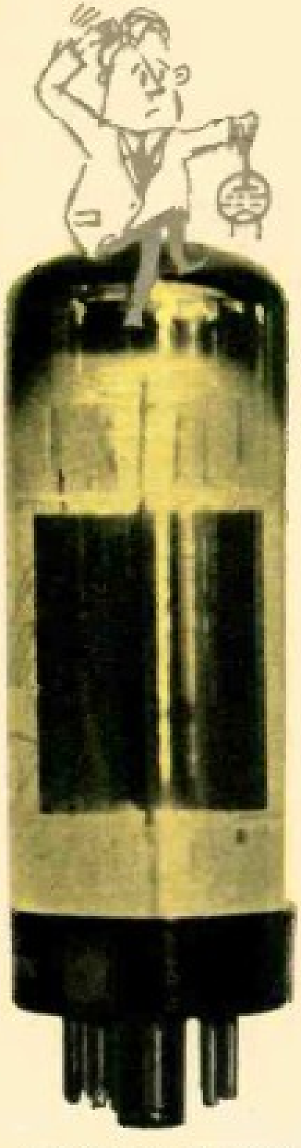
BASIC COURSE IN VACUUM TUBES

By JOHN T. FRYE,
W9EGV



OUR SPECIAL FEATURES ON THE VACUUM TUBE

GETTING TO KNOW vacuum tubes is, for some people, a little like getting to know next-door neighbors. They live right along with tubes and neighbors for years without ever taking the trouble to lean over the fence and introduce themselves.

Obviously, the vacuum tube can't introduce itself to you, so we've arranged this introduction to accomplish the job. To prepare you, we'd best tell you first of all that the tube comes in many shapes and sizes. And, though tubes have been around for years, they aren't necessarily wrinkled and grey. Matter of fact, spanking new ones in a dozen different configurations are being developed at this instant.

Bear in mind, too, that the vacuum tube appears in more guises than a chameleon has colors. A tube can be, among other things: a rectifier that changes alternating current into direct current, a generator changing direct current into alternating current of any desired frequency, a flawless magnifier of varying voltages, a cross-breeder mating two frequencies and producing an entirely new offspring frequency, or a lightning-fast artist painting pictures rich in detail in a thirtieth of a second.

Ready to meet the vacuum tube? Come on, then—let's go!

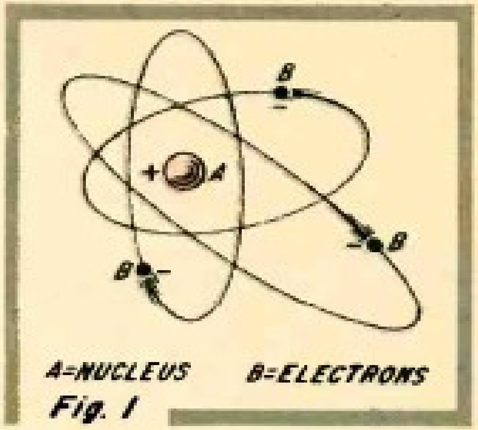


Fig. 1

The Ingenious Electron. "I owe everything I have to spaghetti," a curvaceous, well-endowed Italian movie star said recently. In a similar vein the vacuum tube might confess, "I owe all my magic power to electrons." This being the case, let's begin by brushing up on our electron theory.

All matter is made up of atoms. And an atom consists essentially of a positive nucleus surrounded by whirling planets of negatively-charged *electrons*. The total charge of the negative electrons in Fig. 1 just balances the positive charge of the nucleus so that the atom normally has a neutral charge.

"Like charges repel; unlike charges attract." Remember this, even if you have to tattoo it on your chest. It explains why electrons keep circling their nucleus, why they are strongly attracted to any positively-charged object, why they are repelled by a negatively-charged object, and why, having similar charges, they even repel each other.

Consider what happens when a wire is connected from the electron-starved positive terminal of a battery to its negative terminal, just oozing with a surplus of electrons. The positive terminal steals electrons from the near-by atoms of the wire, leaving them with positive charges. They, in turn, grab electrons from neighboring atoms; and this bucket-brigade thievery goes on until it reaches the other end of the wire. There the atoms replenish their raided electron complement from the negative battery terminal.

The directed movement of electrons through the conductor constitutes an electric current. But what would you say if we proposed to create an electric current *without a conductor?* Sounds like asking a tight-rope walker to do his act without a rope, doesn't it? Let's try it, anyway.

The first step is somehow to persuade the electrons to leave their conductor. We do this by giving them a hot-foot. A certain amount of random electron-swapping always is going on among the atoms of a conductor even when no current is flowing through it. But at ordinary temperatures the atom-hopping electrons do not have sufficient kinetic energy to breach the surface. Heat, though, affects them the way it does Mexican jumping beans; they become livelier and friskier until some manage to go through the surface like leaping carp. As the temperature goes higher, more of them accomplish this feat until the heated conductor is surrounded by a cloud of escaped or *emitted* electrons.

We can do two things to aid their emission: (1) select a conductor for good emitting qualities or coat it with oxides, such as barium or strontium, that have these qualities; and (2) place the conductor inside a glass bulb and pump out the air. This last step is necessary so the truant electron will not have to shoulder aside atoms of air or gas 1,800 times its mass in leaving the conductor. Surrounding the hot *filament*—that's the alias our heated conductor assumes when it becomes a tube element—with lots of nothing has another advantage. It keeps the filament from burning up or "oxidizing" the way the tip on a soldering gun does in the air.

