a later chapter.

Gas Triodes or Thyratrons

It will be recalled that the addition of a small amount of gas to the diode greatly increased the electron current through the tube. Gas-filled triodes are similarly capable of carrying high currents, with the additional advantage that small controlling voltages applied to the grid can control large amounts of power transferred through the anode circuit. Gas triodes (also called thyratrons) have their most extensive use in control circuits, and would never be used to amplify speech or music.

The presence of atoms of gas in a triode causes the triode to function in a completely different manner from the way in which a vacuum triode operates. Figure 39 shows the construction of a typical gas triode. The grid is a cylinder almost completely enclosing the cathode and the anode. Between the anode and the cathode is a baffle which has a small hole in it. When the tube is conducting, the electrons pass from cathode to anode through this hole.

The cathode of a thyratron should *always* be given time to heat to operating temperature before the anode potential is applied to the tube. If the anode potential is applied too soon, the voltage will try to cause a current greater than the number of electrons being emitted. Those emitted electrons are unduly accelerated, and cause much greater ionization than is normal. The increased bombardment by the heavy atomic particles may destroy the cathode.

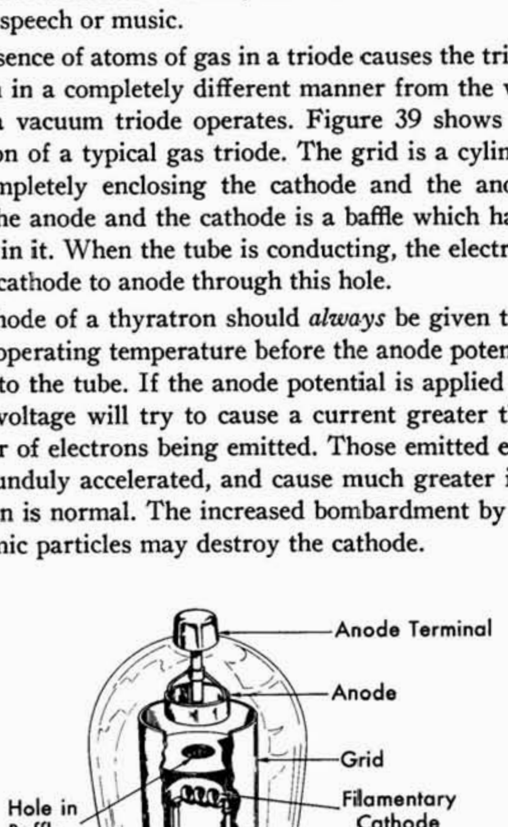
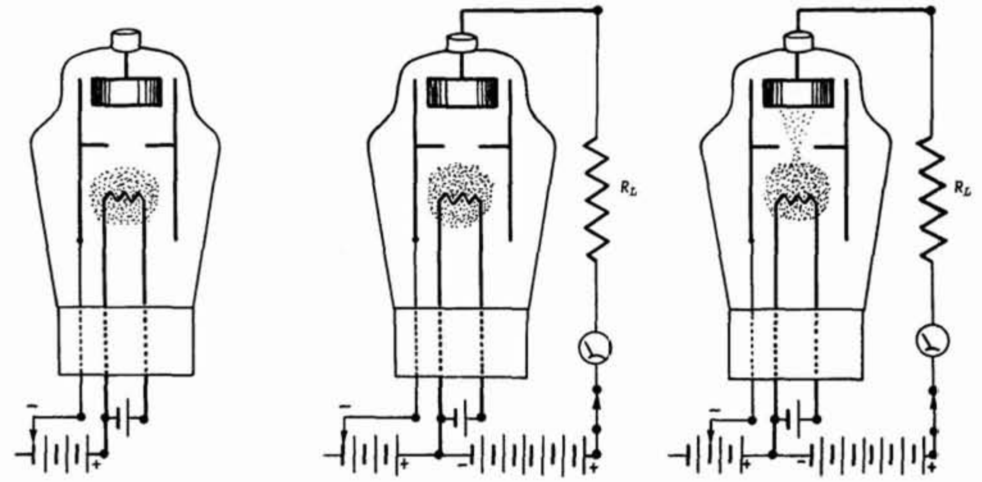


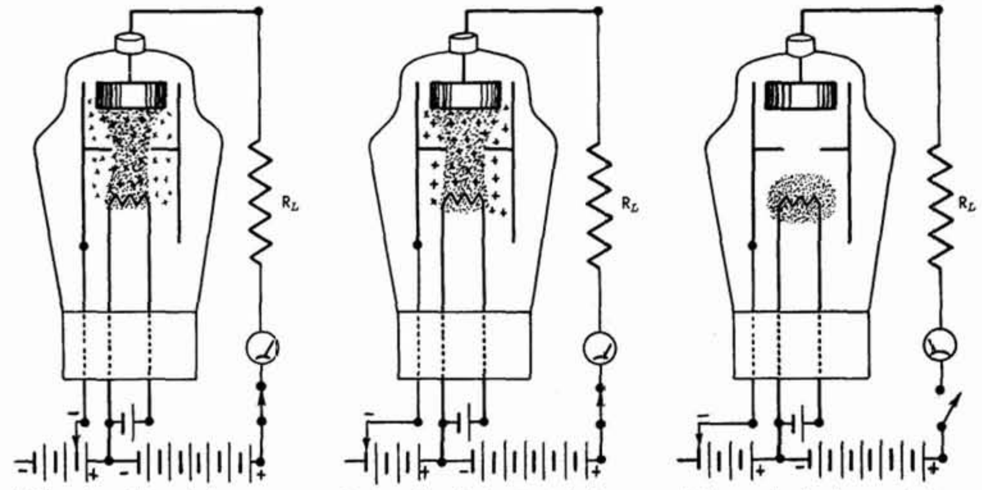
Figure 39. Thyratron



1. The heater of a thyratron is energized, and a strong negative potential is placed on the grid.

2. If the anode is now made positive, no current can flow through the tube.

3. As the negative grid bias is decreased, the anode will begin to collect electrons.



4. When the grid is made less negative, the electrons will gain enough momentum to cause ionization of the gas atoms.

5. Once the tube has ionized, the grid loses control, and cannot cut off the anode circuit.

6. The anode circuit can only be stopped by lowering the anode voltage below ionization potential or opening the anode circuit.

Figure 40. Thyratron Operation

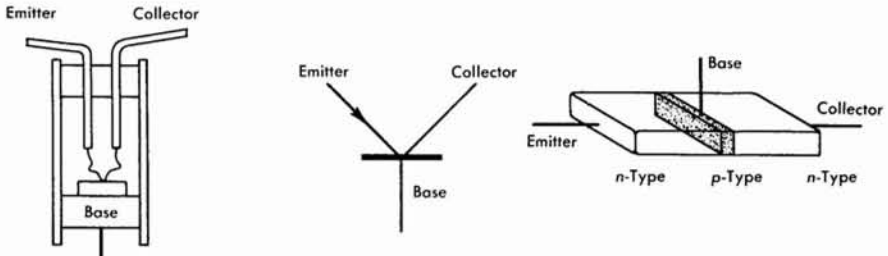
When the grid of a thyratron is made negative in relation to the cathode, the negative field electrically closes the hole in the baffle plate, preventing electrons from reaching the anode. The anode potential may now be applied, and no current will flow, provided the anode voltage is not so high as to overcome the effect of the negative grid bias. If the grid potential is now decreased, the negative field closing the baffle plate will be decreased, and a few electrons may find their way to the anode. As the grid potential is further decreased, the electrons reaching the anode may collide with gas atoms with sufficient velocity to cause ionization. Once ionization starts, current flow builds up almost instantly because of the cumulative effect of ionization, and the grid loses control of the electron stream because the negative field is neutralized by the presence of positive ions. The anode current can only be stopped by opening the anode circuit or by lowering the anode potential below the ionization potential of the tube. The *time* required for *ionization* to occur is about ten microseconds (.000010 second) for mercury-vapor thyratrons. The thyratron cannot stop conducting the instant the voltage drops below ionization potential, however, and the *de-ionization time* is of the order of 1000 microseconds, or one millisecond for most thyratrons. This time is required for all the ions to obtain electrons and revert to neutral atoms. Thyratrons containing other gases have much lower ionization and de-ionization times.

The Crystal Triode or Transistor

The transistor, announced by the Bell Laboratories in 1948, is one of the latest developments in electronics. The earliest transistors were not very dependable, but research and development have brought about great improvements. Scientists now predict that crystal elements will eventually make thermionic vacuum tubes obsolete for certain applications.

The earlier types of transistors employed two metal cat whiskers welded to a slab of crystaline germanium. The potential applied to one whisker controlled the electron current flowing from the crystal to the other whisker to the germanium. A more recent form of transistor has been made possible by the discovery of a type of germanium that readily loses electrons and is called *n*-type germanium. A tiny slab of germanium which readily gains electrons (*p* type) is sandwiched between two pieces of *n*-type germanium. The slab of *p*-type germanium is called the *base*, and corresponds to the grid of a vacuum tube. The end sections are called the emitter (cathode) and the collector (anode). Because the area of the junction of the two types of germanium is much greater than the cat-whisker contact, more current can flow through the new transistor than was possible with the older type.

The theory of transistors is very involved, and a thorough explanation of the behavior of electrons and "holes"—a place where an electron should be, but isn't—would take a volume in itself. The flow of electrons across the junction between electron-rich and electron-deficient regions of germanium can be controlled by an applied signal much as the plate current of a vacuum tube is varied by voltages applied to the grid. Because the transistor can control a greater power than is applied to the base, it can be used as an amplifier. No heater power is required, and for this reason the transistor is much more efficient than a thermionic tube. A three-stage amplifier using transistors has been built in a case smaller than a flashlight cell. The power required is less than one-millionth of the power required to heat conventional tubes. Such an amplifier will operate for months or even years on a standard flashlight cell. When mass-production techniques have been developed, the transistor will be a very valuable circuit element.

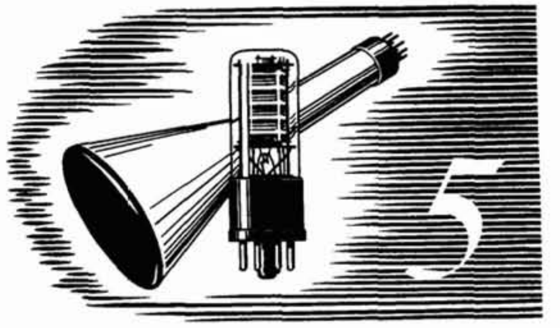


(A) POINT-CONTACT TRANSISTOR

(B) SYMBOL

(C) *n-p-n* JUNCTION TRANSISTOR

Figure 41. Germanium Transistor



MULTI-ELEMENT tubes

If one grid was desirable, two might be better—but why stop there? More grids are introduced, creating the tetrode and pentode; then the pentagrid tube, multi-unit tubes, and television's cathode-ray tube

THE TRIODE has several disadvantages that no amount of design work can remove. As a voltage amplifier, the triode is limited in voltage gain and frequency range. The grid and plate are parallel cylindrical elements, and act as a capacitance. The grid-plate capacitance tends to allow alternating currents to flow between grid and plate circuits. At higher frequencies, the reactance of the grid-plate capacitance acts as a short-circuit to the signal voltage, and the gain of the tube is thereby decreased. Because plate power is reflected through the grid-plate capacitance to the grid, the tube has a tendency to oscillate[1]—an undesirable effect in an amplifier. In trying to cure these defects, Dr. A. W. Hull of the General Electric Company introduced another grid between the control grid and the anode, and thus invented the *tetrode* (*tetra* = four).

The insertion of another grid between the control grid and the anode has the effect of breaking the grid-plate capacitance into two small series capacitances, the center point of which is electrically neutral to alternating currents. The added grid is called a *screen* grid because its function is to establish an electrostatic shield between the anode and the control grid. The addition of the screen grid reduces the grid-plate capacitance from values of the order of 3 micromicrofarads for a triode to values of the order of .01 micromicrofarad for a comparable tetrode.

Ideally, the screen grid should be connected to ground or cathode potential, but the accelerating effect of the anode on electrons being emitted from the cathode would be greatly diminished by the zero-potential field around the screen grid so connected. It is possible to apply a DC potential to the screen grid and to maintain a high positive-accelerating field. A fairly large capacitor is connected between the screen grid and the cathode (Figure 42); this capacitor grounds the screen grid to alternating currents.

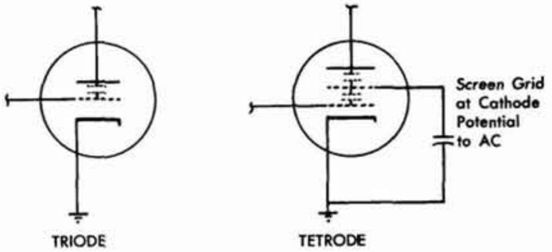


Figure 42. Grid-Plate Capacitance

The screen grid is therefore maintained at a positive, accelerating DC voltage, while being held to a zero AC potential. Figure 43 shows a typical arrangement for a tetrode amplifier.

Because the screen grid is at a positive DC potential, some of the electrons from the cathode will strike the screen and return to the power supply, forming a screen current (although a majority of electrons penetrate the holes in the screen grid and arrive at the anode). If the anode potential were removed, however, the screen grid would attract all the electrons; and since the screen is of small area and can-

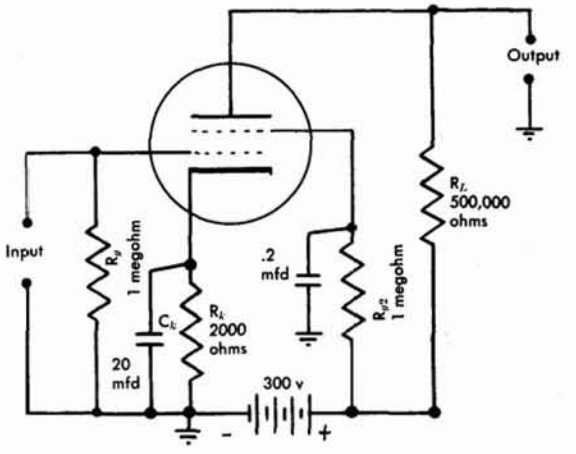


Figure 43. Tetrode Amplifier

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[1] Oscillation is covered in greater detail in Chapter 6.

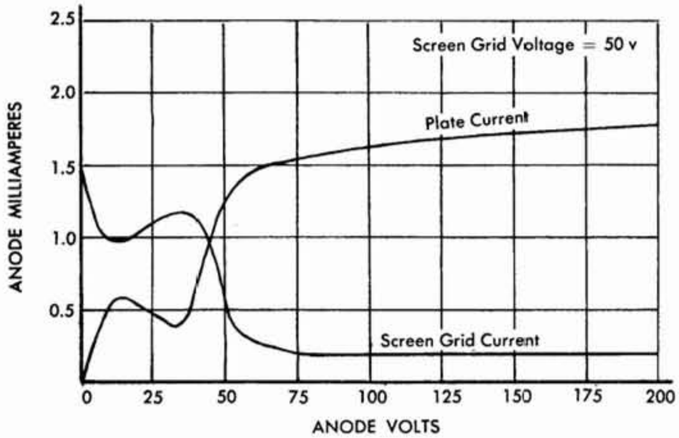


Figure 44. Tetrode Characteristics

not readily radiate the heat energy conveyed to it by the electrons, it might overheat or melt. The anode potential should never be removed from a tetrode without first disconnecting the screen grid.

Figure 44 shows the anode characteristic of the tetrode. This chart shows the anode and screen-grid currents when the control-grid and screen-grid voltages are held constant, and the anode voltage is varied. When the anode potential is zero, no anode current flows, and the screen grid attracts all the electrons. Obviously, the tube should not be operated under these conditions. As the anode voltage increases, the anode current increases just as it did in the triode. As the anode voltage is further increased, however, the electrons reaching the anode arrive with considerable velocity and may dislodge electrons by secondary emission from the anode. Because the screen grid is more positive than the anode at this point, these secondary electrons may be attracted to the screen grid. Thus, although more electrons are reaching the anode, fewer electrons remain there, and the anode current decreases. As the anode voltage is increased to a potential above the screen-grid potential, the electrons released by secondary emission are attracted back to the anode, and the tube characteristic becomes a smooth line beyond this point. The tetrode is generally operated on the portion of its characteristic curve where the anode voltage exceeds the screen-grid voltage.

When it was introduced in 1928, the tetrode made possible increased sensitivity and improved performance of radio sets. In efforts to overcome the undesirable secondary emission from the anode, many methods of construction were tried. In 1930 the solution was discovered: the addition of another grid between the screen grid and anode. Thus, the tetrode was superseded by the *pentode* (*penta* = five).

The Pentode

The invention of the five-element tube, or pentode, eliminated the secondary-emission fault of the tetrode by the insertion of a third grid, called a *suppressor,* between the screen grid and anode. The suppressor grid is connected to cathode potential, and so is very negative in relation to its neighboring elements—the anode and the screen grid. Electrons from the cathode are accelerated by the positive field of the screen grid. Some of the electrons may still strike the screen and cause screen current. The electrons that go through the spaces in the screen grid are accelerated sufficiently to penetrate the negative field of the suppressor grid and to strike the anode. Electrons released by secondary emission face a strongly negative field and must return to the anode. The distortion caused by secondary emission is thus removed, as the characteristic curves of a typical pentode (Figure 45) will show. The anode potential in a pentode can vary much more widely than the anode potential of a comparable tetrode may swing. Typical triodes have voltage gains of from 10-70, while pentodes have gains of from 30-375. Figure 46 shows a typical pentode amplifier circuit. The pentode operates in the same way that the triode operates in varying the current through the

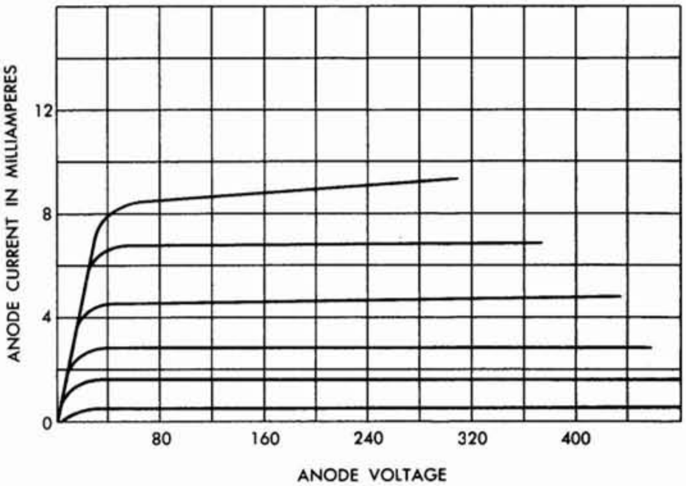


Figure 45. Pentode Characteristics

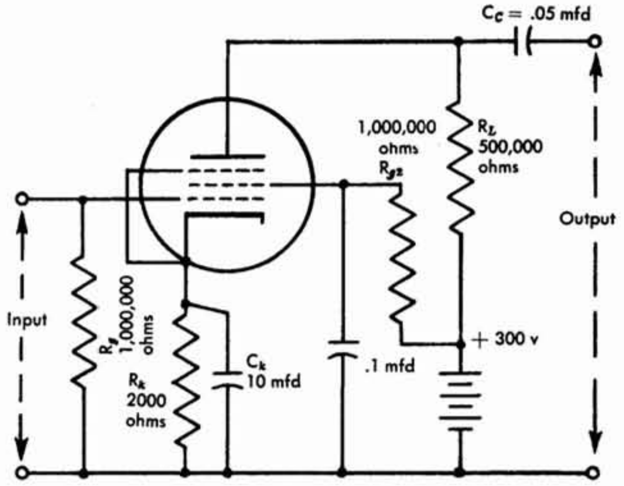


Figure 46. Pentode Amplifier Circuit

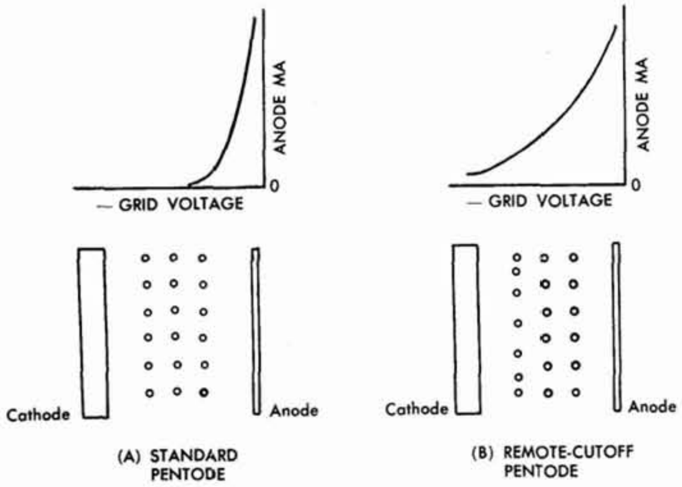


Figure 47. Sharp and Remote-Cutoff Pentodes

anode circuit, thereby obtaining a large voltage variation at the anode.

In the standard pentode the control grid wires are evenly spaced. This spacing causes the tube to have the sharp cutoff characteristic shown in Figure 47A. For some applications, principally in the first stages of radio amplifiers, it is desirable to smooth out the sharp characteristic so that the tube handles both large and small input signals over a wide range with minimum distortion. A smooth characteristic is obtained by spacing the grids closer together near the ends of the cathode and farther apart near the center. A tube with this type of grid is called a remote-cutoff pentode, and has the characteristics shown in Figure 47B.

With the invention of the pentode it became possible to obtain much greater amplification from a single tube; however, the pentode has the disadvantage of being three to five times as noisy as a comparable triode. For this reason a triode is frequently used in the first stage of a cascade amplifier, thus obtaining amplification without introducing appreciable noise. The following tubes amplify the signal and the noise proportionally; so it is important that as little noise as possible be introduced in the first stage.

