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If any information contained herein conflicts with a technical order, manual, or other official publication of the U.S. Armed Forces, the information in the official publication should be used.

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Editorial

ELECTRONIC COMPUTERS

by John E. Remich, Manager, Technical Department

In this issue, we are releasing the fourth installment of the current series of articles on "Electronic Computers." Probably no other electronic device, with the possible exception of radar, has received as much attention and widespread interest in the popular press during the past five years as has the electronic computer. Man has always been fascinated by machines of any type, and particularly by "automatic" machines which seem to think for themselves.

The development of truly intelligent thinking machines, capable of undirected creative thought is, of course, extremely unlikely. However, although they are limited to certain specific types of computation, a number of presently existing electronic computers exhibit capabilities which are almost unbelievable. The almost fantastic rapidity with which previously laborious mathematical calculations can be carried out in such instruments has been widely publicized, but some of the more recent applications are less well known.

In engineering, for example, the use of computers to test the feasibility of new designs in airfoils, servomechanisms, electronic-control systems, etc., is daily becoming more important. The mathematical equivalents of all pertinent factors can be set up in the computer and all conceivable variations of each parameter tested before the projected device itself is even built. The result is the elimination of almost all "trial-and-error" research, and consequent saving of vast sums of time and money.

It would be difficult to even attempt to predict the future development of such devices, but the head of one of the nation's largest electronics manufacturers recently stated that, in his opinion, the joint development of electronic computers, transistors, and miniaturized components will rapidly lead to computers so efficient that the great burden of thinking in research, development and production will be done entirely by such machines. In fact, he even went further, and implied that the result would be as great a revolution in human affairs as that caused by the Machine Age.

THE MAGNETIC PUMP

by Gail W. Woodward
Technical Information Section

How basic electronics has assisted in the resolution of a major problem in the field of nuclear energy.

T HE DEVELOPMENT of the nuclear reactor (atomic pile) has resulted in a fantastic source of power in the form of heat. Theoretically, if the heat generated by a reactor could be extracted at a great enough rate, a huge turbo-electric system generating vast quantities of electricity could be driven with the energy produced by a very small quantity of fuel. Practically, however, engineers in the atomic-energy field have found it difficult to develop a satisfactory heat exchanger capable of extracting the heat at the necessary rate.

The search for a practical heat exchanger has led researchers into the realm of liquid-metal coolants. (The types of heat exchangers used in refrigeration prove impractical at the temperatures and radiation levels encountered in an atomic pile.) To date the best heat-exchanger substance is a liquified alloy of sodium and potassium. The corrosive nature of both of these metals is well-known—particularly violent reactions occur in the presence of water. Obviously, such a fluid is difficult to pump through the exchanger system. Many pumping schemes have been tried with varying degrees of success. Most pumps employ a mechanical impeller, and the motive power is usually supplied by an electric motor. In one type of pump, however, the mechanical impeller and the external motor are eliminated, and the pump itself functions in a manner similar to that of an electric motor, with the fluid to be pumped serving as the only moving part. This pump, known as a mag-

netic pump, is a remarkable achievement in terms of simplicity alone.

Figure 1 shows the essentials of a magnetic pump. The main component of the pump is a section of thin-wall tubing made of stainless steel or other substance that resists corrosion. Aside from its corrosion-resistance properties, this tube must have a resistivity that is great compared with the resistivity of the liquid metal being pumped. Heavy copper bus wires are soldered or welded to opposite sides of the tube so that a good electrical contact is secured (these bus wires may have cross-sectional areas of several square inches, depending upon the required current). The bus wires are connected to a power supply that is designed to supply a very large current at low voltage. A magnet of suitable properties is situated on the side of the tube
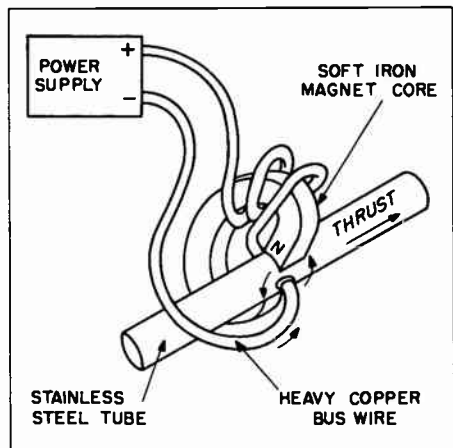

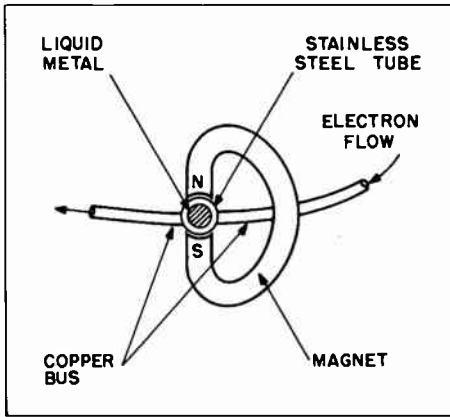*Figure 1. Simplified Sketch of Magnetic Pump*

Figure 2. Cross-Sectional View of Magnetic Pump, Taken at Center of Magnet

so that the direction of the magnetic field is at right angles to the direction of current flow. Figure 2 shows a cross-sectional view of the pump at the point of bus-wire connection. It can be seen that a major portion of the current must pass through the liquid metal rather than the walls of the tube, because of the lower resistance of the liquid.

It is a well-known fact that a current-carrying conductor in the presence of a magnetic field is subjected to a mechanical force which is mutually perpendicular to the direction of current flow and the direction of the magnetic field. Applying the left-hand rule to figure 2 shows that the resultant force, or thrust, is along the axis of the tube, into the paper. Therefore, the liquid metal is made to move along the tube. Using reasonably large values of power results in correspondingly large values of thrust.

The magnet could be a permanent magnet, but merely winding a couple of turns of the copper bus around a soft-iron core will provide an adequate magnetic field. This is illustrated in figure 1.

A typical magnetic pump produces a flow of 200 gallons per minute at a pressure of 15 lbs. per square inch. In this pump, the tube is three inches in diameter, and a current of 20,000 amperes is required. Since the voltage used is very low, this current value does not represent an exorbitant amount of power (746 amperes is required to produce one horsepower at one volt).

A magnetic pump has many outstanding features. The low voltage used involves no shock hazard, and insulation is no problem. Since there are no moving mechanical parts, there is no mechanical hazard or wear (impeller bearings, lubrication, and wear are major problems in ordinary pumps). The rate of flow can be controlled by very simple electronic means, so that automatic control is greatly simplified. The direction of flow can be reversed simply by reversing either the direction of the current through the tube or the direction of the current through the magnet winding (reversing the polarity of the power source will not change the direction of flow because both the magnetic field and the current flow would reverse, and the thrust would be in the same direction as before).

Most commercial magnetic pumps are operated from a d-c source. Selenium or copper-sulphide rectifiers are very efficient for such low-voltage high-current applications. However, it appears that for light pumping jobs, the pump could be operated from a conventional current transformer.

At first glance it would appear that the efficiency of the magnetic pump could be increased by merely increasing the magnetic field strength. Unfortunately, this is not the case—there is actually an optimum field strength for a given system. Too strong a magnetic field reduces the thrust, because eddy currents induced into the moving metal set up magnetic fields which, in effect, oppose the applied current.

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What's Your Answer?

Here is another very interesting switching problem, submitted by LCDR Harold K. Long, Operational Communications Officer, Headquarters, Thirteenth Naval District, and editor of "Thirteenth Naval District Reserve Electronics Bulletin."
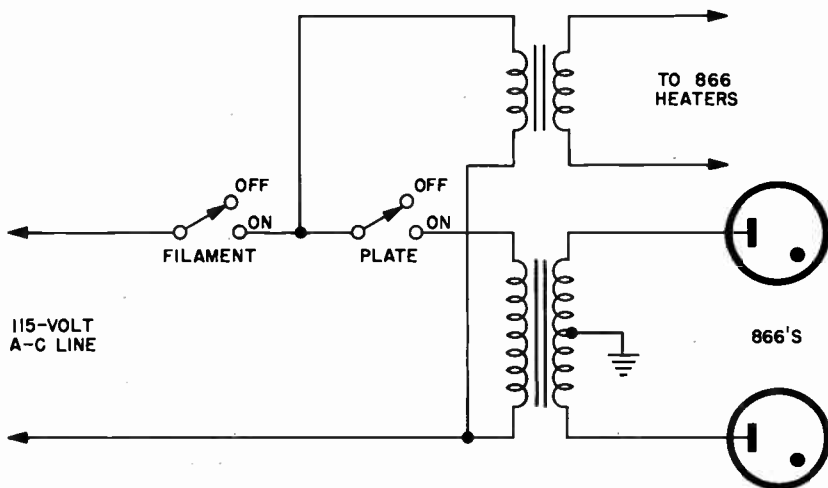
The drawing shows the typical circuit used in conjunction with hot-cathode mercury-vapor rectifiers. So long as the operator is careful to follow the correct switching sequence, he will not place high voltage on cold mercury-vapor rectifiers. However, inspection will show that operating the switches in the wrong sequence might apply filament power and plate power simultaneously to the 866's, with probable resulting damage to the tubes.

After replacing a few sets of 866's, a technician decided to redesign the primary switching system so that closing either switch first will always apply filament power. Closing the second switch, after a suitable delay interval, will then apply plate power. It is immaterial which switch is closed first.

How did the technician accomplish this without resorting to "trick" switches or relays?

(Solution next month)

ELECTRONIC COMPUTERS—Part IV

Basic Binary Adder and Static Register Circuits

by Warren M. Kitter

Technical Publications Department

The fourth in a series of articles discussing electronic computers. This article shows how the basic logic circuits are combined into a workable adder circuit, and how a binary number can be stored in a "memory" circuit of the static-register type.

BEFORE CONSIDERING the logic behind the operation of an adder, it is necessary to discuss the means used to time the computer operations, and the pulse method of representing binary numbers.

In a modern computer, accurate operation dictates that a master cycling, or clock, unit be employed to generate pulses for the timing of the various circuit functions and for use in the representation of binary numbers. Master pulses of constant width and separation are generated continuously, and are passed by means of gating circuits to appropriate sections of the computer.

The master-cycling-unit output used for the representation of numbers in a computer that operates to ten binary places is shown in figure 1. For the purpose of this discussion, assume that the pulse width is two microseconds, and that the spacing between any two adjacent pulses is the same. Under these conditions, 40 microseconds are required to generate the entire chain of ten pulses representing ten binary places.

There are two different methods of representing numbers with pulses; one method uses both the positive and negative pulses, and the other uses only the positive pulses. In the latter method, which is the only one that will be described, each positive-pulse position in the master-pulse chain represents a place in the binary number. In other words, each place is represented by a definite position in time with respect to the start of the pulse chain. The value of the digit in each place is represented by the presence or absence of the pulse in that place, the pulses being selected or rejected from those in the master-pulse chain by means of gating circuits. The presence of a pulse indicates the digit "1," and the absence of a pulse the digit "0." Using this method, the number 001101 (13) would be represented as shown in figure 2. If every pulse in the chain were present, as in figure 1, the number would be 1111111111

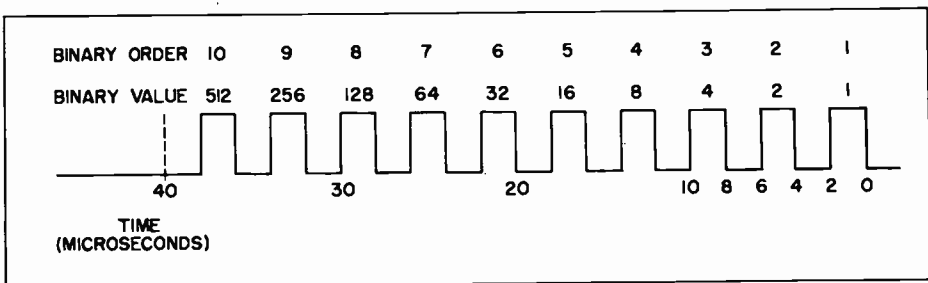| BINARY ORDER	10	9	8	7	6	5	4	3	2	1
BINARY VALUE	512	256	128	64	32	16	8	4	2	1

Figure 1. Master-Cycling-Unit Output Used for Representing Numbers in Computer Capable of Operating to Ten Binary Places
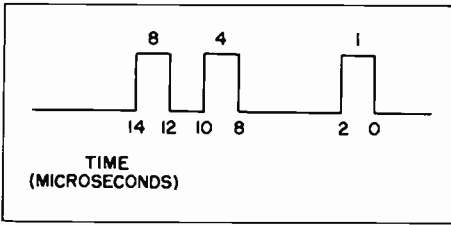
Figure 2. Binary-Pulse Representation of Number 13 (See Figure 1)

(1023), which is the largest number that can be accepted by the computer under consideration.

When considering computer circuits, it is important to remember that it is the time position of the pulses, as well as their presence or absence, that governs the use of logical elements in the arithmetical sections of a computer. In this series of articles we shall make a practice of showing an inverted time order. For example, in figure 1 the pulse on the extreme right is actually generated first, and the one on the extreme left is generated last. This inversion is used so that the pulse train will show the binary number with the digits in the same order as they would appear in written form. A service oscilloscope connected to our hypothetical computer, however, would display the pulses in reverse order to that shown in the figure.

In Part III of this series (January, 1953) two numbers in the form of pulses were presented to an adder on separate inputs. The adder combined the pulses and produced a carry pulse, which, after being delayed by an ap-
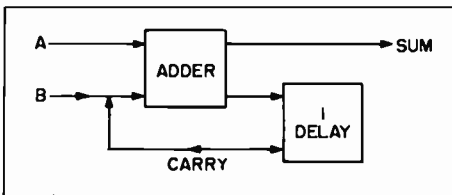
propriate time interval, was presented to the adder input along with the pulses representing the next higher order of digits (see figure 3). The operation of the adder is based entirely on the use of logical AND, OR, and NOT circuits.

In the development of an adder circuit, let us apply 00011 (3) to input A and 00101 (5) to input B of the circuit in figure 4. The chains of pulses are then applied simultaneously to both the logical OR circuit and the logical AND circuit. (As will be recalled, a logical OR circuit produces an output when a pulse is applied to either input line, but a logical AND circuit requires the presence of a pulse at both inputs to produce an output pulse.) In the above example, pulses occur at both A and B during the presentation of the first-order digits. Therefore, the requirements for operation of both the logical OR and AND circuits are met, and an output pulse appears at both C and D. The second-order digits trigger the OR circuit but not the AND circuit, so that an output pulse appears only at C (the same condition will exist for the third-order digits).