Passing an electric current through the emitter is a good way to make it hot enough to emit electrons, but there are times we do not want heating current going through the emitting material. In that case, we simply form the material into a sleeve and slip it over the filament as has been done with the tube shown in Fig. 2. The temperature of this sleeve, or *cathode*, is raised by heat radiated from the filament. With this arrangement, the filament is called a heater since it has the job of heating up the cathode to make it emit electrons.

Current Without Wires. You probably have heard of diode, triode, and pentode tubes (that's a pentode in Fig. 2); but did you ever hear of the *monode* one-element vacuum tube? That's odd; it's the most common type. Every incandescent lamp bulb is a monode vacuum tube! It has a heated, electron-emitting filament inside a vacuum, doesn't it? Admittedly, though, it's not much good for working vacuum-tube magic. The emission of negative electrons leaves the filament with a positive charge that tends to draw them back to it; furthermore, the electrons already emitted are pretty repulsive to would-be AWOL electrons. (Like charges repel, you know.) The end result is a kind of fountain-in-a-fishbowl action in which electrons are constantly leaving the filament or cathode and returning with no really significant change in the electronic *status quo*.

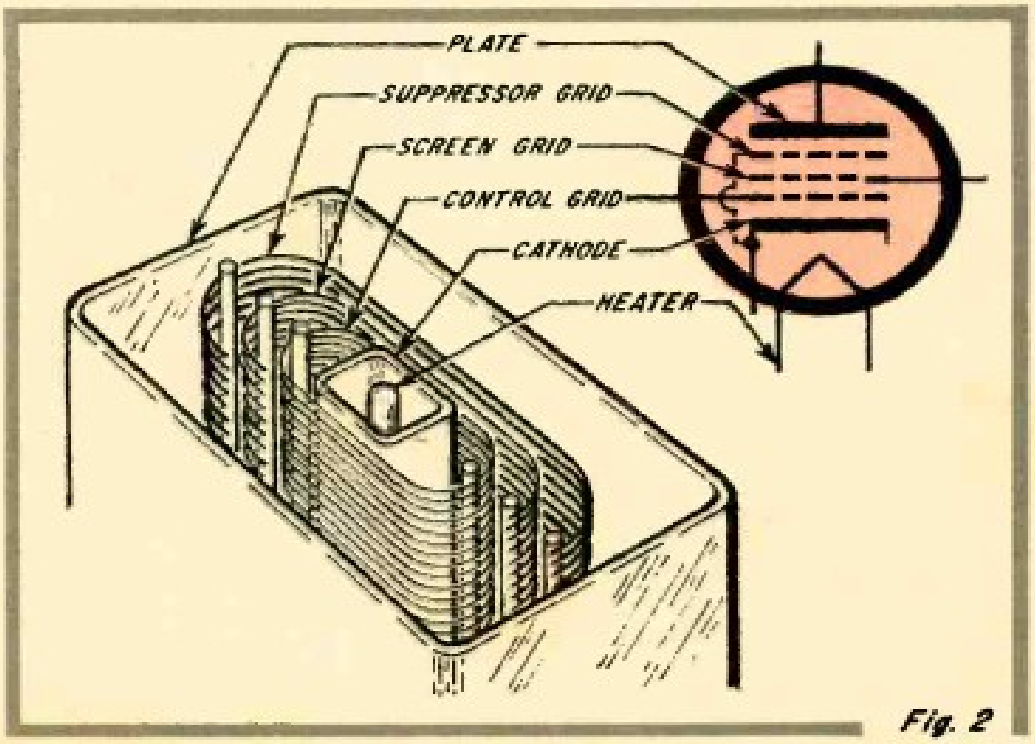


Fig. 2

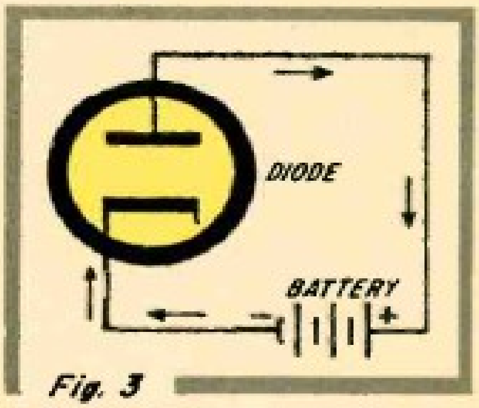


Fig. 3

What we need is some way to collect the emitted electrons and keep them from returning to the filament. This is as easy as pie for us hindsighted scientists! We simply put a metal *plate* inside the tube and use a battery to place a strong positive charge on it with respect to our cathode (see Fig. 3). Now many emitted electrons, instead of going back home, will be lured to the plate by its stronger attraction. Their places on the cathode will be filled from the negative terminal of the battery. Note the arrows in Fig. 3 and you will see that this movement of electrons from cathode-to-plate, plate-to-battery, and battery-to-cathode constitutes an electronic current flowing through the cathode-to-plate span without the aid of a conductor. We did it!

The tube is called a *diode* because it has two elements. The filament, or heater-and-cathode combination, counts as one "emitting" element. The positively-charged plate, or *anode,* is the other "collecting" element.

AC to DC."So what good is a diode?" you ask. For one thing, a diode is a *rectifier* that can change zig-zagging alternating current (AC) into pulsating, one-way, direct current (DC). Look at Fig. 4. Transformer winding L1 furnishes current to heat the filament of the diode. Winding L2 connects between the plate and filament through the load resistor. The AC induced in this winding makes the plate first positive and then negative sixty times a second with regard to the filament. When the plate is positive, it attracts electrons from the filament and current flows in the direction indicated by the arrow. But what happens when the plate is negative? Not a thing! A negatively-charged plate is great big nothing to electrons, and they stay home. In other words, our diode is an electronic check-valve that permits current to flow freely through it in one direction but stubbornly bars movement in the opposite direction. No wonder the British call a vacuum tube a "valve"!