The Beam-Power Tube

The beam-power tube is a special type of tetrode. The power capacity is increased by causing the electrons to move from the cathode to the anode in dense beams. The screen-grid wires are located directly behind the control-grid wires (Figure 48). This alignment causes the electrons to move to the anode in beams, and reduces the magnitude of the screen-grid current. Beam-confining plates, connected to the cathodes, prevent electrons from passing the grid near its end supports and form the beams into tight vertical beams. Because the electrons are concentrated as they pass from the grids toward the anode, they present a highly negative field to any electrons removed from the anode by secondary emission. The negative field acts as a suppressor grid, but because it is only a concentration of charges and not a physical element, it is called a *virtual suppressor*. The beam-power tube has high efficiency. It has high power sensitivity which means that a large output power is obtained for a small AC potential on the control grid. Increased power output is possible because the permissible range of anode swing is increased by straightening the "dip" in the tetrode characteristic (Figure 49). Finally,

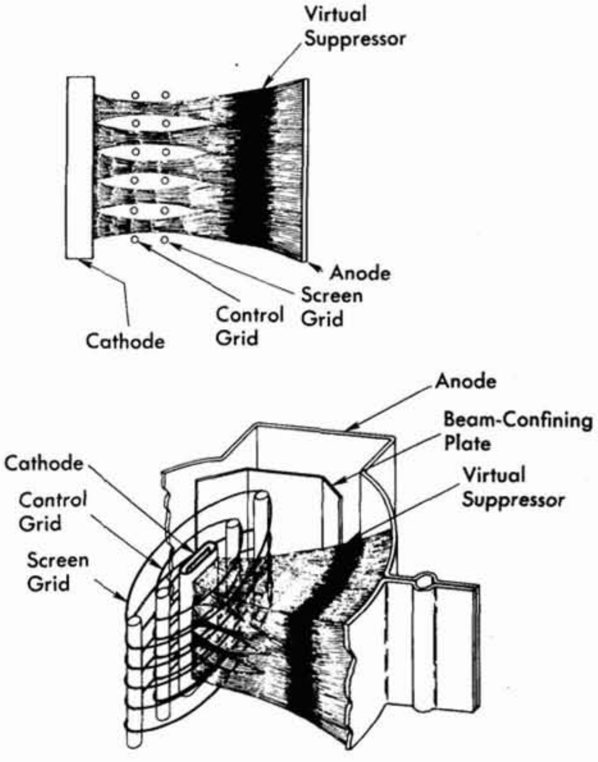


Figure 48. Beam-Power Tube

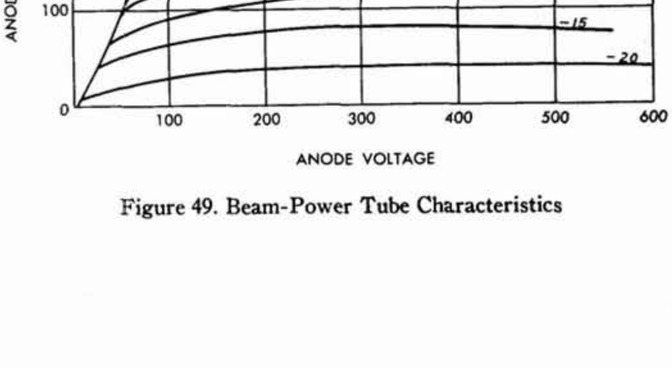


Figure 49. Beam-Power Tube Characteristics

odd harmonic distortion is decreased. Employing a push-pull circuit will decrease even harmonic distortion. Therefore, beam-power tetrodes in push-pull arrangement greatly decrease harmonic distortion.

The Pentagrid Tube

In certain applications even more control electrodes between the cathode and the anode are desirable. The pentagrid tube, as its name implies, has five grids separating the cathode and the anode. Many circuits have been devised in which the five grids serve different functions. The most general use of pentagrid tubes is in mixing circuits. For example, in many amplitude-modulated radio receivers, the incoming signal is amplified and mixed with a signal generated within the receiver that is always 456 kilocycles higher than the radio signal. The pentagrid tube mixes the two signals, and the anode circuit carries the sum and difference of the two frequencies. Since the difference frequency is always 456 kilocycles, the amplifier following the mixer stage can be tuned to amplify only 456-kilocycle signals.

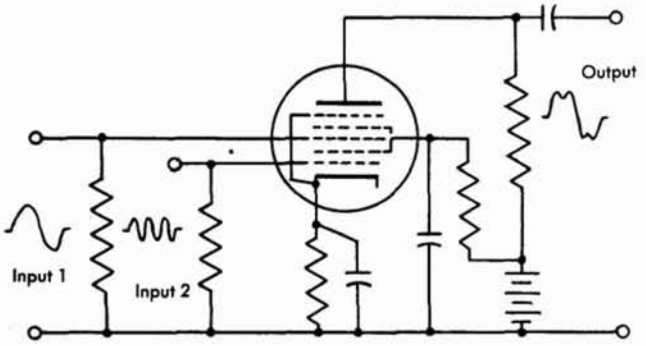


Figure 50. Pentagrid Mixer

Figure 50 shows a pentagrid tube connected as a mixer. The radio frequency wave is connected to the grid nearest the cathode. Grid 2 and grid 4 are connected together and serve as screen grids. Grid 3 is connected to the local oscillator, and operates on the electron stream as an independent control grid. Grid 5 serves as the suppressor to eliminate secondary emission. In this way both the radio signal and the signal generated in the set control the electron stream, and the anode circuit always contains the 456-kilocycle signal needed in the next stage.

Another common circuit employs the cathode and the first two grids of a pentagrid tube as a triode oscillator. Grids 3 and 5 serve as screen grids, and the radio signal is impressed on grid 4. This circuit is called a *pentagrid converter* (Figure 51).

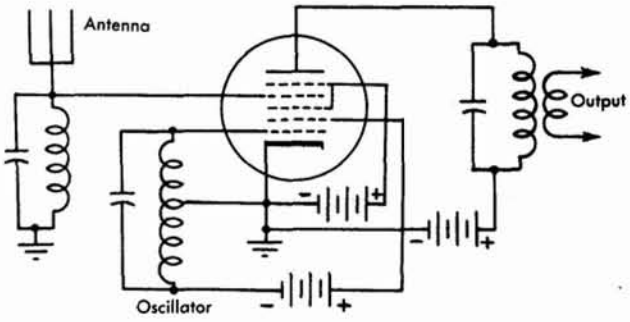


Figure 51. Pentagrid Converter

Multi-Unit Tubes

Multi-unit tubes contain several tube structures in one envelope, and serve to conserve space and heater current. Typical types include the twin-diode triode, the twin-diode pentode, and the twin-triode tube. The multi-unit type 117N7 contains a power rectifier and a power-output pentode. Figure 52 shows schematic diagrams of some typical multi-unit tubes.

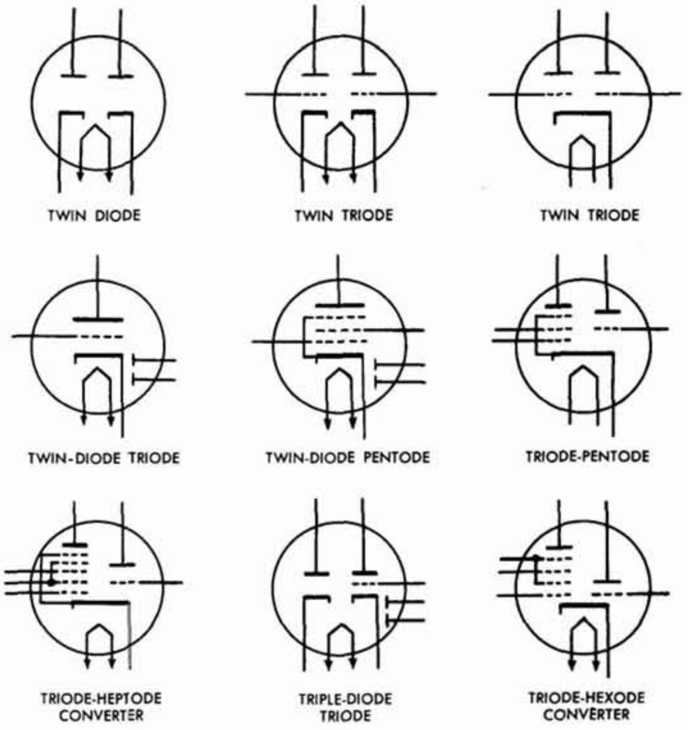

TWIN DIODE
TWIN TRIODE
TWIN TRIODE
TWIN-DIODE TRIODE
TWIN-DIODE PENTODE
TRIODE-PENTODE
TRIODE-HEPTODE CONVERTER
TRIPLE-DIODE TRIODE
TRIODE-HEXODE CONVERTER

Figure 52. Multi-Unit Tubes

The Cathode-Ray Tube

With the advent of television the cathode-ray tube has become commonplace, for it is upon the face of this tube that the television picture is developed. The cathode-ray tube was originally developed as a test instrument for recording the variation of current strength and voltages with time. Through television and electronic calculators its use has spread rapidly to many other fields. The cathode-ray tube makes it possible to show graphically the change of any scalar quantity (such as voltage, length, temperature, speed, etc.) in relation to time. The cathode-ray tube has even been used to measure the twitching of a muscle fibre when stimulated by electric shocks.

The cathode-ray tube is a long evacuated glass envelope shaped as in Figure 53. At the small end of this tube is the cathode, a small button of material that emits electrons freely when heated indirectly by the heater filament. A system of positively-charged electrodes forms the electrons into a narrow beam and accelerates and directs them to the screen of fluorescent material covering the large end of the tube. Where the beam of electrons strikes the phosphor screen, the fluorescent material glows, and a spot of visible light is produced. Focusing is accomplished by causing the electron beam to pass through a series of electrostatic fields of differing intensity. By properly arranging the sequence of fields, the electron beam can be focused much as light rays are focused. Figure 54 shows how the electron beam can be focused by passing through a decreasing and then increasing electrostatic field so that a pin-point of light may be formed at the screen.

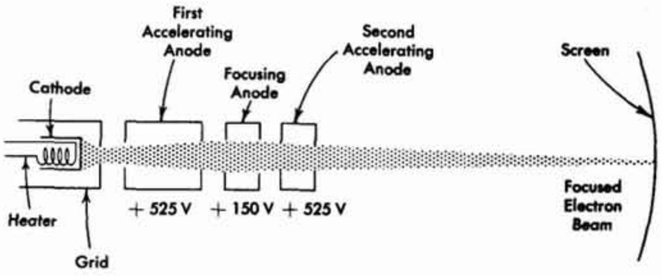


Figure 54. Electrostatic Focusing

For the tube to impart any information, the tiny spot of light must be deflected from its position in the center of the screen. The beam is formed of negatively-charged electrons. The electron beam will bend toward a positively-charged electrode, and will be repelled by a negatively-charged electrode. This principle, called ***electrostatic deflection,*** is used in many cathode-ray tubes. Figure 55 shows how a positively-charged deflection plate deflects the electron

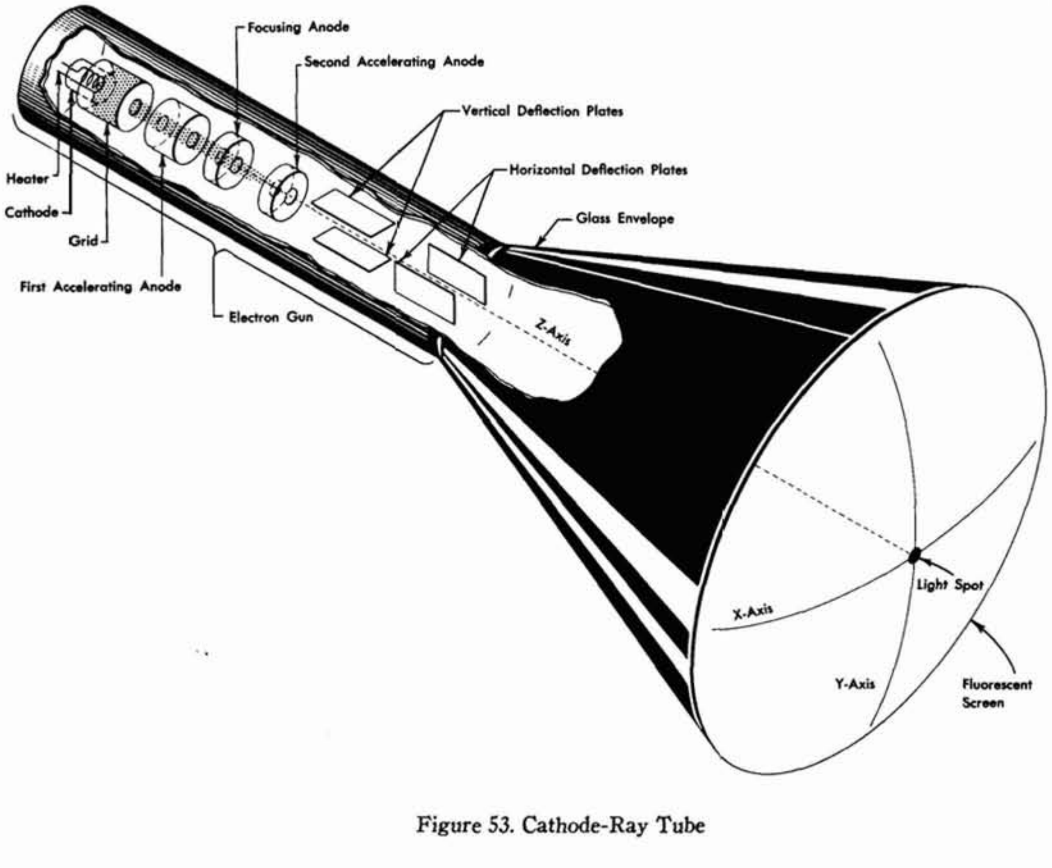


Figure 53. Cathode-Ray Tube

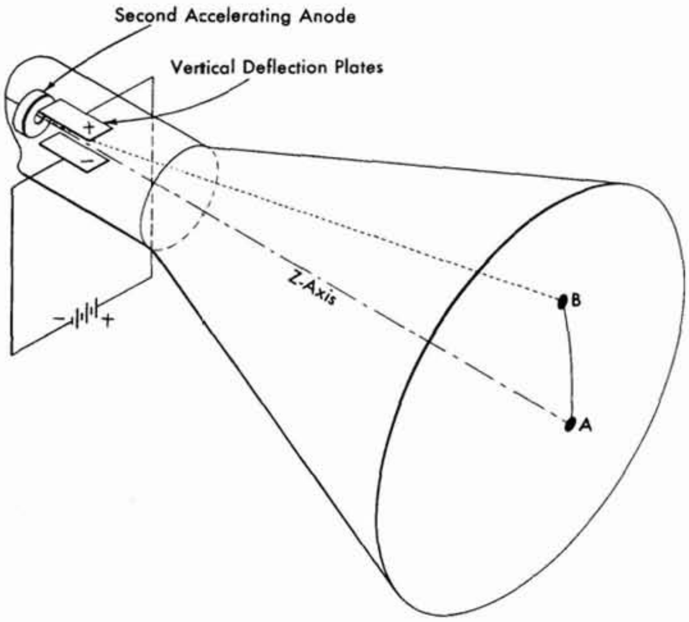


Figure 55. Electrostatic Cathode-Ray Deflection

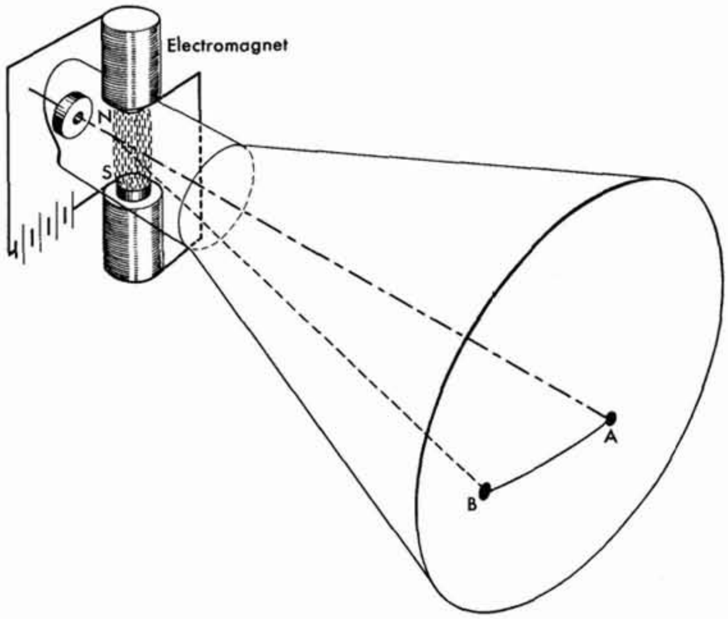


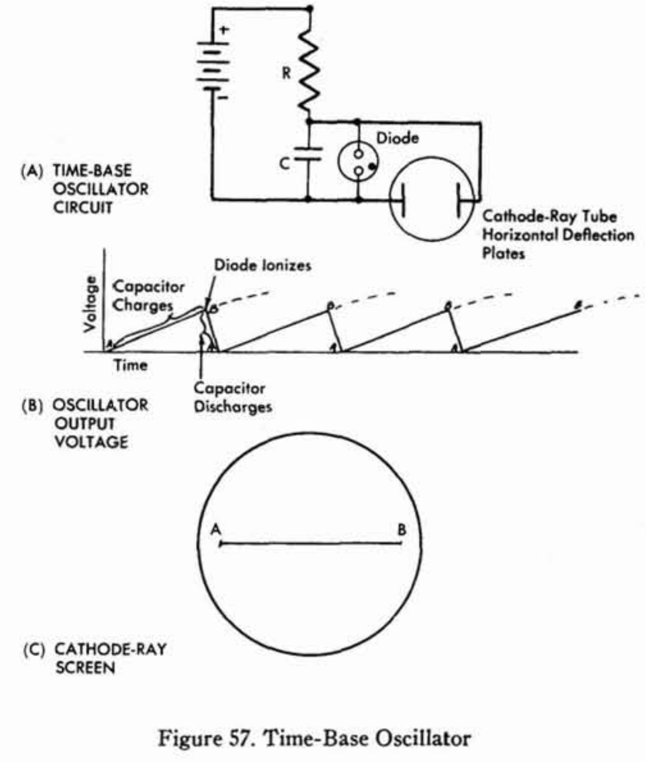
Figure 56. Magnetic Deflection

beam. Two deflection plates are placed parallel to one another, and the electron beam is directed between them. If both plates are charged to the same potential, the electron beam will be unaffected, but if either plate is made positive in relation to the other, the electron beam will be deflected toward the positive plate. By using two pairs of deflection plates, one pair may be adjusted to deflect the electron beam across the screen of the tube from left to right, while the other pair may be arranged to deflect the beam from top to bottom. By properly arranging voltages on the deflection plates, the spot may be moved to any position on the screen.

The electron beam consists of negative charges (electrons) moving in a path; the beam behaves like a conductor carrying a current—which, figuratively speaking, it is. A magnetic field can cause a force to be exerted on a conductor which is carrying current; and similarly, the electron beam of the cathode-ray tube can be deflected by a magnetic field. Some cathode-ray tubes employ electromagnets to deflect the electron beam. These tubes employ *electromagnetic deflection* in the form of a coil assembly placed around the neck of the cathode-ray tube. Figure 56 shows the deflection of the electron beam caused by a magnetic field. Note that the electron beam is deflected at right angles to the magnetic field. Because the *electrostatically* deflected cathode-ray tube is more easily understood, it will be used as a basis for remainder of this discussion.

The cathode-ray tube is, by itself, an insensitive device. Potentials of about 100 volts per inch are required for deflection of the electron beam. For the tube to indicate signals of relatively small potential, amplifiers are used in the circuits to the deflection plates.

Because it is so often desirable to show graphically the relation between a scalar quantity and time, a device for generating a time base is necessary. The *time-base generator* provides a voltage that deflects the fluorescent spot across the screen of the tube from left to right at a steady rate. The voltage required to deflect the spot must increase at a steady rate in relation to time. Figure 57A shows a simple circuit for the time-base oscillator. Capacitor C is



(A) TIME-BASE OSCILLATOR CIRCUIT

(B) OSCILLATOR OUTPUT VOLTAGE

(C) CATHODE-RAY SCREEN

Figure 57. Time-Base Oscillator

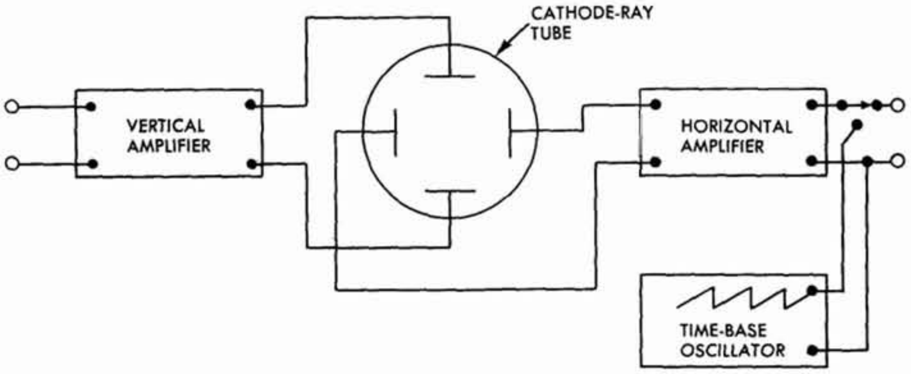
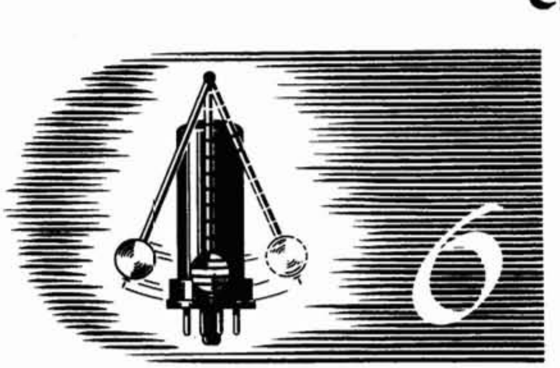


Figure 58. Block Diagram of Cathode-Ray Oscilloscope

charged slowly through the resistor R; the voltage across the capacitor increases as time passes. When the voltage across the capacitor reaches the ionization potential of the gas in the cold-cathode diode, the gas ionizes, and a low resistance path is provided through which the capacitor discharges *almost instantaneously*. The gas de-ionizes, and the capacitor again starts to charge. The voltage across the capacitor takes the form shown in Figure 57B, and is called a saw-tooth wave. The frequency may be varied by changing the values of R and C. On the screen, the spot of light moves from point A to point B as the voltage rises, returning to point A when the gas tube ionizes.

The cathode-ray *oscilloscope* consists of a cathode-ray tube, two deflection amplifiers, and a time-base oscillator assembled as a unit. Figure 58 shows a simplified schematic diagram of a cathode-ray oscilloscope.



electron-tube OSCILLATORS

Electron tubes can generate pendulum-like oscillations—and alternating voltages of high frequency. The multivibrator as a source of many unusual voltage waveforms

IT HAS BEEN shown that under proper conditions an amplifier tube can develop more power across its load impedance than is required for the input signal to the grid. Early experimenters with triode amplifiers soon found that if a portion of the output power were fed back to the grid, the tube could be made to furnish its own grid excitation. If the circuit elements were properly chosen, the tube could develop self-sustained oscillations, and serve as a generator of alternating voltage waves. Such a circuit is called a vacuum-tube oscillator. Because a vacuum-tube oscillator has no moving parts, it can develop alternating voltages of much higher frequency than can be developed by conventional rotating generators. The invention of the oscillating circuit made possible the later development of radio and television.

Tuned-Circuit Oscillators

The frequency of the alternating voltage generated by the vacuum-tube oscillator is determined generally by the resonant frequency of the circuit, including the tube. A resonant circuit might be compared to a pendulum. If the bob is pushed back and forth so that each push adds to the motion of the pendulum, it will swing back and forth at a fixed rate. A resonant circuit behaves in the same manner.