Each time A and B are pulsed simultaneously, an output pulse appears at D. Since this condition occurs only when 01 and 01 are added, the pulse appearing at D indicates a carry, and may be used for that purpose. The pulses at C can represent the sum of the addition but
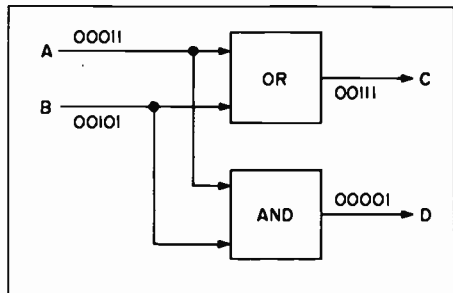

Figure 3. Simplified Block Representation of Adder Circuit

Figure 4. First Step in Development of Adder

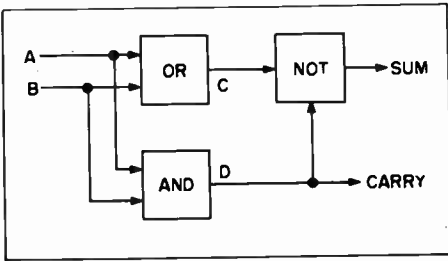**Figure 5. Block Diagram of Half Adder**

Figure 6. Simplified Block Symbol of Half Adder Shown in Figure 5

they do *not* represent the sum if a carry pulse is also present at D. In order to convert the pulses at C into a true sum, it is necessary to include a logical NOT circuit in the adder to suppress the pulse at C whenever a carry is indicated. The logical NOT circuit will permit pulses to pass through it except when an inhibitory pulse from D is applied. A block diagram is shown in figure 5. This block diagram does not represent a complete adder, because the carry pulse is not combined with the sum. It can be seen that if the carry pulse were applied to either A or B, a situation might occur in which a binary input pulse and a carry pulse would be present on the line at the same time. Such a condition would, of course, produce ambiguous results. Therefore, the circuit diagram in figure 5 is more properly referred to as a *half adder*, and is symbolized as shown in figure 6.

To form a full adder, it is necessary to use two half adders and a one-pulse-interval delay line as shown in figure 7.
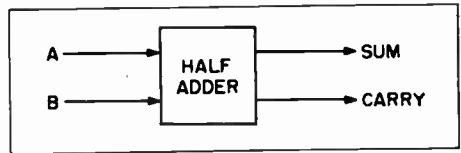
The operation of the full adder is as follows: At the first time interval, pulses are presented to both input leads of Half Adder I. As previously explained, this condition produces a sum of 0 and a carry pulse. Since the carry pulse is delayed by one pulse interval in traveling through the delay line, no pulses are applied to either input of Half Adder II during time 1. Hence, the true-sum output is 0. At time 2, Half Adder I produces a sum pulse, which is applied to Half Adder II along with the delayed carry pulse from time 1. The simultaneous presentation of two pulses to Half Adder II results in a true sum of 0 and a carry of one. At time 3, Half Adder I produces a sum pulse, which is applied to the input of Half Adder II simultaneously with the delayed carry pulse previously produced by Half Adder II. Again this produces a true sum of 0 and a carry of 1. The carry pulse drifts through the delay line, but this time no input pulses are presented. Therefore, when the carry pulse enters Half Adder II at time 4, a sum pulse is produced and the addition is complete. 00011 + 00101 equals 1000. For the
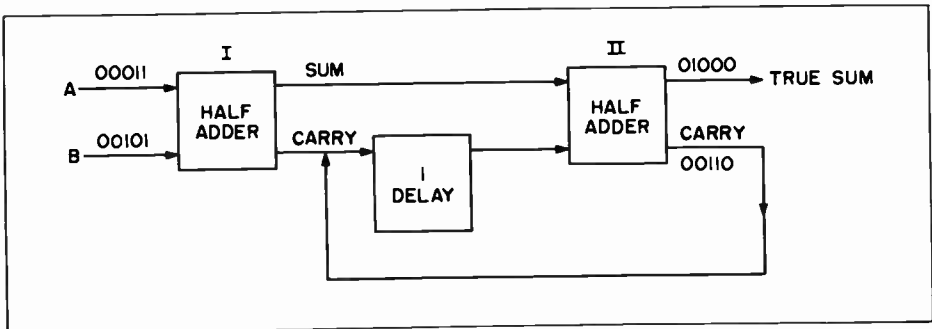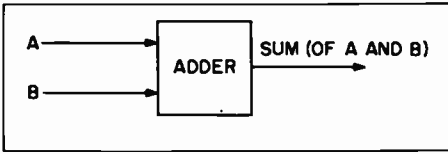

Figure 7. Block Diagram of Full Adder

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Figure 8. Simplified Block Symbol of Full Adder Shown in Figure 7

remainder of this series of articles, all of the blocks shown in figure 7 will be condensed into the single block shown in figure 8.

It must be remembered that a computer follows a definite program, so that at any instant it can be made to apply the output of a particular adder to either an additional arithmetical element, a storage register, the output circuits, etc. This can be accomplished by gating circuits (logical AND), which serve to switch information from one section to another. In figure 9, it can be seen that the output of the adder can be switched to the memory, output, or arithmetical circuits, depending upon whether inputs one, two, or three are pulsed.

In the hypothetical circuit shown in figure 9, if it is desired to store the sum for use later in the computation, a memory circuit must be employed. Memory circuits may be divided into two categories—static and dynamic. For the present, this discussion will be concerned with only the static form. In this type of memory circuit (exemplified by a flip-flop multivibrator), a pulse is stored by creating a change of state in the circuit, and the static state can be read out at a later time to re-establish the pulse train. In a static memory system, one flip-flop circuit consisting of two tubes must be used for each binary digit stored; inasmuch as ten decimal places require 35 binary positions, a ten-decimal-digit computer will require 70 tubes in each static storage register. It is apparent that economic considerations prevent the tying up of that many tubes for each number stored. Static

memory circuits are practical only when the information is to be stored for short intervals, as would be the case for information required in a subsequent arithmetical operation. For example, the computer may be programmed to add 00011 (3) and 00101 (5) and then to subtract the result from a number stored in another section of the computer. In this case, it is justifiable to feed the results of the addition to a static memory as the addition of each binary order is completed.

The output of the adder is in serial form; that is, the binary orders occur in a definite time sequence. Since a static register is usually of the parallel type, which stores all of the binary orders simultaneously, it is necessary to convert the serial pulse train into a parallel arrangement for simultaneous application of all the pulses to the memory circuits. This is accomplished by the circuit shown in figure 10. Figure 10A shows the over-all block diagram, and figure 10B shows a flip-flop multivibrator schematic. Note that each flip-flop circuit is provided with two input leads and one output lead. The operation of the flip-flop under this condition is as follows: In the normal state, which indicates binary 00, V_1 in figure 10B is cut
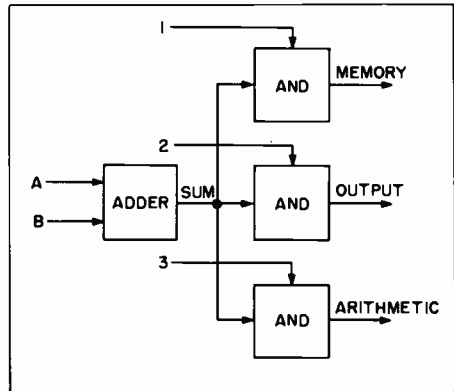
Figure 9. Typical Gating-Circuit Arrangement Used to Switch Output of Adder to Various Points in Computer

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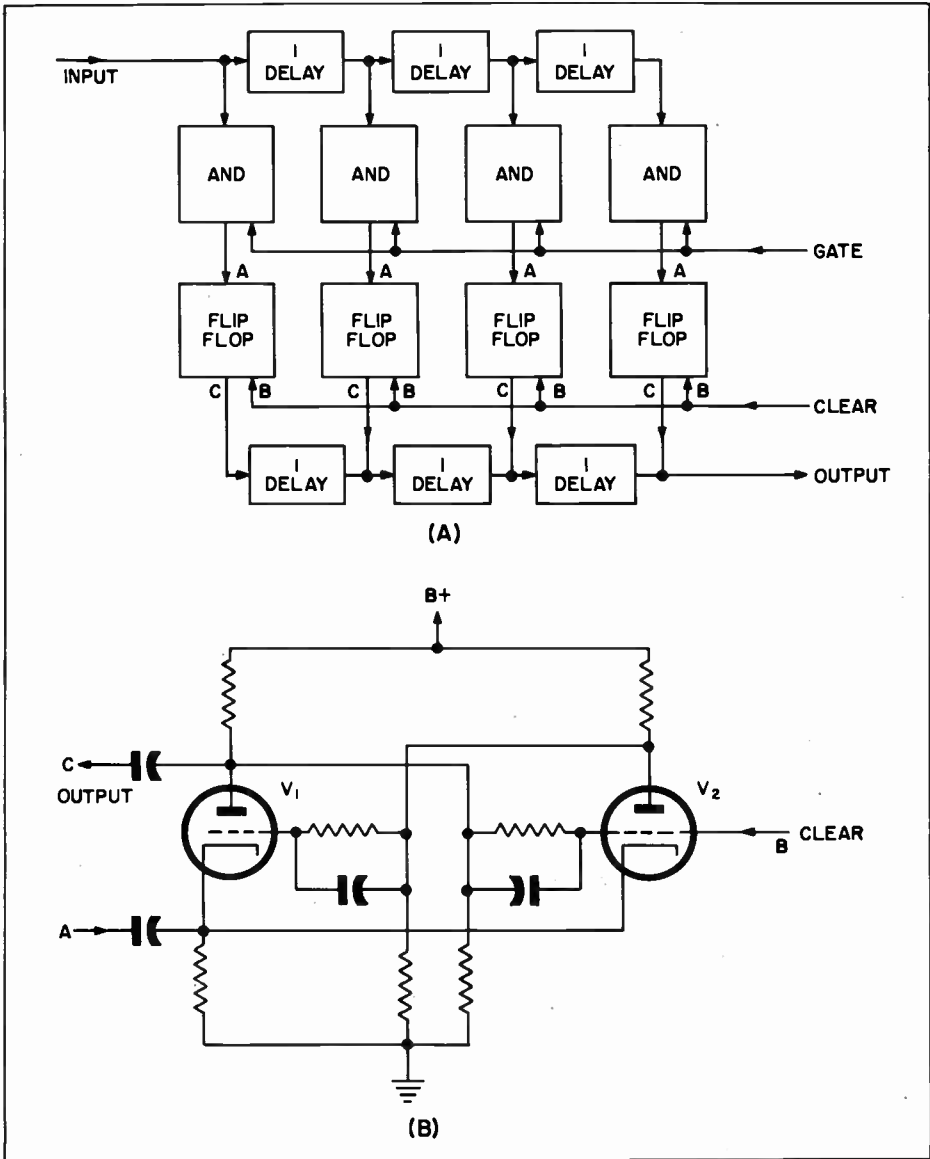
Figure 10. (A) Block Diagram of Circuit for Converting Serial Train of Pulses to Parallel (Simultaneous) Pulses for Application to Memory Bank (Flip-Flop Stages), and for Reconverting Output of Memory Bank to Serial Pulse Train for "Reading Out" (B) Schematic Diagram of Flip-Flop Circuit Used to Store Binary-Pulse Information

off. If a previous arithmetical operation has reversed this state, the circuit can be returned to the normal state by applying a positive pulse to the grid of V_2. If the circuit is in the 00 condition, the positive pulse will have no effect on the status of the circuit. However, when the circuit does reverse, a positive output pulse will appear at C.

In the static-register circuit, all flip-flops are "cleared," or returned to the 00 condition, by an appropriate pulse applied to the clear line. Then the serial

train enters on Line A. Each delay line provides a delay of one pulse interval, so that when the fourth pulse of the series arrives at the input the first pulse of the series is just arriving at the output. At this instant a gate pulse, applied to the gate line, simultaneously opens all gates and permits the information at each gate to enter the respective flip-flop. Hence, the state assumed by each flip-flop depends upon the presence or absence of a pulse at the associated gate.

Information stored in a static reg-ister will stay as long as power is applied to the circuit. When the information is required, it must be read out of the register. This is accomplished by having the plate leads of the flip-flops connected to taps of delay lines which are duplicates of those employed in the inp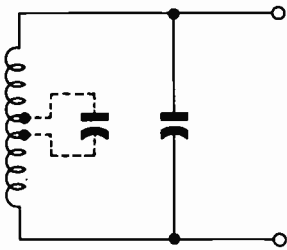ut circuit. When a clearing pulse is applied to the clear line, the outputs produced by all the flip-flops that hold information are applied to the delay lines, which provide the correct intervals between pulses to re-establish the serial train.

$\mathcal{S}olution$ to . . .
Last Month's "What's Your Answer?"

A   B

If a large capacitor is connected across a small portion of a tank-circuit inductance, the inductance value will decrease, thus raising the resonant frequency.

Figure A shows this condition. We could assume a self-supporting, air-core inductor for ease of connection. For simplicity, assume that X_C is small when compared to the X_L value for the shunted portion of the coil. In effect, we then have a shorted turn—the removal of a turn will decrease inductance, and the effect of the induced circulating current will also effectively decrease the inductance of the remainder of the coil. The overall effect is a fairly large decrease of inductance.
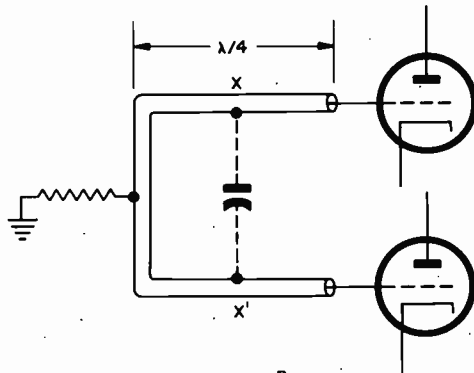
The same effect can readily be shown with the aid of a transmission-line type of oscillator tank (see figure B). The line is electrically one quarter-wavelength long. Placing a large value of capacity $(X_C \ll Z_o)$ at point X-X' will cause the effective length of the quarter-wave section to decrease, thus increasing the operating frequency.

It can be concluded that shunt capacitance does not always decrease the resonant frequency of a tank circuit.

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"LEVELS" AND "POWERS" IN A CARRIER SYSTEM

In this article the concept of "level" is discussed to show the difference between the use of this concept and the use of the defined quantity "power." Some of the reasons for common erroneous usage of the two terms are explained, and examples are given to show where and why both terms are properly used.

A brief discussion of the reasons why certain levels have been established in wire-line carrier equipment is also included.

Two of the most troublesome terms in communications language are "level" and "power." Although they are often used interchangeably in daily conversation, the two terms are not synonymous. A knowledge of the actual meaning and proper usage of each term will help show why both terms are necessary in communications work.

LEVEL

Generally speaking, the word "level" is used to indicate the relative value of a quantity. The established value is known as the "zero reference level." This general concept of level has many applications. For example, in the aircraft industry the speed of supersonic aircraft is measured with respect to the speed of sound rather than in terms of distance per unit time. The speed of sound is arbitrarily called *Mach 1,* and the speed of any aircraft can then be stated as a *Mach number* to express that speed with respect to the speed of sound.

In telephone work, the term "level" is used in a similar manner to express the relative amount of power at various points in a circuit. Just as the speed of an aircraft is expressed as a multiple

of the speed of sound, the amount of power at the output of a telephone repeater can be expressed as one-half, two, or three times the power at the zero reference level.

In practice, relative levels in a telephone circuit are expressed in db (decibels) rather than in arithmetical ratios. This is done because of the convenience of using this logarithmic expression for the relatively large ratios involved. They are sometimes as great as 100 million to one (80 db).

Unless some other reference is stated, the zero reference level for a signal in in a telephone circuit is that amount of power which the signal has when measured at the two-wire input to the toll circuit.

The concept of level is illustrated in figure 1. In this figure, the attenuation of each subscriber loop has been arbitrarily set at 6 db for illustrative purposes. Since the level at the input to the toll switchboard has been defined as the zero reference level, the level at the talking subscriber's subset is +6 db.