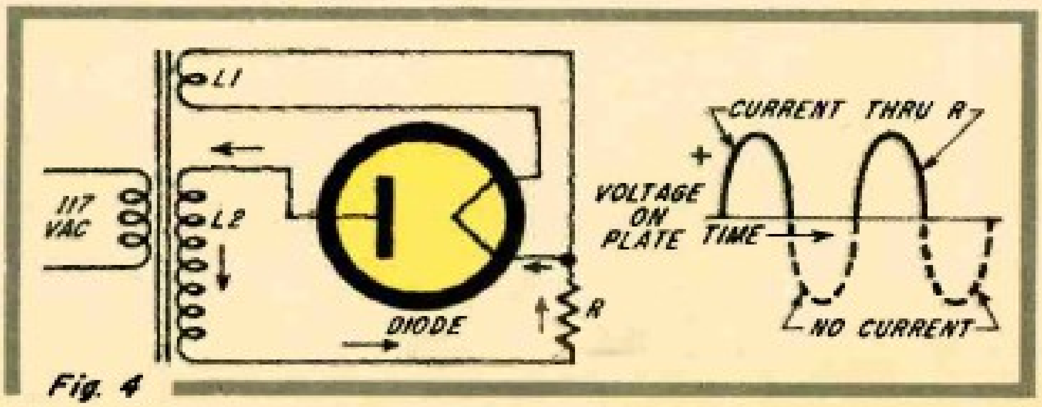


Fig. 4

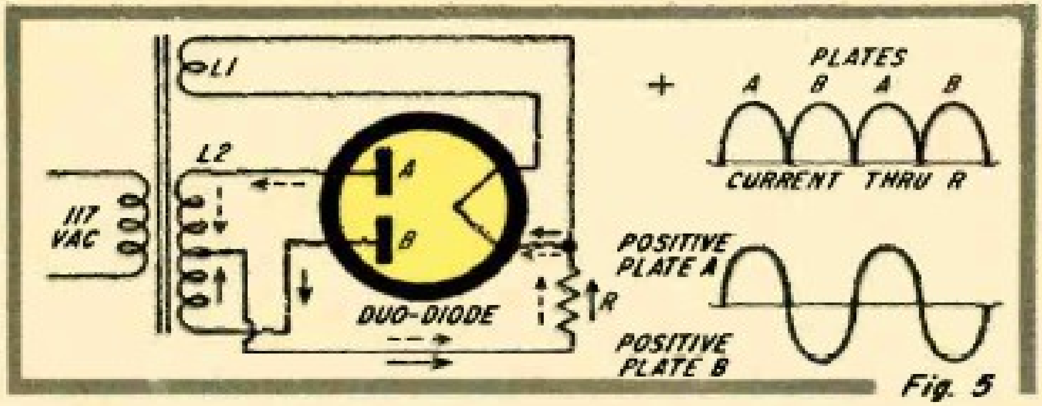


Fig. 5

Fig. 4 shows how pulses of current through the load resistor correspond to excursions of the AC voltage applied to the plate. Now we see why this arrangement is called a *half-wave rectifier*. The tube loafs while its plate is negative, and we get no current output during that half of the AC cycle. We can fix that! We just put another plate in our diode, making it a *duo-diode*, and connect the plates to the ends of a center-tapped transformer winding as shown in Fig. 5. The resulting *full-wave rectifier* puts out current during practically the whole AC cycle. When one plate is negative, the other is necessarily positive, and current is kept flowing through one half or the other of the transformer winding as indicated by the arrows.

Though both the half-wave and the full-wave rectifier perform the same task—that of changing AC to DC, the full-wave version obviously does a much better job. Assuming that our rectifier is operating from a standard 60-cycle AC line, the half-wave setup will deliver DC pulses 60 times every second. But a full-wave circuit will furnish 120 DC pulses every second, and, more importantly, there will be almost no gaps between them. This means that the output of a full-wave rectifier can be smoothed into pure DC much more easily than can that of a half-wave hookup. As a result, the simpler, half-wave version appears primarily in inexpensive electronic equipment—AC/DC radios, for example.

The graphs of Fig. 4 and 5 show that the amount of current flowing at any instant depends on the plate voltage at that time. Why don't all the electrons the filament is capable of emitting flock to the plate the instant it becomes slightly positive? The answer is *space charge*. While some of the emitted electrons are attracted to the slightly-positive plate, others just stand around, doing nothing, in the space between the filament and the plate. And electric charge exerts force according to its distance. Therefore, electrons trying to escape from the filament hear the negative "Stay put!" of the space charge much louder than the positive "Come on!" of the more distant plate. Increasing the plate voltage gradually cuts down this distance advantage of the space charge, and more electrons are drawn to the plate. A forthright way to reduce the current-limiting effect of the space charge is simply to move the plate closer to the filament so that there is less room for the space charge to exist!

The Piggy-back Rider. Before we discuss the diode *detector* that recovers modulation from a radio-frequency carrier, we'd better examine a modulated carrier as shown in Fig. 6. Here the modulating signal "A" operates on unmodulated carrier "B" to produce modulated carrier "C." Notice modulation affects the amplitude of the carrier with regard to time. The carrier develops bulges and dips that correspond, both in frequency and amplitude, to the respective positive and negative peaks of the modulating signal. And, since the modulating signal would not go far without the carrier, you might say it's really stealing a ride, piggy-back fashion.

