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NOTES AND DISCUSSION

What Makes an Electric Current "Flow"

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VERY few undergraduates seem to have any idea of what makes an electric conduction current flow in an electric conductor. They generally say that it is a battery or a generator or a thermocouple that drives the current. They are generally completely foxed by the following question: "The mean drift velocity of the conduction electrons in a conductor is typically of the order of 10^{-4} m/sec, yet when somebody presses the bell switch at your front door the bell sounds almost immediately and does not have to wait for current to flow at the rate of 10^{-4} m/sec along the connecting wires. Why is this so?" The reason for the students' confusion is that the topic is never discussed adequately in elementary text books. A possible way of introducing the subject is discussed below.

As a first introduction to a seat of emf it has become fashionable to use an idealized Van de Graaff generator. In this example, the moving belt of the Van de Graaff generator literally lifts charges mechanically from a low to a higher electric potential and in this way can maintain the current flow in an external circuit. When a Van de Graaff is operating on open circuit, there are electric charges of opposite signs on the positive and negative terminals. (The leakage current is ignored at present.) The charges on the terminals give rise to an electric field which extends into the space outside the terminals. For purposes of discussion, assume that a conducting wire is brought up "instantaneously" so as to join the terminals of the Van de Graaff generator. The electric field due to the charges on the terminals extends into the connecting wire and acts on the free electrons in the connecting wire. There is a conduction current given by $\mathbf{J}=\sigma\mathbf{E}$, where $\mathbf{J}$ is the conduction current density, σ the conductivity, and $\mathbf{E}$ is the instantaneous value of the electric field inside the conductor. In the present idealized case, the initial direction of current flow is parallel to the electrostatic field due to the charges on the Van de Graaff generator terminals. (In practice, there are transient currents as the wire is brought up to join the terminals.) The charges constituting the conduction current in the connecting wire build up charge distributions on the surface of the wire, which give rise to electric fields which, in the steady state, prevent current flow in a direction perpendicular to the connecting wire. Thus, during the transient state, charge distributions are built up on the surface of the connecting wire which serve to "guide" the electric current along the length of the connecting wire. Under the influence of the electric field due to the charges on the terminals of the generator, electrons flow from the connecting wire into the positive terminal of the generator and from the negative terminal into the connecting wire, thereby reducing the charges on the terminals. This loss of charge is compensated, to some extent, by the electric charges carried mechanically by the belt of the Van de Graaff generator from one terminal to the other. A state of *dynamic* equilibrium is reached when the charge carried by the belt per second is equal to the conduction current flowing in the connecting wire. At "dynamic" equilibrium, the conduction current flow is parallel to the wire, the conduction current is given by $\mathbf{J}=\sigma\mathbf{E}$, where $\mathbf{E}$ is now the local electric field due to both the charges on the terminals of the Van de Graaff and on the surface of the connecting wire. The transient currents flow to the surface of the connecting wire until such a time that, for Ohmic conductors, the potential drop along the wire is consistent with Ohm's law.

It has been illustrated how electric fields propagate conduction currents. This point can be illustrated more vividly by considering what happens if the speed of the belt of the idealized Van de Graaff generator changes, e.g., goes faster. More positive charge is carried to the positive terminal leaving the negative terminal more negative. Let the extra charge give an extra contribution, $\Delta\mathbf{E}$ which is a function of position, to the electric field in space. Transient currents again flow in the connecting wire in the direction of the extra field $\Delta\mathbf{E}$. There is again some current flow towards the surface of the connecting wire until more charge builds up on the surface of the wire and "guides" the extra current along the connecting wire. In empty space, the electric fields are propagated from their sources with the velocity of light. We can imagine the changes in field $\Delta\mathbf{E}$ moving from the generator terminals with the velocity of light. However, as $\Delta\mathbf{E}$ is propagated along the wire, the surface charge distributions built up by transient currents also give a contribution to the change in the total electric field. The build up of these latter charge distributions depends on the capacitance C, and the inductance L, per unit length of the connecting wire, so that the speed of propagation of changes in total electric field depends on L and C. However, the changes in electric field intensity (and the associated changes in potential and conduction current) are generally propagated with a velocity comparable to, but less than the velocity of light. If the wire connecting the terminals of the generator is very long, say stretched to the moon and back, the changes in field and current associated with a change in the speed of the belt of the generator would take a few seconds to reach the moon. One would not have to wait for electric charges to flow along the whole length of the wire at 10^{-4} m/sec, to give a change in conduction current. When expressed in terms of a transmission line (actually the Lecher's wires problem) it is obvious that conduction currents are propagated by electric fields with a velocity comparable to the velocity of light, but it is surprising how few students, even after doing transmission lines, associate these ideas with the build up and maintenance of ordinary direct current flow.