From the toll switchboard, the transmitted speech passes to a carrier ter-
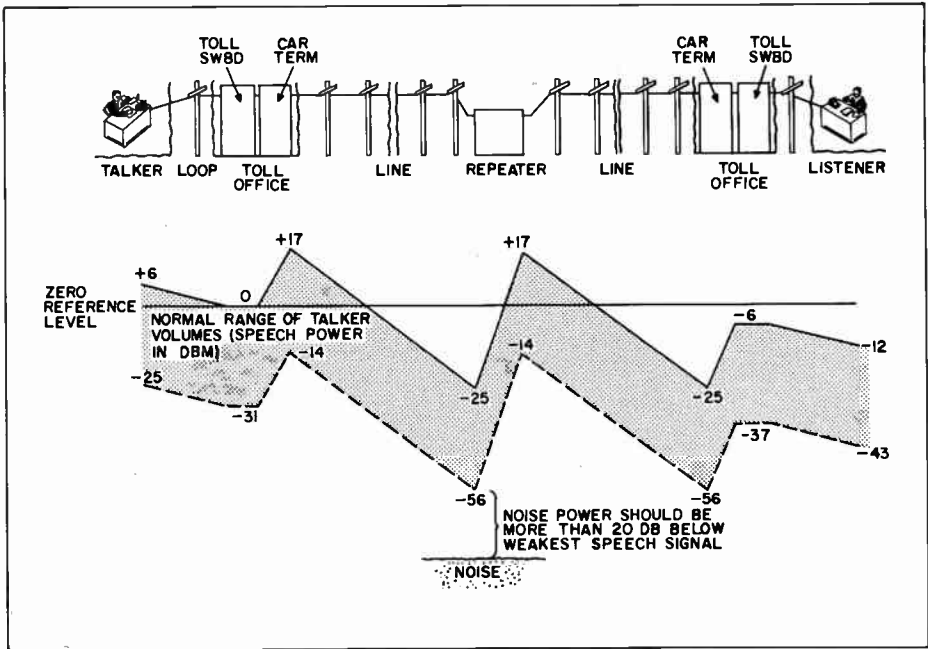
Figure 1. Level Diagram Showing Relative Strength of Transmitted Signals at Various Points in Typical Toll Circuit (Normal range of talker volume is indicated, and relation of noise to signal strength is shown.)

minal, which provides a gain of 17 db. The line attenuation between carrier terminals and the repeater is 42 db. Therefore, the level of the received signals at the repeater is −25 db. Since the gain of the repeater is 42 db, the transmitted level from the repeater is +17 db. With 42 db of line attenuation between the repeater and the receiving carrier terminal, signals will be received at the terminal at a level of −25 db. The receiving branch of the carrier terminal provides a 19-db gain, so the signals will be delivered to the toll switchboard at a level of −6 db. Then, since the loop attenuation is 6 db, the received level at the listener's subset will be −12 db. Thus, the range of speech signals from the talker will be heard by the listening subscriber at a level 18 db below the signal strength leaving the transmitter.

At all level points, the strength of the transmitted speech has been clearly stated as having a definite ratio to the strength of the speech at the zero reference level. The statement of level at each point indicates only how much gain or loss the transmitted signals have received between the various points along the transmission path.

Level, therefore, is purely a relative term. Whenever level is expressed, the zero reference level is understood to be at the point where the circuit being considered becomes a toll circuit.

POWER

While level is always a ratio, the term "power" always designates a definite quantity. This quantity is defined in electrical terms as the rate at which electric energy is taken from or fed to a device. The most common unit for expressing power is the "watt."

In addition to the watt, a number of other defined units are commonly used for expressing the amount of power in telephone equipment. Among

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Figure 2. Difference Between Level and Power, Shown by Their Use with Fixed-Gain Amplifier

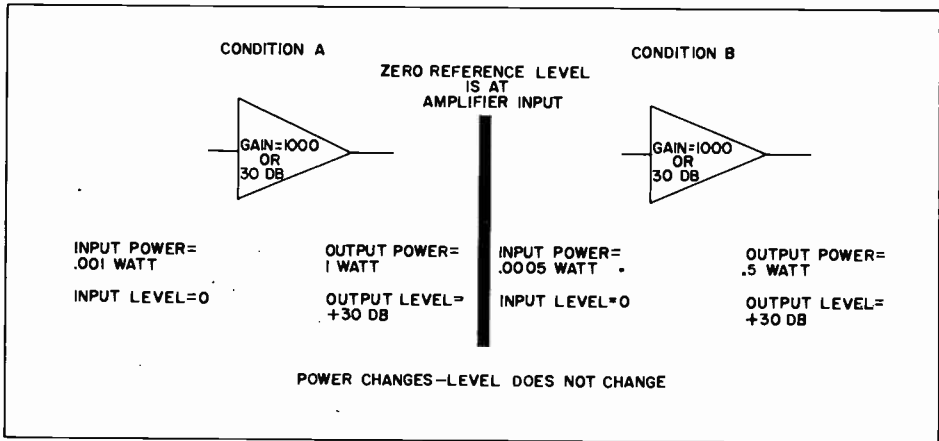these are the "dbm," the "dba," and the "vu." Each of these units is based upon use of the decibel to express the amount of power above or below a convenient amount of reference power.

Because of the use of the decibel and of a reference power in defining these units, powers expressed in them are sometimes erroneously called levels. They are not—because in every case a value stated in dbm, dba, or vu can be readily converted to a value in watts.

The difference between power and level can be shown more clearly by considering the use of the dbm unit. This unit is perhaps the most common of the three mentioned. Stating that the power at a certain point is $\pm X$ dbm simply means that the power is X db greater or less than one milliwatt.

A 1000-c.p.s. test tone with a power of one milliwatt is ordinarily available at toll switchboards. When this test tone is transmitted over a telephone circuit, the test-tone power in dbm at any point in the circuit is numerically equal to the level in db at that point. It is this similarity which can cause confusion between proper usage of level and power.

The distinction between level and

power can also be illustrated by considering the two terms with respect to a fixed-gain amplifier, as shown in figure 2. Two conditions are shown. In the first, the input to the amplifier is 0.001 watt. In the second, the input to the amplifier is 0.0005 watt. For both conditions, the amplifier has a fixed gain of 30 db.

In this example, the input in both cases is arbitrarily considered to be zero level. Therefore, the output level in both cases is $+30$ db, and it cannot change unless the gain of the amplifier changes.

The power input and the power output change in both cases, however. In the first, the input signal of .001 watt is amplified 1000 times to produce an output of 1 watt. In the second, the input signal of .0005 watt is amplified by the same amount, since the gain of the amplifier is fixed at 30 db (or 1000). The output power is therefore 0.5 watt.

It is obvious that the power output of a fixed-gain amplifier will change when the input power changes. *But the level remains the same* so long as the gain or loss (in decibels) between the zero reference level and the output of the amplifier remains the same.

Both level and power are useful terms. Each is best suited for specific purposes in telephone-circuit engineering and operation, and they serve to supplement each other.

USE OF LEVEL

* Transmitted speech consists of a large range of frequencies and powers which vary widely for different speakers. For this reason, it is impossible to determine exactly what power will exist at any point in a circuit when the circuit is in use. However, regardless of the specific power at any point, the level, or in other words, the loss or gain between the point in question and other points in the circuit, can be determined either by calculation or by measurements with a transmitted test tone.

When laying out telephone circuits, it is necessary to know the net loss that the circuit will give to speech currents passing through it. It is neither necessary nor practical in this type of planning to know exactly what the actual power will be at any point, particularly since the power will vary over wide limits, depending upon the talker and the words spoken. The normal range of speech volumes transmitted over a telephone circuit is shown in figure 1.

Since the gain or loss of a circuit is independent of power (within the power-handling capacity of the equipment), it is convenient to have the concept of level to express the relative strength of a signal at any point, and to determine the net loss of the circuit between any two points.

USE OF POWER

Although level has definite value in circuit planning, it is necessary to consider actual power involved when designing and operating the electronic equipment used at voice- and carrier-frequency terminals and repeaters.

Operation of electronic equipment depends upon the minimum and maximum powers that can be supplied to the input of the equipment and delivered from the output. Equipment sensitivity and coincident power strength of noise and other disturbances usually determine the lowest practical input power. Maximum output power (and consequently the maximum input) depends upon the power-handling capacity of the equipment.

Specifications for carrier equipment normally give the test-tone power at the inputs and outputs of each channel. In some cases, it is desirable or necessary to know the total peak power that may be delivered to common equipment or to the line by several channels.

Per-channel power is normally stated in dbm. Because dbm is a logarithmic value, two powers expressed in dbm cannot be added to obtain the total power. Instead, each channel power must be converted to watts, added, and the total then reconverted to dbm.

If the per-channel power of all channels is the same, doubling the number of channels increases the total power by 3 db. Thus, if a system has eight channels, each with a signal-output power of $+10$ dbm, the total power delivered to the line is $+19$ dbm.

In speech-communication circuits, it is unlikely that all channels of a carrier system will be transmitting signals of the maximum value simultaneously. Therefore, the common equipment is usually designed to handle the total expected power rather than the total possible power.

LEVELS AND POWERS IN A CARRIER SYSTEM

Although levels are more important than actual power to the engineer laying out a telephone circuit, the transmission engineer interested in the installation or operation of a carrier system must

WEST–EAST

HIGH FREQUENCY DIRECTION–MAXIMUM LINE LOSS
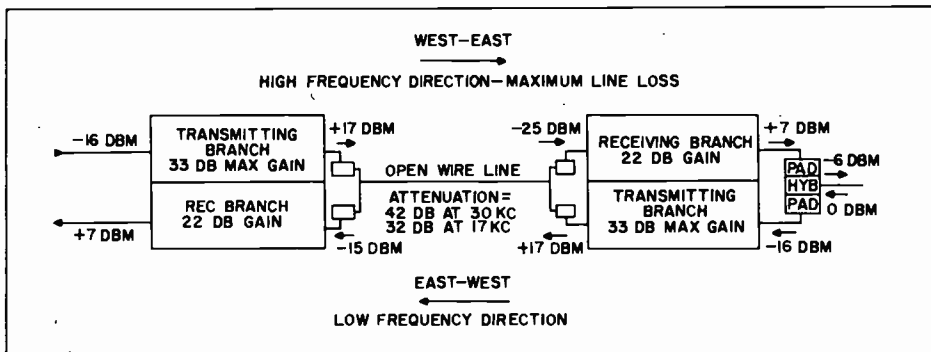
EAST–WEST

LOW FREQUENCY DIRECTION

Figure 3. Simplified Block Diagram of Two-Wire Carrier System, Illustrating Typical Test-Tone Power Values at the Connections to the Carrier Equipment

usually know the actual power at the various points. Otherwise, there is a possibility of operating a circuit with either less input power or more output power than the equipment is designed to handle.

When test-tone power at the point of zero reference level is one milliwatt, the power at any point in a circuit as measured in dbm is numerically equal to the level as expressed in db. When the test-tone power is any other amount or when power is measured in any unit other than dbm, the numerical value of level is not the same as that of the power at that point.

Any consideration of power in a carrier system can be divided into two sections—the amount of power at the connections to the carrier equipment, and the amount of power at various points inside the carrier equipment. Power values inside the carrier equipment are of interest primarily to the design engineer.

The amounts of power at the line and drop terminations of the transmitting and receiving branches are of more importance to the operator of carrier equipment. These power values determine where carrier systems may be operated, how repeaters must be spaced, and how coordination may be achieved.

A typical two-wire carrier circuit with a four-wire termination at one drop and a two-wire hybrid termination at the other is shown in figure 3. Typical test-tone power values at the connections to the equipment are indicated.

POWER AT THE V-F INPUT AND OUTPUT

The v-f power at the input to the transmitting branch of a carrier system is primarily based on the normal amounts of power delivered to the line from the toll switchboard. Because many telephone offices are arranged for patching circuits on a four-wire basis at a −16-db level, and the usual test-tone power at the transmitting toll switchboard is 0 dbm, the input stages of carrier systems are often adjusted to receive a test-tone power of −16 dbm on a four-wire basis. This really means that the input to the carrier system is at a −16-db level, or a circuit point 16 db removed from the two-wire v-f level at the transmitting toll testboard.

The amount of v-f power obtained from the receiving branch of a carrier system is also determined primarily by switching requirements. If all of the other values indicated in figure 3 are within proper limits, the v-f output for each channel with a 0-dbm test tone

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at zero level would normally be about +7 dbm on a four-wire basis.

POWER DELIVERED TO AND RECEIVED FROM THE LINE

A number of factors influence the amount of power which can be transmitted to or must be received from the line. Since the difference between these two values is the maximum span attenuation, these factors also influence repeater spacing for a carrier system. Among these factors are the noise level of the line, the line attenuation, the frequencies at which the system operates, the characteristics of the directional filters, and such things as line configuration which influence the amount of crosstalk encountered.

Basically, the amount of power transmitted must be high enough so that sufficient power will reach the receiving terminal to permit recovery of the transmitted intelligence unimpaired by excessive noise. The power received must be sufficient so that the proper v-f output power can be delivered with the receiving branch gain available, and so that the received power will be sufficiently higher than the line noise to maintain the proper signal-to-noise ratio.

TRANSMITTED AND RECEIVED POWER

The amounts of power now commonly transmitted have been established as a result of attenuation studies conducted during many years of experience with telephone lines used for carrier circuits. These studies have provided engineers with information concerning line characteristics and their effect on carrier systems under a variety of conditions. By using this information, standardized transmitted power values and levels have been adopted for various carrier applications.

Among the factors which determine the minimum amount of power that should be received from the line at a carrier terminal are the receiving-branch gain and the noise level of the line.

The ultimate objective of a carrier circuit is to deliver a certain amount of power to the drop. Therefore, the minimum received power must be such that, after being amplified an adequate amount, the signal will have the proper amount of power at the drop.

Higher receiving-branch gain will not necessarily permit lower minimum amounts of power to be received, since the received signal must be sufficiently greater than the noise level of the line to maintain the desired signal-to-noise ratio. Since noise is amplified by the same amount as the desired intelligence, the signal-to-noise ratio at the output of the receiving branch cannot be any better than it is at the input. This is illustrated in figure 1 where the noise power at the repeater is indicated.

LOOP GAIN AND LEVEL COORDINATION

Loop gain is defined as the sum of the gains that are given to a signal of a particular frequency in passing around a closed loop. The loop can be a carrier terminal, a repeater, or a complete carrier circuit.

Excessively high gains in the transmitting or receiving branches of a carrier system terminal or repeater can cause "singing." This occurs if the gain around the system, terminal, or repeater loop for any frequency is greater than the losses around the same loop for that frequency.

Loop gain is affected by a number of complex factors. Among them are the suppression by directional filters, the losses due to hybrid balance, and the effects of the other frequency-selective elements in a carrier system.

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All of these factors are considered by design engineers when they determine operating levels and the amounts of power that will be transmitted and received by a carrier system when it is operating under various conditions.

A further limiting factor which must be considered in determining the amounts of power that will be transmitted or received by a carrier system is coordination of the levels and powers between two or more systems operating at the same frequencies on the same lead. If all systems transmit the same amount of power, they are not subjected to power differentials along the line; consequently, any crosstalk between adjacent line conductors is then not further increased by a difference in power.

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In Coming Issues

We told you several months ago that we were preparing an article for publication on "Simultaneous Transmission Systems," by Francis R. Sherman, technical editor on the BULLETIN staff. The article was nearly complete at that time, but so much interest was voiced in it when we first announced it, that we gave the manuscript back to the author for a major expansion to cover all phases of the subject, including detailed tuning techniques and discussions of alternate matching systems which could be employed in such installations. The result (scheduled for the May issue) is a very comprehensive coverage of the entire subject, in an article which should meet with wide reader interest and field application.