Unfortunately, this modulated carrier will not operate an earphone directly, either. We need an AC current surging back and forth through the earphone coil to vibrate its diaphragm. The voltage of our modulated carrier is increasing and decreasing, all right, but it goes two ways at once. Every increase or decrease on the positive side is countered perfectly by a similar change on the negative side. This is like two men trying to operate a crosscut saw by both pulling or pushing at the same time. If one yells, "Please . . . I'd rather do it myself!" and the other lets go, the saw starts working. There's an idea! Let's use our half-wave rectifier to get rid of half the modulated carrier.

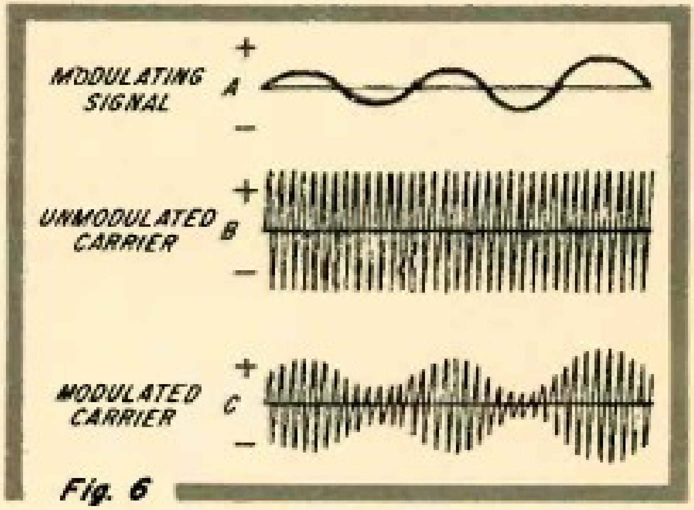


Fig. 6

Replace the AC transformer of Fig. 2 with an RF or IF transformer, substitute a pair of earphones for the load resistor, add capacitors C1 and C2 and you have Fig. 7. The diode doesn't care if the frequency has gone up from 60 cycles to 455,000 cycles per second or better and that the voltage of this high frequency is varying all over the place. It just goes right ahead chopping the negative half off each carrier cycle and passing the positive half as a pulse of current. We're not interested in the individual pulses of carrier current; so capacitor C2 is added to blend these pulses together. Its size is such it cannot charge and discharge during the time of a single carrier cycle; therefore the voltage across it follows the *average* height of the positive pulses, as shown in Fig. 8. Now the voltage across our earphones, and consequently the current through them, rises and falls exactly in step with the carrier modulation. Our rectifier has become a diode detector right before our eyes!

Controlling the Flow. Something about a flowing current of any kind invites interference; so before long an engineer stuck a loose grid of wire

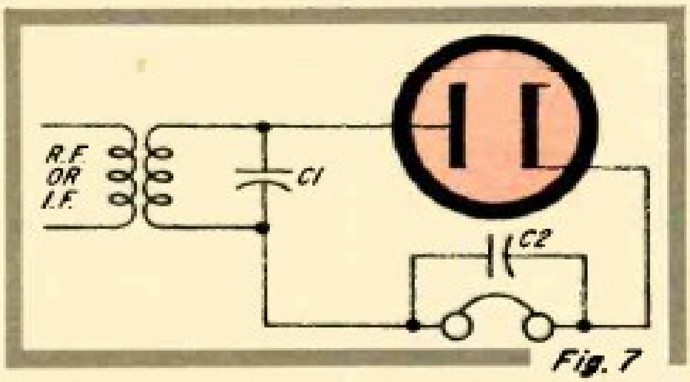


Fig. 7

in the stream of electrons flowing from cathode to plate. He quickly discovered small variations in a negative *bias* voltage applied to this grid had tremendous effect off plate current. A few negative grid volts completely nullified the attraction of many positive volts on the more distant plate and entirely cut off the flow of electrons. As the grid voltage was reduced, an increasing number of electrons slipped between the grid wires and reached the plate, causing plate current to rise. In other words, the grid voltage exerted a smooth, control-valve action on plate current. This is shown in Fig. 9 in which plate current is plotted against grid voltage for a typical *triode* tube.

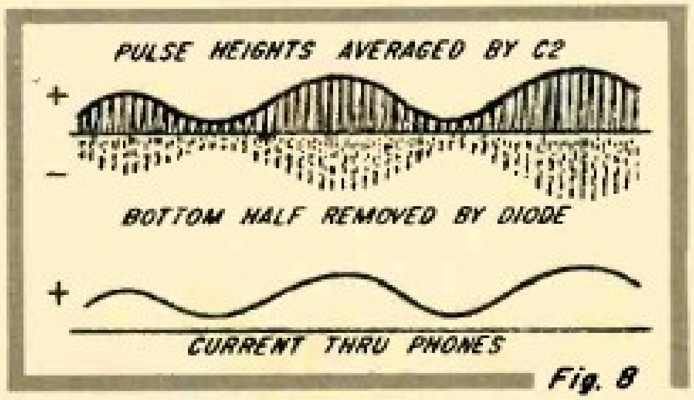


Fig. 8

If you imagine the electrons in the tube as a group of cars or people, the control grid becomes a sort of traffic policeman. It not only tells electrons to stop or go, but it also decides how many can pass by at any given instant. Thing is, the control grid is so fast even the best of policemen could not even begin to keep pace. For the grid can stop or start its electron traffic with the speed of light—186,000 miles per second! Furthermore, it does not matter one bit to the tube whether the voltage on its grid is steady DC or AC that's varying from soup to nuts. The tube will go right on controlling electron flow in precise accordance with whatever voltage happens to be on its grid at a particular time.