Figure 59A shows a simple resonant circuit consisting of an inductor and a capacitor. When the switch is turned to position *A,* electrons flow from the battery and charge the capacitor to the potential of the battery. An electrostatic field is developed between the plates of the capacitor. If the switch is now turned to position *B* (Figure 59B), the battery is disconnected, and the inductor is connected in series with the capacitor. The electrostatic field around the capacitor will collapse as the capacitor is discharged through the inductor; however, the electron current required to discharge the capacitor builds up an electromagnetic field around the inductor. In a short time the capacitor will be completely discharged; however, the current continues because the electromagnetic field around the inductor collapses, causing a counter-voltage that charges the capacitor in the opposite polarity. When the field about the in-

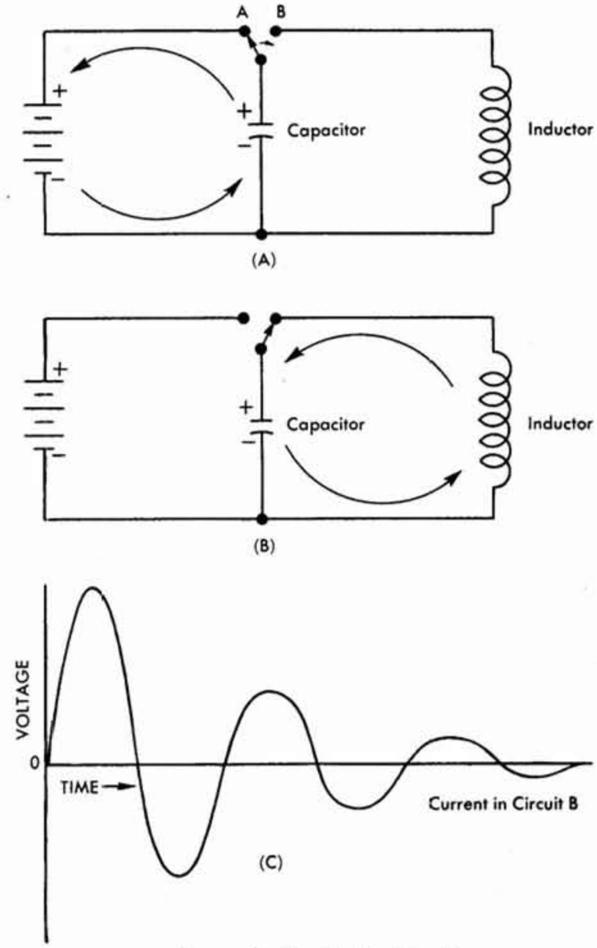


Figure 59. Oscillating Circuit

ductor has decreased to zero, the capacitor will again discharge through the inductor, building up an electromagnetic field of polarity opposite to the earlier field. Thus, the energy stored in the capacitor by the battery is exchanged between the electrostatic field around the capacitor and the electromagnetic field around the inductor. The rate at which the circuit *oscillates* is determined by the size of the capacitor and inductor.[1]

If an inductor could be built of a material having no resistance, and if it could be connected to a capacitor having no leakage by wires having no resistance, the oscillations would continue indefinitely. Since these conditions cannot be met, the electric energy stored in the circuit will gradually be turned into heat energy in overcoming resistance. The oscillations, accordingly, will decrease gradually to zero, as in Figure 59C.

The vacuum-tube oscillator makes possible the generation of sustained oscillations. Circuits can be arranged to supply enough new energy to make up for the losses. The new energy must be added at the proper time to sustain the oscillations. To return to the pendulum example, the bob will continue to move back and forth only if it is given an added push at the right instant.

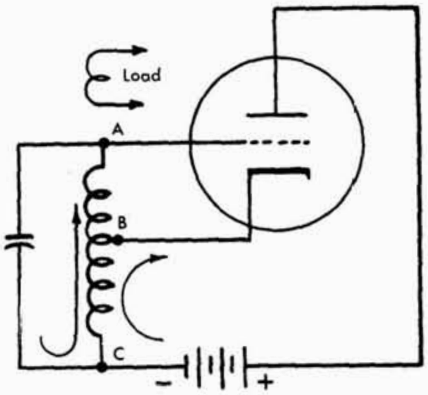
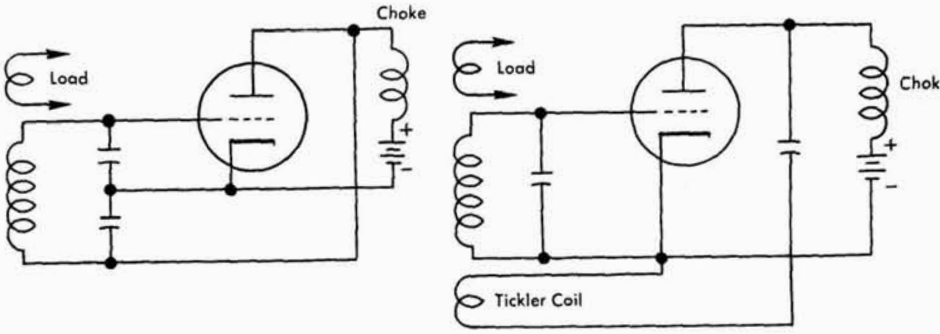


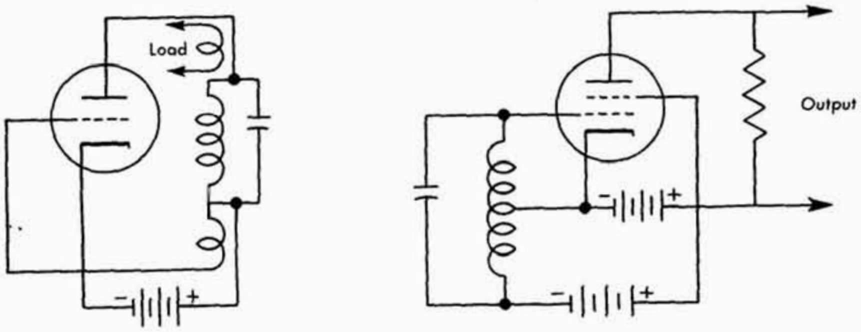
Figure 60. Hartley Oscillator

Figure 60 shows a circuit developed by Ralph V. L. Hartley and called a Hartley oscillator. The plate and grid are connected to opposite ends of the coil, while the cathode is connected to a center tap. Whenever the capacitor is discharging in the direction shown by the arrow, point A is positive in relation to point B, causing the grid to be positive in relation to the cathode. Electrons can then flow from the negative side of the battery to point C, through the



COLPITTS

TUNED GRID



TUNED PLATE

ELECTRON COUPLED

Figure 61. Vacuum-Tube Oscillators

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[1] For a discussion of the manner in which the resonant frequency may be calculated, see Appendix B, page 74.

inductor to point B, to the cathode, through the tube to the anode and back to the positive terminal of the battery. By transformer action, point A is driven more positive, further increasing the electron flow. The passage of electrons through part of the inductor increases the electromagnetic field about the inductor and thus adds to the power in the circuit. As the capacitor charges, point A will become more negative than point B, cutting off the tube. The capacitor now discharges in the reverse direction through the inductor; but on this half-cycle, point A is negative in relation to point B, and the tube cannot conduct. The vacuum tube has been used to add energy to the circuit at the proper time to make up for losses and sustain the oscillations. Generally the vacuum tube is biased beyond cutoff (class C) so that it may conduct only when point A is quite positive with respect to point B.

To use the alternating voltage developed by the oscillator, a transformer arrangement, consisting of several turns of wire, wound around the inductor but insulated from it, may be used. Frequently the output must be amplified before it can serve a useful purpose.

Figure 61 shows some additional oscillator circuits. The Colpitts circuit differs from the Hartley circuit only in that the capacitor instead of the inductor is split to provide the proper voltages. The choke coil prevents the AC signal from flowing through the battery. The tuned-grid circuit obtains its sustaining power from a "tickler" coil which, by transformer action, transforms anode power into grid signal. Similarly, a tickler coil wound on the tuned anode circuit supplies a small grid signal for the tuned-plate oscillator. The electron-coupled oscillator employs a tetrode and operates as an oscillator and amplifier. The cathode, grid and screen grid are connected as a triode in the Hartley circuit. The screen grid serves as the anode in this circuit. Variations in grid potential with respect to the cathode also control the flow of electrons to the anode and through the load. Only a few electrons are intercepted by the screen; most of the space current goes on to the anode to furnish power to the load. The electron-coupled oscillator is more stable than the types previously described, which tend to change frequency of oscillation when the load is changed.

The Multivibrator

Another type of oscillator valuable in electronic devices is the relaxation oscillator. One type of relaxation oscillator is called the multivibrator. A typical multivibrator circuit is shown in Figure 62. Note that this circuit is essentially a two-stage RC-coupled amplifier with the output of the second stage fed back to the grid of the first stage. Since the anode voltage of the second stage is decreasing when the grid voltage of the first stage is decreasing, the output reinforces the input. Oscillation consequently occurs. However, the output waveform from a multivibrator is generally adjusted to give sharp, pulse-type waves rather than the sinusoidal waves generated by the tuned oscillators previously discussed.

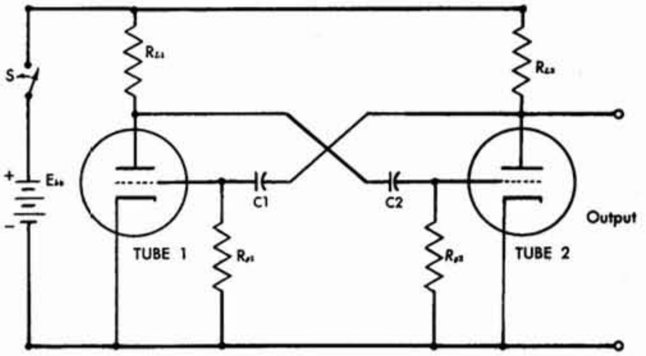

Figure 62. Multivibrator

The action of the multivibrator is as follows: at the instant voltage is supplied to the multivibrator by closing switch S, no current flows in either tube. Because of variations in tube construction and the fact that the load resistors are not precisely of the same value, current will start to flow in one tube faster than in the other tube. Assume that the series resistance of tube 1 and R_{L1} is lower than the series resistance of tube 2 and R_{L2}. More current would start to flow through tube 1 than through tube 2. So the anode potential of tube 1 would decrease more rapidly than the anode potential of tube 2. As a result the grid of tube 2 is made more negative than the grid of tube 1, because of the coupling action of the capacitors.

The more-negative grid decreases the current through tube 2, causing the anode voltage to tend to rise. The anode potential is coupled through C1 to the grid of tube 1, and causes tube 1 to pass more electrons. The anode potential consequently decreases a bit more; this change of voltage, coupled through C2, decreases the current through tube 2. Thus, the current in tube 1 increases, decreasing the grid voltage of tube 2 until the tube is completely cut off.

As soon as tube 2 is cut off, there is no tube current through R_{L2}. However, electrons flow through R_{G1} and R_{L2} to charge C1 toward the potential of E_{bb}. More charging current flows through the cathode-grid circuit of tube 1, through C1 and R_{L2}. As the capacitor charges, the grid of tube 1 gradually becomes less positive, and the electron flow through the tube begins to decrease.

The moment the current through tube 1 begins to decrease, the anode potential begins to increase; this change in potential is coupled to the grid of tube 2, where it makes the grid a little less negative. Soon tube 2 will start to conduct; at the instant this occurs, the anode potential of tube 2 will decrease. The decrease in potential, coupled to the grid of tube 1, causes the current through tube 1 to decrease

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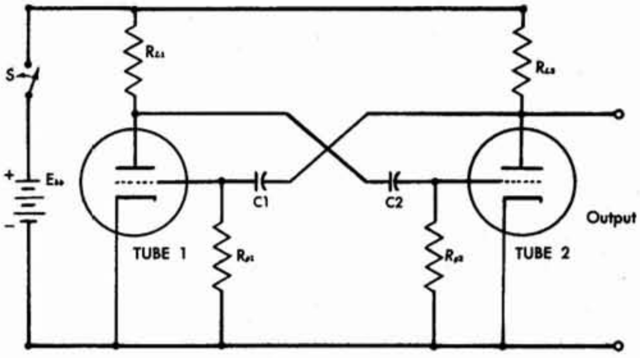

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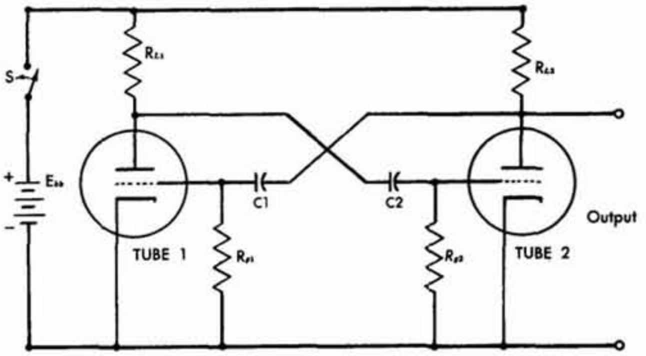

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faster, which further increases the current through tube 2. Very quickly tube 2 goes into full conduction, while tube 1 is completely cut off. Capacitor C2 charges toward the potential of the power supply. When the grid of tube 2 becomes less positive, the circuit will transfer again. Thus, the multivibrator has two unstable states (always with one tube conducting and one cut off) and it alternates rapidly between these states. The time of oscillation is dependent upon the size of the resistors and capacitors in the circuit. The larger the capacitors and resistors, the slower the circuit will be in changing states.

The multivibrator is a very useful electronic circuit because it serves as a source of many unusual voltage waveforms. Figure 63 shows the anode waveforms taken at the output of the multivibrator of Figure 62. A multivibrator is used as the source of voltage pulses for the Type 604 Electronic Calculator. The output pulses are amplified and clipped (made more nearly square) in order to serve as impulses to be counted by the calculator. The next chapter will show several applications of oscillators in IBM equipment.

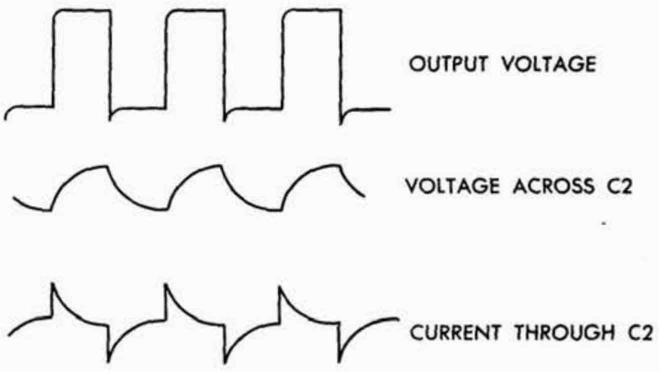
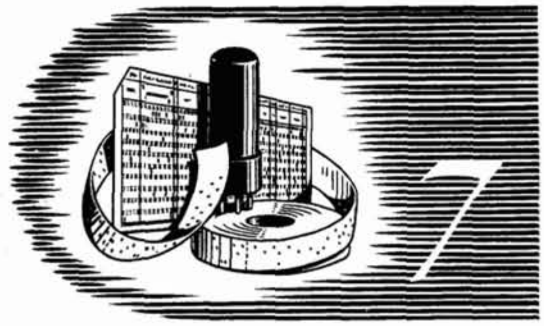


Figure 63. Multivibrator Waveforms

electron-tube
APPLICATIONS in IBM



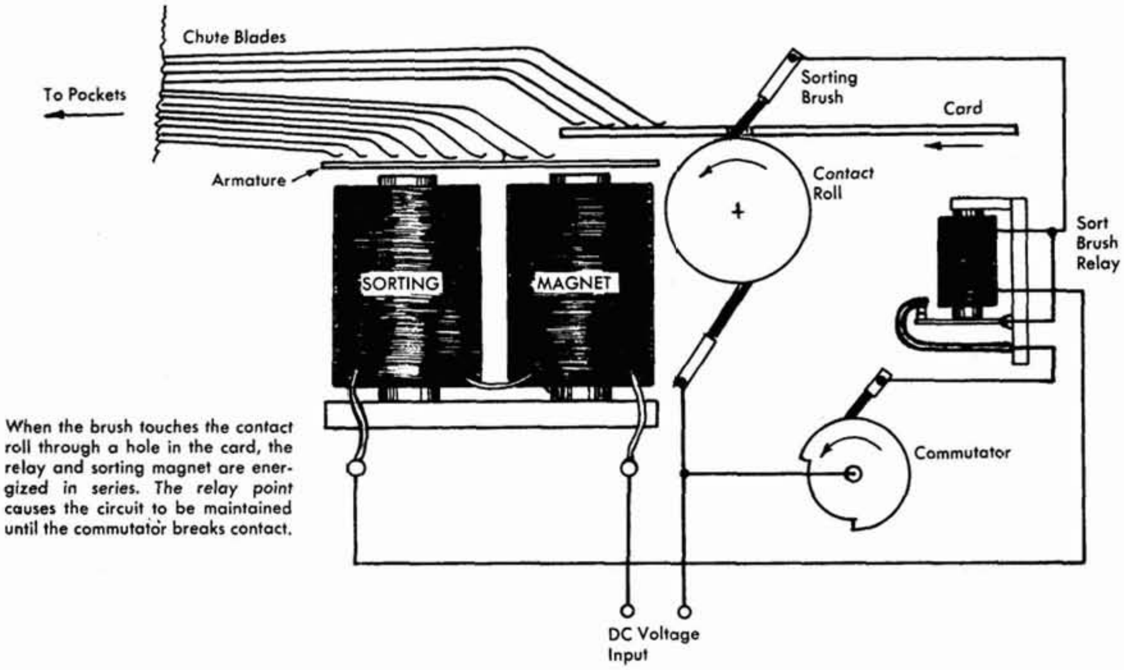
How IBM uses electronic tubes in the Electronic Sorter, the Mark-Sensing Reproducer, the Electronic Time Control System, and the International Traffic Recorder

ELECTRONS can move infinitely faster than any mechanical linkage. They can be started and stopped almost instantaneously. IBM has pioneered in the research and development of the application of electronics to computing machines. The introduction of electronics has made possible machines hundreds of times faster than comparable machines based on mechanical principles. Because electronic circuits have no moving parts, there are none of the problems of noise and mechanical failure.

In this chapter a number of IBM's applications of electronic principles to business machines will be explained. Because of space limitations, it is impossible to cover every instance where electronic circuits have been used to improve machine operation. Consequently, applications have been chosen that are representative of the general types of electronic circuits used.

THE TUBE-CONTROLLED SORTER

ELECTRONIC TUBES have been applied to the IBM horizontal sorter to produce a faster, quieter machine. Punched cards are sorted in this machine by energizing a sorting magnet to direct the cards to the proper pockets. Figure 64 shows



When the brush touches the contact roll through a hole in the card, the relay and sorting magnet are energized in series. The relay point causes the circuit to be maintained until the commutator breaks contact.

Figure 64. Sorter Schematic Diagram

how the standard sorter operates. Cards are fed through a reading station consisting of a sorting brush and contact roll. As they leave the contact roll they pass between the chute blade tips and the sorting-magnet armature. The chute blades are positioned so that the leading edge of the card is just under the appropriate chute-blade tip when the brush touches the contact roll through a hole in the card. When the brush senses a hole, the sorting magnet is energized. The sorting magnet pulls down the sorting-magnet armature, and the chute blades which are not resting on the card follow it. The card passes over the lowered chute blades to the proper pocket. The armature and chute blades must remain down until the card has passed the sorting station. In the standard sorter these operations are performed by a rotating commutator and a high-speed relay known as the brush relay.

In Figure 64, when the brush makes contact through a hole in the card, a circuit exists to energize the sorting magnet and the brush relay in series. When the brush relay attracts its armature, the contact points close, establishing a circuit through the sorting magnet, relay coil and commutator to by-pass the sorting brush. Once energized, the sorting-magnet and brush-relay circuits are maintained until the card has passed the sorting station, when the commutator opens the circuit. Using the relay circuit allows reliable operation at speeds of about 450 cards per minute.

When it was desired to increase the speed of the sorter it became obvious that the sorting-magnet armature would have to be attracted very quickly (in .005 second or less). Relay operation is not dependable at this speed; therefore, an electronic circuit is used. Not only does the electronic circuit provide the necessary speed of operation, but it also eliminates arcing at the contact roll and the selector commutator, since these devices no longer make and break an inductive circuit. Using the electronic circuit allows reliable operation at the speed of 650 cards per minute.

The running circuits of the machine operate from a DC power supply of 150 volts. To provide a negative-bias supply for the grids of the control tubes, a rather unusual circuit is employed. An oscillator circuit converts some of the DC power into AC. The AC output is then rectified to provide a 40-volt DC grid-bias supply. Figure 65 shows how the bias supply is connected.

Capacitor C1 and the portion of the coil between point A and point C form a resonant circuit tuned to about 1130 cycles per second. The resonant circuit is connected to the 25L6 tube to form a Hartley oscillator. Capacitor C2 and R11 form a grid-biasing arrangement. When the 150-volt supply is turned ON and the filaments of the tubes have heated, the Hartley oscillator circuit will cause oscillations to occur in the resonant circuit. The changes in magnetic field across the coil between point A and point C induce an AC voltage between point C and point D.

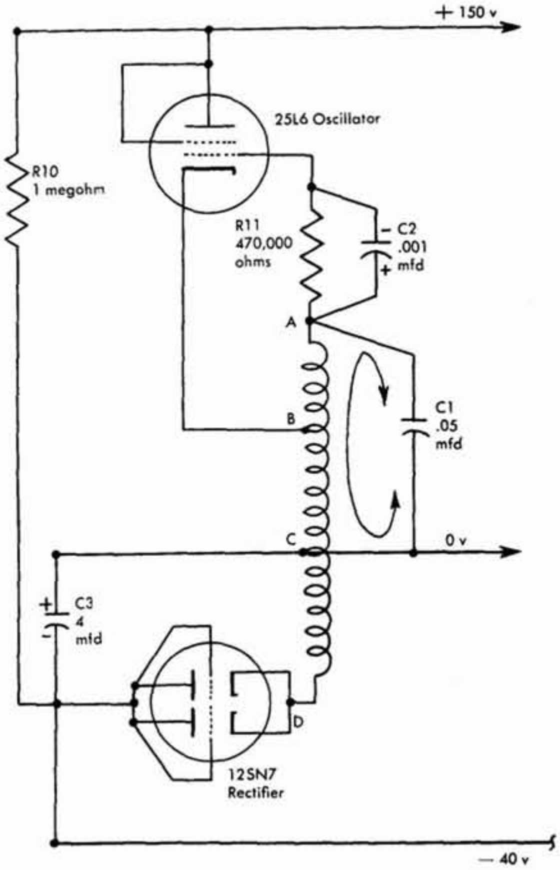


Figure 65. Grid-Bias Power-Supply Circuit

The type 12SN7, a twin-triode tube, is connected to serve as a single diode. When point D is negative in relation to point C, electrons can flow from point D through the diode and C3 to point C. When the polarity is reversed, no electron flow can occur, and C3 consequently charges to about 40-volts potential with the polarity indicated. Because the positive terminal is connected to ground potential, a voltage 40 volts negative in relation to ground is developed. This voltage is normally connected to the grids of the control tubes to prevent conduction. Resistor R10 (one megohm) is provided to put a slight load on the oscillator. When C3 has charged, electrons can flow from the negative plate through R10 to the positive terminal of the 150-volt supply. This loads the rectifier and stabilizes the oscillator output at about 40 volts. R10 also bleeds off the charge when the machine is turned off.

The negative terminal of the 40-volt supply is connected through R14 to the cathode of the OA4G cold-cathode tube and to the grids of the three 25L6 control tubes through R16, R17 and R18 (Figure 66). Note that the three control tubes are connected in parallel with the sorting magnet as their common load. When the negative 40-volt potential is applied to their grids, the tubes cannot conduct, and the magnet receives no current.

