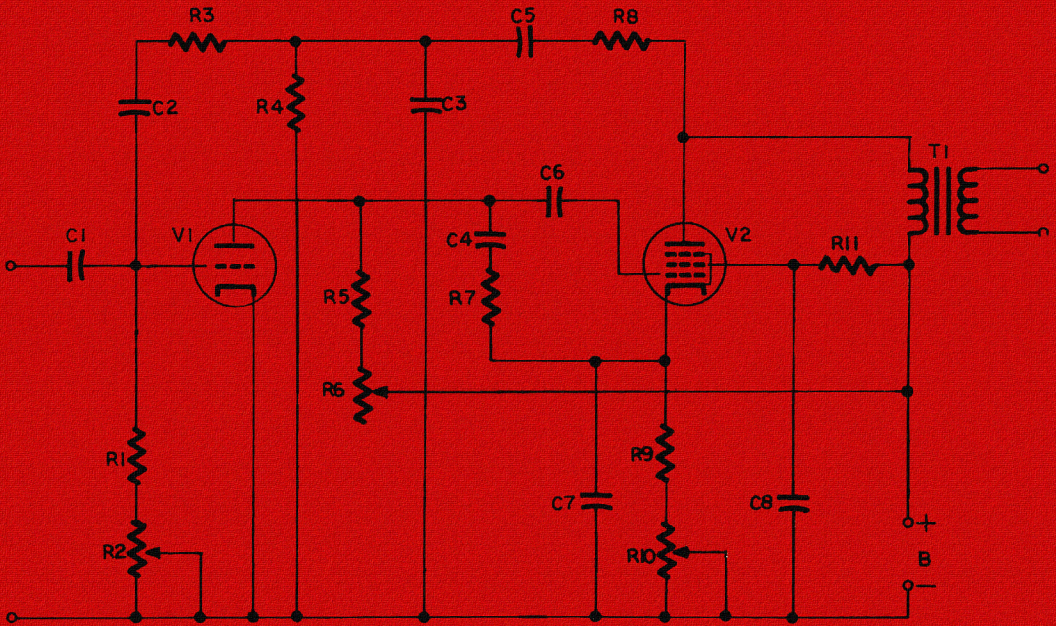Here, in this fact-filled guidebook, are step-by-step explanations of how to read schematic diagrams for more than 150 commonly-used electronic circuits.

COMPLETE GUIDE TO READING SCHEMATIC DIAGRAMS

by John Douglas-Young

Covering all types of electronic equipment, from industrial to home entertainment, this book shows you the function of every circuit, the purpose of every part at a glance. Written in clear, easy-to-understand language, it takes the work out of reading schematics, and helps to identify quickly a wide variety of circuits.

COMPLETE GUIDE
TO READING
SCHEMATIC
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JOHN DOUGLAS-YOUNG

What You Will Learn
from This Book

Complete Guide to Reading Schematic Diagrams takes the toil out of reading schematics. With it you'll find your way through even the most formidable with the ease of reading a road map. You'll be able to make the most of these "electrical pictures," know the function of every circuit, the purpose of every part, at a glance.

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Each chapter covers one of the main groups of circuits. First, you get the basic circuit, with the distinctive features emphasized to enable you to identify it quickly, so you'll know right away whether it's an amplifier, an oscillator, or something else. You'll then get a brief description of the circuit, which will help you decide whether it's the one you need to investigate further.

If it is, you'll be shown how to break this circuit down into its sub-circuits, with an explanation of each component, what its function is, and how a defect in it might affect the operation of the whole.

To help you in your circuit analysis there is also a comprehensive Appendix, with abundant supplementary data. Here you'll find charts, conversion tables, equations, definitions—everything you'll need to get

the most out of each chapter—placed in an easy ready-reference section for convenience in looking things up and to keep the main text uncluttered and simple.

This new guidebook will help you become so at home with schematic diagrams that you'll be able to use them with speed and certainty, whether you want to understand fully the operation of a piece of equipment or one of its circuits, or whether you want to diagnose troubles, locate faulty components and make faster repairs.

Either way, this means more money for you, faster results and greater satisfaction from a job well done. In the rapidly changing world of electronics it's the man who really knows and understands schematic diagrams who stands the best chance of success.

John Douglas-Young

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1

SCHEMATIC DIAGRAMS

The Importance of a Schematic Diagram

A SCHEMATIC DIAGRAM shows the electrical connections of an electronic device, using symbols and straight lines to represent the parts and their connections.

Electronic Symbols

An electronic symbol represents the *function* of a part in a circuit, not its outward appearance. Table I gives a list of electronic symbols in general use, and the reference letters of the principal types.

Reference Designations

As shown in Table I, the principal types of symbols have reference letters. In a schematic all the components with the same reference letter are numbered in sequence from left to right, and downwards where two or more are equidistant from the left-hand margin, for ease of correlation with descriptions, instructions and parts lists. Symbols which represent different sections of a multiple component, such as a dual-triode vacuum tube, or a ganged control in which one knob moves two or more decks or sections, are given the same number, but the individual sections are identified by letter suffixes. For example,

17

TABLE I SYMBOLS
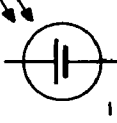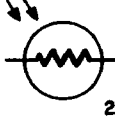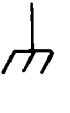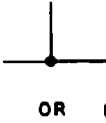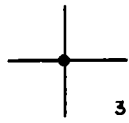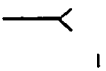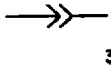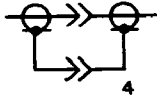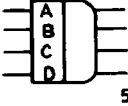
ANTENNA (ANT)
1. General.
2. Loop.
3. Dipole.

BATTERY (BT) (B)
1. Single cell.
2. Multicell.

CAPACITATOR (C)
1. Fixed.   (Curved element indicates lower
2. Variable.   potential, out-side or moving electrode.)

CELL, PHOTO-
1. Voltaic.
2. Resistive.

CIRCUIT-BREAKER (CB)

CIRCUIT RETURN (E)
1. Earth ground.
2. Chassis ground.

CONNECTION
1. Two conductors connected.
2. Two conductors crossing, but not connected.
3. Two conductors crossing and connected.

CONNECTOR
1. Female (J).
2. Male (P).
3. Male and female mated.
4. Coaxial connection.
5. Four-conductor connector.
6. Power-line receptacle (2-pin).
7. Power plug (2-pin).
8. Terminal.

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TABLE I   SYMBOLS (continued)

FUSE (F)

Both forms have same meaning.

HEADSET (HT)

1.   Both ears.
2.   One ear.

INDUCTOR (L)

1, 2.   indicate a coil.
3.   Coil with magnetic core.
4.   Tapped inductor.
5, 6.   Adjustable inductors.

KEY, telegraph (S).

LAMP (P, DS)

1.   Ballast.
2.   Incandescent.
3.   AC Glow (neon).

METER (M):   inscribed letter
               indicates type.

1.   MICROPHONE.
2.   LOUDSPEAKER (LS).

PICKUP (PU).

PIEZOELECTRIC CRYSTAL (X, Y).

TABLE 1   SYMBOLS (continued)

RECTIFIER (solid-state) (D, CR). Electron flow is opposite to direction of arrow.
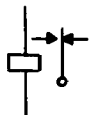
RELAY (K).

RESISTOR (R)

1. Simple resistor.
2. Tapped resistor.
3. Variable resistor.

SHIELDING (drawn around part that is shielded, or between parts shielded from each other.)
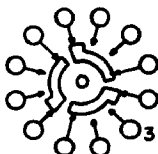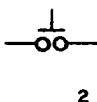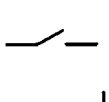
SWITCH (S)

1. Simple ON-OFF.
2. Push-button.
3. Rotary wafer.
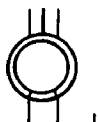
SYNCHRO (B)

1. Transmitter or receiver.
2. Differential.
    (See Chapter 11 for details)

THERMISTOR (RT).
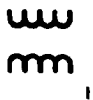
TRANSFORMER (T)

1. Air core.
2. Magnetic core.
3. Magnetic core with inner shield grounded to case.
4. Permeability tuned.
5. Tapped.
6. Autotransformer (adjustable).

TABLE I   SYMBOLS (continued)

TRANSISTOR (Q)

1.	PNP.	(Circles may
2.	NPN.	be omitted.)
3.	UJT.	
4.	MOS/FET.	

TUNNEL DIODE (D)

VACUUM TUBE (V)

1. Triode.
2. Pentode.
3. Dual triode in one envelope.
4. Gas regulator.
5. Thyratron.
6. Ignitron.
7. Picture tube.
8. Cathode-ray tube (CRT).
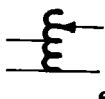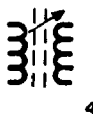
ZENER DIODE (D).
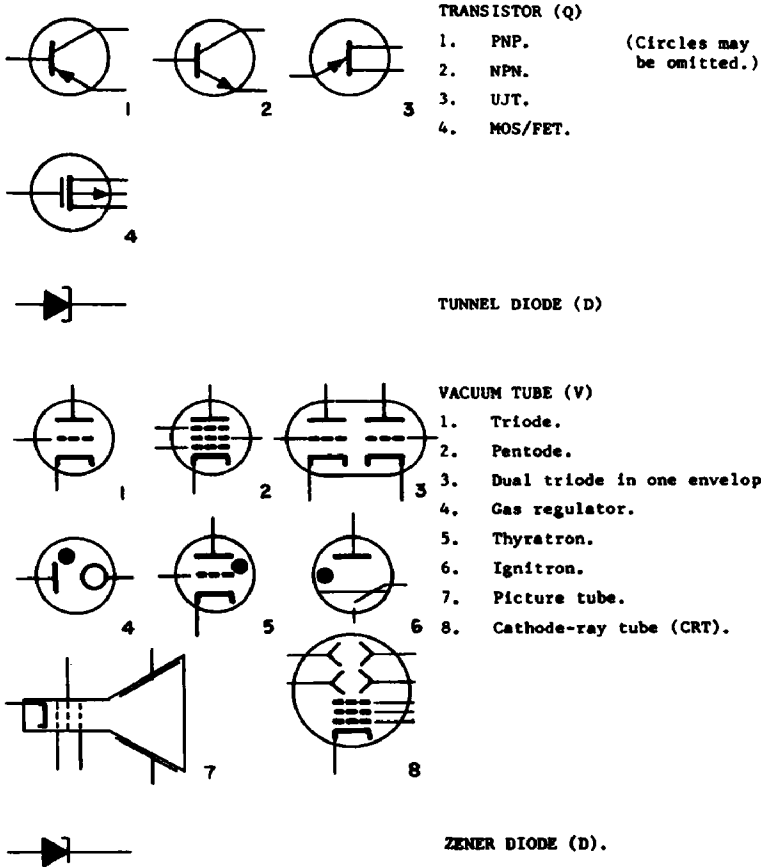
C2A, C2B and C2C would designate three sections of a ganged variable capacitor (see Figures 2.26, 5.10, 5.11 and 5.14 for examples).

Where a schematic diagram is broken down into subordinate sections because it is too large or complex to be shown on one sheet of paper, it is customary to use three-figure number groups starting with 1, 2 and so on, for each section (like the numbering of rooms by floors in a hotel). For example, C102, R115 and Q167 will all be in the first section, and R455, C407 and Q410 will all be in the fourth.

Schematic Analysis

Schematic analysis consists in separating the overall electrical picture into its parts, so as to determine their nature, function and relationship. It is a process like anatomy. The following chapters will tell you about the "organs" found in schematic "bodies."

Individual Circuits

These "organs" are individual circuits. Taken separately, you'll find each is easy to understand and recognize, because all circuits are laid out in a conventional way. The signal input is almost invariably from the left, the output to the right. This horizontal flow takes place along two parallel paths (see Figure 1.3). The upper path is the "high" side of the circuit, the lower the "low." The low side is the return path, and is usually considered to be at zero or ground potential, even though it may not be connected to a real earth ground at all.

In some diagrams the return path or low side of the circuit is emphasized with a heavier line (as in Figure 1.1). But in many others it is left to the imagination, and connections to it are indicated by use of the circuit return, or ground symbol (as in Fig. 1.2). This is understandably necessary in complicated schematics, especially in small-scale reproductions. In this book, however, we shall stick to showing the complete return path, as we are dealing mostly with individual circuits.
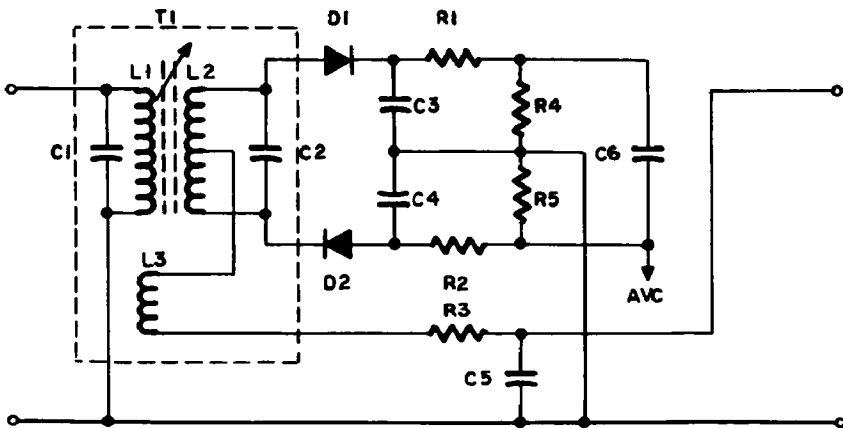
Figure 1.1   Typical Circuit Schematic
(Parts Values Omitted)

Active and Passive Elements

Circuit elements are either active or passive. Passive elements are those which do not require an external source of power in order to function. They include resistors, capacitors, inductors and the like.

R I
1K

CIA
40

CIB
40
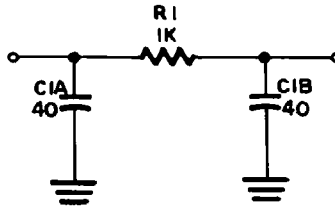
Figure 1.2   Pi Filter
(Parts Values Included)

DC POWER

HIGH SIDE | ACTIVE ELEMENT

SIGNAL INPUT

PASSIVE ELEMENTS

POWER SOURCE

SIGNAL OUTPUT

LOW SIDE, ZERO POTENTIAL, GROUND RETURN
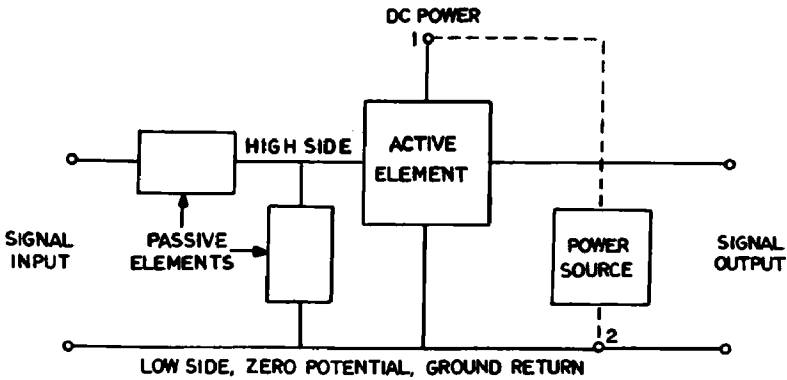
Figure 1.3   Circuit Conventions

Active elements are vacuum tubes, transistors and other devices that use external power, which they introduce into the circuit to modify an existing signal or to generate a new one. In this book diodes are classified as active elements also, although in many respects they seem to be more like passive elements.

External Power

When an active element is included in a circuit the external power is generally shown as entering and leaving in a vertical direction, perpendicular to the signal flow. Since this power is direct current (DC) its path is also characterized by the absence of capacitors (which block DC).

In Figure 1.3 the power source is drawn as if it were part of the individual circuit, but the dashed lines indicate that this is not usually the case. In the overall schematic of a complex piece of electronic

equipment, such as a television set, where many circuits share one power source, the power supply would be shown separately, and the external connections to it (1 and 2 in Figure 1.3) might even be omitted.

Circuit Identification

The majority of circuits consist of a small number of passive elements built around an active element. The type of active element gives you your first hint as to the nature of the circuit. A tube or transistor has a type number, apart from the reference number, and if you look it up in a tube or transistor manual you'll often see what type of circuit it is likely to be used in. Some tubes, for instance, are only used in certain types of circuit. A 12BE6, which is a pentagrid converter, is only used in a converter circuit, so you know what type of circuit it is without looking further. But this is like looking up words in the dictionary. The purpose of this book is to show you how to read schematics without having to look things up.

Circuit-Finder Table

Until you have had some practice, however, it will help to use Table II as a guide in identifying circuits. This table is provided to steer you to the right part of the book, where you'll find specimen circuit diagrams and descriptions which you can compare with the circuit you're interested in to confirm your identification and find out how it works, and how to diagnose troubles in it if necessary.

How to Use the Circuit Finder

Examine your circuit, and ask yourself the following questions:

(1) Is the active element a vacuum tube or semiconductor?
(2) Is it a diode, or other type?
(3) Is it single, paired, or in a set of four?
(4) What principal passive elements or special connections are associated with it?

Then find in the first four columns of Table II the right combination of answers to these questions. In the column at the right you'll see where to look in the book for further details. For example, suppose you're looking at the circuit shown in Figure 1.1. The first thing

you notice is that there are two semiconductor diodes in the circuit. Then you'll note the centertapped transformer at the left, with another winding connected to the centertap. In Table II look down the semiconductor column until you come to Diodes (2). Then look in the Significant Passive Elements column, where you'll find your transformer listed opposite Diodes (2). In the right-hand column you're told the circuit is an FM Demod. When you turn to the reference given in the last column you find it can be either a Discriminator or a Ratio Detector, depending upon which way the diodes are facing. These are facing in opposite directions, so its a Ratio Detector.

TABLE II — CIRCUIT FINDER

Active Elements		Significant Passive Elements				Probable Type of Circuit	Chapter
Vacuum Tube Type	Semiconductor Type	Qty	Input Circuit	Output Circuit	DC Circuit		
Diode	Diode	1	IF transformer			Demodulator	6
Diode	Diode	1	Line cord, fuse, etc.	Pi-filter*		Power Supply	7
Diodes	Diodes	2	Power transformer, line cord, etc.	Pi-filter*		Power Supply	7
Diodes	Diodes	2	Line cord, fuse, etc.	Pi-filter*		Power Supply	7
Diodes	Diodes	2	IF transformer with extra winding			FM Demod.	6
Diodes	Diodes	3	Line cord, fuse, etc.	Pi-filter*		Power Supply	7
Diodes	Diodes	4	Power transformer, line cord, etc.	Pi-filter*		Power Supply	7
Triode	Transistor	1	RC or DC coupled	RC or DC coupled	Load resistor	Audio V. Amp.	2
Triode	Transistor	1	Antenna, tuned circuit	Tuned circuit		RF Amp.	2
Triodes	Transistor	2	Antenna, tuned circuit	Tuned circuit,	DC path through triodes in series	RF Amp. (Cascode)	2
Triode	Transistor	1	Grid or base grounded thru capacitor			Grounded-grid or -base Amp.	2
Triode	Transistor	1	Tuned circuit	Tuned circuit	Ext. bias	Linear RF Amp.	3
Triode(s)	Transistor(s)	1-4	Tuned circuit Neutralizing capacitor	Tuned circuit, Antenna, neutralizing capacitor	Ext. bias	RF Pwr. Amp.	3

* Pi filters are usually drawn as in Figure 1.2, although the resistor R1 is often replaced by a choke (see "coil with magnetic core" under Inductors in Table I). The name comes from the resemblance of the circuit to the Greek letter π. See chapter 7 for further examples.

TABLE II — CIRCUIT FINDER (cont.)

Active Elements		Significant Passive Elements				Probable Type of Circuit	Chapter
Vacuum Tube Type	Semiconductor Type	Qty	Input Circuit	Output Circuit	DC Circuit		
Triode	Transistor	1	Tuned circuit	Supersonic Oscillator		Detector	6
Triode	Transistor	1	Tuned circuit or resonant circuit or crystal	Feedback inductively coupled to input, or crystal		Oscillator	4
Triode	Transistor	1	Transformer and large capacitor			Blocking Oscillator	4
Triodes	Transistors	2	Each plate or collector is coupled to the opposite grid or base			Multivibrator Flip-flop	4 12
Pentode	Transistor	1	RC or DC coupled	RC or DC coupled	Load resistor	Audio V. Amp.	2
Pentode	Transistor	1	RC coupled	Peaking coils	Load resistor	Video Amp.	2
Pentode(s)	Transistor(s)	1–4		Output transformer		Audio Power Amp.	3
	Transistors	2		Speaker, but no transformer		Audio Power Amp.	3
Pentode	Transistor	1	Antenna, tuned circuit	Tuned circuit, IF transformer		RF Amp. or Mixer	2 5
Pentode	Transistor	1	IF transformer	IF transformer		IF Amp.	2
Pentode	Transistor	1	Tuned circuit	Tuned circuit	Ext. bias	Linear RF Amp.	3
Pentode(s)	Transistor(s)	1–4	Tuned circuit	Tuned circuit, Antenna	Ext. bias	RF Pwr. Amp.	3
Pentode	Transistor	1	Grid-leak, resonant circuit	Resonant circuit with feedback to grid resonant circuit		Oscillator	4
Pentode		1	RC coupled	Resonant circuit connected to third grid		FM Demod.	6

2

VOLTAGE
AMPLIFIERS

A VOLTAGE AMPLIFIER is a means of using the current from a power supply or battery to produce a stronger replica of a weaker original signal. The weak signal is able to control the flow of current from the power source by means of a vacuum tube or transistor. The circuit, therefore, consists of three subcircuits: one for direct current from the power source, one for the weaker input signal, and one for the more powerful output signal.

In a voltage amplifier the emphasis is on the *voltage* of the output signal. Since current flows at all times this type of amplifier wastes power and its efficiency is low, but its output is free of distortion because the excursions of the input signal remain within the distortion-free limits of the tube or transistor.

AUDIO VOLTAGE AMPLIFIERS

Figure 2.1 shows an audio voltage amplifier with a vacuum tube. Figure 2.2 shows the same circuit with a transistor. Ignore for the moment the extra resistor R1 in Figure 2.2. You'll see the reason for it later.

Distinguishing Features

These circuits clearly fit the description of an amplifier given above. In Figure 2.1 you see a circuit in which a weaker signal input is applied between the grid and cathode of a tube in order to control the flow of current from the battery so as to produce a stronger signal in the output circuit connected between the plate and cathode. Because the cathode is common to both input and output this is a common-cathode amplifier—more often called a *grounded-cathode* amplifier.

Similarly, in Figure 2.2 the emitter of the transistor is common to both input and output, so this is a *common-emitter* amplifier.

Tubes and transistors can be connected with either of their other two elements common (or grounded), but the grounded-cathode and common-emitter circuits are the most used because they give the highest gain.

Amplifiers must be *voltage* amplifiers or *current* amplifiers. The latter, which are more often called power amplifiers, must be able to pass a fairly heavy current. The presence of *load resistors* (R2 in Figure 2.1, R3 in Figure 2.2), which always have a resistance of several kilohms, will not allow a large current output, thus eliminating the possibility that these are power amplifiers. They are, therefore, *voltage amplifiers.*

The absence of any inductors in these circuits shows you that they are handling *audio* frequencies. AF circuits sometimes have iron-core transformers or chokes, but designers today generally avoid them
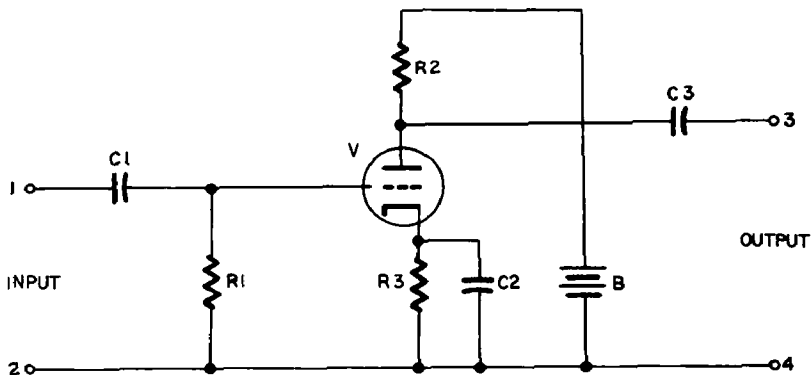
Figure 2.1   Audio Voltage Amplifier with Vacuum Tube
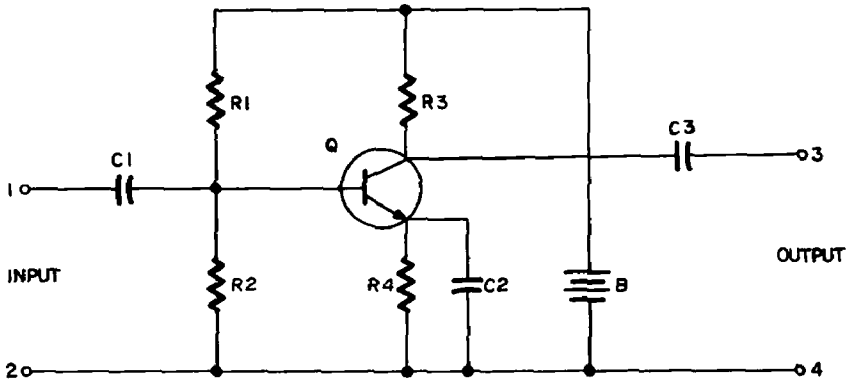
Figure 2.2   Audio Voltage Amplifier with Transistor

wherever possible, to lower costs and to obtain a more even response to audio frequencies. Since iron-core inductors are the only type of inductor used at audio frequencies, the presence of any other type would indicate the circuit is used for higher frequencies.

Uses

Audio voltage amplifiers are used in radio and television, hi-fi, tape recorders, phonographs, public address systems and the like, to build up weak signals to the point where they can be used to control power amplifiers. For this reason you wouldn't expect to find an audio voltage amplifier in the final stage of a radio or stereo amplifier, but in the preceding stage or stages handling audio frequencies. Thus the position of the amplifier in the overall schematic is an additional way in which you can tell what type it is.

Detailed Analysis

DC Subcircuit: In Figure 2.3 electron flow is from B— through R3, V and R2, and back to B+. Although the power source is shown as a battery it is in practice more likely to be one of the electronic power supplies discussed in chapter 7, as tube power requirements are greater than those of transistors. You'll notice that this diagram does not show the tube's filament circuit. It is standard procedure to show this in the power supply circuit, as in the examples given in chapter 7.

As far as DC is concerned R1 serves only to tie the grid to B— (zero
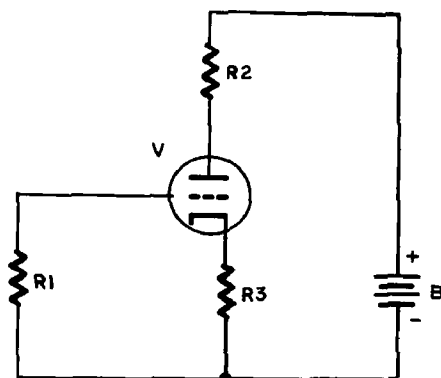
Figure 2.3   Vacuum-Tube DC Circuit

potential), and to serve as a leakage path for any electrons gathering on the grid. The current through the resistor is negligible, therefore no voltage drop takes place across it.

In the main current path through R3 and R2 you can visualize V as a variable resistor, its resistance varying with the signal voltage on the grid. When no signal is applied to the grid a steady current will flow. The values of R3 and R2 are chosen to give the proper operating voltages at the cathode and plate. A positive voltage on the cathode is provided by the voltage drop across R3, making the cathode positive with respect to the grid, which is the same as saying that the grid is negative with respect to the cathode. The value of R3 is chosen so that the voltage across it biases the grid for operation approximately in the center of the linear portion of the tube's characteristic curve (Class A operation: see Appendix).

The value of R2 depends upon the resistance of V (its plate resistance). When the resistance of V varies, the current flowing through it varies, and consequently the voltage flowing through R2. The value of R2 must be such that maximum voltage variations can be obtained across it, but if it is made too large there will be too great a voltage drop for proper operation of the tube. For a triode the maximum value of R2 should not exceed three times the plate resistance. (See further on for notes on the use of pentode tubes as voltage amplifiers.)

Similarly in Figure 2.4 electron flow is from B— through R4, Q and R3, and back to B+. However, the bias on the base is established by the voltage drop across the emitter-base junction in the transistor instead of by the voltage drop across R4, as was the case in the tube
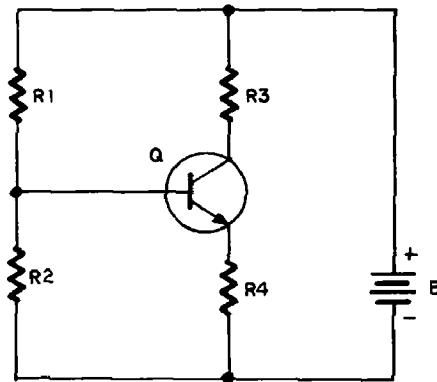
Figure 2.4   Transistor DC Circuit

circuit. In the tube a steady plate current flows when there is no signal on the grid. In the transistor a steady emitter-base current flows under *the same conditions, which in turn* permits a steady (but larger) current to flow from emitter to collector. In the NPN transistor shown this will be electron current; in a PNP transistor it would be hole current. (See more about transistors in the Appendix.)

The purpose of R4 is to stabilize the emitter-base current. Transis*tors are sensitive to temperature variations. If the temperature rises* the emitter-base resistance decreases, so that the current increases. This, in turn, allows the emitter-collector current to increase. As the current increases it heats the junctions further, so their resistance decreases further, and this situation eventually results in the destruction of the transistor if steps are not taken to prevent it.

The voltage drop across the emitter-base junction will be about .2 volt for a germanium transistor, and about .7 volt for a silicon transistor. If the current flowing through R4 results in a voltage drop of 1 volt across it, the emitter will be at a potential of +1 volt. In a germanium transistor, therefore, the base voltage will be +1.2 volts. This gives the correct forward bias across the junction for Class A operation (see Appendix).

If the emitter-base current increases due to increased temperature the current through R4 increases, with a consequent rise in voltage on the emitter. But the voltage on the base is still held at +1.2 volts by the voltage divider formed by R1 and R2. These resistors' values *are chosen so that the resistance of R1 will be nine times the resistance*

of R2. If the battery voltage is 12 volts, nine-tenths of it will be dropped across R1 and one-tenth across R2. One-tenth of 12 is 1.2, of course, so the voltage at the junction of R1 and R2 must be +1.2 volts. Since this voltage is also the base voltage, and remains at this figure while the emitter voltage rises (or tends to), you can see that the forward bias across the junction actually decreases. This decreases the current across the junction, and counteracts the effect of the temperature rise.

As in the case of the tube, the transistor can be visualized as a variable resistor in series with R4 and R3, its resistance varying with the signal voltage on the base. When no signal is applied a steady current will flow. However, when the resistance of Q varies, the current flowing through it varies, and consequently the current flowing through R3. The value of R3 must be such that maximum voltage variations can be obtained across it, but at the same time it must also provide for the proper operating voltage for the collector of the transistor, and, as in the case of the tube circuit, the actual value has to be a compromise between these two requirements.

This circuit uses an NPN transistor. A PNP would work just as well with the battery polarity reversed.

AC Input Subcircuit (Tube): Figure 2.5 shows the AC input sub-circuit for the tube. As C1 and R1 are the means of coupling it to the previous stage, it is *RC-coupled*. C1 also prevents DC from reaching the grid of V from the previous stage. The values of C1 and R1 are chosen so that C1 presents a low reactance to signals in the audio range, and R1 has as high a value as possible without preventing it from acting as a leakage path for electrons collected by the grid of the tube.

Current cannot flow between the grid and the cathode of the tube, so the signal voltage divides between the low reactance of C1 and the
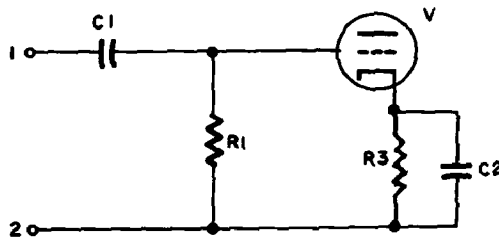
Figure 2.5   Vacuum-Tube Input Circuit

high resistance of R1. Nearly all of it appears across R1, and consequently as large a portion of the available signal as possible is applied between the grid and cathode of V.

The value of C2 is such that it offers very low reactance to audio frequencies. Its purpose is to bypass the signal frequencies around R3, so it is called a *bypass capacitor*. In this way the cathode is at *signal ground* for AC, at the same time as it is *above ground* for DC.

Output AC Subcircuit (Tube): Figure 2.6 shows the output AC subcircuit. The signal voltage on the grid is alternating between positive and negative at various audio frequencies. The grid is biased to be at a negative voltage which places the tube's operating point in the middle of the linear portion of its characteristic curve. When the signal swings in a positive direction this negative bias is reduced, so the tube resistance is decreased and it conducts more current. When the signal swings in a negative direction this negative bias is increased, so the tube resistance is increased and it conducts less current.

When the tube conducts more, more current flows through R2, and therefore a greater voltage is dropped across it. This makes the plate voltage less. When the tube conducts less, less current flows through R2, so the plate voltage rises. In short, a positive swing of the grid voltage results in a negative swing of the plate voltage, and vice versa. The gain of an audio voltage amplifier such as this should be close to 100, which means that the amplitude of the voltage variations at the plate is 100 times that on the grid. Remember that although they are a faithful replica, they are 180° out of phase with the grid signal voltages.

C3 can pass AC but not DC, therefore it passes the *variations* of voltage on the plate of the tube, because they are varying at audio frequencies, but it blocks the DC portion which is not varying. Since
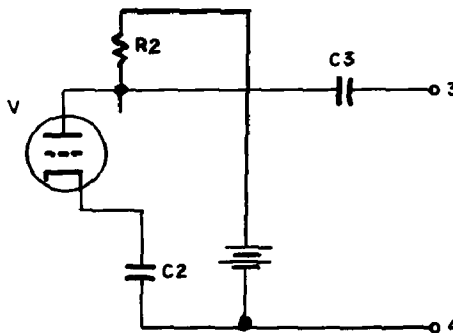
Figure 2.6   Vacuum-Tube Output Circuit
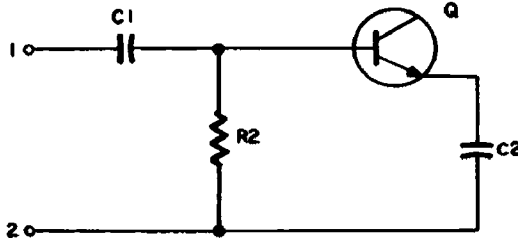
Figure 2.7   Transistor Input Circuit

C3 is coupling the output signal into the next stage the same consid-
erations affect the choice of its value as applied to C1.

AC Input Subcircuit (Transistor): Figure 2.7 shows the AC input
subcircuit for the transistor. The remarks above concerning the tube
input circuit apply equally here. However, in a transistor circuit you
will find that C1 has a higher value, while R2 has a lower value.
(Sometimes it is omitted altogether.) This is because the resistance
between the emitter and the base is low enough to allow an appreci-
able current to flow, so that the transistor has a low input impedance.
To avoid dropping an excessive amount of the signal voltage across
C1 its value has to be such that it offers much less reactance to the
signal frequency than was the case with the tube, where the grid re-
sistor had a very high value.

Output AC Subcircuit (Transistor): In the same manner as in the
tube circuit, the signal voltage on the base of the transistor in Figure
2.8 is alternating between positive and negative, resulting in variations
in the voltage on the collector which reflect those on the base but are
180° out of phase with them. R3 is the load resistor across which the
output signal voltage is developed.
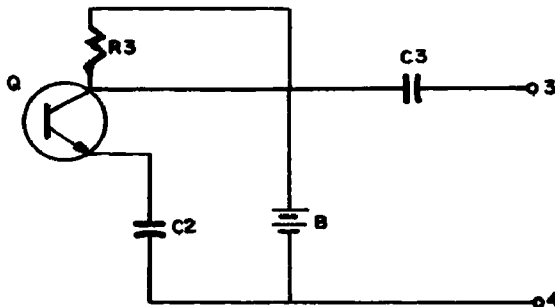
Figure 2.8   Transistor Output Circuit

The gain of an audio voltage amplifier such as this should be between 50 and 100.

Circuit Variations

Although the audio voltage amplifiers just discussed are typical, you are bound to meet variations in them, though not such as to make identification difficult. For example, a pentode tube could be used in place of the triode, as in the example in Figure 2.12; or the amplifier may be DC-coupled instead of RC-coupled, as in the example in Figure 2.25.

Hi-fi amplifiers usually require additional low-frequency compensation. A low-frequency limit of 100 hertz is adequate for AM radio, but a good hi-fi amplifier is expected to handle frequencies down to 20 hertz or lower, which introduces problems with the cathode-bypass capacitor.

In microelectronics incredibly small circuits are "etched" on substrates of silicon or sapphire. On postage-stamp size "chips" hundreds of amplifiers may be formed, each having a complete circuit similar to that in Figure 2.9, which shows a typical MOS/FET amplifier. The operation of this circuit is identical to that of the triode tube already discussed. (See the Appendix for a brief explanation of the operation of a MOS/FET.)

Tone controls are often found in audio voltage amplifier circuits. The reactance of a capacitor varies with its capacitance and with the frequency of the AC passing through it. This makes it possible to design circuits which can attenuate some frequencies without attenuating others.
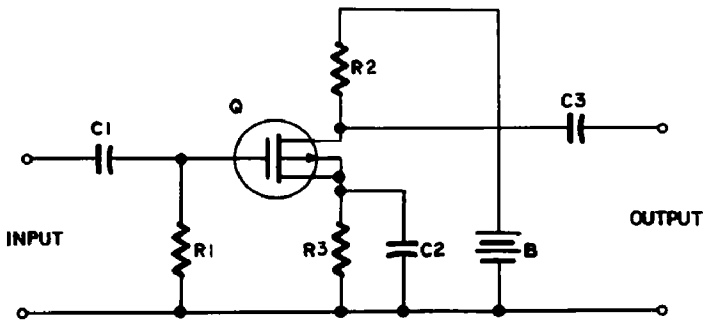
Figure 2.9   Audio Voltage Amplifier with MOS/FET
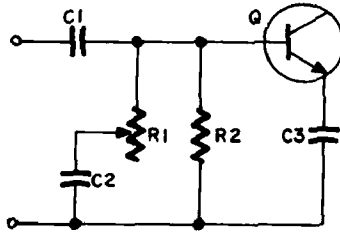
Figure 2.10   Bass Tone Control

Bass Tone Control: In Figure 2.10 the input to an audio voltage amplifier is shown with the addition of a variable resistor R1 and capacitor C2. If the slider of the variable resistor is at the upper end of R1 all the signal voltage applied across R2 will be shunted by C2. The value of C2 is chosen so that it offers little reactance to higher frequencies. Consequently the higher frequencies pass readily through C2, and their voltage across R2 is greatly reduced. The lower frequencies, meeting more reactance, are attenuated less, and the lowest not at all. As a result, the bass or low-frequency end of the audio voltage spectrum becomes predominant. As the slider of the variable resistor is moved downwards, resistance in series with C2 increases, reducing the shunting effect across R2, so that the higher frequencies are attenuated less.

Treble Tone Control: In Figure 2.11 capacitors C2 and C3 have been added between C1 and R2, and a variable resistor R1 connected in parallel with them. The reactance of C2 is very great to lower frequencies, but becomes increasingly less to higher frequencies. When R1's slider is all the way to the right C3 is shorted out, but C2 is shunted by R1, and offers high reactance to all lower frequencies. However, if the slider is moved all the way to the left, C2 is shunted and all frequencies bypass it, and pass through C3 (which has a much
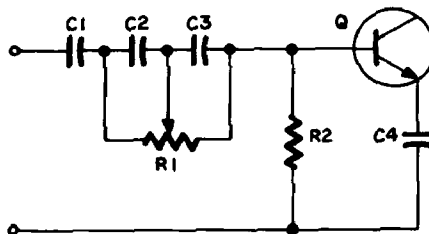
Figure 2.11   Treble Tone Control

higher value) without attenuation. Intermediate positions of the slider give proportionate attenuation to lower frequencies.

We have analyzed this audio voltage amplifier circuit in greater detail than we shall analyze most of the other circuits in this book. This is such a basic circuit that most of its features will be found over and over again in other circuits, so that it will not be necessary to repeat the explanations given here. Instead, we shall continually refer to this section.

VIDEO AMPLIFIER

Video amplifiers are similar to audio voltage amplifiers except for additional features required to broaden the frequency response. Fig-
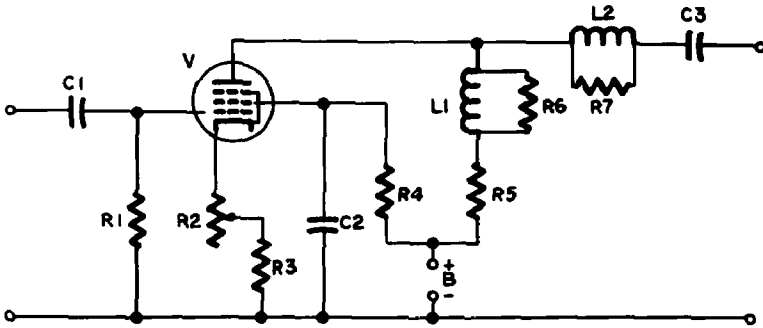
Figure 2.12   Video Amplifier with Vacuum Tube
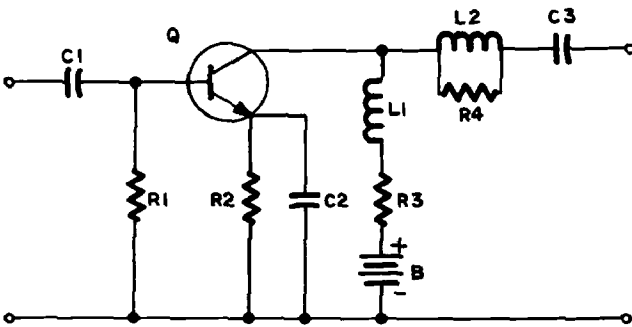
Figure 2.13   Video Amplifier with Transistor

ure 2.12 shows a typical video amplifier using a vacuum tube. Figure 2.13 shows another with a transistor.

Distinguishing Features

Video amplifier circuits are *grounded-cathode* or *common-emitter* circuits (to obtain maximum gain), and have *load resistors* (to obtain a voltage output) in the same way as audio voltage amplifiers.

However, they are different from circuits handling only audio frequencies since they require *peaking coils* to extend their high frequency response. L1 and L2 are peaking coils, which with their associated resistors are characteristic identifiers for video amplifier circuits.

Uses

Video amplifiers are voltage amplifiers which have to amplify the demodulated television signal so it can drive the picture tube. They are, therefore, found in television sets between the picture tube and the video detector. Whereas the maximum frequency handled by audio voltage amplifiers does not usually exceed 30 kilohertz, the video frequency range extends to 4 megahertz.

Detailed Analysis

DC Subcircuits: In Figure 2.14 the electron flow is from B— through R3, R2, V and back to B+ through the parallel paths of R4 and L1–R5. The main difference between this DC circuit and the triode circuit is the additional path through R4, which drops the supply voltage to the proper value for the screen grid of the pentode.
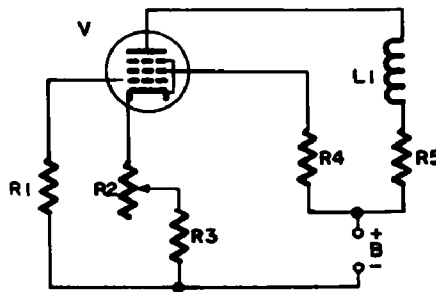
Figure 2.14   Vacuum-Tube DC Circuit

You can visualize V as a variable resistor, its resistance varying with the signal voltage on the control grid. The resultant changes in current flowing through load resistor R5 provide the required voltage output.

A positive voltage on the tube cathode is obtained by the voltage drop across R2 and R3. In the absence of a signal the steady tube plate current will give a voltage that will bias the grid for Class A operation (see Appendix).

The grid-leak resistor R1 keeps the grid at zero potential (or negative with respect to the positive potential on the cathode).

The value of load resistor R5 is considerably lower in a video amplifier than in an audio amplifier, though still several kilohms, to avoid high-frequency attenuation. The peaking coil L1 offers no impedance to DC.

Similarly, in Figure 2.15 electron flow is from B— through R2, Q, L1 and R3, and back to B+. Bias on the base is again established by the voltage drop across the emitter-base junction in the transistor. With no signal on the base, steady emitter-base current flows, which in turn permits a steady (but larger) current to flow from emitter to collector. In the NPN transistor shown this will be electron current; in a PNP it would be hole current (see Appendix).

The purpose of R2 is to stabilize the emitter-base current.

Visualize the transistor as a variable resistor in series with R2 and R3, its resistance varying with the signal voltage on the base. When the resistance of Q varies, the current varies, including the current through R3. The value of R3 must be such that maximum voltage variations can be obtained across it, but at the same time it must provide for the proper operating voltage for the collector of the transistor,
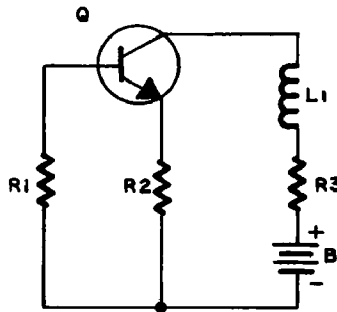
Figure 2.15   Transistor DC Circuit

and not permit undue degeneration of high frequencies in the output circuit.

This circuit uses an NPN transistor. However, a PNP would perform just as well if the battery polarity were reversed.

AC Input Subcircuit (Tube): Figure 2.16 shows the AC input subcircuit for the tube, which is *RC-coupled* (see Figure 2.5).

In this circuit there is no cathode-bypass capacitor as there was in Figure 2.1. The reason for this is that at low frequencies its reactance may be as high as or higher than the cathode resistor. Therefore these low frequencies would suffer *degeneration*.

Degeneration is caused by the voltage on the cathode varying in accordance with variations in the signal voltage on the control grid. When the grid voltage swings in a positive direction the current flowing through R2 and R3 increases, so that the voltage on the cathode increases. This results in a smaller potential difference between the grid and cathode than would have been the case if a cathode-bypass capacitor had been present to ground the cathode voltage variations. When the grid voltage swings in a negative direction the current through R3 and R2 decreases, so that the voltage on the cathode decreases, again canceling out part of the potential difference between grid and cathode. Actually, the total resistance of the tube is increased, so you get a smaller output signal, but as the degeneration is the same for all frequencies the lower frequencies are not penalized.

The variable resistor R2 is a *contrast control*. It operates by varying the potential difference between the grid and cathode, thereby effectively varying the tube resistance, and ultimately the strength of the picture on the TV screen.

Degeneration has the overall result of decreasing the amplification of the circuit. For this reason a higher gain tube is required than would be the case without it. Pentodes with high gain are used in preference
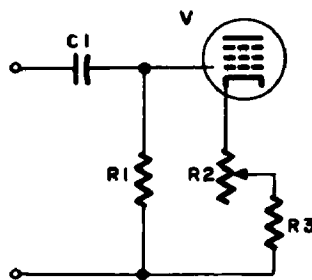
Figure 2.16 Vacuum-Tube Input Circuit

to triodes, and sometimes more than one stage is required. The output signal is reversed 180° with respect to the input signal.

Output AC Subcircuit (Tube): Figure 2.17 shows the output AC subcircuit for the tube. C3 couples the output signal into the next stage, and the same considerations affect its choice as apply to C1. Capacitor C2 bypasses the screen-grid resistor so that the screen grid remains at AC-ground potential for signal frequencies, to prevent degeneration. Any circuit which bypasses unwanted AC to ground is called a *decoupling circuit*.

The main concern in the output circuit is to prevent attenuation of the high-frequency end of the video spectrum. The reason for this attenuation is that a certain amount of capacitance exists between the high and low sides of the circuit anyway, and the higher frequencies "leak" to ground through it. This capacitance is not due to actual capacitors, but to the natural capacitance that exists between various components and wires, and is called *distributed capacitance*. At higher frequencies the effect of distributed capacitance becomes so great that such signals bypass the load resistor R5. Consequently the output for higher frequencies is at a much lower voltage than for lower frequencies, with a great loss of fine detail in the TV picture.

This can be offset to some extent by making the load resistor smaller, as mentioned before. The use of peaking coils, however, is the most important compensation.

Peaking coil L1 forms a *parallel-resonant* circuit (called *shunt peaking*) with the distributed capacitance, so as to offer increased resistance to the higher frequencies, thereby increasing the gain of the amplifier for them. The addition of resistor R6 across the coil broadens its bandpass.
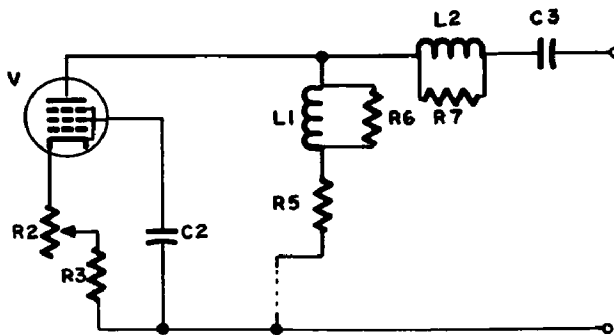
Figure 2.17   Vacuum-Tube Output Circuit

L2 forms a *series-resonant* circuit (*series peaking*) with the input capacitance of the following stage, allowing for maximum transfer of signal energy at the upper end of the video spectrum.

By proper choice of inductance values, the two peaking coils can be made resonant over different frequency bands, to extend the amplifier high-frequency response linearly to cover the upper part of the frequency range required.

AC Input Subcircuit (Transistor): Figure 2.18 shows the AC input subcircuit for the transistor, which is *RC-coupled* to the previous stage. C1 will have a higher value than its opposite number in the tube circuit as mentioned in our discussion of the audio voltage amplifier.

In this circuit the emitter-bypass capacitor has been left in, so no degeneration will be experienced, except for the very low frequencies (which may be compensated for in another way, as explained in Circuit Variations). In this way, the full gain of the transistor can be realized, an important consideration since it is less than that of a pentode tube.

Operation of the transistor is the same as for the audio voltage amplifier. The output signal is 180° out of phase with the input signal.

Output AC Subcircuit (Transistor): Figure 2.19 shows the output AC subcircuit. C3 couples the output signal to the next stage, and the same considerations apply to the choice of its value as affect the choice of C1.

As in the tube circuit the main concern in the output circuit of the transistor is to avoid attenuation of the high-frequency end of the video spectrum through losses via distributed capacitance.

Shunt-peaking coil L1 forms a parallel-resonant circuit with the distributed capacitance, so as to add to the value of the load resistor
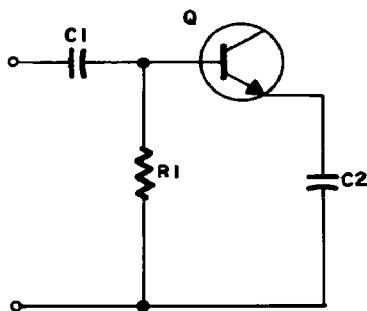
Figure 2.18   Transistor Input Circuit
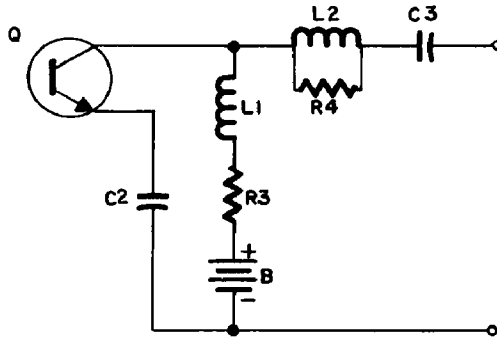
Figure 2.19   Transistor Output Circuit

R3 for the higher frequencies for which it is resonant. The bandpass of this resonant circuit does not have to be broadened by the addition of a capacitor shunting L1 as the value of R3 is already sufficiently low to load it enough. Series-peaking coil L2 forms a series-resonant circuit with the input capacitance of the following stage, allowing maximum transfer of signal energy at the upper end of the video spectrum. By proper choice of inductance values the two peaking coils are made resonant over different frequency bands to extend the high frequency response of the amplifier linearly over the higher frequencies required.

Circuit Variations

Although the video amplifiers just discussed are typical, you are bound to meet variations in them. However, you will never have any difficulty in identifying a video amplifier (a) because of its position in the overall schematic (between the video detector and the picture tube), and (b) because of the series-shunt peaking coils in the output subcircuit.

One way in which video amplifiers may vary is in the manner in which they provide for low-frequency compensation. You've seen one method in the tube circuit. Another method, which is a *decoupling circuit,* is illustrated in Figure 2.20. In this circuit the value of C2 is such that at high frequencies its reactance is negligible, so that R3 is bypassed and the load resistance consists solely of R2. At low frequencies the reactance of C2 increases until R3 adds to the resistance of R2, which increases the voltage gain for these frequencies, compensating for the losses caused by C1. The values of C2 and C3 must be
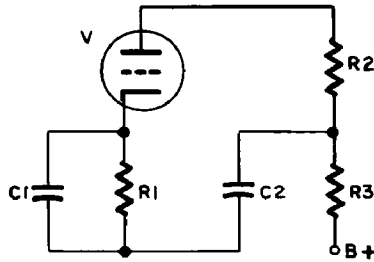
Figure 2.20   Another Type of Low-Frequency Compensation

chosen carefully to balance out the low-frequency degeneration caused by C1 and R1.

You may be wondering how C2 bypasses R3! Although Figure 2.20 doesn't show it, the power supply is connected between B+ and the low side of C2 (refer back to Figure 2.12). The large filter capacitors in the power supply offer negligible impedance to signal voltages, so for these frequencies the low side of C2 is to all intents and purposes connected to B+.

Because of the cathode-bypass capacitor C1, the contrast control must be located elsewhere than where it was in Figure 2.12. It is often found in the picture-tube circuit instead. However, another way of doing it is shown in Figure 2.21, where bypass capacitor C1 is connected between the cathode and R2's slider, so that degeneration may be introduced as required to reduce the contrast.
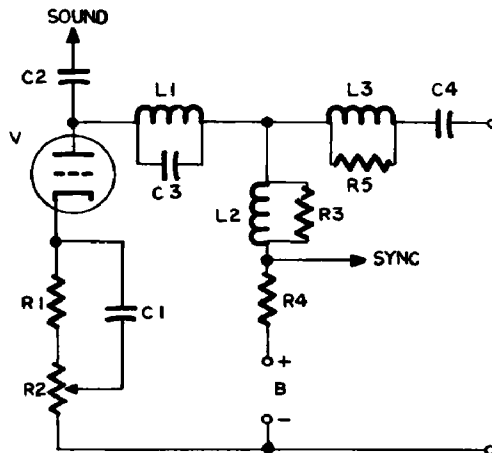
Figure 2.21   Sound and Sync Take-Off

Other variations may be introduced in order to provide for taking off the sound or sync signals from the video amplifier circuit, which is often done. The sound take-off may be from the plate of the tube, which will require the provision of a 4.5-megahertz parallel-resonant trap L1–C3 to block the 4.5-megahertz sound component of the television signal from getting to the picture tube.

The sync signal is usually removed from between the shunt-peaking coil L2 and the load resistor R4, as shown.