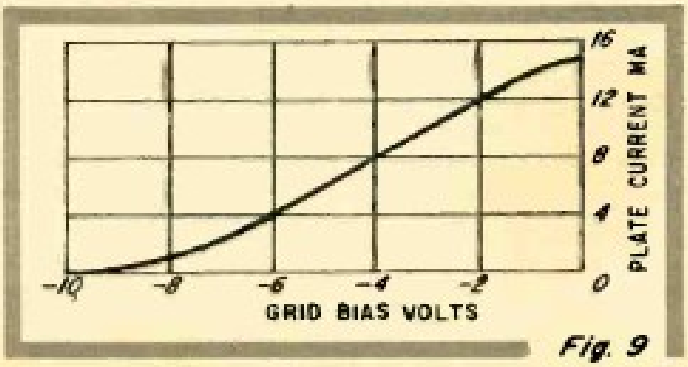


Fig. 9

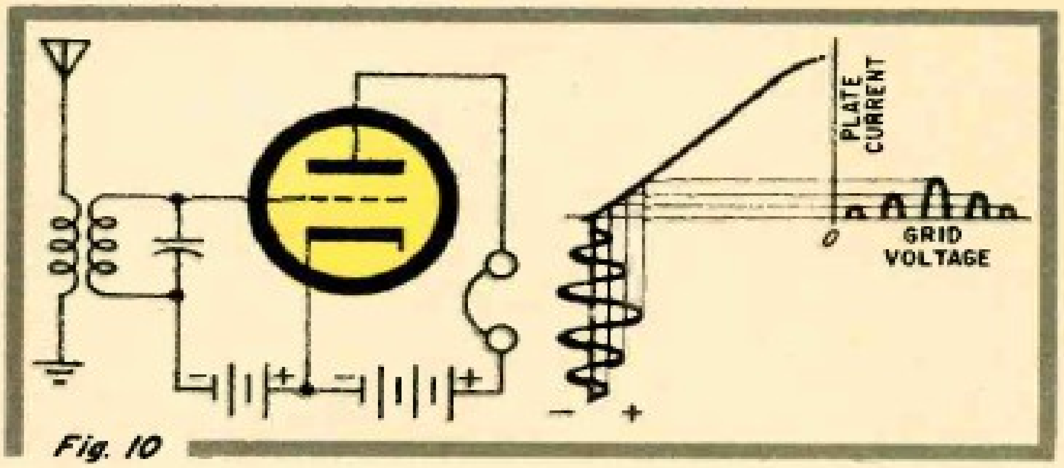


Fig. 10

We can put our new triode to work immediately as a *plate detector*. Fig. 10 is the circuit. Enough bias voltage is placed on the grid to reduce the plate current to nearly zero. A modulated carrier from a broadcast station is introduced in series with this bias voltage so positive and negative swings of the signal voltage add to or subtract from the bias voltage, as shown in Fig. 10. Negative excursions of the signal voltage, making the grid more negative, have no effect on the already-zero plate current; but positive swings reduce the bias voltage and cause plate current to flow. Thus, plate current responds only to variations in the positive half of the carrier and will work earphones in the plate lead. What's more, the plate current variations are stronger than the feeble carrier-current variations producing them.

This last fact is very important because it hints at the real advantage of a triode over a diode: the triode can *amplify* a signal. We need such amplification because the signal delivered by a detector is ordinarily quite weak and must be beefed up a great deal before it can fill a room with sound from a loudspeaker.

The Artful Amplifier. Fig. 11 shows the basic circuit and operation of a *voltage amplifier*. Grid bias from the battery sets the no-signal plate current near the center of the straight portion of the *characteristic curve*. Current through R produces a voltage drop across it directly proportional to the plate current. Making the grid less negative increases the plate current and the voltage drop across R, but it also decreases the plate voltage. Making the grid more negative decreases plate current and voltage drop across R, but increases plate voltage.

Now let's start our grid-circuit signal generator, which serves as a stand-in for a signal fed from the detector, and see what happens. The output of the generator is a low-voltage, AC, audio-frequency signal. The varying, reversing voltage of the generator output combines with the bias voltage to produce a resultant voltage on the grid that bobs up and down equally on either side of the fixed bias voltage. The plate current "twists" right along with the dancing grid voltage; and so, consequently, does voltage drop across R. But since the instantaneous voltage on the

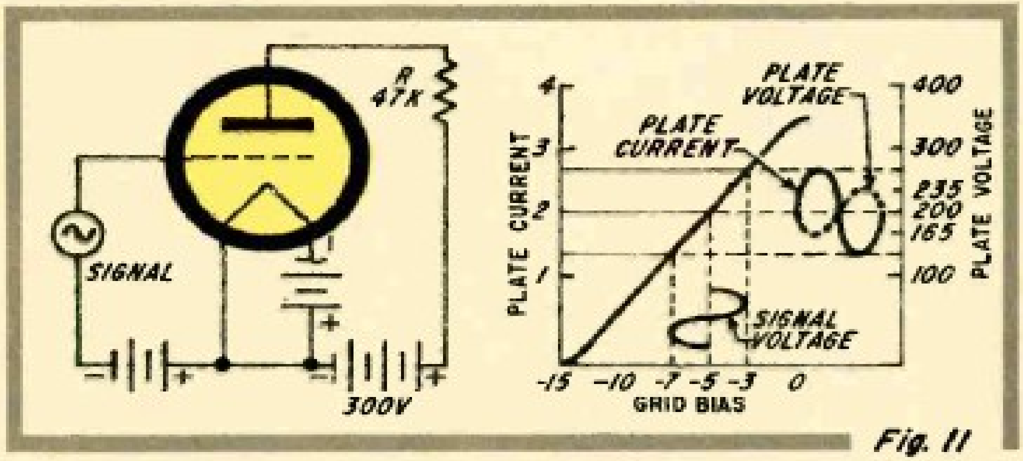


Fig. 11

plate equals 300 minus the voltage drop across R, the plate voltage goes more positive as the grid goes more negative, and *vice versa*.