The May issue will also contain another article of great interest to field-engineer readers, titled "Magnetron Theory and Maintenance," by Philco Field Engineer John Marchesano. Whether you are teaching Basic Radar, or simply have a general interest in the subject of magnetrons, you will find this article most enjoyable.

EMERGENCY REPAIR OF SILICON CRYSTAL 1N21

A simple effective method for the emergency repair of 1N21 silicon crystal rectifiers.

(Editor's Note: This article originally appeared in the "Electronics Installation Bulletin," NavShips 900,022A, No. 347, and appears here through the courtesy of the Bureau of Ships, Dept. of the Navy.)

RADIO ELECTRICIAN WILLIAM E. CONNORS, of the USS MELLETTE (APA-156), has suggested a method for the emergency repair of silicon crystal 1N21 used in the SG-1 wavemeter. This suggestion, described below, is an effective method for the emergency repair and reconditioning of silicon crystal 1N21.

The following is Mr. Connors' report on the emergency repair of 1N21 and 1N21B silicon crystals on the USS MELLETTE:

"This vessel recently had on hand a number of 1N21A and 1N21B silicon crystals, used in the SG-1 radar equipment, which had been damaged as a result of failure of duplexer tube Type 721A. Failure of the crystal was indicated by the loss of echoes and current on the oscillation indicator meter. Also, the crystals had backward-to-forward current ratios of the order of 1:1 to 2:1.

"The base of the crystal was securely held in a vise. A screwdriver was ground on a stone so that its blade was a good fit for the slot of the screw in the base of the crystal. The cement securing the screw adjustment in the base of the crystal was broken by careful application of the screwdriver. An ohmmeter was connected with its positive lead to the tip of the crystal and the negative lead to the base. (When the meter is connected in this manner, the backward resistance will be measured.) The screw on the base of the crystal was turned slightly (about $\frac{1}{8}$ turn) while watching the ohmmeter for a change in resistance indication, usually an increase. This indicates that the catwhisker is resting on a different spot of the silicon crystal surface. It was not necessary to turn the screw more than one complete revolution, nor did it matter if the screw was turned in or out.

"Four crystals were repaired in this manner, and the backward-to-forward resistance raised to the order of 10:1 to 20:1. Operation of the repaired crystals compared very favorably with two new crystals, no difference in performance being noted. OBU-2 echobox ringtime was used in performance evaluation. The repaired crystals seemed as stable as new ones.

"In checking duplexer tubes which were in stock, to determine condition of same, one crystal was burned out three times, and repaired successfully. This crystal is now in service in the wavemeter of the SG-1.

"It is realized that the repaired crystals may not be generally as reliable as tests show, but it is felt that in an emergency the repaired crystal is better than no crystal."

INTRODUCTION TO TRANSISTOR ELECTRONICS

Installment V

The Electron as a Particle

by John Buchanan
Technical Publications Dept.

A return to the story of the quantum and the electron, with the discussion primarily concerned with the development of the evidence that established the particle nature of the electron.

SYNOPSIS

This is the fifth in a series of articles covering the fundamentals of transistor electronics. The first article of the series, which appeared in the January, 1952, issue of the BULLETIN, covered the atomic view of solids. This view maintains the particle nature of the electron, but introduces the quantum to restrict the electron's motion within the atom to definite shells, or energy levels. Each shell, in turn, permits a finite number of planetary orbits, or electron states, at the shell's respective energy levels. Outside an atom, an electron is assumed to be completely free to move about with random thermal motions. Electronic conduction is visualized as a drift of free electrons, or as a drift of empty electron energy states (electron holes), or as a combination of the two.

The second article, published in the April issue, laid the groundwork for the more involved free-electron view of solids. The first elements of the kinetic theory of gases were presented as a point for beginning the transition from the classical laws of ideal gases to the wave-mechanical laws of electron gases.

The third article, published in the September issue, continued the discussion of classical theories as applied to systems of ideal particles. Here the "degree of freedom" was introduced

as a mathematical concept useful in interpreting particle behavior and in analyzing the distribution of energy within a system. The discussion led to a theory of metallic heat capacity based upon the atomic view that the free electrons behaved approximately as ideal gas molecules. Actual measurements, however, revealed that the "free" electrons have a negligible capacity for absorbing thermal energy at room temperatures—a complete contradiction of the atomic view of classical electrons in thermal equilibrium with the atoms.

The fourth article, published in the February, 1953, issue, completed the discussion of systems of classical particles with an introduction to the methods by which the theory of probability is applied to problems of statistical mechanics. Maxwell's original derivation of the law for distribution of velocities in an ideal gas was presented, as well as a general description of the mathematical concept of an ensemble gas in phase space, by which the quantum, as well as the classical, distribution laws may be derived. The controversy between the deterministic and statistical approach in natural philosophy was briefly discussed, and the article closed with an introduction to the concept of dynamic degeneracy.

* * *

Today we return to the story of the quantum and the electron; but the adventures to be reported are largely those that occurred before the two pranksters were found to be so intimately related. We start with the quantum at the time it was slipping down the slopes of heat-capacity curves to steal its way into solids, where it left the atoms and molecules in a permanent state of jitters. The estimations that follow concerning the contributions of the atoms to the heat capacity of a metal serve as a guide to an approximate evaluation of the number of thermally free electrons that are present. Although the information is purely hypothetical, it does provide a basis for examining the thermal activities of free electrons more closely. This we do on the assumption that the electron is a particle according to the atomic view of solids. Again, however, we are led to contradiction—this time through an analysis of the thermal conductivity of a metal. Where the measurements of metallic heat capacity revealed the electron to have far too little freedom, the measurements of thermal conductivity reveal it to have far too much freedom. Serious doubts arise as to whether the electron should be credited with so much activity; but soon afterwards it receives such a thorough and well-deserved shaking, that no doubt remains as to the great agility of its capers. Disrobed of all its loose-fitting, solid-state costumes, the little imp is dragged into view where its bare particle nature can be exposed to the critic's cold eye. Although the physical exam reveals a bona fide negative particle, a peculiar deformity is observed whenever the electron moves. An investigation finally leads to the strange Lorentz electron of variable shape, volume, and mass. At this point there is a determined knocking on the door. That powerful reformer of classical physics, the theory of relativity, has sent a detachment of guards demanding that the electron be returned to the classical fold. Puffs of dust are to be seen in the far distance—the quantum, too, has detached a force with orders to bring in the electron. Here, the present episode ends.

TURNING ON THE ATOMIC HEAT

It will be recalled that the quantum first appeared in the guise of a simple operator mathematically regulating the heat radiation and absorption of an ideal black body. The second milestone in its career was its daring attack upon the radiated waves, themselves, which resulted in the creation of the photon, discovered by Einstein in 1905. In our discussion of the atomic view of solids, we next found the quantum as a grand entrepreneur directing the electron in an electrifying performance of jumps and spins in Bohr's hydrogen circus. However, the truth of the matter is that by 1907, only two years after the photon adventure, and well before the hydrogen electron enterprise, the quantum had succeeded in burrowing its way into the solids. Again it was discovered by Einstein, but not until after it had committed the incredible deed of hacking to bits the degrees of freedom of every atom and molecule in sight. For the story behind this amazing vandalism, we must return to the scene of the disaster where the classical theories collided with the stubborn facts of heat-capacity measurements.

The disagreement which we previously witnessed between the observed and the theoretical values of heat capacity for copper was but a single example of a whole sequence of puzzling encounters with the thermal properties of solids. The case of the missing free electrons in copper is duplicated, to a greater or lesser degree, in the behavior of all the other metals. However, the free electrons are by no means the only contrary performers according to

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classical standards. The atoms and molecules of all the solids—insulators, semiconductors, and metals as well— also exhibit strange capacities for thermal excitation, which would not occur if ideal laws prevailed. It was during a study of odd variations in atomic behavior that Einstein was led to believe that the quantum might be found at the root of the mischief.

It had long been known that one common characteristic of all the solids was that the heat capacity decreased as the temperature decreased. In other words, at the lower temperatures it requires less heat to raise the temperature of a solid one degree, than at the higher temperatures. Indeed, well before absolute zero is reached the heat capacities of some solids seem to vanish entirely, so that the addition of a minute amount of internal energy might jump the temperature several degrees. Theoretically, for one mole of atoms vibrating in simple harmonic motion, the heat capacity should be 6 gram-calories per absolute degree at all temperatures. Now a large number of solids tend to approach this molar heat capacity at normal temperatures, particularly the metals and the less complex crystals, but some solids have much lower capacities, whereas others have capacities that are

Figure 1. Molar Heat Capacities of Diamond, Aluminum, and Silver

higher. The higher capacities can usually be explained by transitions within the solid or by the actions of the electrons. However, our immediate concern is to find an explanation of why a molar heat capacity, due entirely to the vibration of the atoms, should be *lower* than 6 calories, and why it should depend upon the temperature.

Figure 1 shows the molar heat capacities of silver, aluminum, and diamond, plotted against temperature. These are the types of curves that Einstein sought to explain, and that ultimately disclosed another major conquest for the quantum.

HERE COMES THAT QUANTUM AGAIN

It has been easy for the classical physicist to suppose that as the temperature decreased, more and more degrees of freedom become "frozen"; however, the chief problem has been to explain why some atoms can remain sound asleep, while at the same time their neighbors are shaking the crystal lattice in thermal revelry. The first real clue was to be found in Planck's original quantum postulate — that electromagnetic radiations are emitted and absorbed only in quanta of energy equal to hf, where h is Planck's constant, and f is the frequency. Next, it was reasonable to assume that the frequencies of the heat radiations from a solid were determined by the frequencies of the atomic vibrations — just as the frequency of an antenna's radiation is determined by the frequency at which the antenna is driven. Thus, if the radiation is found to be restricted by the quantum, it must be because the radiator, itself, is restricted. This was Planck's explanation, and it was with this idea in mind that Einstein approached the heat-capacity problem.

For the sake of simplicity, Einstein assumed that each atom in a crystal was
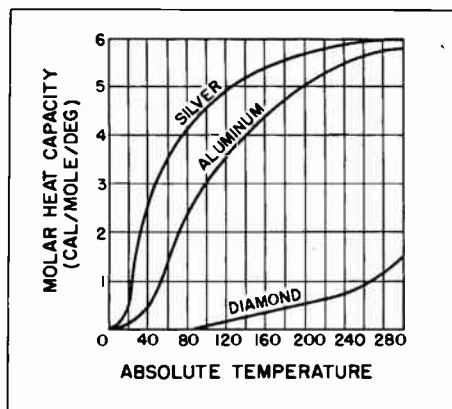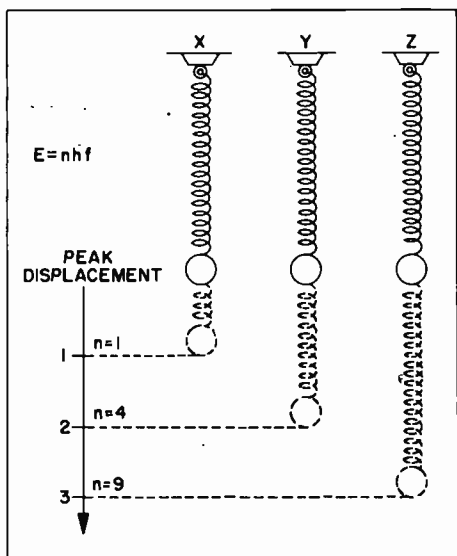
Figure 2. Three Independent Quantized Einstein Oscillators, Corresponding to the Three Vibrational Degrees of Freedom of an Atom (The frequency, f, is the same for each oscillator, while the energy, nhf, is proportional to the square of the peak displacement.)

an independent vibrator with three degrees of freedom of motion, and that the normal frequency, f, was the same for each atom. In other words, a crystal of N atoms is to be visualized as 3N (or more exactly, $3N - 6$) oscillators, none of which is coupled to each other, but all having the same fixed frequency regardless of their individual energies, and each oscillator with but one degree of freedom of motion. The key assumption, however, was suggested by Planck's theory of radiation. Einstein assumed that the energy of each of these oscillators must obey the equation

$$E = nhf$$

where n, the quantum number, is any integer $0, 1, 2, 3, \ldots$

This conception of a vibrating atom is illustrated in figure 2, where three oscillators are shown which correspond to an atom's X, Y, and Z vibrational degrees of freedom. Assuming simple

harmonic motion for each oscillator— i.e., the displacement of each oscillation can be plotted as a sine wave against time—the energy of each will be proportional to the square of the peak displacement. Thus, the energies of the X, Y, and Z oscillators in figure 2 are respectively in the ratio 1:4:9, corresponding to vibrational energies of:

$$E_X = hf$$
$$E_Y = 4hf$$
$$E_Z = 9hf$$
$$E_T = 14hf = \text{total vi-}$$

brational energy of the atom.

This theory of atomic vibrations marked the third major triumph of the quantum, for the concept not only offered an explanation of the low heat capacities at low temperatures, but also agreed with the explanation of why electromagnetic radiations are emitted and absorbed in quanta of energy equal to hf.

The low heat capacities result whenever the smallest energy quantum (hf) sufficient to excite an atom is large in comparison with kT, where k is the Boltzmann constant, and T is the absolute temperature. Remember that 1/2 kT is the average energy per degree of freedom of translational energy, so that twice this amount, kT, is the average energy per vibrational degree of freedom.* At temperatures near absolute zero, very little thermal energy can be absorbed from the surroundings, for only a rare bombarding particle can

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* These average values assume ideal particles which we are no longer postulating. However, they provide a standard of reference for explaining the deviations from ideal behavior. By assuming a Maxwell-Boltzmann distribution among only those phase-space cells permitted by the above quantum restrictions, the average energy per vibrational degree of freedom is not equal to kT, but to:

$$E_X = E_Y = E_Z = \frac{hf}{e^{hf/kT} - 1}$$

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possibly acquire a kinetic energy sufficient to excite a vibration. Since the frequency of a harmonic oscillator is directly proportional to the magnitude of the restoring force for a given displacement, and is inversely proportional to the mass of the moving element, we would predict that the solids having the stronger valence bonds and composed of the lighter atoms would have the higher vibrational frequencies, and hence the lower heat capacities at a given low temperature. Thus, the lightweight carbon atoms held by the intensely strong valence bonds in the diamond crystal would certainly be expected to exhibit much smaller heat capacities than do aluminum and silver. Another glance at figure 1 will indicate that this prediction is well confirmed by experiment.

COMPARISON OF
PLANCK-EINSTEIN AND BOHR
QUANTUM RESTRICTIONS

Once it is assumed that a vibrating atom can have only those energies which are integral multiples of hf, we are tempted to imagine each change of energy as a jump from one energy level to another. In a jump from the 2nd to the 1st level, a photon of energy hf is emitted, where f is the same as the frequency of the atomic vibration. A jump from the 2nd to the 0th level, presumably will emit a photon of energy hf_2, where f_2 is the second harmonic of the atomic frequency.

This concept of photon radiation and absorption by vibrating atoms is similar to that in which the Bohr electrons have been pictured as radiators and absorbers of photons. However, there is a somewhat puzzling distinction between the types of quantum units that are involved. In the case of the Planck-Einstein atom, the quantum number, n, specifies an integral number of units of energy, but in the case of the Bohr electron, the quantum number specifies an integral number of units of *action*.