IF AMPLIFIERS

IF (intermediate-frequency) amplifiers are voltage amplifiers which handle frequencies very much higher than audio frequencies. Figures 2.22 and 2.23 show IF amplifiers for radio. Figure 2.24 shows one for TV.

Distinguishing Features

IF amplifiers resemble other voltage amplifiers in having *grounded-cathode* or *common-emitter* circuits.

They are distinguished from other voltage amplifiers by the use of *IF transformers* to couple into and out of each stage. In Figures 2.22 through 2.24, T1 and T2 are IF transformers.

Uses

All superheterodyne receivers (this includes nearly all modern radio, TV and radar receivers) convert signals of various frequencies picked up by the antenna to a fixed lower frequency, which is then amplified by the IF amplifier. The process of conversion is dealt with in chapter 5. IF amplifiers are therefore located between the "front end" (tuner-converter section) and the audio or video portions of a receiver.

As you know, audio signal information covers a much narrower range of frequencies than video. For this reason radio IF amplifiers are narrow-band amplifiers, and TV IF amplifiers are wideband.

Figure 2.23   Transistor IF Amplifier

resonant voltage step-up across the coil in addition to the transformer
step-up, so that the signal has already received a boost before it gets
to the tube. This voltage is then applied between the control grid and
cathode of the pentode tube, through cathode-bypass capacitor C3.

AC Input Subcircuit (Transistor): In Figure 2.23 T1 is a *step-down*
transformer, and its secondary is tapped so that the low input imped-
ance of the transistor will not load it excessively to the detriment of
its selectivity. For this reason transistor-radio IF amplification requires
more than one stage as a general rule. The average is two stages for
AM and three for FM. A connection through R1 allows AGC voltage
(see chapter 6) to provide the proper bias on the base.

AC Input Subcircuit (Video IF Amplifier): A similar AGC con-
nection appears in Figure 2.24. In this circuit a resistor R2 is con-
nected so that it shunts L2. This broadens its frequency response to
enable the amplifier to handle the wider bandwidth of the TV signal.
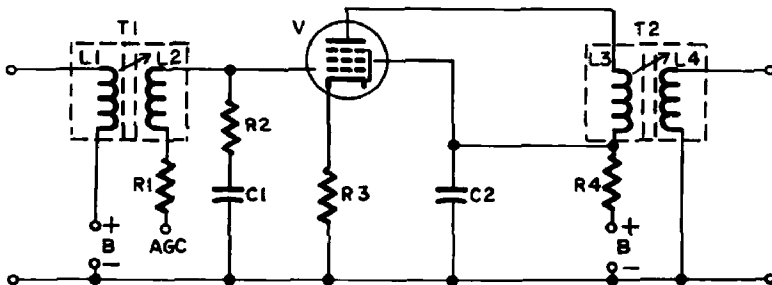
Figure 2.24   Video IF Amplifier

See how this is exactly the opposite of the radio IF amplifiers, where steps are taken to keep the pass band as narrow as possible. You will also notice that no capacitors are connected across L1, L2, L3 and L4. At the much higher frequency of the TV IF signal (45.75 megahertz) the distributed capacitance of the circuit is sufficient for the purpose.

In this circuit the cathode-bypass capacitor is omitted also, but because R3 is very small the effect on the circuit is not enough to cause degeneration.

AC Output Subcircuit: In the output circuits of all three IF amplifiers L3 forms a parallel-resonant circuit with the shunt capacitance. The output current from the tube or transistor consists of a DC current with its voltage varying at an IF rate. This current really consists of two currents. One is a steady DC current of constant voltage, which forms the base for the other, which is AC fluctuating at the IF. The DC portion flows through L3 without obstruction, but the AC portion that is fluctuating at the IF encounters a high impedance because the coil has been tuned to be resonant at this frequency. Therefore this portion develops a maximum-signal voltage drop across L3. Any signals of other frequencies, however, do not meet with such an impedance, since they are not at the resonant frequency. Consequently they develop only small voltages. This is what makes this circuit selective for the chosen frequency.

The circuit in Figure 2.22 is one you'd expect to see in a vacuum-tube radio. Usually only one IF stage is required. The narrow bandwidth of an AM radio signal (10 kilohertz) or an FM radio signal (150 kilohertz) allows the use of a sharply tuned circuit, which gives maximum amplification when used with a high-gain tube.

In Figure 2.23 the transistor is connected across only part of L3. This is because the lower output resistance of the transistor acts like a resistor and would broaden the frequency response unduly if connected across the whole winding, to the detriment of good selectivity. Since the centertap on the coil is grounded for AC through C6, the two opposite ends of the winding will have signals that are 180° out of phase with each other. A connection from the lower end of the coil goes via C5 to the base of Q. This places a signal on the base which is of opposite phase to the collector signal, and serves to cancel any feedback through the transistor that might cause oscillation. (The same precaution would have to be taken with a triode tube, but is not required with a pentode because the screen grid—at AC ground potential—prevents feedback from the plate to the grid.)

In Figure 2.24 the shunting capacitor across L3 has been omitted

because the distributed capacitance is sufficient for the purpose. The loading effect of R4 in series with L3 broadens the frequency response enough for video IF amplification.

Because of the reduced amplification resulting from loading the IF transformers, video IF amplifiers require more than one stage (usually three for tubes). In a three-stage IF amplifier there will be four IF transformers. These will be *stagger-tuned*. This means that instead of all four being tuned to the same frequency, they will be tuned to different portions of the 4-megahertz bandwidth of the video signal. For example, the four frequencies might be 43.1, 43.5, 44.2 and 46.0 megahertz (they will differ slightly in different models of TV sets), which would combine in the overall picture to cover frequencies from 41.75 to 45.75, the difference of 4 megahertz required. These frequencies are usually shown on the schematic of the IF amplifier beside each IF transformer. When the picture-carrier signal is removed in the demodulator stage only the 4-megahertz band of video frequencies will remain, as explained in chapter 6.

RF AMPLIFIERS

RF amplifiers used in receivers are voltage amplifiers, having circuits similar to the voltage amplifiers described in the preceding portion of this chapter. In fact, RF pentode amplifiers are the same as IF pentode amplifiers, except that the input is from an antenna and tunable resonant circuit.

Most RF amplifiers in use today will be found in TV and FM tuners. For this reason Figure 2.25 shows an extremely popular type of TV circuit, and Figure 2.26 a typical solid-state FM circuit.

Distinguishing Features

In Figure 2.25 you see an RF *cascode amplifier*. This circuit uses a dual-triode tube (two tubes in one envelope). The antenna and tunable resonant circuit in the input tell you it handles RF. The first triode section is connected in a *grounded-cathode* circuit, as in other voltage amplifiers. The second is connected as a *grounded-grid* amplifier. In the output from the second tube section is a transformer (tunable to each TV channel) which couples the signals into the next stage.

In Figure 2.26 the input from the antenna and tunable resonant
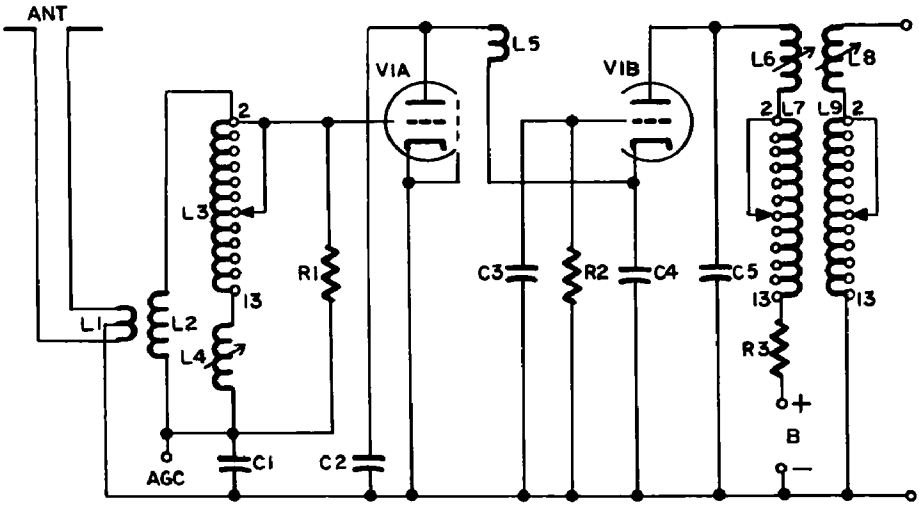
Figure 2.25 RF Cascode Amplifier
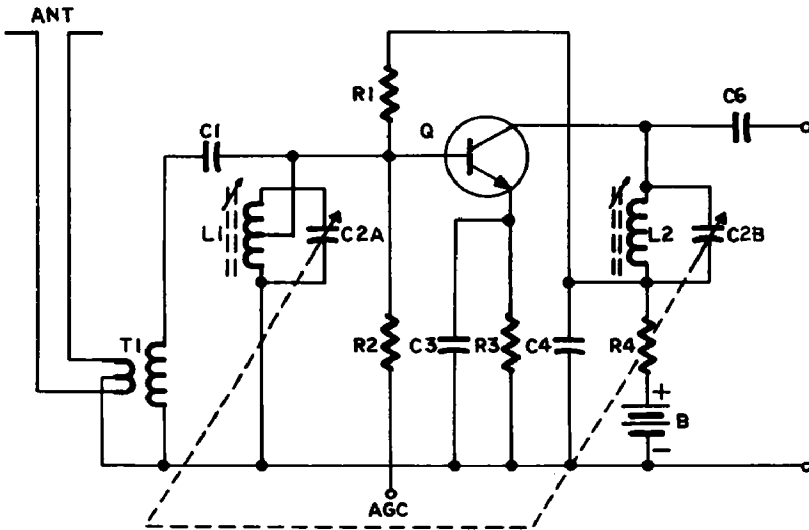
Figure 2.26 RF Transistor Amplifier

circuit is applied to the base of the transistor, from which you know that this circuit must also be handling RF. It is connected in a *common-emitter* circuit, with another tunable resonant circuit in the output, after which the signal is capacitor-coupled into the next stage.

Uses

Cascode amplifiers are used extensively in TV tuners. The gain from the dual-triode is approximately the same as that from a single pentode, but the noise level is very much lower. However, triodes are susceptible to oscillation at very high frequencies, which has to be prevented by careful design. Pentodes were used in some older circuits before the dual-triode was developed. The two triodes in the dual-triode are shielded from each other by a screen which is grounded.

Transistors also may be used in TV tuners and modern FM radios. RF amplifiers are seldom used in AM radios, except in some automobile models. But they are used extensively in communications receivers. In any receiver the RF amplifier will be in the first stage or stages.

Detailed Analysis

DC Subcircuit (Vacuum Tube): In Figure 2.25 electron flow is from B— to the cathode of V1A, thence to the plate, and via L5 to the cathode of V1B. From V1B's plate the flow is through L6, L7 and R3 back to B+. Grid bias on V1A is supplied by AGC voltage (see chapter 6).

DC Subcircuit (Transistor): In Figure 2.26 electron flow is from B— through R3 to the emitter, through Q to the collector, thence through L2 and R4 back to B+. In a PNP transistor, with polarities reversed, the flow would be in the opposite direction. The bias across the emitter-base junction is stabilized by R1 and R3. AGC voltage is supplied via R2.

Input Subcircuit (V1A): The signals picked up by the dipole antenna are inductively coupled from L1 to L2 (Figure 2.25). This is a *balun* transformer, since it couples the *bal*anced line from the antenna to the *un*balanced amplifier circuit. (The amplifier circuit is said to be unbalanced because it has a high and low side.) The RF signals then are applied across L3 and L4, of which the upper end is connected to the grid of V1A and the lower end to the low side of the circuit via C1. L3 and L4 are the antenna section of the TV tuner, which may be a turret tuner or a rotary tuner. The sliding contact represented by the arrow selects the desired channel by shorting out more or less of L3. At the Channel 2 tap all the inductance is in the circuit; at the Channel 13 tap only L4 is left in. L4 is adjustable for touching up the

overall tuning when necessary (when a tube is changed in the tuner, for example). The tuning coils L3 and L4 form a resonant circuit with the distributed capacitance of the circuit—mainly in the tube—which applies a maximum voltage between grid and cathode for the selected channel, while attenuating all the others. R1 broadens the tuning enough to give the wide pass band (about 6 megahertz in the tuner) required for the TV signal.

Output Subcircuit (V1A) and Input Subcircuit (V1B): The output of V1A is developed across V1B, which is its load resistor, as it were. This is a fairly low resistance, so there is no danger of oscillation in V1A. (Oscillation requires a strong signal in the output to give enough feedback.) Unwanted higher frequencies are blocked by L5, and de-coupled by C2.

The signal is applied between the cathode and grid of V1B. Since the grid is connected to the low side of the circuit through C3, this is a *grounded-grid* amplifier circuit. The gain is not as high as in a grounded-cathode amplifier, but the grounded grid blocks feedback from the plate to the cathode, thus preventing oscillation.

Output Subcircuit (Figure 2.25): The output of V1B is applied across the RF tuning coils L6 and L7, and coupled by transformer action to L8 and L9. Tuning L7 and L9 is performed simultaneously with L3, all three moving contacts being connected to the same tuning control. R3 in series with L7 broadens the response in the same way as R1 does.

Input Subcircuit (Figure 2.26): The signals picked up by the dipole antenna are inductively coupled via the balun T1, and are then applied across the resonant circuit L1–C2A. The signal of the frequency to which the circuit is tuned is then applied between the base and emitter of Q.

Output Subcircuit (Figure 2.26): The output of Q is applied across the RF tuning coil L2, which is tuned to resonance by C2B. This variable capacitor is ganged with C2A (as indicated by the dashed lines) so that both input and output circuits are simultaneously tuned to the same frequency. The output signal is then coupled into the next stage through C6.

TROUBLESHOOTING TABLE FOR VOLTAGE AMPLIFIERS	SYMPTOM							
	No output	Weak output	Distorted output	Intermittent	Hum (tubes only)	Motorboating (tubes only)	Interference	Wrong station
Vacuum Tube	X	X	X	X	X			
Tube socket	X			X				
Transistor	X	X	X	X				
Input coupling capacitor	X		X	X				
Grid resistor	X		X	X		X		
Cathode resistor	X			X				
Bypass capacitor	X		X	X	X			
Load resistor	X		X	X				
Output coupling capacitor	X	X	X	X				
Battery	X	X	X					
Power supply	X	X	X		X			
IF transformer (detuned)		X						
IF transformer (defective)	X			X				
Tuner	X	X		X			X	X
Antenna		X		X				

3

POWER
AMPLIFIERS

P OWER AMPLIFIERS are *current* amplifiers. The vacuum tube, transistor or other device used in a power amplifier circuit must be capable of handling much greater current than a voltage amplifier. Consequently, power tubes and transistors are generally larger physically and must dissipate more heat. Distortion is also a problem requiring special treatment, but efficiency is higher.

SINGLE-ENDED AUDIO POWER AMPLIFIERS

Figure 3.1 shows a single-ended audio power amplifier using a pentode tube. Figure 3.2 shows a similar amplifier using a transistor.

Distinguishing Features

Single-ended audio power-amplifier circuits are *grounded-cathode* or *common-emitter* circuits, to obtain maximum gain. They differ from audio voltage amplifiers in not having load resistors. Instead, an *output transformer* is used to transfer *power* from the active element to the driven device (in this case a loudspeaker), which is the real load.

Detailed Analysis

DC Subcircuit (Vacuum Tube): In Figure 3.1 electron flow is from B—, through R2, V, and back to B+ via the parallel paths through the primary winding of T1 and the screen-grid resistor R3. Grid bias for Class A operation (see Appendix) is established by the voltage drop across R2, and R1 serves as a grid leak. Variations in the resistance of V are caused by variations in the signal voltage applied between the grid and cathode, resulting in variations in the current flowing in R2 and the primary winding of T1. The value of R2 must be comparatively low because of the heavier current it has to pass.

DC Subcircuit (Transistor): In Figure 3.2 electron flow is from B—, through the primary winding of T1, Q and R3, and back to B+.
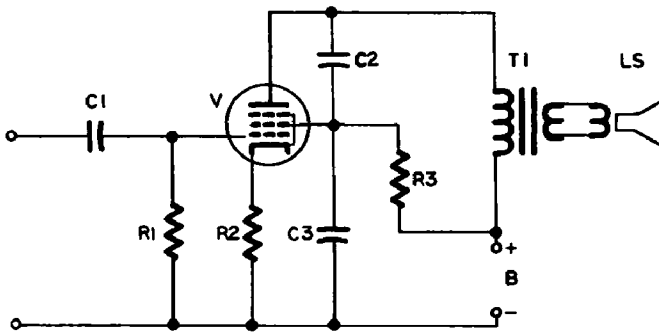
Figure 3.1   Single-Ended Audio Power Amplifier Using Pentode
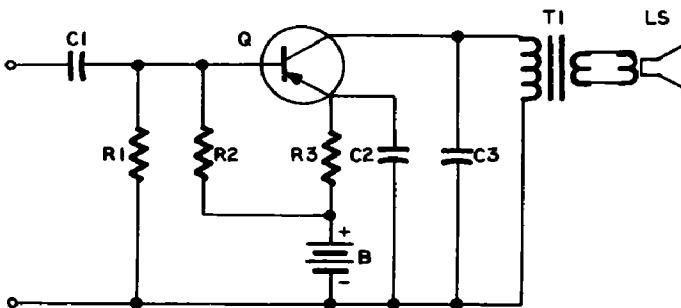
Figure 3.2   Single-Ended Audio Power Amplifier Using Transistor

Bias for Class A operation is established by hole current (this is a PNP transistor), and stabilized by R2 and R3. Variations in the resistance of Q are caused by variations in the signal voltage applied between the base and emitter, resulting in variations in the current flowing in the primary of T1. The value of R3 must be comparatively low because of the heavier current it has to pass.

AC Input Subcircuits: Both vacuum-tube and transistor amplifier inputs are RC-coupled from the previous stage in the same way as audio voltage amplifiers. In the tube circuit the cathode-bypass capacitor has been omitted to obtain degeneration, as explained in the video amplifier analysis in chapter 2. In the transistor circuit the bypass capacitor has been retained to keep the emitter at ground potential as far as the signal is concerned, and because degeneration would still further reduce the amplification of the transistor, which is not so great as for a pentode. Since the heavier current through R3 would still cause considerable voltage variations at low frequencies, the capacitance of C2 must be large. (An electrolytic capacitor is often used.)

AC Output Subcircuits: The output transformer used in each amplifier is an impedance-matching device. The real load is the loudspeaker. Loudspeaker impedances are very low, from 4 to 16 ohms as a rule, whereas the plate impedance of a tube or the output resistance of a transistor is likely to be 1000 times greater. To match these different impedances (which is necessary if all the power is to be transferred) the output transformer must have many more turns on its primary winding than it has on its secondary. The *turns ratio* is equal to the square root of the impedance ratio. If the latter were 1000:1, then the turns ratio would have to be approximately 32:1, in theory, although it is usually made somewhat higher in practice to cut down on distortion.

The current flowing in the primary winding of the transformer consists of DC current flowing from the tube to the power source, varying in strength because of variations in the resistance of the tube. You can look at this current as consisting of two parts: a base of unvarying DC, and a superstructure of varying AC. The unvarying DC meets little resistance as it flows through the transformer winding, and because it causes no flux variations in the transformer core it has no effect on the secondary winding. The superimposed AC, however, is varying all the time, and the flux variations it induces in the core induce similar current variations in the secondary. Consequently the AC component is transferred to the secondary, but not the DC component. This AC component is the current that drives the voice coil of the loudspeaker.

In Figure 3.1, C2 is a plate-bypass capacitor and in Figure 3.2 C3 is a collector-bypass capacitor. Their value is chosen so that it will provide a path to ground for high-frequency signals which might cause high-frequency oscillation.

PUSH-PULL AUDIO POWER AMPLIFIERS

Single-ended audio power amplifiers are limited to low-power applications. Where more power is required push-pull power amplifiers are used. Figure 3.3 shows a typical push-pull audio power amplifier using tubes, and Figure 3.4 shows one using transistors.

Distinguishing Features

Two tubes or transistors sharing one output transformer, in a circuit consisting otherwise of resistors and capacitors only, indicates a push-pull audio output amplifier. However, many transistor circuits now eliminate the output transformer by using low-collector-resistance transistors, but they are still easily recognizable as audio power amplifiers because of the doubling-up of transistors and because they are the final stage in the amplifier before the loudspeaker or other output.

Uses

Push-pull audio power amplifiers produce more power with less distortion than do single-ended amplifiers. This power can be further enhanced by doubling the active elements (two push-pull pairs in parallel), or by using more powerful tubes or transistors. Some power amplifiers are used to drive vibration test equipment, in which considerable loads are shaken for long periods to test the reliability of their construction. Another advantage of push-pull circuits is that they cancel out much of the harmonic distortion that is generated in pentode and beam-power tubes. Because of these factors push-pull output stages are almost invariably used in hi-fi amplifiers.

Detailed Analysis

In a push-pull circuit the input signal has to be split to feed the two output active elements. After splitting, the two signals must be of opposite phase, so that when one is swinging positive the other is swinging

negative. In this way the outputs of the two tubes or transistors, applied at opposite ends of the output-transformer primary winding or other load, are of opposite polarity. (If they were of the same polarity they'd cancel each other out!) Consequently, in all push-pull circuits there must be some means of phase-splitting to obtain phase inversion for one of the output tubes. We shall discuss various methods of doing this in the following section.

DC Subcircuit (Tube): In Figure 3.3 the DC path for the two output tubes V2 and V3 is from B— to R7, which is the common cathode resistor for both. The current then divides and passes through each tube to the opposite ends of the primary winding of T1, joins again at the centertap, and returns to B+. The screen-grid supply follows the same route, except that it bypasses the output transformer. The value of the cathode resistor will be one that gives Class AB operation (see Appendix) and some degeneration to reduce distortion.

The DC path for V1 is from B— through R4, R3, V1 and R2, then back to B+.

DC Subcircuit (Transistor): The DC path in Figure 3.4 runs from B— at the top of the diagram to B+ at the bottom. There are three paths. The main path through the output transistors Q3 and Q4 also
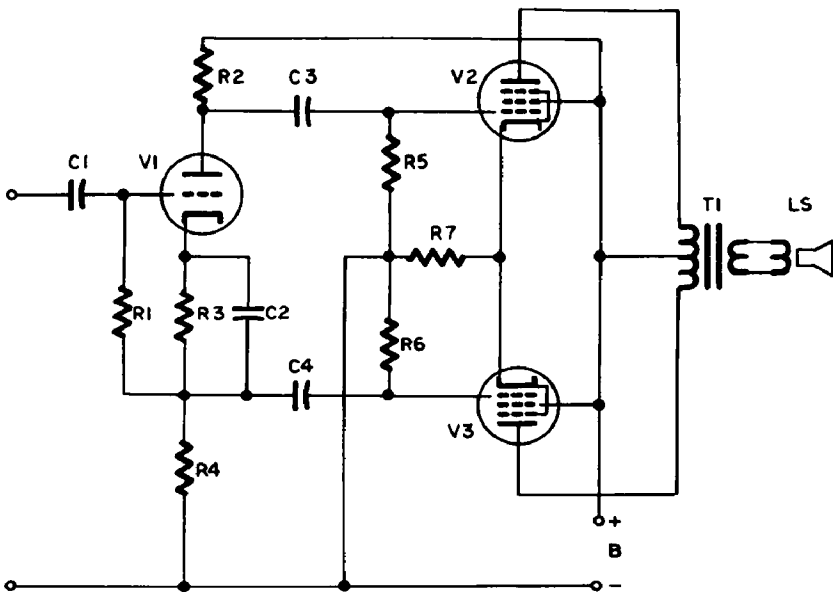
Figure 3.3   Push-Pull Audio Power Amplifier Using Pentodes, with Phase Inverter

passes through R7 and R8. These two resistors are low value (often less than one ohm) and high wattage. They are current-limiting resistors, to protect the circuit from the effects of a sudden surge of current from B— to B+.

The second path is via Q1, R4, R5, Q2 and R6. Both these paths are designed so that in a no-signal-applied condition the voltage at the point between R4 and R5 will be half the B— voltage. (In some circuits a variable resistor is provided to adjust it, if necessary.)

The third path is via R1, R2 and R3, and the base-emitter junctions of Q1 and Q2, and is for the purpose of stabilizing the bias on these transistors. The thermistor R2 is mounted on the heat sink of the output transistors so that as the temperature rises the resistance of R2 goes down (this being the virtue of thermistors). This compensates for increases in resistance with temperature in other circuit elements.
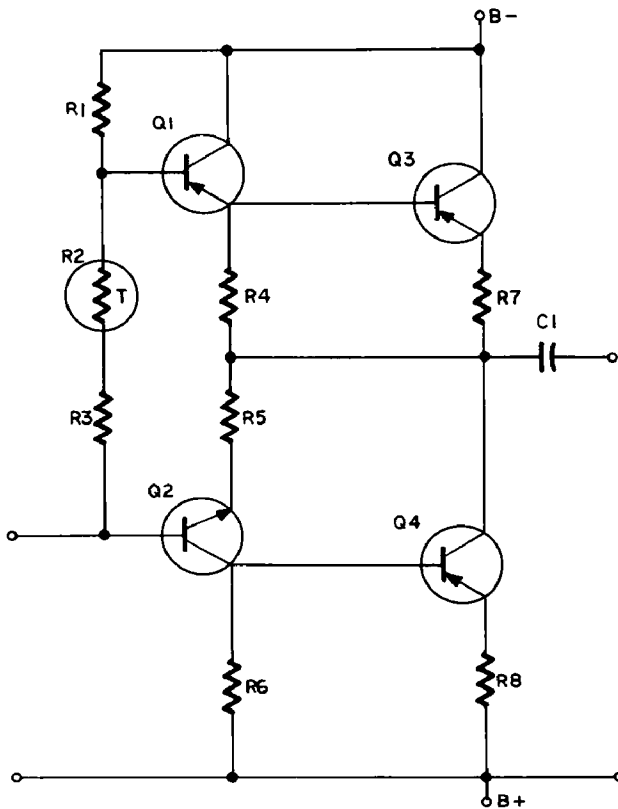
**Figure 3.4   Push-Pull Audio Power Amplifier Using
Transistors, with Phase Inverter**

AC Input Subcircuit (Tube): The signal is RC-coupled from the previous stage to the grid of V1. This tube is operated as an ordinary Class A audio voltage amplifier. A negative swing of the signal voltage on the grid results in a positive swing of the plate voltage, and vice-versa. However, current flowing through R4, which is not bypassed, varies directly with the grid voltage. As a result, the signals coupled through C3 and C4 to the grids of V2 and V3 are of opposite phase. Proper choice of values for R2, R3 and R4 ensures that their amplitudes are equal.

AC Output Subcircuit (Tube): With identical signals of opposite phase applied to their grids, V2 and V3 produce output signals which are not exactly symmetrical (because they are being operated as Class AB amplifiers), but which combine in the output transformer to give a true replica of the input signal. T1 couples it inductively to the load.

AC Input Subcircuit (Transistor): Q1 is a PNP transistor, and Q2 an NPN. Their characteristics are identical, and complement each other in what is called *complementary symmetry*. Each base-emitter junction has a small forward bias when no signal is applied, and under this condition a small current flows from B— through both transistors to B+.

When a signal is applied to the input it changes the bias on each transistor, causing the currents through them to change. When the bias changes in a positive direction it opposes the forward bias on Q1, and increases it on Q2. This results in an increase in the resistance of Q1 and a decrease in that of Q2. This makes the voltage on the emitter of Q1 become less negative, so that it in turn opposes the forward bias on the emitter-base junction of Q3. At the same time the collector voltage on Q2 becomes more negative, which increases the forward bias on the emitter-base junction of Q4. When the signal voltage swings the bias in a negative direction, the opposite happens in each case.

The result is that Q3 conducts more on negative-going swings of the input signal voltage, while Q4 conducts more on positive-going swings.

Output Subcircuit (Transistor): The output circuit in Figure 3.4 is extremely simple. As Q3 and Q4 alternate between conducting more and conducting less, the voltage on the collector of Q4 swings back and forth from less negative to more negative than the resting voltage. These are audio-frequency variations, of course, and they are coupled through C1 (an extremely high-value capacitor of probably 1000 microfarads) to a loudspeaker connected across the output terminals.

INVERSE FEEDBACK

Inverse feedback is the method used to reduce distortion in an audio power amplifier. There are two kinds. In Figure 3.5 a signal A is applied to the input of the amplifier. The output signal B is an enlarged inverted replica of A, but a spurious spike has appeared on the leading edge of the square wave. This is *amplitude distortion:* the amplitude of the output signal is not a faithful (enlarged) reproduction of the input signal. By feeding back to the input a portion C_1 of the
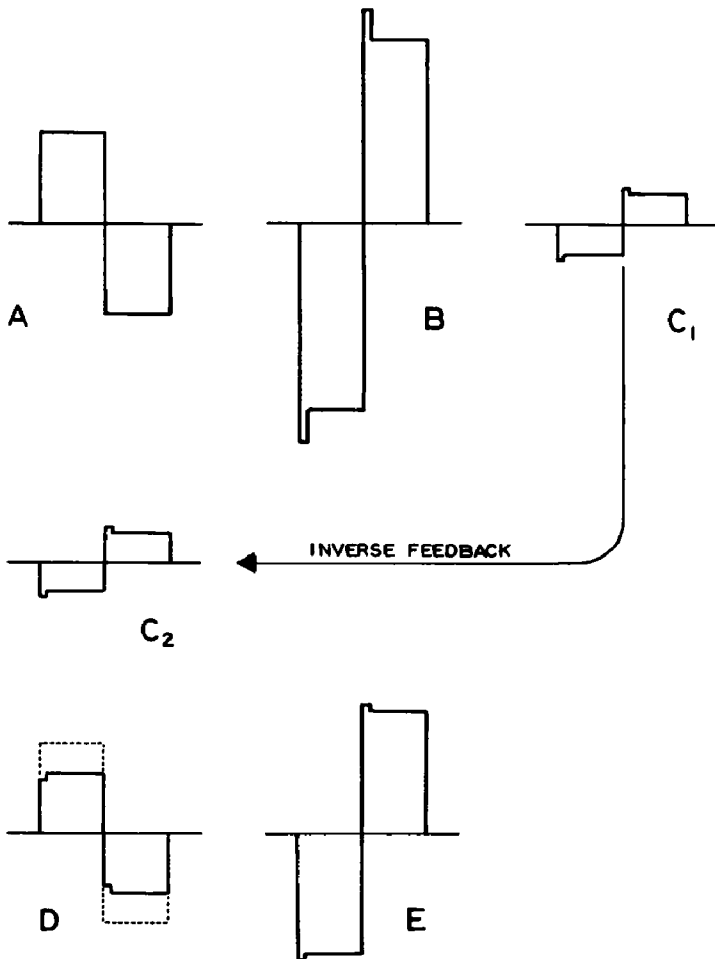
Figure 3.5   Using Inverse Feedback to Correct Amplitude Distortion

output signal, the distortion can be reduced. In the input the feedback signal C_2 combines with the input signal A and modifies it. Being of opposite phase, it is subtracted from A to produce a new signal D. The portions enclosed by the dotted lines have been canceled out, and the modified input signal now has notches where the feedback signal had spikes. When the modified signal is amplified, the notched portions receive the same excessive amplification that gave the high spikes on B, but now the spikes are much reduced, as in E.

Amplitude distortion does not necessarily take the form of spikes. It is any deformation of the shape of the signal as it passes through the amplifier.

The other form of distortion is illustrated in Figure 3.6. A good amplifier should amplify all frequencies equally. Curve A shows that the higher frequencies are being amplified more than the lower. By supplying inverse feedback from the output to the input in the same way as in reducing amplitude distortion, we can flatten the response. In Curve B we partially reduce the distortion by moderate feedback; in Curve C we eliminate it almost entirely by using more feedback.

You can see that inverse feedback also has the disadvantage of reducing the gain of the stage. In hi-fi equipment a great deal of feedback is used to reduce distortion. Consequently the audio signal must be given increased amplification to compensate for the loss. Fortunately the distortion reduction remains at a satisfactory level.

There are two types of inverse feedback. You are already familiar with *inverse current feedback* under the name of degeneration, ob-
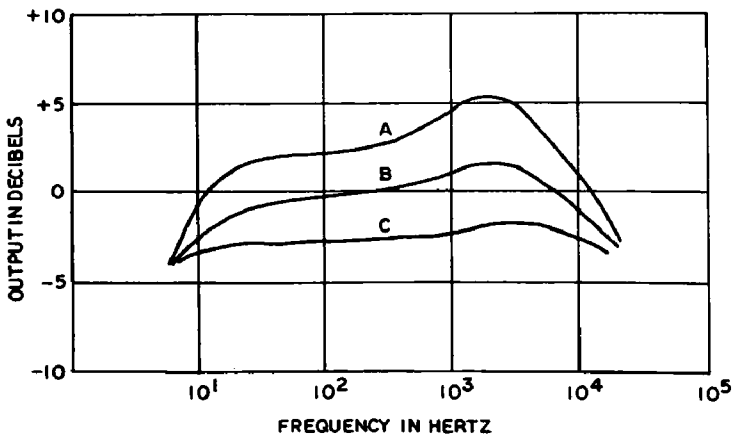
Figure 3.6   Using Inverse Feedback to Correct Frequency Distortion
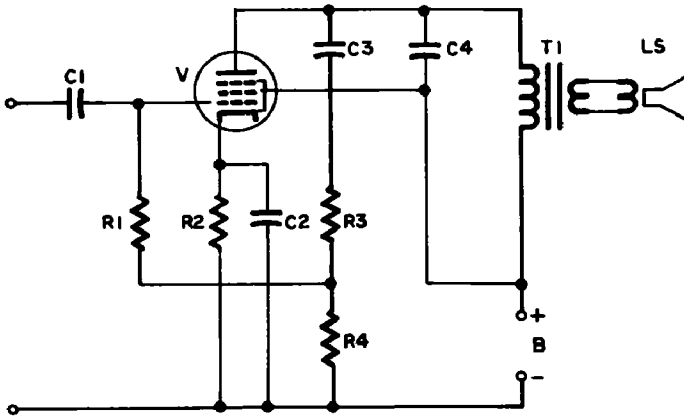
Figure 3.7   Inverse Voltage Feedback

tained by omitting the cathode-bypass capacitor. It is called current feedback because the feedback signal is obtained from the current across the cathode resistor, which is varying with the signal voltage. As you saw in chapter 2, inverse current feedback, or degeneration, is often used to improve frequency response.

The second method is called *inverse voltage feedback,* and is obtained by feeding part of the output voltage back to the input, using a circuit such as that in Figure 3.7, where the feedback is via R1 to the grid of the tube from the junction of R3 and R4. Capacitor C3 blocks the DC voltage only, so R3 and R4 are connected between the plate output and ground, or the low side of the circuit. The amplitude of the voltage appearing at their junction will depend upon their relative values. For example, if the required feedback voltage is 25 percent of the output signal, R3 will be three times the value of R4.

Inverse voltage feedback can also be supplied to the previous stage, or even to several stages. In hi-fi equipment, as we've already said, a great deal of feedback is used, and it reduces the gain of each stage considerably, but as the paramount requirement is fidelity the extra expense of additional stages has to be accepted.

Circuit Variations

Another method of obtaining phase inversion for a vacuum-tube push-pull power amplifier is shown in Figure 3.8. Each half of the dual-triode tube V1 is connected as a voltage amplifier. The input signal is applied between the grid and cathode of V1A, and the output
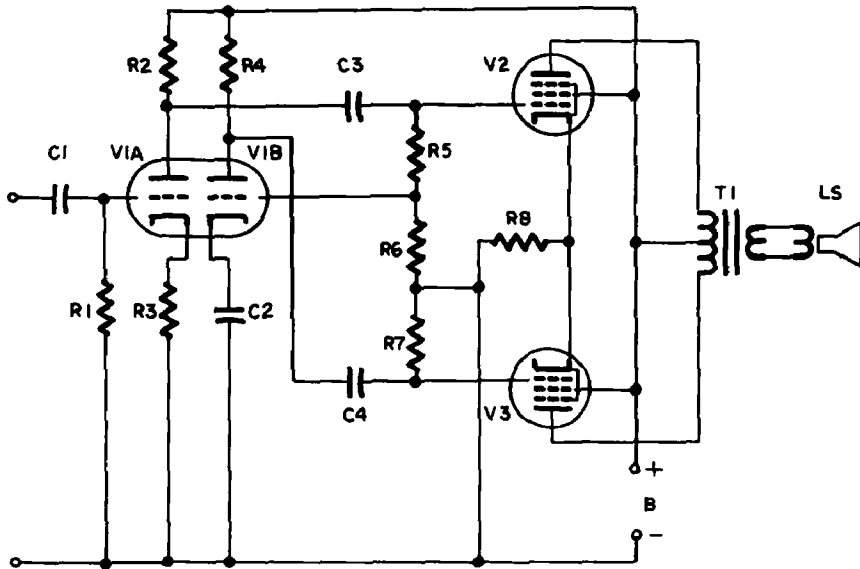
Figure 3.8   Dual-Triode Phase Inversion

signal is then fed to the grid of V2. This signal is reversed in phase with respect to the input signal. A portion of it is fed back to the grid of V1B, where it is amplified as the original input signal was in V1A, and the output then goes to the grid of V3. This output is also reversed in phase with respect to the input to V1B, but as the input signal to V1B was a portion of the input to V2, you can see that V3's input will now be of opposite phase to that of V2, which is what we want.

The amplitude of the input signal to V1B must be equal to the amplitude of the input signal to V1A. This is obtained by choosing the values of R5 and R6 so that their ratio gives the required reduction. For example, if V1A amplifies the input signal 60 times, the ratio of R5 to R6 must be 59 to 1 to get an input signal of the right amplitude to apply to V1B, so that when it has amplified it 60 times the signal fed to V3 will be the same amplitude as that supplied to V2.

Unfortunately, the two halves of the dual-triode tube may not amplify equally, especially as the tube ages. For this reason this method of obtaining phase inversion is inferior to that using a single tube. However, since each half of the dual-triode is operating as a voltage amplifier it saves having a preceding amplifier stage. The choice therefore boils down to a matter of dollars and cents.

Phase inversion may also be obtained by using a transformer, as in Figure 3.9, where an interstage transformer T1 is shown with its sec-
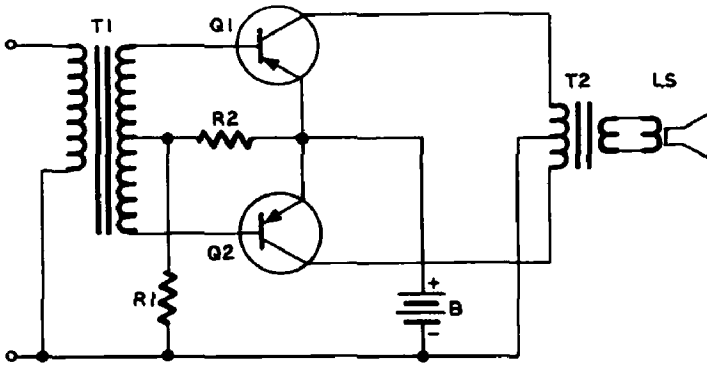
Figure 3.9   Transformer Phase Inversion

ondary divided so that the upper half drives Q1 and the lower Q2. The centertap is connected via R2 to the two emitters. When one end of the secondary of T1 swings in a positive direction the other end swings in a negative direction, and vice-versa. Consequently, the signals applied to Q1 and Q2 will be of opposite phase.

SINGLE-ENDED RADIO-FREQUENCY POWER AMPLIFIERS

Figure 3.10 shows a single-ended RF power amplifier using a triode tube.

Distinguishing Features

Single-ended RF power amplifiers are *grounded-cathode* circuits to obtain maximum gain. Input and output subcircuits are *tuned resonant circuits:* the output resonant circuit is usually a *tank circuit* feeding an *antenna.*

Tubes used in RF power amplifiers often require *neutralization* (see explanation in detailed analysis of the circuit). This is invariably the case with triode tubes. An RF power amplifier is operated with a much higher negative bias on the grid than other power amplifiers, requiring in most cases an *external source of grid bias voltage.*

Uses

Single-ended RF power amplifiers are operated as Class C amplifiers (see Appendix), and are capable of delivering moderate power (depending on the tube) to an antenna, and are used in many types of transmitters of low or moderate power.

Detailed Analysis

DC Subcircuit: In Figure 3.10 electron flow is from B— through both halves of T1's secondary to the filament of V, then from the plate via the upper half of L4 and L3 to B+. Grid bias voltage is supplied by a separate source C as shown, via L2.

Filament Subcircuit: The plate voltage used in transmitter tubes is much higher than that used in other types, and tubes of special design are required. Dissipation of heat necessitates tubes equipped with fins or even water cooling. Oxide-coated cathodes, indirectly heated, have to be replaced with heavy tungsten filaments which can stand up to the high voltage. To heat such a filament to incandescence a filament transformer is needed to reduce the line voltage to the filament voltage used
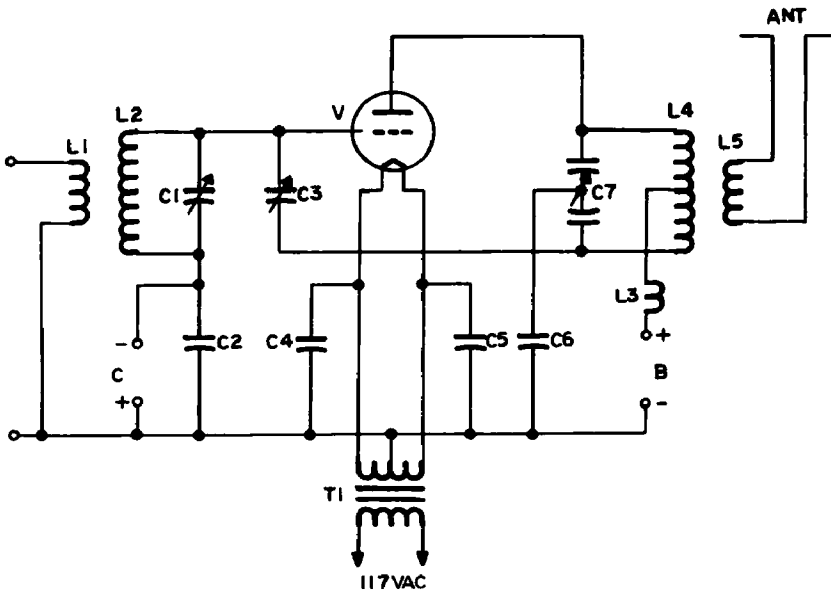
Figure 3.10   Single-Ended RF Power Amplifier

by the tube. In Figure 3.10 T1 is the filament transformer. The center-tap on the secondary is connected to the low side of the circuit, to provide a path for the plate voltage, and the two ends of the secondary are connected to the filament. Both ends of the filament are also connected to the low side of the circuit through C4 and C5, which provide a path for the signal voltage but not for the filament voltage.

AC Input Subcircuit: Coil L1 is inductively coupled to L2. L2 and C1 form a series-resonant circuit, connected between the grid and filament of V via C2, C4 and C5. Maximum input signal voltage is developed when L2 and C1 are tuned to the signal frequency.

AC Output Subcircuit: C7 and L4 form a parallel-resonant circuit. C7 is a split-stator variable capacitor. The rotor is connected to the low side of the circuit through C6, and the two stators are connected to the opposite ends of L4. The powerful current pulses from the tube become sine waves in the resonant circuit C7–L4 (as explained in chapter 4), and are coupled inductively to L5, and thence to the antenna. L3 is an RF choke to keep the RF signal out of the power supply.

Neutralization Subcircuit: The lower end of L4 is connected via C3 to the grid of V. Since V is a triode, energy from the plate is fed back internally to the grid, and would cause V to oscillate as it is in phase with the grid signal. However, the signal fed back via C3 is of opposite phase (being from the opposite end of L4 to the plate), and by adjusting C3 can be made exactly equal to the positive feedback, which is therefore neutralized. C3 is consequently a *neutralizing capacitor.*

Circuit Variations

Circuits similar to Figure 3.10 will be seen also with tubes with indirectly heated cathodes (in which no filament subcircuit is required), or using tetrodes or pentodes (in which neutralization may not always be necessary).

PUSH-PULL RF POWER AMPLIFIER

Figure 3.11 shows a push-pull RF power amplifier. As in the audio power amplifiers discussed earlier in this chapter, they also require some type of phase inversion.

Distinguishing Features

Push-pull RF power amplifiers are quite similar to audio push-pull power amplifiers, except for the *resonant circuits* used in the input and output, and provision for *neutralization* and an *external grid-bias voltage source*.

Uses

Push-pull circuits not only increase power output but also minimize distortion. This is especially true for triodes. Successive push-pull RF power amplifier stages are employed in transmitting systems between the oscillator and the antenna to develop the output power required. They are operated as Class C amplifiers (see Appendix).

Detailed Analysis

DC Subcircuit: In Figure 3.11 electron flow is from B— to the cathodes of V1 and V2, thence from each plate to the opposite ends of L4, returning to B+ via the centertap and L3.

Filament Subcircuit: T1 is the filament transformer, with secondary centertap connected to the low side of the circuit. C5 and C6 bypass the signal voltage around the transformer.

AC Input Subcircuit: Coil L1 is inductively coupled to L2. L2 and C1 form a series-resonant circuit. C1 is a split-stator variable capacitor, with the two stators connected across the two halves of L2. The rotor of C1 is connected via C2, C5 and C6 to the tube filaments. When the signal induced in L2 is such that its upper end is positive, the lower end will be negative, and vice-versa. In this way signals of opposite phase are applied between each grid and filament of V1 and V2.

AC Output Subcircuit: C8 and L4 form a parallel-resonant circuit. C8 is a split-stator variable capacitor. The rotor is connected to the low side of the circuit through C7, and the two stators are connected to the opposite ends of L4. The powerful current pulses from the tubes become sine waves in the resonant circuit C8–L4, and are coupled inductively to L5, and thence to the antenna. L3 is an RF choke to keep the RF signal out of the power supply.

Neutralization Subcircuit: The plate of V1 is connected to the grid of V2 via C3, and the plate of V2 is connected to the grid of V1 via C4. This is called *cross-neutralization*. It provides signals of opposite
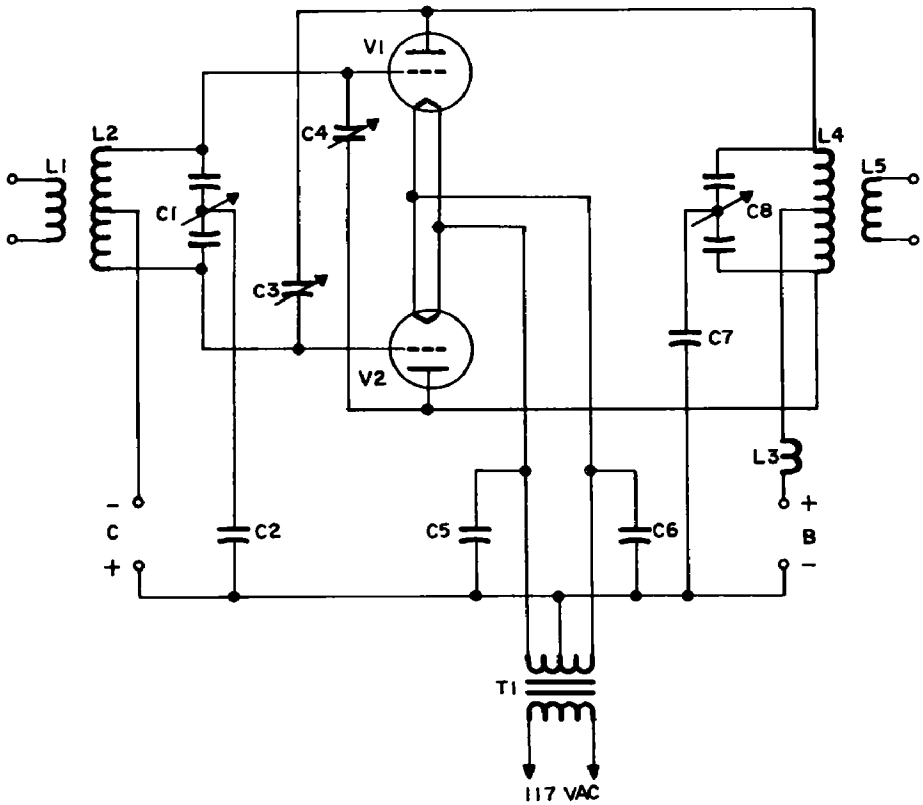
Figure 3.11   Push-Pull RF Power Amplifier

phase on each grid to neutralize the tube's internal plate-grid feedback. C3 and C4 can be adjusted for exact neutralization.

Circuit Variations

Circuits similar to Figure 3.11 will be seen also with tubes with indirectly heated cathodes (in which no filament subcircuit is required), or using tetrodes or pentodes (in which neutralization may not always be necessary).

LINEAR RF AMPLIFIERS

Figure 3.12 shows a single-ended linear RF amplifier. In this example a pentode is used, but triodes and tetrodes may be used as in other RF power amplifiers.

Distinguishing Features

Linear RF power amplifiers are a special form of RF power amplifier, and are therefore similar in their circuitry. You can tell a linear RF power amplifier, however, by its position in the overall schematic. *Any RF power amplifier after the point where the carrier is modulated* (see chapter 5) *must be a linear amplifier.*

Uses

As explained above, linear amplifiers, operated Class B (see Appendix), are used to bring the power of the modulated carrier up to the level required for transmission, where this has not already been done. You can't do this with a Class C amplifier once the carrier has been modulated, because some of the modulation will be lost.

Detailed Analysis

DC Subcircuit: In Figure 3.12 electron flow is from B— to the cathode of V. From V one path goes from the plate via L3 and L4 (an RF choke to keep the RF signal out of the power supply) back to B+. The other path goes from the screen grid directly to B+.

AC Input Subcircuit: This circuit is similar with that of Figure 3.10.

AC Output Subcircuit: This circuit is similar with Figure 3.10.

Neutralization: Neutralization will be required for all triodes and many pentodes. In Figure 3.12, however, we have shown a circuit without neutralization for comparison with Figure 3.10.
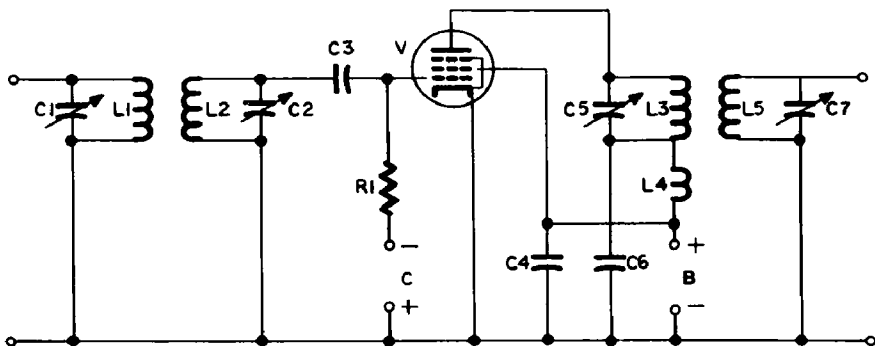
Figure 3.12 Single-Ended Linear RF Amplifier

Circuit Variations

Push-pull RF linear power amplifier circuits are similar to other RF push-pull power amplifier circuits, and are used in the same way to obtain greater power output and efficiency with less distortion than with single-ended circuits.

MAGNETIC AMPLIFIERS

In magnetic amplifiers you see a power amplifier that does not use a vacuum tube or transistor to introduce power into the circuit. Instead, a special type of transformer is used. Figure 3.13 shows a half-wave magnetic amplifier, Figure 3.14 a full-wave one.

Distinguishing Features

Magnetic amplifiers consist of *transformers* with three or four windings. One (or sometimes two) of these windings is the *control winding,* which is supplied with *direct current.* This is quite a distinguishing feature, for a transformer using DC is practically never met with in any other connection. (Do not let the practice of routing the plate supply to a tube through a power output transformer, which we've just been looking at in other types of power amplifiers, confuse you, because both DC and AC are flowing in the primary of these.)

A further distinguishing feature, of course, is that there are no tubes or transistors associated with the transformer in the circuit.

Uses

Magnetic amplifiers are a means whereby a large amount of power can be controlled by a quite small amount of DC. They are not used for amplifying audio or other signals, but for controlling power used in industrial applications. For example, a magnetic amplifier may be used to control the AC current supplied to a heater, maintaining a constant temperature by means of a DC current derived from a temperature sensor.

Figure 3.14 Full-Wave Magnetic Amplifier

D2, D3 and D4. When the right-hand side of the AC input goes negative, electrons flow through D2 to the low side of the output. They return via L5, D3, D5 and L3 to the left (positive) side of the AC input.

When the left-hand side of the AC input goes negative electrons flow through L4, D6 and D4 to the low side of the output. They return via L5 and D1 to the right (now positive) side of the AC input.

In this way both half-cycles of the AC sine wave are used, which is twice as efficient as in the half-wave rectifier. However, there is no loss of efficiency in the circuit of Figure 3.13 when used for an AC output, of course.

TROUBLESHOOTING TABLE FOR POWER AMPLIFIERS *As heard in a speaker. For non-audio power amplifier read equivalent symptom as see on oscilloscope.	S Y M P T O M							
	Output absent or weak	Output inter-mittent	Output distorted	Oscillation Howling*	Hum*	Buzz*	Hiss*	Rasping or Crackling*
Vacuum Tube	X	X	X	X	X	X	X	
Transistor	X	X						
Coupling Capacitor	X	X						
Bypass or Decoupling Capacitor			X	X	X			
Defective Resistor	X	X					X	X
Feedback Capacitor	X	X	X				X	X
Broken Wire or Defective Insulation	X	X						
Defective Control								X
Misadjusted Control	X							
Dirty Contacts Anywhere	X	X						X
Incorrect Operating Voltages			X				X	
Defective Power Supply					X	X		X
Defective or Unsuitable Speaker	X		X					X
Neutralization Misadjusted				X				

4

OSCILLATORS

SINCE OSCILLATORS generate their own signals they do not
require an external input. This is the most obvious difference
between oscillators and the amplifiers you read about in chap-
ters 2 and 3. (However, you'll see that some oscillators have to be
synchronized with an external signal, so this "rule" is not always true.)

There are two types of oscillators: *L-C oscillators,* in which fre-
quency is determined by an inductance-capacitance network; and *R-C
oscillators,* in which frequency is determined by a resistance-capaci-
tance network.

In both types the active element is a vacuum tube or transistor
acting as an automatic switch that chops the DC supply current into a
series of pulses. In most R-C oscillators the output will be in the form
of pulses of various shapes. In an L-C oscillator the resonant circuit
transforms the chopped DC into sine waves, as you will see in the first
circuit we discuss: the *Hartley oscillator.*

L-C OSCILLATORS

HARTLEY OSCILLATOR

The Hartley oscillator is one of the most important and widely used
oscillator circuits. Figures 4.1 and 4.2 are two examples of this circuit.

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Distinguishing Features

The Hartley oscillator employs a vacuum tube or transistor connected in a *grounded-cathode* or *common-emitter* circuit.

There is no external AC input. Instead, a *resonant circuit* consisting of a fixed or variable capacitor in parallel with a *tapped inductor* is connected across what would be the input in an amplifier. (Compare Figures 4.1 and 4.2 with Figures 2.1 and 2.2 in chapter 2.)