Most interesting is the *amount* the plate voltage changes compared to the grid voltage change. Using Ohm's Law (Oh, come on now! You know about Ohm's Law!) to compute the voltage lost across R will convince you a change in plate current of only 1 milliampere will cause a plate voltage change of 47 volts. In Fig. 11 a peak-to-peak grid voltage swing of 4 volts causes a peak-to-peak plate-current change of about 1.6 ma and a peak-to-peak plate-voltage change of 70 volts. The output signal is a curve-by-curve mirror-image of the input signal, but it is 17½ times greater!

Our voltage amplifier is no more frequency-conscious than was our diode. If we replace the input and output circuits with tuned circuits, as shown in Fig. 12, it will amplify RF or IF voltages just as readily as it does audio voltages. The tuned circuit in the plate lead takes the place of resistor R, and a varying voltage drop occurs across its high impedance just as happened across the high resistance of R. By transformer action, this voltage is induced in the secondary of the transformer for use by the following stage. Tuned circuits not only deliver high-frequency signals to our amplifier and take them away after they are amplified, but they also serve to select particular frequencies to be amplified and to reject others. Our tube, meanwhile, merrily amplifies anything that is fed into it, silently but efficiently performing a well-nigh invaluable task.

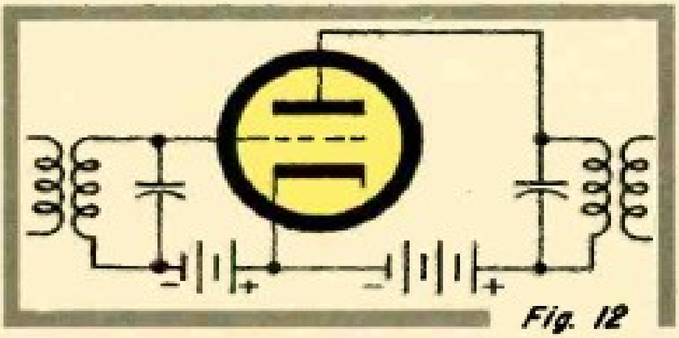


Fig. 12

The Weight Lifter. Voltage amplifiers before and after the detector can take a weak signal and build it up to a peak value of several volts, but such a signal still lacks the power to drive a speaker. Electrical power equals voltage-times-current, and the plate circuits of our voltage amplifiers have only two or three thousandths of an ampere flowing in them. We must use another tube, as shown in Fig. 13, to transform our amplified signal voltage into power.

A power amplifier resembles a voltage amplifier the way Gina Lollobrigida resembles a skinny weight-watcher; there's just lots more of everything. In fact, the power tube is the weight lifter of the tube family. Its plate is larger and heavier; its huskier filament or cathode puts out more electrons; its bias is many volts more negative; its resting plate current is much greater; and the signal applied to its grid has much more swing. The impedance of the transformer primary in the plate circuit usually is a fraction of the resistance of the load resistor of a voltage amplifier, but much heavier current surges through it develop equal or greater voltage drops across it. The combination of high voltage and heavy current in the primary produce several watts of power to drive the speaker connected to the secondary.

More and More Grids. Great as it is, the triode is not a perfect tube for all applications. For one thing, its grid and plate form a small capacitor that sometimes permits power from the output circuit to leak back into the input circuit and cause trouble. A second fault with the triode is that an increase in signal to the grid produces an increase in plate current that causes a droop in plate voltage that tends to decrease plate current. You better read that again—slowly. Now do you understand that any change in plate voltage usurps and opposes some of the grid's rightful control over plate current? When the grid has only partial control, the tube's ability as an amplifier is impaired.

Both of these defects were solved at one stroke by placing another grid in the tube between the control grid and the plate, thus making the tube a *tetrode*. But this new *screen grid* created other problems all its own, which, in turn, were solved by adding still another grid—the *suppressor*,

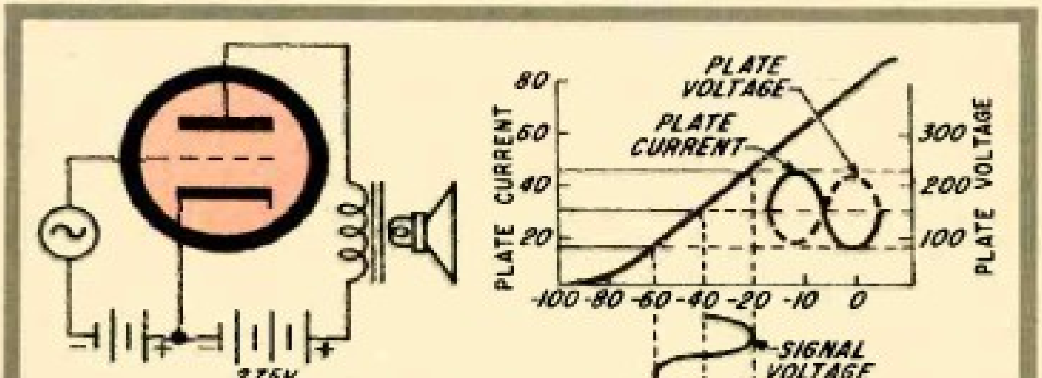


Fig. 13

thus producing a *pentode*. Each of these various types of tubes has its individual characteristics, of course, but all are variants on the simple triode. They just make greater use of some wire-mesh grids, that's all.