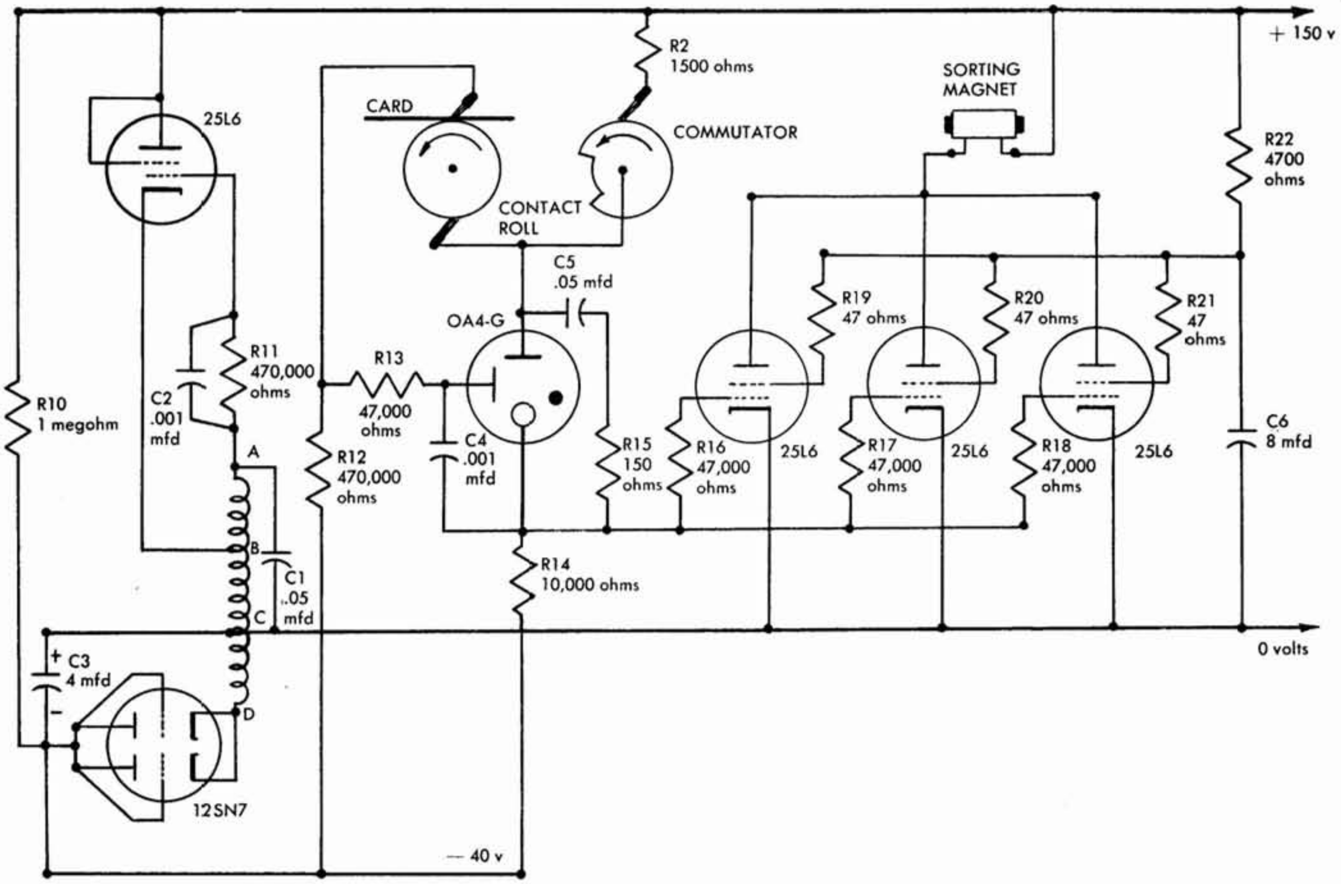


Figure 66. Schematic of Sorting Circuit

As the card passes over the contact roll and under the chute-blade tips, the commutator makes contact and connects the anode circuit of the OA4G tube through R2 to the +150 volt terminal. Thus, the anode circuit is established for any time that the sort magnet could be energized. Since no current flows as yet, the cathode of the OA4G is at a potential of —40 volts, and the starter anode is also connected to the —40-volt potential through R12 and R13. It will be recalled that when the anode voltage is lower than breakdown potential, the cold-cathode tube cannot conduct until the starter anode is made positive. This condition is met when the brush and contact roll make contact through the hole in the card. Electrons can now flow from the —40-volt terminal through R12, the hole in the card, to the contact roll, through the commutator and R2 to the +150-volt terminal. The starter anode tends to rise to +149 volts (one volt is dropped across R2), and the OA4G begins to conduct. Once conduction occurs, the gas in the OA4G ionizes, and the tube will continue to conduct until the commutator opens the circuit. Thus, the OA4G tube takes the place of the brush relay in the standard circuit.

When the OA4G conducts, there is a constant drop of 70 volts across the tube. The remaining voltage divides as 16 volts across R2, and 104 volts across R14. Thus, the cathode of the OA4G and the grids of the three 25L6 control tubes tend to rise to +64 volts. Grid current will flow in the 25L6 tubes and limit the voltage rise. The 25L6 tubes will conduct, energizing the sorting magnet. The sorting magnet will remain energized as long as the commutator causes the OA4G to conduct.

The action of R22 and C6 has a valuable effect on the more rapid operation of the sorting magnet. Before the 25L6 tubes are caused to conduct, C6 charges through R22 to a potential of 150 volts, and this potential is impressed on the screen grids of the tubes. When the tubes are caused to conduct, the electrons are given high acceleration by the action of both screen and control grids being positive. Consequently, when the OA4G tube fires, the current through the 25L6 tubes and the sorting magnet increases rapidly, energizing the magnet very quickly. The initial high surge of current exceeds the maximum rated value for continuous current through 25L6 tubes. This is permissible because under normal operation of the machine, excessive current flows for only a part of each cycle. However, if the machine were to be stopped at a time when the tubes were conducting, a large continuous flow of current might damage the tubes. Capacitor C6 and R22 reduce the flow of current through the tubes to a value well below the safe maximum continuous-current rating of the 25L6 tubes. When the control-grid bias is removed, electron current flows to the screen grid to decrease the charge on C6 from +150 to about +65 volts. Lowering the screen voltage in this manner causes the anode current to decrease to a safe steady-state value.

Condensers C4 and C5 and R15 are transient eliminators for the OA4G to prevent a stray impulse from triggering the tube prematurely.

R13 prevents the flow of excessive starter-anode current when the OA4G is ionized.

R16, R17, and R18 prevent excessive grid current when the 25L6 grids are driven positive.

R19, R20 and R21 stabilize the screen-grid currents of the control tubes, and prevent a possible cause of oscillation in these tubes.

The 12SN7 tube appears illogical as a rectifier; however, several considerations prompted its choice. The filament requires 300 milliamperes—the same current required for the 25L6 tubes. By connecting all the filaments in series across the 110-volt line, no filament transformer is required for AC operation, and the machine can be converted from AC to DC operation simply by changing the drive motor. Type 12SN7 tubes are used in other IBM equipment, and so are readily available.

The electronic tube-controlled sorter is thus capable of much faster operation because of the speed at which electrons can be controlled.

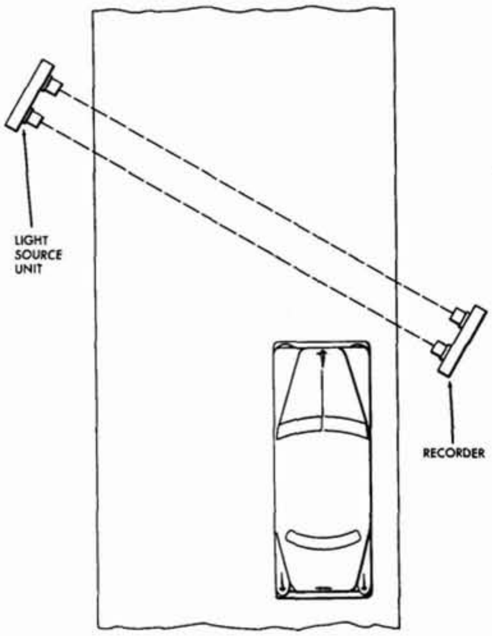


Figure 67. Typical Traffic Recorder Installation

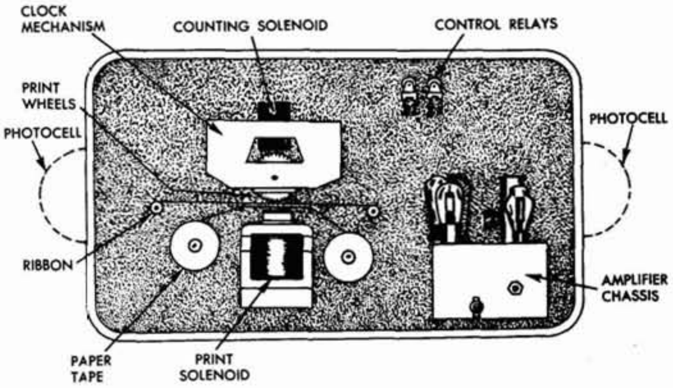
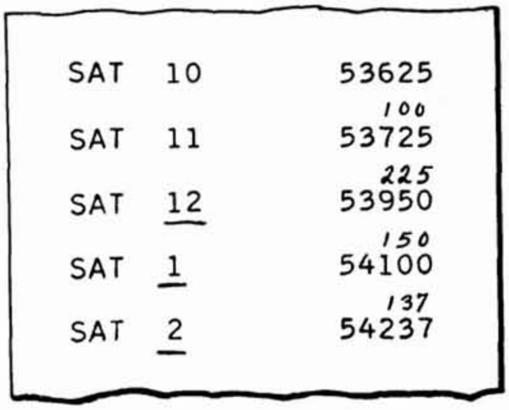


Figure 68. Interior of Traffic Recorder

THE TRAFFIC RECORDER

HIGHWAY DEPARTMENTS of many states keep records of the traffic on public highways to apportion construction and repair funds. To aid in gathering the necessary data, many instruments have been developed which count and record the flow of traffic during the course of each day. Some of these use mechanical devices activated by the weight of the vehicle. A neater solution, used in the International Traffic Recorder, employs photocells to count the vehicles electronically. Once each hour the total number of vehicles that have passed the recorder is recorded on a paper tape.

The device consists of two units, which are placed on opposite sides of the road. One unit contains the traffic recorder, and the other unit contains a source of light. The light-source unit produces two concentrated beams of light 31 inches apart. These light beams are directed across the highway (Figure 67) and focused upon two phototubes within the recorder unit. The circuits in the recorder are arranged so that the counter adds 1 every time both light beams are interrupted simultaneously. The interruption of either beam by itself will not cause the counter to operate. Since the two light beams are 31 inches apart, a pedestrian passing between the recorder and light source unit will in-



SAT 10 53625

100

SAT 11 53725

225

SAT 12 53950

150

SAT 1 54100

137

SAT 2 54237

Figure 69. Tape Specimen

terrupt only one beam at a time and will not be counted. Vehicles passing between the two units interrupt both beams simultaneously and thereby cause operation of the counter.

Figure 68 shows the interior arrangement of the traffic recorder unit, and Figure 69 is a specimen of the tape on which the recorder totals traffic.

Figure 70 shows the photoelectric detection circuit of the traffic recorder. For simplicity, the power supplies are indicated by batteries. If no light reaches the photocells, no electrons are emitted from their cathodes, and a virtual open-circuit exists between point G and point H. Under this condition, the grid of the 6Q7 is more negative than the cathode by the voltage of the grid bias supply E_g. The bias voltage prevents any electrons from flowing through the 6Q7; with the 6Q7 tube cut off, the anode potential, point P, is the same as the supply potential, point E.

Normally when no vehicles are passing the recorder, the light from the two light sources is focused on the two phototubes and causes the phototube cathodes to emit electrons. Electrons can now flow from the negative terminal of E_g through R1 to the cathodes of the photocells, through the photocells and R7 to the positive terminal of E1. From the negative terminal of E1 electrons flow to the positive terminal of E_g to complete the circuit. The current through R1 causes a voltage drop across R1 that has the same effect on the circuit as inserting a small battery in place of R1 with a polarity that opposes the polarity of E_g. As a result of this voltage drop, the potential of point G rises and tends to become positive. With the grid less negative, electrons can flow through the 6Q7. The circuit is as follows: from the negative terminal of E1 to the cathode of the 6Q7, through the triode and R6 to the positive terminal of E2. From the negative terminal of E2 electrons flow to the positive terminal of E1 to complete the circuit. The current through R6 causes a voltage drop across R6, and point P becomes *less positive* or more negative than point E.

Resistor R6 has been incorporated in the grid circuit of the 25A6 pentode. When point P is more negative than point E, the 25A6 is cut off. If the potential of point P is the same as that of point E, the 25A6 conducts, energizing the counter-control relay.

So long as nothing interrupts the light falling on the phototubes, the phototubes conduct, the 6Q7 conducts, and the 25A6 is cut off. When both light beams are interrupted simultaneously, the phototubes stop conducting, the 6Q7 stops conducting, and the 25A6 conducts, energizing the counter-control relay. The counter-control relay causes a mechanical counter to add 1, indicating the passage of a vehicle. Each hour the counter prints the total on the paper tape. Interruption of either light beam alone will not cause the counter to operate. With such an interruption, electron flow in the phototube circuit is not decreased enough to make the triode grid of the 6Q7 tube very negative; so the voltage drop across R6 is not reduced to a value that will permit sufficient electron flow in the 25A6 anode circuit to energize the counter control relay.

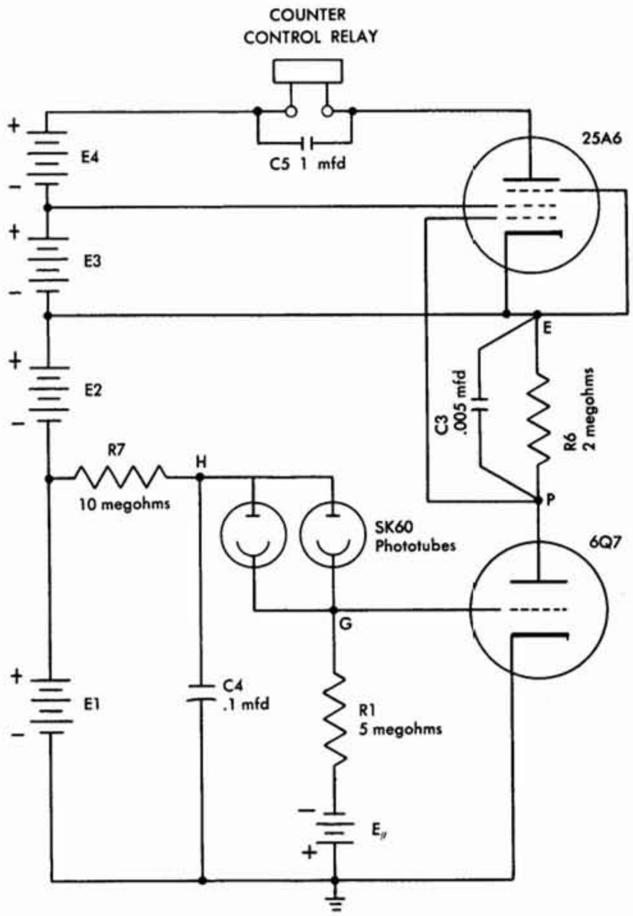


Figure 70. Traffic Recorder Sensing Circuit

After a vehicle has passed the recorder, it is desirable to re-establish quickly the voltage across R6 so that the counter-control relay may be de-energized; capacitor C4 assists in accomplishing this condition. Normally, when light shines on the phototubes, the potential applied to the phototube circuit is less than the potential of E1 as a result of the voltage drop across R7. At this time capacitor C4 charges to the potential of E1, minus the potential drop across R7. When the light beams are interrupted, there is no electron flow through R7 and the phototubes, and hence no voltage drop across R7. Capacitor C4 then charges to the potential of E1. When light is again restored to the phototubes, this higher potential across C4 is applied to the phototubes momentarily (until the capacitor discharges through the phototubes to its normal potential) and hastens the return of this circuit to its normal potential.

To furnish a reliable count, a definite time interval must be obtained during which both light beams are interrupted.

Capacitor C3 controls the maximum counting speed of this device by determining the time required to change the voltage drop across R6. If a large capacitor is used, it might take too long to change the voltage drop across R6, and short vehicles might pass the recorder without registering. If the capacitor were too small, the unit would be too sensitive, and the operating speed might be reduced to such a value that semi-trailers would be counted twice as a result of the space between the trailer and the cab.

Figure 71 shows the power supply circuit diagram of the traffic recorder. Power is obtained from an AC line through the transformer. The primary winding of the transformer is tapped for operation on 105, 115 or 125-volt AC supply. The transformer secondary is also tapped to provide the necessary voltages for the heaters of the tubes. The heater of the 6Q7 tube is connected across taps B and C, which supply 6.3 volts. The heaters of the 25A6 and 25Z6 tubes are connected in series across connections A and B.

The 25Z6 is a double-rectifier tube. The two sections of this tube are employed as half-wave rectifiers in two separate DC power-supply circuits. Both power supplies receive their AC input from the power transformer through their common connections to the A and D terminals of the secondary winding. On the half-cycles when point D is positive in relation to point A, electrons can flow through section 1 of the 25Z6 and charge capacitor C6. On the half-cycles when point A is positive in relation to point D, section 2 conducts, and C7 is charged. A fairly constant voltage drop is maintained across R8, R9, R10 and R11, and these voltages are supplied to the photoelectric circuit (Figure 70). The voltage across R8 takes the place of E4; that across R9, E3; etc.

The 6Q7 is a two-section tube consisting of a triode and a twin diode in one envelope. The two sections of the tube are independent except for the cathode which is common to both sections. The twin-diode section is used to develop a negative voltage for grid bias of the triode section. The circuit is unconventional in the manner in which rectification is accomplished. It will be recalled that in a conventional circuit the rectifier tube is connected in *series* with the load and prevents electron flow through the load for one-half of each cycle by effectively opening the circuit during these periods. In the circuit shown in Figure 72, however, the rectifier tube is connected *across* the AC input, and the electron flow through the load is prevented for one-half of each cycle by the tube effectively *short-circuiting* the AC input during these periods.

When point D is negative in relation to point A, electrons may flow from point D through the following circuit: C2, R5, R4, R3, R2 and capacitor C7 to point A. There will also be electron flow from point D through capacitor C2, R5, capacitor C1, capacitor C7 to point A. Electron flow through these two circuits will cause a charge on capacitor C1 and a voltage drop across resistors R2, R3 and R4. No electrons will flow through the twin-diode section of the tube at this time, because both diode anodes are negative in relation to the cathode.

When point A is negative in relation to point D, electron flow will be from point A to C7, the cathode of the 6Q7 to the two anodes of the twin-diode section, through capacitor