Part of the inductor is connected between the cathode or emitter and "ground" (B—), or between the plate and collector and ground, to provide *positive inductive feedback,* as in Figures 4.1 and 4.2.

Uses

Hartley oscillators are used in a great many different circuits, including radio receivers and transmitters, audio oscillators and other applications where a sine wave signal is required.

Detailed Analysis

DC Subcircuits: In Figure 4.1 electron flow is from B—, via the lower portion of L1 to the tap, to the cathode of V; and from the plate of V back to B+.

In Figure 4.2 electron flow is from B— to the emitter of Q; and from the collector via L2 back to B+.

AC Input Circuits: In Figure 4.1, when power is applied current flows through the lower portion of L1 to the cathode of V, increasing
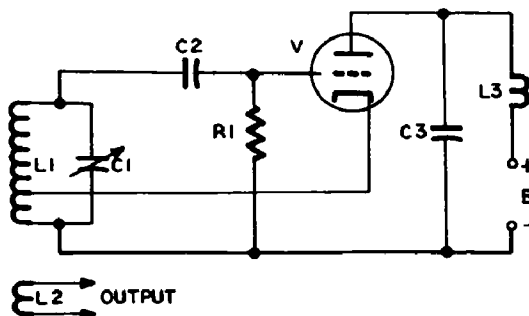
Figure 4.1   Hartley Oscillator (Cathode Feedback)
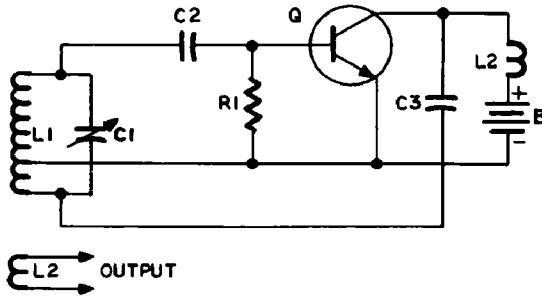
Figure 4.2   Hartley Oscillator (Collector Feedback)

as it overcomes the coil's inductive reactance. The changing flux lines induce a similar build-up of current in the upper portion of L1, which charges positively the upper side of C1. This increasing positive voltage is coupled to the grid of V by C2.

A positive bias on the grid of V causes the tube to conduct heavily, resulting in a further increase of current in L1, and even higher voltage on the grid of V.

The positive voltage on the grid would continue to rise indefinitely except that it increasingly attracts electrons in transit from the cathode to the plate, until they build up a negative charge that balances the positive voltage. The current through the tube levels off, and consequently the current through the lower part of L1. No more is induced in the upper part of the coil, because the flux has stopped changing. C1 now starts to discharge. Its positive charge dissipates faster than the negative charge on the grid, so the tube is gradually cut off, and ceases conducting.

C1 is discharging through L1. The excess of electrons on its lower side flows up through L1 to neutralize the positive charge on the upper side. However, as the nature of a coil is to oppose any change in the current flowing through it, this current goes on flowing even after C1 is completely discharged, until the upper side of C1 becomes negatively charged, reinforcing the negative bias on the grid of V. Eventually the negative charge on the upper side of C1 builds up sufficiently to stop the current flowing through L1, and now the excess of electrons begins to flow in the opposite direction. This continues until the negative charge has been returned to the lower side of C1 and a deficiency of electrons makes the upper side positive again.

The restoration of a positive charge to the upper side of C1 is coupled by C2 to the grid of V, and starts the tube conducting again,

so that the complete cycle is repeated. This goes on, cycle succeeding cycle, as long as power is applied to the circuit.

The frequency of oscillation depends upon the reactance of L1 and the capacitance of C1, as their combination determines the rate at which the charge of electrons is switched back and forth between the two sides of C1.

In Figure 4.2 the only difference is that the lower portion of L1 is in series with the collector, so that the feedback is from the output side of the transistor, and is therefore of opposite phase to the input. The tap on L1 is therefore connected to the low side of the circuit instead, so as to have the feedback in proper phase to reinforce the oscillations in the grid.

AC Output Subcircuits: The current flowing to and fro in L1 builds up and dies down in such a way that the voltage across it alternates between positive and negative in the smooth curve we call a sine wave. These sine waves are coupled inductively into the output coil L2.

COLPITTS OSCILLATOR

The Colpitts oscillator is very similar to the Hartley oscillator, except that it uses capacitative feedback instead of inductive feedback. Figures 4.3 and 4.4 are examples of this circuit.

Distinguishing Features

The Colpitts oscillator employs a vacuum tube or transistor connected in a *grounded-cathode* or *common-emitter* circuit.

There is no external input. Instead, a resonant circuit consisting of an inductor in parallel with *two capacitors in series* (or a split-stator variable capacitor, or the equivalent), which is the capacitative opposite number of the Hartley tapped inductor, is connected in a similar way to give *positive capacitative feedback.*

Uses

Colpitts oscillators are used in a great many different circuits, including radio receivers and transmitters, audio oscillators and other applications where a sine wave signal is required.

Detailed Analysis

DC Subcircuits: In Figure 4.3 electron flow is from B— via V and L2 to B+. In Figure 4.4 it is from B— via Q, R3 and L2 to B+. Bias for Q is stabilized by R1 and R2.

AC Subcircuits: In Figure 4.3, when the oscillator is first turned on current flows through L2, causing a voltage drop which charges C3. The charge on C3 starts oscillation in the resonant circuit consisting of L1, C1, C2 and C3. (As far as resonance is concerned the three capacitors count as one.) The voltage developed across C2 is the feedback voltage, which is applied between the grid and cathode of V. As
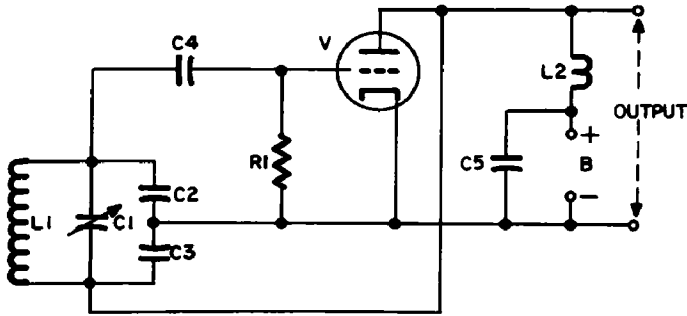
Figure 4.3   Basic Colpitts Oscillator
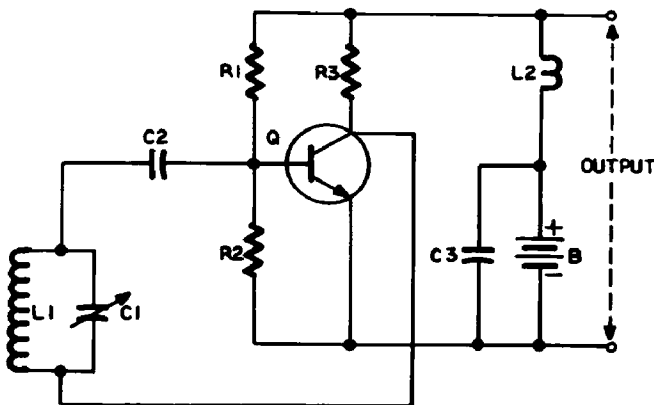
Figure 4.4   VHF Colpitts Oscillator

this voltage increases positively it causes the resistance of V to decrease, so that it conducts more. This, in turn, increases the current flow through L2, and charges C3 more. Eventually the electrons collecting on the grid of V balance the increase in the positive voltage, as you saw in the Hartley oscillator, and C2 starts to discharge through L1.

The amount of feedback depends upon the ratio of the values of C2 and C3. The smaller capacitor will have the higher reactance, and will have the greater voltage drop across it. If this is C2, a higher voltage will be applied between grid and cathode; if C3, a lower voltage.

C1 is a variable capacitor, which allows the resonant circuit to be tuned to the desired frequency. If it is omitted, the resonant circuit will oscillate at a single frequency determined by the combination of L1 and C2 and C3 (which will act as a single capacitor).

In Figure 4.4, the capacitors C2 and C3 of Figure 4.3 have been omitted, but otherwise the circuit is the same. At the higher frequencies used in TV and FM tuners the base-emitter capacitance of Q replaces C2, and the collector-emitter capacitance of Q replaces C3. If you were to sketch in these capacitances you'd have the circuit of Figure 4.3 again, except for a transistor instead of a vacuum tube.

The circuit in Figure 4.4 is also known as the Ultra-Audion oscillator. When it was invented it was not immediately recognized for what it was—a VHF Colpitts oscillator. It doesn't matter which name you use.

ELECTRON-COUPLED OSCILLATOR

Figure 4.5 shows an electron-coupled oscillator.

Distinguishing Features

The electron-coupled oscillator employs a *pentode or tetrode* vacuum tube in a *grounded-cathode* circuit.

There is no external input. Instead, a Hartley or Colpitts resonant circuit is connected across what would be the input in an amplifier.

The vacuum-tube cathode, control grid and screen grid are connected as if they were the cathode, grid and plate of the triode in Figure 4.1. The output is taken from the pentode plate.

Uses

Triodes provide considerable capacitative coupling between input and output. In some cases this can be a problem, as, for example, when loading the output causes a frequency shift in the resonant circuit in the input. In circuits subject to this, and where it would be a disadvantage, the isolation between input and output provided by a pentode or tetrode vacuum tube in an electron-coupled oscillator is one answer.

Detailed Analysis

DC Subcircuit: In Figure 4.5 electron flow is from B— via the lower portion of L1 to the cathode of V, and thence from the plate via L2 and the screen grid via R2 back to B+.

AC Subcircuits: The circuit in Figure 4.5 is a Hartley oscillator, identical with that in Figure 4.1, except that the output is taken from the plate of V. The cathode, control grid and screen grid of V act as a triode which is kept cut off most of the time by the negative voltage on the control grid. When the grid goes positive a strong current pulse flows through the tube, causing output signals from both screen grid and plate. The screen-grid signal provides positive feedback via C3 to maintain oscillation, the action of this part of the circuit being exactly as described previously for the Hartley oscillator. In the plate circuit the output signal voltage across L2 is coupled to the next stage. A resonant circuit similar to that in Figure 4.6 may replace L2.
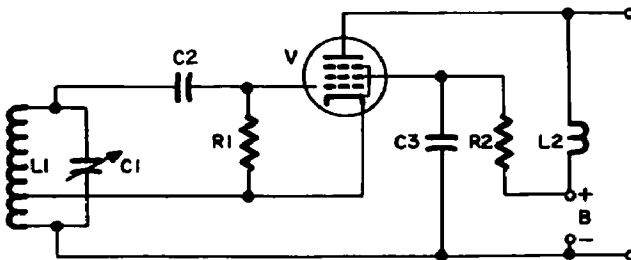
Figure 4.5   Electron-Coupled Oscillator

TUNED-PLATE, TUNED-GRID OSCILLATOR

Figure 4.6 illustrates a tuned-plate, tuned-grid oscillator, so called because there are tuned resonant circuits in both input and output circuits.

Distinguishing Features

A triode or transistor is connected in a *grounded-cathode* or *common-emitter* circuit.

There is no external input. Instead, a tuned resonant circuit is connected across what would be the input in an amplifier.

A tuned resonant circuit in the plate or collector circuit provides the means of coupling the signal into the next stage.

Uses

This circuit is not used as much as the Hartley or Colpitts circuits, but you will meet it frequently in the form of a *crystal oscillator* (described next).

Detailed Analysis

DC Subcircuit: In Figure 4.6, electron flow is from B— via V, L2 and L3 back to B+.

AC Subcircuits: When power is turned on electrons flow through the tube and into the side of C3 connected to the plate. At the same
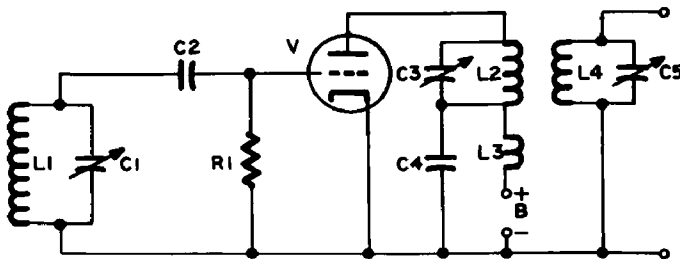
Figure 4.6   Tuned-Plate, Tuned-Grid Oscillator

time, current begins to flow through L2. The resonant circuit C3–L2 begins oscillating, and at the correct moment a positive voltage pulse is fed back to the grid, through the plate-grid capacitance.

The effect of this feedback voltage is to drive the grid in a positive direction, which increases current through the tube and charges C3 still further. However, the positive grid now attracts electrons from the stream of electrons passing from cathode to plate, and they start to flow back to the cathode via R1. This resistor has a high resistance, so at this stage electrons build up on the side of C2 connected to the grid faster than they can leak away through R1.

When the positive feedback signal was swinging the grid in a positive direction it was also coupled through C2 to C1, and caused a positive charge to appear on the upper side of this capacitor. But as electrons build up on C2 the grid gradually becomes negative and the tube ceases to conduct. When this happens the feedback voltage disappears and C1 starts to discharge through L1. This causes the resonant circuit C1–L1 to start oscillating at a frequency determined by the inductance of L1 and the capacitance of C1.

Meanwhile C2 completes discharging through R1, and the grid loses its negative voltage, so that V can conduct again. The resonant circuit C3–L2 gets another current pulse to sustain oscillation, and in turn sends one back through V as before, so that the same cycle is repeated continuously as long as power is applied to the circuit.

C3 has to be adjusted so that the frequency of C3–L2 is slightly lower than that of L1–C1 if the feedback voltage is to be in proper phase. The oscillations of the output circuit are coupled into the next stage via L4 and C5, which also form a tuned resonant circuit.

CRYSTAL OSCILLATORS

Figure 4.7 illustrates a crystal oscillator, which is identical to a TPTG oscillator, except that a crystal replaces L1-C1-C2 in Figure 4.6.

Distinguishing Features

A triode or transistor is connected in a *grounded-cathode* or *common-emitter* circuit.

There is no external input. Instead, a *crystal* (X) is connected across what would be the input in an amplifier.

A tuned resonant circuit in the plate or collector circuit provides the means of coupling the signal into the next stage.

There is no visible feedback path.

Uses

Crystal oscillators are much more stable than other oscillators; consequently they are preferred where frequency must be controlled to close tolerances. Examples are found in radio transmitters operating on fixed frequencies (such as broadcast stations), precision signal generators, counters and similar applications.

Detailed Analysis

The operation of the circuit in Figure 4.7 is identical with that in Figure 4.6. The crystal (X) replaces the resonant circuit in the grid circuit of the TPTG oscillator.

A quartz crystal will vibrate mechanically at a frequency depending upon its thickness, therefore this frequency is fixed by physical considerations only. In the oscillator the feedback pulses excite mechanical vibrations in the crystal which in turn generate electrical vibrations exactly as if the crystal were a resonant circuit consisting of inductance, capacitance and some resistance. This interaction between mechanical and electrical functions in a crystal is called the *piezoelectric effect.*

As the dimensions of the crystal are affected by temperature, the frequency is temperature-sensitive. For very accurate frequency control, crystals are installed in *crystal ovens,* in which they are maintained at a constant temperature by a thermostat.
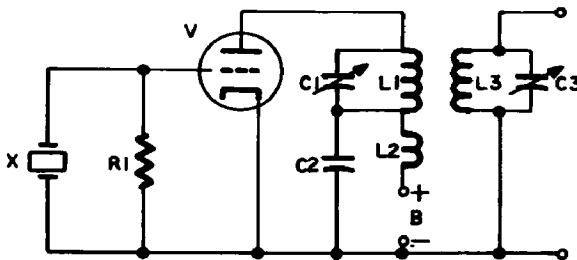
Figure 4.7 Crystal Oscillator

Circuit Variations

A crystal can replace an L-C circuit in other types of oscillator. For example, Figure 4.8 shows how this can be done with a Colpitts oscillator. Compare this circuit with the one shown in Figure 4.3.
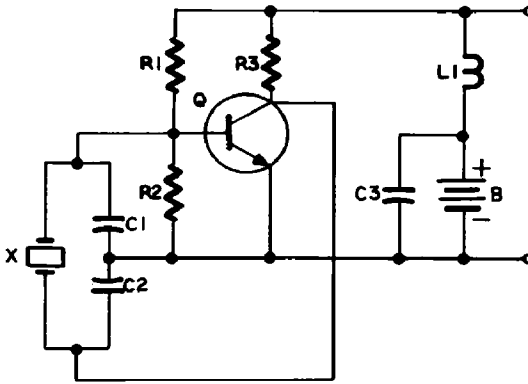
Figure 4.8   Crystal Oscillator (Colpitts Type)

ARMSTRONG, OR TUNED-GRID OSCILLATOR

Figure 4.9 shows an Armstrong oscillator, with the tuned circuit in the grid circuit.

Distinguishing Features

A vacuum tube or transistor is connected in a *grounded-cathode* or *common-emitter* circuit.

There is no external input. Instead, a tuned resonant circuit is connected across what would be the input in an amplifier.

A feedback circuit inductively couples the output signal to the grid resonant circuit.

Uses

This circuit is not used as much as the Hartley or Colpitts circuits, but is very similar to the popular blocking oscillator circuit discussed next, to which it makes a good introduction.
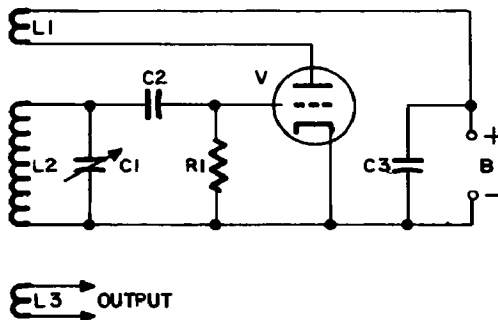
Figure 4.9   Armstrong or Tuned-Grid Oscillator

Detailed Analysis

DC Subcircuit: In Figure 4.9 electron flow is from B— via V and L1, back to B+.

AC Subcircuit: The operation of this oscillator is similar to that of the TPTG oscillator, except that feedback is by means of inductive coupling between L1 and L2 instead of via the interelectrode capacitance of the tube. When power is turned on, the plate current starts to flow through L1, building up a magnetic field which induces a voltage in L2. This induced voltage charges C1, and the resonant circuit begins to oscillate in the same way as in the Hartley oscillator discussed at the beginning of the chapter.

R-C (RELAXATION) OSCILLATORS

Another name for an R-C oscillator is relaxation oscillator. Any oscillator in which the frequency is determined by the rate at which a capacitor can be charged and discharged through a resistance is an R-C or relaxation oscillator. Multiplying the value of the resistance (in ohms) by the value of the capacitance (in farads) gives the time constant or period, and its reciprocal is the oscillator frequency.

BLOCKING OSCILLATOR

A blocking oscillator is a well-known type of relaxation oscillator. Figure 4.10 illustrates a blocking oscillator as used in a TV set to generate a sawtooth waveform.

Distinguishing Features

A triode or transistor is connected in a *grounded-cathode* or *common-emitter* circuit.

The AC input subcircuit contains a *transformer* by which feedback from plate circuit to grid circuit is obtained. You might possibly think that this makes it an L-C oscillator, but another look at the transformer will show that there is no parallel capacitor to tune it to resonance, so it is not part of a resonant circuit.

There is usually an external input (a *synchronizing signal*) which is another indication that this is different from oscillators discussed previously.

Uses

Blocking oscillators are used in many TV circuits to provide the driving signals for vertical (field) and horizontal (line) deflection in the picture tube. These signals take the form of a sawtooth, in which a steady linear rise in voltage is followed by a sharp drop-off.

Detailed Analysis

DC Subcircuit: In Figure 4.10 electron flow is from B— via V, the secondary winding of T1, R3 and R4, to B+.

AC Subcircuits: When power is first applied to this circuit an increasing plate current flows through the upper winding of T1, and because the magnetic field is building up it induces a voltage in the lower winding, with a polarity that couples through C1 to make the tube grid positive. This attracts electrons to the grid, and a negative charge begins to build up on C1 until V is cut off. It doesn't take long to charge C1 from the grid, because the tube internal resistance is low between the cathode and grid when the latter is positive. However, when the tube cuts off it is as if a switch had opened. The only way for
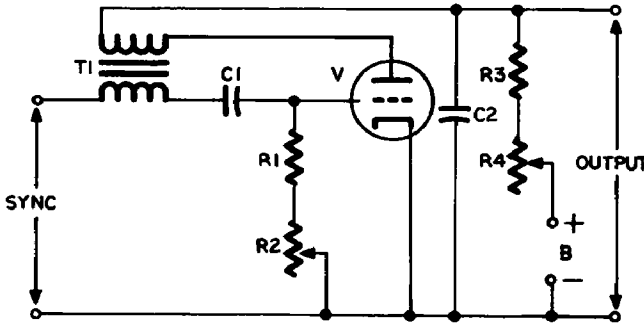
Figure 4.10   Blocking Oscillator (Vacuum Tube)

C1 to discharge is through R1 and R2. But these resistors have comparatively high values, so it takes C1 considerably longer to discharge than it did to charge. This means that the time during which the tube is conducting is much shorter than the time when it is not. In short, the tube is an automatic switch which is normally "off," but which turns "on" briefly to allow short bursts of current.

So far the circuit has been performing somewhat like the Armstrong oscillator in the previous section. But something different is happening in the plate circuit. While the tube is "turned off" the B voltage starts to charge C2 by pulling electrons away from its upper side. The values of C2, R3 and R4 are chosen so that C2 will not charge to more than about a tenth of the B+ voltage before the tube conducts again. When this happens the burst of electrons supplied by the current pulse through V wipes out the positive charge on C2 (by restoring the missing electrons), and the voltage drops back to its initial value. The result is a sawtooth output voltage, with a slower, steady rise and a faster, sudden fall. Its amplitude is adjusted by R4, which in a TV set would be the height control in a vertical deflection circuit, or the width control in a horizontal deflection circuit.

The frequency of this sawtooth output signal is determined by the time constant of C1, R1 and R2. Since R2 is variable it can be used to vary the frequency of the oscillator. In a TV set this variable resistor is the hold control.

Without a synchronizing signal the oscillator would free-run at its own frequency, which would not be exactly that of the TV signal, so you would get a picture that drifted or rolled. A sync signal is therefore introduced as shown. In a vertical deflection circuit the sync signal will consist of a sequence of positive pulses at the vertical sync

rate (60 hertz). On arrival at the grid each positive pulse will cause the tube to turn on, and the circuit will perform one cycle of oscillation and one sawtooth, provided that R2 has been adjusted so that the grid cycle is almost at the point where the tube would have turned on of its own accord.

In a horizontal deflection circuit the sync signal frequency is compared with the oscillator frequency in a *frequency comparator* circuit (see chapter 12). The frequency difference becomes a DC voltage. If the oscillator is too slow the voltage will be positive, if too fast it will be negative. This voltage is applied to the grid of the tube or base of the transistor. A positive voltage will decrease the negative voltage on C1, so that it will discharge faster, speeding up the frequency of oscillation, while a negative voltage will have the opposite effect. As the DC voltage is proportionate to the frequency difference, the frequency will be adjusted automatically to that of the sync signal.

Circuit Variations

Transistor blocking oscillators work on the same principle as vacuum-tube blocking oscillators, with some variations due to the different characteristics of transistors. In Figure 4.11 you see an example of one used in solid-state television sets. The feedback is from collector to base, as in the vacuum-tube circuit you've just seen. The free-running frequency is determined by C2, R1 and R2 in the same way as C1, R1 and R2 in Figure 4.10. Diode D1 is provided to protect the
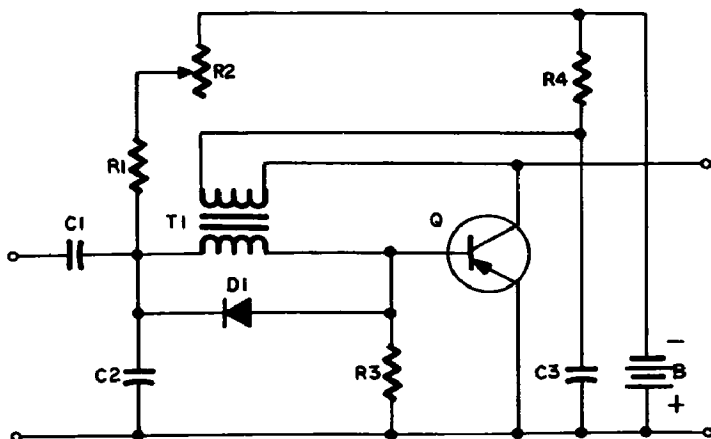
Figure 4.11   Blocking Oscillator (Transistor)

transistor from damage when it cuts off. When this happens the sudden collapse of the magnetic field in T1 generates a sharp voltage pulse of opposite polarity which is high enough to cause the transistor to break down if not suppressed. The diode is connected with its polarity such that it has no effect on the positive feedback or sync pulses, but short-circuits the reverse spike which we don't want. R4 and C3 are the sawtooth-forming combination, operating in the same way as R4, R3 and C2 in Figure 4.10. The height control in this circuit is located elsewhere. (You will often find it in the following stage instead of where we show it in Figure 4.10.)

In some transistor circuits the feedback is from emitter to base instead of from collector to base. Also, a PNP transistor would perform just as well, provided that we reversed the voltage polarity, including that of the sync pulses.

MULTIVIBRATOR

Multivibrators are also R-C or relaxation oscillators. There are two principal types, the *plate-coupled* (Figure 4.12) and the *cathode-coupled* (Figure 4.13).

Distinguishing Features

Two vacuum tubes (or sections of a dual tube) or *transistors,* each connected in a *grounded-cathode* or *common-emitter* circuit, are interconnected in either of the following ways:

1. *Plate-Coupled:* The plate of each tube is connected via a capacitor to the grid of the other (in the case of transistors, read collector and base, of course).
2. *Cathode-Coupled:* The cathodes of each tube are connected to each other, and share a common cathode resistor. The plate of V1A is connected via a capacitor to the grid of V1B, but not vice-versa.

External input of a synchronizing or triggering pulse or DC control voltage is usual, as in the case of blocking oscillators.

Since a multivibrator circuit looks very like a flip-flop, check under flipflop in chapter 12 if you have any doubt about which it is.

Uses

Multivibrators are used in TV sets in the same way as blocking oscillators. They are also used in many industrial, military and space applications where a pulse output is required. Such uses are legion, but examples would include: timing pulse trains for multiplexing or time-sharing requirements for multi-channel communication and computer-controlled processes; cybernetic controls in guidance systems; sampling systems; and many more.

Detailed Analysis

DC Subcircuits: In Figure 4.12 electron flow is from B— through V1A and R1, and V1B and R4, back to B+. In Figure 4.13 electron flow is from B— to R3, and thence through V1A and R1, and V1B and R5, back to B+.

AC Subcircuits of Plate-Coupled Multivibrator: The circuit of Figure 4.12 is symmetrical. Each component in one half is duplicated in the other. It is a double switch, in which the tubes turn each other on and off alternately.

Actually, if the circuit were perfectly symmetrical it would be impossible to get it started, but as nothing is ever that perfect one tube will always begin to conduct before the other. For example, suppose V1A is just a fraction faster than V1B. As current begins to flow through R1 the voltage on V1A's plate starts to fall, and a negative-going pulse is coupled through C1 to the grid of V1B. This negative bias keeps on increasing as the current through V1A and R1 builds
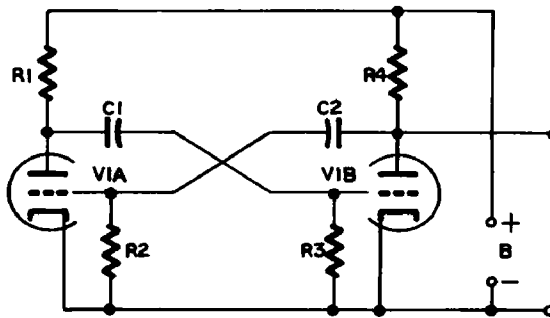
Figure 4.12   Plate-Coupled Multivibrator
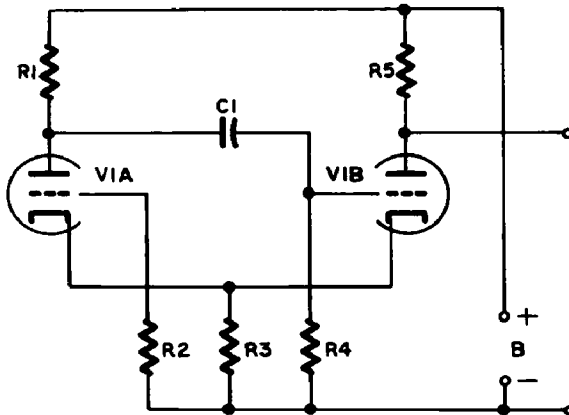
Figure 4.13   Cathode-Coupled Multivibrator

up, so that by the time V1A is conducting fully V1B is completely cut off.

However, when V1A's current levels off the negative charge on V1B's grid begins to leak away through R3 until V1B can conduct. When this happens its plate voltage falls, because of the potential drop across R4, and the negative-going voltage coupled to V1A's grid now starts to turn it off. This process continues back and fourth as long as power is applied to the circuit.

If we just consider what is happening on C2, we can see that when V1B is turned off no current flows through R4, so the side of C2 connected to V1B's plate charges up to the full B+ voltage. When V1B turns on, the voltage drops by the amount dropped across R4. Since V1B is switching on and off continuously we get an output from C2 which alternates between these two voltage levels.

The resulting signal is a symmetrical *square wave,* in a symmetrical multivibrator, but if the R-C combination C1–R3 has a different time constant to C2–R2 the duration of V1A's on and off times will be different from V1B's. This will give an asymmetrical output, in which the upper and lower voltage levels will not have the same duration.

AC Subcircuits of Cathode-Coupled Multivibrator: In Figure 4.13 the two halves of the multivibrator are not symmetrical as far as their components go, since there is only one coupling capacitor, C1. The action of this circuit is more like that of the blocking oscillator, where V1B is the tube and V1A the transformer. Let's see how this is.

Current flowing through V1B causes a voltage drop across R3, which is also V1A's cathode resistor. This voltage drop across R3

biases V1A's grid negatively, so that conduction in V1A decreases and its plate voltage rises. This rising voltage is coupled through C1 to V1B's grid, increasing conduction in V1B. This, in turn, increases the voltage drop across R3, and the bias on V1A's grid, so that eventually V1A is cut off altogether.

However, the increasing positive voltage coupled through to the grid of V1B disappears as soon as V1A cuts off, because C1 can only pass a *changing* voltage, not a DC voltage, and is replaced by a negative bias resulting from conduction through R3. This leads to a downward swing in the conduction rate through V1B, which reduces the voltage drop across R3, and the bias on V1A's grid. V1A begins to conduct and its plate voltage starts to fall. This negative-going change in its plate voltage is coupled through C1 to V1B's grid, until the tube is turned off. V1B remains turned off until the negative charge on its grid leaks away through R4. When it gets down to the level where V1B starts to conduct again a new cycle begins.

The output of this circuit is the same as in the plate-coupled multivibrator, a two-level DC voltage, the levels changing as V1B switches on and off. This DC signal becomes an AC signal by coupling it through a capacitor to the next stage.

Sawtooth Generator

By connecting a capacitor and resistor in series across the output, as was done in Figures 4.10 and 4.11, the output signal would become a sawtooth. The operation of the circuit would be the same as was explained for those circuits.

Sync Input

Sync input is similar to that for blocking oscillators, and works in the same way.

Circuit Variations

Transistors frequently replace tubes in substantially similar circuits, although to date transistor multivibrators are not used in TV sets. There are also multivibrators in which a triode and a pentode replace the two triodes. Such a circuit would be one in which the second stage had, for reasons of economy, to double as a power output amplifier.

Such a circuit is shown in Figure 4.14. The tubes shown are often half-sections of a dual tube.

At first you might not see much similarity between Figure 4.12 and Figure 4.14, but this is only because we have shown the entire circuit, in which V2 is also a power amplifier driving the vertical deflection coils of the picture tube. The plate of V1 is connected to the grid of V2 through C6, and the plate of V2 is connected back to the grid of V1 through R8, C5, R3 and C2. It is only this feedback loop that complicates the picture.

The output signal from the plate of V2 is far too strong to apply directly to the grid of V1, and must also be filtered to get rid of nearly all the sawtooth, not to mention some strong spikes on it, before it can be used to control V1. The resistors and capacitors through which it passes, together with R4 and C3, form a filter. You can read about filters in chapter 8, so we'll not take time to go into it here. There are several variations possible in the arrangement of the resistors and capacitors in the filter, but they all serve the same purpose, to transform a portion of V2's output into a form suitable for application to V1's grid.

The sawtooth is formed by the charging and discharging of C4,
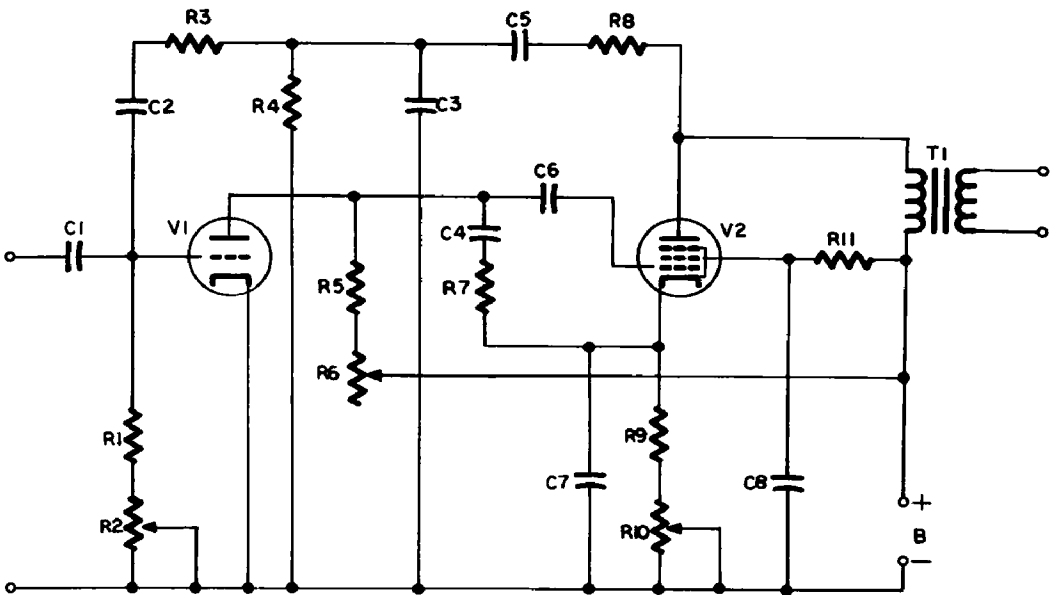
Figure 4.14   Plate-Coupled Multivibrator for TV Vertical Deflection

and its amplitude is controlled by R6 (the height control), so this part of the circuit is the same as C2, R3 and R4 in Figure 4.10. Similarly, R2 is the hold control. The other control, R10, is the linearity control. It varies the DC bias on the grid of V2 in the same way as the control shown in the video amplifier in Figure 2.12. It allows you to shift the operating point of the tube to the proper point on its characteristic curve to give a linear sawtooth output. (See Appendix for explanation of vacuum-tube characteristic curves and class of operation.)

T1 is the vertical deflection output transformer, R11 the screen-grid voltage-dropping resistor, and C8 the screen-grid bypass capacitor.

SIMPLE RELAXATION OSCILLATOR

Figure 4.15 shows the simplest form of relaxation oscillator.

Distinguishing Features

Capacitor and resistor in series with power source, shunted by a gas-filled tube or lamp.

Uses

A simple relaxation oscillator is not stable or linear enough for TV circuits, but has practical applications elsewhere. In simple oscilloscopes it has been used to generate the sawtooth sweep signal, and it can be used also to make a light flash at a chosen frequency, as in a strobe lamp or the warning lamps used in road repairs.

Detailed Analysis

In Figure 4.15 the battery, B, charges C through R at a rate depending upon the time constant $C \times R$. The gas in P ionizes when the voltage across C (which is also across P) reaches a certain critical level. P then becomes a low resistance, discharging C rapidly. The lamp then reverts to its original condition of high resistance, and C begins to charge again.
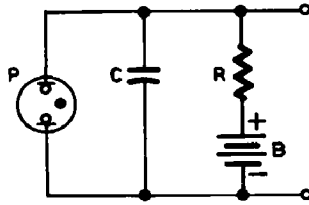
Figure 4.15   Simple Relaxation Oscillator

Circuit Variations

By using a *discharge tube* instead of a neon lamp a sync signal can be applied to its grid to trigger the tube, thus synchronizing the rate of discharge of C to the external source.

A *unijunction oscillator* is a similar circuit, where the UJT is a solid-state equivalent of a discharge tube, as shown in Figure 4.16, where C1 and R2 are the sawtooth-forming combination. When the voltage on C1 reaches a level high enough to trigger Q, the resistance between the emitter (arrow) and base 1 (connected to R1) drops, and C1 discharges through Q and R1. The voltage on the emitter now is back where it was, the UJT turns off, and C1 starts to charge again.

A sync signal applied between the emitter and the low side of the circuit will control the rate of firing, as with a discharge tube.

This oscillator can also give a pulse output similar to that of a multivibrator (a rapid switching between two voltage levels) by taking the output from across R1 instead of C1.
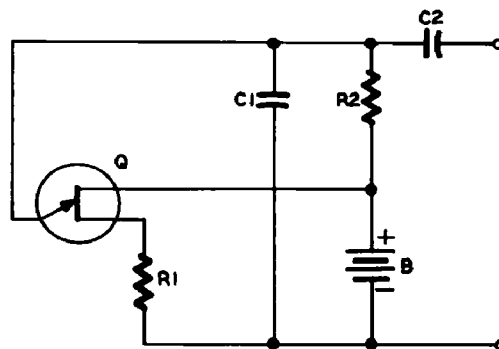
Figure 4.16   UJT Relaxation Oscillator

TROUBLESHOOTING TABLE FOR OSCILLATORS	S Y M P T O M						
	Oscillation absent or weak	Oscillation Intermittent	Oscillates at Wrong Frequency	Distorted output			
Vacuum Tube	X	X		X			
Transistor	X	X					
Coupling Capacitor	X	X					
Bypass or Decoupling Capacitor			X				
Defective Resistor	X	X					
Broken Wire or Defective Insulation	X	X					
Defective Control		X					
Misadjusted Control	X						
Dirty Contacts Anywhere	X	X					
Incorrect Operating Voltages	X		X				
Defective Power Supply	X		X				
Feedback Phase Reversed	X						

5

MODULATION

S INCE VIDEO AND AUDIO signals cannot be propagated
through space they must be carried by radio signals that can.
Adding audio or video information to a radio "carrier wave" is
called *modulation*. In this chapter we shall discuss circuits used in
amplitude modulation (*AM*), *frequency modultion* (*FM*) and *phase
modulation* (*PM*), all of which are used in color television transmis-
sion. *Pulse modulation*, which is used in *telemetry* with spacecraft, will
also be explained.

The modern radio and TV receiver is a *superheterodyne receiver*,
in which the incoming modulated radio carrier is mixed with another
radio-frequency signal generated in the receiver itself, and converted
to an *intermediate frequency* (*IF*), which is then amplified in the *IF
amplifier* (chapter 2). Since this is also modulation, we include mixers
and converters in this chapter.

AMPLITUDE MODULATION

In AM we wish to vary the power of the transmitted signal in
accordance with audio information, so we need a circuit in which the
output of an RF amplifier is controlled by an audio signal. In such
an amplifier the carrier signal generated in a previous stage is ampli-

fied by the addition of power by means of a vacuum tube or transistor. The output-signal amplitude depends upon the type of circuit, tube characteristics and operating voltages. If one of the operating voltages is varied in accordance with an audio signal, the output power of the carrier will be varied proportionately.

PLATE MODULATION

In plate modulation, varying the plate voltage causes the DC current through the RF power amplifier tube to vary, thereby varying the output power. Figure 5.1 illustrates a typical circuit.

Distinguishing Features

The DC plate supply for the RF power amplifier comes through the secondary winding of a *modulation transformer* in the output circuit of an audio power amplifier. Both amplifiers may be single-ended or push-pull.

Uses

This circuit will be found in AM transmitters of all sizes.

Detailed Analysis

In Figure 5.1 the audio power amplifier is the same as those discussed in chapter 3, and its operation is identical. Similarly, the RF power amplifier is also the same as those described in the same chapter.

B+ current for the RF amplifier plate circuit has to pass through the secondary of T3. The audio signal from V3 and V4 is also present in the secondary of T3, and its variations in amplitude add to or subtract from the DC supply voltage. The resulting variations in the plate supply voltage cause corresponding variations in the gain of V1 and V2, so that the output amplitude of the carrier fluctuates in accordance with the audio signal.

The degree to which the carrier is modulated depends upon the power of the audio signal, and is expressed as a percentage. In 100 percent modulation the carrier is driven all the way to zero at its minimum amplitude, and to double its "resting" amplitude at the maximum value. This requires that the audio power amplifier be capable of as great an output as the RF power amplifier. This might seem a drawback, but plate modulation is much more efficient than grid modula-
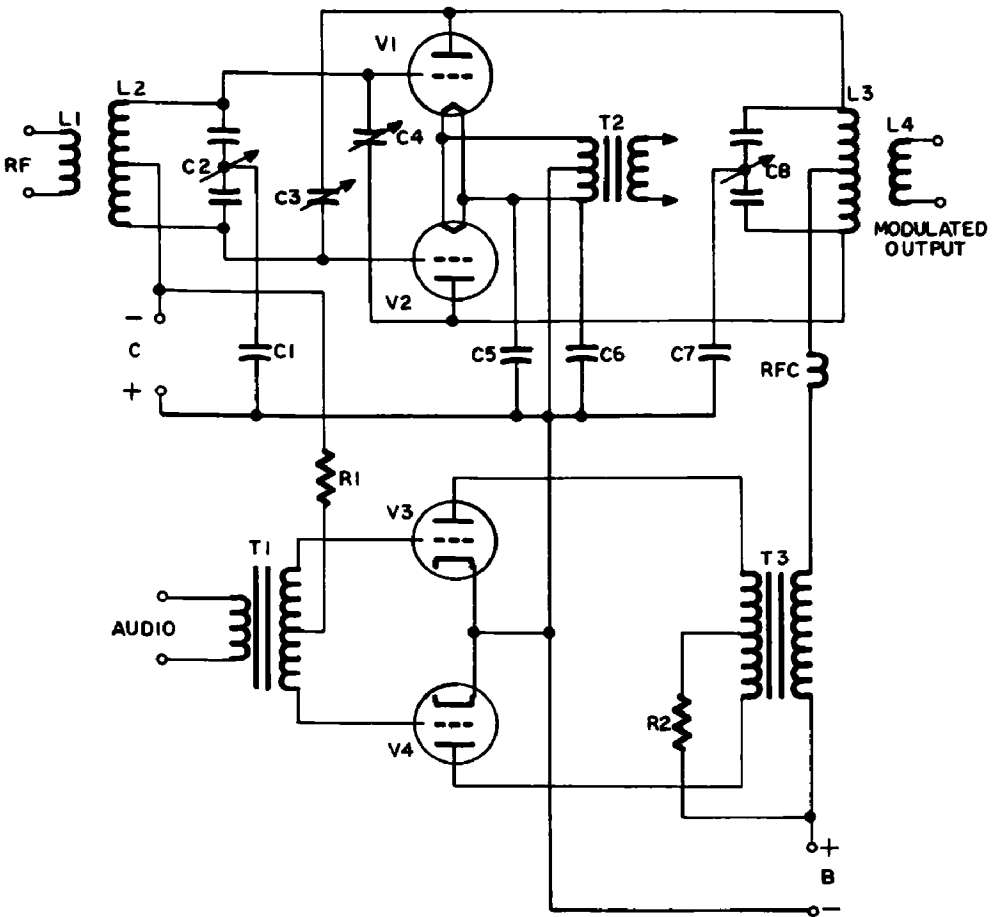
Figure 5.1   Plate Modulation

tion because the RF power amplifier can be operated Class C (see Appendix).

GRID MODULATION

Figure 5.2 shows a grid modulation circuit.

Distinguishing Features

The grid-bias supply voltage to the RF power amplifier is routed through the secondary winding of the modulation transformer in the audio power amplifier output. Both amplifiers may be single-ended or push-pull.

Uses

This circuit will be found in AM transmitters of all sizes.

Detailed Analysis

In Figure 5.2 both amplifiers are similar to those discussed in chapter 3, so will not be analyzed in detail here.

C— (grid bias voltage) for the RF amplifier is routed through the secondary winding of T1. The audio signal from V1 is also present in the secondary of T1, and its variations in amplitude add to or subtract from the DC supply. The resulting variations in the grid bias voltage cause corresponding variations in the gain of V2, so that the output
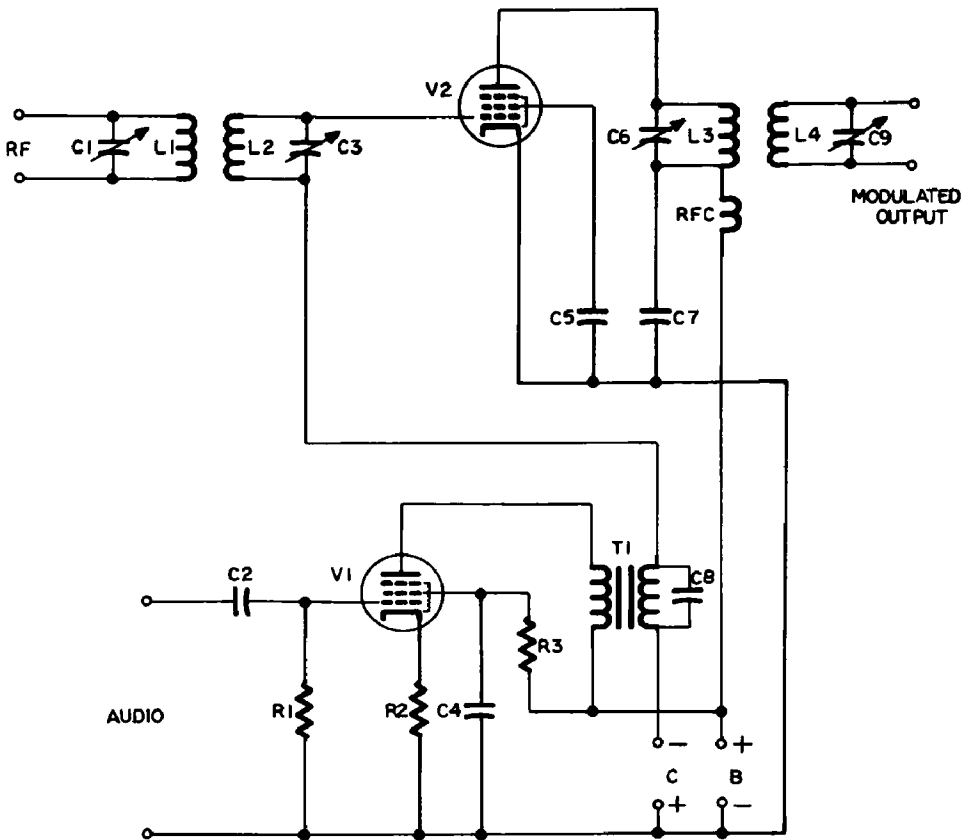
Figure 5.2   Grid Modulation

amplitude of the carrier fluctuates in accordance with the audio signal.

The secondary of T1 is shunted by C8. This capacitor's value is such that while it does not bypass T1 for audio it does for RF. In this way a connection is provided from the lower end of L2 via C8 and the grid-bias power supply to the cathode of V2.

In grid modulation the audio power amplifier does not have to be as powerful as the RF amplifier it modulates, since the output power must all come from the RF amplifier. This amplifier can only be operated Class B, however, since the audio information would be lost in Class C operation. In Class B operation (see Appendix) the positive swings of the modulating signal are completely reproduced in the tube. The cut-off negative swings are restored by the "flywheel" action of the output tank circuit C6–L3, as explained in chapter 4.

FREQUENCY MODULATION

In FM we wish to vary the *frequency* of the transmitted signal in accordance with audio information, so we need a variable frequency oscillator in which the frequency of the signal generated is not fixed, but is controlled by an audio signal. The variable-frequency carrier may then be amplified in subsequent RF amplifier stages as necessary for broadcasting.

Varying the frequency of an oscillator can be achieved in various ways. The two most well known are the *reactance circuit* and the *Armstrong balanced modulator.*

REACTANCE CIRCUIT

In Figure 5.3 a Hartley oscillator is shown controlled by a reactance circuit. The other sections of the FM transmitter are illustrated in block form.

Distinguishing Features

The Hartley oscillator (V2) is identical with that shown in Figure 4.1, so its distinguishing features need not be repeated here.

The reactance circuit (V1) is similar to the audio voltage amplifier of Figure 2.1, except for the addition of C2 and the substitution of L1 for R2. An audio amplifier does not handle frequencies high enough

to require an RF choke in its output. These two items, taken in conjunction with its position in the overall circuit, should make it difficult to mistake this circuit for an audio voltage amplifier despite its apparent similarity.

Uses

It is employed in FM transmitters.

Detailed Analysis

Analysis of the Hartley oscillator circuit is in chapter 4. Analysis of the reactance circuit is as follows:

DC Subcircuit: In Figure 5.3 electron flow is from B— via R3 to V1's cathode, and from its plate via L1 to B+. A DC voltage produced by the *discriminator* (see chapter 6) is applied to V1's grid via R1. R1 and C1 form a *low-pass filter* (see chapter 8).

AC Subcircuits: To L3 (the inductor in the oscillator resonant circuit) the entire reactance circuit looks like a capacitor. This is because the current in the circuit leads the voltage by 90 degrees, due to the predominant influence of C2. This capacitor has a capacitive reactance at the resonant frequency that is ten times the resistance of R2. Since the reactance circuit is equivalent to a capacitor connected in parallel to L3, any change in its apparent reactance will affect L3 as if a change in actual capacitance had taken place, and consequently the resonant-circuit frequency will change.

The apparent reactance of the reactance circuit includes the resistance of V1. But the tube's resistance varies with the signal on the grid. When an audio signal is applied, the tube's resistance varies with the audio voltage. Consequently, the apparent reactance of the circuit varies at an audio rate, with the result that the frequency of the oscillator resonant circuit varies accordingly. In this way the amplitude and frequency of the audio signal are impressed on the carrier as the amount of deviation and rate of deviation from the resting frequency of the FM carrier.

R3 is the cathode resistor, selected to give the required bias voltage for V1's grid as in an amplifier, and C3 bypasses it to prevent
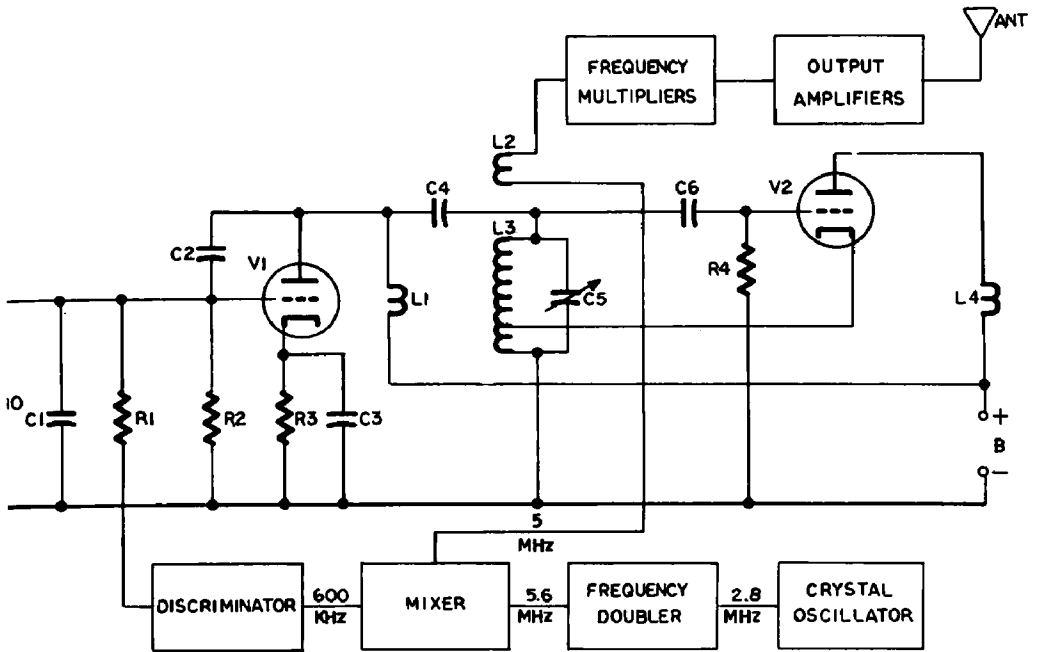
Figure 5.3   Reactance Circuit and Oscillator for FM Transmitter

degeneration, as explained in chapter 2. L1 is an RF choke, to keep the carrier signal out of the power supply. C4 is a DC blocking capacitor to keep the power supply from being short-circuited through L3.

The modulated carrier is coupled inductively from L3 to L2, and goes via frequency multipliers (see chapter 12) and output amplifiers (see chapter 3) to the antenna. If the modulated carrier is 5 megahertz, as in Figure 5.3, the frequency multipliers will raise it to the radio frequency. In the FM broadcast band this is between 88 and 108 megahertz.

The carrier frequency of an FM broadcasting station must not be allowed to drift more than 2 kilohertz from its assigned frequency. This means that a broadcast frequency of 100 megahertz (approximately in the middle of the band) must be held to a tolerance of

±0.002 percent. Only a crystal-controlled oscillator can be this stable. Obviously, you cannot control a variable-frequency oscillator directly with a crystal as it would no longer be variable; so an indirect method must be used.

A separate crystal oscillator (see chapter 4) is provided to supply a very stable signal at a slightly higher frequency than the resting frequency of the Hartley oscillator. The two frequencies are combined in a *mixer* (discussed later in this chapter), and the *difference signal* is applied to a discriminator.

If the carrier begins to drift the discriminator converts the change in the difference-signal into a DC voltage, which changes the bias on the grid of V1 so as to bring the resonant frequency of the Hartley oscillator back to its proper value. Audio voltage feedback is filtered out of the DC voltage from the discriminator by C1 and R1.

Circuit Variations

A reactance can be made inductive instead of capacitive by substituting an inductor for C2. In this case the circuit will have inductive characteristics: the voltage will lead the current. The resonant frequency of the oscillator will vary with the varying inductance of the reactance circuit.

An inductive effect will also be obtained by interchanging R2 with C2, and making R2 ten times the value of C2 at the resonant frequency. The grid voltage now appears across C2, and because it lags the current, the plate current of V1 will lag the oscillator voltage, so that the reactance circuit will look like an inductor to L3.

Similarly, if an inductor is used in the place of C2, now between the grid and low side of the circuit, the reactance circuit will present a capacitive appearance to L3.

In the three variations just mentioned an additional DC blocking capacitor is required in series with the inductor or resistor connected between the plate and grid of V1. A large value capacitor is used so it will offer virtually no reactance to the resonant frequency, while keeping the plate voltage from reaching the grid.

ARMSTRONG BALANCED MODULATOR

Another method of FM is shown in Figure 5.4, which illustrates the Armstrong balanced modulator.

Distinguishing Features

The balanced modulator in the upper part of the schematic consists of a push-pull output stage which resembles an audio power amplifier (see chapter 3) with its output coupled to a single-tube audio voltage amplifier.