The mathematical function referred to as *action* is less familiar to the average reader than the functions called *force, momentum,* and *energy;* however, in quantum mechanics the former function is of primary importance, for Planck's constant, itself, has the dimensions of action. These dimensions are those of momentum x distance, or of the equivalent relation, energy x time. Thus, action can be expressed in units of gram-centimeters^2 per second, or more commonly in *erg-seconds* or *electron volt-seconds*.

It will be recalled that the electron in a Bohr atom can enter only those orbits in which its action per cycle is some integral multiple of Planck's constant, h. The total number of h's per orbit is given by the principal quantum number, n, and these units of action, in turn, are divided according to the three degrees of freedom of motion, in a manner similar to the three quantized oscillators of the vibrating atom in figure 2. However, for an orbital electron, the degrees of freedom are more conveniently expressed in the spherical coordinates, r, ϕ, and Θ. Thus, the action per cycle back and forth along r, and in the directions of ϕ and Θ, must, for each degree of freedom, be an integral multiple of h. The particular energy level is determined by the total number of h's per orbit; and the subshells are determined by the particular ways in which these h's are divided among the different degrees of freedom. However, the *energy* of a planetary electron is not necessarily an integral multiple of some basic unit, and this fact distinguishes the Bohr energy levels from the Planck-Einstein energy levels. The cyclic motions of the former are composed of n units of action, h, and those of the

latter are composed of n units of energy, hf.*

IMPROVEMENT IN THE QUANTUM THEORY OF ATOMIC JITTERBUGS

Einstein's postulates were intended only to offer a first approximation for predicting the heat capacities of simple solids. The hypothesis, for instance, that the atoms vibrated independently of each other was known to be false from the beginning. By 1912, other theorists were developing more accurate analyses by assuming more complex modes of vibration, although maintaining the quantum restriction that the energy for each mode must conform to nhf.

Debye was the first to introduce a spectrum of frequencies. He accomplished this by ignoring the atoms and assuming that a solid was a completely homogeneous elastic medium. A system such as this would have a fundamental frequency and an infinite number of higher harmonics; but Debye arbitrarily assumed that the highest harmonic for a solid containing N atoms would be the 3Nth harmonic. This upper mode would thus represent a maximum frequency, f_m, which would be determined by the density of atoms and the mean speed at which the transverse and longitudinal (sound) waves are propagated through the solid.

Later, other physicists, notably Born, von Kármán, and Blackman approached the problem from more vigorous assumptions and improved the accuracy of the quantum theory in interpreting the heat capacities of some of the slightly more complex solids. However, insofar as the simpler solids are concerned, the Debye equations have proved surprisingly accurate.

Finally, when the equations of quantum wave mechanics were applied to simple harmonic oscillators of frequency f, it was found that the energy should obey the equation: $E = (n + 1/2)$ hf. Note that this quantity of energy is greater than that originally postulated by an amount equal to $1/2$ hf. An interesting consequence of the above equation is that when $n = 0$, even at a temperature of absolute zero, all the vibrational modes in a crystal are still ticking away with energies of $1/2$ hf!

A biographer of the quantum's career would point to the episode of the atomic heat capacities as the first decisive victory by the quantum over classical particles. Both the Maxwell-Boltzmann Law and the principle of equipartition of energy were rendered invalid at low temperatures insofar as they applied to the atoms in a solid. Only at relatively high temperatures, where the average energy per degree of freedom is suffi-

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* Had not the development of quantum mechanics from the time of Bohr to the present day been so successful in interpreting Planck's constant as a unit of action, there would probably have been a legitimate temptation to actually treat h as a constant of energy. Such an interpretation is suggested when the dimensions of frequency are closely inspected. These are expressed as *cycles per unit time;* however, the *cycles* are usually treated as dimensionless, and frequency thus has the dimension of $(time)^{-1}$. On the other hand, when frequency is expressed in particular units of time, such as *cycles/second,* one might consider the *second* as a unit cycle, or as a certain fraction of

the standard cycle (the earth's revolution about its axis), so that both the numerator and denominator of cycles/second become dimensionally equivalent—insofar as they are both periodic functions of time. Hence

$$f = \frac{\text{time/second}}{\text{time/cycle}}$$
$$= \frac{\text{cycles}}{\text{second}}$$
$$= \frac{\text{cycles}}{\text{unit cycle}} = \text{pure number}$$

Thus, with f in the formula $E = hf$ interpreted as a relative frequency—i.e., a pure number—then h, indeed, would assume the dimensions of a quantum of energy.
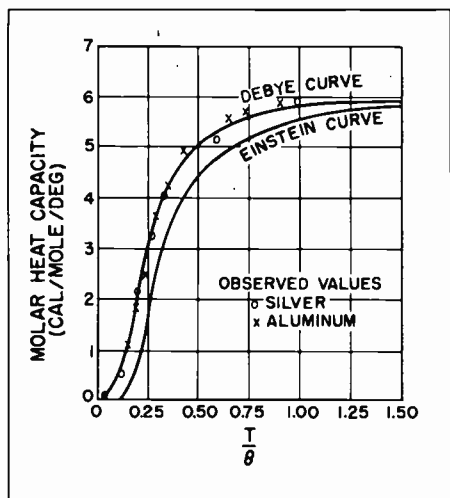
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Figure 3.   Debye and Einstein Molar-Heat-Capacity   Curves   Compared with Observed Values for Silver and Aluminum

cient for the quantum number n to be large for each vibration, will the ideal laws prevail.

IN SEARCH OF FREE ELECTRONS ABOVE A DEBYE CURVE

It is now time to turn our attention once again to that incorrigible problem child of modern physics—the free electron. The immediate problem is to follow a Debye curve into the metals and search the region between it and the observed heat capacities for as many *thermally* free electrons as we can find. Aside from the electronarian virtues of rescuing electrons from the clutches of the quantum, we shall need as many of these thermal carriers as possible if a particle concept explaining the various thermoelectric properties of conductors and semiconductors is to have any validity.

Figure 3 compares observed molar heat capacities with a Debye curve and with an Einstein curve. The plotted crosses and circles indicate actual values observed for aluminum and silver, respectively.

Θ is called the "Debye characteristic

temperature," and is defined by the equation: $k\Theta = hf_m$, where k is Boltzmann's constant, h is Planck's constant, and f_m is the maximum permissible frequency.

Θ is thus the absolute temperature at which the average energy of a vibrational degree of freedom is equal to the largest unit quantum of vibrational energy for the particular solid.

Θ is determined empirically, and has a different value for each solid. Representative values of Θ are 88° for lead, 96° for mercury, 170° for gold, 215° for silver, 290° for germanium, 315° for copper, 400° for aluminum, and 1000° for beryllium.*

In figure 3, note the close agreement of the Debye curve with the observed heat capacities of both aluminum and silver. The success of the Debye equations in accounting for the heat capacities of metals, however, destroyed whatever hope still lingered that the free electrons in metals could be treated as an approximately ideal gas. Prior to the Debye equations, the remote possibility had existed that perhaps the free electrons actually did account for a large share of a metal's heat capacity, and that the chief degeneracy was to be found in the atomic vibrations. However, the fact that the Debye curve so accurately accounted for practically the entire heat capacity by atomic vibrations left little doubt that only a small fraction of the valence electrons could be absorbers of thermal energy.

If the Debye junction were one-hundred percent dependable, an evaluation of electronic heat capacity would be quite easy; for the latter would simply be the difference obtained by subtracting the theoretical atomic heat

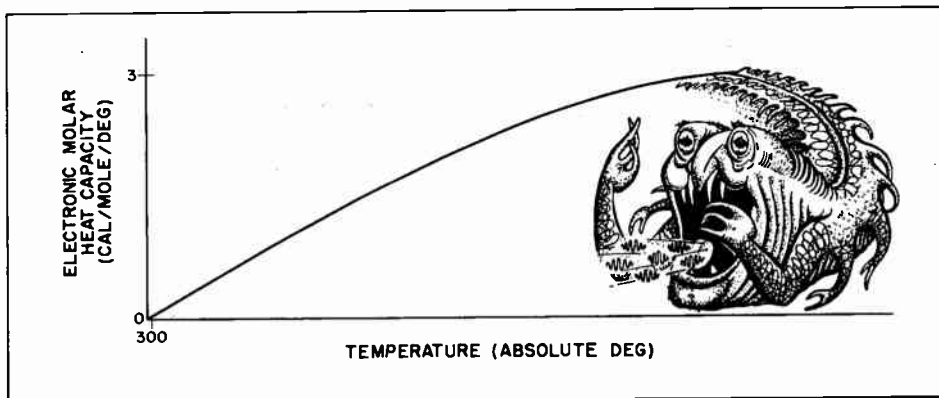* All these are expressed in absolute degrees, of course.

Figure 4. Hypothetical Heat-Capacity Curve for Metallic Electrons

capacity from a measured value of the total capacity. Unfortunately, the contribution of the electrons is too small a percentage of the total for an accurate evaluation with measurements at room temperature, but at extremely low temperatures this method is quite useful.

As the temperature approaches absolute zero, the heat capacity of a metal also approaches zero, which, according to the Debye function, should vary directly with T^3 when T/Θ is less than $1/10$. However, the observed values are somewhat larger than those predicted on the basis of Debye's equation alone. When the Debye heat capacities are subtracted from the observed values, the remainders are found to vary directly with the absolute temperature. Apparently this excess heat capacity is due to the electrons, and it provides a strong clue for approximating the electronic heat capacity at room temperature.

First, imagine how the shape of a curve might appear if it represented the molar heat capacity of the electrons in a metal plotted against the temperature. Perhaps it would resemble the curve shown in figure 4. At least we know that at zero degrees the curve would begin at zero and eventually should approach 3 calories per mole-degree. Observed values for copper tell us that at very low temperatures the

curve will be a straight line approximately obeying the equation $C_v = 1.7 \times 10^{-4}T$ gram-calories/mole/deg., where C_v is the molar heat capacity of the electron gas at constant volume.

Furthermore, we know that C_v at room temperature is still negligible compared with its maximum theoretical value, so the slope of the curve cannot appreciably increase between absolute zero and normal values. In other words, the curve from $0°$ to $300°$ is simply the tip of the tail of some plotted statistical equation—an equation that reduces to approximately a linear function of T when the values of T approach zero. By applying Fermi-Dirac statistics such an equation can be derived, but for the present, the exact shape of the creature attached to the tail is not important—only the evidence that the curve from $0°$ to $300°$ involves such a small percentage of the electrons that it can be treated as a small straight-line segment. Thus, at $300°$ the heat capacity of the electrons in copper is approximately: $C_v = 1.7 \times 10^{-4} \times 300 = 0.051$ gram-calories/mole/deg.

An electronic molar heat capacity of approximately 0.05 cal./deg. requires but one "heat-absorbing" electron for every 60 atoms. Since the number of metallic atoms per cubic centimeter is

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on the order of 10^{22}, we may assume that the number of "heat-carrying" electrons per cubic centimeter of metal at room temperature is $N = 10^{20}$.

Now, 10^{20}, a billion billion one hundred times, is certainly no small number, but we should remember that from 98 to 99 percent of the valence electrons are still unaccounted for. The early proponents of the electron-gas theory more or less ignored the heat capacities of metals and assumed that there were 10^{22} thermally free electrons per cubic centimeter, and on the basis of this were able to derive plausible equations from classical theories to explain electrical conduction in metals. However, the paradox could not long remain unchallenged. Energy is energy, and if a collection of particles can easily absorb electrical energy and dissipate it as heat, there is no reason to assume that the same particles should not with equal ease be able to absorb thermal energy directly. The scientific world pondered the dilemma, but few ripples of excitement were stirred until Sommerfeld grasped the tail of the curve in figure 4, and suddenly, in the seething wake of some fearful quantum-breathing thing, was plunged beneath the glassy surface of a dead Fermi sea. This adventure is one the many interesting exercises that await those who pursue the quantum, but the immediate task is to gather, as best we can, the 10^{20} room-temperature free electrons under the protection of ideal laws.

THE THERMAL CONDUCTIVITY OF METALS

Except for the heat-capacity experiments, almost all other thermoelectric data supported the atomic view of solids. There was the unmistakable evidence of the electronic absorption of heat during thermionic emission. There was the fact that all chemical elements become increasingly ionized as the temperature is increased, which can

only mean that the electrons must absorb thermal energy and escape from the atoms. In solids, there was the additional evidence of thermal electrons in the fact that an increase in temperature increases the conduction of insulators and semiconductors. Other thermoelectric properties, such as the thermocouple effect, equally supported the view that the free electrons in a solid could be treated as a system of minute particles which obeyed approximately the laws of ideal gases.

Now, of the early experiments with solids, none were more suggestive of the atomic view than the investigations of thermal and electrical conductivities. Theoretically, to the extent that the conduction of heat depends upon the *atoms alone*, there is little to favor one solid over another, provided the temperature is sufficient to awaken all the degrees of freedom in each case. If one end of a glass or metal rod, for instance, is heated, the agitated atoms at once arouse their less active neighbors, and these in turn will pass the alarm on down the line. Because of this type of interatomic communication, no solid is a perfect heat insulator. If the temperature is insufficient to excite a single vibration, a solid will still pass, to a certain extent, low-energy heat radiations. Nevertheless, we know that there are many poor, as well as many good conductors of heat, and this is where the conductivity experiments have proved so important in deriving a theory of solids; for it has been found that those solids that can be classed as heat insulators are also electrical insulators, and that good thermal conductors are also good electrical conductors. For example, the heat conductivity of silver with its many free electrons is approximately 500 times that of the insulator, mica. This correspondence between thermal and electrical conductivities was one of the original keystones that joined the early atomic and electronic
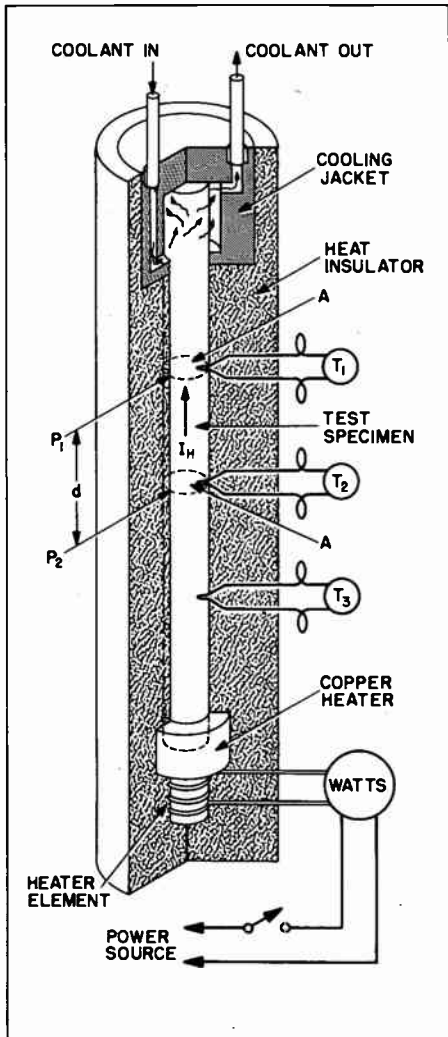
Figure 5. Measurement of Thermal Conductivity of Metal Bar

theories into what we have called "the atomic view of solids."