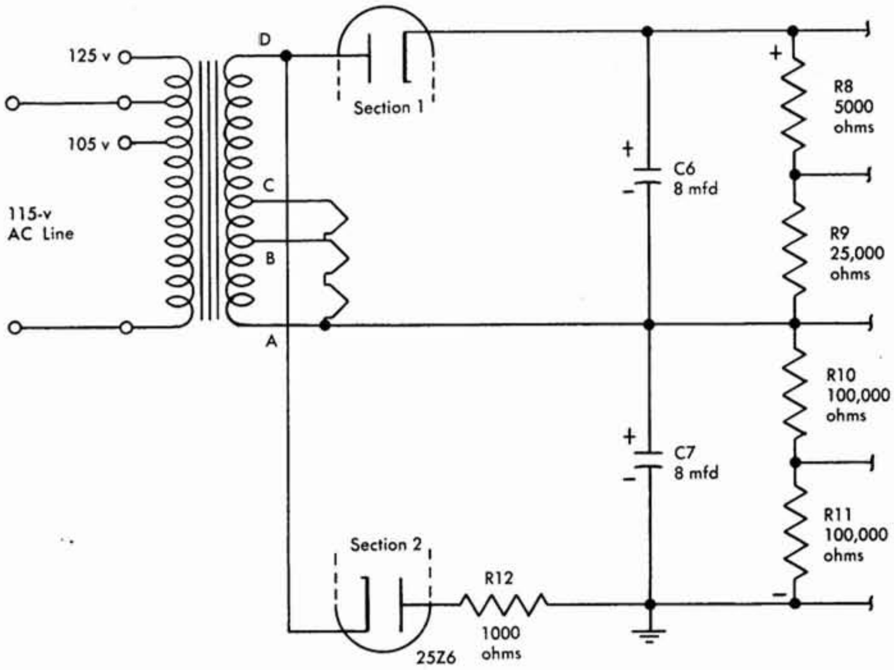


Figure 71. Power Supply of Traffic Recorder

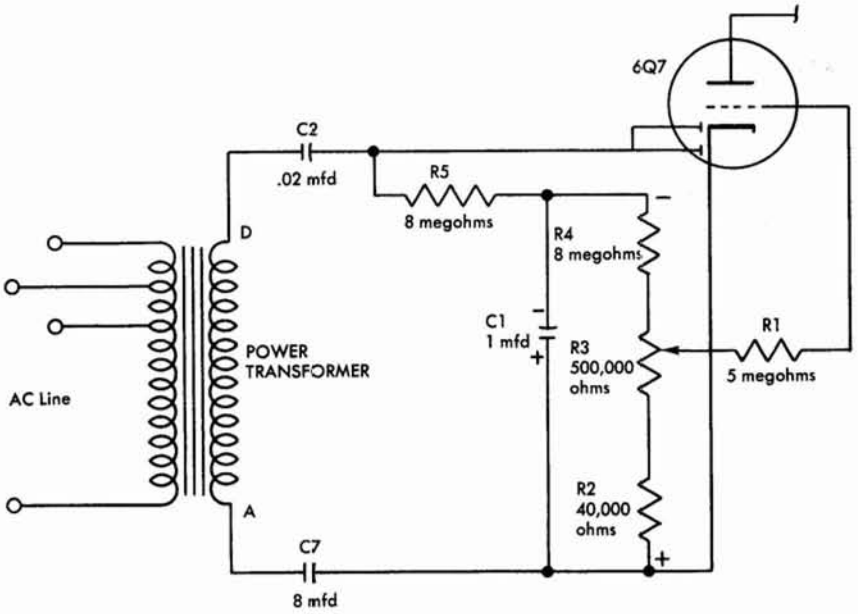


Figure 72. Grid-Bias Power-Supply Circuit for the 6Q7 Tube

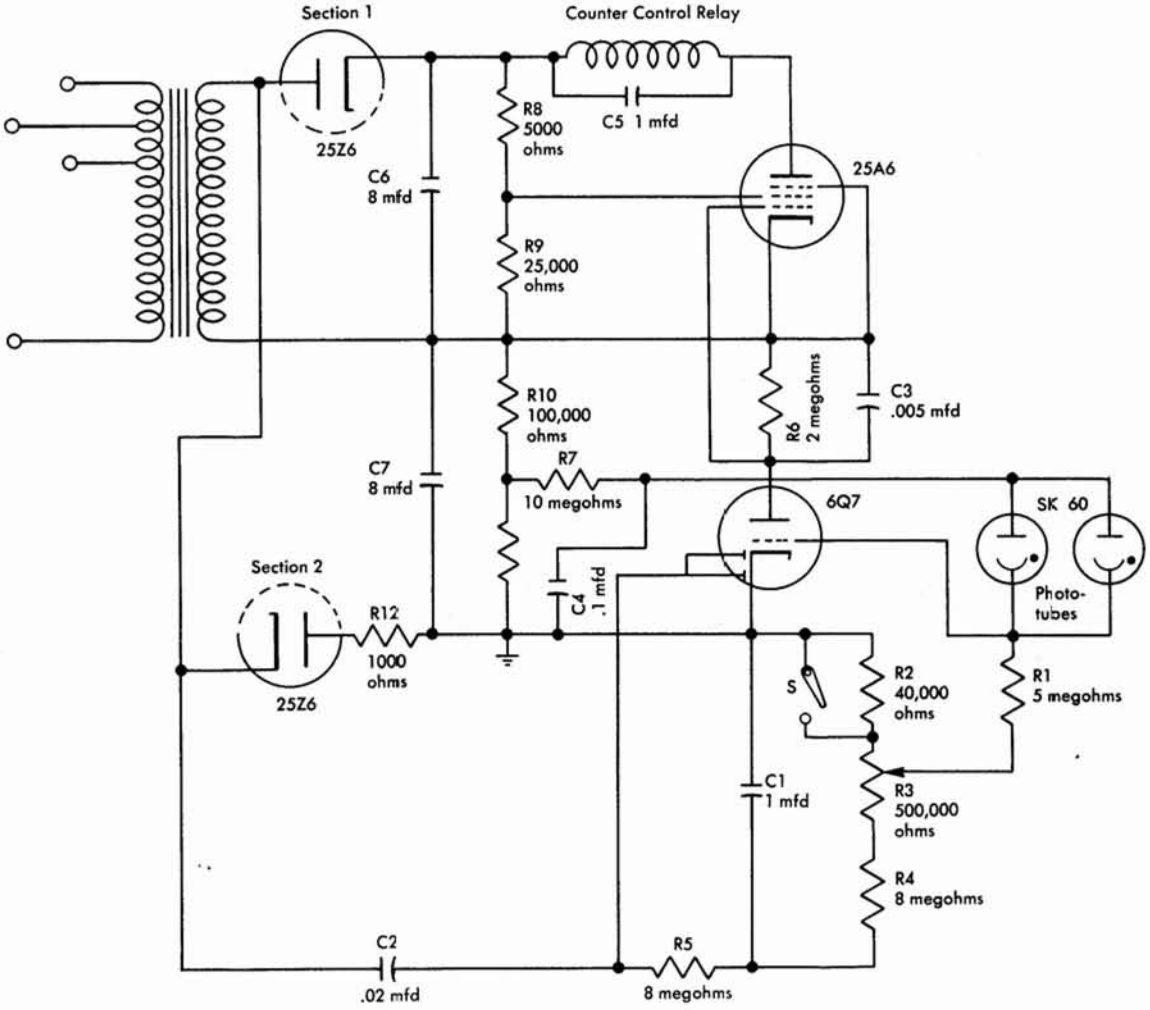


Figure 73. Complete Schematic Diagram of the Traffic Recorder

C2 to point D. On this half-cycle, the plate resistance of the twin-diode section is extremely low, and acts as a virtual short-circuit around R5, R4, R3 and R2. Therefore, almost no current flows through these resistors during this half of the AC cycle. However, the capacitor C1 discharges through R2, R3 and R4 on this half-cycle, maintaining electron flow through these resistors in the same direction as during the previous half cycle. Thus, a nearly constant voltage drop with a fixed polarity is maintained across R2, R3 and R4. Resistor R5 prevents the capacitor from being short-circuited by the tube during the half-cycles when the tube is conducting. Capacitor C2 and C7 isolate this circuit from the other power supplies because they block the passage of DC. As a result of their AC impedance, the current through the tube is limited to a safe value on the half-cycles when the tube is short-circuiting the AC input.

The DC voltage developed across R2 and a part of that across R3 is applied through R1 to the grid of the triode section of the 6Q7 tube, making the grid negative in relation to the cathode. This negative grid voltage is sufficient to bias the triode section to cutoff.

Potentiometer R3 is adjusted by closing switch S and blocking the light from the phototubes. The potentiometer is then adjusted so that the counter-control relay is energized. The potentiometer is then left in this position and switch S opened. After the light has been restored to the phototubes, the unit is ready for operation. Figure 73 (page 53) shows the complete wiring diagram of the recorder.

The IBM Traffic Recorder thus serves as an example of photoelectric tubes applied to a counting application. In addition, it demonstrates three distinct DC power-supply circuits, one of which employs an unusual principle of rectification. This device was one of the earliest IBM applications of electronics. IBM now manufactures the recorder only for special orders.

THE ELECTRONIC TIME CONTROL SYSTEM

ACCURATE MEASUREMENT of time in schools and industry is vitally important, for frequently the mass movement of people can only be accomplished smoothly if accurate time is available from synchronized clocks. As early as 1880 systems were available in which a master clock could control the time indicated on many remote clocks by means of electrical impulses sent over wires. The impulse system solved the problem of time control, but the system was cumbersome, and the cost of special wiring often exceeded the cost of clocks. While many improvements were made on the impulse system, one disadvantage remained: the location of the units could not be changed without changing the connecting wires.

These problems have been solved by the development of a new system of time control employing carrier-current signals. In this type of control the synchronizing signals are sent over the existing power lines and are available anywhere a clock may be plugged in within the installation. No special wiring is required, and the location of the units may be readily changed. Figure 74 shows a typical installation.

Each of the secondary clocks contains a small synchronous motor that drives the clock hands through reduction gears. The synchronous motor runs in synchronism with the power-line alternating current, and the secondary clocks

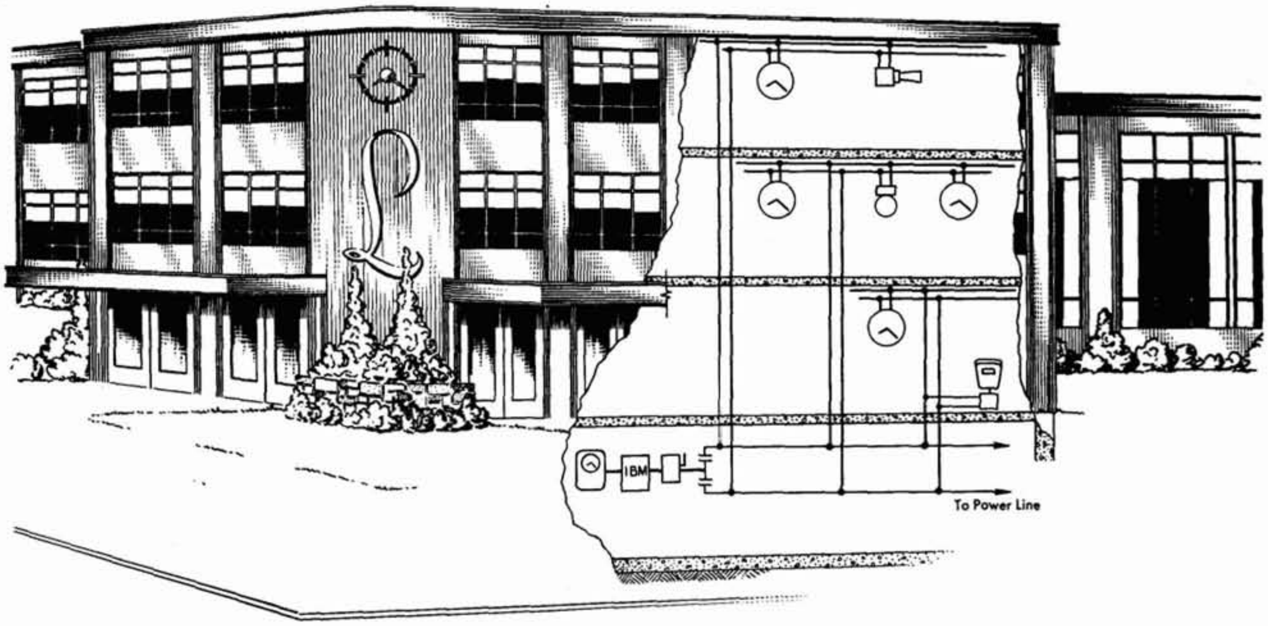


Figure 74. Schematic of Electronic Time Control System

Since the pencil marks are not sufficiently conductive to permit direct operation of the punch magnets, an amplifying unit is used. In addition, it is necessary to delay the impulse from the amplifier to the punch magnets until the card can be moved from the brushes to the proper punching position. Because of the physical arrangement of the punching mechanism, the brushes must be located slightly ahead of the punches. The cards are fed through the punch in such a manner that the mark-sensing brushes are reading marks two cycle-points before they cause punching. For example, when the machine is punching 3's, the mark-sensing brushes are sensing 5's (Figure 77). The sensed mark is amplified and delayed while the card moves forward and passes 4's, and an impulse reaches the punch magnets just as the machine is ready to punch 5's. A group of mark-sense brushes, an amplifier and delay unit, and a punch are required for each position to be sensed.

The circuit arrangement of the equipment required for sensing and punching one column is shown in Figure 78. For simplicity, the power supply is here represented by batteries. In the upper left corner, P11 is an electrical cam that closes a circuit each time a mark *could* be under the mark-sensing brushes. The circuit is interrupted by P11 between positions to prevent an accidental energization of the amplifier at the wrong time.

Before the mark is sensed, the grid of tube 1 is held negative in relation to the cathode by 25 volts through resistors R2 and R3. Each time cam P12 closes, the cathode of tube 1 is connected to the zero potential source. Since the tube cannot conduct while the grid is held negative in relation to the cathode, the closing of cam P12 has no effect until the negative grid bias is removed.

Cam P11 will "make" after a mark has moved under the brushes. Electrons can then flow from the −25-volt supply through R2 to the MS entry hub on the control panel, by control panel wire to the MS brush hub, through the pencil mark on the card, through cam P11 to the +125-volt supply. The resistance of the pencil mark will vary from 10,000 ohms to one megohm, depending on the amount of the graphite deposited when the mark was made. Actually, any mark up to five megohms will bring the grid to a potential where the thyratron can conduct. Assuming the mark under the brushes has a resistance of one megohm, the 150-volt potential (+125 to −25 volts) is developed across two

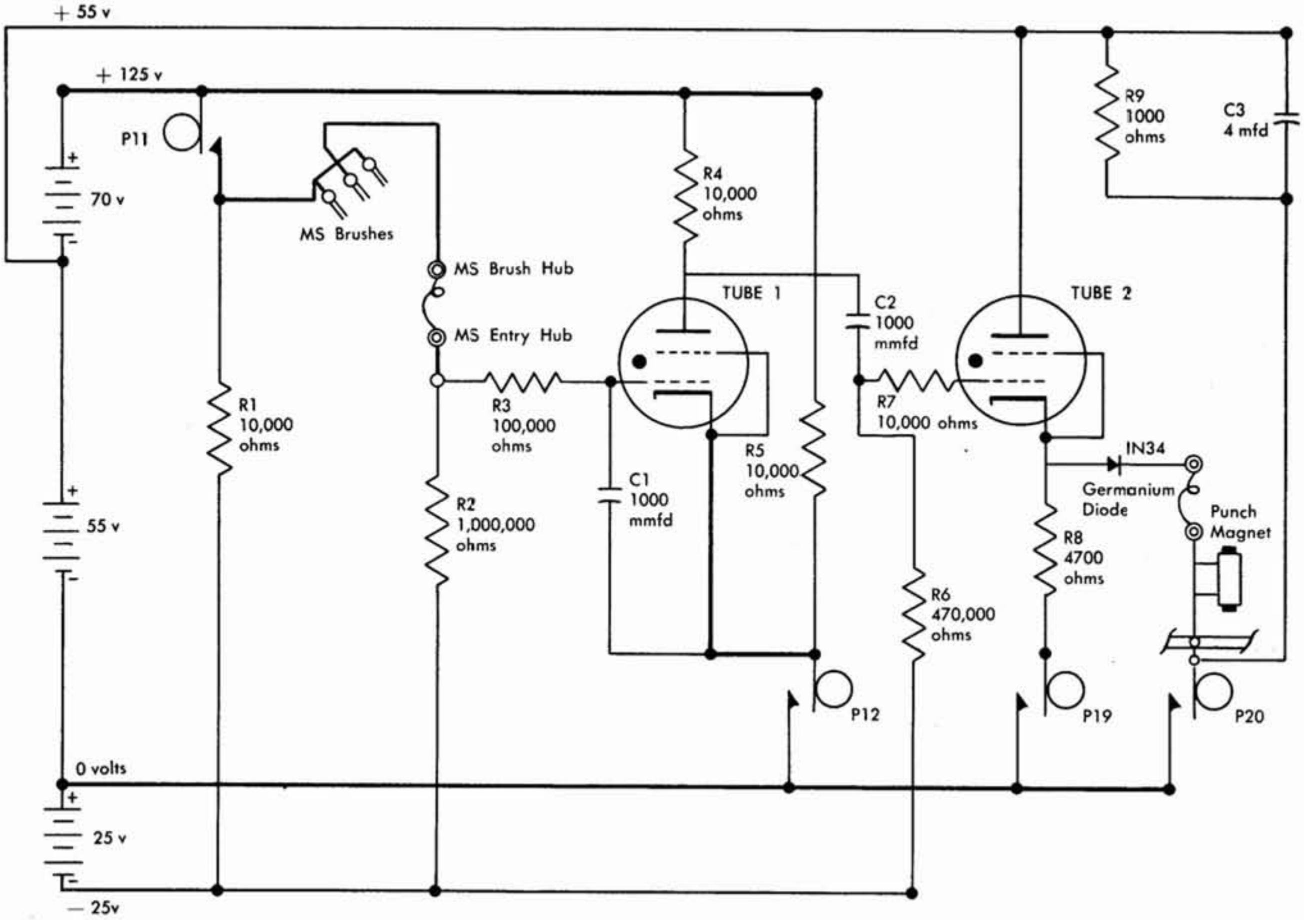


Figure 78. Mark Sensing Amplifier and Delay Circuit

1-megohm resistances in series. So the grid will tend to rise to a potential of +50 volts in relation to the cathode, and the thyratron will conduct when cam P12 closes.

Now consider the anode circuit. Before the thyratron conducts, the anode is at +125 volts potential. When cam P12 closes with the control grid positive, the electron current through cam P12, tube 1 and R4 is about 11.5 milliamperes. The IR drop across R4 is 115 volts, with a 10-volt drop across the thyratron. The anode potential of tube 1 consequently drops from +125 volts to +10 volts. So long as cam P12 remains closed, the tube will continue to conduct. The card is now advanced, removing the mark from under the brushes. The grid potential drops to —25 volts, but because a gas tube is being used, the anode circuit is not affected.

During all the foregoing, tube 2 has been prevented from firing by a —25-volt potential on its grid. Just before cam P12 opens, cam P19 closes the circuit to the cathode of tube 2. Since no current can flow through R8, the cathode will be at zero potential, while the anode is directly connected to the +55 volt supply.

When cam P12 opens, the circuit through tube 1 and resistor R4 is broken. The anode potential of tube 1 suddenly rises from +10 volts to +125 volts. The sudden rise of voltage constitutes a positive pulse, and is coupled through capacitor C2 to the grid of tube 2. The anode pulse is a 115-volt change (from +10 volts to +125 volts), and the grid potential of tube 2 will rise momentarily from —25 volts toward +90 volts. Capacitor C2 will quickly charge to 150 volts, with the grid potential of tube 2 decreasing to —25 volts, but the tube will have fired and will continue to conduct until cam P19 is opened. The +55 volt potential is developed as eight volts drop across the tube and 47 volts across the load resistor, R8.

Meanwhile, the card has advanced the two cycle-points to its punching position. When the card has been properly positioned, cam P20 closes, establishing a circuit from the zero voltage terminal through P20, the punch magnet, punch hub, control panel wire, MS exit hub through the IN34 crystal diode to the cathode of tube 2, through tube 2 to the +55 volt supply. Since the diode has less than two volts drop in the forward direction, at least 45 volts are impressed across the punch magnet. The magnet, when energized, causes a punch to be made in the card.

Some circuit elements were not mentioned in the preceding analysis because they do not apply directly to the operation of the delay unit.

R1 is used to increase the amount of current flowing through cam P11 to burn off any oxide film that might form on the contacts. The current flowing through the mark-sensing brush is insufficient to keep the cam contacts clean.

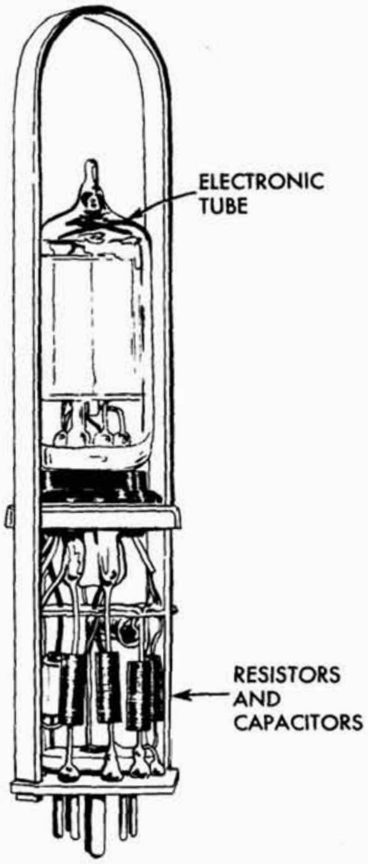


Figure 79. Pluggable Unit

R3 and R7 limit the grid current which their respective grids draw when driven positive.

R5 ties the cathode of tube 1 to the positive side of the line when cam P12 is open. This resistor causes the cathode to be very positive in relation to the grid when P12 is open. So the grid is very negative in relation to the cathode, and stray impulses induced in the cables cannot accidentally trigger tube 1.

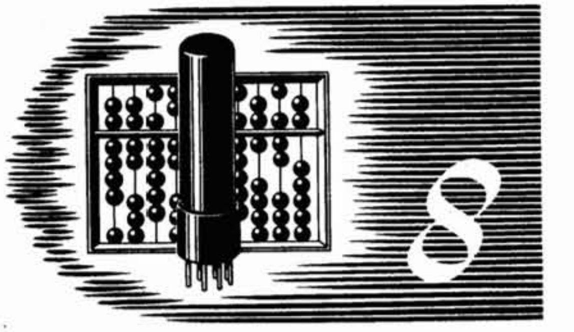
R9 and C3 are used as a filter to bleed off the voltage impulse developed when cam P20 opens and the magnetic field of the punch magnet collapses.

The IN34, a germanium diode, is used as a polarity trap or rectifier to prevent back circuits.

Capacitor C1 serves as a transient eliminator for tube 1 to prevent accidental triggering of the tube by stray impulses.

To simplify and expedite servicing, the electronic tubes and their associated circuit components are arranged in a holder that plugs into a tube socket on the machine. If any failure should occur, the entire circuit can be replaced in a moment. Figure 79 shows the arrangement of a pluggable unit.

electronic
CALCULATORS



The ancient abacus had beads for counting: the electron-tube equipped calculator counts electrical impulses. How electrostatic and electromagnetic storage contribute to electronic counting

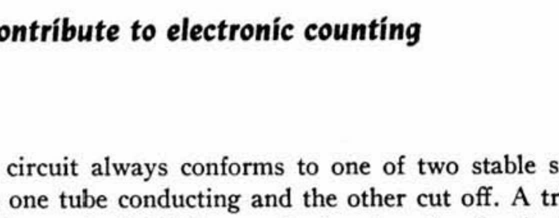
THE TYPE 604 STORAGE UNIT

SOON after man learned to count, using his fingers and toes, he found the need for a device to help him count above twenty. So he invented the abacus, which consists of a frame having several parallel wires stretched across it; several beads are strung on each wire. To add a number, beads are pushed along the wire from one end to the other. Each bead represents 1, and the operator adds by moving the appropriate number of beads along the wire. The beads become a "memory" device, enabling the operator to store numbers that are part of the answer while the answer is being developed. When the problem has been completed, the answer is obtained by counting the beads that have been transferred.

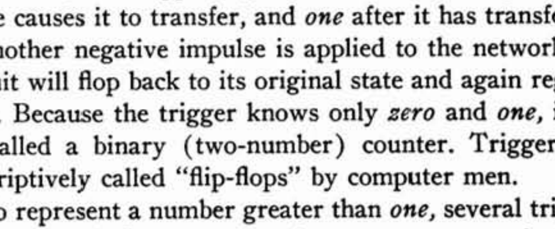
Modern accounting machines operate on much the same principle. Instead of using beads, however, a modern calculator uses electrical impulses traveling on wires. Electronic circuits count the impulses and remember the totals. The problem may be computed and the answer printed in less time than is required to transfer one bead on the abacus.

Electronic counting is accomplished in the Type 604 Calculator by using electronic-tube circuits called triggers. A trigger is the electronic counterpart of a bead on the abacus. Each trigger consists of two triodes coupled by an electric network represented by a box in Figure 80. The network is arranged so that each tube controls the other tube. A trigger circuit takes advantage of the fact that the tubes have two well-defined conditions: conduction and non-conduction or cutoff. The network couples the two tubes so that only one tube can conduct at any instant. The voltage developed in the anode circuit of the conducting tube prevents the other tube from conducting. However, a negative impulse applied to the network gives the circuit a flip that causes the tube that was conducting to be cut off. Simultaneously, the tube that was cut off begins to conduct. The circuit always conforms to one of two stable states, with one tube conducting and the other cut off. A trigger can "remember" if it has received an impulse. In electronic calculators, the trigger registers *zero* until a negative impulse causes it to transfer, and *one* after it has transferred. If another negative impulse is applied to the network, the circuit will flop back to its original state and again register zero. Because the trigger knows only *zero* and *one,* it can be called a binary (two-number) counter. Triggers are descriptively called "flip-flops" by computer men.

To represent a number greater than *one,* several triggers must be used. Suppose two triggers are connected so that the following sequence occurs: the first impulse transfers the first trigger; a second impulse causes the first trigger to revert to its original state but transfers the second trigger;



TRIGGER IS OFF WHEN SECTION 2 CONDUCTS



TRIGGER IS ON WHEN SECTION 1 CONDUCTS

Figure 80. Trigger Operation

the third impulse transfers the first trigger again, but does not affect the second trigger; the fourth impulse would cause both triggers to revert to their original states. If a value of 1 is assigned to the first trigger and a value of 2 is assigned to the second, the two triggers can count zero, one, two, or three impulses. By representing a transferred trigger by a white circle and an untransferred trigger by a black circle, this is diagrammed in Figure 81.

Similarly, three triggers may be connected to extend the counting capacity to eight numbers. Figure 82 shows the patterns the three triggers take in counting from zero to seven. The eighth pulse would cause all triggers to revert to their original condition and indicate zero. A three-trigger circuit is called an *octonary* system, and is sometimes called *octal*. Some computers operate on an octonary system; however, it is awkward to convert decimal numbers to the octal system.