It differs from an actual audio push-pull amplifier, however, because the audio output transformer is replaced by the three coils L1, L2 and L3; and the screen grids of V1 and V2 are connected to opposite ends of the secondary of the modulation transformer T1. The audio input is connected to the primary. The output from an oscillator is connected to the input. (There may be an amplifier between the oscillator and the balanced modulator.)

Uses

It is used in FM transmitters.

Detailed Analysis

DC Subcircuits: In Figure 5.4 electron flow is as follows:

V1: From B— via R4 to the cathode; from the plate via R10 back to B+; and from the screen grid via the upper half of T1 and R9 back to B+.

V2: From B— via R5 to the cathode; from the plate via R11 back to B+; and from the screen grid via the lower half of T1 and R9 back to B+.

V3: From B— via R7 to the cathode; from the plate via R6 back to B+; and from the screen grid via R8 back to B+.

V4: From B— via R13 to the cathode; from the plate via R18 back to B+; and from the screen grid via R14 back to B+.

V5: From B— via R16 to the cathode; from the plate via R6 back to B+; and from the screen grid via R17 back to B+.

Grid bias for all tubes is determined by their cathode resistors.

AC Subcircuits: The master oscillator is a crystal oscillator with a tightly controlled frequency, typically of 200 kilohertz, so you can see these amplifiers will not be handling RF. The oscillator signal is applied to the input of V3 and also to the grids of V1 and V2. The
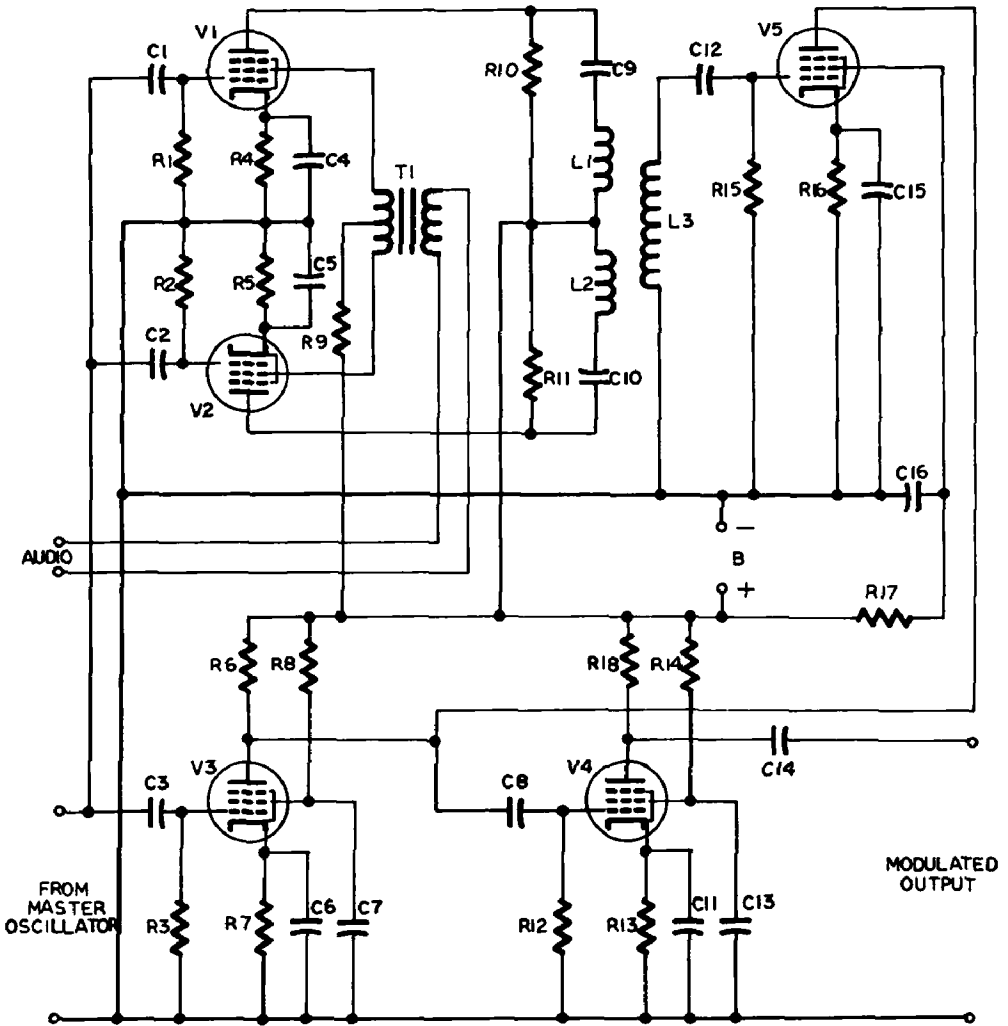
Figure 5.4   Armstrong Balanced Modulator

input circuit of V3 is identical with that of similar audio voltage am-
plifiers described in chapter 2.

The oscillator signal is applied simultaneously to each grid of V1
and V2 without inversion; so as far as this signal is concerned the
outputs of both tubes are in phase.

The audio input is obtained from an audio amplifier section in
which the audio has been amplified and *pre-emphasized* (see next
circuit in this chapter), hence this amplifier is called a *correction
amplifier*. The audio signal from the correction amplifier is applied

to the screen grids of V1 and V2 via the transformer T1. The secondary of T1 is tapped, so that when the upper end of it swings positively in respect to the tap the lower end is swinging negatively; consequently the screen grids receive identical signals of opposite phase. Notice that these screen grids are not bypassed by capacitors, so the audio voltage appears on them and controls the plate current in each tube.

When no audio signal is present, equally amplified 200-kilohertz signals from V1 and V2 flow in opposite directions through L1 and L2, and because their induced magnetic fields are of opposite polarity they cancel each other, so no voltage is induced in L3 by the unmodulated carrier.

However, when an audio signal appears on the screen grids of V1 and V2 the tube receiving a positive-swinging signal will amplify more (because the grid will be more positive) than the other, with its negative-going signal, which will conduct less. Consequently, the 200-kilohertz signals appearing in L1 and L2 will be of unequal amplitude, and so a voltage will be induced in L3 by the stronger one. As this alternates between L1 and L2 the polarity of the voltage of the signal induced in L3 will alternate also.

The values of L1–C9 and L2–C10 have been chosen so that the currents in them are in phase with the voltage output from V1 and V2, but the voltage induced in L3 lags by 90 degrees.

This signal in L3 consists only of the sidebands, because, as you saw, the carrier by itself cannot induce any signal in L3. After amplification in V5's circuit they are recombined with the carrier at the output of V3. Because their phase is shifting back and forth at the audio rate, they cause the phase of the carrier to do the same.

However, when the phase shifts, the frequency shifts also, so the carrier signal that arrives at the grid of V4 is frequency modulated. V4's circuit is designed to *limit* the amplitude of the signal to get rid of any AM, some of which is bound to be present at this point.

The path followed by the signal from here to the antenna is similar to that in the reactance-modulator circuit described previously. However, in practical systems a *converter* stage will also be used, with a *local oscillator* which must be crystal-controlled as well. This is to overcome difficulties arising from using an excessive number of frequency-multiplication stages. Converter circuits are discussed later in this chapter.

PRE-EMPHASIS CIRCUIT

Before leaving this section on FM circuits we must consider the pre-emphasis circuit illustrated in Figure 5.5. In appearance this is an ordinary audio voltage amplifier. However, the value of C1 has been chosen to offer considerable reactance to lower frequencies. This reactance tapers off as the frequency increases, becoming virtually
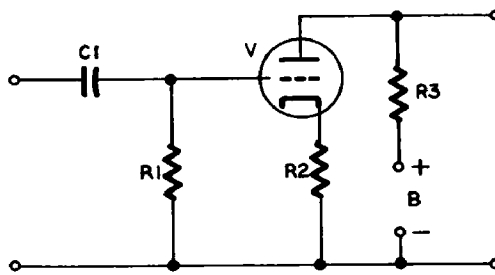
Figure 5.5 Pre-Emphasis Circuit

zero at the permitted upper audio limit of 15 kilohertz. As a result, the higher frequencies are emphasized, which gives a better signal-to-noise ratio in transmission. The value of R1 that gives the best performance is one that makes the C1–R1 time-constant 75 microseconds.

You will see that in FM receivers a corresponding de-emphasis circuit must be provided to restore the upper audio frequencies to their original level.

PHASE MODULATION

Phase modulation affects everyone who watches color television. The monochrome TV signal carries video by AM and audio by FM. The color signal includes color by PM.

In FM we vary the frequency of the carrier in accordance with the amplitude of the modulating signal, but in PM we vary its *phase angle*. This brings up the subject of *vectors,* which we must touch on briefly before going any further.

VECTORS

If we take a piece of paper and designate the top edge as north, and the left-hand side as west, and make a pencil dot in the middle for a ship, we can draw a vertical line from this dot to represent the ship traveling north, or a horizontal line to represent it traveling west. We have done this in Figure 5.6.

We can also represent the ship's speed. If we choose a scale of 10 knots to an inch, and the ship's speed is 20 knots, we shall draw the lines two inches long.

Suppose our ship is traveling northwest. Its course and speed are now represented by a two-inch line sloping up toward the left-hand upper corner of the paper, midway between the other two lines.

The point at the end of this line also shows that at the end of one hour the ship is 20 nautical miles northwest of its starting position.
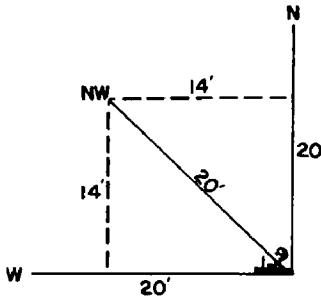
(a)

(b)
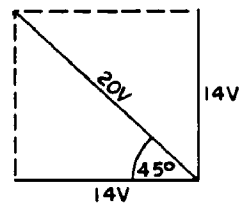
Figure 5.6   Vectors

By measuring along the dotted lines, we can also say that the ship is now 14 miles north and 14 miles west of its starting point. Since it got there in one hour we could also say that the ship's speed was 14 knots to the north and 14 knots to the west, resulting in a total speed of 20 knots to the northwest.

In this diagram the three courses and speeds of the ship have been represented by lines drawn to show direction and velocity. Such lines are called *vectors*. In electronics, vectors are also used to show angles and voltages.

If, instead of compass headings and speeds, we substitute angles (measured clockwise from W) and voltages, we could use this diagram to show that two vectors, one of 14 volts at 0 degrees and one of 14 volts at 90 degrees, result in a vector of 20 volts at 45 degrees.

This is called *vector addition*. It is not the same as arithmetical addition, where $14 + 14 = 28$, because the quantities added do not lie in the same straight line.

If they did they would be *in phase*. Where they do not the angle between them is called a *phase angle*.

COLOR MODULATION

In transmitting the color in color television a subcarrier is used. The space between the video and sound carriers in monochrome TV is occupied by the upper sideband of the video signal, which consists of groups of frequencies centered on harmonics of the line frequency, with spaces between. The color subcarrier has a frequency of 3.579545 megahertz (usually approximated to 3.58 MHz), which places it in the gap between the 227th and 228th harmonic of the line frequency. Harmonics of the color subcarrier fall into other spaces on either side of this one, since they are also separated by intervals equal to the line frequency (15.734264 kHz). In this way we can transmit a second signal interleaved within the main one.

This color signal has been modulated by shifting its phase according to the wavelength of the color. However, as we have just seen, a phase vector can be broken down into two vectors at right angles to each other. This is done by using a *doubly balanced modulator*.

DOUBLY BALANCED MODULATOR

Figure 5.7 shows a doubly balanced modulator that can be used to encode the 3.58-megahertz subcarrier with color information.

Distinguishing Features

You will notice a distinct similarity between this circuit and the Armstrong balanced modulator in Figure 5.4. However, the modulating signal is actually fed to a phase-inverter triode (V1), from which *two* outputs of opposite phase go to the grids of V2 and V3. The carrier signal is applied to the third grids of these tubes, so the inputs are different from those of Figure 5.4.

Uses

TV color information encoding.

Detailed Analysis

DC Subcircuit: In Figure 5.7 electron flow is from B— (the low side of the circuit) via R2, V1 and R1 to B+; and via R6, both V2 and V3, and R3 to B+. Connections from the screen grids of V2 and V3 to B+ have been omitted.

AC Input: The color information derived from the red, green and blue cameras was changed by previous circuits into the Y, I and Q signals. The Y, being equivalent to the monochrome of black-and-white pictures, bypasses this circuit. The I signal is fed to one of two doubly balanced modulators, the Q signal to the other.

The I Signal is used to transmit colors in the orange and cyan regions, and since more fine detail is visible in these colors it is given a greater bandwidth (1.3 MHz). We will deal with this signal first.

When the I signal on the grid of V1 is positive, it will be reproduced by this tube as a positive signal on its cathode and a negative signal on its plate. (See chapter 3 for more about phase inverters.) Consequently two signals of opposite phase reach the grids of V2 and V3. V2's grid will go more negative and V3's will go more positive. V2 will therefore conduct less, and V3 will conduct more.

Meanwhile a 3.58-megahertz signal is being applied to the primary
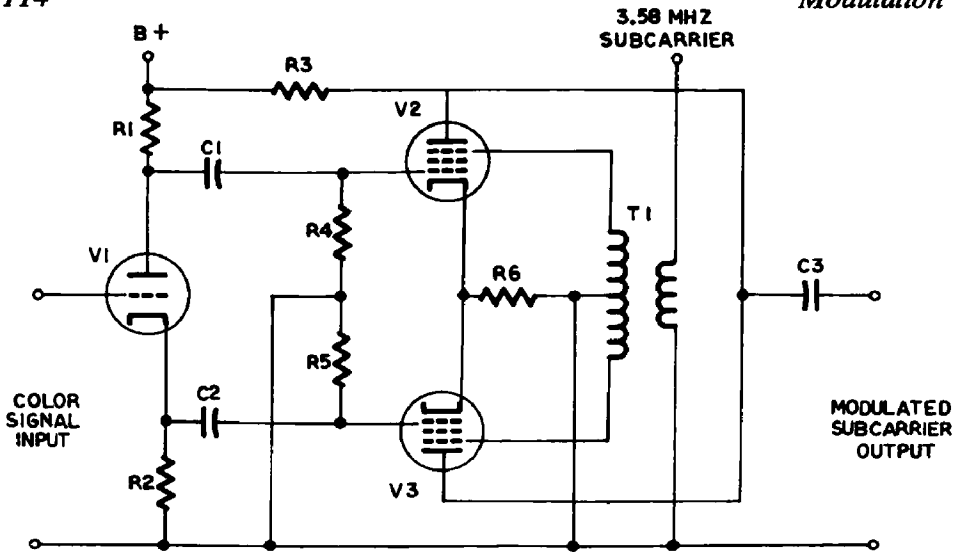
Figure 5.7   Doubly Balanced Modulator

of T1. T1's secondary has a centertap connected to the low side of the circuit. When the signal at the upper end of the secondary is positive, that at the lower end will be negative, and vice-versa.

AC Output: Because V2's gain has been decreased by the negative voltage on its control grid, the amplitude of the 3.58-megahertz signal appearing at its plate will be lower than that at the plate of V3, where the gain has increased.

The output from V3 will not only be greater, but will also be of opposite phase to the subcarrier input. A signal consisting of the excess of V3's output over that of V2 will be coupled out through C3.

The same action takes place when the input to V1 is negative, except that the output signal is now in phase with the subcarrier.

The Q Signal: In the other doubly balanced modulator, the Q signal is applied to V1, and the operation of the circuit is identical. However, the phase of the subcarrier applied to this circuit is 90° different from the other. Consequently its output is also 90° different. The bandwidth of this signal is also less (.4 MHz), as colors other than those in the I signal have less visible detail.

In our brief discussion of vectors you saw how two vectors at a 90° angle would add to give a resultant vector. The angle of this vector would depend upon the values (in this case amplitudes) of the first two. This is illustrated in Figure 5.8, where the red, blue and green vectors are shown as the result of adding different I and Q modulation
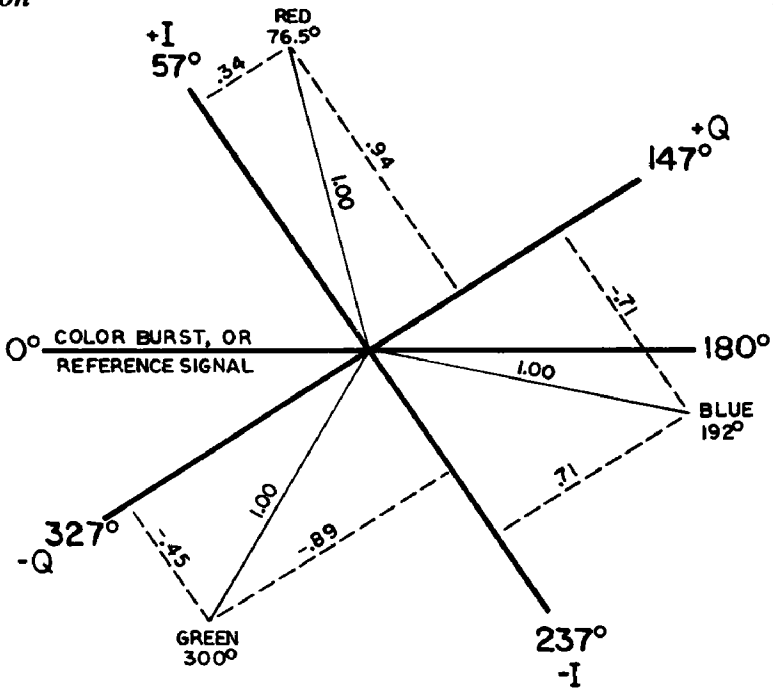
Figure 5.8 Color-Signal Phase Relationships

amplitudes. The outputs of the two doubly balanced modulators are actually combined in this way, and since their amplitudes are rising and falling, and varying between being in-phases and being of opposite phase to their subcarriers, you can see that the resultant vector is swinging back and forth around the center like the hand of a seriously deranged clock. Each direction it points to is a different color, of course, so that in this way the phase angle of the subcarrier is made to vary in accordance with the color information.

As already mentioned, more detail is visible in the orange and cyan portions of a scene than in those of other colors, and the I signal, with greater bandwidth, is used to transmit this part of the spectrum. Since the phase angle for orange is 57° and that for cyan approximately 180° the opposite, the I subcarrier is delayed by this angle before being applied to the I modulator. Consequently the Q subcarrier is delayed 147° (57 + 90) before being applied to the Q modulator. The color bursts, however, are not phase-shifted.

Don't forget that the Y signal bypasses the color modulators. Yet it contains the "whiteness" information for the picture. In the receiver

it is recombined with the color signals so that the colors on the screen have the proper saturation as well as hue.

PULSE MODULATION

Pulse modulation is another way of sending more than one signal on the same carrier. It can employ any of the foregoing methods of modulation, but generally AM is used. A continuous modulating signal is chopped into pulses before modulating the carrier. You could compare this to a motion picture, in which the moving scene is recorded by a series of snapshots. If this is done rapidly enough, they blend together on the screen so that the eye does not detect the individual frames. In pulse modulation the spaces between the pulses are used for other pulses. As long as proper synchronization is maintained, the receiver can separate the channels and reproduce the separate signals as well as if they had been sent on individual carriers. This process is called *multiplexing*.

Uses

Pulse modulation is used to enable a single computer to control several processes simultaneously. The high-speed pulses from the different locations are kept in rigid synchronization by a *"clock"* running at microsecond speed. The computer accepts their inputs in rotation, called *time-sharing*, so that each stream of data is kept separate. The computer's outputs are made in the same way.

Pulse modulation is also used in *telemetering*. This is the method of transmitting on one carrier data from several sensing instruments from a space ship to earth. As you can see, it is practically the same as time-sharing or multiplexing.

Circuits

The circuits used in pulse modulation are similar to those used for AM, FM or PM. The essential difference is that the modulating signal must be chopped, or *gated* (see chapter 9) to form it into pulses.

Variations

The main types of pulse modulation are:

(1) *Pulse-amplitude modulation* (PAM): only amplitude of pulse varies.
(2) *Pulse-width modulation* (PWM): only width of pulse varies.
(3) *Pulse-time modulation* (PTM): only space between pulses varies.
(4) *Pulse-code modulation* (PCM): combination of (2) and (3).

MIXER CIRCUIT

Figure 5.9 shows a mixer circuit using a pentode tube.

Distinguishing Features

A mixer resembles other RF or IF voltage amplifiers (compare with Figure 2.22), having a *grounded-cathode* or *common-emitter* circuit.

It is distinguished from other RF or IF voltage amplifiers by having an additional input to the grid from an oscillator. This oscillator, which is often a Hartley or Colpitts type (see chapter 4), is known as a *local oscillator*.

Uses

A mixer is used in a radio receiver, TV tuner or similar application, in order to change the frequency of the incoming RF signal to the IF frequency of the following IF stage(s).

Detailed Analysis

DC Subcircuit: In Figure 5.9 electron flow is from B— via R1 to the cathode of V. From V's plate, current returns to B+ via L3, and from the screen grid via R2.

The value of R1 is chosen to bias the tube so that it operates on the non-linear portion of its characteristic curve, which makes it act
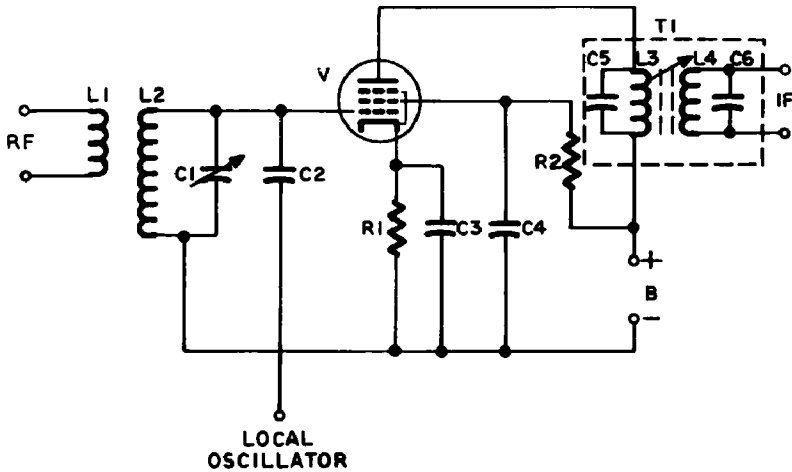
Figure 5.9 Mixer

like a detector. Consequently, in a radio receiver, this circuit is often called the "first detector." However, audio information is not removed here but at a later stage, sometimes referred to as the "second detector," which will be discussed in chapter 6.

AC Input Subcircuit: The resonant circuit L2–C1 is tuned to be resonant at the frequency of the radio or TV signal it is desired to receive. This signal is present in L1, is inductively coupled into L2, and gets a resonant-voltage step-up in the process. It is then applied between the control grid and cathode of V.

As you just saw, the tube is operating on the non-linear portion of its characteristic curve (see Appendix). Consequently, when the grid voltage swings in a negative direction the tube is cut off; it conducts only on the positive swings. This is similar to the operation of the RF amplifier used in the grid-modulation circuit discussed earlier in this chapter. However, that was a high-power amplifier, whereas this is a low-power voltage amplifier.

The reason for operating the tube near the cut-off point is because it is then able to modulate one signal with another. The oscillator signal, which is applied to the grid by way of C2, "beats" with the incoming RF signal to produce upper and lower sidebands that are equal to the sum and difference frequencies of the two signals. This process is called *heterodyning.*

If the incoming signal is at a frequency of, say 1070 kilohertz, and the local oscillator is operating at 1520 kilohertz, the upper sideband

frequency will be 2590 kilohertz (1070 + 1520), and the lower side-band 450 kilohertz (1520 − 1070). If the incoming signal was already modulated by (for illustration) a single frequency of 1 kilo-hertz, it will have sidebands of its own at 1069 and 1071 kilohertz. These will give sidebands on sidebands: upper sidebands of 2589 and 2591 kilohertz; and lower sidebands of 449 and 451 kilohertz. Of course, in a real transmission there are many more sidebands, all of which will appear in the output with new upper and lower sidebands also.

We're only interested in the lower sidebands around 450 kilohertz. In AM broadcasting most stations are allotted a bandwidth extending 5 kilohertz above and below the carrier frequency. (A few stations are allowed up to 15 kilohertz, but there are not many of these "clear-channel" stations.) The IF transformer T1 is made resonant at 450 kilohertz, with a broad enough bandwidth to allow the 450-kilohertz carrier and its sidebands to pass, but excluding the rest. (See also section on IF amplifiers in chapter 2.) This type of radio receiver is called a *superheterodyne* receiver, and is almost the only type used today.

Circuit Variations

Mixers using transistors are found with circuits similar to that in Figure 5.9. They may also be found with dual tubes, containing a triode (for the oscillator) and a pentode (for the mixer) in one en-velope. Such a tube might be employed in the next stage after the RF cascode amplifier shown in Figure 2.25.

CONVERTERS

Figures 5.10 and 5.11 are examples of converter circuits, in which mixer and local oscillator are combined in one circuit.

Distinguishing Features

a. Vacuum-tube converters use *pentagrid tubes* (tubes with five grids, also called heptodes because there are seven electrodes). A penta-grid tube is enough to identify a converter. However, it is usually also connected in a circuit with a tunable resonant input which is ganged to track with the oscillator resonant circuit; and an IF trans-

former is provided in the output, as in the mixer circuit discussed previously.

b. Transistor converters are just as easy to identify, even though the transistors do not have five grids, since they are connected in the same kind of circuit. In the example given in Figure 5.11 a loop-stick antenna with a ferrite core (L1 and L2) is also shown, a feature of practically all transistor radios today.

Uses

Just about all AM broadcast receivers use converters today. They are also used in many other types of receiver, though sometimes preceded by an RF amplifier stage, as, for example, in TV receivers.

Detailed Analysis

DC Subcircuits: In Figure 5.10 electron flow is from B— via the lower part of L3 to the cathode of V. From the plate it returns through L4 to B+, and from grids numbers 2 and 4 via R2 to B+.

In Figure 5.11 electron flow is from the negative pole of the battery through R3 to Q's emitter, and from the collector via L5, the lower portion of L4 and R2, back to the positive pole of the battery. Bias is stabilized by R3 and R1.

AC Subcircuits: Each circuit has two inputs, the oscillator and the external RF. The oscillator in each case is a Hartley oscillator (sometimes a Colpitts is used). That in the tube circuit (Figure 5.10) is
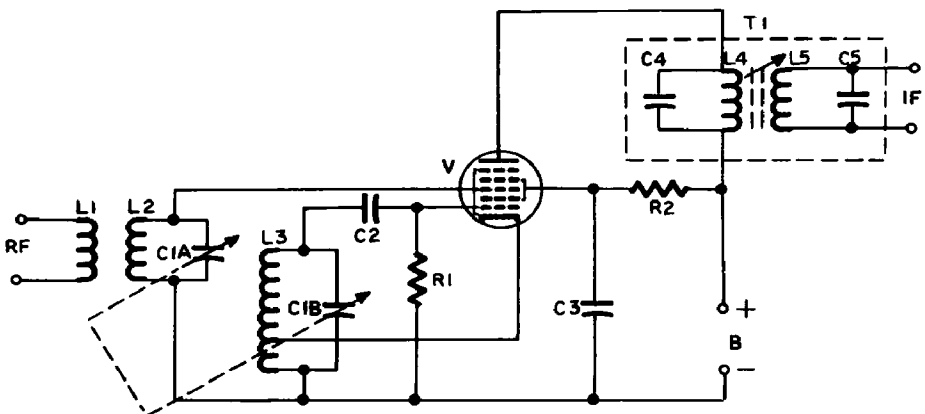
Figure 5.10   Pentagrid Converter

identical with the circuit in Figure 4.1. The transistor circuit differs a little, but you'll see why that is when we get to it.

In the pentagrid tube the grids are numbered from 1 through 5, starting from the one next to the cathode. Grids 2 and 4 are connected internally, so as to shield the third grid and minimize coupling between the circuits. Grids 2 and 4 are maintained at signal ground (AC zero) potential by C3. Grid No. 5 is a suppressor grid, and is connected internally to the cathode as shown, or externally to the low side of the circuit.

In Figure 4.1 the tube is a triode. In the pentagrid in Figure 5.10 the function of the triode is performed by the cathode, No. 1 grid and No. 2 grid (No. 2 grid acting as the triode plate). The electron current flowing from the cathode to No. 2 grid is made to vary at the oscillator frequency by the oscillating voltage on the No. 1 grid. The operation of the Hartley oscillator is explained in chapter 4, so will not be repeated here. However, the No. 2 grid does not present a complete barrier to electrons. Attracted by the higher positive potential of the plate, most of them pass on through grids 2, 3, 4 and 5.

As they pass through grid No. 3 the stream of electrons is modulated by the varying RF signal voltage on this grid. This results in the appearance, in the output stage, of the oscillator and RF carrier signal frequencies, together with all the sidebands, as already explained in the section on the mixer circuit preceding this. T1 is an IF transformer tuned to let pass the IF frequency and its set of sidebands, while excluding the others.

The RF input may be from an external antenna or an internal loop antenna. In modern sets the ferrite loopstick L1 and L2 shown in Figure 5.11 is very popular for broadcast-band reception. It is tuned to resonance at the desired frequency by means of C1A, which is ganged with C1B (Figure 5.10). Usually a combined variable capacitor is used, in which both rotors share a common shaft, and turn together. This is to enable them to "track" or maintain a fixed difference frequency. The oscillator frequency must always be above that of the incoming RF frequency by the amount of the IF frequency, or there will be no difference frequency able to pass through to the IF stage.

C1A, C1B and L3 are always provided with trimmer capacitors and adjustable ferrite slugs for exact alignment for accurate tracking and tuning dial indication. These are shown in Figure 5.11 (C1A, C1C and L4), and are indicated in most schematics.

In the transistor converter, apart from the features already mentioned, we see that the oscillator signal is coupled inductively to the
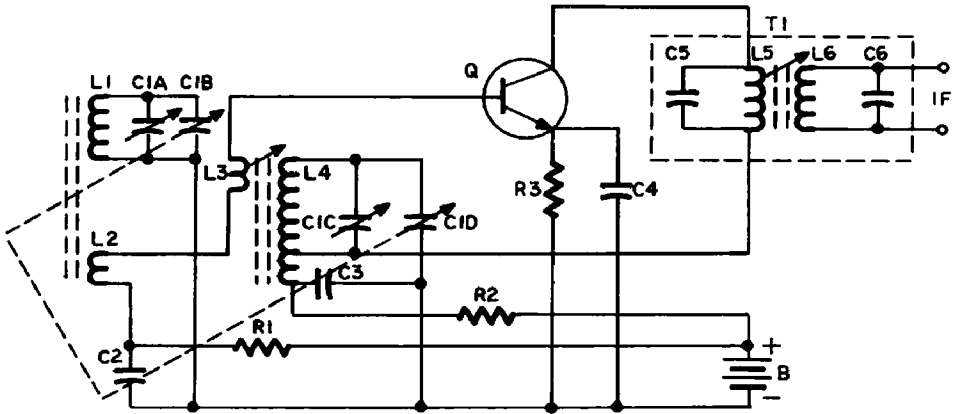
Figure 5.11 Transistor Converter

base by L3 and L4 instead of capacitively by C2 as in Figure 5.10. You will meet both types of coupling in these circuits.

The main difference between the pentagrid converter and the transistor converter is that in the tube we can see the cathode and grids 1 and 2 acting as a triode oscillator, and the cathode and grid 3 and the plate acting as a mixer, but in the transistor there are only the usual three elements to do everything.

At first you may wonder about this. However, there is no rule that says a transistor can only do one thing at a time. This one is a mixer and an oscillator simultaneously, just as if it were two entirely separate transistors. To make this clearer, Figure 5.11 has been redrawn in Figures 5.12 and 5.13 as a separate oscillator and mixer.
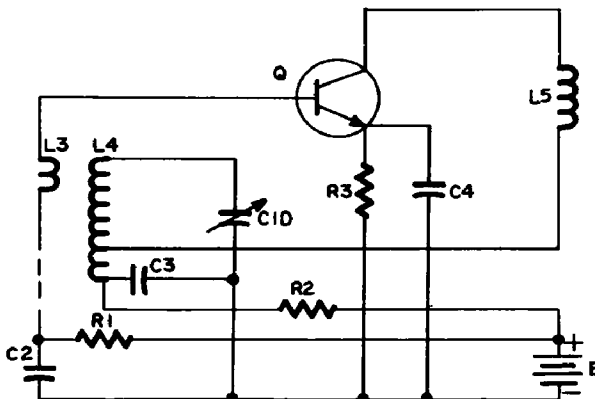
Figure 5.12 Transistor Converter—Oscillator Circuit
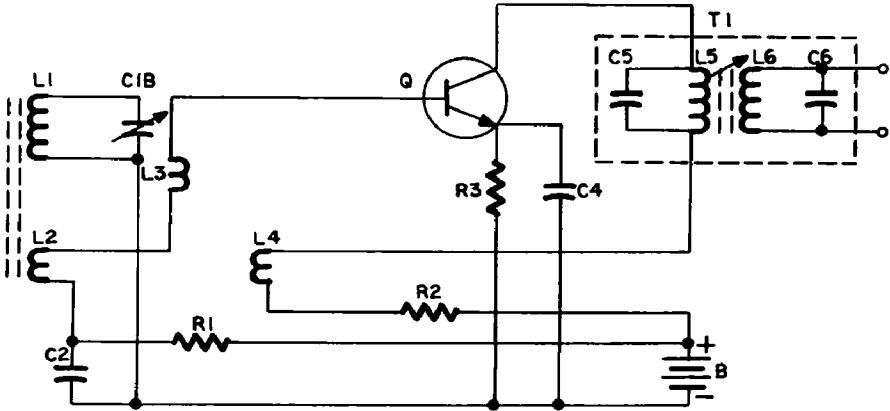
Figure 5.13   Transistor Converter—RF Amplifier Circuit

In Figure 5.12 you see a Hartley oscillator which only differs from that in Figure 4.2 by having the tap on L4 connected via L5 to the collector instead of to the emitter, and the oscillations of L4–C1D inductively coupled to the base by the "tickler" coil L3 instead of by a capacitor. These circuit variations do not change the principle of operation.

In Figure 5.13 you see that the mixer circuit is almost the same as that in Figure 5.9. If Figure 5.13 is superimposed on Figure 5.12 you get back Figure 5.11.
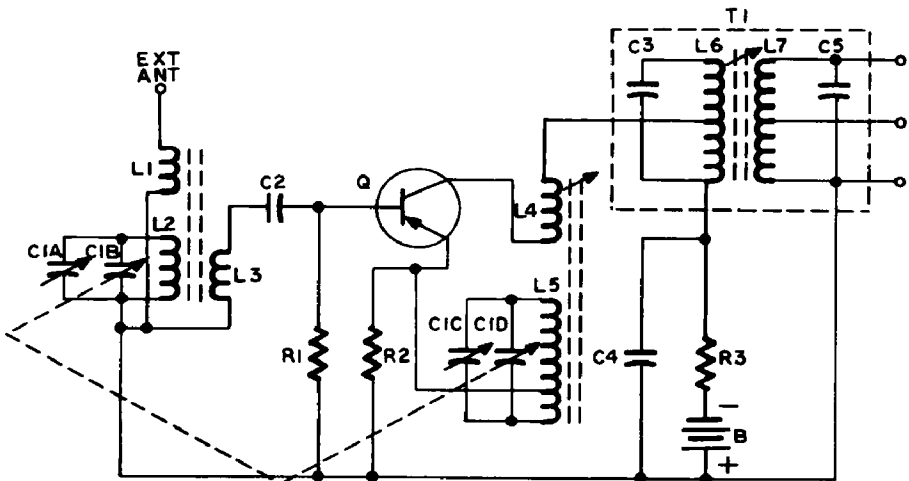
Figure 5.14   Transistor-Converter Circuit Variation

Circuit Variations

Pentagrid converters are pretty much standardized, but transistor circuits do offer some variety. An alternative to that shown in Figure 5.11 is shown in Figure 5.14.

As you can see, the main difference is that the "tickler" (L4) is now connected in the output circuit instead of in the input, while the oscillator resonant circuit is connected to the emitter instead of to the collector via the IF transformer. The net result is the same.

A connection for an optional external antenna is shown which is sometimes provided in the better type of receiver.

The collector of the transistor is connected to a centertap on the IF transformer, which is often done, as explained in the section on IF transistor amplifiers in chapter 2.

TROUBLE-SHOOTING CHART FOR MIXERS AND CONVERTERS	SYMPTOM							
	TV -No Picture	TV - Snow in Picture	TV - High Band Missing	TV - Poor Contrast	TV or Radio - Interference	Radio - No Sound	Radio-Weak Signals	Radio - Background Noise
Tube Faulty or Tube Voltage Wrong	X	X	X	X		X	X	
Wrong Alignment of Tuning Adjustment		X		X	X		X	X

6

DEMODULATION

D EMODULATORS ARE the opposite of modulators. They re-
cover the information from the modulated radio-frequency
signal. For this reason they are also called detectors. Many de-
modulator circuits are built around one or more diodes, though triodes
and specially designed tubes are used also.

In the process of modulation an RF and an audio or video signal
were mixed together to produce a carrier with sidebands containing
the audio or video information, which could then be radiated through
space. At the receiver another signal was mixed with the RF signal and
its sidebands to convert them to the IF frequency. Now, after ampli-
fication and removal of all undesired elements in the IF section, we
have to get rid of the IF carrier in such a way that we are left with the
audio or video information alone.

Detector circuits are also a source of feedback voltage to provide
for automatic gain or volume control.

DIODE DEMODULATOR—CRYSTAL DETECTOR

Figure 6.1 shows a semiconductor diode used to demodulate an AM
radio signal. Such a circuit may be called a diode demodulator or
crystal detector circuit.

Distinguishing Features

This circuit contains a *semiconductor diode,* and is located between the last IF stage and the first AF stage of a superheterodyne AM receiver (radio or television).

The input is via the last IF transformer, and the output, in a radio receiver, usually is taken from the moving arm of a potentiometer (volume control).

In many cases a DC voltage for automatic volume (gain) control is extracted from the stage by means of a filter (R1, C2, R2, C3, in Figure 6.1).

No external DC is supplied to the circuit, for the diode is really a resistor which has much more resistance to current flowing in the direction of the arrow than against it.

Uses

AM radio and television receivers.

Detailed Analysis

In Figure 6.1 the output from the IF amplifier (see chapter 2) is coupled into L2, the secondary of T1, which with C4 is resonant at the IF frequency.
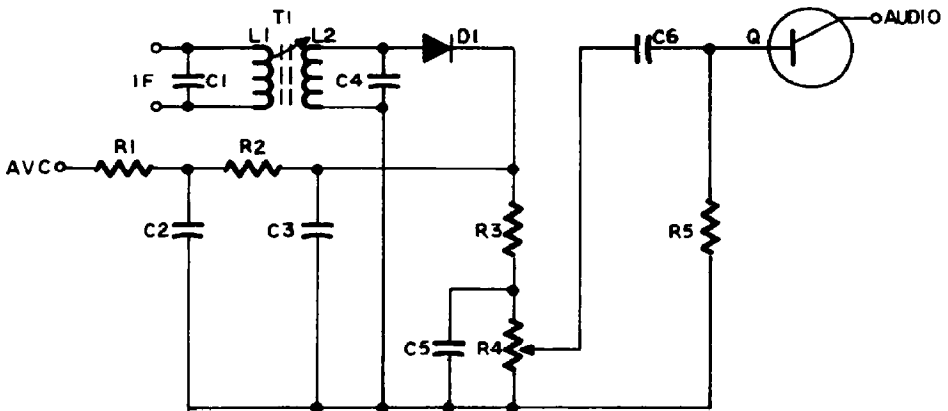
Figure 6.1   Crystal Diode Detector and AVC

As this is an AC signal the upper and lower ends of L2 are alternately positive and negative. If there were no D1 an alternating current would flow in the circuit connecting L2, R3 and R4, but as the diode only allows current to flow in the direction opposite to the arrow, it can only do so when the upper end of L2 is positive.

This results in a succession of pulses of direct current through R4 and R3 at the IF frequency, each one producing a voltage drop across R4 so that its upper end is positive with respect to its lower end. As a result C5 becomes charged so that its upper end is positive also.

During the interval between each pulse C5 starts to discharge by sending a current through R4 in the opposite direction, but before it can lose much the next positive pulse recharges it. As a result its charge stays very close to the amplitude of the positive voltage pulse developed across R4.

In the absence of modulation the IF carrier would be of constant amplitude, which would produce a constant voltage on C5. However, as you know, in amplitude modulation the amplitude of the signal is varying all the time in accordance with the audio information impressed on it, and so the voltage dropped across R4 varies, and the voltage on C5 rises and falls with it. The values of R4 and C5 are such that although C5 cannot discharge fast enough through R4 to follow the IF fluctuations it can follow the audio-frequency ones. The voltage across C5 and R4 therefore reflects the audio information originally impressed on the RF carrier. The movable arm of the potentiometer picks off as much of this AF voltage as will give the output desired, and couples it via C6 to the base of the audio amplifier transistor in the next stage.

Automatic Volume Control

The diode D1 is connected so that current pulses flowing through R4 and R3 give a positive voltage at the upper end of R3 with respect to the low side of the circuit. The filter R1, R2, C2, C3 smoothes out these pulses so that pure DC is provided for application to an earlier stage or stages of the circuit. This voltage varies only with the *average* amplitude, or strength, of the carrier, not with the audio fluctuations. For strong signals it will be higher, for weak it will be lower. When applied to previous stages it reduces the gain proportionately to overcome variations in the strength of the radio signal as received.

The polarity required for AVC voltage depends upon the application. For PNP transistors it will be positive, as shown, but for NPN

transistors and vacuum tubes a negative voltage is necessary. In this circuit reversing the polarity of the diode would reverse the polarity of the AVC voltage, if a negative voltage was required.

Circuit Variations

As explained above, the polarity of the diode may be reversed, or a different take-off point may be used to provide the AVC voltage of the proper polarity and amplitude.

When used in a TV receiver the diode detector circuit (Figure 6.2) has to handle the much greater bandwidth of the video signal (4.5 megahertz), while at the same time eliminating everything above that frequency. The values of C1, L3, C3 and L4 are chosen so that frequencies above the video frequency are so attenuated that they cannot get through the video amplifier to appear as interference on the TV screen. If a variable resistor like R4 (Figure 6.1) was provided in Figure 6.2 it would be a contrast control. However, this will more often be found in the next stage, the video amplifier discussed in chapter 2.
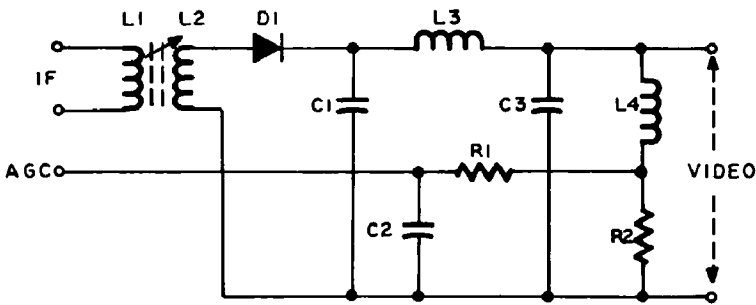
Figure 6.2   Video Detector

Automatic Gain Control

AGC considerations in the video detector are similar to those for AVC in a radio. They are different names for the same thing.

However, the type of AGC shown in Figure 6.2 is not always adequate for TV, and many receivers obtain it from a different circuit (Figure 6.4). Also, it is quite a common practice, if AGC is taken from the video detector, to make R2 a variable resistor, with R1 con-

nected to the moving arm, so that the AGC voltage may be adjusted to suit local conditions.

Another circuit variation is the addition of a second diode as *AGC rectifier,* parallel with L4 and connected to conduct on negative alternations of the IF signal if negative AGC voltage is required (in which case D1 would face the other way also). In a vacuum-tube receiver a dual-diode tube may be used, or a triode connected so that the grid acts as the anode for one diode and the plate as the anode for the other, the cathode being common to both. Of course, the two diodes may also be semiconductors.

Peak Detector

As you have just seen, diode demodulators operate by *averaging* the amplitude of the rectified IF signal. However, if a single pulse at the IF frequency came along with a much greater amplitude it would pass unnoticed.

But if the circuit in Figure 6.2, for example, consisted only of the IF transformer, D1 and C1, then C1 would charge up to the maximum voltage of the pulse, and remain there because there would be no resistor through which it could discharge.

This is the principle of the *peak detector,* which is used for detecting *transients* (momentary voltage surges) that otherwise would not be observed. After each measurement of the voltage, the capacitor is discharged by a gate (see chapter 9), so as to reset it for further measurements.

The peak detector is *not* a demodulator, but is included here because it is a form of diode detector which you may run across, and therefore should know about.

VACUUM-TUBE DIODE DETECTOR

Vacuum-tube diodes perform in the same way as semiconductors, allowing current to flow through them in one direction only. They have the disadvantages of being larger and requiring a heater current to heat the cathode. However, the invention of the dual-diode-triode tube shown in Figure 6.3 enabled manufacturers to combine the diode detector function with the first audio amplifier stage in one tube, which was an important saving of cost in the heyday of vacuum-tube radios,

and as these sets are still being produced the circuit is by no means superseded by the semiconductor type.

Distinguishing Features

The circuit contains a *dual-diode-triode tube,* and is located between the last IF stage and the audio output stage of a superheterodyne AM receiver.

The input is via the last IF transformer, and the output to the triode section of the tube is taken from the moving arm of a potentiometer (volume control).

An external DC supply is required for the operation of the triode section of the tube, but not for the diode. DC voltage for AVC is extracted from the diode stage by means of a filter (R1, C2, R2, C3).

Uses

AM tube radios.

Detailed Analysis

The input signal is coupled from the previous IF stage (see chapter 2) by the IF transformer L1–L2, which is tuned to resonance at the IF by C1 and C4. The triode section of V is used for audio voltage amplification, and as this circuit is explained in chapter 2 it will not
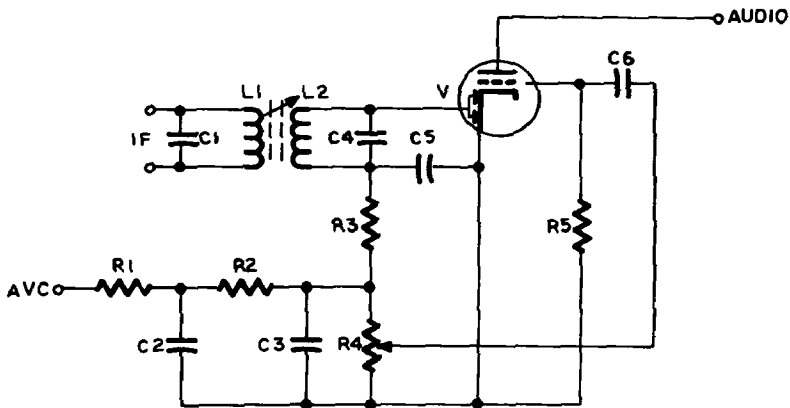
Figure 6.3   Vacuum-Tube Diode Detector and AVC

be explained here. C6 and R5 in Figure 6.3 correspond to C1 and R1 in Figure 2.1.

The diode section of V consists of the cathode and two anodes beside it. When electrons are emitted from the cathode they will be attracted by a positive anode voltage, and current will flow. When the anode voltage is negative they will be repelled, and no current will flow. When the upper end of L2 is positive, current will flow in the circuit from the lower end of L2, via R3 and R4 to the cathode of V, and from the diode anodes back to the upper end of L2. When the upper end of L2 swings negative the diode blocks current flow in this circuit.

When the diode conducts, electrons flow from V down through L2 to charge C5 with a voltage equal to the amplitude of the IF signal. When the diode does not conduct, the charge on C5 begins to leak away through R3 and R4 (with which it is in parallel). However, if the values of C5 and R3 and R4 are chosen correctly C5 will not discharge very much before the next pulse recharges it, because it has to discharge through the high resistances of R3 and R4, whereas it charges through V, which has a very low resistance when conducting.

This means that C5 cannot follow the individual IF cycles, and remains virtually at the IF amplitude all the time. But this amplitude is fluctuating at the audio rate because of the audio signal with which it was modulated. The values of C5 and R3–R4 are such that the voltage on C5 can follow the audio fluctuations. Consequently the voltages across R3 and R4 vary with the audio modulation of the carrier.

The movable arm of the variable resistor R4 picks off as much of the voltage dropped across R4 as the user desires, and couples it through C6 to the next stage. C6 blocks the DC part of the signal, so that only AC appears at the grid of V.

The DC component for AVC is derived from the average or unmodulated amplitude of the IF carrier, and is extracted by the filter circuit R1, C2, R2, C3, as in the crystal diode circuit of Figure 6.1.

KEYED AGC

Simple AGC from the diode detector circuit, as shown in Figure 6.2, is not as efficient for TV as the circuit shown in Figure 6.4, because it cannot follow rapid fluctuations of the carrier strength, such as occur when an airplane flies over, when the picture would flutter

severely. A keyed AGC circuit is designed to overcome this, and to reduce noise interference also.

Distinguishing Features

Although the circuit in Figure 6.4 looks like an amplifier you'll notice one startling difference right away. *The B+ voltage is connected to the cathode of the tube!* It is also connected to the screen grid, *but not to the plate* as in all regular amplifiers.

Instead, the plate is connected to the output of the horizontal deflection section, so as to apply powerful flyback pulses to it.

Uses

To provide AGC voltage in TV sets.

Detailed Analysis

DC Subcircuit: In Figure 6.4 B+ voltage is applied to the screen grid of V, and to the cathode via R3, but electron flow can only take place when a high-voltage pulse is present on the plate to make it positive with respect to the cathode. These pulses are frequently coupled to the plate through a capacitor to block DC voltages, and have a repetition rate of 15.75 kilohertz.

AC Input Subcircuit: A portion of the output of the video amplifier is applied to the control grid of V. The relationship between the cath-
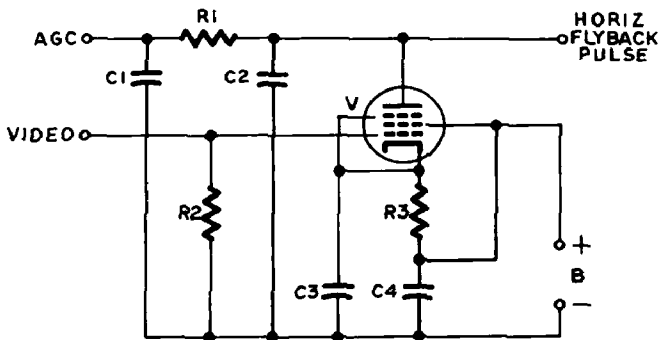
Figure 6.4   Keyed AGC

ode voltage, the control-grid voltage and the plate voltage (when a positive pulse is on it) is such that the grid voltage would prevent conduction at any time except when a horizontal sync pulse is received. In other words, the tube can only conduct when both a flyback pulse is present on the plate and a horizontal sync pulse is present on the control grid. Furthermore the amount of current it can pass depends upon the strength of the sync pulse on the control grid.

AC Output Circuit: The bursts of electrons flowing away from the plate charge C2 negatively. This capacitor acts like a storage battery, current flowing out of it between charging pulses through the filter network R1–C1.

The voltage on C2 varies with the amount of current passed by V, which in turn depends on the strength of the positive-going pulses applied to the control grid.

Circuit Variations

In the circuit in Figure 6.4 the plate of V would be connected directly to a separate insulated winding on the horizontal output transformer. In other cases the source of flyback pulses may be a tap on the main winding, the width control inductor, or damper circuit. As mentioned before, they are frequently coupled through a capacitor, and sometimes through a dropping resistor.

When flyback pulses are coupled through a capacitor, C2 may be replaced by a resistor. The coupling capacitor then acts as storage for the output current pulses from the tube.

The control-grid signal may be obtained from the sync amplifier instead of from the video amplifier.

A variable resistor is often placed in series with R3 and the B+ voltage in order to adjust the bias on the tube to compensate for the average strength of signals in the area where the set is operated. This is usually called the AGC control.

GRID-LEAK DETECTOR

Figure 6.5 illustrates a grid-leak detector. Though it is not often encountered anymore, it is particularly good on weak signals, so is sometimes used experimentally. However, some TV sets use it, as mentioned previously under automatic gain control.

Distinguishing Features

A triode with a tuned resonant circuit for RF or IF in its input, with an audio or video output.

The grid-leak resistor R1 may be shown paralleling C2, as in Figure 6.5, or connected directly to the low side of the circuit, as R1 in Figure 2.1. Effectively, the connections are the same, since the first really connects to the low side of the circuit through the coil.

Uses

Radio receivers (not superheterodyne), and some TV detector and AGC circuits.

Detailed Analysis

DC Subcircuit: In Figure 6.5 electron flow is from B— via V and R2 to B+. Electrons collecting on the grid of V return to the cathode via R1 and L2 (or R1 alone if connected direct to the low side of the circuit).

AC Input Subcircuit: RF or IF signals inductively coupled from L1 to L2 (which is tuned by C1 to be resonant at the desired frequency) are coupled by C2 to the grid of V. When the signal cycle is such that the upper end of L2 is positive, the lower end is negative. The grid and cathode of V act as a diode, and because the positive voltage of L2 is connected through C2 to the grid the "diode" conducts. When the signal polarity reverses so that the grid is driven negative, the "diode" does not conduct. This action is similar to the diode detectors discussed earlier in this chapter.
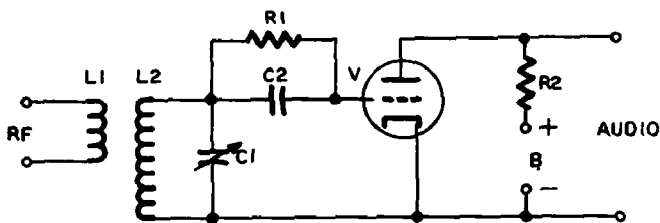
Figure 6.5   Grid Leak Detector

When the "diode" conducts, electrons flow from the cathode to the grid, and charge C2 so that the side connected to the grid is negative and the other side is positive. A voltage is developed across C2 which varies in amplitude with the modulation on the RF signal. Again, this action is the same as you saw in Figure 6.1, where an audio voltage was developed across C5.

As far as this audio voltage is concerned L2 is a straight piece of wire, so you have in effect only C2 and R1 connected between grid and cathode. V amplifies this audio voltage in the same way as any other audio voltage amplifier (see chapter 2).

AC Output Subcircuit: The output audio signal voltage appears across R2, and in a radio is coupled into the next stage, or to headphones. The use of this circuit in a TV set was covered under video detectors and AGC, and also as follows under circuit variations.

Circuit Variations

When this circuit is used in a TV video detector stage the cathode-grid diode replaces D1 in Figure 6.2. The triode amplifier output is then filtered and becomes an AGC voltage as in the AVC and AGC voltage circuits shown in Figures 6.1 through 6.4.

REGENERATIVE DETECTOR

The regenerative detector uses positive feedback to return a portion of the signal in the output to the input circuit as shown in Figure 6.6.

Distinguishing Features

The feedback coil L2, the RF input, the audio output and the variable resistor R1 *in the grid circuit* of V, taken together, enable you to tell this circuit from an RF amplifier or an oscillator.

Uses

Sometimes used in experimental receivers because it is very sensitive, and can be used to receive both modulated and CW signals.