DC to AC. Now that we've learned something about how they amplify, let's see what else tubes can do. A very important bit of electronic magic is turning DC to AC with a vacuum-tube *oscillator*.

Think hard about what happens when a charged capacitor is connected across a coil of wire. Electrons from the negatively-charged plate race through the coil toward the positive plate, creating an expanding magnetic field around the coil. As charges on the capacitor plates begin to equalize, the current tries to slow down; but then the collapsing magnetic field drives the electrons on into piling up on the plate that was originally positive. Eventually the crowded electrons start back through the coil, and the whole process is repeated. Electrons keep sloshing back and forth through the coil the way water in a tipped dishpan sloshes back and forth. But each "slosh" of this damped oscillation (no pun intended!) is a little weaker than the previous one—unless carefully timed bits of energy are fed into the circuit to replace the energy losses.

In the case of the water, this energy can take the form of one-per-slosh nudges of the dishpan; but no one can work a switch fast enough to inject a bit of electrical help into each half-cycle of an oscillation rocking back and forth millions of times a second. A tube is fast enough, though, when it is connected to our oscillating circuit as shown in Fig. 14. Any tiny disturbance that makes the grid a bit positive causes plate current to increase and the magnetic field about L2 to expand. Voltage induced into L1 by this field drives the grid more positive, producing more plate current. The self-inflating process stops only when the voltage drop across the impedance of L2 is so great that the reduced plate voltage no longer will support an increase in plate current. At this point, the magnetic field about L2 starts to collapse, reversing the voltage induced in L1, and starting the grid voltage in the negative direction. It keeps going, pushed by the induced voltage from the collapsing field, until plate current is cut off. Then the grid moves in the positive direction, and we are back where we started.

Do you see how cleverly the vacuum tube succeeds in feeding just the right amount of energy into the oscillating circuit at just the right time to keep it going? And do you also see that a vacuum-tube oscillator actually is a special, dog-chasing-his-tail application of a vacuum-tube amplifier? Good! You're thinking while you read.

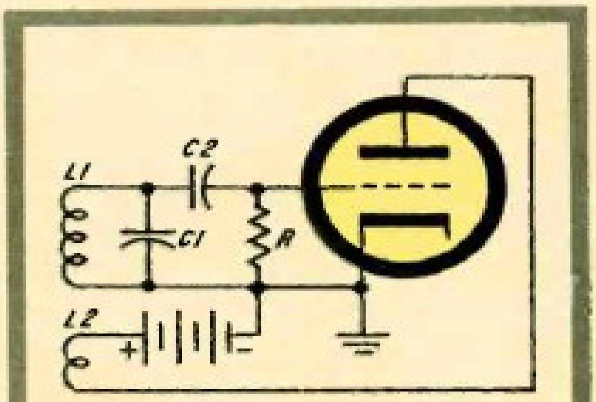


Fig. 14

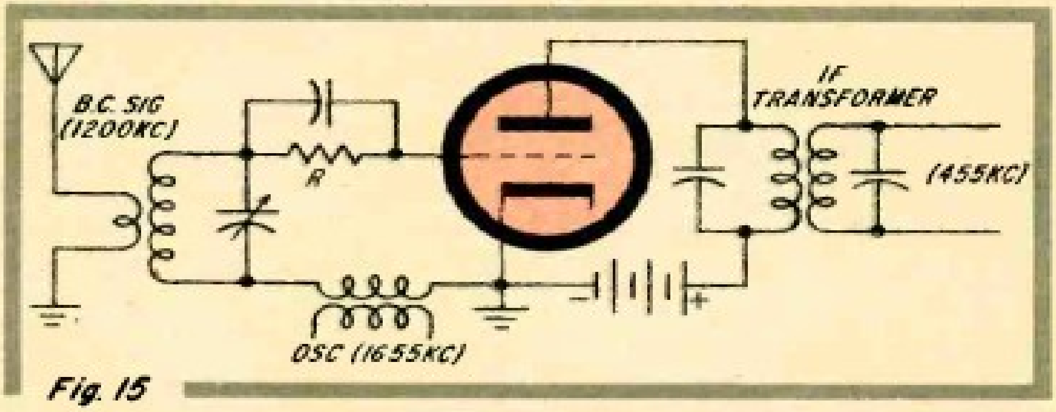


Fig. 15

Now let's talk about the tube that rubs two frequencies together and produces a new one. We call it a mixer, and Fig. 15 is the diagram of a simple circuit. Here, the carrier from a broadcast station (1200 kc) is connected in series with a signal from a local oscillator (1655 kc) between the grid and cathode of the triode. What happens? The 1200-kc carrier modulates the 1655-kc signal to produce a frequency equal to the difference between the two original ones—in this case, 455 kc.

Think first of the grid as the plate of a diode, and you can see that the demodulated signal of 455 kc will appear across the load resistor R, and consequently on the grid of the triode. Since it *is* the grid of a triode, the triode will amplify this 455-kc signal, and it will appear across the primary of the IF transformer tuned to that frequency. The carrier of any broadcast station can be converted to 455 kc simply by parking our local oscillator 455 kc above or below the broadcast frequency and allowing our mixer to extract the difference frequency. That is how the front end of a superheterodyne receiver works.