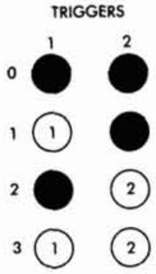


Figure 81. Two Triggers Count Four Numbers

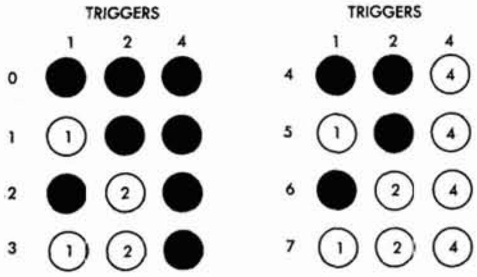


Figure 82. Three Triggers "Remember" Eight Numbers

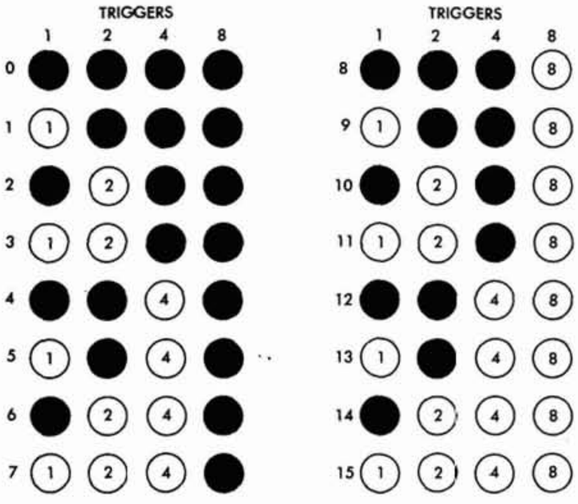


Figure 83. Four Triggers Represent Sixteen Numbers

Adding a fourth trigger (Figure 83) enables the counter to remember 16 numbers.

Most problems encountered today occur in the decimal (ten-number) system. In order to count to nine, four triggers must be used. A circuit can be arranged to allow a four-trigger circuit to count to nine, and return to zero on the tenth impulse. The counting capacity is not fully utilized, but this is offset by the advantage of having the computer operate directly in decimal numbers.

From this it is evident that eight tubes (four triggers consisting of two tubes each) are required for each decimal counter circuit. In addition, provision must be made for carrying into the next higher counter every time an impulse is added into a counter containing a 9. Twelve tubes are required for the completed counter position. A ten-digit number would require 120 tubes. Fortunately, this number can be reduced to 65 tubes by employing twin-triode tubes for the triggers.

Since it would be impossible to cover all the circuits of an electronic calculator in the space available, the basic storage circuit alone will be considered in detail. Other circuits are required to form and control the impulses; switching circuits from the Type 604 and possible future machines will be covered in somewhat less detail. The operating principles of the electrostatic storage tube and the electromagnetic storage device as they apply to the new Electronic Data Processing Machine complete the discussion of calculator components.

Figure 84 shows a two-stage directly-coupled cascade amplifier. The two triodes have identical characteristics, and are cut off when —8 volts are applied to their grids. The switch in the grid circuit allows a choice of cathode potential (zero volts) or —25 volts to be applied to the grid of tube 1.

When the switch is set to connect the grid to cathode potential, tube 1 can conduct. Electrons flow from the negative terminal of the 150-volt supply to the cathode of tube 1, through the vacuum to the anode, through R1 to the positive terminal of the 150-volt supply. With the grid at zero volts, the DC anode resistance of the tube is about 10,000 ohms, and the 150-volt potential is divided across the anode resistance of tube 1 and R1. Across the 10,000-ohm anode resistance 50 volts are developed, while 100 volts are developed across R1. So the voltage at the anode of tube 1 is +50 volts when the tube is conducting.

A circuit also exists from the negative side of the 100-volt supply through the voltage divider R4 and R3, to the anode of tube 1, through R1 to the positive terminal of the 150-volt supply. Thus, a total potential of 250 volts is impressed on this circuit. Because the current through the

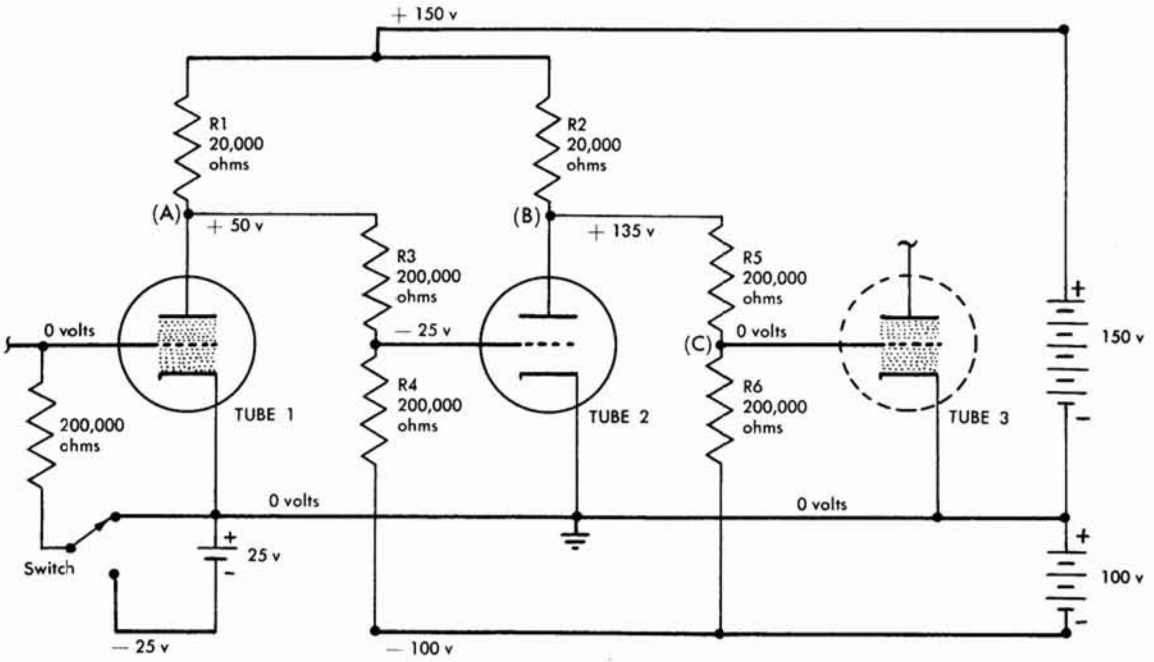


Figure 84

tube and R1 is ten times the current through R4, R3, and R1, the voltage at point A is fixed at +50-volt potential; and since R3 and R4 are equal in resistance, the voltage at the grid of tube 2 will be half-way between —100 volts and +50 volts, or —25 volts. With —25 volts on the grid, tube 2 cannot conduct. About .6 milliampere flows from the negative terminal of the 100-volt supply through R6, R5 and R2 to the positive terminal of the +150 volt supply. The .6-milliampere current causes a drop of about 120 volts across R6; so the voltage at point C tends to reach +120 volts above —100 volts, or +20 volts. However, as this point is connected to the grid of tube 3, grid current will flow as soon as the grid becomes positive, and the added IR drop across R5 and R2 causes the potential at the junction of R5 and R6 to remain substantially at zero volts. Figure 84 shows the stable voltages existing in the circuit when the grid of tube 1 is at zero potential.

In Figure 85 the switch in the grid circuit of tube 1 has

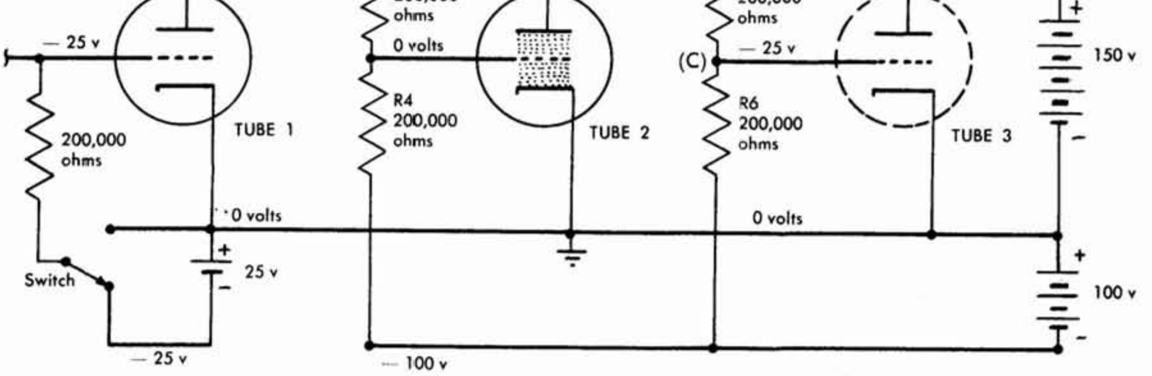


Figure 85

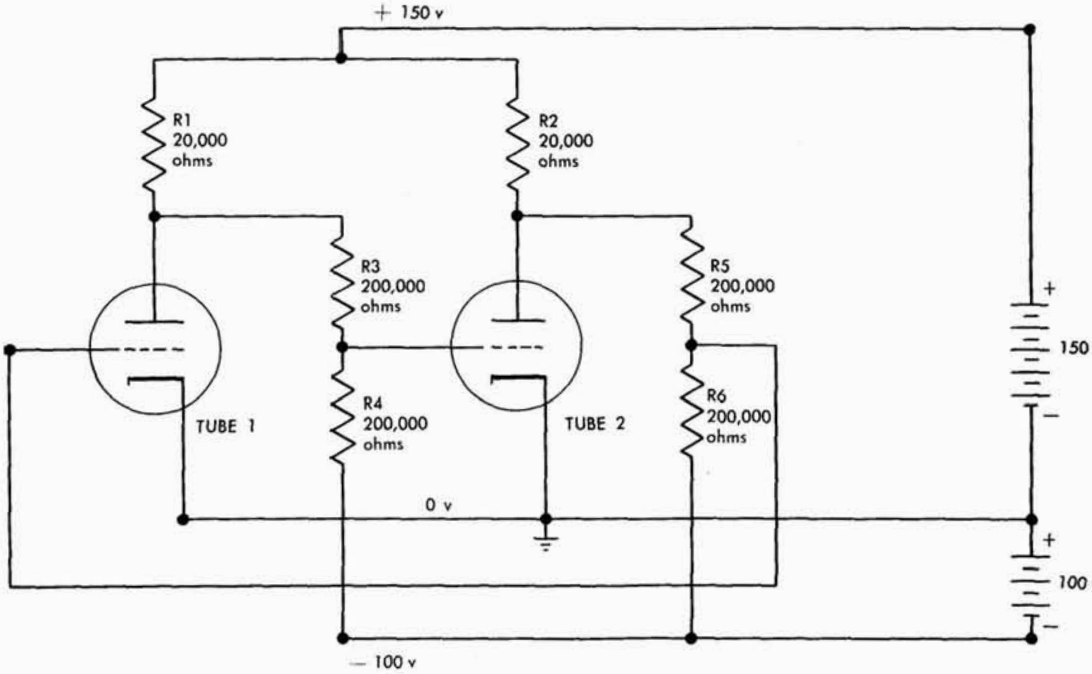


Figure 86. Trigger Circuit

been thrown to the —25-volt position. Eight volts can cut off the electron flow; consequently no electrons pass through tube 1. Electrons can flow from the negative terminal of the —100-volt supply through R4, R3 and R1 to the positive terminal of the +150-volt supply. The grid of tube 2 tends to rise to +25 volts, but again grid current would flow and hold the potential to zero volts. Tube 2 can now conduct, and the potential at point B now drops from +135 volts to +50 volts. Resistors R5 and R6 divide the difference between +50 volts and —100 volts, and the potential applied to the grid of tube 3 is now —25 volts. Figure 85 shows the stable voltages existing in the circuit after the switch connects the grid of tube 1 to —25 volts.

When the grid of tube 1 is at 0 volts, the grid of tube 2 is at —25 volts, and the grid of tube 3 is at zero volts. When the grid of tube 1 is at —25 volts, the grid of tube 2 is at 0 volts, and the grid of tube 3 is at —25 volts. Note that the grid potential of tube 3 is the same as the grid potential of tube 1. Since the circuits are identical, the wire going to the grid of tube 3 can be connected instead to the grid of tube 1, as in Figure 86. Since one tube is always conducting and one tube is always cut off, the device has two stable states. Unless it is influenced from an external source, the circuit will remain in whichever state it is put. Such a circuit is called a "trigger," and is the basic unit of the Type 604 Electronic Calculator.

To use the trigger in a calculating machine responding to high-frequency impulses, the vacuum-tube circuits must be arranged to compensate for the grid-plate capacitance. When a signal is applied to the tube, the interelectrode capacitance must be charged before the signal voltage can occur between the grid and the cathode. The input capacitance delays the response of a tube when extremely rapid voltage shifts occur at the grid. In order to speed the response of a tube, compensating capacitors may be connected as shown in Figure 87. The 100-micro-microfarad compensating capacitor balances the interelectrode capacitance so that the grid can follow the applied voltage pulses without appreciable time delay.

Figure 88 shows how trigger circuits are usually drawn. The circuit is identical to Figures 84 and 85, except that

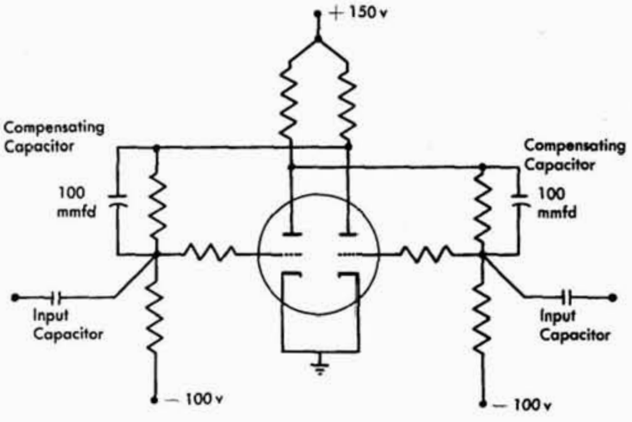


Figure 87. Conventional Trigger Circuit

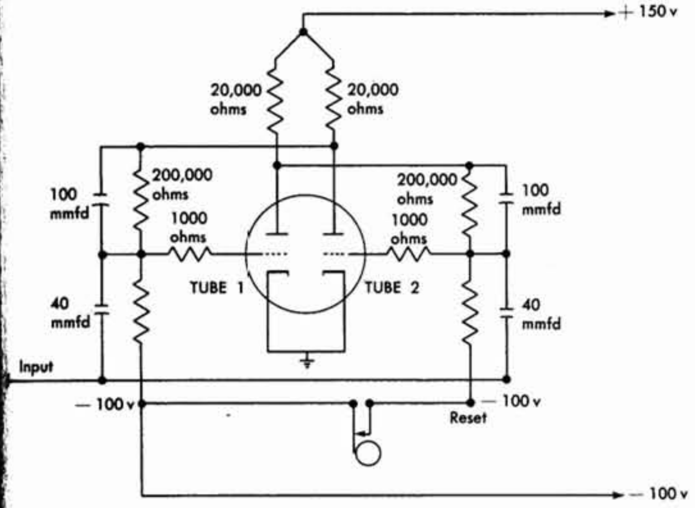


Figure 88. Principle of Trigger Reset

compensating capacitors, coupling capacitors and grid resistors have been added. The grid resistors increase the stability of the trigger circuit. The coupling capacitors allow the trigger to be transferred by external pulses.

The IBM convention in trigger circuits is to consider the trigger ON if the left-hand triode (tube 1, as drawn) is conducting; the trigger is OFF if the right-hand triode (tube 2) is conducting. Since the trigger must be turned OFF before a calculation is begun, a reset circuit is provided. Resetting is accomplished by momentarily opening the —100-volt bias line to the grid of the tube which should normally be conducting when the trigger is OFF. Removing the —100-volt bias from this grid causes the trigger to transfer to the OFF condition. All the storage triggers are turned OFF before a number is read into them. In Figure 88 this is represented as being accomplished by the opening of an electrical cam, although actually an electronic circuit decreases the —100-volt potential momentarily.

Figure 89 shows how a trigger is impulsed. The grids of both triodes are connected through the capacitors to the input wire. It will be recalled that the size of the compensating capacitors determines the speed of response of a trigger. To have stable operation, the compensating capacitors must be larger than the input capacitors. A compromise must be reached between desired speed of response and stable operation. Because the input capacitors are consequently quite small, the pulses fed to the trigger must have a very steep wave front. The pulse must be of an amplitude sufficient to drive the conducting grid beyond cutoff. If the trigger is in its OFF status initially, as shown in Figure 89, a negative pulse to the input of grid G2 will cause the trigger to go ON. When a 20-volt negative pulse with a steep wave front is applied to the input capacitor at G2, there will be a sudden negative shift of voltage at G2. This will cause the voltage at the grid to drop momentarily to —20 volts, and section 2 is cut off. Immediately the voltage at A2 rises to about +140 volts, and point G1 rises above cutoff, permitting section 1 to conduct. As soon as section 1 starts conducting, point A1 drops to about +40 volts, and point G2 drops to —30 volts, thus keeping section 2 cut off. So a negative pulse applied to G2 caused the trigger to go ON. The pulse can be of very short duration, because the triggering action is extremely fast.

Once the trigger has been turned ON, it can be turned OFF by resetting or by applying a negative pulse to the grid of tube 1. With the trigger ON, a negative pulse applied to the grid of tube 1 will cause the trigger to go OFF in the same manner. It is important to note that triggering can be accomplished only by applying a negative pulse to the grid of the *conducting* side of the trigger. Negative pulses applied to the non-conducting side can have no effect, because that side is already cut off. Therefore, both inputs can be connected in parallel, and the trigger will transfer from one state to the other every time it receives a negative pulse.

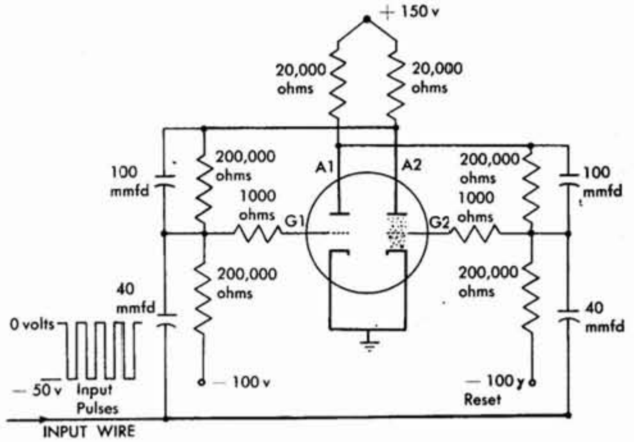


Figure 89. Method of Impulsing a Trigger

A second trigger has been added in Figure 90. Note that the anode resistance of the OFF side of trigger 1 has been split into two resistors. Part of the voltage drop across this resistance is available at the junction of the two resistors; this voltage is connected to the input of trigger 2. Note that when a trigger goes off, the anode potential at the plate drops from +135 volts to +50 volts. This drop in voltage constitutes a negative pulse. Therefore, whenever trigger 1 goes OFF, a negative pulse available at the tap (A, Figure 90) turns trigger 2 ON.

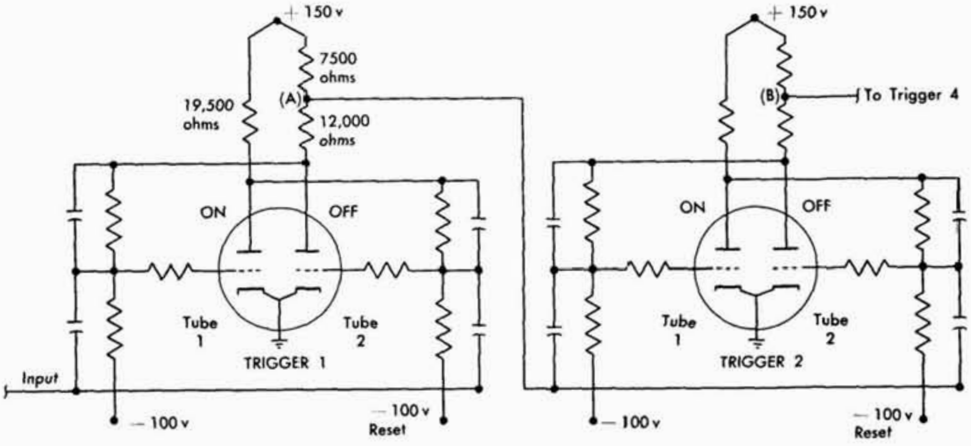


Figure 90. Two Triggers in Cascade

In Figure 91 four triggers and a blocking tube have been arranged to form a storage circuit that can count numbers up to 9. If a series of negative impulses is now connected to the input of trigger 1, the following sequence will occur (assume all triggers are OFF initially):

The first negative pulse applied to the input causes both grids of trigger 1 to be driven momentarily negative. Cutting off the right-hand triode causes trigger 1 to transfer, or go ON. Thus, one pulse turns trigger 1 ON.

The next negative pulse applied to the input causes both grids of trigger 1 to be driven momentarily negative. Cutting off the left-hand triode causes trigger 1 to transfer again, or go OFF. While the trigger was ON, point A was at a potential of +150 volts. As soon as trigger 1 is turned OFF, the voltage at point A drops to +100 volts. This constitutes a negative pulse, and because this negative pulse is coupled through capacitors to the grids of trigger 2, both grids of trigger 2 will be driven negative momentarily. Cutting the right-hand triode OFF causes trigger 2 to transfer, or go ON. Therefore, the second negative pulse turns trigger 1 OFF and trigger 2 ON. This negative pulse is also coupled to the grid of tube 1, trigger 8, but because trigger 8 is OFF, it has no effect.

The third negative pulse causes both grids of trigger 1 to be driven momentarily negative. Trigger 1 is again turned ON, and trigger 2 is already ON. Thus, three negative pulses turn on triggers 1 and 2 ($1 + 2 = 3$).

The fourth negative pulse again drives both grids of trigger 1 momentarily negative. This time trigger 1 is turned OFF, and the moment the right side of trigger 1 conducts, point A drops in potential from +150 volts to +100 volts. The negative 50-volt pulse applied to trigger 2 turns it OFF. The moment the right side of trigger 2 conducts, point B drops in potential from +150 to +100 volts. The negative 50-volt pulse is applied to the input of trigger 4, and consequently turns trigger 4 ON.

The fifth negative pulse turns trigger 1 ON again. Trigger 4 is already ON.

The sixth negative pulse turns trigger 1 OFF, and trigger 2 ON. Trigger 4 is still ON.

The seventh negative pulse turns trigger 1 ON, and triggers 2 and 4 are still ON ($4 + 2 + 1 = 7$).

The eighth pulse turns trigger 1 OFF, trigger 1 turns trigger 2 OFF, trigger 2 turns trigger 4 OFF, and trigger 4 turns trigger 8 ON. When trigger 8 goes ON, a positive pulse is produced at the anode of tube 2, and a negative

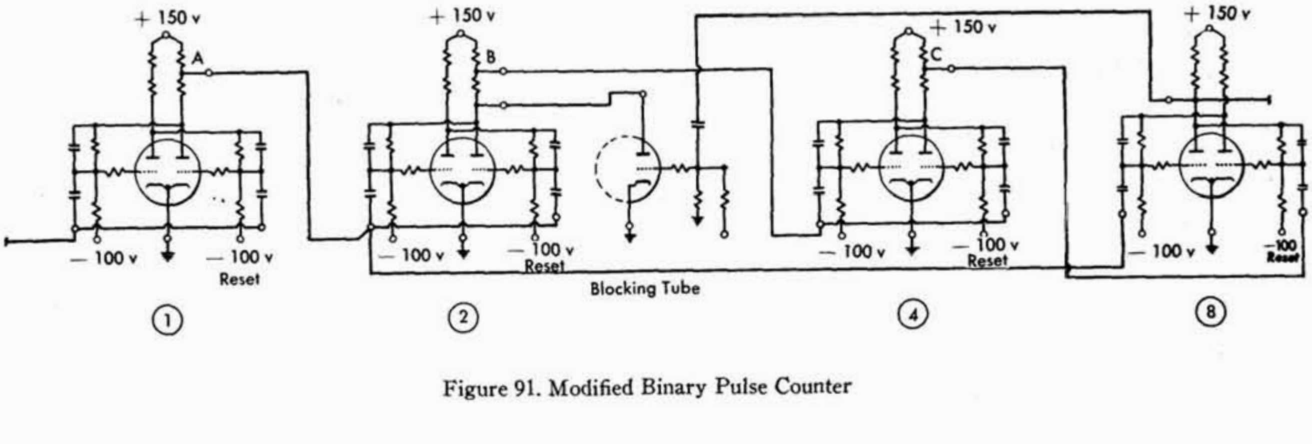


Figure 91. Modified Binary Pulse Counter

pulse is produced at the anode of tube 1. The negative pulse is fed to the grid of the blocking tube but has no effect because the grid is already cut off.