Detailed Analysis

DC Subcircuit: In Figure 6.6 electron flow is from B— via V, L2 and the primary of T1 to B+.

AC Input Subcircuit: The RF signal picked up by the antenna is coupled from L1 to L3, which is tuned to resonance by C1, and then applied via C2 to the diode consisting of the grid and cathode of V. Demodulation takes place in the same way as in the grid-leak detector of Figure 6.5.

AC Output Subcircuit: The audio and RF signals present on the grid appear in the output after amplification by the triode V. The audio is coupled to headphones or to another stage. The RF signal is coupled by L2 back into the input, where it reinforces the signal applied to the grid. The degree of coupling sometimes can be adjusted by moving L2 closer to or further from L3. However, it is more usual to adjust the bias on the grid of V by means of R1. The return path for RF is by means of C3 which bypasses T1 for RF, but offers a high reactance to audio signals, and does not bypass them.

Adjusting R1 increases the sensitivity of the circuit by increasing the gain of V, until the amount of feedback becomes sufficient to cause oscillation. The most sensitive point for reception is just below the point where oscillation begins.

However, when listening to CW (code) the signal produced when oscillating beats with the incoming signal to give an audio difference frequency which can be heard in the headphones or speaker.
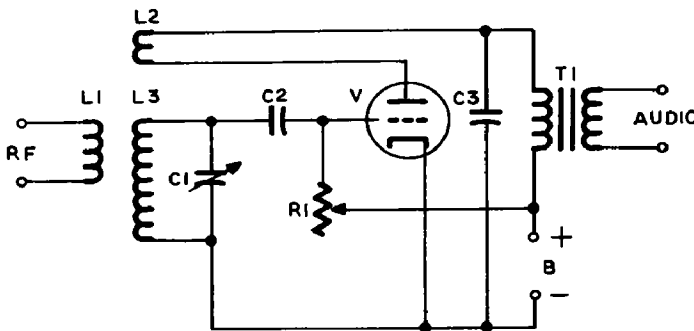
Figure 6.6   Regenerative Detector

Circuit Variations

A transistor may be used instead of a tube, and the audio output transformer is not required with headphones. As mentioned previously, L2 (which is sometimes called a "tickler" coil) may be movable to adjust the degree of coupling, in which case R1 may be replaced with a grid-leak resistor.

FM DISCRIMINATOR

With the schematic illustrated in Figure 6.7, we begin discussion of a group of circuits used in FM demodulation. The FM discriminator is not used much anymore because it requires a *limiter* (or noise suppression) preceding stage, whereas the *ratio detector* discussed next does not. But you may still meet with it (for example, one was shown in block form in the section on FM modulation in the previous chapter, in Figure 5.3).

Distinguishing Features

An IF transformer with an extra winding connected to a centertap on its secondary winding.

The opposite ends of the IF secondary connected to two diodes, *both facing the same way*.

Uses

FM radio receivers, TV sound sections and FM transmitters.

Detailed Analysis

L3 and C2 form a resonant circuit tuned to the intermediate frequency, which is 10.7 megahertz in an FM radio or 4.5 megahertz in TV. As you know, a resonant circuit seems like a pure resistance to a signal at its resonant frequency; that is to say, the current and voltage are in phase. But when the signal frequency is at some other frequency the resonant circuit acts like an inductor or a capacitor, depending upon whether the frequency is higher or lower.

T1 is constructed so that when the signal induced in L3 is exactly
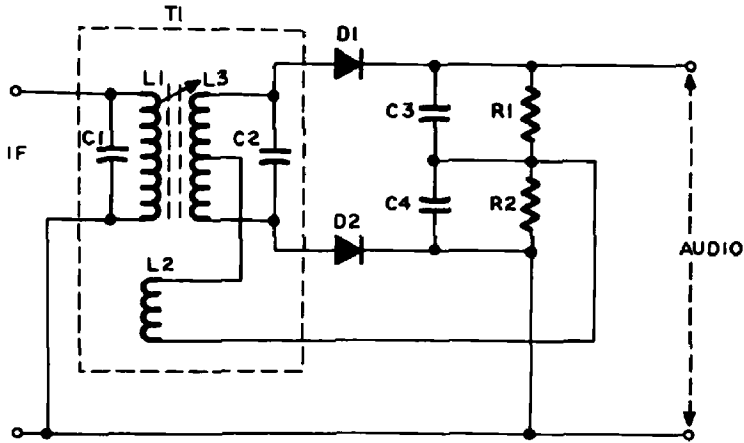
Figure 6.7   FM Discriminator

at the resonant frequency it will be 90 degrees different in phase from the signal in L1. The signal from L1 is also induced in L2, but in this winding it is in phase.

The signal voltage in L2 combines with the signal voltage in each half of L3 to produce voltages at each end of L2 that are equal and opposite. When the upper end of L3 swings negative the lower end swings positive, and vice-versa.

When the frequency changes, due to modulation, the phase angles between the signal voltages in L3 and the signal voltage in L2 change accordingly, but in opposite directions. This results in unequal voltages at the opposite ends of L3.

When the upper end of L3 is positive, electrons flow from the upper side of C3, and flow to L3 through D1. At the same time the lower end of L3 is negative, but no current can flow through D2. On the next half-cycle, when the voltage on the lower end of L3 swings in a positive direction, C4 becomes positively charged also.

The charging current consists of a train of pulses that, as we've just seen, charge C3 and C4 positively. Between pulses these capacitors do not have time to discharge through R1 and R2, since these resistors have a high value, so each becomes charged with the average peak voltage across the corresponding half of L3.

As long as the voltages on the opposite ends of L3 are equal the charges on C3 and C4 are equal. Likewise, the voltages at the two audio output terminals are equal, and therefore cancel each other out, so no output signal is produced.

But when the voltages on C3 and C4 differ, because of frequency modulation, unequal voltages appear at the output terminals. These alternate at the audio rate, because while the time-constants of C3–R1 and C4–R2 are such that they cannot follow the IF fluctuations in the signal voltage, they are designed to keep up with the audio modulation rate.

Circuit Variations

Some discriminators do not have a third winding on the IF transformer (L2). The centertap is connected to the upper end of L1 by means of a capacitor. A dual-diode vacuum tube may also be used instead of two semiconductors.

RATIO DETECTOR

There is a close similarity between the ratio detector (Figure 6.8) and the discriminator (Figure 6.7).

Distinguishing Features

An IF transformer with an extra winding connected to a centertap on its secondary winding.

The opposite ends of the secondary are connected to two diodes, *facing in opposite directions.*

Uses

FM radio receivers and TV sound sections.

Detailed Analysis

As already mentioned, the ratio detector has replaced the discriminator because it does not require a preceding limiter (clipper) stage, so is more economical to produce.

The operation of the transformer T1 is the same, however, and need not be repeated here. But because D2's polarity is reversed the voltages appearing on C3 and C4 are now in series. A large capacitor C6 (usually an electrolytic of 5 microfarads) is connected in parallel with
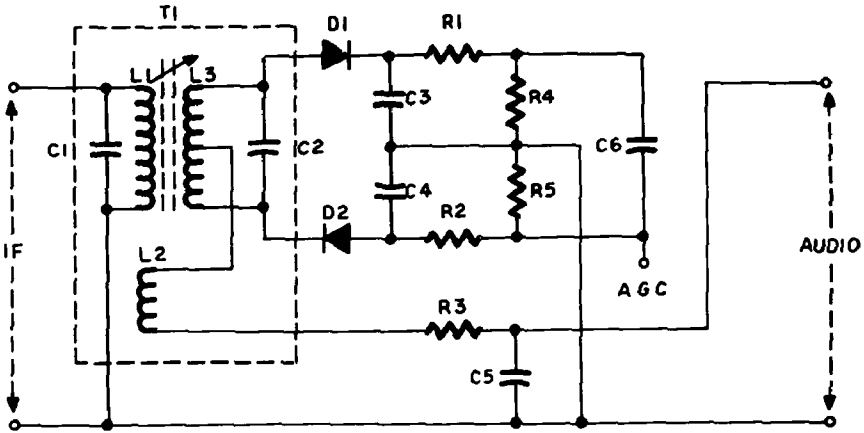
Figure 6.8   Ratio Detector

both C3 and C4. Because of its large capacitance it damps out noise coming in with the signal.

The total voltage across C3 and C4 will equal the voltage across C6, which is the same as the total voltage across L3. However, as the signal swings back and forth in frequency, the *ratio* of the voltages on C3 and C4 will change with respect to each other. Consequently, the voltage at the point between them will fluctuate accordingly. A voltage difference varying at the audio rate will also exist between this point, which is connected to one side of the audio output, and the lower end of L2, which is connected to the other side of the audio output.

Circuit Variations

The lower end of L2 may be connected to the junction of C3 and C4, and the junction of R3 and R4 will then be omitted. The audio output signal will then be taken from these two junctions.

C3 and C4 may be omitted altogether if circuit capacitances are adequate.

C3, C4, R1, R2, R3 and R4 may be encapsulated together in an integrated circuit (IC). In the schematic they will be enclosed in dashed lines to indicate this.

GATED-BEAM FM DETECTOR

Figure 6.9 illustrates a typical gated-beam demodulator, the most economical FM detector, since it combines limiting, detection and audio amplification in one stage.

Distinguishing Features

A vacuum tube of special construction is used in this circuit, such as a 6BN6, 6JC6 or 6HZ6. In the schematic it has the same symbol as a pentode. Its three grids, reading from nearest the cathode, are named and connected as follows:

1. *Limiter grid:* IF input.
2. *Accelerator grid:* B+ voltage.
3. *Quadrature grid:* parallel resonant circuit with quadrature coil.

Plate and cathode connections are as in other amplifiers.

Uses

FM radio or TV sound demodulation stage.

Detailed Analysis

DC Subcircuit: In Figure 6.9 electron flow is from B— via R1 to V. From V's plate it returns via R2 and R5 to B+. From the accelerator grid, current flows to B+ via R6.

AC Input Subcircuit: The IF signal is coupled from the previous stage by T1 to the limiter grid of V. The construction of this tube is such that it has a very steep characteristic curve. A swing of two or three volts is enough to drive it from saturation to cutoff (see Appendix for explanation of tube operation). The value of R1 is chosen so that the grid bias is about —4 volts, or midway on its characteristic curve. Consequently the action of the grid is to clip or limit the signal so that it has a constant amplitude, and noise and interference are removed. The action of this grid is to switch the electron current from the cathode on and off in a series of flat-topped, steep-sided pulses, at the frequency of the IF signal. The electrons of these pulses are focused in
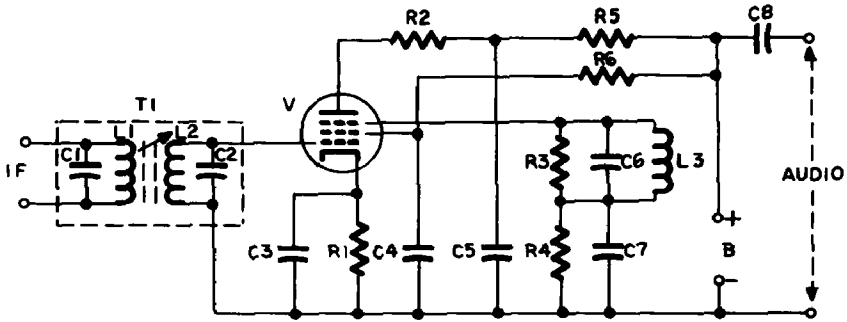
Figure 6.9 Gated Beam FM Detector

a beam and accelerated by the second grid, which has a voltage of around 100 volts.

Quadrature Grid Subcircuit: Connected to the third grid is a resonant circuit consisting of C6 and L3. R3 and R4 are not really part of this circuit as their values are too high to have any loading effect on the circuit. They provide a path to ground for electrons collecting on the quadrature grid. (In some circuits they are omitted.)

This resonant circuit is connected between the quadrature grid and the cathode (by way of C7 and C3). It is tuned to the IF resting frequency. In the absence of modulation a stream of electrons travels from the cathode to the plate in pulses, as previously explained, and some of the electrons in each pulse strike the quadrature grid, causing pulses of current to flow in the resonant circuit. As this circuit is tuned to their frequency it oscillates, causing the voltage on the quadrature grid to swing back and forth. When it swings negatively it cuts off the flow of electrons to the plate, but when positive it allows them to pass; so, like the limiter grid it also acts as a switch.

It is switching at the IF resting frequency, and as long as the limiter grid (in the absence of modulation) is doing the same the pulses of electrons passed by the two grids are at the same rate. However, the construction of the tube is such that the positive swings of the quadrature grid lag behind those of the limiter grid by 90 degrees.

It is like having two gates opening and closing in such a way that the second gate opens half way between the opening and closing of the first, and then closes half way between the closing and opening of the first. Electrons can only flow when both gates are open, which is during the second half of each positive swing of the voltage on the limiter grid.

However, changes in frequency of the input signal caused by modu-

lation change the amount by which the opening and closing of the "gates" overlap. The greater the overlap, the longer the burst of current, and vice-versa.

AC Output Subcircuit: These bursts of electrons arrive at the plate, and thence flow through R2 to charge C5. This RC combination is what is called an *integrating circuit* (see chapter 8). Wider bursts mean more electrons, causing the voltage on C5 to build up; narrower bursts allow it to fall. Since the width of the bursts varies with the frequency, which in turn varies with the amplitude of the modulating signal, you can see that the voltage on C5 will rise and fall proportionately to the audio voltage with which the carrier was frequency modulated.

The tube is basically a voltage amplifier (see chapter 2) even though it also performs the limiting and demodulating functions just described. Consequently the output is usually sufficient to drive an audio output stage, whereas the ratio detector requires an audio amplifier to follow it and drive the output stage. The discriminator not only requires an audio voltage amplifier to follow, but a limiter to precede it. (Limiters, or clippers, are covered in chapter 8.) Since the gated-beam tube enables limiting, demodulation and voltage amplification to be done in one stage it is easy to see why this is such a popular circuit in vacuum-tube FM receivers.

Circuit Variations

As mentioned before, R3 and R4 may be omitted, and the lower end of L3 may be connected directly to the low side of the circuit instead of via C7. Another variation sometimes met is the replacement of R1 with a variable resistor called a *buzz control*. This adjustment is provided to select the best bias point for the limiting grid, which is that which gives the least hissing sound with a weak signal. The quadrature coil often has an adjustable slug which may also be adjusted for the strongest and clearest sound. The cathode bypass capacitor C3 is also omitted sometimes for the reasons explained in chapter 2 under *degeneration.*

The output signal is usually coupled through C8 to a volume control, as in other detectors.

ENVELOPE DETECTOR

Figure 6.10 shows a switching-bridge detector, the most common form of envelope detector. Envelope detectors are named so because

they are used to detect the *envelope* of the complex signal used in stereo FM broadcasting.

Distinguishing Features

A four-diode bridge follows an IF transformer, and has left- and right-channel outputs.

The detector is the final stage of a multiplex circuit, the rest of which is illustrated in block form in Figure 6.10. Each of the other circuits is discussed elsewhere in the book.

Uses

Envelope detectors are used in stereo-multiplex circuits to separate the right and left channels of a stereo broadcast.

Detailed Analysis

FM stereo broadcasts must be receivable by monaural equipment also, therefore the audio from both channels is mixed together at the station in what is known as the L + R signal. Thus a single-channel set receives both channels of a stereo transmission. This is what is meant by the expression "compatible FM stereo."

To provide for two-channel reception an additional audio signal is generated at the transmitter by splitting the two channels, so that there are *two* right- and *two* left-channel signals. Then the phase of the second right-channel signal is inverted before mixing it with the second left-channel signal. There are now an L + R and an L − R signal, the L − R representing the *difference* between the two channels.

Both signals are used to modulate the carrier, but in order to keep them separated the L − R signal is first made to modulate a 38-kilohertz subcarrier, using AM. Sidebands are produced above and below this frequency over the range from 23 kilohertz to 53 kilohertz.

This 38-kilohertz signal is then used to modulate the carrier along with the L + R audio signal. However, so as to improve the signal-to-noise ratio, the 38-kilohertz carrier is suppressed; consequently the signal received by the FM receiver consists of the FM carrier, modulated by the audio and the 38-kilohertz sidebands only.

In order to recover the L − R signal it is necessary to re-insert the 38-kilohertz subcarrier, which is done in the multiplex circuit of the receiver, or "stereo adapter" as it was called when purchased separately. A locally generated signal by itself will not do, because it must have
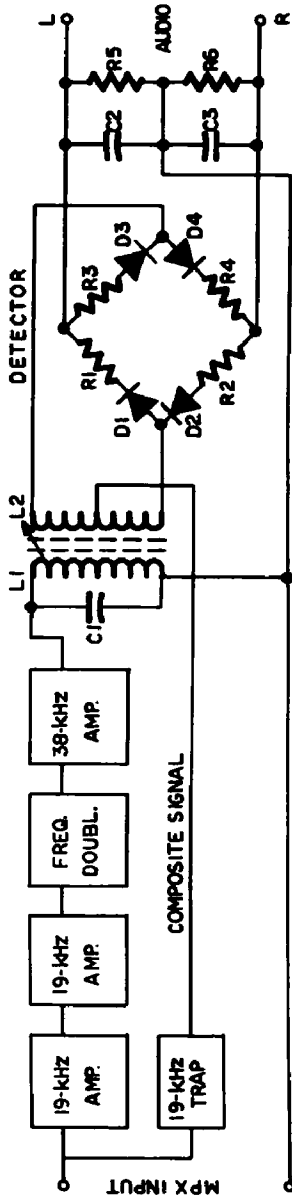
Figure 6.10   Envelope Detector in Stereo Multiplex Circuit

exactly the same frequency and phase as the original. Therefore a pilot signal of 19 kilohertz is also transmitted. This doesn't affect the signal-to-noise ratio, because it is transmitted in the unused space between the maximum audio (L + R) frequency of 15 kilohertz and the lower limit of the lower L — R sideband, which as you already saw is 23 kilohertz. This pilot is also of lower amplitude than the subcarrier before suppression.

The output of the FM detector—probably a ratio detector—contains the L + R audio signal, the L — R 38-kilohertz sidebands and the 19-kilohertz pilot. In a monaural receiver the 19-kilohertz and 38-kilohertz signal cannot pass through the audio output stages to the speaker, therefore only the L + R audio would be heard.

But in a stereo set the composite audio output of the ratio detector will be routed through a stereo-multiplex circuit similar to that in Figure 6.10, where the 19-kilohertz pilot signal is extracted and amplified by IF amplifier stages similar to those described in chapter 2. It is then applied to a frequency-doubler, which reconstitutes it as the original 38-kilohertz carrier. (Frequency-doubling is discussed in chapter 12.)

Meanwhile the composite audio signal is fed to the secondary of the 38-kilohertz IF transformer in such a way that the L — R sidebands are recombined with their carrier.

The diodes in the detector bridge are arranged so that D1 and D3 demodulate the 38-kilohertz signal when it swings so that the upper end of L2 is negative, and D2 and D4 demodulate it when the lower end of L2 is negative. This gives demodulated audio from D1 and D3 which is L — R, while that from D2 and D4 is of opposite phase, or —L + R. These combine algebraically with the L + R signal, which is present also, of course, as follows:

$$\begin{array}{ll} L + R & L + R \\ \underline{L - R} & \underline{-L + R} \\ 2L & 2R \end{array}$$

The left and right channels then pass through separate audio amplifiers to the left- and right-channel speakers.

Circuit Variations

The circuit we have just discussed uses four diodes in what is called a switching bridge because it switches back and forth as the 38-kilohertz carrier swings back and forth between its positive and negative peaks. In other words, it *samples* each channel alternately. This

can also be done with only two diodes, operating alternately to charge capacitors as in the discriminator, except that the audio signals appearing on the capacitors are now for separate channels.

A rather more complex circuit, using bandpass filters (see chapter 8), separates the output of the FM detector into its three components: the L + R signal (up to 15 kilohertz); the 19-kilohertz pilot signal; and the L − R signal (23 to 53 kilohertz). In this circuit, which is called a *bandpass and matrix* circuit, a 19-kilohertz local oscillator generates a signal which is synchronized by the 19-kilohertz pilot (as explained in chapter 4). This is then doubled and re-inserted to reconstitute the original L − R signal. This signal is then demodulated, using two diodes as just described, to give the L − R and −L + R signals, which are then combined with the L + R signal in an arrangement of capacitors and resistors called a matrix, which is to ensure that they are combined in the right proportions.

DE-EMPHASIS

In chapter 5 you saw that in FM transmission it was necessary to use *pre-emphasis* to obtain a more favorable signal-to-noise ratio. This resulted in the higher audio frequencies being transmitted with greater power than the lower. In the receiver it is necessary to restore the proper proportion between the higher and lower frequencies, and this is done by *de-emphasis*.

In Figure 6.8 de-emphasis is performed by R3 and C5, which have a time-constant corresponding to that of the pre-emphasis circuit in the transmitter. Such a high-frequency attenuation circuit is similar in operation to the bass control of chapter 2, but without the variable resistor.

While de-emphasis must take place between the detector and the audio amplifier following it, it cannot come before a stereo-multiplex circuit, since it would attenuate the 19-kilohertz pilot and the 38-kilohertz sidebands. Consequently it will always be placed in the output of a multiplex unit. However, sets designed to receive stereo broadcasts usually have a function switch with a monaural position which bypasses the multiplexer when not required. In this case the FM detector has two outputs, one for stereo without de-emphasis, and one for monaural with de-emphasis, and the switch selects the appropriate output.

SYNCHRONOUS DETECTOR

In the previous chapter you saw how phase modulation as used in color TV was accomplished by using a pair of doubly balanced modulators. PM demodulation is the same process in reverse. Figure 6.11 shows a synchronous detector using a pentode. Two of these are required to extract the signal's two component vectors, just as two modulators were required to combine them.

Distinguishing Features

The 3.58-megahertz reference signal is applied to the No. 3 grid of the pentode, and the modulated color subcarrier (chroma) is applied to the control grid. In the output appears a filter circuit (L1–C1) to eliminate the 3.58-megahertz subcarrier, which is no longer required.

Uses

Color television reception.

Detailed Analysis

DC Subcircuit: In Figure 6.11 electron flow is from B— via R2 to V1. From the plate of V1 current returns via L1, R4 and L2 to B+. From V1's screen grid it reaches B+ through R3.

AC Input Subcircuit: The modulated subcarrier (chroma) is applied across R1, *the color gain control,* which is adjusted to give the desired signal on the control grid. This is biased to avoid complete cutoff, so that the whole color signal is amplified.

The 3.58-megahertz reference signal, synchronized with the transmitter, is applied to the No. 3 (suppressor) grid. A negative voltage on this grid will cut the tube off completely. In a receiver designed for I and Q color signals the reference signal for the I demodulator must be phase-shifted 57° before reaching the grid. That for the Q signal must be 90° more, as you saw in the previous chapter. However, many receivers use different vectors for which other phase angles are required. This does not alter the principle of operation of this circuit.

AC Output Subcircuit: V1 can only conduct when the suppressor grid is not negative. During each positive half-cycle of the 3.58-
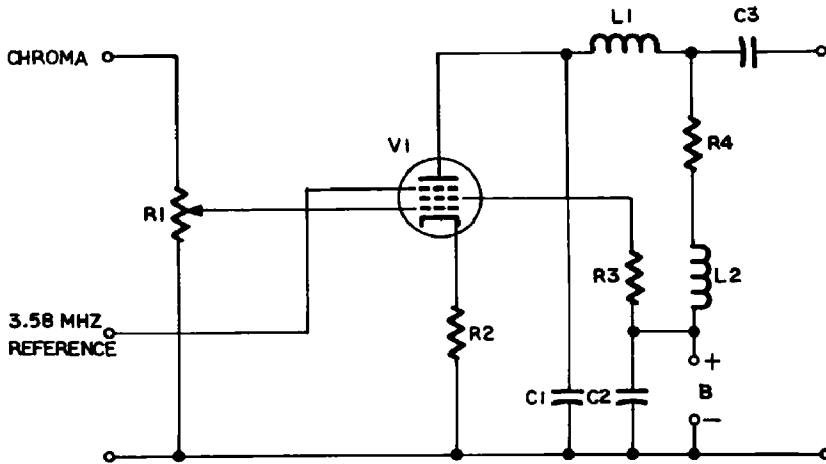
Figure 6.11   Synchronous Detector

megahertz reference signal, current will flow in proportion to the volt-
age on the control grid. The greatest current will flow when a positive
half-cycle of the color signal on the control grid coincides with a
positive half-cycle of the reference signal on the suppressor grid. This
happens when both signals are in phase.

However, the phase angle of the color signal is constantly changing
as the color information changes. Therefore the direct current out of
VI will consist of a series of pulses at 3.58 megahertz which will vary
in width and amplitude according to the amount of overlap between
the two signals. This action is similar to that of the gated-beam tube
previously discussed in this chapter.

Since the reference signal of each of these demodulators is 90°
different from the other, their output will consist of the two vectors
added at the transmitter. In each demodulator these pulses are inte-
grated and smoothed by C1 and L1, and coupled through C3 to the
next circuit.

Circuit Variations

Demodulators sometimes employ two gated-beam tubes of the type
used in FM detection instead of pentodes. Dual-beam-deflection tubes
have been developed (such as the 6JH8) to give a push-pull action.

Transistors can replace tubes in essentially similar circuits. Diodes
may also be used in circuits resembling the ratio detector already dis-

cussed (see Figure 6.8). Two pairs of diodes are required, but they share a centertapped transformer that supplies reference signals at 90° phase difference. The diodes conduct according to the phase and amplitude of the color signal.

TROUBLE-SHOOTING CHART FOR DEMODULATORS	SYMPTOM							
	Radio - Sound Absent or Weak	Radio - Sound Intermittent	Radio - Hum	Radio - Buzz or Hiss	Radio - Distortion	TV - No Picture	TV - Contrast Poor	TV - Interference Pattern, or Grainy
Tube Weak, Dead	X		X		X	X	X	
Tube Socket Contacts Dirty or Broken		X						
Volume Control Dirty or Defective	X	X						
IF Transformer Misadjusted	X			X	X			
Buzz Control Misadjusted	X			X				
Quadrature Coil Misadjusted	X			X	X			
Cathode-Bypass Capacitor Defective			X	X	X			
Storage Capacitor (Ratio Detector)				X				
De-emphasis Filter					X			
Peaking Coil (L3 in Figure 6.2)						X		
Peaking Coil (L4 in Figure 6.2)							X	X

7

POWER
SUPPLIES

A POWER SUPPLY IS a circuit which provides the operating voltages for the other circuits in a piece of electronic equipment. Except for heater current for tubes, all operating voltages are DC. While small radios can obtain all their requirements from batteries, most electronic equipment plugs into the 117-volt power line. This does not mean that all power supplies convert AC to DC, but the majority do. In their circuitry they are similar to the AM demodulation circuits described in chapter 6. There are also independent power supplies, portable or otherwise, which are not part of some other piece of equipment.

BATTERY POWER SUPPLY

The simplest and one of the most widely used sources of power for electronic equipment is a *battery*. The same symbol is used, regardless of type. The long line is always positive, but polarity may be indicated in addition, as in Figure 7.1. Sometimes a distinction is made between single cell and multicell batteries, symbolizing the first by a single pair of lines, one short and one long, although this may be used also to
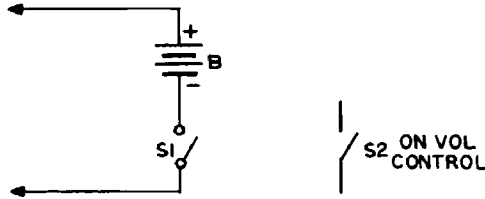
Figure 7.1   Battery Power Supply

indicate only a generalized direct-current source. Voltage value may also be shown.

Switches are usually shown as S1 or S2, in Figure 7.1. S1 seems to be more popular. They are usually shown open. (S2 could not be shown any other way!)

Battery power supplies seldom have any other components, unless they are rechargeable-battery supplies. These have a simple rectifier-type supply as, for example, that illustrated in Figure 7.7. (L1 will probably be a resistor, however.) On most radio and TV receivers the physical switch is mounted on the rear of the volume control, and is turned on or off by the same knob. This may be indicated in a schematic by a statement beside the switch symbol (as by S2 in Figure 7.1), or by a dashed line connecting the switch symbol to the variable resistor symbol to indicate they are ganged together. In this way the two symbols can be located according to their functions.

UNIVERSAL AC-DC POWER SUPPLY

This power supply got its name because it could be operated from both AC and DC power lines, as it does not use a transformer. You are not likely to encounter a DC power line today, but the name is supposed to sound better than "transformerless power supply." Figure 7.2 gives a typical example.

Distinguishing Features

1. Rectifier (diode) tube, or solid-state rectifier.
2. Pi-filter, in which R1 may be replaced by a choke.
3. Series-string of filaments across the power line, as shown.
4. No power transformer.
5. Connection to power line, and on-off switch.

Detailed Analysis

In this supply the tube heaters are connected in series across the power line, which is assumed to be at 120 volts. As you know, the first figure, or figures, of tube numbers give the heater voltage required. Those shown in the diagram add up to 121 volts.

Five tubes, each requiring 24 volts, would also add up to 120 volts. However, when this circuit was adopted heater voltages had already been pretty well standardized at 6.3 or 12.6 volts, which were the battery voltages originally used. Furthermore, using higher AC voltages for heaters introduces hum when the heater current is AC. Consequently the lower-voltage tubes already available were used in the circuits most susceptible to hum pickup, and two special tubes were developed for the less sensitive audio output and power supply circuits. By arranging them so that the most sensitive circuits' tubes are also at the low end of the string (lowest AC voltages), hum pickup has been kept below an audible level.

The numbers 3 and 4 indicate the tube pins for the heaters. By showing the heaters separately in the power supply like this, it saves showing them in the tube symbols, and avoids the additional congestion
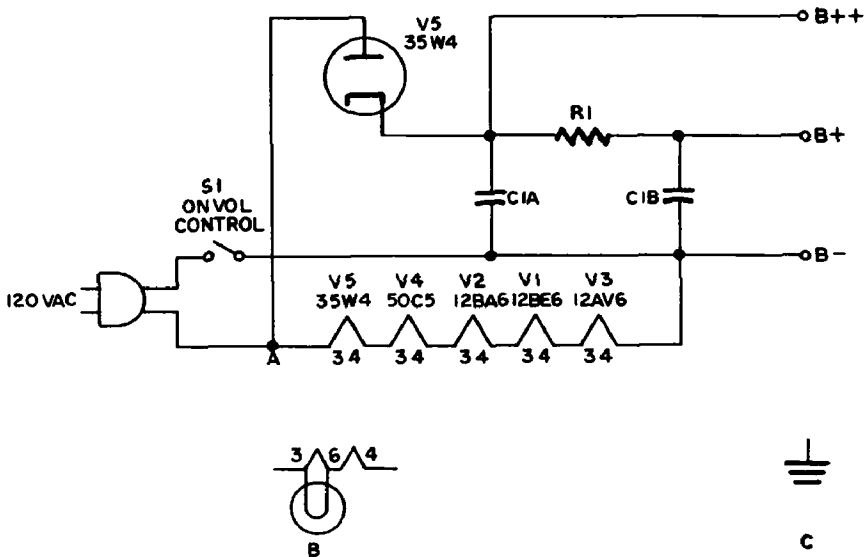

Figure 7.2   Universal AC-DC Power Supply

and confusion of having to draw heater connections running all over the schematic.

The AC of the power line is converted to DC by the rectifier tube V5. When the side of the power line connected to the plate swings positive the other side swings negative and supplies electrons via S1 to the low side of the circuit, B—. Current flows from B— to the cathodes of the four tubes in the radio, from the cathodes to the plates and screen grids, and back to B+ and B++. From these points it reaches the cathode of V5, flows to the plate, and from there to the positive side of the power line.

When the AC line reverses polarity on the alternate half-cycle, V5's plate becomes negative with respect to the cathode, and V5 cannot conduct. Consequently, bursts of current flow through V5 in one direction only on the half-cycles that make its plate positive, but no current flows on the alternate half-cycles; hence it is called a *half-wave rectifier,* which means that half the power available from the power line is not being used. For the small power requirements of this type of radio this is not important.

These pulses of DC cannot be used for most of the tubes, as they would still create a loud hum, so a pi-filter circuit is provided to smooth them out and give a constant voltage at B+. The filter consists of C1A and C1B, which are two sections of a dual electrolytic capacitor (usually from 30 to 50 microfarads each), and R1, a resistor capable of handling the plate supply current of V1, V2 and V3. Its value will probably be around 1000 ohms.

Filters are covered more fully in chapter 8. Without going into too much theory we can say that in this one, when V5 conducts, C1A charges up to the voltage at V5's plate, since the tube has a low resistance when conducting. When V5 cuts off it cannot conduct, so C1A starts to discharge through R1 and the rest of the circuit. The circuit resistance is much higher, of course, so C1A has not discharged very much before V5 starts conducting again on the next positive half-cycle and replaces whatever was lost. The voltage on C1A therefore fluctuates between the maximum value and that to which it falls when V5 is not conducting.

This fluctuating voltage can be thought of as consisting of two components: a steady DC voltage at the lower value, and an AC voltage ripple "riding" on it. This AC component is still too much for our B+, so R1 and C1B are provided as a voltage divider to reduce it to an acceptable figure. For AC at 60 hertz, C1B has a reactance of 100

ohms or less, whereas R1 is at 1000 ohms (or thereabouts). This divides the AC voltage appearing between R1 and C1B by a factor of at least eleven. However, as C1B offers a very high resistance to DC the latter is hardly affected at all. For small loads this amount of filtering is quite adequate.

The one tube that draws a heavier plate current than the rest (V4) is supplied directly from C1A (B++ supply). As this tube is an audio power amplifier, fluctuations in the plate *voltage* have very little effect on it (see chapter 3), and the ripple on its supply is therefore of no consequence.

Circuit Variations

As you just saw, resistor R1 is perfectly adequate as part of the pi-filter as long as the amount of current required is small (and when the plate supply of V4 is drawn directly from C1A). Therefore, in small and inexpensive clock radios and the like this will be the normal arrangement. However, as soon as a higher current requirement arises, as in a set with more tubes, or with pretensions to high fidelity, then a choke will be substituted for R1. A 5-henry choke presents a reactance of approximately 2000 ohms to the AC component, while offering negligible resistance to the DC component. As a result higher DC currents can be passed without dropping the voltage. For AC the effect is the same as when a resistor is used. You might meet this type of filter more in TV sets today, as we shall see later on in this chapter.

A pilot light is sometimes connected across half of V5's heater filament, as shown at B. This not only tells you that the set is on, but also acts as a safety device. The plate of V5 is connected to the centertap of the filament (pin 6) instead of to point A (in the main diagram). If a short develops somewhere in the set so that a heavy current is drawn through V5, the half of the filament between pins 3 and 6, and the pilot light, will burn out as if they were a fuse.

A ground symbol (as at C) is frequently drawn at B— to indicate a chassis ground return. This saves drawing in the low side of the circuit. The same symbol is then used at other points in the set to indicate points also connected to the chassis, and therefore to B—. This has become such a habit with radio and television manufacturers and others that they do it even though there may be no real chassis (as in today's printed-circuit boards). It has a distinct advantage in small crowded diagrams, but in the much larger prints used in industrial

work it is more usual to draw in the "ground return" or low side of the circuit.

FULL-WAVE RECTIFIER

A disadvantage of the AC-DC power supply was that drawing a heavy current from it would cause the voltage on C1A to fall excessively between the half-cycles when V5 conducted. While this could be overcome by elaborate filtering it is more economical to charge the input filter capacitor on both half-cycles. Full-wave rectifiers which do this are shown in Figures 7.3 and 7.4.

Distinguishing Features

This type of power supply uses a power transformer with various windings. Diodes are connected to the opposite ends of the secondary winding or windings used for the DC supply. In vacuum-tube types the diodes may be in one tube (as in Figure 7.3), or in separate tubes (more usual for higher voltage supplies).

Input connections from the power line are indicated by illustrating a plug or similar connection, switch, fuse, line filter, all on the primary side of the transformer.

The output is via a filter and voltage divider network. There may be more than one supply, as in Figure 7.4.
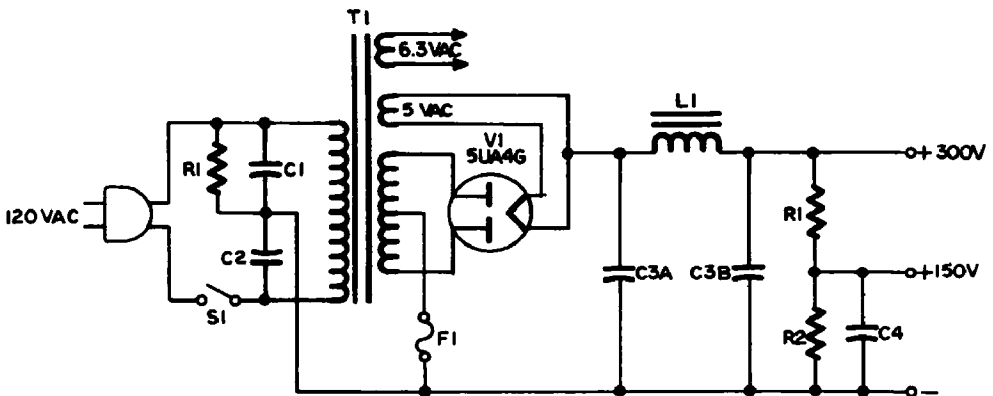

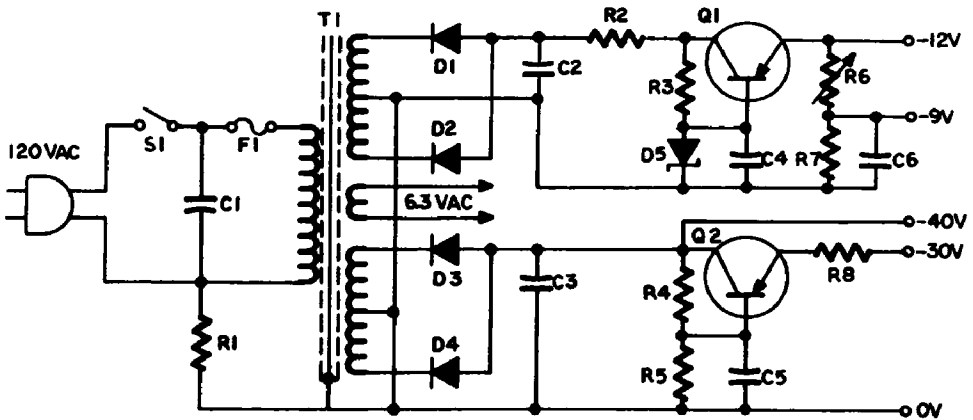**Figure 7.3 Vacuum-Tube Full-Wave Power Supply**

Figure 7.4   Solid-State Full-Wave Power Supplies

Uses

TV, radio and other electronic equipment with comparable require-
ments.

Detailed Analysis

Vacuum-Tube Full-Wave Power Supply: The input to this power
supply is shown as a simple two-wire cord and plug. However, a third
wire could be used, and would be connected to the junction between
C1 and C2. These capacitors are usually of .01-microfarad capaci-
tance and form, with R1 (100 kilohms), a filter for reduction of
power-line interference (pops from operation of switches, interference
from motors, and so on). A *switch* (mounted as part of the volume
control), and sometimes a *fuse,* will also be part of the input circuit.

The principal secondary winding is the high-voltage winding, of
which the opposite ends are connected to the two plates of V1. The
centertap is connected to the low side of the circuit via the fuse F1.
This centertap is the most negative point in the circuit.

The filament of V1 is heated by a special 5-volt AC winding. Elec-
trons flow from this filament alternately to each plate according to
which end of the winding is positive. The resultant DC current is
drawn through the filter and voltage divider from all the tubes in the
set, which in turn draw electrons from their cathodes, which are sup-
plied from the low side of the supply.

The pi-filter (C3A, C3B, L1) operates in the same way as dis-

cussed under the AC-DC supply, and the voltage divider divides the +300V supply equally to give a +150V supply for the more sensitive tubes. C4 gives additional filtering to this supply.

Tube heaters get a 6.3 AC voltage from the other filament winding. Some power transformers have more than one 6.3V winding, or a 12.6V winding with a centertap, or both. Color-coding for leads for power transformers is given in the Appendix.

SOLID-STATE FULL-WAVE POWER SUPPLY

Figure 7.4 really depicts two power supplies sharing one power transformer. The remarks made about the input to Figure 7.3 power supply also apply to this one, but the two main secondaries give rise to two sets of voltage outputs. The pair of semiconductor diodes in each case function in the same way as the 5UA4G tube of Figure 7.3, but require no heater current, so no filament winding is provided. The 6.3-volt winding shown is for dial lamps and such.

Transistors Q1 and Q2 are provided for voltage regulation, discussed later in this chapter.

Circuit Variations

The circuits of Figures 7.3 and 7.4 appear in many variations. Sometimes there are two rectifier tubes instead of a dual tube, sometimes two dual tubes are connected in parallel. As already mentioned, there can also be differences in the number and arrangement of windings on a power transformer.

Line filters can vary also from the examples shown, though the principles are the same.

The filter, voltage divider and regulation circuits can sometimes get quite complicated where many different supply voltages are required. However, they all work according to the principles explained in this chapter.

TRANSFORMERLESS VOLTAGE-DOUBLER POWER SUPPLY

Figure 7.5 illustrates a very popular type of power supply. It is similar to the AC-DC power supply of Figure 7.2, but capable of higher voltage and current output, which makes it suitable for economy TV use.

Distinguishing Features

1. Two diodes (rectifiers), usually solid-state.
2. Pi-filter with choke.
3. Series-string of tube filaments.
4. No power transformer.
5. Connection to power line, on-off switch, fuse or fusible resistor.

Uses

Radio, TV and the like.

Detailed Analysis

With S1 closed the alternating power-line voltage is applied across C1A and D1. The lower side of D1 is alternately positive and negative. When positive, D1 conducts, allowing electrons to leave the right-hand side of C1A. The other side of C1A is charged negatively. As D1 can only conduct in one direction the positive charge on C1A builds up to the peak value of the power-line voltage ($120 \times 1.4 =$ 168V). This positive voltage stored on C1A acts as a base, with the power-line AC superimposed on it, so that the voltage at the upper end of D1 is the algebraic sum of the DC and AC peak voltages. This voltage varies between $+336$ and 0 ($+168 \pm 168$) volts. The action of the rest of the circuit to the right of D1 is the same as that of Figure 7.2, except that the filtered DC voltage will be approximately 250 to 300 volts instead of 100 to 150 volts.

R1 is a *surge resistor,* a low- value resistor which controls the rush of current into C1A when S1 is closed, which might otherwise destroy D1. It can be combined with the fuse F1 in a *fusible resistor* ("sur-
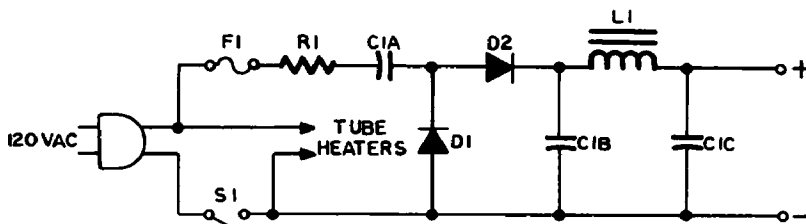

Figure 7.5   Transformerless Voltage-Doubler Power Supply

gistor"). This can withstand the heavy charging current which only lasts for a very short time, but melts if a short elsewhere in the set draws a sustained heavy current.

Circuit Variations

Although fundamental principles remain the same there are several different ways of arranging these circuits. Much of the variation is in voltage dividers and filters (discussed later).

A disadvantage of this type of circuit is that one side of the chassis (when using a metal chassis) is connected to the power line. To avoid this the low side may be connected to the chassis through a large capacitor located in series with C1B. This capacitor then replaces C1A, which is not required.

Considerable variation is also possible in the order in which the series-string of tube heaters is arranged. If there are very many it may be necessary to arrange them in two parallel strings (see Figure 7.8). Occasionally a filament transformer is used instead, and the tubes are then connected in parallel. A filament transformer is a less expensive type of transformer which reduces the power-line voltage to 6.3 or 12.6 volts. (Such transformers are used for domestic purposes also, such as bells, thermostats, and so on.)

TRANSFORMERLESS VOLTAGE-TRIPLER POWER SUPPLY

The voltage-tripler circuit illustrated in Figure 7.6 works in exactly the same way as the voltage-doubler of Figure 7.5. Compare the two circuits. (Switch, fuse, heater connections and surge resistor have been omitted for convenience.)

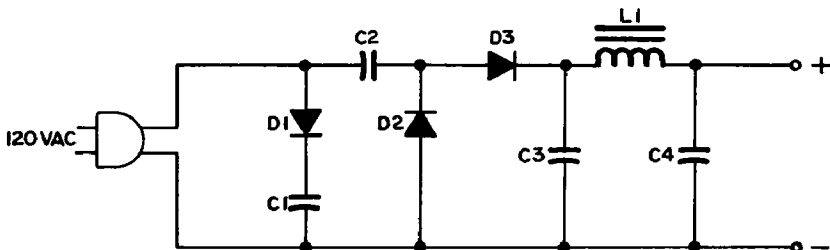C1 and D1 store a positive charge in the same way as C1A and D1

Figure 7.6   Transformerless Voltage-Tripler Power Supply

in Figure 7.5. This additional voltage brings the output up to between 400 and 450 volts. Further capacitor diode pairs could be added to make voltage-quadruplers, -quintuplers, and so on, but capacitors that can stand higher voltages are expensive, so there is a practical limit to what can be done.

BRIDGE RECTIFIER POWER SUPPLY

Figure 7.7 illustrates a bridge rectifier circuit.

Distinguishing Features

Four diodes (not necessarily diagramed in a diamond pattern) connected across the secondary (or principle secondary) of a power transformer. This secondary does not have a centertap.

Uses

TV, radio, and other electronic equipment with comparable requirements.

Detailed Analysis

When the lower end of the secondary winding is negative, electrons flow via D2 to the load across the output terminals. From there the current returns through the filter L1–C2–C3 and D3 to the upper end of the transformer secondary. On the next half-cycle the polarities reverse, and the current flows from the upper end of the secondary winding through D1, and thence through the load and filter as before. However, this time it returns through D4 to the lower end of the winding.
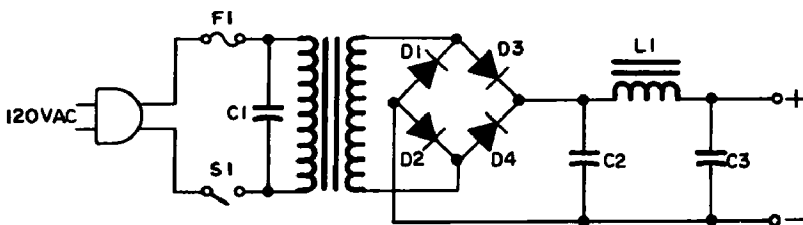

Figure 7.7   Bridge-Rectifier Power Supply

VOLTAGE DIVIDERS

Power supplies which have to provide for more than one B voltage may do so by means of voltage dividers. A voltage divider consists of several resistors connected in series between the high and low sides of the output of a power supply. The current flowing through these resistors does the following:

(1) It stabilizes the power supply voltage.
(2) It discharges the capacitors when the equipment is turned off.
(3) It gives a voltage drop across each resistor which is proportionate to the resistance value.

In Figure 7.8 A, three resistors with values as shown are connected across a 240-volt supply. The total resistance is 40 kilohms, so the voltage divides proportionately as follows:

Resistor	Voltage Drop
10K	60V
15K	90V
15K	90V
40K	240V

In B a similar arrangement is shown connected across a 650-volt supply. However, the low side of the main circuit is not connected to the bottom of R5, but between R4 and R5, making this the zero reference. As a result the voltage at the bottom of R5 is *negative* (below zero) with respect to the zero point. This has the advantage that bypass and decoupling capacitors with lower working voltages can be used, which makes for greater reliability and less cost.

However, in transformerless power supplies there is a limitation on how much current can be supplied. If the voltage divider consumes too much it takes it away from the tubes for which it is supplied. In the examples shown, A draws 6 milliamperes, and B 10 milliamperes. In a TV set this may be more than can be tolerated. Consequently an arrangement similar to that shown at C may be used instead. This uses the voltage drop across a tube which draws considerable current (such as an audio-output tube) to provide two levels of voltage. The current passing through V4 is equal to the combined currents of V5, V6 and V7.

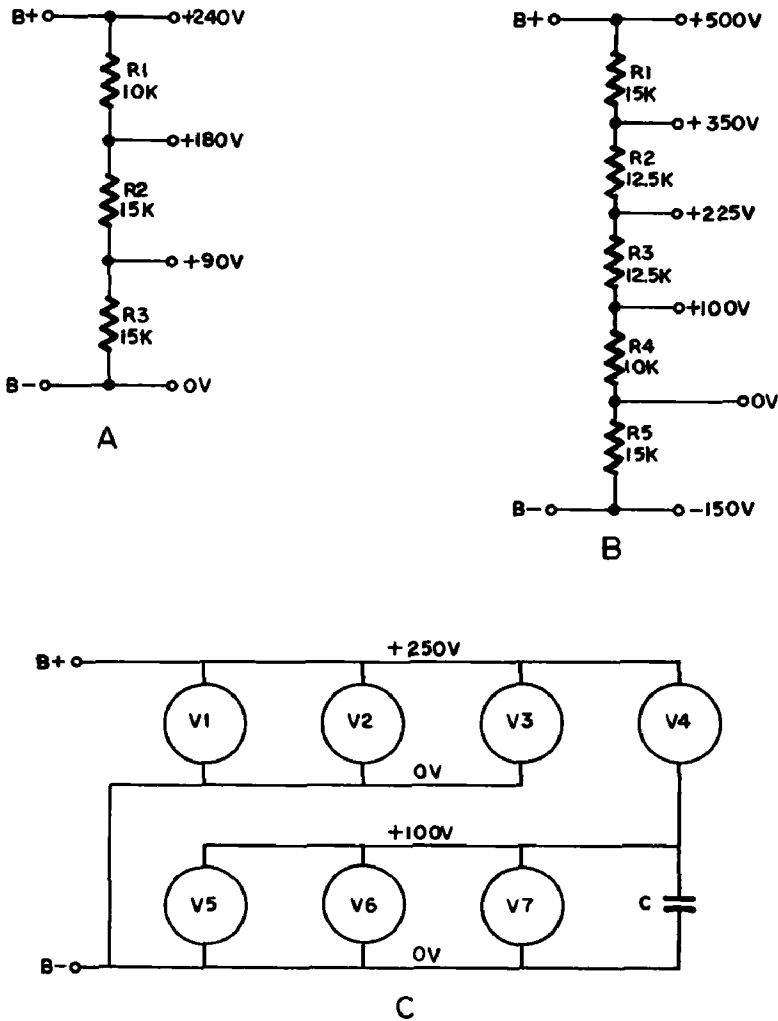Two 100-volt tubes may be connected across a 200-volt supply in

Figure 7.8 Voltage Dividers

series, provided they draw the same current. An example of this eco-
nomical trick is shown in Figure 2.25.

VOLTAGE REGULATION

The voltage output of any of the power supplies discussed so far
will vary according to the load and line voltage. In many cases this
does not matter, but where a constant output is essential a *voltage
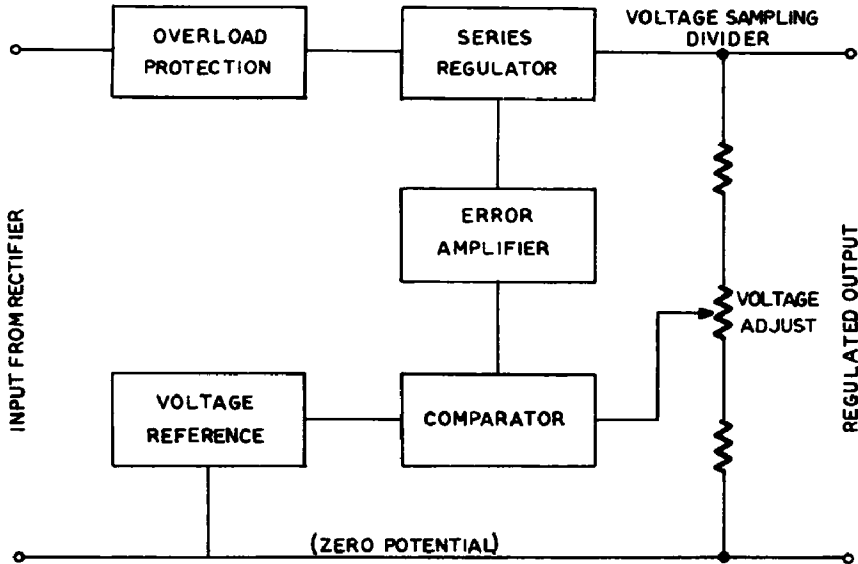regulator* circuit must be provided.

Figure 7.9   Voltage Regulation

A voltage regulator consists of the elements illustrated in block form in Figure 7.9. It is connected to the output of a power supply (such as a bridge rectifier, Figure 7.7).

If the output voltage changes, the voltage at the movable arm of the "voltage adjust" resistor changes, and this change is sensed by the *comparator,* which monitors it constantly against the *reference.* The comparator passes on this information to the *error amplifier,* which in turn controls the *series regulator.*

In Figure 7.10 is shown a voltage regulator which also contains an *overload protection* circuit (R1, Q1). If a short circuit occurs somewhere so that a very heavy current is drawn through R1, the base-emitter junction is forward-biased so that current can flow through Q1 and R4. The voltage drop across R4 is such that the base-emitter junction of Q4 (the error amplifier) is reverse-biased, so Q4 is cut off. As no current can now flow through R6, the forward bias on the base-emitter junction of Q5 disappears, and it also ceases to conduct.

When the overload is removed, so that normal current flows through R1, Q1 returns to its usual non-conducting condition, and Q4 and Q5 become conductive again. R1 has a resistance value of .5 ohm or less, so normal current does not produce enough voltage drop to bias Q1 into conduction. C3, a large-value capacitor, absorbs noise and spikes so that operation is not interrupted by transients.

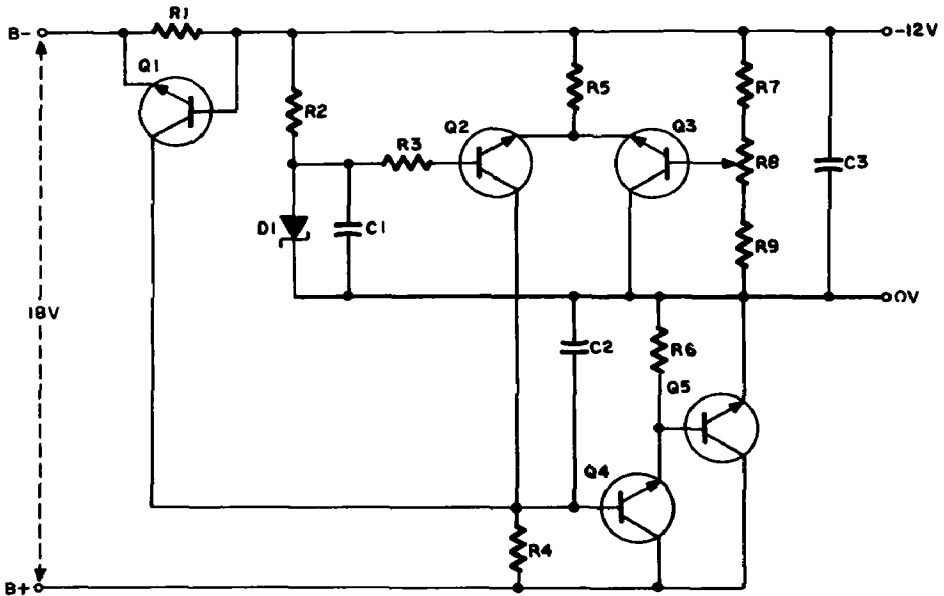D1 is a *zener diode* connected in series with a limiting resistor R2,

Figure 7.10   Voltage Regulator

and it gives a reference voltage of 9 volts at their junction. It also clamps the voltage on the base of Q2 at a value close to this. The base of Q3 is connected to the movable arm of R8. If the voltage at this point changes, due to a change in the output voltage of the power supply, the bias on Q3 changes. This changes the resistance of Q3, so that the current flowing through it changes.