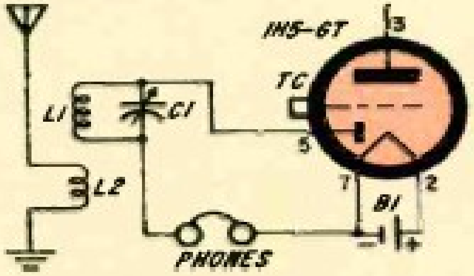
Pictures Yet! The most spectacular of all vacuum tubes probably is the kinescope or picture tube. You certainly already know about this creation, since every TV set uses one. It's a wing-ding of a tube and, by controlling electron flow with a grid, just like most any other tube, it succeeds in painting a picture made up of shaded horizontal lines. What's more, by making minute changes in that picture 30 times a second, it's fully capable of producing the illusion of movement!

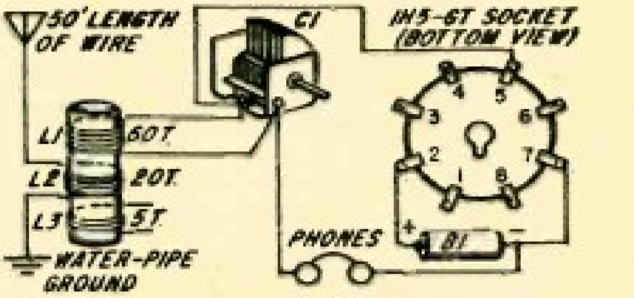
A detailed explanation of a picture-drawing tube would be as hard to follow as a talking dog; so reluctantly we bring down the curtain on the vacuum-tube's one-man show. Many more characters are in his repertoire: the phase inverter, the thyratron—but just listing all the roles takes up too much space. You're not chicken, though, or you would not have held on this long; so the following list of books is appended to help you keep right on grappling with the protean vacuum tube and wringing answers out of him. Don't forget: he *has* the answers to all your electronic problems!

Basic Radio Course, by John T. Frye. Gernsback, $5.75
Electronic Technology Series. Rider
Radio & TV Circuitry and Operation, by A. A. Ghirardi.
Holt, Rinehart & Winston, $9
Radio Amateur's Handbook. American Radio Relay League, $3.50
RCA Receiving Tube Manual. Radio Corporation of America, $1

3 EXPERIMENTS with vacuum tubes

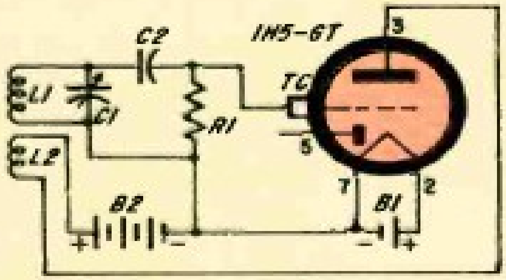
Diode Detector

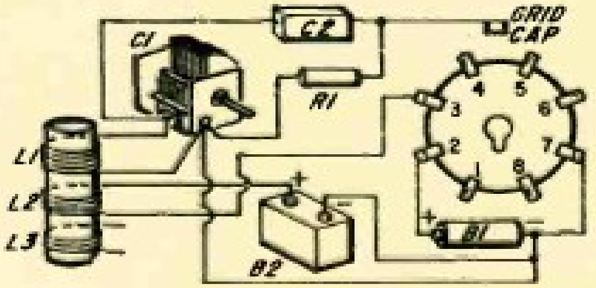




Circuit is wired in breadboard fashion and will receive local stations. Knob can be added to C1.

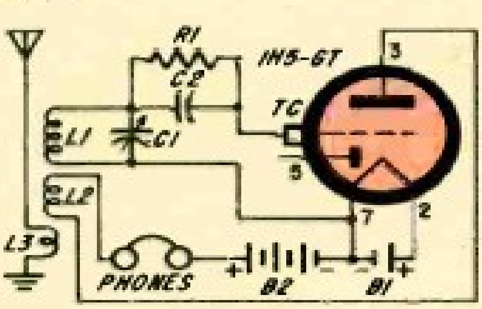
Oscillator

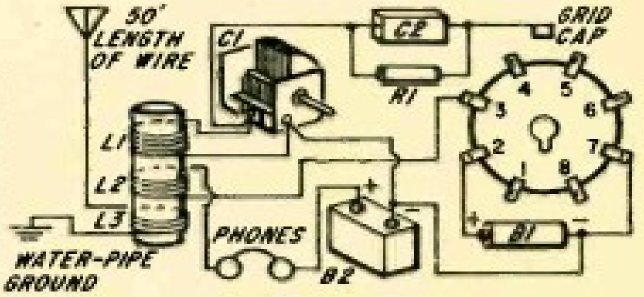




Armstrong oscillator produces unmodulated RF signal which can be picked up on nearby AM set.

Mixer





Broadcast signal induced into oscillator circuit forms mixer. Beat frequency is heard in phones.

PARTS LIST

B1—1.5-volt battery (Type D flashlight cell)
B2—67.5-volt battery (Burgess XX45 or equivalent)
C1—Variable capacitor with maximum capacity of 250-mmf or greater
C2—0.005-mf mica capacitor
L1, L2, L3—60, 20 and 5 turns respectively of #22 enameled wire closewound on 3-inch dia x 5-inch long cardboard tube (¼-inch between windings)
Phones—Magnetic earphones with impedance of 500 ohms or greater
R1—220,000-ohm, ½-watt resistor
V1—1H5-GT tube
Misc.—Octal socket, grid cap, wire, solder, etc.