The ninth input pulse turns trigger 1 ON again, but produces no other effect. So triggers 1 and 8 are ON for nine pulses.

The tenth pulse turns trigger 1 OFF, producing a negative-output pulse which would normally turn trigger 2 ON, but the blocking tube prevents trigger 2 from going ON at this time. This negative pulse is also fed to the grid of tube 1 in trigger 8, which is also conducting at this time; therefore, trigger 8 goes OFF on the tenth pulse, and produces a positive pulse at the anode of tube 1. This positive pulse is fed to the grid of the blocking tube, causing it to conduct. The anode of the blocking tube is in parallel with the anode of tube 2 of trigger 2; so as long as the blocking tube is conducting, both anodes are at low potential (+50 volts). To turn trigger 2 ON, the potential at the anode of tube 2 must rise to permit the grid of tube 1 to go above cutoff. If the blocking tube keeps the anode of tube 2 in trigger 2 at low potential, the negative pulse received from trigger 1 can have no effect. Although the grid of tube 2 in trigger 2 is driven below cutoff by the negative pulse from tube 1, the potential at its anode cannot rise because of the blocking tube. The blocking tube is maintained in a conductive status long enough to insure that the input pulse is dissipated and so can have no effect on trigger 2. Thus, it is seen that the tenth input pulse turns all the triggers OFF, and restores the unit to zero. On the Type 604 Calculating Punch the entire operation occurs in 1/5000 second.

SWITCHING CIRCUITS

THE SMALLER, slower electric calculating machines use electromagnetic relays to accomplish circuit switching; such a circuit is shown in Figure 92. The electrical cam C closes the circuit at intervals, but so long as the relay is de-energized, no circuit exists from point A to point B. If a current is sent through the relay coil, however, the contact closes, and the electric impulses are available at point B. Several milliseconds are required to transfer the relay.

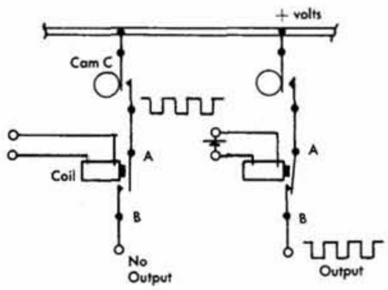


Figure 92. Relay Switching Circuit

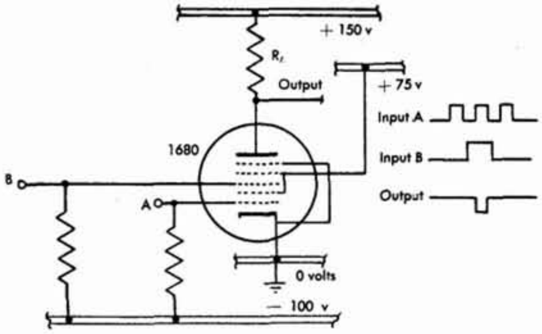


Figure 93. Pentagrid Coincidence Switch

In an electronic calculator several milliseconds is a long time. It is desirable to have electronic switches that can transfer almost instantaneously; there are several methods of accomplishing this objective. Figure 93 shows a circuit known as a coincidence switch. The type 1680 tube is a specially-designed type in which the third grid has virtually the same control characteristics as the first grid. Either grid can cut the tube off when its potential is −20 volts in relation to the cathode.

In the circuit of Figure 93 both grids are returned to the −100-volt supply. Thus, the tube is normally cut off. Now suppose that a series of impulses are fed to grid 1. These impulses raise the grid 1 potential above cutoff, but grid 3 prevents any electron flow through the tube. However, when grid 3 is impulsed simultaneously, the tube can conduct, and an output pulse is generated across R2. This circuit is the electronic equivalent of the relay circuit in Figure 92.

Another type of switching circuit is shown in Figure 94. Two triodes, which may be in the same envelope, are connected with their cathode and anode circuits in parallel. The tubes are biased so that the grids are normally positive with respect to the cathodes. Grid current holds the grid

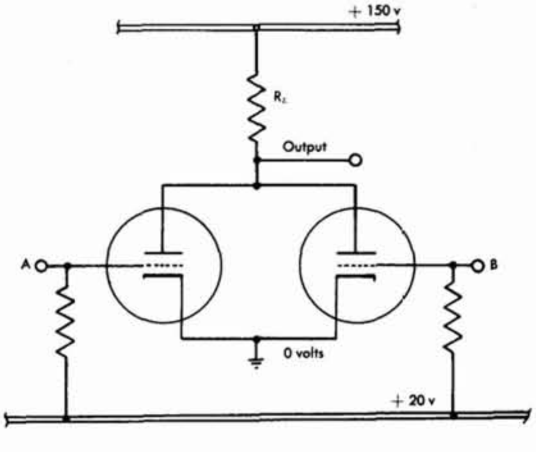


Figure 94. Parallel Gate Circuit

potential to essentially zero volts. Both triodes normally conduct. The resistors and power supply are designed so that if either tube is cut off, the other tube assumes the full load current. This is possible because the tubes have nonlinear characteristics, and their anode resistance changes with a change in current. If either tube is cut off by a negative signal applied to its grid, the anode voltage rises only slightly. If both tubes are cut off simultaneously, however, the anode potential rises abruptly, giving a large output pulse. This circuit is sometimes called a *Rossi circuit,* or *parallel gate.*

Frequently it is desirable to add or mix impulses from two or more sources. A "mixing" circuit is shown in Figure 95A. This circuit takes the place of a parallel-relay circuit. Either relay point can establish the circuit in Figure 95B. Similarly, in the electronic circuit, if either tube conducts, there will be a voltage drop across R2 and a consequent output pulse. This circuit is especially valuable where it is necessary to mix several waveforms to obtain a complex output wave. For example, a saw-tooth wave and a square wave could be added to obtain the output shown in Figure 95A.

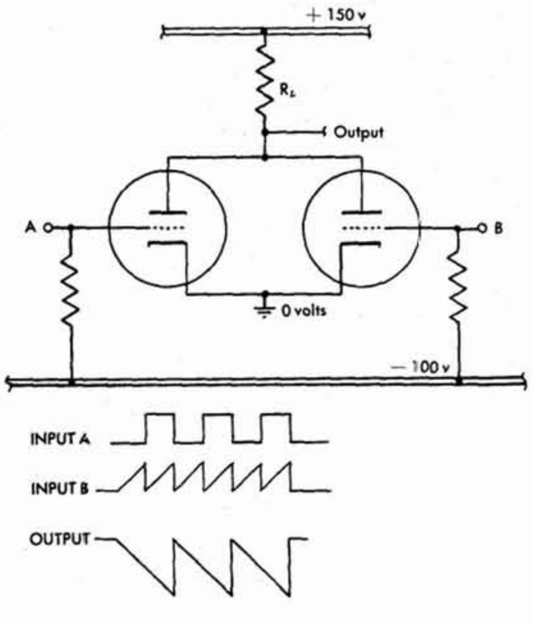


Figure 95A. Mixing Circuit

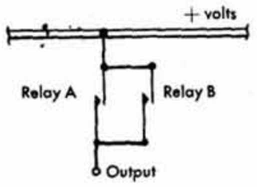


Figure 95B

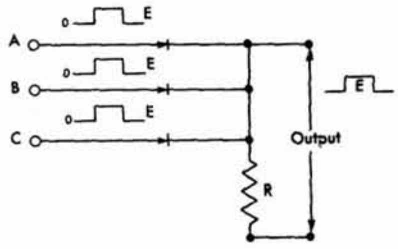


Figure 96. Crystal-Diode Mixing Circuit

Crystal diodes are finding application in calculator circuits. A mixer circuit is easily arranged, as shown in Figure 96. The terminals at A, B and C might be connected to the output of trigger circuits. So long as the potentials at A, B and C are zero, no current flows from ground through resistor R, and no voltage appears at the output. If any of the input leads receives a positive impulse, electrons flow from ground through R and the diode to the input terminal which is positive. An output pulse having the same wave shape as the input pulse, is developed across resistor R. The output follows the input waves, and can mix them in the manner of Figure 95.

A coincidence circuit can be arranged using crystal diodes. Figure 97 shows a switching circuit employing three crystal diodes. Electrons flow from the negative terminal of the power supply through ground, R1 and R2 to the positive supply terminal. A slight output voltage E1 is developed across R1 in the normal condition.

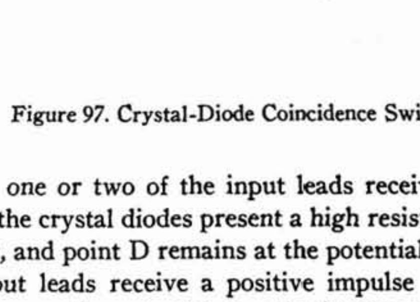


Figure 97. Crystal-Diode Coincidence Switch

If any one or two of the input leads receive a positive impulse, the crystal diodes present a high resistance to electron flow, and point D remains at the potential of E1. If all three input leads receive a positive impulse at the same time, however, the potential at point D rises to the voltage E2. The output pulse occurs when the input leads are impulsed simultaneously.

ELECTROSTATIC STORAGE

THE MODIFIED binary vacuum-tube storage circuit has the disadvantage of requiring a large number of components to store each decimal digit. The Type 604 unit, which is a comparatively small computer, requires 288 triodes to store 32 decimal numbers. Design engineers, in trying to decrease the bulk and power requirements of electronic computers, thought that the ability of a capacitor to acquire and hold a charge made it a promising storage element. The capacitor could represent 0 when it had no charge, and 1 when it became charged. If a storage device could be built using capacitors, it might be much smaller and cheaper than a storage device employing vacuum triodes.

One of the problems involved in any computer is "access time"—how long it takes to find and read numbers out of storage units once the machine is ready to accept them. In attempting to decrease the access time and to use an electrostatic charge as a storage medium, Professor F. C. Williams of the University of Manchester, England, developed the idea of using the phosphor screen of the cathode-ray tube to accept and store tiny charges.

The phosphor screen on the cathode-ray tube is an excellent insulator. If a spot on the phosphor is momentarily bombarded by a steady, well-focused electron beam, a charged circular area of about the diameter of the beam is left on the phosphor. Because of secondary emission, more electrons leave the point where the beam strikes than arrive in the electron beam. The secondary electrons are attracted to the positive electrodes in the tube. The bombarded spot on the screen has a deficit of electrons, and so is a positive charge. Because the phosphor is an insulator, the charge will remain for several seconds, if undisturbed. Electrons from other sources will eventually cancel the positive charge.

A circular spot charge caused by a static beam is called a "dot." If the beam is moved by several beam diameters while it is turned on, it will leave an oblong area of charge on the screen, as shown in Figure 98B. A charged area of this kind is called a "dash." The names "dot" and "dash" came into use as a result of the relative bombardment times, and not because of their appearance on the storage tube. The dot and dash represent the two well-defined states needed for a binary storage device. The dot may represent a binary *one*; a dash will then represent a binary *zero*. A great many dots and dashes can be written on the face of a cathode-ray tube.

The electron beam is normally cut off by maintaining the control grid at a negative potential. To write information on the screen, the potentials of the deflection plates are adjusted to position the electron beam to strike a predetermined area on the screen. The negative grid bias is then removed, allowing the electron beam to strike the screen. The beam is left on for only one microsecond if a dot is to be written. If a dash is required, the beam is left on for a slightly longer time and moved slightly away from its original position, leaving an oblong area of charge.

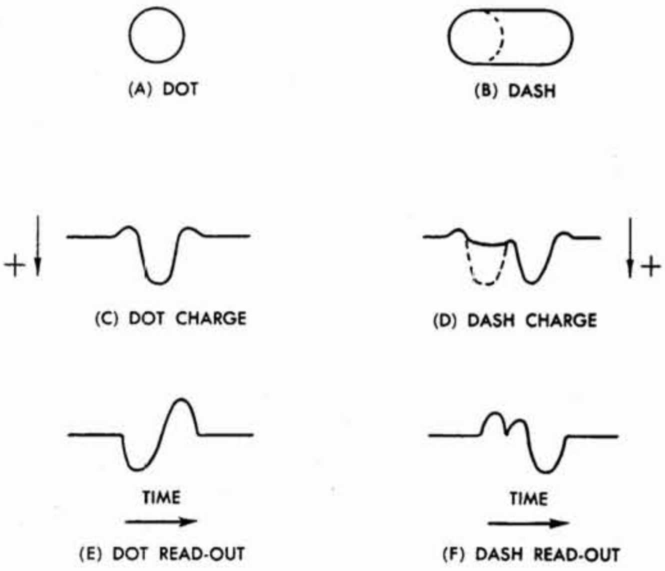

(A) DOT
(B) DASH
(C) DOT CHARGE
(D) DASH CHARGE
(E) DOT READ-OUT
(F) DASH READ-OUT

Figure 98. Electrostatic Storage-Tube Patterns

When a dot is placed on the screen, a positive charge or "well" is caused by secondary emission. This charge has the cross-sectional potential distribution shown in Figure 98C. However, if a dash is placed on the screen, as the electron beam is deflected to form the dash, some secondary electrons tend to fill up the well. The dash has the potential distribution shown in Figure 98D. The difference in potentials of the original area makes read-out possible.

From the preceding, it is evident that "writing" on the phosphor is not particularly difficult. The trick lies in reading out the information once it has been stored.

Figure 99 shows the basic circuit used to read out the charge stored on the face of the tube. A conducting plate is placed immediately in front of the cathode-ray screen. To permit visual inspection of the screen, this plate is made of *conducting glass.* The conducting plate is connected to ground through resistor R.

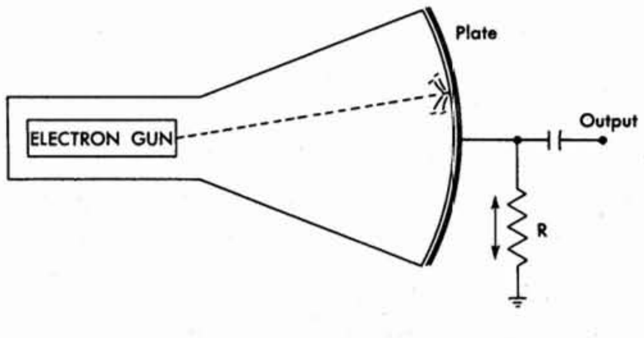


Figure 99. Storage Tube Read-Out

Imagine that a dot or dash has been stored on the screen of the cathode-ray tube. To read the charge, the electron beam is caused to fall on the spot where the charge is stored. When the spot is bombarded by electrons, the charge on the phosphor will be changed, and electrons will move through resistor R to equalize the charge on the two sides of the screen. As a result of this electron flow, a voltage is developed across resistor R.

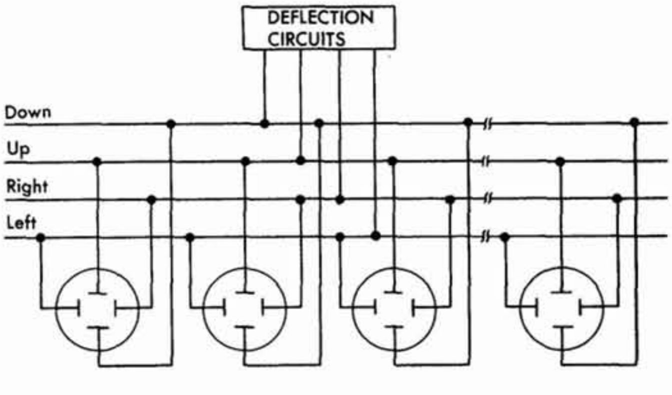
If a dot has been stored on the area, when the electron beam again bombards the area, the voltage developed across resistor R has the waveform shown in Figure 98E. If a dash has been stored, the voltage across resistor R has the waveform shown in Figure 98F. Note that when a dot is read, the voltage output goes negative and then positive; when a dash is read, the output goes positive, then negative. The output from the storage unit is obtained by sampling only the first half of the output. If a negative output pulse is developed, the area contains a *one*; a *zero* is indicated by a positive output pulse.

Although the phosphor is a good insulator, it is not a perfect insulator. The positive charges placed on the screen tend to deteriorate after a period of time. Stray electrons in the tube are attracted to the positive areas, neutralizing the charges. For the computer to retain the stored information indefinitely, a method of systematic restoration or regeneration is used.

Regeneration is accomplished by causing the electron beam to test all the areas on the screen one at a time. This operation, while similar to the read-out operation, occurs at a time when the computer is not accepting information from the tubes. If the electron beam strikes an area on which a *one* is stored, the charge is strengthened as the area is tested. If the area contains a dash, the positive output pulse obtained causes the beam to move over a few diameters, regenerating a dash.

If the calculator is idling, regeneration proceeds without interruption, keeping any stored information intact for an indefinite period of time. If the calculator is operating and making references to memory, the regeneration is automatically interspersed between the operating references to memory. Because some of the areas may have been regenerated when it becomes necessary to read or write in the tube, circuits must be provided to cause regeneration to continue from the area where the interruption occurred, rather than start again from the beginning.

In practice, the Williams tubes will be operated in parallel. For example, to store a ten-digit binary number, plus its algebraic sign, 36 storage tubes must be used. The deflection plates are connected in parallel; therefore, only one amplifier is required to move all 36 electron beams vertically, and only one is required to position them horizontally (Figure 100). Similarly, the control grids are unblanked simultaneously, and the output voltage across the resistor R associated with each tube occurs at the same instant. Parallel read-out is a much faster operation than reading the areas serially.



36 STORAGE TUBES
Looking at Tube Faces

Figure 100. Parallel Operation of Storage Tubes

Thirty-six cathode-ray tubes make the storage unit rather expensive; however, it is anticipated that perhaps a thousand areas will be available in each tube. Thus, 36 cathode-ray tubes would allow storage of 1,000 ten-digit numbers. Using trigger storage circuits, this capacity would require the use of about 50,000 vacuum tubes.

With the increased capacity made possible by further circuit refinements, the Williams tube should prove a great saving in space and power requirements for future electronic computers. Even with the associated circuits required for recycling, the tube should provide a great saving over the trigger method of electronic storage.

ELECTROMAGNETIC STORAGE

ANOTHER DEVICE offering good possibilities for rapid storage and transfer of numbers in electronic calculators is the electromagnet. Use is made of the fact that a magnetic material can be magnetized and demagnetized quickly. Once the material has been magnetized, it will retain its magnetic state until the magnetization is erased. Magnetic storage thus offers an advantage over electrostatic storage in that once information is stored, no recycling is necessary. It retains information even if the power to the calculator is interrupted.

The magnetic recording process is quite simple. The magnetic material, or medium, is carried past an electromagnet. When the electromagnet is energized, it causes the medium to become magnetized. Thus, it is possible to record pulses corresponding to coded numbers on the magnetic medium. To read the pulses, the medium is again carried past an electromagnet. This time the magnetism of the medium generates tiny voltage pulses in the electromagnet.

The voltage pulses are amplified by electronic means and entered into the computer circuits.

The recording medium usually takes one of two forms: powdered iron oxide may be coated on the surface of a rapidly rotating drum or it may be coated on paper tapes. It is also possible to plate a magnetic material on the surface of a nonmagnetic drum. Since it is desirable to record very short signals, the electromagnetic field must be concentrated in a very small area. The recording and play-back electromagnets are designed with a tiny gap, as shown in Figure 101. The electromagnetic lines of force pass through iron much more easily than they pass through air. Consequently, the field is concentrated in the air gap. As the recording medium passes the field concentration, it becomes magnetized. If no current is flowing in the coil of the electromagnet, no field will exist in the air gap, and no magnetization of the medium will take place.

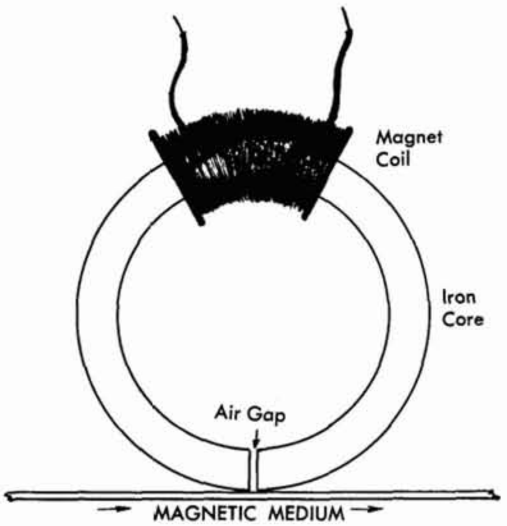
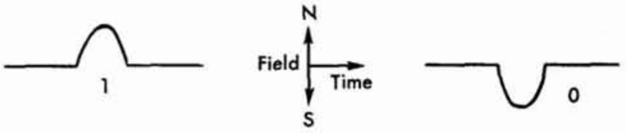
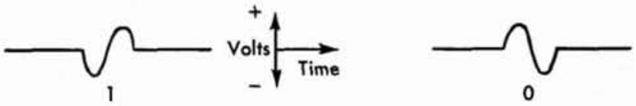


Figure 101. Recording Magnet

There are two possible methods of erasing the recorded signals. The medium can be carried past a DC erase magnet that causes the medium to be magnetized constantly in the opposite polarity to the magnetic signals used for the recorded pulses. Any pulses on the medium are thereby cancelled. A DC electromagnet or a permanent magnet may be used for the DC erase magnet. AC erasure requires that the medium be completely demagnetized. This is accomplished by causing the medium to pass an electromagnet that is excited with high-frequency alternating current. The medium is magnetized first in one polarity, then in the other, with a weakening field as the medium passes the magnet. Left with no residual magnetism, the medium is ready to receive and store more pulses.



POLARITY OF MAGNETIZATION



OUTPUT PULSES

Figure 102. Magnetic Storage Patterns

A definite coding must be developed to store binary digits on the magnetic drum. The drum surface is magnetized in one direction to represent a zero and in the opposite direction to represent a one (Figure 102). When the magnetized area passes under the reproducing head, the magnetic fields generate output pulses as illustrated. Note that the output resembles the output of the electrostatic tube. By sampling only the first half of the output waveform, the signal can be decoded.