Q2 and Q3 form a *comparator circuit,* and share R5. When the current through R5 changes (which it does when the current through Q3 changes) the voltage drop across R5 also changes. This changes the bias on Q2, so that its resistance changes in accordance with the increase or decrease of output voltage across R7, R8 and R9.

The change in voltage on the base of Q4 due to the change in voltage drop across R4 is amplified and applied to the base of Q5, causing this transistor to decrease or increase resistance to correct the rise or fall in the output voltage. Since the output of the power supply is dependent on the voltage at the movable arm of R8 the value of the output voltage can be adjusted by moving this control.

This is a very sensitive circuit, and is used extensively in well-regulated power supplies. The identical circuit will also be met where

Q2 and Q3 are a dual-triode tube, Q4 is a pentode, Q5 a triode (or two or more triodes in parallel) and D1 is a gas glow-tube.

Circuit Variations

A circuit which is also often used is shown in Figure 7.11. This combines the comparator and error amplifier in one tube, V3. Changes in voltage at R9 change the voltage on V3's grid, thereby changing its resistance, and consequently the current through V3 and R5. The resultant change of plate voltage appears on V2's grid, so that when the output voltage rises V2's resistance increases to correct it. The neon glow-tube V1 clamps the cathode of V2 at approximately half the output voltage.

Very much simpler and more economical circuits were illustrated in Figure 7.4, where Q1 and Q2 are also voltage regulators. Here only one transistor in each supply is doing the work of all four in Figure 7.10. Of course, the regulation is nowhere near as good, but it is much more economical, and adequate for hi-fi and the like.

In the case of Q1, D5 is also a zener diode, which clamps the base of Q1 to approximately 12 volts. Any variation in output voltage is felt by the emitter, changing the emitter-base bias, and controlling the conductivity of Q1. R6 is a variable resistor. By adjusting R6 the 9-volt output can be set to the exact value.

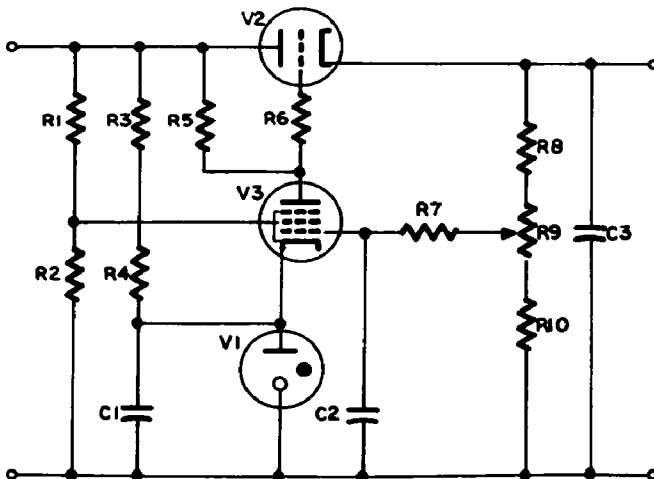In the case of Q2 no zener-diode reference is provided, and conse-

Figure 7.11   Voltage Regulator

quently regulation is less efficient. Line-voltage variations are not compensated for, only load variations. The 40-volt supply is not regulated at all.

HIGH-VOLTAGE POWER SUPPLIES

Low-voltage power supplies, such as those we have been discussing, provide voltages up to around 500 volts. Applications needing higher voltage are served by high-voltage power supplies.

High-voltage power supplies fall into two classes: those where power is required, and those where voltage is the main consideration.

HIGH-VOLTAGE POWER SUPPLY FOR TRANSMITTER

Figure 7.12 illustrates one of the first type, to provide power for a transmitter. It is a full-wave power supply which differs only from a low-voltage supply in tube and transformer sizes. Its distinguishing features and mode of operation are the same as those for Figure 7.3, except for two additional features.

L1 is a *swinging choke*. This is a choke operated with the core close to saturation, so that the inductance varies with the current (see discussion of Magnetic Amplifiers in chapter 3). It has a smoothing effect on the DC pulses coming from the rectifier tubes.
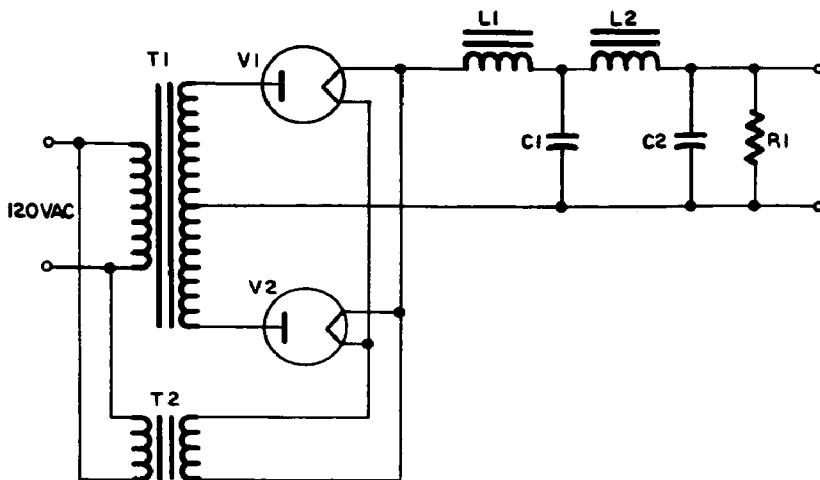

Figure 7.12   High-Voltage Power Supply for Transmitter

R1 is a bleeder resistor. By providing a constant current drain it stabilizes the output voltage, and also discharges the filter capacitors when the power is switched off.

Note that there are *two* transformers. T1 is called the *plate transformer*. It is not uncommon for the AC potential across its secondary to be 2000 volts, or 1000 volts across each half.

T2 is the *filament transformer*. It provides the current to heat the filaments of V1 and V2. Since the DC potential on these filaments may be 1000 volts or more this transformer has to be well insulated. The tungsten filaments of these tubes will usually draw a heavier current than those used in smaller power supplies.

The tubes themselves are often heavy-duty mercury-vapor rectifiers, such as 816s.

Capacitors C1 and C2 are generally of much smaller capacitance than those used in low-voltage power supplies. Electrolytics are not able to withstand the higher voltage, so these will probably be oil-bath types. Because they can only be around 5 or 10 microfarads at most, chokes with considerably higher inductance values have to be used.

HIGH-VOLTAGE POWER SUPPLY FOR CATHODE-RAY TUBE

Cathode-ray tubes (CRTs) are mostly used in oscilloscopes, although a TV picture tube is really a CRT also. However, picture tubes are classed by themselves in this chapter. CRTs require a high anode-to-cathode voltage. In many cases this may be as much as 12 kilovolts, but the current drawn is very small. Consequently the type of power supply shown in Figure 7.13 is used. TV HV supplies are similar, but are discussed in the next section.

Distinguishing Features

The output of an oscillator V1 is stepped up by a high-voltage transformer T1. The secondary voltage is rectified by diodes and filtered by resistors and capacitors, and the DC output is applied to the CRT, positive going to the anode, negative to the cathode and grid. A sample is often fed back to a comparator which controls the oscillator.

Uses

Mainly in high performance oscilloscopes or similar equipment.

Detailed Analysis

In Figure 7.13 V1 and the primary of T1 form a Hartley oscillator, in which the inductor resonates with the distributed capacitance of the circuit (see chapter 4). The supply voltage for this oscillator comes from the low-voltage supply of the oscilloscope. The frequency of oscillation will be in the order of 50 to 100 kilohertz. Filtering such a frequency is easier, and requires much smaller capacitors, which is an important consideration at high voltages.

Two voltages are supplied by this circuit. A positive voltage of 10 kilovolts is required for the CRT anode, and a negative voltage of 2 kilovolts for the cathode and grid.

The anode voltage is obtained by using a voltage tripler (see Figure 7.6). However, the higher frequency makes filtering easier, so smaller values are required for C5, C6, C7 and C9, and the choke is replaced by R10 and R11.

The cathode voltage, being much lower, is provided by the half-wave rectifier circuit consisting of D1, C4 and C8. Because of the higher frequency and the very small load involved this simple filtering is sufficient.

R7, R8 and R9 form a voltage divider in which R9 is very much larger than the other resistors. The voltage sensed at the movable contact of R8 is only a small percentage of the total. This voltage is fed to the right-hand grid of the dual-triode V2.

The right-hand cathode of V2 is connected to the negative B supply (usually −150 volts). This supply is well regulated, so the cathode voltage is constant. Consequently any change in the grid voltage is followed by a change in the plate voltage. This *error voltage* is coupled directly to the left-hand grid, and the resultant amplified change of plate voltage appears on the screen grid of V1.

This in turn changes the amplitude of the Hartley-circuit oscillations. If the negative voltage on R8 decreases, the right-hand plate voltage decreases, the left-hand grid voltage decreases, the left-hand plate voltage increases and the screen-grid voltage of V1 increases. This causes the oscillations to increase in amplitude, so that the high voltage rises.

The high voltage is set to the exact potential required by adjusting R8. L1 is a choke to keep the oscillator signal from coupling into the power supply (whence it would be distributed all over the set). R1, R5 and R6 are voltage-dropping resistors. R4 is the bias resistor for the left-hand half of V2; C1 and C2 are bypass capacitors.
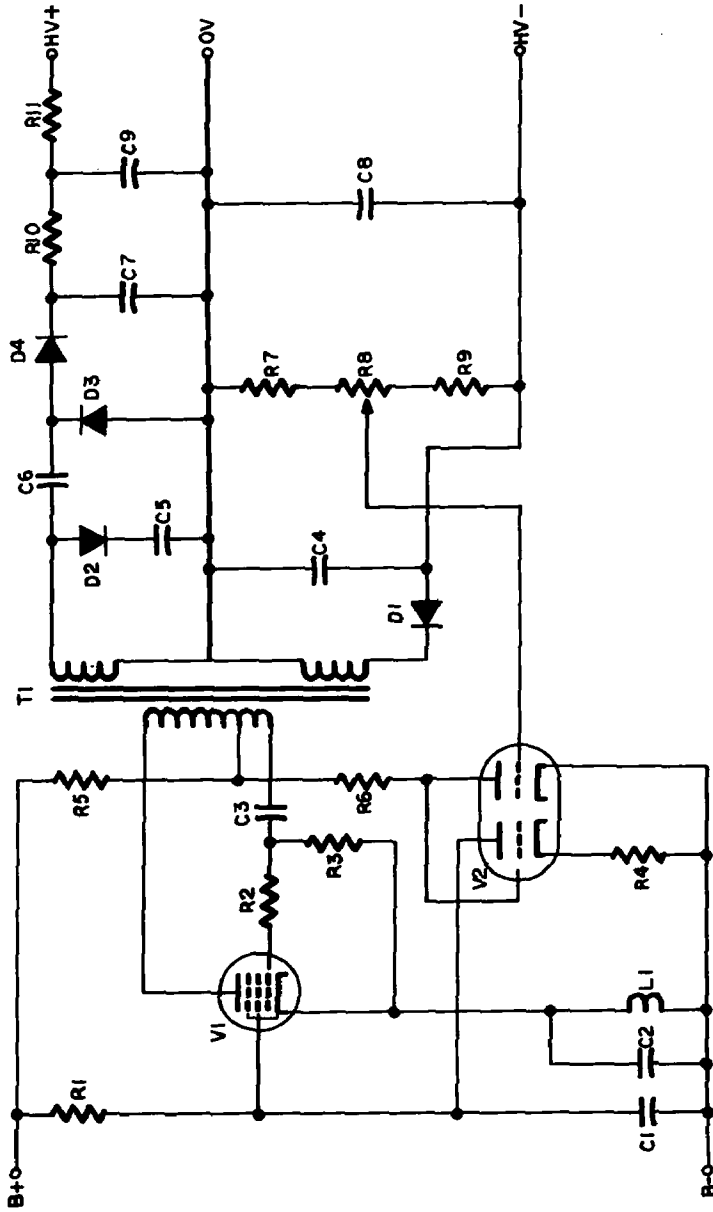
Figure 7.13 High-Voltage Power Supply for CRT

Circuit Variations

In some models solid-state diodes may be replaced by high-voltage vacuum-tube rectifiers. V1 and V2 also may be transistors. The oscillatory circuit may be any suitable type instead of a Hartley. Part of the high voltage may go to the CRT intensity control. The anode or cathode may have independent supplies.

Finally, smaller or more economical equipment may obtain a sufficiently high voltage from a secondary on the low-voltage power supply transformer.

TV HIGH-VOLTAGE SUPPLY

Figure 7.14 shows a typical high-voltage supply for the picture tube of a TV set.


Distinguishing Features

a. One or more pentode or beam-power tubes, often with the plate connection to a cap on top of the tube, as symbolized in V1.

b. A diode with indirectly heated cathode (V2), frequently having an adjustable inductor in its plate circuit.

c. A transformer, usually an autotransformer as shown, with connections to V1, V2, the picture-tube horizontal yoke coils, a high-voltage rectifier (V3), and the picture tube itself (V4).

d. In color TV sets an additional tube, usually a triode (V5), is added for regulation.

e. Any of these tubes may be replaced by an equivalent semiconductor.
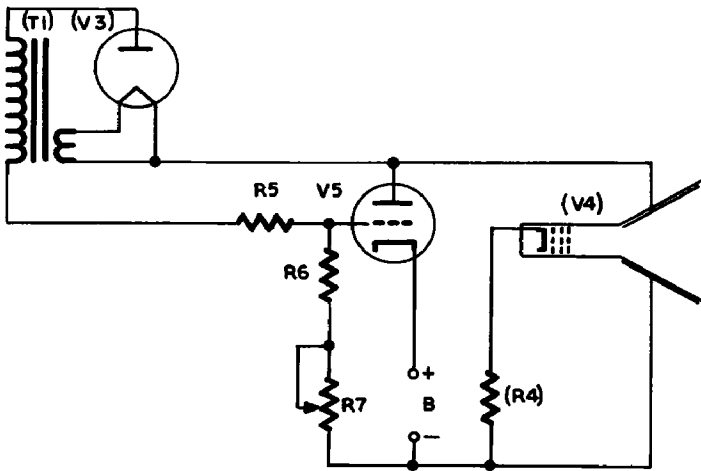

Uses

TV high-voltage section.

Detailed Analysis

Figure 7.14(A) illustrates a circuit which has become pretty well standardized for black-and-white sets. It has some similarities to the circuit in Figure 7.13. For example, the drive is from an oscillator
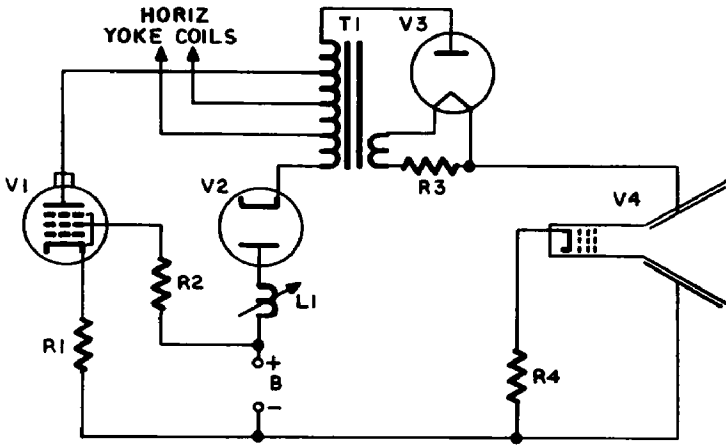
Figure 7.14 TV High-Voltage Supply

and, because of the higher frequency, filtering is much simpler.

DC Subcircuit: Electron flow is from B— via R1 and V1 to T1, through T1 to V2, and via V2 and L1 to B+; also, from B— via R4 to V4, and via V4 and V3 to T1, and thence via V2 and L1 to B+.

AC Input Subcircuit: The horizontal oscillator (not shown) drives V1, which is a power amplifier, often called the horizontal-output tube, and similar to an audio-output stage. However, the oscillator

frequency is 15.75 kilohertz, so it is a little too high for most people's hearing.

The oscillator signal is a modified sawtooth. V1 is biased so that current does not begin to flow until the sawtooth is halfway up its rise. At this point the electron beam in the picture tube is halfway along one of the horizontal lines. In other words, no current is flowing in the horizontal yoke coils to move it one way or the other. But when V1 starts conducting, an increasing current in the yoke coils causes a magnetic field to build up which drives the electron beam at a steady rate to the right-hand edge of the picture-tube screen.

At this point the peak of the sawtooth arrives, and the grid voltage on V1 dives down to its starting value. V1 cuts off abruptly, and the energy stored in the magnetic field of the yoke coils is suddenly released in a tremendous surge of current in the opposite direction.

The reverse current whips the beam back to the left-hand side of the screen (during the brief period when it is blanked out), and also cuts off V2 (the damper tube) by making its cathode more positive than its plate.

However, the positive surge now reverses in a negative direction, which starts the damper tube conducting again. This puts a heavy load on the resonant circuits, damping out the high-amplitude oscillations so that the energy is now released through the yoke coils in such a way as to allow the beam to return to the center of the screen. The circuit is designed so that the beam moves at a steady rate across the screen, with a smooth transition at the midpoint.

The high voltage is generated by the first surge of current, when V1 cuts off. Since V2 is also cut off, loading on T1 for the moment is minimal. The pulse amplitude can be as much as 2 or 3 kilovolts. T1 steps this up to 12 or 15 kilovolts for black-and-white sets, 25 kilovolts approximately for color.

These positive pulses are rectified by V3, and fed to the anode of V4. The inner and outer conductive coatings on the envelope of the picture tube are connected as shown, and form a capacitor (with the glass as dielectric) that, with the internal resistance of V4 in series with R4, is sufficient to smooth the positive pulses into DC.

Filament voltage for V3 is obtained from an additional winding (usually only a turn or two) on T1. R3 is a low-value resistor to protect the filament, and is often omitted.

L1 is the *linearity control*. Adjusting it modifies the waveform of V1's plate current and also V2's discharge waveform. Another variable inductor (not shown) is usually connected in parallel with part

of T1. This is the *width control*. It has the effect of varying the turns ratio of T1, and hence the step-up ratio.

In Figure 7.14(B) is shown an additional circuit used in color TV sets. V5 is a voltage regulator. Its grid voltage is set by adjusting R7. This varies the conductivity of V5, and so changes its loading effect on the high-voltage power supply.

The picture-tube load on the high-voltage power supply is varying all the time with changes in picture brightness. A bright scene increases the load on the high voltage supply. This is reflected in a fall in the voltage across the voltage divider R5, R6 and R7. As a result V5's grid voltage drops and the tube's internal resistance rises, so that it loads the high voltage less. When the scene is dark the opposite happens. In this way V5 compensates for changes in the loading effect of V4, so as to maintain a constant voltage on its anode. This is important for good color.

Circuit Variations

All the tubes except the picture tube may be replaced by equivalent semiconductors. However, the single high-voltage rectifier tube is usually replaced by a solid-state voltage doubler, tripler or even quadrupler. (A quadrupler is a tripler with an additional diode-capacitor pair, as mentioned in the discussion of Figure 7.6.) This gets the necessary high voltage from the flyback transformer, even though the input voltage to it—from a transistor—is much lower than would have been the case with a tube.

Regulation may also be performed on the primary side of T1. In a circuit somewhat similar to Figure 7.13, V1 is controlled to maintain a constant voltage output.

DC INVERTERS

So far we have been mostly concerned with converting AC power to DC power. Circuits for converting DC to AC are also required. Since transformers will not operate on DC it is necessary to convert DC to AC before it can be applied to the primary of a transformer to obtain a voltage step-up.

Oscillators convert DC to AC, of course, but are not generally suitable for power supplies unless the power requirements are small, as in high-voltage power supplies (Figure 7.13). Where the load is heavier

some device must be used that "chops" a considerable DC current into pulses.

Such devices are *electronic* or *mechanical,* and are used in circuits called *DC inverters.* Electronic devices include *thyratrons, ignitrons* and *silicon-controlled rectifiers* (SCRs). Mechanical devices consist of *choppers, vibrators* or *dynamotors.*

In Figure 7.15(A) is shown a DC inverter circuit with a thyratron. The same circuit could also use an ignitron (C) or an SCR (D).

Distinguishing Features

A gas-filled triode (note black dot, which indicates gas content instead of vacuum) is connected in a circuit with a DC input, and an AC output.

No DC operating voltages are provided from a power supply, as this *is* the power supply.

An ignitron is even more recognizable, and so is an SCR, because of their distinctive symbols.

Uses

Heavy-duty power supplies converting DC to AC.

Detailed Analysis

A *thyratron* is a hot-cathode gas tube in which the control grid acts as a switch to turn it on. As long as the grid remains negative the tube cannot conduct, although the anode is positive, but a positive voltage on the grid initiates electron flow. Once this has started it cannot be stopped by making the grid negative; the anode must also be made negative.

An *ignitron* is a cold-cathode gas tube. The control element is the *ignitor,* which is a carbide-tipped rod dipping slightly into the surface of a pool of mercury. The mercury is the cathode. In other respects the ignitron is the same as the thyratron, except it can handle heavier currents and does not require any heater current for the cathode.

A *silicon-controlled rectifier* is the semiconductor equivalent of a thyratron or an ignitor. It is a diode with a third lead to a gate. With the proper bias applied to the gate it switches to a conducting state, when it can pass a heavy current.

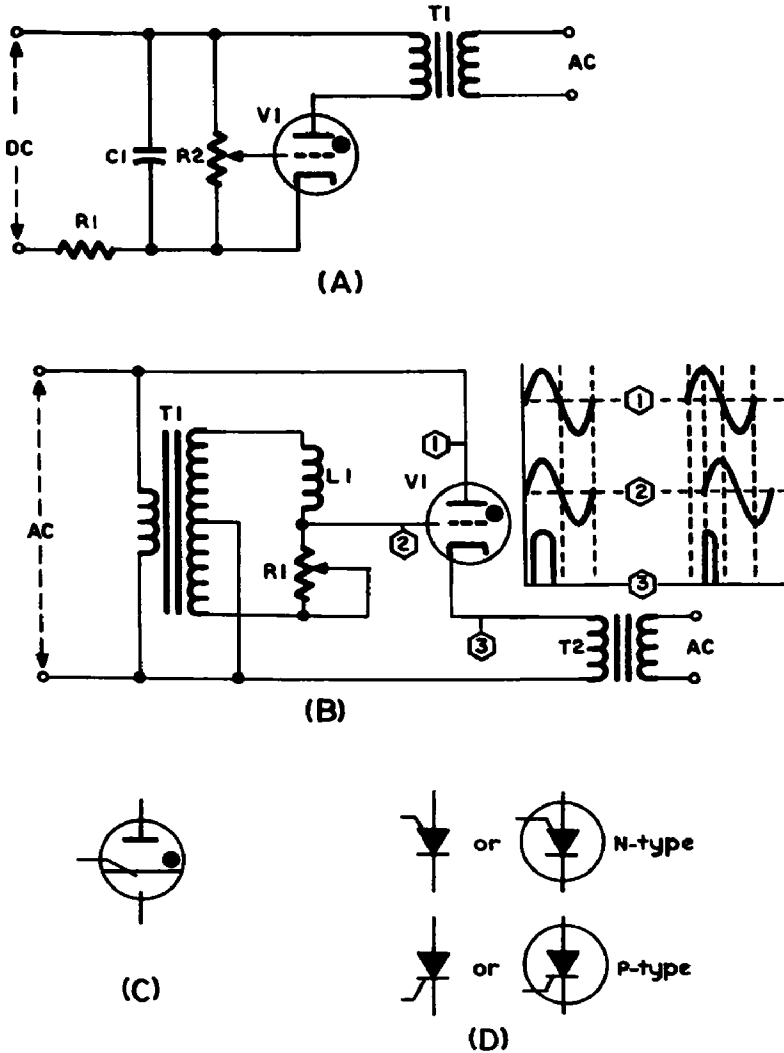In Figure 7.15(A), before any voltage is applied to the input C1

Figure 7.15 Controlled Rectifier Circuits

is not charged. When power is turned on all the current flows into C1 at first, so no voltage appears across V1 and the primary of T1. Consequently V1 does not conduct. The voltage builds up across C1 at a rate determined by the R1–C1 time-constant. When it reaches the value that makes V1 fire, the gas in the thyratron ionizes, and V1 goes from being a very high resistance to a very low one. This enables C1 to discharge practically instantaneously through V1 and T1's primary. In fact, because the primary of T1 tries to maintain current flow even

after C1 is totally discharged, there is momentary overshoot which serves to reverse the voltage across V1, so that it switches back to a non-conducting state. The cycle is now repeated as the input voltage again begins to recharge C1 through R1.

R2 is used to adjust the voltage on the grid of V1 for best performance. The chopped DC current passing through the primary of T1 induces an AC output in the secondary. The output voltage depends on the turns ratio of T1.

Dynamotors are used to convert DC to AC or to DC of a higher voltage. They are essentially DC motors with a secondary winding on the armature from which the output is obtained, and so are really rotating transformers.

Choppers and Vibrators are electromechanical devices for interrupting the flow of current, operating in the same way as a buzzer or telephone bell. At one time all automobile radios obtained their power from the car's battery by using a vibrator in a circuit similar to Figure 7.16. Although modern car radios are solid-state it's worth noting this power supply because the principle of chopping DC and converting it to AC is well illustrated by it.

It is readily identified by the vibrator, which consists of an electromagnet, symbolized by the rectangle, and a reed. The reed rests against the two lower contacts (arrows). When S1 is closed current flows from the negative side of the 12V supply to the reed. Some of the current then flows through the lower half of the primary of T1 (via the right-hand contact) and back to the positive side of the supply from the centertap. The rest flows via the left-hand contact, through the electromagnet, and back to the positive side of the supply.

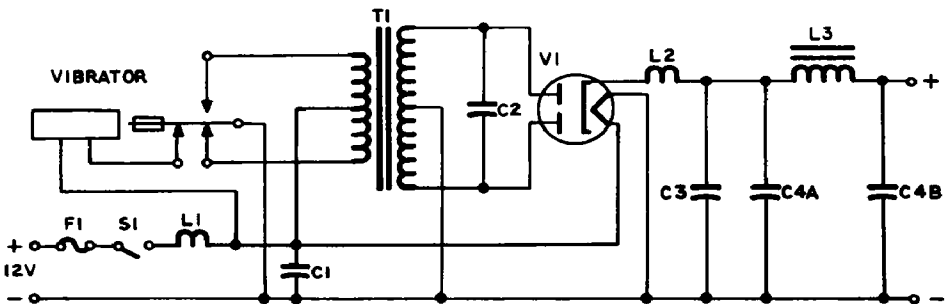The electromagnet, being magnetized by the current, attracts the

Figure 7.16   Vibrator Power Supply

armature on the reed. This swings the reed over to the upper contact, breaking the connection with the two lower contacts. Current now flows in the upper half of T1's primary and back via the centertap, but in the opposite direction to that which flowed in the lower half. However, the current flowing in the electromagnet is now cut off, its magnetic field collapses, and the reed returns to its initial position, where the cycle starts again.

You can see that the alternate surges of current in opposite directions in T1's primary are an AC current, which is stepped up by the secondary, after which it is rectified and filtered by a full-wave power supply similar to that in Figure 7.3.

The cathode of V1 is indirectly heated by the 12-volt battery supply, as are all the other tube cathodes.

C2 is a *buffer capacitor*. It is used to reduce voltages surges ("spikes") that might damage the following parts. L2 and C3 together form a *hash suppressor* that filters out RF noise from the vibrator. L1 and C1 do the same for RF noise picked up by the car's wiring (such as spark-plug noise).

Thyratrons as Industrial Power Controls

Thyratrons are also used to control AC power for machinery by means of a phase-shifting circuit such as that in Figure 7.15 (B).

The AC power source is connected to the anode and cathode of VI as shown. The transformer T1 is also connected to the power source. Because of the centertap the polarity of the signal at the upper end of the secondary winding is opposite to that at the lower end.

The phase of the signal applied to V1's grid, relative to that of the signal on the anode, depends on the setting of R1, which forms a phase-shifting network with L1. If both signals are of the same phase, positive excursions will be applied simultaneously to anode and grid, and the thyratron will conduct for the maximum length of time until both signals swing negative, as illustrated in the left-hand set of waveforms.

However, if the phase of the grid signal is shifted, as shown in the right-hand set of waveforms, the period of conduction is shortened to the length of time during which the positive excursions overlap, so that the output power is reduced accordingly. R1 shifts the phase up to 90 degrees, with a corresponding variation in output from full power to zero.

TROUBLE-SHOOTING TABLE FOR POWER SUPPLIES	SYMPTOMS							
	No output	Low voltage	Hum or ripple	Video poor (TV)	Sound bars (TV)	No picture (TV)	No sound (TV or radio)	Vert.sync.critical (TV)
Line voltage low		X		X				
Line voltage zero	X					X	X	
Fuse blown, surge resistor open	X					X	X	
Power transformer open	X					X	X	
Power transformer - shorted turns			X					X
Rectifier(s) weak		X	X	X		X		X
Rectifier(s) open or shorted	X					X	X	
Filter capacitor(s) old, open, leaky		X	X	X		X		X
Filter capacitor(s) shorted	X					X	X	
Choke or series resistor open	X					X	X	
Choke shorted			X					X
Audio output tube defective*				X		X		
Audio decoupling capacitor defective*					X	X		
High-voltage power supply defective						X		

*Series-parallel system.

8

MODIFIERS

THE SIGNALS USED IN electronic circuits usually have to be tailored to fit the purpose for which they are required. This tailoring is done with a variety of standard circuits which reduce the amplitude, change the shape, separate, or otherwise modify a signal.

Attenuators and Pads

The distinguishing feature of attenuators and pads is that they consist of resistors. Attenuators are resistive networks that reduce the strength of a signal without introducing appreciable distortion. A pad is a resistive network that attenuates a signal without introducing an impedance mismatch. It is also used to match dissimilar impedances to avoid unnecessary signal attenuation, in which case it is called a minimum-loss pad.

Fixed pads are either *symmetrical* or *asymmetrical*. In the first the input and output impedances are the same, in the second they are not. They are also *balanced* or *unbalanced*, depending upon whether the two sides are alike or unlike with regard to a common reference (usually ground). This means that an unbalanced pad is one with one side grounded or at zero potential, as in most circuits, while a balanced pad has neither side grounded.

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In Figure 8.1 the first unbalanced pad is called an *L-pad* because the arrangement of its resistors resembles an upside-down L. Its balanced counterpart is a *U-pad,* because it looks like a U lying on its side. The resistors drawn horizontally are *series* resistors; the vertical are *shunt* resistors. These are impedance-matching pads, and are also called *minimum-loss* because they do not cause much attenuation.

Unbalanced   Balanced

L-Pad   U-Pad
                                                  (Balanced L)

Matching Pads

T-Pad   H-Pad
                                                  (Balanced T)

π -Pad   O-Pad
                                                  (Balanced π)
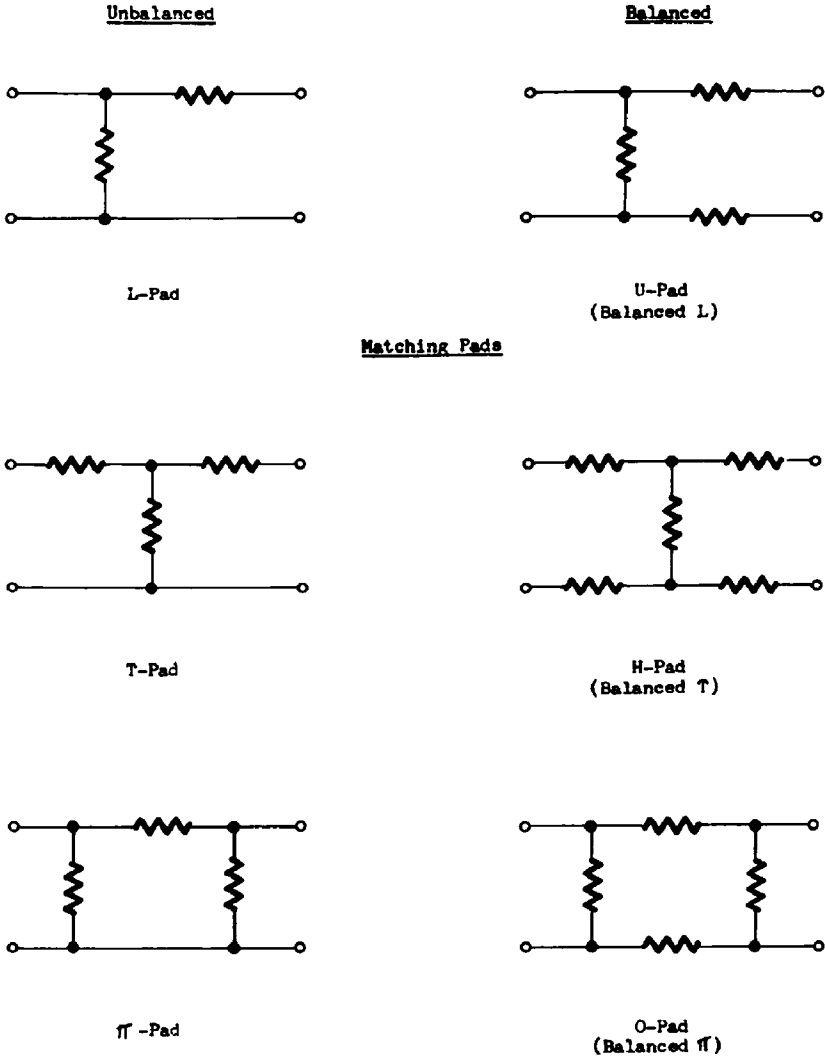
Attenuators

Figure 8.1   Fixed Pads

The next unbalanced pad is a *T-pad*, and its balanced version is an *H-pad*. These pads are used for attenuation. They should be connected between similar impedances.

The bottom two pads are also for attenuation, not for impedance-matching. The π-*pad*, like the π-*filter*, is named for its resemblance to the Greek letter π (pi).

Figure 8.2 shows T and H pads with resistors shunted across the series resistors. They are called *bridged-T* and *bridged-H* pads.

Variable pads are also illustrated in Figure 8.2. These are designed so that the attenuation can be varied while maintaining the impedance match. In a simple potentiometer the amount of resistance shunting the device connected to it varies with the setting. In the examples shown, one resistor increases as the other decreases to maintain a constant impedance.
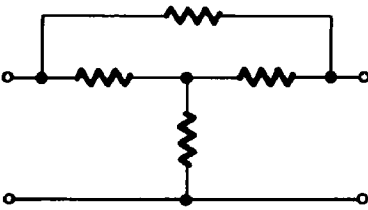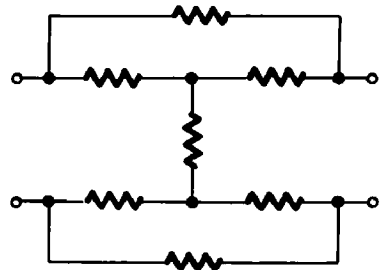
Bridged T-Pad   Bridged H-Pad
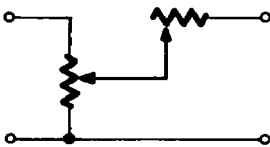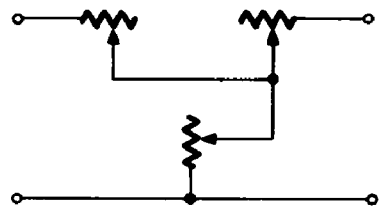
Variable L-Pad   Variable T-Pad

Figure 8.2   Bridged and Variable Pads

Filters

A filter is a selective network designed to pass signals within a certain frequency range ("pass band"), while attenuating those of other frequencies. Filters are categorized as *low-pass, high-pass, bandpass* and *bandstop*. The distinguishing feature of all of them is the use of inductor-capacitor (L–C) circuits. A low-pass filter passes lower fre-
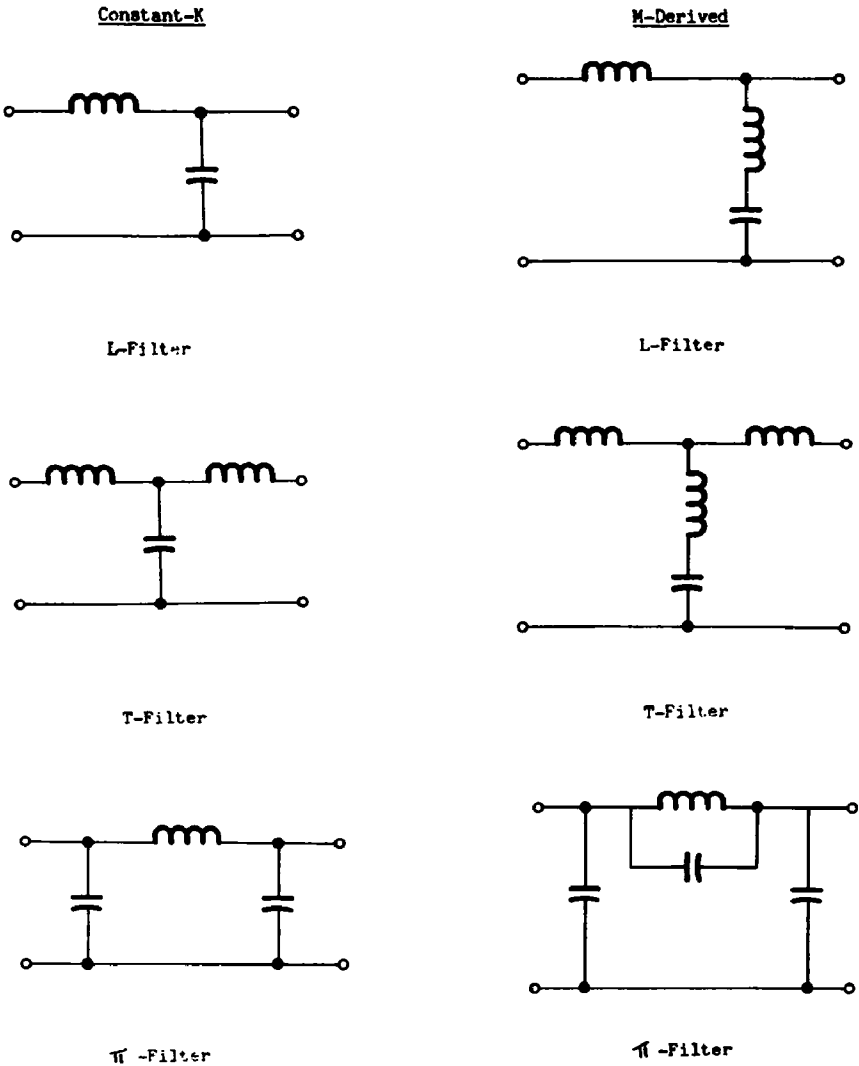
Figure 8.3   Low-Pass Filters

quencies but attenuates higher ones. Figure 8.3 shows six low-pass filters. They look somewhat like the pads in Figure 8.1, except that all are unbalanced. In each there is a *series inductance* and a *shunt capacitance*. The inductance has more reactance to higher frequencies, while the capacitance has more reactance to lower ones. Consequently, higher frequencies find an easier path through the capacitance, and so are bypassed, but the inductance offers less reactance to the lower frequencies which therefore are not bypassed.

Constant-K

M-Derived

L-Filter

L-Filter

T-Filter

T-Filter
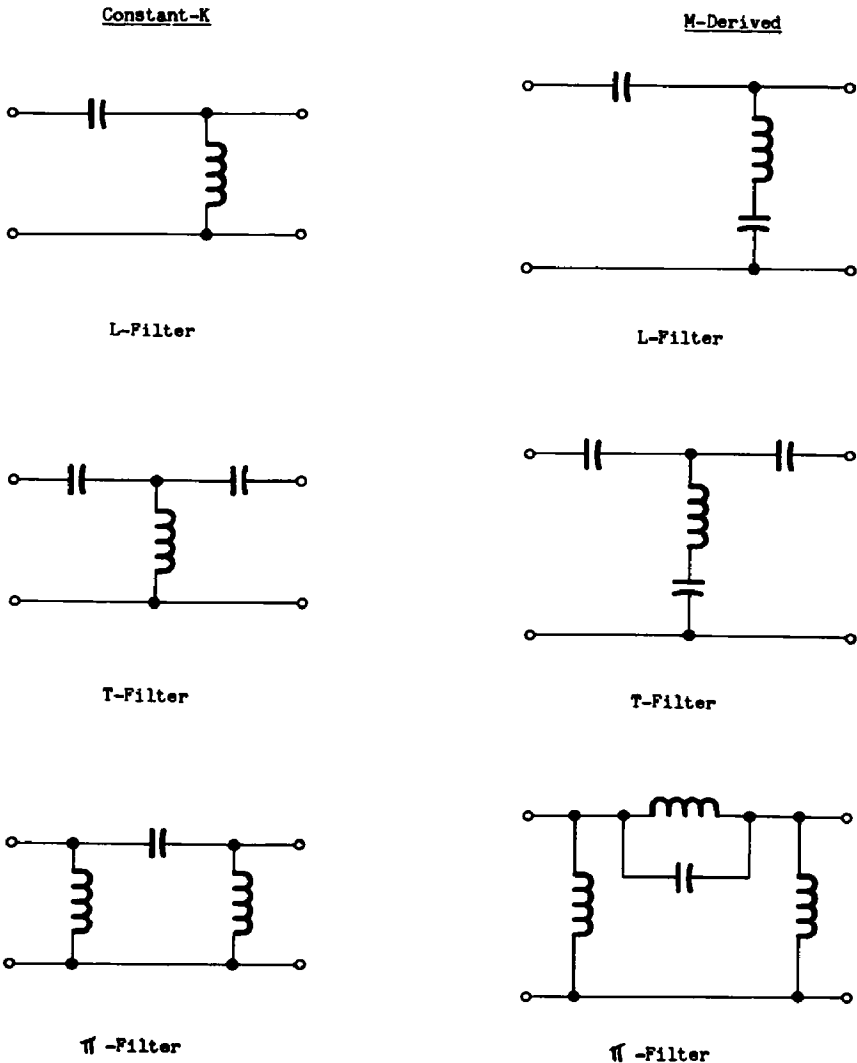
π -Filter

π -Filter

Figure 8.4 High-Pass Filters

Constant-k filters are simpler than *m-derived filters,* and do not have as sharp a cutoff. For many purposes this is no disadvantage. The power supplies discussed in chapter 7 make extensive use of low-pass filters, especially filters to eliminate 60- and 120-hertz AC, while passing DC (which in this connection can be regarded as ultra-low-frequency AC).

In the m-derived filters the addition of shunt inductances in the first two makes, with the shunt capacitance, series-resonant circuits having a very low shunt impedance to frequencies just below the cutoff frequency. This results in a steep drop in the frequency response below
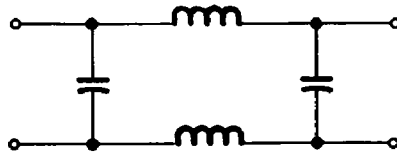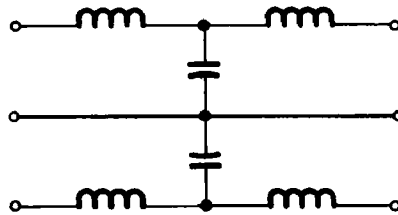
π -Filter
(Low-Pass)

T-Filter
(Low-Pass)
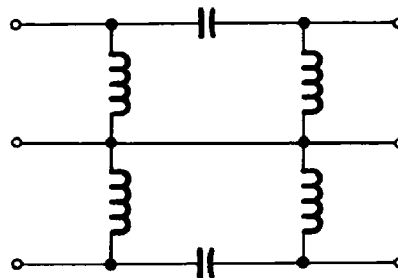
π -Filter
(High-Pass)

Figure 8.5   Balanced Filters

the cutoff frequency. The circuit in the third filter is a parallel-resonant circuit, and so offers a high series reactance to frequencies below cutoff.

A *high-pass filter* passes higher frequencies but attenuates lower ones. Figure 8.4 shows six high-pass filters. They are the counterparts of those in Figure 8.3. In each one there is a *series capacitance* and a *shunt inductance*. The lower frequencies find an easier path through the inductance, and so are bypassed, while the capacitance offers much less reactance to the higher frequencies, which are not bypassed.

The distinctions between k- and m-derived filters are also similar to those that apply to low-pass filters.

L-Filter
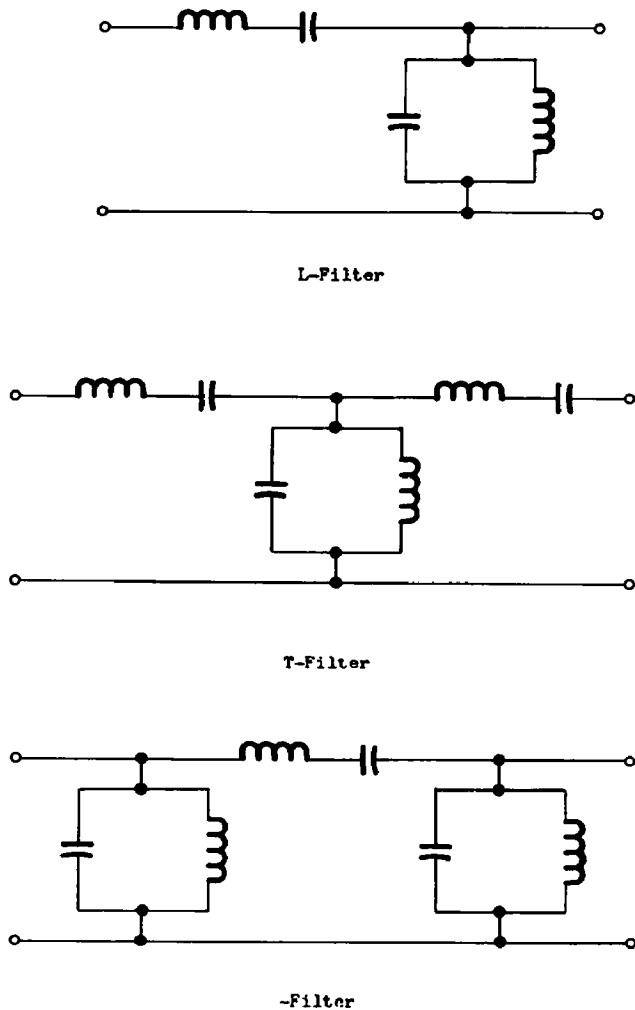
T-Filter

-Filter

Figure 8.6   Bandpass Filters

The filters in Figures 8.3 and 8.4 were unbalanced filters. Examples of balanced versions are shown in Figure 8.5.

Bandpass filters allow signals with the desired frequency to pass while rejecting all others. The width of the band depends on the selectivity of the circuit, which can be made broader by increasing the resistance in it. Figure 8.6 illustrates three typical bandpass filters of the constant-k type. They resemble the unbalanced pads shown in Figure 8.1, with series-resonant circuits substituted for the series resistors and parallel-resonant circuits replacing the shunt resistors. Series-resonant circuits offer a very low reactance to signals at and near the
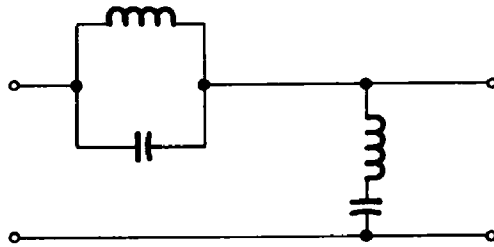
L-Filter
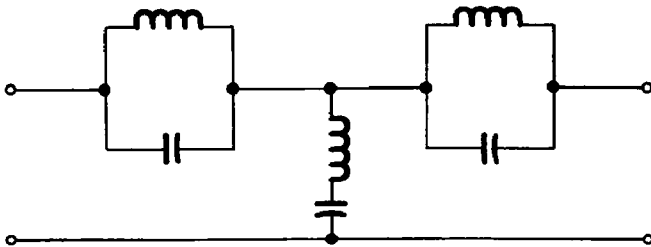
T-Filter
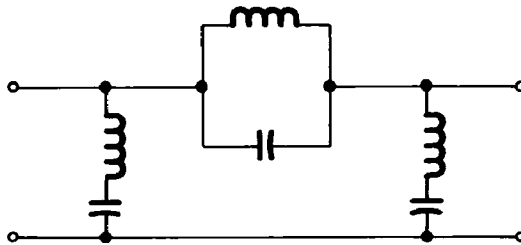
-Filter

Figure 8.7   Bandstop Filters

resonant frequency, but parallel-resonant circuits are the opposite. To signals of other frequencies the series-resonant circuit offers a much higher reactance, the parallel-resonant one much lower. Consequently signals within the pass band find an easy path along the upper part of the circuit, and are not bypassed, while other frequencies are severely attenuated.

Bandstop filters are illustrated in Figure 8.7. If you compare this with Figure 8.6 you will see that they are counterparts. The series and parallel-resonant circuits have changed places. As a result, bandstop filters discriminate against the selected frequency instead of favoring it.

Integration and Differentiation

The two circuits in Figure 8.8 each consist of a capacitor and resistor only, which is what distinguishes them from the attenuators and filters we've just considered.

Integration
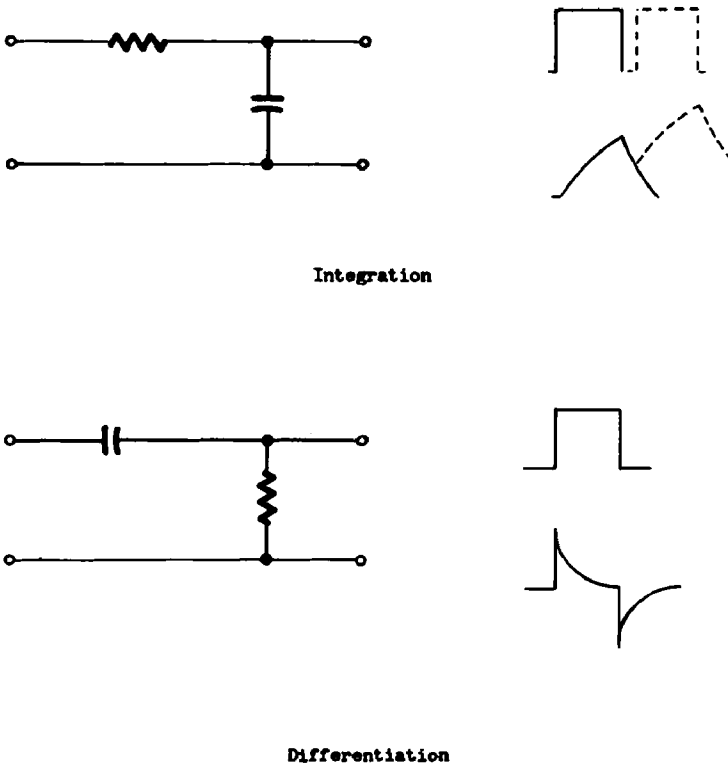
Differentiation

Figure 8.8   Integration and Differentiation

An *integrator* consists of a capacitor charging through a resistor. Its output represents the time integral of its input or, in other words, the output voltage is proportional to the time constant of the R–C combination. When a pulse with a waveform similar to the upper outline is applied to the input it is changed so that the output waveform is like the lower outline. This happens because the capacitor cannot charge instantly to the voltage of the pulse, but must build up the voltage at a rate determined by the flow of current through the resistor.

This circuit is used in television receivers to build up a voltage to trigger the vertical oscillator by accumulating the vertical synchronizing pulses that occur between each field (frame). These pulses have a long duration compared to the time interval between them, so that each pulse adds its voltage to that of its predecessor before the capacitor has had time to discharge, as shown in the dashed outlines in Figure 8.8.

Integrators are used in a similar way in counters, frequency dividers and the like. They may be compared to low-pass filters.

A *differentiator,* on the other hand, resembles a high-pass filter. This circuit consists of a capacitor and resistor arranged as shown. When a voltage is applied to the input, current flows to charge both sides of the capacitor. As the capacitor has no charge at first, the initial current is high, tapering off as the capacitor becomes charged. This current flowing through the resistor produces a corresponding voltage drop that has the waveform shown, with a sharp positive-going spike initially when the leading edge of the pulse arrives, and a negative-going spike, caused by the discharge current, at the pulse trailing edge.

In television receivers this circuit serves to change the vertical synchronizing pulses into sharp triggering pulses to maintain horizontal synchronization during the period between fields when these extrawide pulses are being received.

Clippers (Figure 8.9) may be either series or shunt. The distinguishing feature is a diode. Those shown in the figure are semiconductors, but vacuum-tube diodes could be used in the same way. These diodes have been *biased* by placing a DC source where it applies a reverse-bias to the diode, such that this voltage has to be overcome before the diode can conduct.

In the *series-clipper,* current can flow through the diode whenever the anode voltage is positive with respect to the cathode (the right-hand side of the diode symbol, with the line). The DC source biases
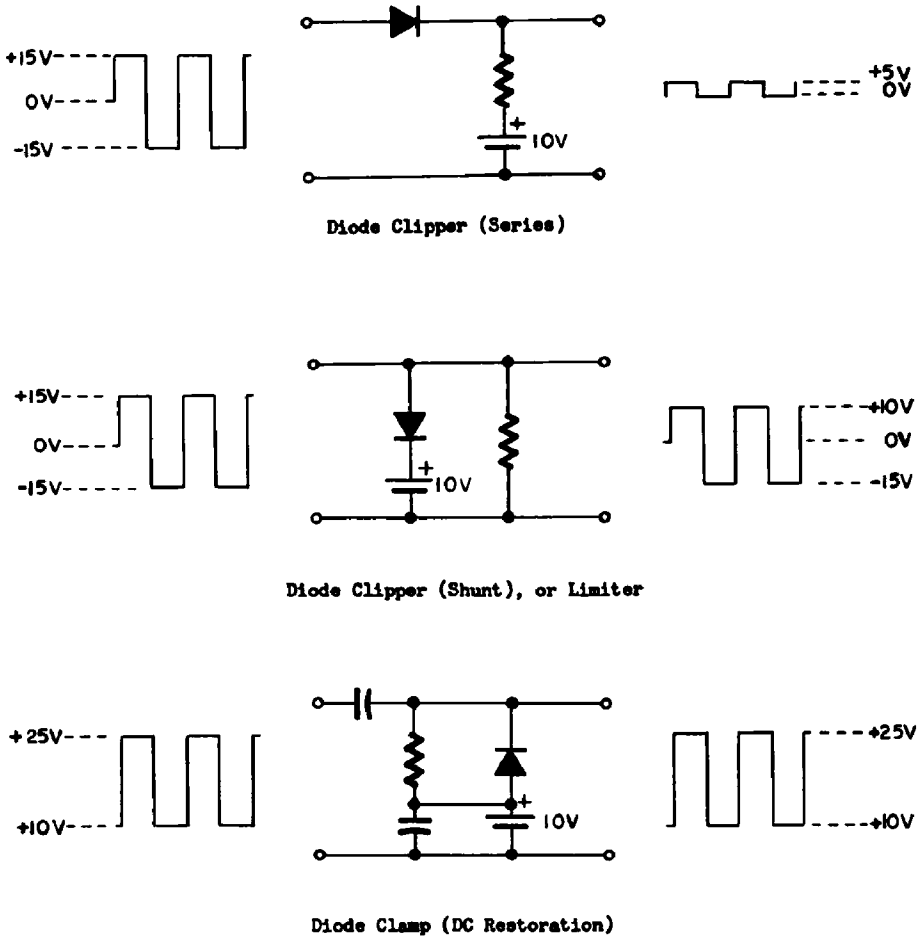
Diode Clipper (Series)

Diode Clipper (Shunt), or Limiter

Diode Clamp (DC Restoration)

Figure 8.9   Clippers, Limiters and Clamps

the cathode with a positive 10 volts. Consequently the diode can only conduct when the voltage on its anode exceeds 10 volts. If a square wave with positive and negative excursions (peaks) of 15 volts is applied to the input, the diode will conduct only during that part of the positive excursion that exceeds 10 volts, which is 5 volts. This gives an output of 5-volt pulses as shown. The rest of the input is blocked by the diode, and is said to have been clipped.