To measure the thermal conductivity of a metal, the ends of a sample bar are maintained at constant temperatures —one end is electrically heated and the other end is watercooled. (See figure 5.) Assuming no surface losses, the rate of thermal flow (heat per second) is equal to the wattage of the electrical heater. If we let $T_1 - T_2 =$ difference in temperature between points P_1 and P_2, and $I_H =$ heat per second flowing by any point between P_1 and P_2, and $R_H =$ reciprocal of thermal conductance between P_1 and P_2, then $T_1 - T_2 = I_H R_H$. This is an "Ohm's Law" for a thermal conductor, where a difference of temperature is the analog of a difference of potential. The equation holds for gases and liquids, as well as for solids, provided that there are no convection currents present—that is, that the particles, themselves, are not streaming in a net flow from one place to another.

The thermal conductivity, K, is readily found since:

$$R_H = \frac{d}{KA}$$

where d is the distance between P_1 and P_2, and A is the cross-sectional area. On substitution we find that:

$$I_H = KA(T_1 - T_2)/d$$
$$= KA(\Delta T/cm.) \quad (1)$$

when d is expressed in cm.

WIEDEMANN-FRANZ LAW

Now, as early as 1853, Wiedemann and Franz discovered that the ratio of the thermal conductivity to the electrical conductivity is practically the same for most metals, if the measurements are taken at the same temperatures. This discovery was a first step in establishing a quantitative relation between the thermal and electrical carriers in conductors. It was not until 1900, however, that Drude made the first suggestion, backed with theoretical arguments, that the parallelism between metallic thermal and electrical conductivities might be explained by assuming the presence of a large number of free electrons in thermal equilibrium with the vibrating atoms. A few years later, Lorentz, the Dutch physicist, attacked the conductivity problem in a more rigorous manner. On the assumption that the electrons obeyed the Maxwell-Boltzmann distribution law—which he modified to

take into account the presence of gradients of temperature and electric potential—Lorentz improved upon the Wiedemann-Franz law by showing that the ratio of the thermal and electrical conductivities, if assumed to be due to free electrons, would not only be the same for all metals at the same temperature, but would vary directly with the absolute temperature. In other words, a universal constant was derived equal to $K/T\sigma$, where K and σ are the thermal and electrical conductivities, respectively, and T is the absolute temperature. The theoretical value of the Wiedemann-Franz constant is 2.45 x 10^{-8} watt-ohm/deg.^{2}.* This agrees approximately with experiment in the case of the better conductors such as silver, copper, and gold, but there are a few extreme exceptions, notably beryllium and manganese.

THE THOMSON EFFECT

Another triumph for the kinetic theory of electrons was in its ready explanation of the Thomson effect. Imagine a uniform temperature gradient existing between two points along a conductor in which no electrical current is flowing, and that the gradient is maintained by a constant heat source. If now, a constant electric current is made to flow through the conductor, the temperature gradient will change, but not in a manner that can be entirely accounted for by the heat generated due to the flow of electrical charges. Even if the resistance losses are assumed to be zero, the temperature gradient becomes greater or less depending on the direction of the electric current. This phenomenon is called the "Thomson effect."

If it is true that free electrons are the carriers of both the thermal and the electrical energy, then it can be predicted that the thermal conductivity of a metal will be increased or decreased, respectively, if the electrons are electrically made to flow down or up the temperature gradient. In other words, a net flow of electrons from the hotter to the colder regions should aid in transporting the excess thermal energy; or if the electrical flow is in the opposite direction, the thermal conductivity should be decreased. Experiment supports this theory, for the difference of temperature—and hence the thermal resistivity—in metallic conductors decreases when the heat and electric charges (if the latter are assumed to be negative) flow in the same direction, whereas the temperature gradient becomes steeper if the direction of the electric current is reversed.

BACKING OFF FOR ANOTHER START

Perhaps the reader will appreciate the intimate connection between the early concept of free electrons and the kinetic theory of gases. Although, we are normally accustomed to considering the thermionic emission of cathode rays as a sufficient cause for assuming free electrons to be the principal carriers of electricity in metals, actually this fact is but one of several necessary pegs supporting the theory. It is not sufficient that the free electrons account for the laws of electrical conduction, it is equally necessary that they obey the mechanical laws of mobile particles—if by the term "free electron" we intend to imply a particle of matter.

Indeed, it was the agreement between these two types of properties, as evidenced in the thermoelectric effects of metals, that formed the foundation of the electronic theory. Foremost among these effects were the Wiedmann-Franz law, and, in general, the close parallel-
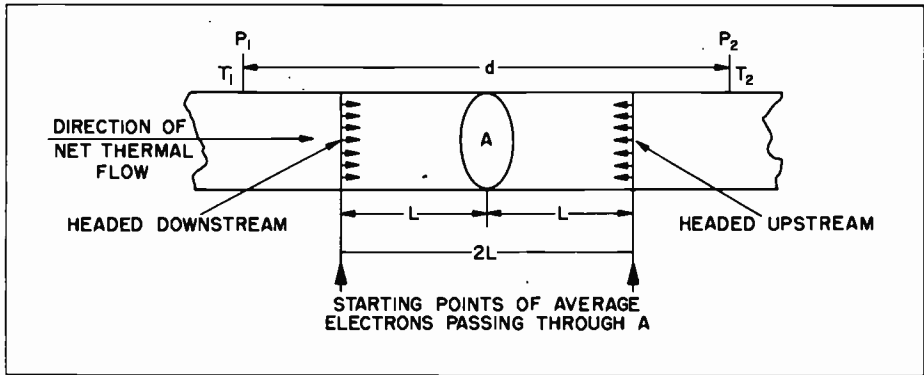
Figure 6. Diagram for Illustrating Electronic Thermal Conductivity in a Metal Bar

ism between the electrical and thermal conductivities of metals. Yet, in spite of all, the theorists during the first quarter of our century ultimately came to such serious doubts that they practically abandoned the idea that electrons, rather than atomic vibrations, were the principal spreaders of thermal energy in metals. Even if there were not the paradox of electronic heat capacities, a quandary in lesser degree would have been faced. Why? Let us see for ourselves.

MAN, DIG THAT CRAZY FIRE BRIGADE!

Assume that there are N thermally free electrons per cm.[3] in a metal bar, along which there exists a temperature drop per centimeter $(T_1 - T_2)/d = T/cm.$, as illustrated in figure 6. For the sake of simplicity assume that the electron velocities are divided equally among the three degrees of freedom of translational motion—one-third of the electrons for each direction. Thus, $1/6$ N electrons per cm.[3] are traveling in the positive (downstream) direction of the heat flow, and $1/6$ N in the negative (upstream) direction. Now if $\bar{c}$ is the average speed of an electron—it is to be assumed that the temperature drop, $T_1 - T_2$, is small enough that $\bar{c}_1 \approx \bar{c}_2$—the number of electrons going downstream that pass through the cross-

sectional area, A, in one second will be $1/6$ $N\bar{c}A$. Note that $\bar{c}A$ is simply the volume occupied by the electrons which in one second would have all passed through A.

We shall assume that the average electron that passes through A has a kinetic energy equal to the average energy at the point of its last collision prior to reaching A. For example, if an electron bounced through A directly from an impact at P_1, its average translational energy would be $3/2$ kT_1, where k is Boltzmann's constant, and T_1 is the temperature at P_1.

The question now is: what is the point of departure for the average electron that passes through A? Consider first the average electron that has a collision just as it reaches A. It will have started at a distance L from A, where L is equal to the mean free path (average length of path) between collisions. Of the electrons starting toward A from any given distance less than L, *more* than half will reach A before another impact; and of the electrons starting from any distance greater than L, *less* than half will reach A before another impact. Since the average electron passing through A can belong to neither the majority nor the minority, the distance from A of its point of departure can neither be less than nor

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greater than L, hence it must be equal to L.

Now the distance between the average points of departure of the electrons traveling through A in opposite directions is 2L, so that the difference in temperature between the two points is $2L\Delta T/cm.$, with L expressed in cm. The average electron going downstream through A thus has an energy greater than that of the average electron going upstream through A, by an amount: $3/2\,k(2L\Delta T/cm.) = 3kL\Delta T/cm.$ Since there are $1/6\,N\bar{c}A$ electrons from each direction passing through A each second, the net downstream flow of heat per second is:

$$I_H = 1/6\,N\bar{c}A(3kL\Delta T/cm.)$$
$$= 1/2\,N\bar{c}kLA\Delta T/cm. \quad (2)$$

However, according to equation 1:

$$I_H = KA\Delta T/cm.$$

So, by substitution, we find that according to the kinetic theory of gases, the electronic thermal conductivity of metals should be

$$K = 1/2\,kN\bar{c}L \quad (3)$$

Remember, however, that this is just a first approximation, and its chief value is to indicate the relationships among the variables. Note that the conductivity varies directly with N, $\bar{c}$, and L. If there were only electrons to consider, K should increase with the temperature, for the $\bar{c}$ would increase. That K for most metals remains approximately constant, or slightly decreases with an increase in temperature is best explained by assuming that L, the mean free path, decreases; for it can be imagined that as the tempo of the atomic vibrations is raised, the writhing latticeways become more tortuous and obstructive for the free electrons scurrying through.

Now the only electrons that can carry the heat are those that are able to absorb it. Here, then, is a job to be done by the same thermally free electrons of the heat-capacity experiments, so we can roughly assume that $N = 10^{20}$ electrons per cubic centimeter. A Maxwell gas molecule has an average speed $\bar{c} = \sqrt{\dfrac{8kT}{\pi m}}$. So at 300°, an electron of mass 9.1×10^{-28} gm. should have a speed $\bar{c}$ of 10^7 cm./sec.—approximately 62 miles per second.

For reasons that will be discussed shortly, the diameter of an electron compared with the diameter of an atom is somewhat in the same proportion as the diameter of the earth is to the diameter of its orbit about the sun; so it would seem that the chance of a random collision of a free electron with another free electron would be very small relative to the chance of its collision with an atom. Indeed, if an electron is imagined to be bouncing randomly about, its mean free path should not be of much greater length than one or two atomic diameters. As a first guess, let us say that $L = 10^{-8}$ cm., which is approximately the distance between the *centers* of two adjacent atoms in a solid.

We can now insert the approximate values of N, $\bar{c}$, and L, as well as the known value of k, 1.37×10^{-16} erg/deg.-/molecule, into formula 3, and see how well our theory checks with experiment. On multiplication, we find that $K = 685$ ergs/deg.-cm.-sec. $= 1.64 \times 10^{-5}$ cal./deg.-cm.-sec. Since our derivation was by no means rigorous, the above value for K may be considered a success if it lies within 1/10 to 10 times the observed thermal conductivity of the average metal.

But alas! Our fine-spun web has again lost its fly. Representative values of metallic conductivities at room temperature (18° C.) are found to be:

Silver—0.974 cal./deg.-cm.-sec.
Copper—0.918 cal./deg.-cm.-sec.
Gold—0.700 cal./deg.-cm.-sec.
Aluminum—0.504 cal./deg.-cm.-sec.

These values are approximately 50,000 times the predicted value. Indeed, our theoretical conductivity proves to be little more than one-tenth that of cork—one of the better heat insulators!

A PAUSE ON THE HORNS OF THE NEW DILEMMA

Again the classical thinkers were greatly perplexed as to whether the metallic electron should be classed as a tyrant or as a slave—whether it moved with unlimited freedom, or with none at all. The scholar in kinetic gases, anxious to preserve the dignity and respect of law within his own domain, was led to argue that the electron gas, if it existed, must be in thermal equilibrium with the atoms, and like other gases, should be a poor conductor of heat. But this was to ignore the prinicpal reason for assuming an electron gas—the parallelism between the thermal and electrical conductivities of solids. A more humble attitude, it seemed to a majority, was to grant the electron the right to make its own rules, since it was a particle even more elementary than atoms, molecules, or ideal billiard balls. Thus, if the thermal-conductivity equations were to agree with experiment, either N, $\bar{c}$, or L, or some combination thereof, must be approximately 5×10^4 times as great as previously assumed. Since N is limited by the heat-capacity experiments,* and since the electrons cannot exceed the velocity of light, and in any event are not apt to be moving at tem-

peratures approaching a trillion degrees, it was the mean free path that was supposed to be thousands of times greater than originally expected. Apparently, the electrons could easily maneuver between the atoms, so that the chance of an immediate collision was relatively small.**

Such an explanation proved a graceful exit for escaping the dilemma, but even so, it seemed improbable and thoroughly confused the concept of an electron gas. Indeed, in the absence of direct proof, it was debatable whether free electrons were actually the principal carriers of either type of metallic conduction — electrical or thermal.***

A possible alternative was to assume that the electrons form more or less rigid structures, somewhat like billiard balls end-to-end, and thus are able to relay energy from point to point without stirring up a general commotion. In this event, however, since the atoms are the principal recipients of the energy, the process of thermal conduction differs but little from that already assumed for insulators. For if the electrons are effectively end-to-end, they must effectively surround the atoms, and thus for all practical purposes, are still parts of the atoms, and the thermal conduction should be described as due to atomic vibrations. A possible distinction would be to imagine that the outer electron shells are threaded more or less rigidly together, but instead of remaining fixed, the electronic

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* Even if N were assumed to equal 10^{22}, one electron per atom, we would still need a correction of 50,000 percent. Actually, this would not be difficult to achieve if we could simply ignore the atoms, and assume that L were only a function of the collisions between electrons.

** Actually, the mean free path L is not as great as we would now suppose, for it will be found that the effective average speed $\bar{c}$ is comparable with that of temperatures measured in thousands of degrees

—even when the temperature of the metal approaches absolute zero.

*** If our original assumptions concerning N, $\bar{c}$, and L had been made in deriving an equation for the electrical conductivity as well as thermal conductivity, except that units of charge instead of quantities of energy were being transported, the same discrepancy would appear between the theoretical and observed conductivities. Thus, the theoretical derivations at least uphold the Wiedemann-Franz Law.

beads are constantly on the move, weaving over and over again the pattern of some sort of resonant web. Extending the electron orbits thus to encompass the entire metal can conceivably offer a substitute for the gas theory of thermal conduction, but it does not explain away all the evidence of free electrons as the cause of electrical conduction, nor all the coincidences between electrical and thermal effects.

Bold pioneers were needed to explore the electron's maze of passageways, but no theorist rejoiced at the thought of arousing the hoarse echoes that generally answered those who shouted down dark alleys of questionable repute. It was first necessary to furnish direct and indubitable evidence that there really are *mechanically* free electrons in metals, and that the electrons can move relatively long distances between collisions. The empiricist of the hour who accepted the challenge was Richard Tolman.

TOLMAN'S PROOF OF FREE ELECTRONS IN METALS

Tolman's proof was quite difficult to achieve, but the logic involved is disarmingly simple. To determine whether a sealed box contains loose objects, the most natural experiment is to pick up the box and shake it. Dr. Tolman, of course, did not hear the rattle of metallic electrons, but he did succeed in connecting a metal to instruments that could do the detecting for him. For instance, striking the end of a metal bar with a sharp blow would catch any loose particles by surprise, and these would be jammed momentarily against the end being struck. If, at the same instant, the bar became electrically polarized, we would say that the loose particles were positively or negatively charged according to the polarity at the crowded end. Better

still, a metal coil could be rapidly rotated and then abruptly stopped. If any electrons were actually free, their inertia would keep them moving after the rest of the coil had stopped, and a pulse of current in a particular direction would occur. By such methods, Tolman discovered that a negatively charged fluid is contained within metals, and that it has the same ratio of charge to mass (e/m) as that measured for cathode rays—i.e., the e/m of electrons.