The storage drum is shown schematically in Figure 103, which shows only one position; actually forty or fifty such circuits can be arranged along the length of the drum. The access time may be improved by placing two sets of magnets on opposite sides of the drum. If the drum revolves at the rate of 7200 RPM (a good number, because it is a multiple of the 60-cycle line frequency and consequently easy to keep in synchronism with the line frequency), digits placed on the drum by magnet A can be read off the drum by magnet B about four milliseconds (.004 second) later. The digits

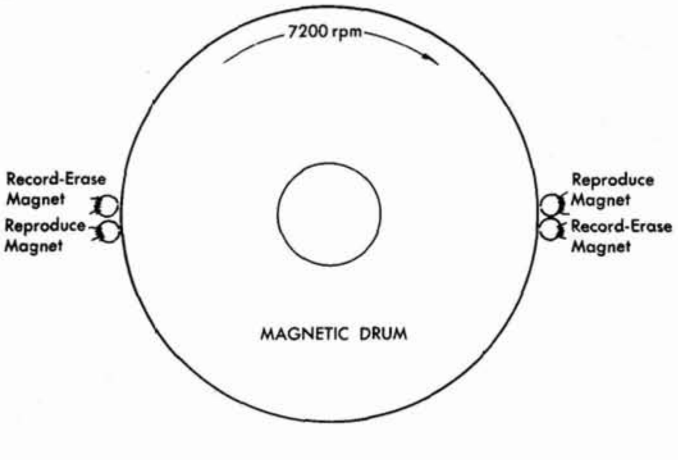
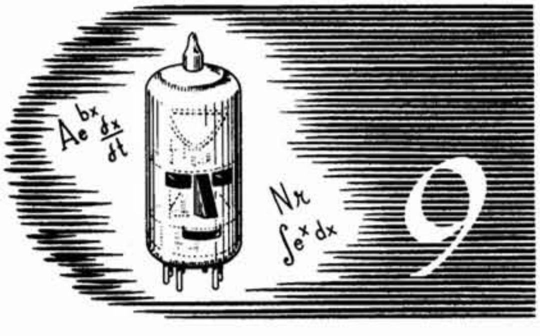


Figure 103. Magnetic Drum Storage Principle

are available at about four millisecond intervals thereafter, from one magnet or the other. If the digits had been placed in the electrostatic storage tube, they would be available in about ten microseconds (.000010 second). So the magnetic drum storage has the disadvantage of being about 400 times slower than the electrostatic tube storage. In a calculator employing both types of storage, the electrostatic tube storage would be used to store information that would be required instantaneously. The magnetic drum storage would be used to store data where a delay in access would not slow down the calculation. Data from the magnetic drum can be transferred at the proper time to the electrostatic tube storage to be available at an instant's notice.

It is also possible to record magnetic pulses on a roll of paper tape that has been coated with magnetic material. The tape is driven past the recording magnet at a fixed rate, and information is recorded on the tape for future reference. The main uses of the magnetic tape are in reading data into the machine and accepting the answers as they are calculated. Obviously, the tape can be recorded and reproduced much faster than cards can be punched or read.



the SSEC

Through electronic speed, vast memory capacity and flexible programming, IBM's Selective Sequence Electronic Calculator assists scientists in heretofore hopelessly time-consuming mathematical computations

ON JANUARY 27, 1948, Mr. Thomas J. Watson dedicated the largest calculating machine IBM has yet built for the advancement of science. This machine, known as the IBM Selective Sequence Electronic Calculator (SSEC), occupies the entire first floor of an office building in New York City. It employs about 12,500 electronic tubes and about 21,500 relays. The calculator reads the numbers involved in the problem and instructions for the solution from IBM cards and paper tapes. By "coding" the instructions, a complex command such as

> Read the number in reading unit number 2, multiply it by the number in memory unit number 1, drop all but four decimal places from the answer, and transfer it to memory unit number six.

can be represented by a few punched holes in a paper tape.

Actually, the computer cannot do any operation that an adult with pencil and paper could not do. Circuits are provided to cause the calculator to add, subtract, multiply and divide. The most complex equations of higher mathematics can be performed by the proper combination of these operations. However, in the course of a typical problem the calculator may do billions of operations. The solution of many problems that would require the entire lifetimes of an army of human mathematicians can be obtained in a period of a few months by the SSEC. Problems previously avoided as being hopeless are now being solved by the calculator.

The high speed of calculation is obtained by using electronic circuits for calculating and control. All the operations required to perform the most complex processes of higher mathematics are accomplished at electronic speed. Because electrons have almost no mass, they can move infinitely faster than any mechanical part. For example, a mechanical computer can add two numbers in about a second. The calculator can read the two numbers from tapes and add them in less than a thousandth of a second. With practice, a person using pencil and paper could multiply two 14-digit numbers together to obtain a 28-digit answer in about twenty minutes. The calculator does 50 such multiplications in a second. If the machine should make an error in an eight-hour day, it would be comparable to a human mathematician making less than one error in his entire lifetime.

Another feature that gives the SSEC an extraordinary advantage over a human mathematician is its prodigious storage reservoir, or "memory" for numbers. The calculator has three distinct types of memory units. Numbers that must be entered into the calculation at a moment's notice are stored in electronic storage units similar to those described in the preceding chapter. Numbers can be entered in or read out of the electronic storage units almost instantaneously. Numbers that are to be held for a greater length of time are stored in electromagnetic relay units similar in principle to the electronic units. However, it requires five milliseconds (.005 second) to transfer the relays —a comparatively long time when compared with electronic speeds. The third type of memory unit employs a card punch and paper tape. When the machine is doing a long problem, it may develop part of the answer hours before it finishes the complete problem. The partial answers can then be punched into paper-tape memory. After the tapes are punched, they pass over a series of contact rolls where they may be read back into the machine when needed. Meanwhile, the circuits in the machine can be cleared out and used for additional calculations. The paper-tape memory is also quite useful when it becomes desirable to shut the machine down for any reason. The partial answers in the electronic and relay storage units can be transferred to tape and stored in permanent form. Later, when the machine is again in operation, the partial answers may be entered into the machine from the tapes.

Think how convenient it would be if a human mathematician could memorize the entire contents of a book of mathematical tables! The SSEC contains a unit known as "table lookup." This unit consists of 36 stations equipped to read table values from punched tape loops. These reading units are connected with a searching mechanism which locates whatever information is required for reference. For example, if the computer receives the command,

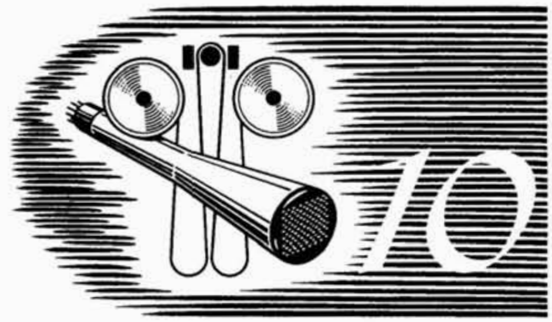
> Find the square root of the number in memory unit number 1, and multiply it by the cosine of the angle whose sine value is in memory unit 2.

the table-lookup unit will spin its tapes to find the square root of the number in memory unit number 1 and to find the cosine of the angle whose sine value is in memory unit number 2. The values of these functions, supplied by the table-lookup unit, are then multiplied together. The table lookup is entirely automatic and locates values determined by the machine in less than a second. Another advantage of this kind of table lookup is that intervals in the table may be varied, permitting the use of fewer table values. For example, the table value of the tangent of an angle changes less than .09 between the angle values of 0° and 5°. Between the angles of 85° and 90°, however, the tangent changes in value by 3,462. Obviously, fewer intervals are required for the first five degrees than for the angles between 85° and 90°.

The memory units, calculating units and control units are arranged behind glass panels that cover three of the walls of the computing laboratory. In the center of the room are the machines that read data from punched cards into the memory units of the machine. A large control board contains switches and indicator lamps that allow an operator to watch the progress of the calculation through the machine.

The men and women who operate the SSEC point out that while the calculator is capable of doing an immense amount of work, it should not be called an "electronic brain," because it is not capable of original thought. The SSEC is the servant of the scientists who use it. Because the SSEC is a general-purpose machine, all fields of science are benefiting from its exceptional versatility and efficiency. It combines electronic speed, vast memory capacity and highly flexible and convenient programming facilities to provide for greater latitude in carrying on mathematical operations that had been impossible before its completion. Scientific advances, speeded by the untiring assistance of the calculator, are opening the way to further improvements of the tools upon which the progress of our civilization depends.

electronic DATA-PROCESSING machine



IBM's newest commercial calculator stores and processes mountains of data in solving problems previously beyond the power of mind or machine

THE ELECTRONIC Data-Processing Machine, Type 701, is the latest electronic calculator IBM has announced for field use. This machine was developed to speed the solution of scientific problems involving immense amounts of data.

The new machine uses the principles of electromagnetic and electrostatic storage discussed in Chapter 8 to provide a huge memory for numbers. Electronic calculating circuits combine these numbers at incredible speeds. For example, certain guided missile problems required 180 to 200 hours for solution on the Card-Programmed Calculator, a portable IBM commercial calculator which was one of the fastest calculators previously available. The Type 701 performs these calculations in less than a minute. The great storage capacity and speed of operation enable the calculator to solve problems beyond the power of earlier machines.

The calculator consists of individual units connected by cables. This makes the calculator semi-portable; the units may be disconnected and moved when desirable. Capacity can be increased by wiring on more units. It is expected that the average installation will consist of about twelve units.

The largest of these units is called the electronic analytical and control unit; this contains all the calculating circuits of the computer. Attached to the analytical unit is the control panel, a desk from which the operator can manually control the machine functions.

Data may be introduced into the calculator from IBM cards read by a card reader unit or from signals read from the tapes in the magnetic tape readers. Decimal numbers thus read are converted to binary numbers and stored on the magnetic drums of the drum unit, or on the cathode-ray tube faces of the electrostatic storage units. From these units, the numbers are transferred to the electronic analytical and control unit when they are required in the calculations. Use of the binary system results in a great saving of calculation time (see Appendix C).

As the answers are developed, they may be printed on paper by a wheel-printing unit (similar to that used in the Type 407 Accounting Machine). Answers may be punched into IBM cards by a high-speed punch unit or stored on magnetic tapes for use in later calculations.

Power for machine operation is supplied by two large power-supply units through a power distribution frame. These units employ gas-tube rectifiers to obtain the DC voltages required for the electronic circuits. The output voltages are carefully regulated by electronic voltage regulating circuits.

The Electronic Data-Processing Machine occupies about one-fifth of the space required for the SSEC. The Type 701 has a larger storage capacity; it can store 80,000 decimal digits in magnetic drum storage and 20,000 decimal digits in electrostatic storage. While the full capability of the new calculator has not yet been measured, on certain problems the EDPM is 40 times as fast as the SSEC.

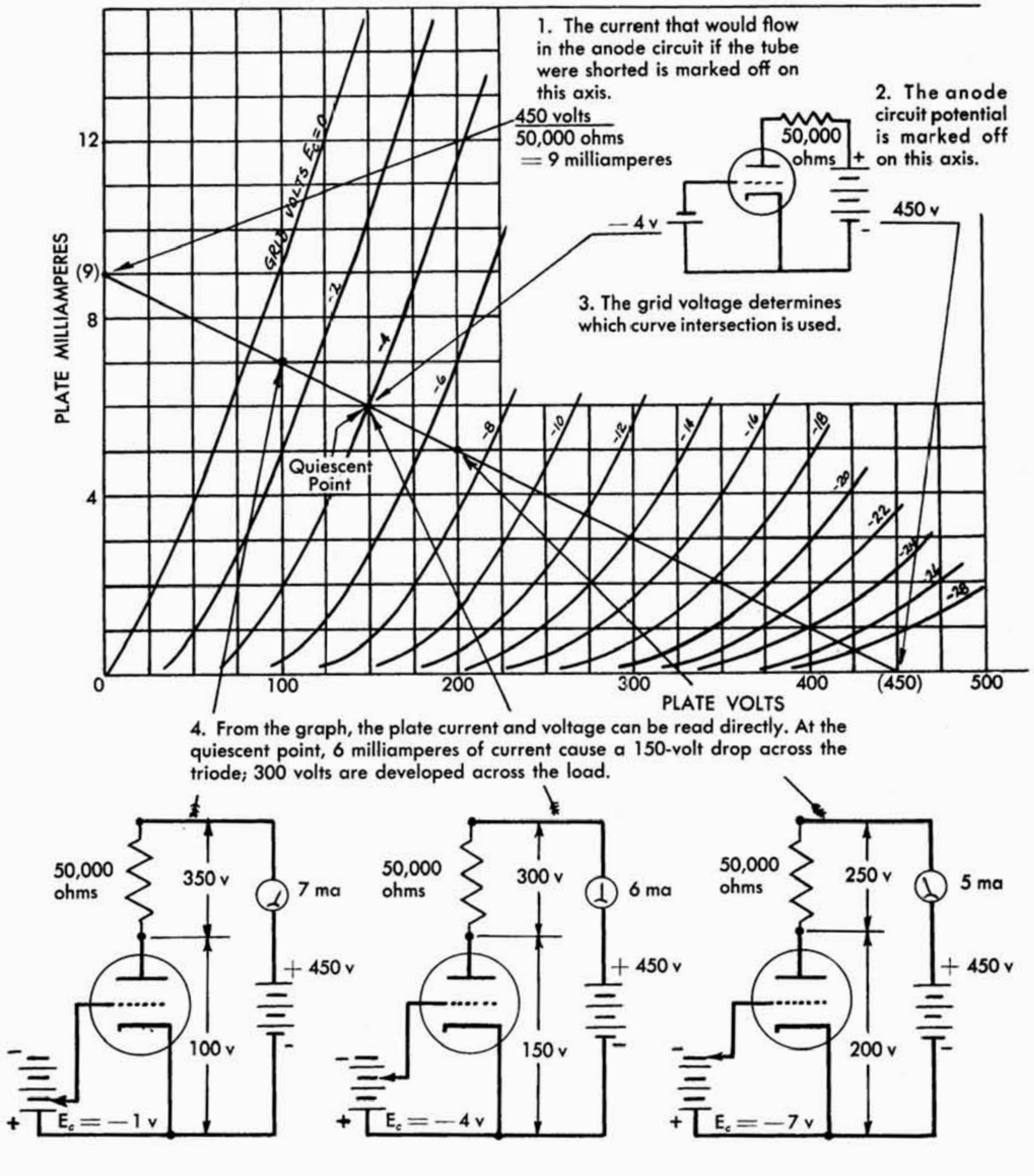
The Type 701 will be a valuable tool for solving scientific and engineering problems that previously were too lengthy or complicated for practical solution. By building the machine on a mass-production basis, IBM is making this tool available to increasing numbers of scientists, who will use it to advance the frontiers of knowledge. Advent of the new calculator marks a forward step in scientific progress and opens the way for further advances. The amazing progress made in scientific computers in the last five years is only the groundwork for the machines of the future.

Appendix A

BECAUSE the characteristics of vacuum tubes vary as the anode current is varied, the mathematical analysis of tube operation becomes quite complex, requiring the use of calculus for proper solution. By using graphs, however, the solution may be obtained in a very simple manner.

The *anode characteristic curves* of a type 6C5 vacuum triode are shown in Figure I. To determine the operating characteristics of the triode in a circuit, these characteristic curves must be consulted. The figure shows how the quiescent point may be determined from the ***direct-current load line.***

In most RC-coupled amplifiers, the alternating-current component of the anode signal is applied to the grid of the next tube through a capacitor and grid resistor. The alternating-current component of the signal is developed across the load resistor in parallel with the coupling capacitor and grid resistor. Therefore, the impedance to AC is lower than the DC impedance, and the load line has a greater slope.



1. The current that would flow in the anode circuit if the tube were shorted is marked off on this axis.

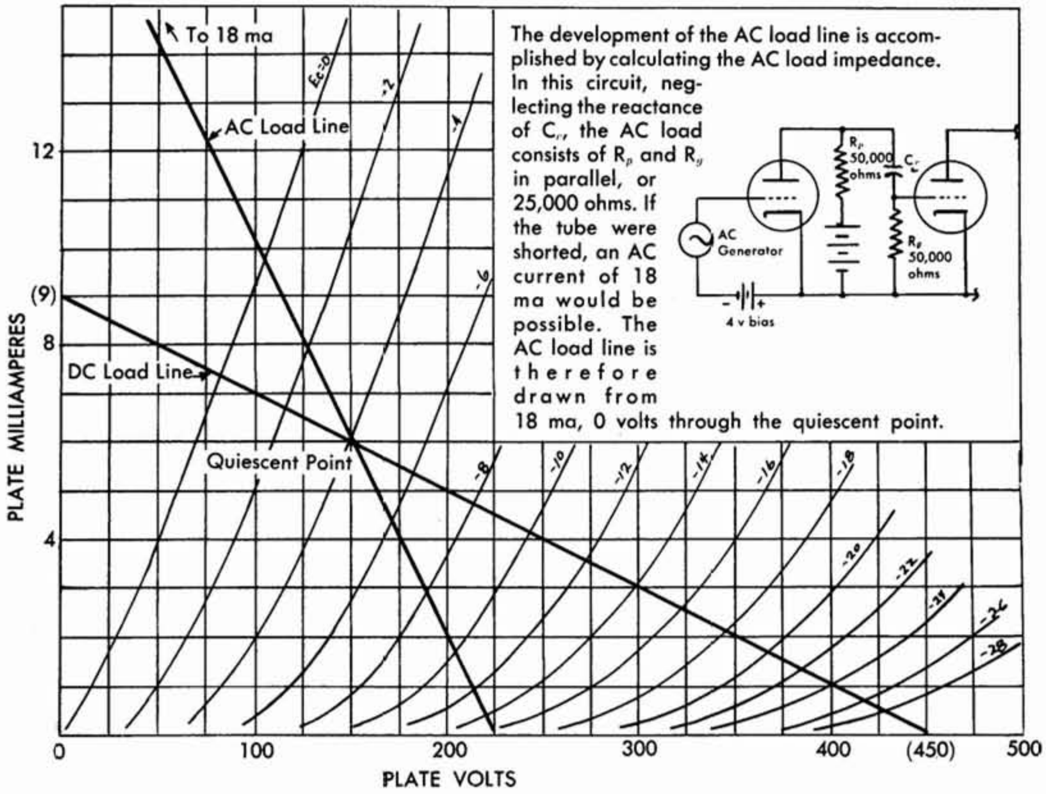
$\frac{450 \text{ volts}}{50{,}000 \text{ ohms}} = 9$ milliamperes

2. The anode circuit potential is marked off on this axis.

3. The grid voltage determines which curve intersection is used.

4. From the graph, the plate current and voltage can be read directly. At the quiescent point, 6 milliamperes of current cause a 150-volt drop across the triode; 300 volts are developed across the load.

Figure I



The development of the AC load line is accomplished by calculating the AC load impedance. In this circuit, neglecting the reactance of C_c, the AC load consists of R_p and R_g in parallel, or 25,000 ohms. If the tube were shorted, an AC current of 18 ma would be possible. The AC load line is therefore drawn from 18 ma, 0 volts through the quiescent point.

Figure II

Figure II shows how the AC load line is developed. It is here assumed that the coupling capacitor is large enough to have no appreciable reactance at the frequency being amplified. At very low frequencies the coupling capacitor decreases the amplification. At very high frequencies the tube interelectrode capacitances shunt the load, decreasing the amplification. In Figure II the load resistor and grid resistor are each 50,000 ohms. The DC load is 50,000 ohms, while the AC load is 25,000 ohms.

Appendix B

RESONANCE occurs at a frequency at which the inductive reactance is equal to the capacitive reactance. It can be shown that

Inductive reactance, $X_L = 2\pi f L$ ohms

Capacitive reactance, $X_C = \dfrac{1}{2\pi f C \text{ ohms}}$

Where $\pi = 3.1416$
L = inductance in henrys
C = capacitance in farads
f = frequency in cycles per second

At resonance, $X_L = X_C$

$$2\pi f L = \frac{1}{2\pi f C}$$

Solving for f,

$$f(2\pi L) = \frac{1}{f(2\pi C)}$$

$$f^2 = \frac{1}{(2\pi)^2 LC}$$

$$f = \frac{1}{2\pi\sqrt{LC}}$$

EXAMPLE: Compute the value of the inductor required to resonate with a .06 microfarad capacitor at 3500 cycles per second.

$f = 3500$ cps. $C = .06$ microfarad $= .00000006$ farad

$$f^2 = \frac{1}{(2\pi)^2 LC}$$

$$L = \frac{1}{(2\pi)^2 f^2 C}$$

$$L = \frac{1}{(2 \times 3.1416)^2 \times (3500)^2 \times .00000006}$$

$$L = \frac{1}{29.0} = .0345 = 34.5 \text{ millihenrys}$$

These are the approximate values used to obtain the 3510-cycle-per-second signal for the Electronic Time Control System.

Appendix C

BINARY ARITHMETIC

ELECTRONIC CALCULATORS are made up of switching devices such as vacuum tubes and magnetic relays. These devices have two definite states, energized and de-energized, or conducting and non-conducting. To apply them to electronic counting, some system must be adopted. Suppose that the value of zero is assigned to a circuit when it is non-conductive (off) and a value of *one* is assigned when it is conducting (on). Such a circuit then knows two numbers—*zero* and *one*—and becomes a *binary* (two-number) element. Because binary elements are the building blocks of electronic computers, binary arithmetic becomes important in computer design.

Now, suppose that instead of ten fingers, people had only two. If mankind had evolved with only two fingers, binary arithmetic would probably have evolved instead of decimal (ten-number) arithmetic. The following table compares numbers under the two systems.

Decimal	Binary	Decimal	Binary	Decimal	Binary
0	0	15	1,111	127	1,111,111
1	1	16	10,000	128	10,000,000
2	10	17	10,001	129	10,000,001
3	11	etc.		etc.	
4	100	31	11,111	255	11,111,111
5	101	32	100,000	256	100,000,000
6	110	33	100,001	257	100,000,001
7	111	etc.		etc.	
8	1000	63	111,111	511	111,111,111
9	1001	64	1,000,000	512	1,000,000,000
10	1010	65	1,000,001	513	1,000,000,001
etc.		etc.		etc.	

Logically, 1 plus 1 equals 2, but 2 is represented by 10. Therefore, $1 + 1 = 0$ with 1 carried into the next higher column of numbers. Obviously, $0 + 0 = 0$, and $0 + 1 = 1$. With these three rules, any sum may be worked in binary arithmetic. As an example:

Decimal	Binary
17	10,001
+63	+111,111
80	1,010,000

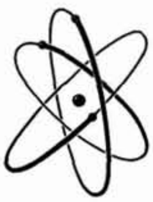
Now, if one microsecond is required to add 1 into a counter, a possible 9 microseconds plus one microsecond for carrying would be required to add each decimal number. Twenty microseconds would be required to reach the sum, using decimal counters. A binary circuit could do the same sum in four microseconds, or add a column of six numbers while the decimal counter added two numbers. The binary system makes possible a great saving in operation time.

Similarly, subtraction of binary numbers can be accomplished by establishing the rules: $1 - 1 = 0$, $1 - 0 = 1$ and $10 - 1 = 1$. For example,

80	1,010,000
−63	−111,111
17	10,001

Multiplication follows the simplest of algebraic rules: $0 \times 0 = 0$, $1 \times 0 = 0$, $1 \times 1 = 1$. By the use of the addition and multiplication tables, multiplication and division operations can readily be accomplished.

Decimal		Binary
89		1011001
×23		10111
267		1011001
178		1011001
		1011001
2047		1011001
2047	=	11,111,111,111
23		10111
89) 2047		1011001) 11111111111
−178		−1011001
267		10011011
267		−1011001
000		10000101
		−1011001
		1011001
		−1011001
		0000000



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