The *shunt clipper* has also been biased with 10 volts. A negative excursion of the square wave is not bypassed, as the diode does not conduct; consequently the whole negative 15 volts appears at the output. The diode does not conduct until more than 10 volts of the positive excursion appears on the anode of the diode. Voltage above this

is bypassed, therefore only 10 volts of the positive excursion appears in the output.

The shunt clipper when used with a pulse train is also a limiter, since by clipping all the pulses to the same height, variations in amplitude (transients, overshoots, noise, etc.) can be removed. The series clipper does not do this, as in its case the bottom of the pulse is removed instead of the top.

The action of a clipper is the same for sine waves as for square waves. In fact, a sort of square wave can be produced by cutting off the tops of sine waves.

Reversing the polarity of diode and bias reverses the polarity of the clipping.

Clamp circuits are used for *DC restoration*. In the circuit shown in Figure 8.9 a train of pulses with voltage alternating between +25 volts and +10 volts is coupled through a series capacitor. This signal is equivalent to a train of 15-volt pulses riding on a 10-volt DC base. The capacitor cannot pass the DC portion, so only the train of pulses appears across the resistor.

The missing DC is restored by the DC source, which replaces the 10 volts that could not pass through the capacitor. This voltage is present on both sides of the diode. When a pulse arrives the voltage on the cathode increases to +25 volts; the diode does not conduct as its anode is still at 10 volts. However, any negative overshoot which takes the cathode below +10 volts causes the diode to conduct, and the overshoot is bypassed. In this way the pulse train is clamped to a 10-volt base.

If the DC source is omitted the pulse train will be clamped to a zero base. Other DC voltages may also be used. The shunt capacitor is provided to bypass the DC source so that no signal voltage is dropped across it.

9

CONTROLS

CONTROL CIRCUITS ARE widely used in industry. In this category are found the logic circuits in computers, gating, inverting and inhibiting circuits. Many of these circuits used to employ relays (and equipment using relays will be around for years) but today transistor and diode switches are used extensively because of their smaller physical size and generally greater reliability. Large electronic computers require thousands of simple on-off switches that can be operated by pulses at extremely high speeds.

Logic Circuits

Modern computer switches must operate at microsecond speed. No mechanical device can do this, hence the use of semiconductors.

A diode or transistor (which is really two diodes back-to-back), when used as a switch, has two states. In its *off* state its resistance is several megohms, in its *on* state its resistance may be as low as 50 milliohms. In this respect it is superior to a vacuum tube, which has an internal resistance of approximately a kilohm, when conducting, so that it dissipates power. It also requires current for its heater.

The semiconductor is switched from one state to the other by changing the bias voltage from forward to reverse, and vice-versa. The voltage required to do this is quite small, and is usually in the form of a pulse.

Various types of logic circuit have been designed. Transistors are used more than diodes, because they also amplify, so that they can compensate for circuit losses.

NOT Gate, or Inverter

Figure 9.1 illustrates a NOT gate, or inverter. As you can see, it is a simple common-emitter amplifier. If the supply voltage is positive (with a PNP transistor, as shown) it requires a positive voltage on the base to make it conduct.

Without a positive voltage on the base the transistor-switch is off,
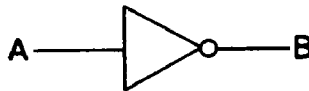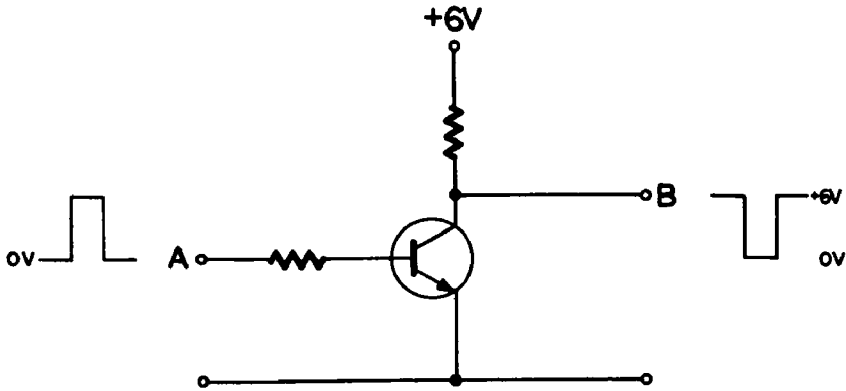
Figure 9.1   NOT Gate, or Inverter

therefore the voltage at B will be the same as the supply voltage. When a positive voltage pulse arrives at A it turns the transistor-switch on, so that B is now approximately at zero potential, giving a negative-pulse output. Since this is the opposite of the positive-pulse input the device is an inverter.

The pulse that turns a switch on is called *true*. The absence of such a pulse (which turns it off) is called *false*. A table showing the operation of the switch with different inputs is called a *truth table*. In it the true signal is indicated by a figure 1, the false by a figure 0. The actual voltage of the signal may be anywhere from 2 to 12 volts, depending on whether diode or transistor circuitry is employed.

In the truth table in Figure 9.1 the false signal at A gives a true output at B, which means, in this case, that no input at A gives a +6-volt output, because the transistor is cut off. When a true signal is received at A the voltage at B drops to zero, which is a false output. As you can see, a true input gives a false output and a false input gives a true output. Thus the device is called a NOT gate because its output is *not* the same as its input.

The triangular symbol represents the device in logic diagrams. It is nearly always called an inverter.

AND Gate

Figure 9.2 shows an AND gate. The transistors Q1 and Q2 are connected in series, so that both have to turn on before current can flow through them. The collector of Q1 remains at the supply voltage until true signals are received at both A and B, when it drops to approximately zero. This turns Q3 off, and the voltage at C rises to the value of the supply voltage (Q3 is an inverter). The effect of different inputs is shown in the truth table.

This device is not used very much any more, but serves as the basis for others, as we shall see. Note the symbol.

OR Gate

The OR gate in Figure 9.3 is activated by a true input at either A or B, since the transistors are in parallel. When both transistors are off, the voltage at C will be zero. When either or both turn on, current flowing through R2 causes the voltage at C to rise approximately to the value of the supply voltage. Consequently a true input at either A or B gives a true output at C, as shown in the truth table.

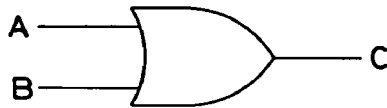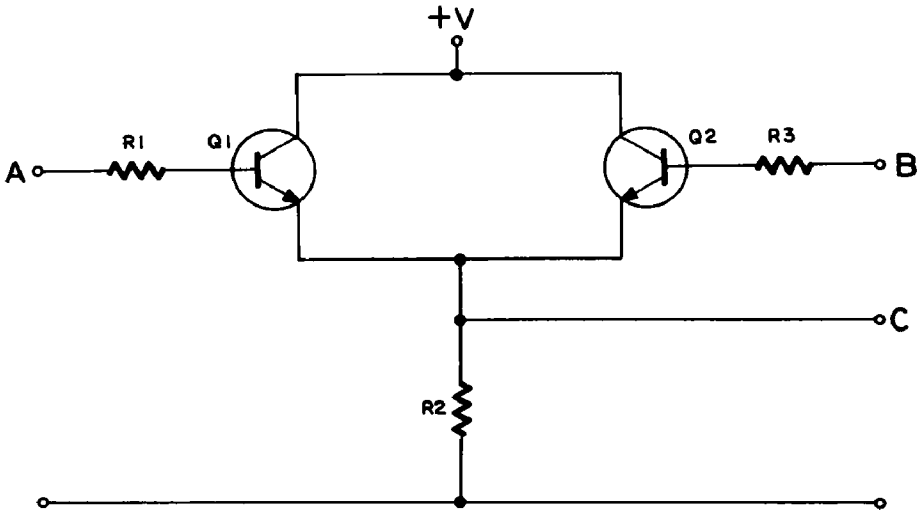This is another basic circuit seldom used as shown. Note the symbol.
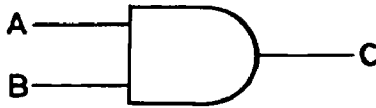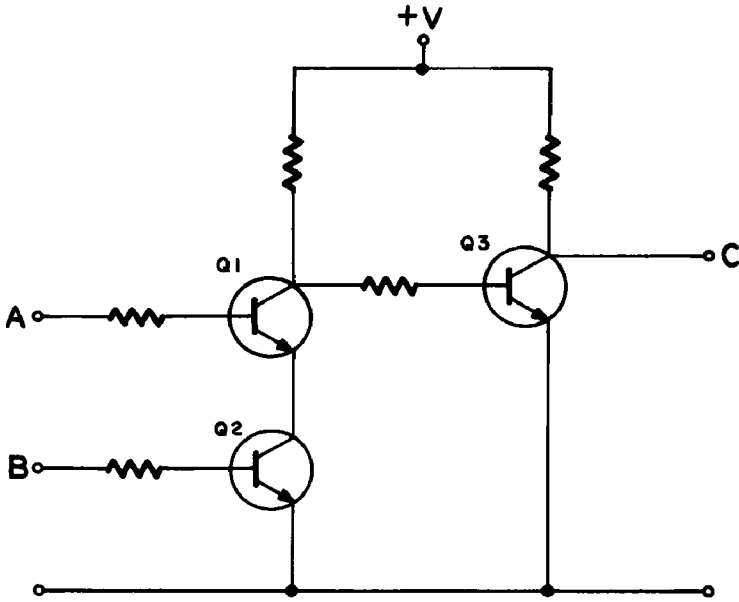
Figure 9.2   AND Gate

RTL NOR Gate

A NOR gate is an OR gate with a reversed output. In Figure 9.4 the OR symbol now has a small circle added, which indicates the in-
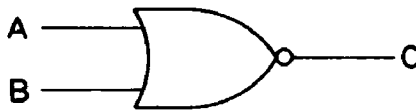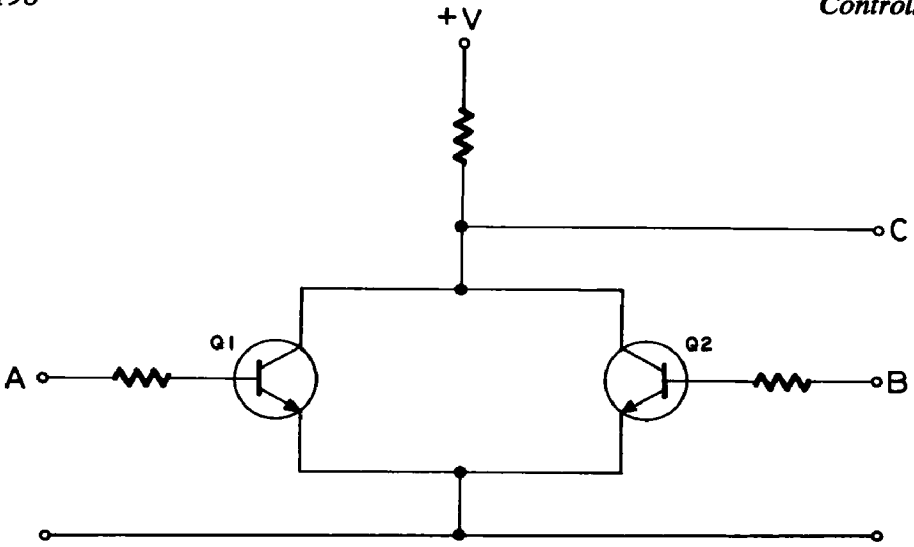
A	B	C
0	0	0
0	1	1
1	0	1
1	1	1

Figure 9.3   OR Gate

version. This could be done by adding the inverter of Figure 9.1. However, in this case, by taking the output from the *collectors* of Q1 and Q2 an inverted output is also obtained, as shown in the truth table.

This is one of the most widely used gates. RTL stands for resistor-transistor logic.

A	B	C
0	0	1
0	1	0
1	0	0
1	1	0

Figure 9.4   RTL NOR Gate

DTL NAND Gate

A NAND gate (Figure 9.5) is an AND gate with a reversed output. Note that the AND symbol now has a small circle added, which indicates the inversion. DTL stands for diode-transistor logic.

As long as either diode can conduct, Q1's base voltage is low, and
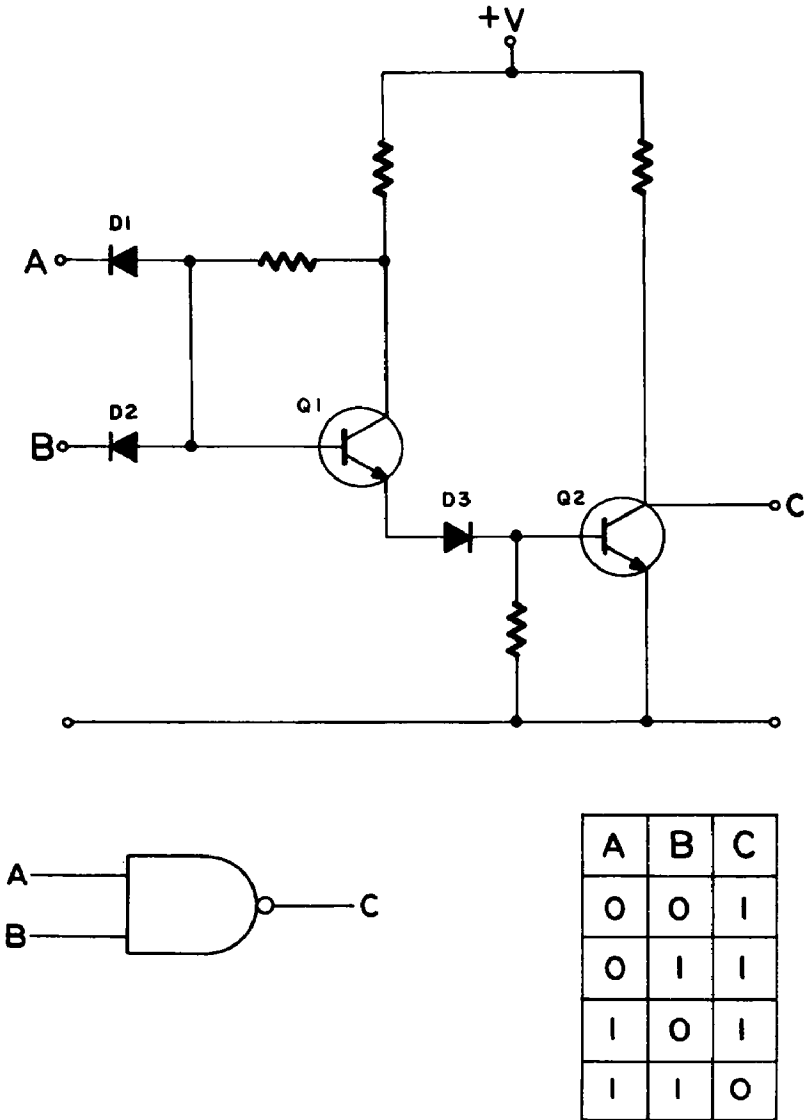
Figure 9.5 DTL NAND Gate

Q1 is cut off. As Q1's emitter is at zero potential (with no current flowing through Q1) Q2 is also cut off. When true signals appear at A *and* B both diodes are reverse-biased and cannot conduct. Consequently Q1's base voltage rises, turning Q1 on. The voltage drop across Q1's emitter resistor turns Q2 on, resulting in a false output at C.

TTL NAND Gate

The TTL (transistor-transistor logic) NAND gate (Figure 9.6) is also widely used. It has a higher speed of operation than the DTL.

Q1 is a special transistor with two emitters (multiple-emitter transistor). When either or both emitters have a false input Q1 is cut off. The output from Q1's collector is essentially zero. As a result Q2 is also cut off. The voltage on Q2's emitter is zero, that on its collector the same as the supply voltage. In other words, with a false signal on its base Q2 has two outputs: false from the emitter, true from the collector. Q2 is therefore a *phase-splitter*.

Q3 and Q4 are connected in series (a "totem pole"). When Q2's collector is true the base of Q3 is true also, so Q3 is turned on. At the same time Q4 is turned off by the false signal from Q2's emitter. As a result the collector of Q4 is at the supply voltage (all the voltage is dropped across Q4), and the output at C is true.
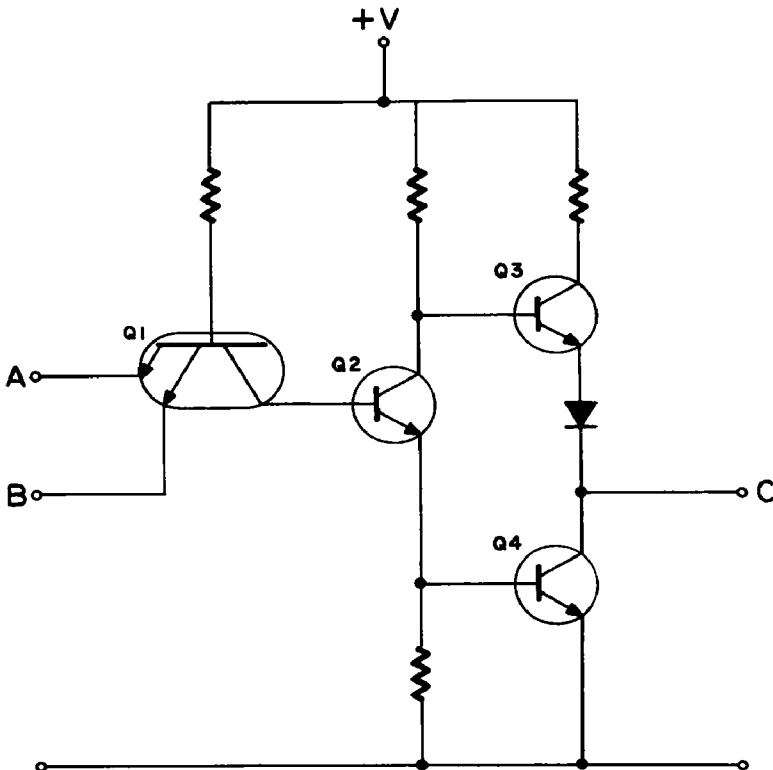
Figure 9.6   TTL NAND Gate

When true signals are applied simultaneously to A and B Q1 turns on. This places a positive (true) voltage on the base of Q2, so its two output signals are now the opposite of what they were before. Consequently Q3 turns off and Q4 turns on. Now a false (zero) output appears at C.

The truth table and symbol for this circuit are the same as in Figure 9.5.

AND and OR Gates from NAND and NOR

Since the NAND and NOR gates just described are used for practically all logic circuits today, the older AND and OR gates are seldom seen. To get an AND or an OR gate the usual procedure is to add inverters to the output or input, as shown in Figure 9.7. In this way a NAND gate can be converted to an AND or an OR gate; similarly, with a NOR gate. In this way the same type of gate can be used throughout an entire digital system. The most popular type is the NAND gate. See also Figures 9.8, 9.9 and 9.10.
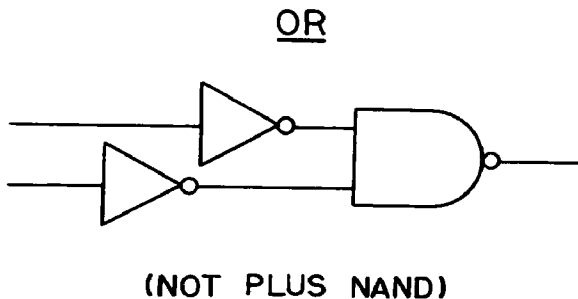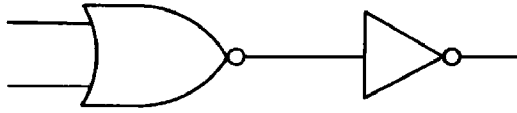
AND

(NAND PLUS NOT)
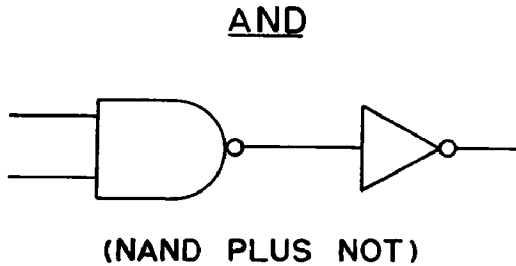
Figure 9.7   AND Gate Used Today

OR

(NOT PLUS NAND)

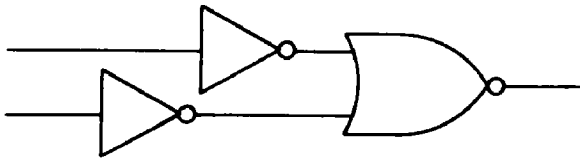**Figure 9.8   OR Gate Used Today**

OR

(NOR PLUS NOT)

Figure 9.9   OR Gate Used Today

AND

(NOT PLUS NOR)

Figure 9.10   AND Gate Used Today

Combining Circuits

It is often necessary to combine or mix two or more different inputs, such as the audio from two microphones. The circuit in Figure 9.3 becomes a combining circuit with the addition of a cathode-bypass capacitor parallel to R2. The two signals to be combined are fed in at A and B, of course, and as their levels will probably require adjusting, volume controls are usually provided for each input.

Gating Circuits

A circuit such as that in Figure 9.6 can also be used to *gate* a signal; that is to say, to turn it on and off. Suppose a train of positive pulses is applied to input A. Nothing will happen, because input B is still false. But if a true signal voltage is now applied at B, each pulse at A will turn Q1 on, so that a train of inverted pulses appears at C. This will cease when we remove the true voltage at B.

Obviously, any NAND gate can be used in this way.

Inhibiting Circuit

Figure 9.11 shows an inhibiting circuit. An inhibiting circuit's function is the opposite of a gating circuit. The inhibiting signal cuts off the other signal by canceling part of it. T1 is a phase-reversing transformer. If the two signals at A and B have the same phase, they will be of opposite phase on the base of Q1. If they are of the same amplitude, cancellation will take place as shown. The residual signal is reversed again to appear at C with the same phase as at B.
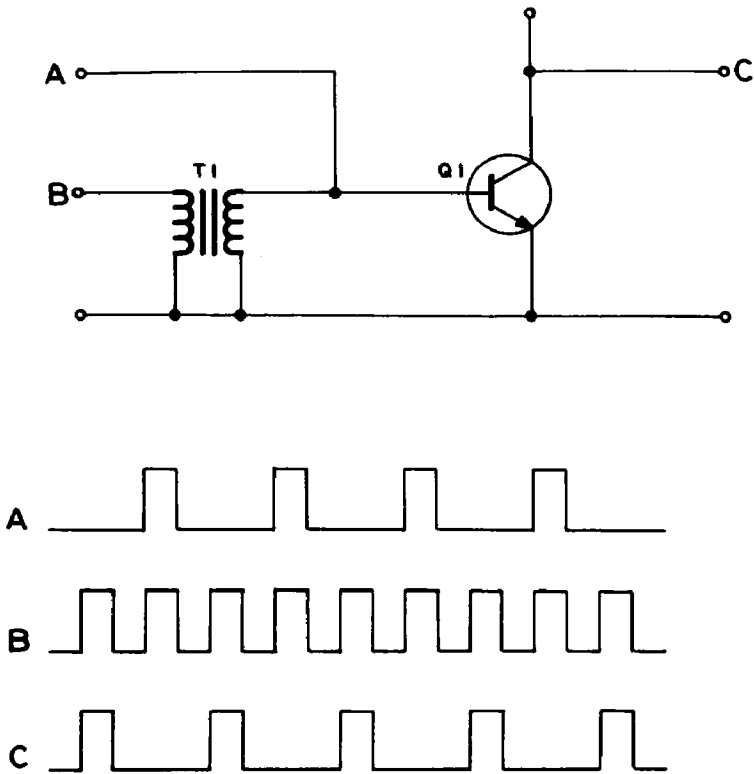

Figure 9.11   Inhibiting Gate

Integrated Circuits

It is now possible to make complete circuits on a very small scale, and many have been standardized for mass-production. Such circuits are called integrated circuits (ICs). Among them are many logic circuits, of which the following one is a typical example.

Figure 9.12 is an outline diagram of such a device. Its actual size, ignoring the leads, is a fourth of an inch long and a twentieth of an inch thick. This is a standard "package" with fourteen leads, numbered as shown. Packages may have fewer or more leads, but they are always numbered counterclockwise when viewed from above. The block diagram does not appear on the device itself, of course. It appears that way in the manufacturer's catalog to show the lead connections.

ICs come in other shapes and sizes as well. Some resemble transistors, except for the larger number of leads. All are very small, and completely encapsulated in ceramic, plastic or metal.

The circuit on the outline diagram in Figure 9.12 is represented by the symbols for two AND gates, with inputs C_1, C_2 and S_1, S_2, and a rectangle with inputs CP (clock pulse), outputs Q and $\overline{Q}$ ("NOT-Q" or inverted Q), S_D (direct set-pulse) and C_D (direct clear-pulse). This is enough to tell us that this circuit is controlled by a clock pulse. Inputs will only be accepted while the clock pulse is present at pin 2. This means that with true inputs at C_1 and C_2 the clock pulse switches the circuit to give a false output at Q and a true output at $\overline{Q}$. True inputs at S_1 and S_2 give a true output at Q and a false one at $\overline{Q}$. These

NC — No internal connection
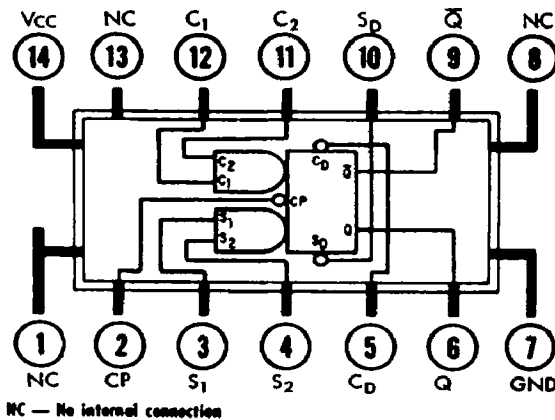
Texas Instruments

Figure 9.12   Integrated Circuit

are shown in the truth table in Figure 9.13, which also shows that other inputs have no effect, or an indeterminate one.

However, an input at S_D overrides the clock pulse, and sets the device to give predetermined true and false outputs at Q and $\overline{Q}$ as long as the preset voltage is maintained. An input at C_D does the same, except that the outputs are reversed.

Figure 9.14 gives the complete functional block diagram for the circuit. You should have no difficulty in identifying the various logic symbols, as they were explained earlier in this chapter. The two transistors directly above the clock-pulse input are also controlled by the pulse, which turns them on to allow the input signal to pass to the

| Input				Output	
C_1	C_2	S_1	S_2	Q	$\overline{Q}$
1	1	0	X	0	1
1	1	X	0	0	1
0	X	1	1	1	0
X	0	1	1	1	0
X	0	X	0	No Change	
0	X	0	X		
0	X	X	0		
X	0	0	X		
1	1	1	1	Uncertain	

X can be either 1 or 0

Figure 9.13 Truth Table of IC

output section. A true input at C_1 and C_2, as we have already seen, passes via the AND gate to the NOR gate, then via the adjacent transistor to the left-hand NAND gate, and appears as a false signal at Q. At the same time part of this output goes across to the right-hand NAND gate and flips it to give a true signal at $\overline{Q}$. This chain of events happens in the right-hand half of the circuit with true inputs at S_1 and S_2, except that the outputs are reversed.

functional block diagram
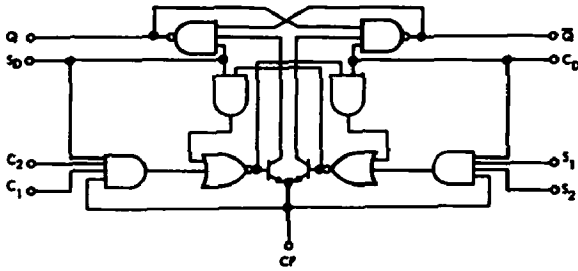
schematic
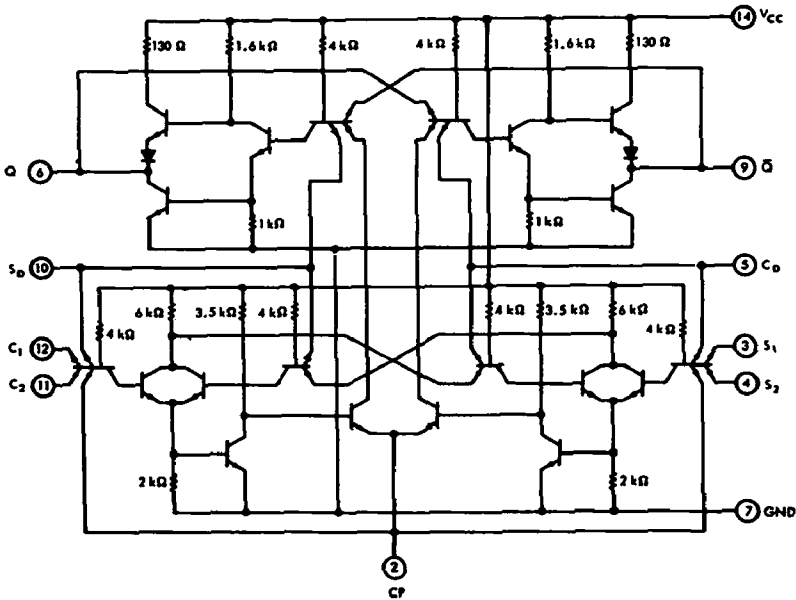
Texas Instruments

Figure 9.14   Functional Block Diagram and Schematic of IC

Figure 9.14 also gives the complete schematic for the circuit. Notice that the transistor symbols do not have circles round them. The circles are optional, and some schematics omit them, like this one.

You will see several multi-emitter transistors similar to that you met with in Figure 9.6. The DC operating voltage (5 volts) comes in at pin 14 (V_{cc}), and the return is from pin 7, which you can see is connected to the low side of the circuit.

See if you can identify the various circuits. It's not as difficult as it looks if you refer back to the examples given earlier in the chapter. (Hint: the multi-emitter transistors connected to pins 11 and 12, and pins 3 and 4, are the AND gates.)

This is a high-speed switching circuit. Typically, the clock-pulse frequency would be 15 megahertz, and the time required for true inputs at C_1 and C_2 or S_1 and S_2 to switch through to the output would be 25 nanoseconds.

10

BRIDGE
CIRCUITS

B RIDGE CIRCUITS ARE mostly used in measuring instruments, but they are also employed in sensing and controlling. They are the electronic equivalent of a pair of scales, in which some unknown quantity is balanced against the known weights. When a bridge is "balanced" its two sides are at the same potential, so no current flows through the indicating device connected between them. Consequently it shows zero, or a "null." When a resistor, capacitor or inductor of unknown value is to be measured on a bridge, known values of resistance, capacitance or inductance are used as "weights" to balance the bridge, and from these values the value of the unknown is found.

Wheatstone Bridge

Bridges are frequently, though not always, shown in the diamond pattern of Figure 10.1. This is the Wheatstone bridge. It is the only bridge that can operate on DC, and then only for measuring resistance.

In Figure 10.1(a) resistors R1, R2 and R3 are bridge resistors, and R_x is the "unknown" resistor whose resistance is to be measured. In (b) the same layout is illustrated, but rotated 90 degrees clockwise. Either way is possible for this layout. R1 and R3 are a voltage divider, and so are R2 and R_x. Current from the battery flows through each
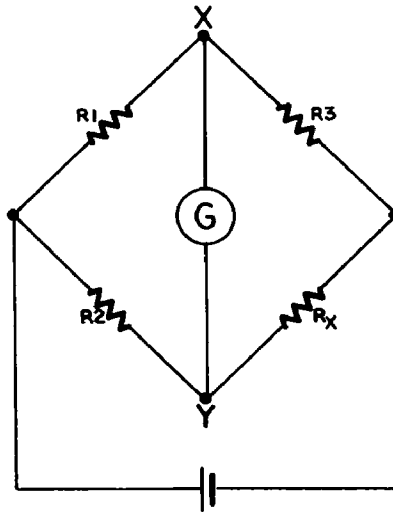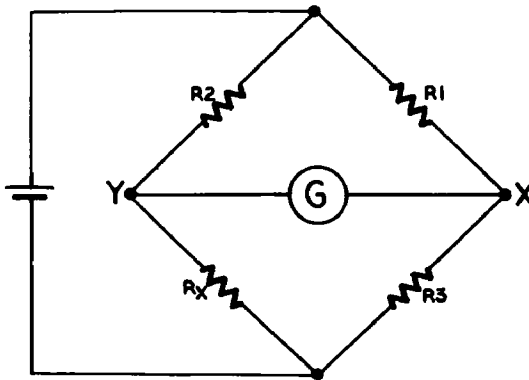
(a)

(b)

Figure 10.1   Wheatstone Bridge

divider, and the voltages at X and Y will be according to the ratio of
the resistances. If R1 and R3 are equal the voltage at X will be half the
battery voltage, and if R2 and R_x are equal the voltage at Y will also be
half the battery voltage. X and Y will be at the same potential, so no
current will flow between them. The galvanometer, G, connected be-
tween them will give no indication. We say the bridge is "balanced" or
the galvanometer is "nulled," or indicates a null.

Since R_x is unknown $R2$ is made variable so that it can be adjusted to balance R_x. It may be an assemblage of fixed resistors, a potentiometer, or both. $R1$ and $R2$ together must provide resistance such that the right current flows through $R2$ and R_x to allow the voltage at Y to change readily as $R2$ is adjusted, so that an accurate reading can be made. The value of $R2$ is read from the dials of the selector controls, and is of course the same as that of R_x.
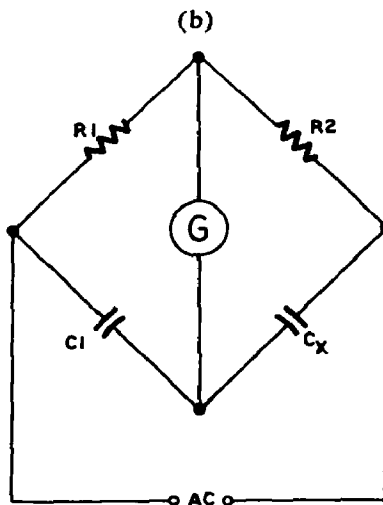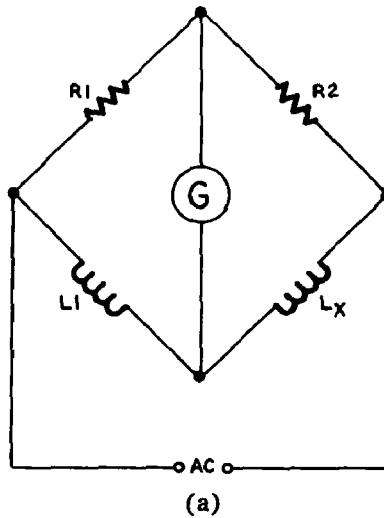

(a)

(b)

Figure 10.2   LC Bridge

LC Bridge

The LC bridge is a Wheatstone bridge adapted for measuring inductances and capacitances. Since we are now measuring reactance we have to use AC instead of DC.

In Figure 10.2(a) the unknown inductance is balanced against a known inductance just as in the resistance bridge. However, the dials giving the reading are calibrated in henries, millihenries and microhenries instead of ohms.

In Figure 10.2(b) a bridge for measuring capacitance is shown, operating in a similar way.

The function of R1 and R3 (or R2) is the same for all three bridges.

Owen Bridge

In the Owen bridge (Figure 10.3) R1 and R3 of the Wheatstone bridge are replaced by C1 and C2. This bridge measures inductance more accurately because it measures both the inductive (L_x) and resistive (R_x) components of an inductor. C1 and R2 are each variable, and must be adjusted to obtain a null. In another version a variable resistor in series with L_x is used instead of C1.
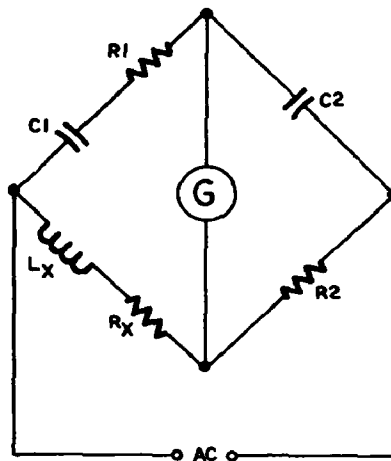

Figure 10.3   Owen Bridge

Maxwell Bridge

The Maxwell bridge (Figure 10.4) is very similar to the Owen, and is used for the same purpose. It is a partial return to the Wheatstone bridge, since R1, R2 and R3 have been modified only by the addition of C1 in parallel with R2. The resistive part of the inductance is therefore measured as in a Wheatstone bridge, but C1 adapts it for measurement of inductance also.
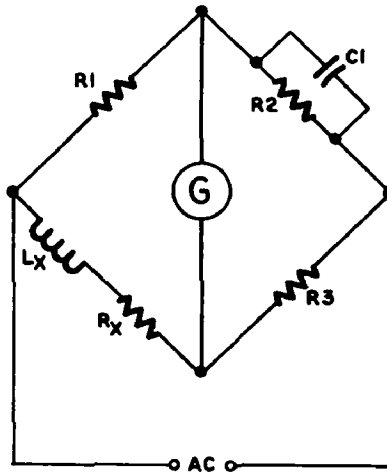

Figure 10.4   Maxwell Bridge

Hay Bridge

The Hay bridge (Figure 10.5) is similar to the Maxwell, except that C1 is now used in series with R2. This arrangement works better for inductors with large inductances.
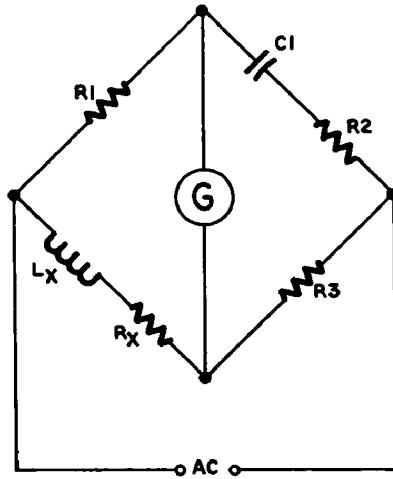
Figure 10.5   Hay Bridge

Resonance Bridge

In this bridge (Figure 10.6) the capacitor C1 is tuned to resonance with the unknown inductor. This serves to measure its inductance, and at the same time leaves only the resistive element (at resonance a series-resonant circuit has no reactance), which is balanced by R3, as in the Wheatstone bridge.
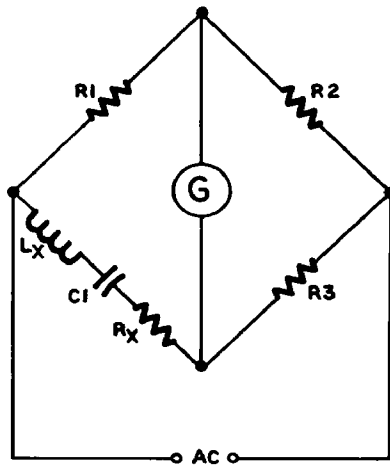

Figure 10.6   Resonance Bridge

Schering Bridge

The Schering bridge (Figure 10.7) measures capacitance. Its operation is similar to the Maxwell bridge, except that C2 replaces R2. The unknown capacitor has a resistive component in its reactance in the same way an inductor does.
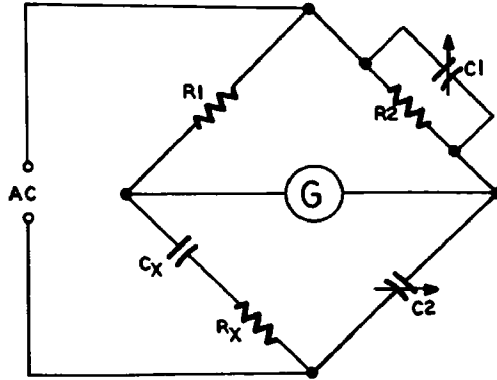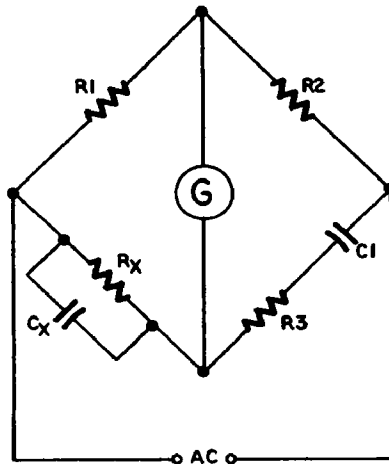

Figure 10.7   Schering Bridge

Figure 10.8   Wien Bridge

Wien Bridge

The Wien bridge (Figure 10.8) is used for measuring frequency. It is similar to the Schering bridge, and can be used to measure capacitance. However, if instead of an unknown value of capacitance at C_x a known value is chosen to balance that of C1 at the frequency being measured, and if R3 is also adjusted to balance the resistive element of C_x, then the frequency of the AC signal applied to the bridge may be determined.

11

SYNCHRO
SYSTEMS

J UST AS A THERMOSTAT senses a drop in temperature and signals the furnace to turn on, so a synchro generator senses a change in the mechanical position of something, and sends a signal which actuates the corrective action. Synchros are used extensively in industrial controls, in the guidance systems of ships, planes and rockets, and in other applications too numerous to list.

Servomechanisms

A household thermostat has a fixed output, and is called a *regulator*. A more sophisticated control system that adjusts its output automatically in accordance with its input is called a *servomechanism*. A well-known example is the governor on a steam engine, in which an increase in speed above that set results in a reduction in throttle opening, and vice-versa, to maintain an even rate.

Synchro Systems

A synchro system is a feedback system in which synchros are used. A synchro (sometimes called a selsyn) resembles a small electric motor. Three field coils mounted in a cylindrical case surround an
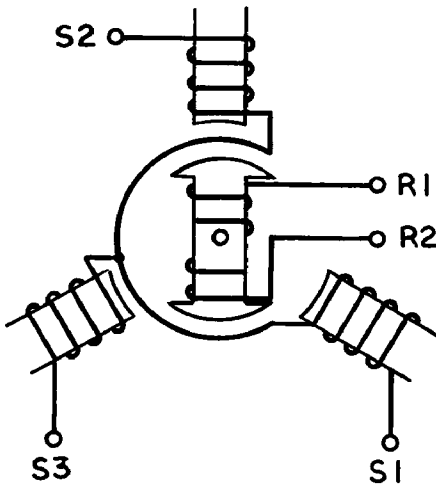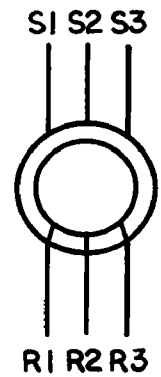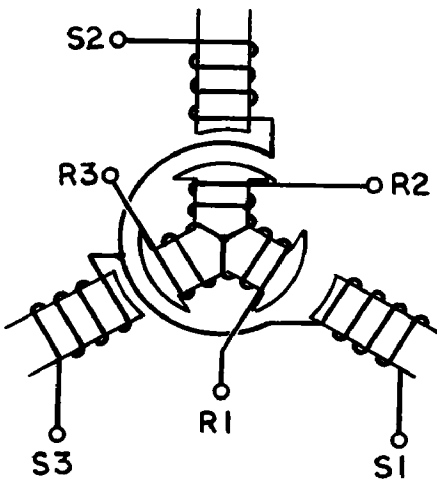
(a)
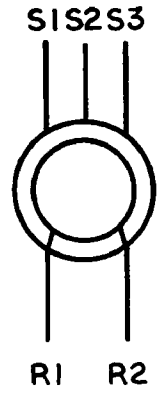
(b)

(c)

(d)

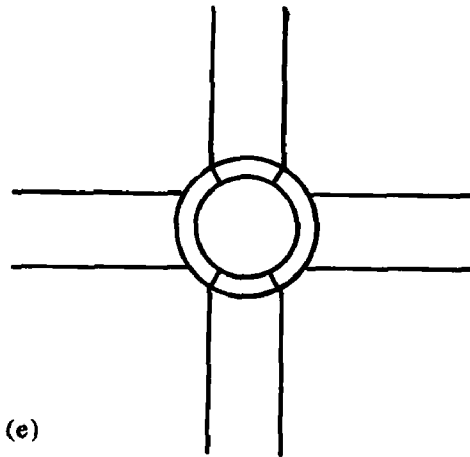**Figure 11.1   Synchro Construction**

(e)

Figure 11.1   Synchro Construction (cont'd.)

armature [Figure 11.1(a)]. The field coils are called *stator windings*, those on the armature are called *rotor windings*. However, when an alternating current of 60 or 400 hertz (depending on synchro type) is applied to the rotor winding the armature does not rotate. Instead its magnetic field induces voltages in the three stator windings. Because each stator winding makes a different angle with the rotor winding a different voltage is induced in each.

These voltages rise and fall as the armature is turned to different positions. They are transmitted separately to another synchro, and applied to its corresponding stator windings. The composite magnetic field generated by these windings interacts with that generated by the second synchro's rotor winding, which is also excited by 60 or 400 hertz AC, and the pushing and pulling of the lines of force turn the second synchro's rotor to the same position as that on the first synchro. If the first synchro is rotated to a new position, the second takes up the same position also.

Synchro Schematics

The different types of synchros used in synchro systems are listed at the top of the next page.

Those in the first group listed are constructed as shown in Figure 11.1(a), with symbol as illustrated at (b). Transmitters and transformers also used to be known as *generators* or *masters,* and receivers as *motors* or *slaves.* These terms may still be found in some schematics.

|	*Identification*
Synchro Type	*Letters*
Control Transformer	CT
Torque Receiver	TR
Control Transmitter	CX
Torque Transmitter	TX
Torque Differential Receiver	TDR
Control Differential Transmitter	CDX
Torque Differential Transmitter	TDX

The simplest synchro system has a transmitter and receiver connected as in Figure 11.2(a). Whatever position is set on the transmitter is assumed by the receiver. The receiver also rotates in the same direction as the transmitter. If the wires are crossed as in Figure 11.2(b) the receiver turns in the opposite direction to the transmitter.

The second group of synchros has three rotor windings. Figure 11.1(c) shows that in the differential type the armature is wound in the same way as the stator. This allows it to receive two inputs and combine them algebraically. The symbol is shown in Figure 11.1(d). In Figure 11.3(a) a torque transmitter (T) signals the position of its rotor to the stator of the torque differential transmitter (D). Voltages are induced in the three rotor windings of D which are a combination of those transmitted from T and those resulting from the position of D's rotor. The voltages transmitted to R will result in the receiver's rotor assuming a position which is equal to the *difference* between the angular positions of T and D, or $R = T - D$.

In Figure 11.3(b) the leads have been crossed. In this configuration the position assumed by the receiver will be equal to the *sum* of the angular positions of T and D, or $R = T + D$.

In Figure 11.3(c) the differential synchro is the *receiver*. Its rotor will assume a position equal to the sum of the angular positions of both transmitters.

The difference between control and torque transmitters and receivers is that control types have more turns and a higher impedance. This improves accuracy, but because current is minimal there is insufficient power output to actuate a control. An amplifier is needed to introduce power into the circuit. Accuracy is also improved by connecting a triple capacitor across the stator leads of a control transformer, as shown in Figure 11.4, to cancel stray magnetizing currents in the stator wind-
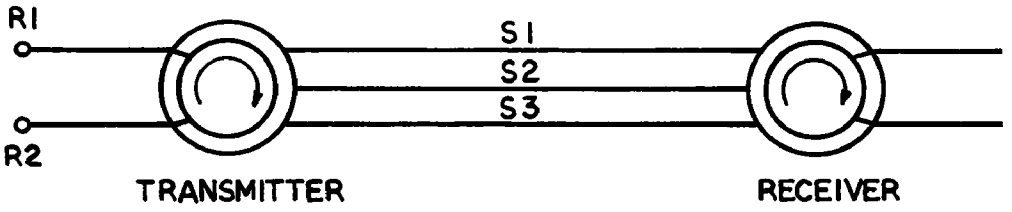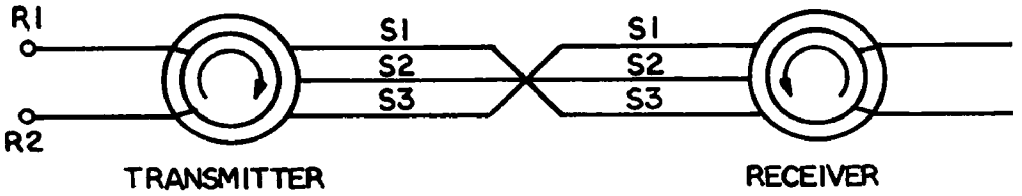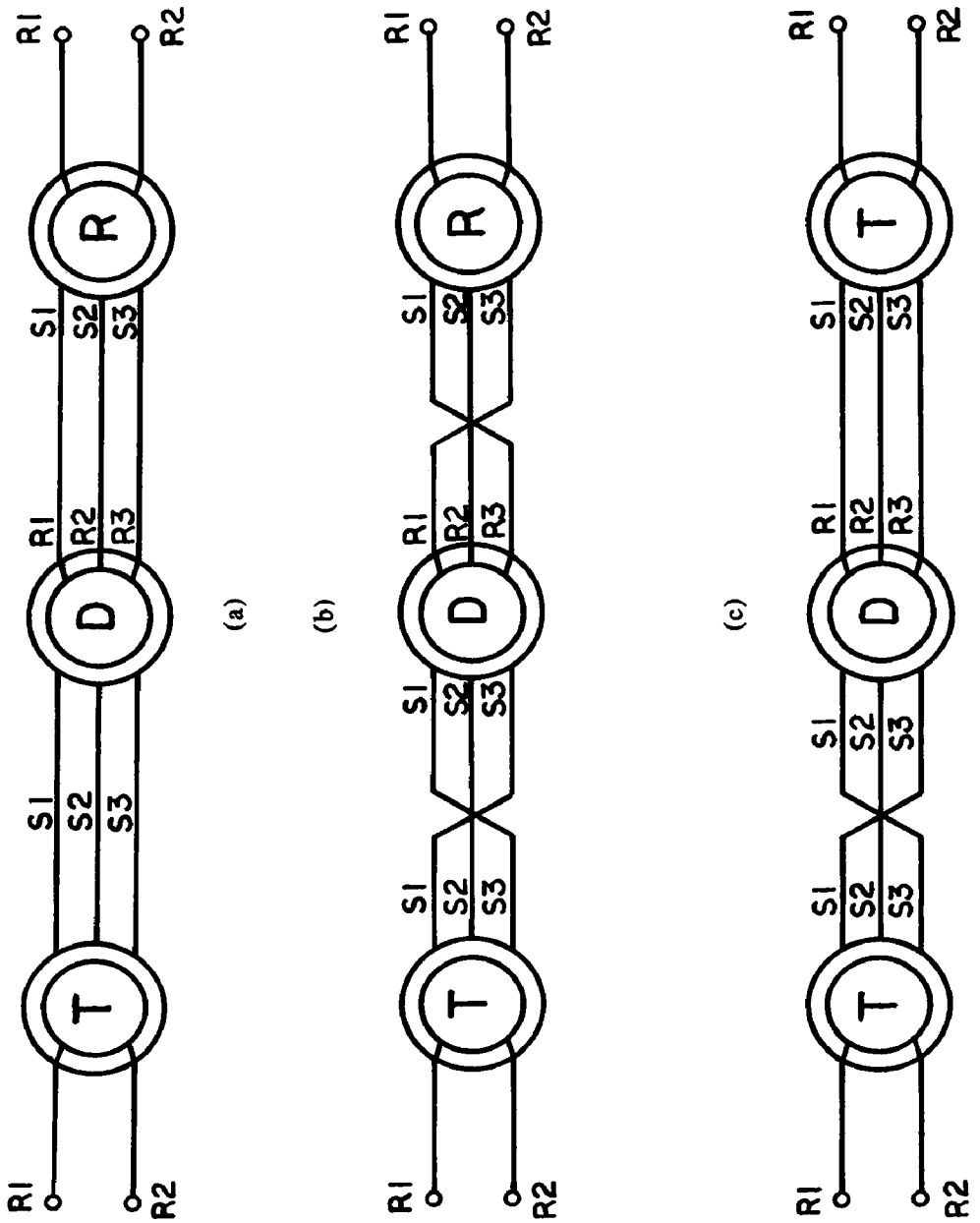
(a)

(b)

Figure 11.2   Synchro System

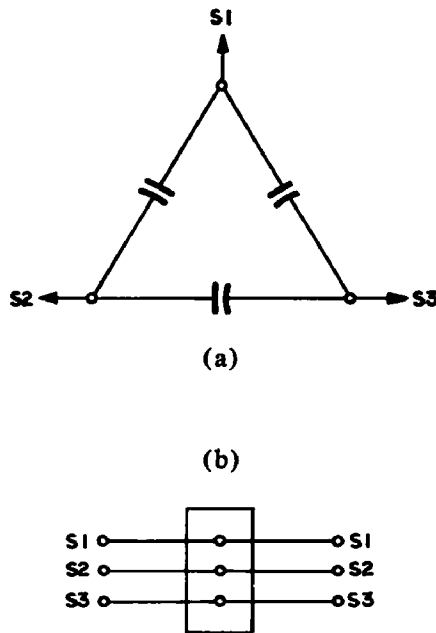**Figure 11.3 Differential Synchro System**

Figure 11.4   Synchro Triple Capacitor

ings. In this figure (a) is the electronic schematic and (b) is the mechanical symbol.

Resolver

   The synchro transmitters we have been discussing operate by generating voltages in their three stator windings that vary according to the angle of the rotor. If the rotor is turned through 360 degrees each stator voltage goes through one cycle of a sine wave with a maximum voltage of 90 volts, where the rotor excitation voltage is 115 volts. However, as the three stator windings are spread equally around the synchro casing the phases of the three signals are staggered 120 degrees. The receiver operates by reproducing the magnetic fields of the transmitter.
   The synchro thus has three poles. A resolver is like a synchro, but with many more poles. As its rotor turns and passes each pole a sine-

wave voltage is induced. The number of sine waves generated depends upon the number of poles passed, or the angular displacement of the rotor.

To get better resolution the rotor and stator windings are usually arranged so that signals of opposite phase are generated. These are then passed through two clippers or shapers which convert the sine waves to pulses (see chapter 8). They are then combined in a logic circuit (chapter 9) in which the final signal becomes a digital input for a readout device, controller or computer, as the case may be.