With it thus proved that a number of metallic electrons are mechanically free, the theory of the electron gas was greatly strengthened. It was now *necessary* that the electrons be regarded as the principal agents of metallic electrical conduction, and hence of thermal conduction; for the long free paths implied by the former would in turn satisfy the conditions for the latter.

The vindication of the electron theory, however, was hardly a triumph for classical mechanics. In the first place, the older laws cannot support the fact that so few free electrons are present, for the energy of disassociation of the valence electrons of metallic atoms is easily overcome by ordinary thermal energies, and one valence electron should be as free as the next. In the second place, classical mechanics cannot explain how the small percentage of electrons that actually are flying randomly about can bypass thousands of atoms without a collision. With the aid of wave mechanics it will be found that the number of "free" electrons is actually that originally predicted— one electron per atom—but that little more than one percent of these are able to conduct. The mystery of the long mean free path will be answered in terms of electron waves—but the solution will depend somewhat upon which interpretation of the waves is most favorable to the reader. However,
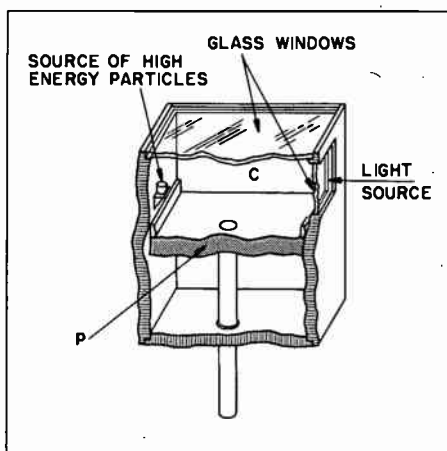
SOURCE OF HIGH ENERGY PARTICLES

GLASS WINDOWS

C

LIGHT SOURCE

O

P

Figure 7. Wilson Cloud Chamber

before the trail of the quantum leads us to waves, it is well to recite those properties of an electron that have led us to think of it as a particle.

ELECTRON TRACKS

First of all there is the direct visual evidence of the path that a high-energy electron makes as it darts through a Wilson cloud chamber. The principle by which the cloud chamber operates is illustrated in figure 7. A small quantity of water is kept in chamber C until at equilibrium as many water molecules are plunging back into the reservoir per second as are escaping from it. Under these conditions, the atmosphere of the chamber is said to be *saturated* with water vapor. Previously all dust particles have been removed so that no nuclei are present to aid the formation of cloud droplets. If, now, the piston, P, is suddenly lowered, the gas expands, losing energy to the piston; the temperature thus falls, and the chamber becomes supersaturated with vapor. If at this instant, a submicroscopic bullet having an energy of several million electron volts is shot through the chamber, a trail of intense excitement is left in the bullet's wake—millions of electrons, having been tossed from their orbits, will be

clinging to strange molecules; and the hordes of panic-stricken ions, positive and negative, will be scurrying for the protection of any alliance that provides them a mended armor. By clutching at bombarding molecules, an ion can soon become the hub of a charged cluster; but because of the supersaturated vapor, the water molecules will continue to pour into the entanglement at a faster rate than they can break away. Thus it is that an unbalanced atom will suddenly find itself the rallying point of trillions of excess molecules, thereby becoming the kingpin in a droplet of water. An observer looking into the chamber will see a thin streak of condensed vapor marking the furrow of ions that had been plowed by the bullet during its passage.

Now the bullets used in these experiments may be the nuclei of atoms such as protons or alpha particles—the nuclei of hydrogen and helium atoms, respectively—or they may be photons, cosmic rays, or electrons. (See figure 8.) It is the fact that the tracks are so well defined—tracing a single line, instead of spreading in all directions—that provides us evidence for classifying these bullets as particles. This, of course, is not conclusive—swarms of photons, for instance, also compose the electro-
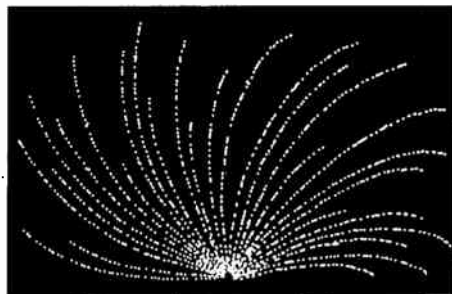

Figure 8. Cloud Tracks of Beta Rays (High-Energy Electrons) (The electrons are identified by the direction of curvature of the paths caused by the presence of a magnetic field directed into the paper.)

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magnetic waves*—but we may accept this evidence as exhibit 1 that an electron is a particle.

Exhibit 2 is the generation of tracks by high-energy electrons when they happen to tear across the surface of a photographic film. The evidence that the tracks are made by particles is essentially the same as that in the case of the cloud-chamber tracks, and the paths are as clearly defined as those shown in figure 8.

ELECTRON STARS

For exhibit 3, there are the tiny scintillations that can be observed when individual high-energy electrons strike a film of fluorescent material such as zinc sulphide. As an electron passes through the film it loses part of its energy to the crystal molecules, and as the molecules collapse back into their unexcited states they radiate the energy in a visible spectrum. This principle, of course, is the same as that of the cathode-ray screen, except that here the observer uses a microscope to observe one scintillation at a time. Each small star that suddenly flares up and dies away is restricted to a fine pin-point, and this fact substantiates the claim that the electron is a particle—that is, the electron is not diffused over an indefinite area, but has a reasonably definite position and boundary in space at each instant.

THE ELECTRONIC CHARGE

Exhibit 4 is probably the most convincing of all the pieces of evidence identifying the electron as a particle. This is the evidence that every electron carries the same charge, and the first conclusive proof was obtained through Millikan's historic oil-drop experiment, an event whose story will be told and retold long after our wars have been forgotten.

It will be recalled that Faraday's electrolysis experiments first suggested the possibility of a fixed unit of ionic charge. Stoney, in 1874, on the basis of approximations concerning kinetic gases, obtained a value of Avogadro's number that was about 1600% too large. Dividing one Faraday by this value he obtained a hypothetical unit charge which he later named the "electron." When J. J. Thomson, the father of electron physics, found that cathode rays were negatively charged, and that they had a measurable ratio of charge to mass, he believed that the rays were composed of negative Stoney electrons. Attempts were made to determine the electron charge by measuring the charges of the water droplets in a cloud chamber,** but although the values derived were generally within 30 to 40 percent of the now-accepted value, there were too many possible sources of error for the results to be accepted with confidence. However, the fact that a Wilson cloud would separate into definite strata when an electric field was applied constituted strong evidence that the droplets contained various multiples of the same unit charge.

A diagram of Millikan's apparatus is shown in figure 9. In place of water droplets, which were constantly varying in mass and size because of fluctuations in temperature, Millikan used less volatile liquids such as oil. The atomizer provides a fine spray in the upper chamber, and a few droplets are allowed to fall through the small hole at O. A and B are capacitor plates which are used to provide a uniform, but adjustable, electric field.

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* Is the photon itself a wave? Let's save this question until later.

** It was in the attempt to measure the ionic charge of water droplets that Wilson invented the expansion chamber.
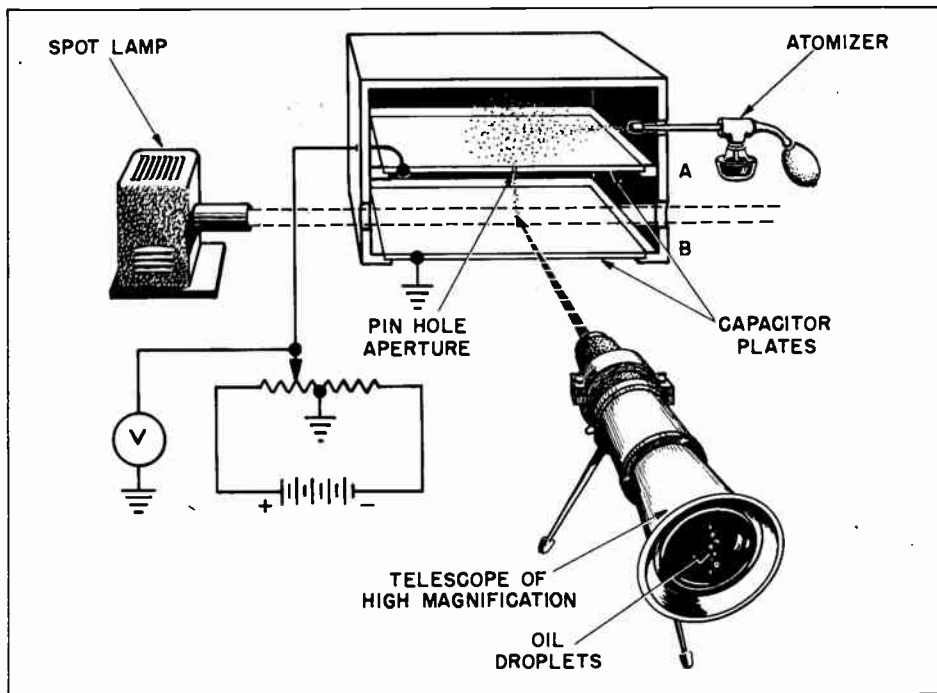
Figure 9. *Millikan Apparatus for Determination of Electronic Charge by Observation of Oil Droplets in Electric Field*

As an observer watches through the telescope, suddenly a tiny globule will be seen to glisten, as if some weird crew of little creatures were sailing a space ship across the beam of light. And then another appears, and another, until finally an entire flotilla glides into view, bent upon some daring mission which we devine to be of a gravitational nature. If now, a voltage is applied across the capacitor plates, the globules react with varying moods. Some will continue their forward motion undisturbed, others will accelerate their pace, still others will hesitate, and some will even shift to full-speed astern. However, by adjusting the intensity of the electric field, or reversing the polarity, if necessary, any of the globules, except those that continue undisturbed, can be brought to a full stop. All these varied maneuvers in the electric field apparently are due to droplets charged with the carriage of captive ions.

For a stationary droplet: $B + Eq =$ mg, where B is the buoyant force of the air, E is the electric field, q and m are the droplet's charge and mass, respectively, and g is the acceleration of gravity. That is, the upward pull of the electric and bouyant forces exactly equal the weight of the droplet. Occasionally a stationary droplet will suddenly begin to rise or fall, indicating that either an ion has escaped or another has been captured. If a strong beam of X-rays are directed through the chamber the little space ships go wild with excitement, shuffling up and down as if some mad convention of diminutive elevator operators had taken charge.

From the observed velocities and known physical constants, Millikan was able to compute the ionic charges, and in all cases these were found to be integral multiples of the smallest observed charge, 1.6×10^{-19} coulombs. This value, then, is defined as one electronic charge.

That an electron is an atom of charge seems to be established beyond all doubt, and this fact combined with the evidence that the electron occupies a very small region in space, and that when isolated it obeys the dynamics of rigid bodies, certainly appears to warrant no other classification but that of particle.

TWO MISSING CLUES

What then is to explain the strange degeneration of the electrons in metals? Are there external forces at play that are as yet unknown? Or does the electron, itself, have properties that have gone undetected? Or is it due to some fundamental architecture of nature that we have yet to discover? Affirmative answers might be given for each of the possible explanations, but it is the last of those mentioned that seems to draw us closest to the unknown. For as our physicists pushed their exploration deeper into the electron's world, new laws foretelling of a new universe began to take command.

Where now to turn to look for these new laws? At this point in our story, still missing are two valuable clues. One involves the speed of light, and the other the variability of the electron's mass. Actually the former is the only necessary clue, for from this the pecularities observed in the electron's mass can be predicted. In fact, Einstein effectively did just that, when he presented his special theory of relativity. Historically, however, experiments and speculations involving the electron's mass antedated Einstein's theory, and, indeed, were part of the stepping stones that led to his work. So it is the electron's mass that we shall investigate first.

THE ELECTRON'S MASS

Prior to an accurate determination of the electronic charge by Millikan,

the measurements taken of the deflection of cathode rays, when the rays were made to pass through known electrostatic and magnetic fields, had rendered fairly accurate values for the ratio of charge to mass, e/m. The best experimental value today is 1.7592×10^8 coulombs per gram. With $e = 1.602 \times 10^{-19}$ coulombs, we find the mass of the electron to be 9.106×10^{-28} grams; a value approximately 1/1838 the mass of a hydrogen atom.

What is the nature of the electron's mass? Or for that matter, just what do we mean by the word "mass"? From our everyday experience, we have formed the habit of associating the mass of a body with the amount of matter it contains and with its weight. But weight is a force, and force $=$ mass x acceleration; thus mass is properly measured by the force required to change a velocity a unit amount in unit time. Intuitively, mass is that property associated with a free body that opposes any change in its motion, maintaining the body in a state of rest or uniform velocity indefinitely unless acted upon by an external force. It is, thus, simply a "quantity of inertia."*

We know that if an electrical circuit has zero resistance—and certain solids at temperatures near absolute zero actu-

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* The definition of mass given above presupposes independent definitions of *acceleration* and *force*. More in favor with theoretical physicists is the definition of mass as developed by Mach, which presupposes an independent definition only for acceleration.

Briefly, any two interacting particles, A and B, isolated from all other particles will accelerate in opposite directions. Whether the accelerations are due to equal and opposite reacting forces, attractive or repulsive, is not a necessary postulate to define mass. For the absolute value of the ratio of the accelerations, $|a_A/a_B|$, can be defined as $m_{BA} = $ mass of B relative to mass of A. If the mass of A is taken as

ally do seem to become perfect conductors—a current will still require a force to start it, and once started, will continue to flow indefinitely, unless another force is applied to stop it. The applied force and the acceleration of the electrons are not the same as, but are proportional to, the applied voltage and the current's rate of change, respectively. The voltage per unit "acceleration" of current we are accustomed to thinking of as the circuit's electrical inertia, or more technically, its *self-inductance*.

Now a single electron moving through space also constitutes a current, and the magnetic lines of flux that encircle it will maintain its motion unless opposed by some external force. In this case, however, instead of thinking in terms of henries—measured as the number of volts required to change the current one ampere in one second—it is simpler to think in terms of grams —measured as the number of dynes required to change the velocity one centimeter per second in one second. Thus, the mass of the electron when inserted in the equation, $F = ma$, is simply a constant of proportionality relating the force on an electron to the electron's acceleration. The question arises: can this constant of proportionality be completely accounted for by

the electron's self-inductance? In other words, is the electron's mass entirely electromagnetic, so that its kinetic energy is actually no more than the "potential" energy stored in the surrounding magnetic field? If we can assume an isolated electron to be a charged spherical particle, the answer to this question is a very probable yes.

THE SPHERICAL ELECTRON

Figure 10 represents the electric lines of force radiating from a charged conductor that is moving perpendicularly to the plane of the paper. The dotted lines indicate magnetic lines of flux at right angles to the moving electric field —note that both the electric and magnetic intensity is greatest where the convex curvature of the surface is sharpest. No electric, and hence, magnetic lines exist inside the conductor, for a difference of potential cannot be maintained in an isotropic conductor without a current flowing (microscopic thermal effects disregarded). Now, the *number* of electric lines of force radiating from a closed surface into empty space depends only upon the quantity of charge enclosed within or on the surface, and is completely independent of the surface's shape, size, the nature of the material it bounds, òr the distribution of charge. However, by im-

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the standard unit of mass, then $m_{BA} = m_B = |a_A/a_B|$. This definition, however, equates mass to a pure number, so that in such equations as force $= ma$ and momentum $= mv$, force and momentum are not dimensionally distinct from acceleration and velocity, respectively. This is not very satisfying to one accustomed to thinking of mass as a physical entity whose presence means the difference between matter and mere shadow or shape. But simply to define the ratio $|a_A/a_B|$ to be a denominate number having the dimensions of mass overlooks the fact that a physical equation must be disciplined qualitatively as well as quantitatively.