Some resolvers, known as optical-electronic resolvers (OERs) use a glass disk with opaque "teeth" printed round the edge. Light passing through the disk and striking a photocell is interrupted by the teeth as the disk turns, producing a train of pulses which are counted by the computer and indicate the angle of rotation. Accuracy is increased by having two outputs of opposite phase, as in the case of electro-mechanical resolvers.

The guidance systems of missiles, space vehicles, aircraft and ships all depend upon the use of gyroscopes ("gyros") and accelerometers (velocity meters). Resolvers "read" their positions and convert the information to digital form, which can then be integrated mathematically by a computer, which in turn issues instructions for adjustments to controls to keep the vehicle on its predetermined course. This same information may also be translated into "human language" for the use of the crew or ground control.

See Figure 11.1(e) for the schematic symbol for a resolver.

Amplidyne

As already mentioned, synchros do not develop any power, and so cannot exert torque to any extent. A device that does develop considerable power is an *amplidyne,* or rotary amplifier. This device steps up the input so that the output will be capable of handling a load.

In Figure 11.5 the symbol for an amplidyne, or regulating generator as it is sometimes called, is shown. The circle represents the armature, and the line crossing it is a connection between two of the four commutator brushes which shorts out the armature winding between them. This allows the creation of strong magnetic fields in the armature, inducing a powerful output current at the other two brushes.

Three of the windings are field coils, and the other two in series with the armature are compensating field windings, which prevent loss of power by canceling opposing fields.

ARMATURE   COM-   MAIN
WITH SHORT-   PENSATING   FIELD
CIRCUITED   FIELD
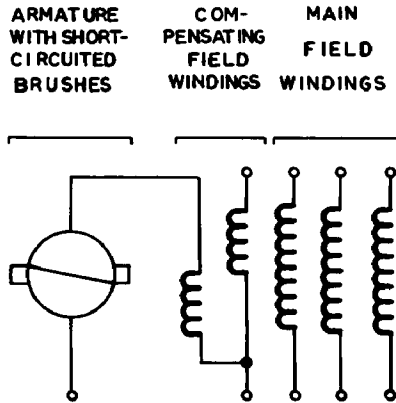BRUSHES   WINDINGS   WINDINGS

Figure 11.5   Amplidyne (rotary amplifier)

The amplidyne is really a generator in which weak input current changes in the field coils (from a synchro, for instance) are converted to powerful output current changes in the armature by a kind of transformer action known as armature reaction.

12

OTHER CIRCUITS

T HIS CHAPTER COULD WELL have been titled "miscellaneous," for in it we deal with circuits which do not fit into any of the categories covered in previous chapters.

MULTIVIBRATORS

A multivibrator is a circuit in which a pair of vacuum-tube or transistor switches turn each other alternately on and off. There are three types:

> *Astable multivibrators* are RC relaxation oscillators and, as such, are discussed in chapter 4. They may also be called *free-running multivibrators.*
>
> *Monostable multivibrators* are the electronic equivalent of push-button switches. As soon as the input signal is removed they return to their normal state. They are also known as *single-shot multivibrators.*
>
> *Bistable multivibrators* are the electronic equivalent of double-throw switches. They require a second input signal to return them to their first state. Bistable multivibrators are also called *flip-flops,* or *binary counters.*

MONOSTABLE MULTIVIBRATORS

The monostable or single-shot multivibrator will be considered first. With this type an output is produced whenever the proper input signal is received.

Distinguishing Features

Figure 12.1 is the same plate-coupled free-running multivibrator that was illustrated in Figure 4.12. Figure 12.2 is a single-shot multivibrator, also employing a dual-triode tube.
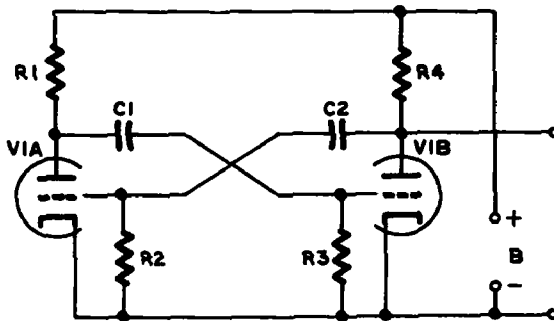

Figure 12.1   Astable or Free-Running Multivibrator

Note that the only important difference between them is the absence of the feedback connection in the single-shot version. In Figure 12.1 this connects the plate of V1B via C2 to the grid of V1A.

It is true that the single-shot multivibrator is shown with an input connected across R2, while the free-running multivibrator does not have one, but as you can see by looking at Figure 4.14 the oscillator type may also have an input.

In Figure 12.2 a cathode resistor has also been added.

Use

This circuit is designed to produce an output pulse with a specified duration and amplitude from an input of any shape, provided it has the proper polarity and voltage to trigger the device.
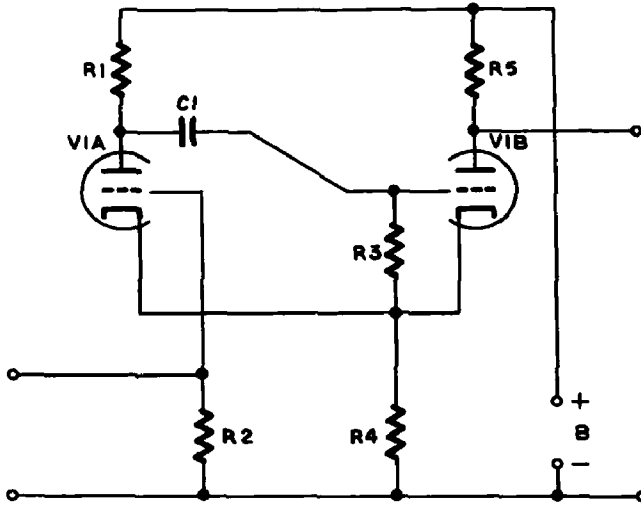
Figure 12.2   Monostable or Single-Shot Multivibrator

Detailed Analysis

DC Subcircuit: In the absence of any input signal, electron flow is from B— via R4 to both cathodes, and from V1A's plate via R1, and V1B's plate via R5, back to B+. Since R3 connects the grid of V1B to the upper end of R4 the grid is not biased by the voltage drop across R4, and consequently the grid voltage is essentially the same as the cathode voltage. Therefore V1B is conducting, and its plate voltage is lower than the supply voltage by the value dropped across R5.

However, the grid of V1A is connected to B— via R2, therefore this tube is biased negatively by the voltage drop across R4, and is cut off. The plate voltage of V1A is therefore equal to the supply voltage, and capacitor C1 is also charged to the same value on the side toward V1A.

AC Subcircuit: When a positive trigger pulse is applied across R2 of sufficient amplitude to overcome the negative bias on V1A and allow the tube to conduct, there is an immediate voltage drop across R1, and this sends a negative-going pulse through C1 to the grid of V1B. V1B now ceases to conduct, and its plate voltage rises to the value of the supply voltage.

After the trigger pulse, V1A returns to its non-conducting state and its plate voltage returns to the supply voltage level. The rise in positive voltage is coupled through C1 to the grid of V1B, and this tube resumes conduction.

The length of time V1B is off, and hence the duration of the output

pulse, is determined by the R–C constant of C1 and the resistors R1, R3 and R4, in series across the supply voltage.

SCHMITT TRIGGER

The Schmitt trigger (Figure 12.3) is a variation of the preceding circuit, and illustrates a typical transistor single-shot multivibrator. Like the vacuum-tube version, it requires an input trigger of proper polarity and voltage, and produces an output of fixed amplitude and duration, determined by the circuit constants. R2 is connected in parallel with C1 to complete a voltage divider, R1, R2 and R5, that stabilizes the base voltage of Q2, which is normally conducting, since its base is more positive than its emitter. Q1 is normally not conducting since the top of R4, though less positive than Q2's base, makes Q1's emitter positive with respect to Q1's base, which is connected to zero potential via R3. The operation of the circuit when a positive input pulse turns Q1 on is the same as for the vacuum-tube circuit.
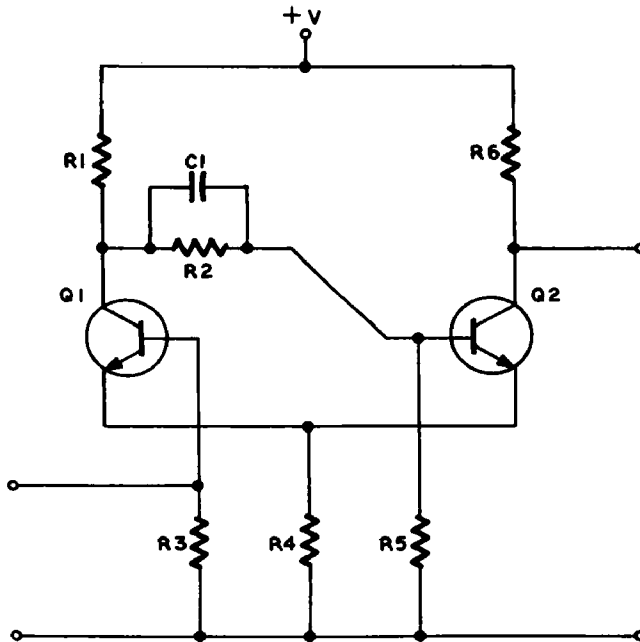

Figure 12.3   Schmitt Trigger

BISTABLE MULTIVIBRATOR, OR FLIP-FLOP

Figure 12.4 shows an Eccles-Jordan flip-flop circuit which is typical of bistable multivibrators.

Distinguishing Features

In this circuit it appears as if the feedback connection of Figure 12.1, removed in Figure 12.2, has been restored. However, the presence of the two diodes indicates that this circuit is not really a free-running multivibrator despite appearances. These diodes form a *steering circuit* that directs the input to each transistor in turn, so we have actually two single-shot multivibrators. If Q1 is off and Q2 on, the input goes to Q1, which then turns on while Q2 turns off. The next pulse is then steered to Q2, turning it back on, and Q2 is turned off again.

Uses

Counters, computers and industrial controls.

Detailed Analysis

Q1's collector is connected to a voltage divider consisting of R2, R3 and R5. Q2's collector is connected to one consisting of R7, R6 and R4. When Q1 is turned off the supply voltage is divided between R2, R3 and R5, so that the collector of Q1 and the base of Q2 are both negative with respect to the emitters. Q2 therefore has forward bias and turns on; consequently the voltage on the collector is zero, while Q1, with zero bias, remains turned off.

Diode D1 also has zero voltage on the cathode, but a negative voltage reaches its anode via R1. D2 has a negative voltage on its cathode but no voltage on its anode, which is connected to Q2's collector via R8. Consequently D1 is turned off but D2 is on.

If a positive pulse appears at the input it goes to both diodes, but as only D2 is conducting, it only reaches Q2's base. Here it overcomes the negative bias on the base, and causes Q2 to turn off. As a result its collector voltage rises, and the negative-going change in the voltage is coupled through to Q1's base, turning Q1 on. Q1's collector voltage
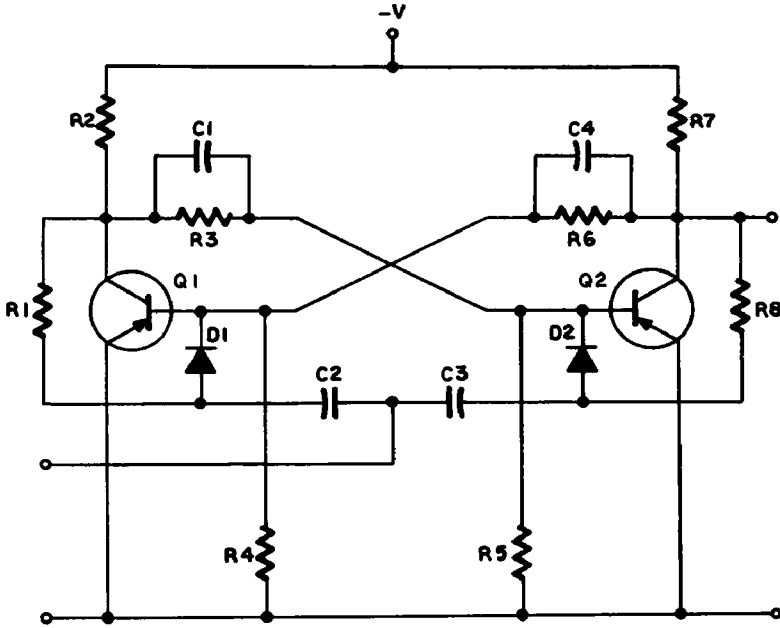
Figure 12.4   Bistable Multivibrator, or Flip-Flop

drops to zero, carrying Q2's base voltage to zero also, so the two transistors are now in exactly the opposite state from when the input pulse arrived. Since Q2's collector voltage has now risen from zero to a substantial proportion of the supply voltage, a negative voltage now appears at the output.

The bias on the two diodes is now the opposite of what it was before. Consequently, the next trigger pulse will be steered to Q1's base. Since Q1 is now in the identical state that Q2 was in, while Q2 is now in Q1's former state, Q1 now turns off, turning Q2 on again, and Q2's collector voltage now becomes zero once more.

The speed at which this circuit can switch depends upon the values of R1–C2 and R8–C3. Both resistors and capacitors cannot be very small values, or the input pulse will not be able to switch the transistor, but will appear at the output. Speed can be improved by connecting diodes parallel with R1 and R8.

Another method is to remove R1–C2, R8–C3 and both D1 and D2. The emitters are connected together, and a resistor placed between them and the low side of the circuit (like R4 in Figure 12.3). The input pulse is then applied across this resistor. It momentarily inter-

rupts the current flow in the "on" transistor by reversing the bias. This type of bistable multivibrator is called *emitter-triggered*. Another type is *collector-triggered*. However, the Eccles-Jordan type is the most widely used.

SAWTOOTH GENERATOR

In chapter 4 the use of relaxation oscillators for the generation of sawtooth waveforms was discussed. However, certain applications require a more linear sawtooth than these can produce. Figure 12.5 shows such a type.

Distinguishing Features

R2, R3 and C1 form a timing circuit in which R3 and C1 are usually two of a set of resistors and capacitors that can be switched in and out of the circuit to obtain different sawtooth slope speeds. R2 is a calibration adjustment. The circuit may employ all tubes or all transistors, or both, as shown.

Uses

Mostly used in oscilloscope sweep generators.

Detailed Analysis

The input to this circuit usually comes from a single-shot multivibrator, such as a Schmitt trigger, so that each sawtooth wave is triggered reliably, not from random pulses or noise spikes.

The proper pulse arrives on the base of Q1, which is called the *disconnect amplifier* (sometimes a diode is used). This transistor is normally conducting, and current flows up the path R4, Q1, R3 and R2 to the positive side of the supply voltage. This voltage divider maintains a constant voltage on the grid of V1 which is slightly negative relative to its cathode, but not enough to cut it off.

When Q1 switches off, this situation changes. The voltage on Q1's collector now starts to rise toward the value of the supply voltage. The rate of this rise is controlled by the R3–C1 combination, since the capacitor can only charge at the R–C time-constant of the two.
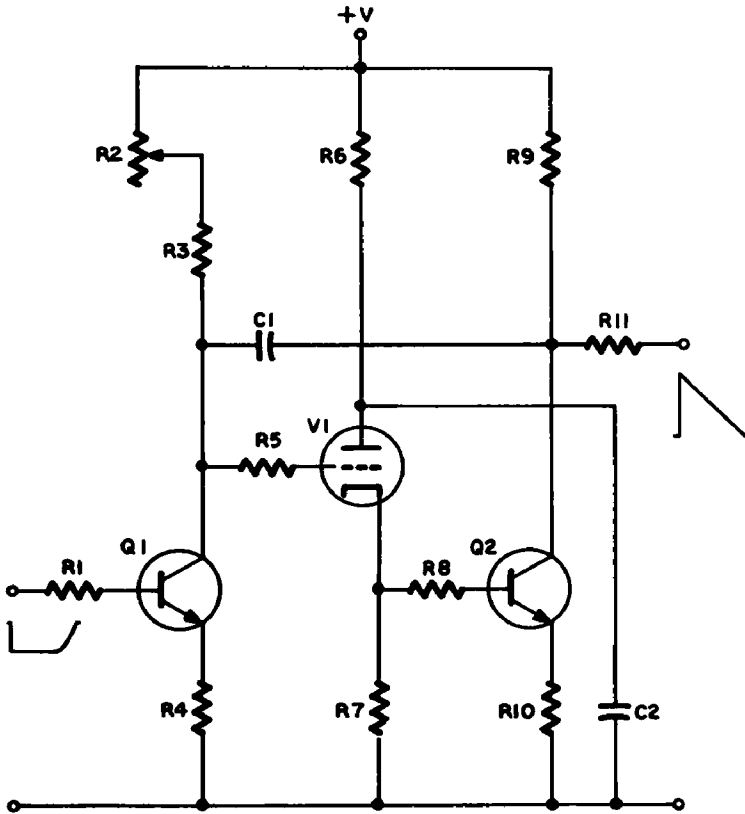
Figure 12.5   Sawtooth Generator

As the voltage rises the tube's conduction increases. The current through R7 increases, and the voltage drop across it increases. Consequently the base of Q2 goes more positive.

This results in Q2's conductance increasing in similar proportion, so that its collector voltage goes down.

This negative-going voltage is fed back to the grid of V1 via C1, and tends to oppose the rising positive grid voltage, thus maintaining a linear rise in this voltage, so that a linear output waveform is obtained.

A feedback from the output to the Schmitt trigger (not shown) turns it off at the end of the ramp, and it turns Q1 back on by removal of the pulse on its base. This places the circuit in readiness for the next trigger pulse to start the next sweep.

FREQUENCY DIVIDER

Figure 12.6 illustrates a typical frequency divider, in which an output pulse is produced only after a certain number of input pulses have been received. For example, if it takes six input pulses to produce one output pulse, the output frequency is only one-sixth of the input frequency.

Distinguishing Features

In this circuit the three-winding transformer connected between the plate and grid of V1 is distinctive, especially when taken in conjunction with the two diodes in the input and the positive voltage applied to the cathode from the variable resistor R2, which, with R1, forms a voltage divider between B+ and the low side of the circuit.

Uses

Counters and similar applications.

Detailed Analysis

V1 is biased beyond cutoff by the positive voltage on the cathode, which can be adjusted by R2.

When a positive-going pulse arrives at the input it is coupled through C1 and D2 to C2. Any negative-going portions of the pulse are bypassed by D1. C1 charges up slightly, but cannot charge more because the pulse does not last long enough. However, the charge cannot leak away because D2 cannot conduct in the other direction, and V1 is cut off.

Successive pulses gradually build up the charge on C2 until the voltage on V1's grid reaches the level where the tube can conduct. V1 becomes a low impedance, discharging C2 and dropping the plate voltage. As soon as C2 discharges, however, the tube cuts off again, the plate voltage rises to its former value, and the cycle is repeated.
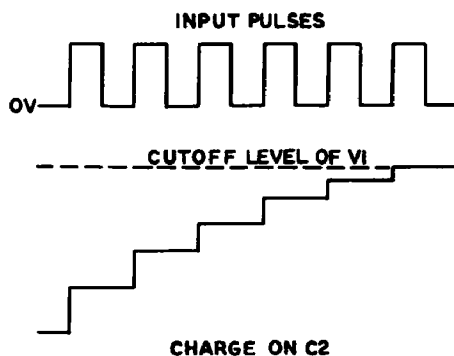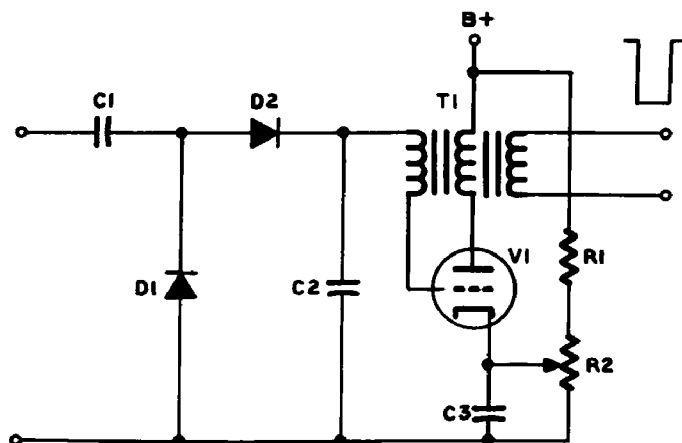
Figure 12.6   Frequency Divider

Circuit Variations

Instead of a three-winding transformer, one with two windings only may be used in conjunction with a dual-triode tube in which one triode replaces the third winding. Both grids and cathodes are connected together. When the first triode conducts, the second does so also, producing an output pulse in the same way as the third winding of the transformer in the previous example.

Thyratrons or silicon-controlled rectifiers may also be used instead of triodes, but since they do not stop conducting under the same conditions as a tube, slightly different circuit arrangements will be required (see chapter 7).

FREQUENCY MULTIPLICATION

The broadcast frequency of a radio station may be many times that of the master oscillator, as we saw in chapter 4. The carrier frequency may be doubled by using the circuit of Figure 12.7. Several stages in succession ("cascaded") will multiply it as many times as necessary.

Distinguishing Features

This circuit is basically the same as that of Figure 3.10, which was a Class C RF power amplifier. The only real difference is that there is no neutralizing capacitor in Figure 12.7.
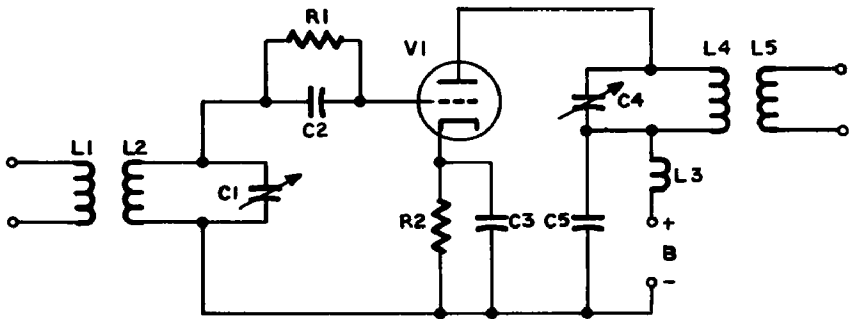
Uses

Transmitters.

Figure 12.7   Frequency Doubler

Detailed Circuit Analysis

This RF power amplifier was discussed in chapter 3, so we need not go over its operation as an amplifier again. The input resonant circuit L2–C1 is tuned to the frequency of the signal from the previous stage.

The output tank circuit L3-C4 is tuned to double this frequency. The tube generates harmonics of the fundamental frequency, and the second, which is double the fundamental, makes the output tank oscillate. In a circuit where the output and the input are at the same fre-

quency this harmonic will be much attenuated, because the output tank is not tuned to that frequency.

Since the output frequency is not the same as the input, oscillation caused by feedback is not as much of a problem, and feedback neutralization is not usually required.

FREQUENCY COMPARATOR

The frequency comparator circuit in Figure 12.8 is similar to the discriminator circuit of Figure 6.7 used in FM receivers.

Distinguishing Features

This circuit only differs from a discriminator in having T2 separate, and not a part of T1.

Use

Use of a discriminator to control frequency was mentioned in connection with FM modulation in chapter 5. Such a discriminator operates as a frequency comparator. The circuit may be used in any application where automatic frequency control is required.
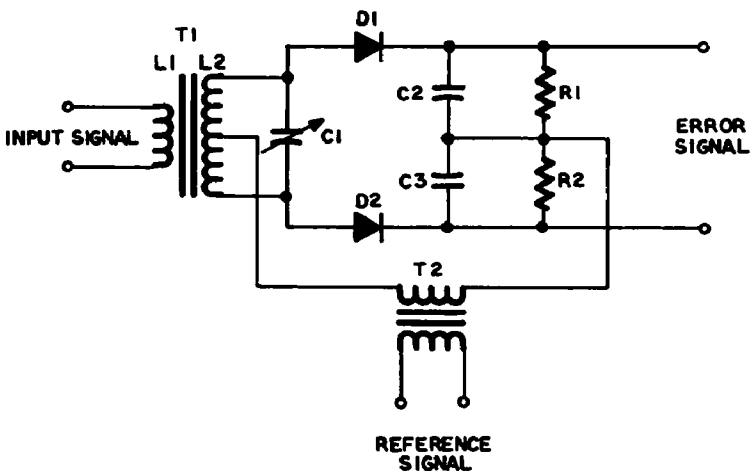

Figure 12.8 Frequency Comparator

Detailed Analysis

A control or standard frequency from a crystal-controlled oscillator is coupled into the circuit through T2. A sample of the signal to be monitored is applied across T1.

The operation of the circuit is the same as the operation of the discriminator (see chapter 6). As long as no difference exists between the input signal and the reference signal the voltages at each end of L2 remain equal, consequently the charges on C2 and C3 are equal also. Since they cancel each other no output voltage is produced.

When the input signal changes so that it is no longer at the resonant frequency of L2–C1 the two halves of L2 develop different voltages due to the resultant phase shifts. C2 and C3 are now charged to different voltages, so an error voltage appears at the output. This error voltage may be used to correct the signal frequency by using a *reactance circuit,* as explained in chapter 5.

PHOTOCELLS

Transducers are devices for converting physical quantities of one kind into corresponding physical quantities of another kind. A loudspeaker changes electrical signals into sound waves, a microphone changes sound waves into electrical signals.

Transducers which do the same for light are also of two kinds:

1. *Photosensitive,* changing light energy to electrical energy.
2. *Photoemissive,* changing electrical energy to light energy.

Photosensitive devices are also of two main types:

1. *Photovoltaic,* generating a voltage; and
2. *Photoconductive,* allowing current to pass.

Figure 12.9 illustrates a photovoltaic transducer or photocell (B) connected in a circuit in which the voltage produced by light falling on it controls a transistor, which amplifies it. Note that the symbol for the photocell is that of a voltaic cell enclosed in a circle, with arrows pointing towards it to represent incident light. The older device was a phototube, and a similar vacuum-tube circuit was used in automobiles for automatic dipping of the headlights. A rather more elaborate cir-
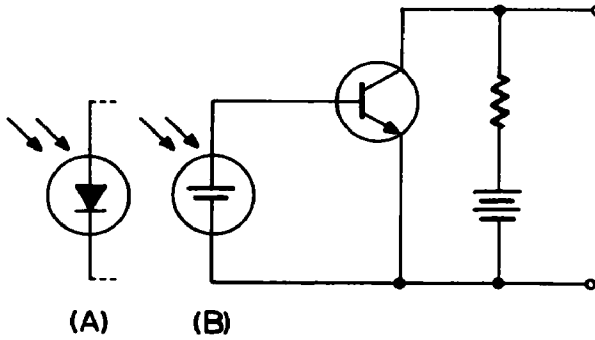
Figure 12.9   Photovoltaic Transducers

cuit is used for "reading" the sound track on the edge of a motion-picture film and converting it to an audio signal.

The solar cell used in solar batteries is also a photovoltaic device, though the idea here is simply to generate power, not to drive an amplifier.

The other device, illustrated at (A), is a photodiode, which changes from non-conduction to conduction under the influence of light.

Figure 12.10 illustrates a *photoconductive* device (a cadmium-sulfide photocell) as used in a modern camera. In this circuit the resistance of the cell varies with the intensity of light falling on it (reflected from the scene viewed by the camera), so that the reading of the exposure meter E, which depends on the battery current passed by the cell, indicates the light value. A variable resistor allows the current to be adjusted to bring the meter pointer or other indicating device back to midscale or some other index, to compensate for different film speeds, lens apertures, and so on. In some cameras this is done automatically.
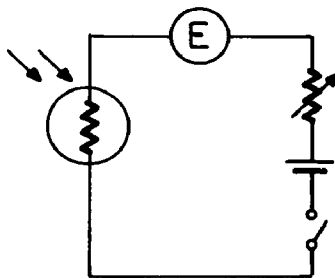

Figure 12.10   Photoconductive Transducer

Lamps of all kinds are the most well-known *photoemissive* devices, but a more recent development is that of *light-emitting diodes* (LEDs), which because of their small size and low current consumption can replace lamps with advantage in many applications, especially as indicators and in readout displays. It is possible that they may also one day be used for TV screens.

CATHODE-FOLLOWER CIRCUIT

Figure 12.11 illustrates a cathode-follower circuit, which is a special type of amplifier circuit having a voltage gain of less than unity, though there may be a power gain.

Distinguishing Features

The cathode-follower circuit has the same features as the voltage amplifiers of chapter 2, except that:

1. The plate is grounded for signals through C2.
2. The output is taken from across R2.
3. There is no cathode-bypass capacitor.

Uses

This circuit is used to couple a high impedance to a lower without the frequency losses inherent in the use of a stepdown transformer.
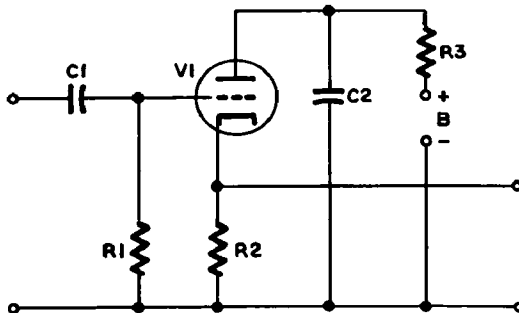

Figure 12.11   Cathode Follower

Detailed Analysis

DC Subcircuit: Electron flow is from B— via R2, V1 and R3 back to B+. R2 provides grid bias by making the cathode more positive than the grid because of the voltage drop across the resistor, and R3 drops the B+ voltage to the correct operating value for the plate.

AC Input Circuit: Input signals are applied between grid and cathode of V1 as in other amplifiers, and using standard types of coupling from the previous circuit. This example is RC-coupled via C1 and R1.

AC Output Circuit: Variations in signal voltage on the grid of V1 cause corresponding variations in the resistance of the tube and, therefore, in the current flowing through it and through R2. Since R2 is not bypassed an output signal voltage appears across it. No output signal appears across R3 because it is bypassed by C2. The output signal is in phase with the input, which it is therefore said to "follow." However, the absence of a cathode-bypass capacitor introduces *degeneration* (see chapter 2), which is why there is a voltage loss with this circuit instead of amplification.

Circuit Variations

Figure 12.12 gives the transistor equivalent of Figure 12.11. This circuit is called a *grounded-collector circuit,* because the collector of Q1 is bypassed by C1, so that no signal voltage develops across R1. The output is taken from R2, therefore, which is not bypassed. The output signal is in phase with the input.
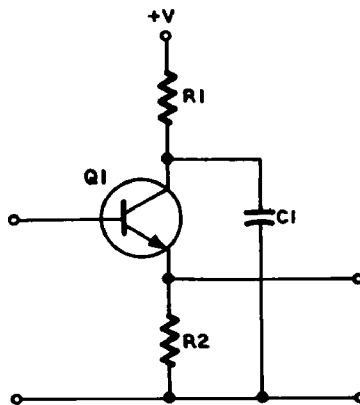

Figure 12.12 Grounded Collector Circuit

APPENDIX

Amplifier Classification

A MPLIFIERS ARE CLASSIFIED according to the operating volt-
ages which determine the bias between cathode and grid in the
case of vacuum tubes, or across the emitter-base and base-
collector junctions in the case of transistors. The relationship between
this *bias voltage* and the *cutoff voltage,* when no signal is present,
places the amplifier in one of the following classes.

Class A operation requires a bias voltage midway between the cutoff
voltage and the bias voltage that would give maximum output current
(see Figure A.1). The input signal must be small enough so that its
positive and negative excursions away from the resting voltage do not
go into the non-linear border areas close to the zero and maximum
current levels. The output current will then be a faithful replica of the
complete input signal.

Class A operation is therefore suitable for voltage amplifiers, where
input signals are small, and faithful reproduction using one tube or
transistor is required. Because a high-value load resistor is used to
change output current to output voltage the output current cannot be
high. This is important, because in Class A operation current flows at
all times, with or without an input signal. This means that power is
being wasted, and efficiency (ratio of useful output to total power
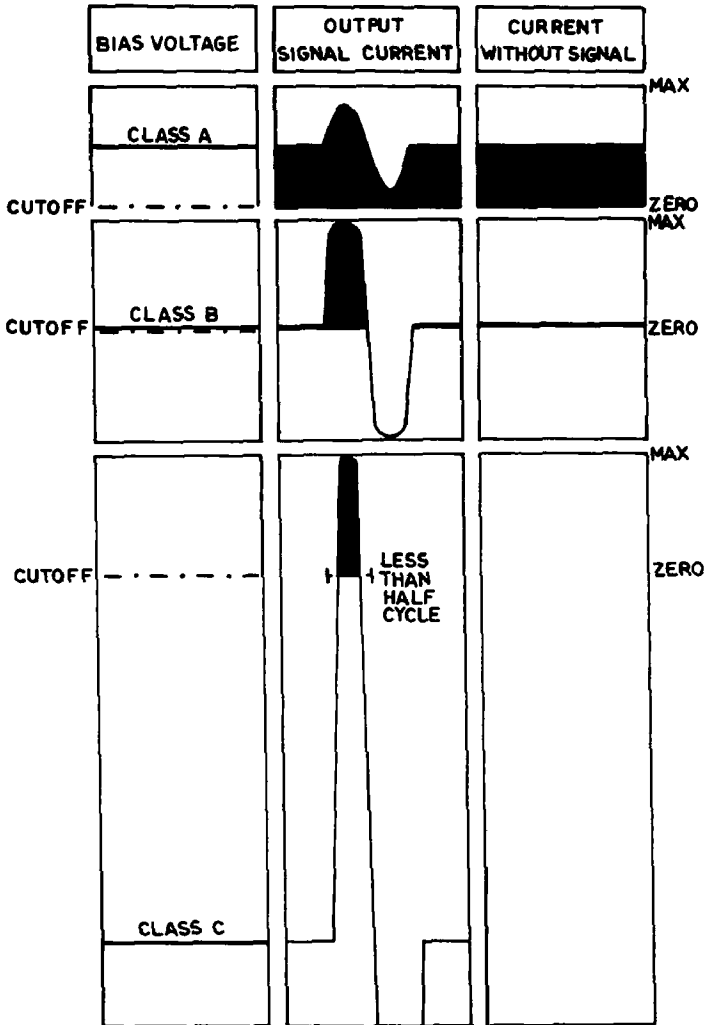consumed) is only 20–25%.

Figure A.1   Amplifier Operation

Class A amplifiers can be single-ended or pushpull, and can be used for both AF and RF.

Class AB₁ operation requires a bias voltage somewhere between the cutoff voltage and the bias required for Class A. A somewhat larger input signal is required but its positive excursion, in the case of a vacuum tube, must not be large enough to draw grid current. Since the opposite excursion of the input signal goes a little beyond cutoff, output current drops to zero, so that the tip of the signal is clipped.

This results in some distortion, and it is preferable for this amplifier

to be a pushpull type, so that the other tube or transistor can supply the missing portion. As a larger input signal is required, this amplifier is more suitable for a power output stage. It can be used for both RF and AF.

Class AB_1 amplifier efficiency is better (25–35%) than Class A because less current is wasted in non-productive operation.

Class AB_2 operation is similar to Class AB_1, except that in vacuum tubes the input signal is allowed to be large enough to draw grid current on a positive excursion. The efficiency (35–50%) is better than Class AB_1.

This is always a pushpull amplifier, and may be used for either RF or AF.

Class B operation requires a bias voltage at cutoff. This will give output-current flow only on one half-cycle of the input signal, as shown in Figure A.1; therefore for audio it must always be used in a pushpull circuit. For RF it can be used with a single-ended circuit.

Since current in the absence of an input signal is negligible, efficiency is much higher (60–70%), which is very important in higher-powered amplifiers.

Class C operation requires a bias voltage which may be two or three times the value of the cutoff voltage. Output current can flow only during a portion of the alternate swings of the input signal, which therefore must be very large. However, as this portion is considerably less than a half-cycle the efficiency of a Class C amplifier is higher than any other (it may be over 90%).

Class C amplifiers cannot be used for audio, and are mainly used for RF power stages in a transmitter. The output current flows in a series of powerful pulses that shock-excite the tank circuit into oscillation. As this is an LC resonant circuit its output waveform is a sine wave, varying in amplitude if modulated. Since the resonant circuit impedance is very high compared to that of the tube virtually all the output voltage appears across it.

Class C amplifiers can be either pushpull or single-ended. Because they are operated intermittently RF output power-amplifier tubes can be driven very much harder than if they had to run continuously.
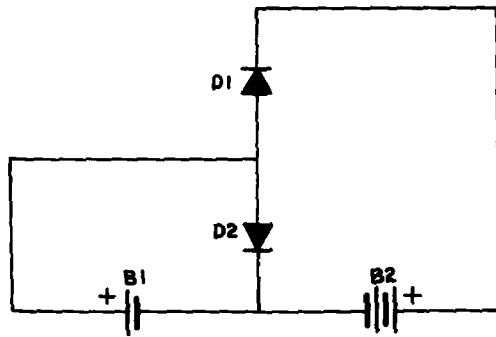
Transistor Operation

You can think of a transistor as consisting of a pair of diodes joined back to back. A diode, whether germanium or silicon, comprises P-type and N-type "regions" which meet at a *junction*. To make a

diode conduct, it must be *forward-biased,* which means that an external voltage has to be applied so that the *P* region is *P*ositive with respect to the *N* region which, conversely, is *N*egative. The P region is the anode, and the N region is the cathode.

In Figure A.2 an NPN transistor (a) and a PNP transistor (b) are drawn as if they were pairs of diodes. In both transistors D2 is forward-biased by B1, and D1 is reverse-biased by B2, consequently D2 should conduct and D1 should not.

Forward-biasing allows conduction by lowering the *barrier voltage* at the junction. Conversely, reverse-biasing raises it. However, because of the proximity of the junctions in a transistor, D1 is influenced by D2. Therefore when D2 is forward-biased both diodes conduct, and when D2 is reverse-biased neither does. Actually, the purpose of D1
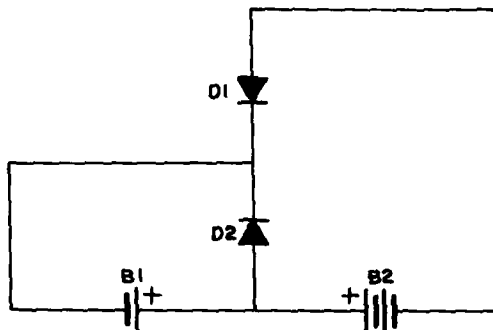
(a)

(b)

Figure A.2   Transistor Operation

is to increase the flow of current from B2 through D1 and D2, so that amplification can take place, since a single diode cannot amplify.

In real circuits B1 is replaced by a voltage divider that drops B2's voltage to the proper value. The forward-bias voltage required to overcome the barrier at the emitter-base junction (D2 in Figure A.2) is .2 volt for germanium and .7 volt for silicon.

When a signal voltage is applied across the emitter-base junction it raises and lowers the barrier voltage in accordance with its own voltage fluctuations, thereby varying the current flow through the transistor (D1 + D2).

The *MOS/FET* ("metal-oxide-silicon/field-effect transistor") illustrated in Figure A.3 (also shown in a circuit in Figure 2.9) is made by oxidizing the surface of a thin wafer of N-type silicon. This oxide, which is a type of glass, is then removed from the source and drain areas by photo-etching. The wafer is then placed in a furnace in which a P-type impurity (boron, aluminum or gallium) is present as a gas that diffuses into the exposed areas, converting them to P-type silicon. A similar process is used to deposit thin films of aluminum to form metal electrodes, and then gold wire leads are bonded to them by a combination of heat and pressure.
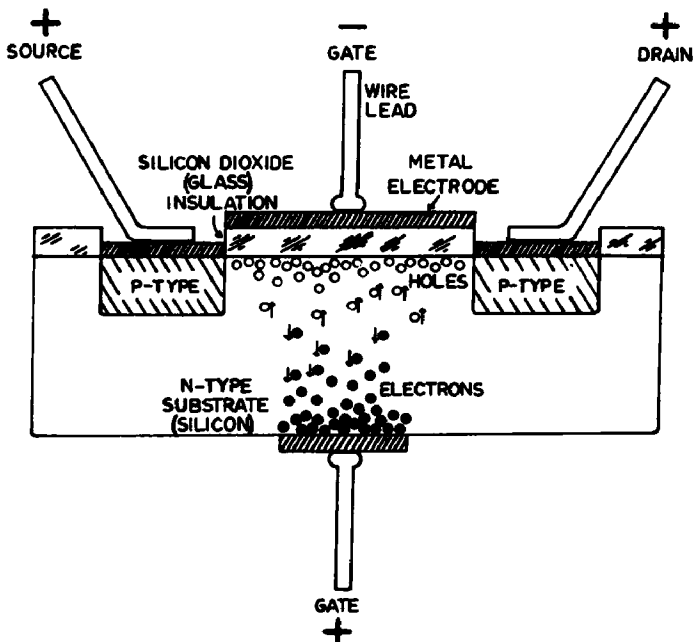
Figure A.3   MOS/FET

In this transistor the *emitter, base* and *collector* have been renamed *source, gate* and *drain*. There are actually *two* gate connections, one reinforcing the other.

The negative and positive voltages on the gate electrodes force electrons toward the lower gate, thereby creating a large number of holes. These, having a positive charge, are repelled by the drain and flow toward the source, because the drain's positive voltage is considerably higher than that of the source.

The actual amount of current flowing depends on the gate voltages, which force more or fewer electrons away, thereby making the path for the hole current wider or narrower. Consequently a signal voltage applied to the gate controls current flow in the same way as it does in a vacuum tube.

This type of MOS/FET is called an *enhancement* type, because the flow of current is enhanced by the gate voltage. Another type, which works in the opposite way, is called a *depletion* type.

The one illustrated in Figure A.3 is also called a *P-channel device*, because the N-type silicon substrate is actually converted to P-type when electrons are driven out of the region between the source and the drain. An *N-channel device* would be constructed with P-type substrate and N-type regions for source and drain. Current would be by electrons instead of holes.

Color Coding

Fixed non-metallic resistors and some other components are color-coded to indicate their values instead of having the information printed or stamped on them. The colors used and their numerical significance are as follows:

Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Gray	8
White	9

On a *composition resistor* there are three or four colored bands around the resistor body, adjacent to one end. Starting with the one nearest the end, the first two colors are the significant figures of the resistor value in ohms, and the third is the power of ten of the multiplier. For example, blue (6), red (2) and yellow (4) should be read as 62×10^4, or 620 kilohms. If the third band is gray (or silver), or white (or gold), the multiplier is 10^{-2}, or 10^{-1}, respectively.

If there is no fourth band the tolerance is $\pm20\%$. Otherwise, silver denotes $\pm10\%$, gold $\pm5\%$. Other tolerances may be indicated by using the applicable colors, but these are seldom encountered as most precision resistors have their values stamped or printed on them.

Some *film-type* resistors also may be color-coded, in which case an additional color may be added at the front end, to provide for three significant figures, followed by a multiplier and tolerance.

Capacitors, for the most part, are not color-coded. Exceptions are some *ceramic* and *mica* types. Ceramic *tubular* capacitors may be coded in the same way as composition resistors, except that an additional color is added in front of the others to indicate the *temperature characteristic*. The colored bands may also be replaced by colored dots. Ceramic *disks* have these arranged around the edge, to be read clockwise. Some very small tubular capacitors have only three dots, which give two significant figures and the multiplier only.

Most *mica* capacitors are no longer color-coded. However, the flat rectangular molded silvered-mica type may employ an arrangement of six colored dots arranged three on each side of an arrow, or some other mark to indicate which way to read them. With the arrow pointing to the right the upper three dots (reading from left to right) indicate EIA standard (this is a white dot, which may be omitted) and two significant figures. The bottom row (reading from right to left) gives the multiplier, tolerance and type.

The significant figures always give the value in picofarads. The temperature characteristic (ceramic capacitors) or type (mica capacitors) is denoted as follows:

COLOR	TEMPERATURE CHARACTERISTIC	TYPE (MFR'S SPEC.)
Black	NPO	A
Brown	NO33	B
Red	NO75	C
Orange	N150	D
Yellow	N220	E
Green	N330	

Blue	N470
Violet	N750

Diodes used in signal circuits are often color-coded because of their small size. Diode designations are always given, for example, in the form 1N914A. The 1N— is common to all and does not have to be indicated, therefore the color bands denote the figures and letter following. Suffix letters are coded as follows:

Black	(no suffix)
Brown	A
Red	B
Orange	C
Yellow	D
Green	E
Blue	F
Violet	G
Gray	H
White	J

The colored bands are grouped at the cathode end of the diode.

Transformer leads are color-coded as follows:

POWER TRANSFORMERS

Primary (tapped)	*Secondary*	
Black (common)		⌈ Red
Black/yellow	High voltage	⎱ Red/yellow
(centertap)		⎰ (centertap)
Black/red		⌊ Red
or		⌈ Yellow
Primary (untapped)	Rectifier filament	⎱ Yellow/blue
Two black leads		⎰ (centertap)
		⌊ Yellow
		⌈ Green
	Amplifier filament #1	⎱ Green/yellow
		⎰ (centertap)
		⌊ Green

Amplifier filament #2 $\begin{cases} \text{Brown} \\ \text{Brown/yellow} \\ \text{(centertap)} \\ \text{Brown} \end{cases}$

Amplifier filament #3 $\begin{cases} \text{Slate} \\ \text{Slate/yellow} \\ \text{(centertap)} \\ \text{Slate} \end{cases}$

IF TRANSFORMERS

Primary	*Secondary*
Blue (plate)	Green (grid or diode)
	Green/black (full-wave diode)
Red (B+)	Black (grid or diode return, AVC or ground)

AUDIO & OUTPUT TRANSFORMERS

Primary	*Secondary*
Blue (plate)	Green (grid or voice coil)
Red (B+)	Black (return or voice coil)
*Blue or brown (plate)	*Green or yellow (grid)

---

* Pushpull only.

Preferred Values

Most resistors and capacitors other than precision or special-buy items are supplied in *preferred values,* to simplify manufacture and stocking by limiting the number of different values to bare essentials. The tolerance provides the necessary spread to cover the gaps between the nominal values. Preferred values for the three principal tolerances are manufactured for each multiplier as follows:

20%	10%	5%
10	10	10
	12	12
15	15	15
		16
	18	18
		20

<u>20%</u>	<u>10%</u>	<u>5%</u>
22	22	22
		24
	27	27
		30
33	33	33
		36
	39	39
		43
47	47	47
		51
	56	56
		62
68	68	68
		75
	82	82
		91
100	100	100

International System of Units (SI Units)

Standard units of measurement have been adopted by most countries, and in electronic work those listed below with their symbols are now in general use.

Physical Quantity	SI Unit	Symbol	Old Name & Symbol (if different)	
Current	ampere	A		a, amp
Capacitance	farad	F		f, fd
Inductance	henry	H		h
Frequency	hertz	Hz	Cycles	c, cps
			Cycles per second	
Wavelength	meter	m		
Resistance	ohm	Ω		
Time	second	s		sec
Voltage, potential difference, electromotive force	volt	V		v
Power	watt	W		w

Standard prefixes that are used with the above to obtain units of convenient size are as follows:

Factor by which unit is multiplied	Prefix	Symbol	Old Prefix & Symbol (if different)	
10^{12}	tera-	T		
10^9	giga-	G	kilomega-	km
10^6	mega-	M		m
10^3	kilo-	k		
10^2	hecto-	h		
10^1	deka	da		
10^{-1}	deci-	d		
10^{-2}	centi-	c		
10^{-3}	milli-	m		
10^{-6}	micro-	μ		
10^{-9}	nano-	n	millimicro-	$m\mu$
10^{-12}	pico-	p	micromicro-	$\mu\mu$
10^{-15}	femto-	f		
10^{-18}	atto-	a		

Examples:

Gigahertz (billion hertz) = GHz
Megohm (million ohms) = $M\Omega$
Kilovolt (thousand volts) = kV
Centimeter (hundredth of a meter) = cm
Millisecond (thousandth of a second) = ms
Microhenry (millionth of a henry) = μH
Picofarad (trillionth of a farad) = pF

Conversion Factors (U.S. and Metric)

Ampere-hour	3.6×10^{-3}	coulombs
Ampere-turn	1.257	gilberts
Angstrom	1.00×10^{-10}	meter
British thermal unit (BTU) (mean)	1.05587×10^3	joules
Centimeter	3.937×10^{-1}	inches
Coulomb	2.778×10^{-4}	ampere-hours
Foot	3.048×10^{-1}	meters
Gauss	1.00×10^{-4}	tesla
Gilbert	7.958×10^{-1}	ampere-turns
Grain	6.479891×10^{-5}	kilograms

Gram	3.527×10^{-2}	ounces (avoirdupois)
Horsepower (electric)	7.46×10^2	watts
Inch	2.54	centimeters
Kilogram	2.205	pounds (avoirdupois)
Kilometer	6.2137×10^{-1}	miles
Kilowatt-hour	3.6×10^6	joules
Liter	2.113	pints (US)
Maxwell	1.00×10^{-8}	weber
Meter	1.094	yards
Micron	1.00×10^{-6}	meter
Mile (nautical)	1.852	kilometers
Mile (statute)	1.609344	kilometers
Oersted	7.9577472×10^{-1}	amperes per meter
Ounce (avoirdupois)	28.349523125	grams
Ounce (troy)	31.1034768	grams
Pint (US)	$4.73176473 \times 10^{-1}$	liters
Pound (avoirdupois)	4.5359237×10^{-1}	kilograms
Tesla	1.00×10^4	gauss
Watt	1.341×10^{-3}	horsepower
Weber	1.00×10^8	maxwells
Yard	9.144×10^{-1}	meter

Ohm's Law Formulas

	E =	I =	R =	P =
DC	IR	$\dfrac{E}{R}$	$\dfrac{E}{I}$	EI
	$\dfrac{P}{I}$	$\dfrac{P}{E}$	$\dfrac{P}{I^2}$	I^2R
	$\sqrt{PR}$	$\sqrt{\dfrac{P}{R}}$	$\dfrac{E^2}{P}$	$\dfrac{E^2}{R}$

E =	I =	Z =	P =
IZ	$\dfrac{E}{Z}$	$\dfrac{E}{I}$	$IE\cos\theta$
$\dfrac{P}{I\cos\theta}$	$\dfrac{P}{E\cos\theta}$	$\dfrac{P}{I^2\cos\theta}$	$I^2Z\cos\theta$
$\sqrt{\dfrac{PZ}{\cos\theta}}$	$\sqrt{\dfrac{P}{Z\cos\theta}}$	$\dfrac{E^2\cos\theta}{P}$	$\dfrac{E^2\cos\theta}{Z}$

AC

Common Electrical Formulas

Resistors in series: $\qquad\qquad R_T = R_1 + R_2 + \ \ldots$

Resistors in parallel (two): $\quad R_T = \dfrac{R_1 R_2}{R_1 + R_2}$

Resistors in parallel (more than two): $\qquad \dfrac{1}{R_T} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \ \ldots$

Capacitors in series (two): $\quad C_T = \dfrac{C_1 C_2}{C_1 + C_2}$

Capacitors in series (more than two): $\qquad \dfrac{1}{C_T} = \dfrac{1}{C_1} + \dfrac{1}{C_2} + \dfrac{1}{C_3} + \ \ldots$

Capacitors in parallel: $\qquad C_T = C_1 + C_2 + \ \ldots$

Capacitive Reactance: $\qquad X_C = \dfrac{1}{2\pi fC}$

*Inductors in series: $\qquad L_T = L_1 + L_2 + \ \ldots$

*Inductors in parallel (two): $\qquad L_T = \dfrac{L_1 L_2}{L_1 + L_2}$

*Inductors in parallel (more than two): $\qquad \dfrac{1}{L_T} = \dfrac{1}{L_1} + \dfrac{1}{L_2} + \dfrac{1}{L_3} + \ \ldots$

Inductive Reactance: $\qquad X_L = 2\pi fL$

---

* No coupling between coils

Coupled Inductance: $\qquad$ $L_T = L_1 + L_2 \pm 2M$

Transformer ratio: $\qquad$ $\dfrac{N_p}{N_s} = \dfrac{E_p}{E_s} = \dfrac{I_s}{I_p} = \sqrt{\dfrac{Z_p}{Z_s}}$

Series impedance: $\qquad$ $Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{R^2 + X^2}$

Parallel impedance: $\qquad$ $Z = \dfrac{RX}{\sqrt{R^2 + X^2}}$

Temperature—Celsius: $\qquad$ $C = 0.556F - 17.8$

Temperature—Fahrenheit: $\qquad$ $F = 1.8C + 32$

Temperature—Kelvin: $\qquad$ $K = C + 273$

Decibels—power: $\qquad$ $db = 10 \log \dfrac{P_1}{P_2}$

Decibels—voltage: $\qquad$ $db = 20 \log \dfrac{E_1}{E_2}$

Power factor: $\qquad$ $pf = \dfrac{P}{EI} = \dfrac{R}{Z}$

Resonance: $\qquad$ $f = \dfrac{1}{2\pi\sqrt{LC}}$

Greek Alphabet

Name	Upper Case	Lower Case	Used For
Alpha	A	α	Angles
Beta	B	β	Angles, flux density
Gamma	Γ	γ	Conductivity
Delta	Δ	δ	Changing value, increment
Epsilon	E	ϵ	Natural logarithm base: 2.71828
Zeta	Z	ζ	Impedance, coefficients, coordinates
Eta	H	η	Efficiency, coefficient of hysteresis
Theta	Θ	θ	Phase angle
Iota	I	ι	
Kappa	K	κ	Constant, coefficient of coupling, susceptibility
Lambda	Λ	λ	Wavelength
Mu	M	μ	Micro-, amplification factor, permeability
Nu	N	ν	Reluctivity
Xi	Ξ	ξ	
Omicron	O	o	
Pi	Π	π	3.14159 26535 89793 23846 ...
Rho	P	ρ	Resistivity
Sigma	Σ	σ	
Tau	T	τ	Time-constant, time-phase displacement
Upsilon	Υ	υ	
Phi	Φ	ϕ	Angles, magnetic flux
Chi	X	χ	
Psi	Ψ	ψ	Dielectric flux, phase difference
Omega	Ω	ω	Ohms (upper case), angular velocity ($= 2\pi f$)

Radio Frequency Spectrum

Frequency	Classification	Abbre-viation	Examples of Use
DC —30 kHz	Very low frequency	VLF	DC, AC power, audio sonar, ultrasonic cleaning
30 kHz —300 kHz	Low frequency	LF	L–F Marker Beacons
300 kHz —3 MHz	Medium frequency	MF	AM Broadcasting[1]
3 MHz —30 MHz	High frequency	HF	Aircraft, amateur radio
30 MHz —300 MHz	Very-high frequency	VHF	TV,[2] FM,[3] VHF Marker Beacons
300 MHz—3GHz	Ultrahigh frequency	UHF	TV,[4] GCA, Tacan
3 GHz —30 GHz	Super-high frequency	SHF	Radar, amateur radio
30 GHz —300 GHz	Extremely high frequency	EHF	Weather radar, NASA communications

1 550 kHz to 1.6 MHz, 10 kHz per station.
2 Channels 2 through 13: 54 to 88 MHz and 174 to 216 MHz, 6 MHz per channel.
3 88 MHz to 108 MHz, 200 kHz per station.
4 Channels 14 through 83: 470 to 890 MHz, 6 MHz to each channel.

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