The purpose of the Mach definition was to avoid any supposition of a quality not directly experienced. (Mach even rejected

the atomic theory of matter since it was purely a hypothetical concept—he was the last of the important physical theorists to do so.) Mass thus becomes simply a constant of proportionality relating the changes in motion of interacting bodies. Force is next defined as the product of mass and acceleration, thereby attributing to this concept nothing more than can be visually experienced. It is here that the principal objection to Mach's method arises; for blind physicists could measure motion and extension in space, but not until after they had first experienced forces. Force is at least as primary an experience as sight itself; and, indeed, it might be argued that the eyes and optic nerves are no more than elaborate tactile organs for feeling the forces of light rays.
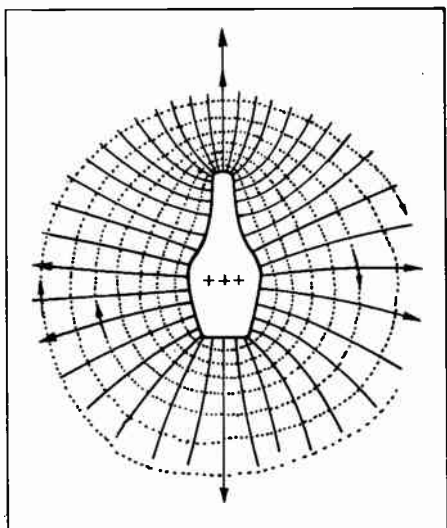
Figure 10. Electric Lines of Force (Solid Lines) and Magnetic Flux (Dotted Lines) Surrounding Charged Body Moving away from Observer

agining a uniform distribution of charge within, or on the surface of a sphere, the electric lines of force will radiate with equal intensity in all directions, so that all the charge may be visualized as being concentrated at the center—though if the sphere is a conductor, no lines of force will actually penetrate the interior. Such a uniform charge distribution, with the lines of force beginning at the surface of a sphere, represents the spherical model of an electron.

The cross sections of two imaginary electrons of different radii are illustrated in figure 11, where the electronic charge is represented as equivalent to eight lines of force radiating from the circumferences and directed toward the center. The direction of the arrows merely indicates that the charge is negative. Since the surface area is proportional to r^2, where r is the radius, the density of the lines of force at the surface will vary inversely with r^2, becoming infinitely greater as r approaches zero. At a fixed distance d from the center of charge, however, the electric

intensity, and hence the density of magnetic energy if the electron is moving, is not affected by the size of the sphere, as long as d extends beyond the surface. Inside the electron, the electric field is assumed to be zero. Thus, it can be seen that to accelerate the large-size electron to a given velocity, a certain quantity of energy must be stored in the magnetic field extending from the surface at r, to infinity; but to accelerate the smaller electron, additional energy must be supplied for the magnetic field between r_1 and r_2. Thus, the smaller the electron, the greater the force required for a given acceleration, and hence the greater the electromagnetic mass.

It can be shown that the electromagnetic mass of a spherical electron in empty space numerically will be:

$$m = \frac{2e^2}{3r} \text{ x } 10^{-2} \text{ gm.} \qquad (4)$$

where e is the electronic charge in coulombs and r is the radius in centimeters. If all the electron's mass is assumed to be electromagnetic, then, by substituting the experimental values of e and m in equation 4, we find that $r = 1.88$ x 10^{-13} cm. Since the radius of an atom is on the order of 10^{-8} cm., or approximately 10,000 times that of
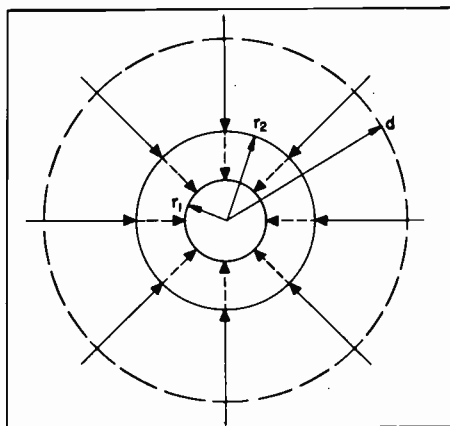

Figure 11. Cross Section of Electric Field Surrounding Spherical Electronic Charge of Radius r_1 or r_2.

our spherical electron, the assumption that the entire electron mass is electromagnetic agrees very well with the portrayal of an atom as a miniature solar system.

WHAT'S THE MATTER?

Note that the electron's radius cannot be smaller than 1.88×10^{-13} cm., for then the electromagnetic mass would be greater than the total observed. In the absence of evidence to the contrary, there is no reason why all the mass of the electron should not be considered electromagnetic.* Indeed, when one recalls that matter is composed of electrified particles, there appears the very great possibility that all mass, electromagnetic, as well as that which we commonly think of as gravitational, is essentially of one and the same nature.

Equation 4 indicates that the mass of an electric charge is inversely proportional to its radius. Thus, the relatively large mass of a proton is attributed to the fact that its radius is proportionately much small than the electron's. This possibility was strongly suggested when Rutherford and his co-workers, Geiger and Marsden, observed the large angles at which alpha particles

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* Certain equations that are used to predict the behavior of conducting solids are found to be more exact if the electron is assumed to have a mass greater or lesser than that observed by direct e/m measurements. However, this difference in mass is merely a mathematical formality that permits simplified assumptions regarding the level of potential energy within a metal.

** Prior to Rutherford's experiments, the Thomson model of the atom was considered the one most probably correct—a Thomson atom was essentially a ball of positive jelly with negative plums stuck in here and there—but with the evidence of intense electric fields within atoms, the nuclear, or Rutherford, atomic model became generally accepted, although destined soon to be modified by Bohr and others.

(high-energy helium ions that escape from radioactive atoms) were scattered when passing through matter. Rutherford assumed that a large deflection was caused by the collision of an alpha particle with an intense electric field inside an atom. To account for the highly concentrated field it was further necessary to assume that all the positive charge was contained in a nucleus occupying but a trillionth of an atom's volume. Nuclei, which were later found to contain many protons and neutrons, apparently were no larger than electrons—the protons, themselves, being much smaller. Rutherford's nuclear theory** (1911) thus indirectly encouraged the belief that all mass, or reaction to acceleration, may eventually be explained in terms of energy stored in magnetic fields. Although the equal and opposite charges of an atom cancel as a whole, they by no means do so at every point within the atom, where the pattern of overlapping fields may reinforce as well as cancel. In any case, the speculations concerning the electron's mass forged one more link in the chain that was eventually to bind particles to waves.

THE LORENTZ ELECTRON

In the early days of cathode rays, when Thomson was first discovering that they were negative electrons, it was found that their ratio of charge-to-mass, e/m, strangely diminished as the electrons attained velocities approaching that of light. On the assumption that the negative charge remained constant, three theorists, Abraham, Bucherer, and Lorentz, investigated the possibility that the electron's mass, if entirely electromagnetic, might be expected to increase with increasing velocity. Each of these physicists assumed a spherical shape for an electron at rest, but, as shown in figure 12, the hypotheses differed concerning the shape of an electron in motion.
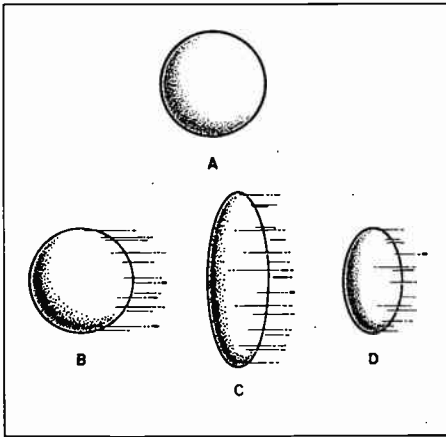
Figure 12. (A) Abraham, Bucherer, and Lorentz Electron at Rest (B) Abraham Electron in Motion—Shape and Size Unchanged (C) Bucherer Electron in Motion—Flattened in Direction of Motion, but Volume Constant (D) Lorentz Electron in Motion—Flattened in Direction of Motion, but Transverse Diameter Constant

Abraham's electron retained the same shape and volume when set in motion; but since its change in position could not be communicated instantaneously, any change in the surrounding electric field had to await the velocity of light; and thus the lines of force were shown to become increasingly distorted as the electron's velocity increased—no longer radiating equally in all directions. Abraham's treatment showed that the electronic mass would rapidly increase as the speed of the particle approached the speed of light. However, the exact predictions did not compare favorably with subsequent observations.

Two years later, in 1904, Bucherer and Lorentz presented models of electrons which changed shape when set in motion, such that the ratio of the diameter in the direction of motion to the transverse diameter was at all times equal to $\frac{\sqrt{c^2 - v^2}}{c}$, where c is the speed of light, and v is the velocity of the

electron. However, Bucherer's electron maintained the same volume in motion as at rest, so that as the velocity diameter became shorter the transverse diameter became longer. In the Lorentz electron, on the other hand, the transverse diameter remained constant, whereas the velocity diameter and the volume both decreased as the velocity increased. Of the two models, that of Lorentz has clearly been proven the more accurate. Also, the Lorentz model is the same as that which in the following year, 1905, was to be predicted by Einstein's theory of relativity.

The original Lorentz electron contained not one, but two values of mass —one for accelerations in the instantaneous-velocity direction, and another for accelerations in the transverse direction. However, this was simply a technical error which arose from using the customary equation of Newton's second law of motion, $f = ma$, instead of Newton's more rigorous form, $f = ma + va_m$, where v is the velocity, and a_m is the rate at which mass is changing with time. Since no evidence had heretofore existed that the mass of a body could vary, the last term, va_m, had long fallen into disuse. When corrected, the Lorentz equation for the electron's mass gives the same value for all directions of acceleration:

$$m = \frac{m_0 c}{\sqrt{c^2 - v^2}} = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$

where m_0 is the mass of the electron at rest—usually called the *rest mass*.

COMMON-SENSE PHYSICS LOSES COMMAND

The hypothesis that an electron contracts in its direction of motion by a

factor $\frac{c}{\sqrt{c^2 - v^2}}$, or $\frac{1}{\sqrt{1 - v^2/c^2}}$, was

much more than a wild conjecture in the dead of night. It was the necessary

consequence of a general system of equations that Lorentz derived in applying Maxwell's field theory to the behavior of electrified particles. The Lorentz equations rescued the laws of electromagnetism from an utter confusion that resulted when a link was sought between these laws and Newtonian relativity of motion. This was at a time when the beginning of the end of common-sense physics was at hand. Just a few years before, Planck had forced the correct answer from a radiation equation by inserting the quantum constant, h. With considerable encouragement from Einstein, this mathematical formality was soon to attain a revolutionary physical significance. In a similar manner, the equations known as the *Lorentz transformations* were at first considered mere mathematical formalities to permit Maxwell's field equations to hold for electrified particles, irrespective of whether the particles were assumed to be at rest or in uniform motion relative to an observer. For instance, an electron in relative motion was not actually believed by Lorentz to be physically flattened—certainly not simply because an observer happened to fly past it, or vice versa; but because by making this assumption, Maxwell's laws could be used in describing the behavior of the electron. Again, however, Einstein was to play a major role in giving an abstract mathematical formality a revolutionary physical significance; for a rederivation and a reinterpretation of the Lorentz transformations were the substance of his "special theory of relativity"—presented in 1905, which was also the year of his photon theory.

Now, it so happened, that Maxwell's electromagnetic field theory, so perfectly substantiated by Hertz' detection of radio waves, firmly established the wave concept of light; but in so doing, a number of hidden implications were introduced. As these began to emerge,

classical physics was in great danger of being corrupted by its own inherent contradictions. So far as its superstructure was concerned, the appearance was one of orderliness and excellence of design, and new wings and floors were growing at a faster rate than ever before. Still, this new construction was the source of the trouble, for the old supports were beginning to strain and creak under the added weight. In the midst of this uneasiness, the quantum chose to strike; and its first objective, as we now know, was to crumble that part of the foundation supporting the continuous nature of electromagnetic waves.

At this dark moment, classical physics suddenly discovers a great champion in the Einstein theory of relativity. A reformation follows, of a magnitude unprecedented since the days of Isaac Newton; and out of the new order the classical laws emerge with an accuracy and unity never before realized. Relativity, with all the vastness of the universe within its sweep, takes command; and classical physics in new armor forsakes its former postures of apology and once again marches forth in quest of new worlds to conquer.

In the train of the rejuvenated forces, one finds the usual ragged band of camp followers, but among these particular scavengers there is one who seems possessed of some dread contagion akin to St. Vitus' dance. Soon an entire division is discovered goosestepping in a most extraordinary manner; and at the height of a crucial engagement even the projectiles begin to zigzag. Needless to say, the carrier of this mad disease is none other than the relentless quantum. But in the art of camouflage, surprise, and deception, this mighty mite soon finds a worthy match in its new and equally ambitious foe, relativity.

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The early quantum theory had erected something of a one-way bridge leading from waves to particles. The relativity theory was now to build a bridge leading from particles to waves.

A clash was inevitable. The conflicting powers began to array their forces, and with the entire universe as the prize, the battle of the century was soon to begin.

AN EMERGENCY POWER SOURCE FOR THE SCR-211 (BC-221) FREQUENCY METER

ALMOST EVERY COMMUNICATIONS site in the Far East has experienced, at one time or another, the unpleasant, crippling loss of use of the SCR-211 frequency meter, because of battery failure. At times, BA2 and BA23 batteries are difficult to obtain, and are occasionally 30% to 50% substandard when received. The RA-133 rectifier unit for this equipment is designed as an a-c power supply, and is also a rarity seldom obtainable through regular supply channels.

Several emergency solutions have been tested, two of which have proven to be quite satisfactory. The BC-221 power requirements are a 6.3-volt filament source and a reasonably stable 135-volt d-c source. (The 6.3-volt requirement may be either a.c. or d.c.) The output of the power supply of a BC-779 receiver was tried, and proved quite satisfactory when a receiver was also connected to the rectifier unit. The BC-221 can be very quickly and easily be "tied-in" by providing extension leads connected between that unit and the BC-779 Receiver terminal strip, since terminals 1 and 2 provide 6.3 volts a.c., and terminal 4 provides 140 volts

d.c. The additional load presented to the power supply does not overload the RA-74 or RA-84, and the five-volt difference causes no noticeable variation in the stability of the frequency meter. The power required for the plate circuit differs slightly with various models, the average being 135 volts at 0.015 amperes, or, roughly, two watts.

A second emergency power source can be built in a very few minutes, utilizing the R-19/TRC receiver in the following manner:

Construct a three-wire cable of suitable length, terminated at one end in an octal plug. (An old tube base will serve.) Tie the six-volt lead to pin 7, the "A" and "B" common lead to pin 1, and the 135-volts d.c. to pin 4. At the B-plus terminal of the frequency meter, connect a 5650-ohm, five-watt resistor in series with the B-plus line. Then plug the cable into test oscillator socket P106 of the R-19, turn on all equipment, and you are in business. In actual tests, a 5000-ohm resistor was used, (dropping the 220-volt supply to 143 volts), and proved quite satisfactory.

Kenneth H. Hines
Philco Field Engineer

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