The flow of a conduction current gives rise to Joule heating. This energy is supplied via the electromagnetic field. As an example, consider an *isolated* wire which is lying on a bench close to, but not connected to, a Van de Graaff generator. When the Van de Graaff generator is being charged up the charges on the generator terminals give rise to an electric field. When the generator is charging, this electric field gives rise to transient currents in the isolated wire. These transient currents flow until the resultant electric field in the isolated wire is zero. These transient currents give rise to Joule heating in the isolated wire. It is obvious in this case that the energy is propagated from the Van de Graaff generator to the isolated wire by the electromagnetic field. The same is true for continuous electric currents. The charge carriers at any point are accelerated by the local electric field, which owes its existence to the presence of a seat of emf. The deceleration of the charge carriers leads to Joule heating. Thus the energy "flows" from the seat of emf to the various parts of a conductor via the electromagnetic field. The use of the Poynting vector to calculate the Joule heat generated in a conductor (see Panofsky and Phillips[1]) is a satisfactory model. The presence of the connecting wire guides the direction of energy flow in the electromagnetic field. The electromagnetic field is sustained, in the present case, by the Van de Graaff generator which does mechanical work against the electromagnetic field, when the belt carries charge from a low to a higher potential and maintains the external potential difference.

We return now to the query about the door bell. It is assumed that the current is derived from an electric battery. When the front door switch is open, the two wires leading to the switch are equipotentials, corresponding to the two different electric potentials of the terminals of the battery. When the switch is closed, at the instant of contact, electrons flow from one connecting wire to the other through the switch, under the influence of the electric field due to the potential difference between the connecting wires. This electron flow upsets the previously existing potential and charge distributions. Transient currents flow in the connecting wires until for Ohmic conductors, the potential differences in various parts of the circuit are consistent with Ohm's law. Some of the initial current flow is towards the boundaries of the conductors, but when the current is steady it is "guided" along the conducting wire. The transient effects after the switch is closed move from the switch along the whole lengths of the connecting wires. The changes in conduction current take place under the influence of the changes in charge and electric field distributions. The electric field changes are propagated with a velocity comparable to the velocity of light, the steady state is reached almost instantaneously and the bell rings. One does not have to wait for charge carriers to move all the way from the battery along the wire to the bell before it rings.

[1] W. K. H. Panofsky and M. Phillips, *Classical Electricity and Magnetism* (Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, 1962), 2nd ed., p. 180.

Undergraduate Laboratory Timer

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IN elementary physics and physical science laboratories, some device for measuring time intervals of a few tenths of a second to a few seconds is needed, and the system described here is a reaction to the frustration caused by contemplation of the expense of stop clocks and the unreliability of cheap stop watches.

The equipment consists of a master timing unit which delivers ten 110-V pulses per second and of counters capable of counting these pulses.

The master unit comprises only three parts: a 1-rps timing motor,[1] a decagon machined from a brass disk 3 in. in diameter and $\frac{1}{8}$ in. thick mounted on the motor shaft, and a microswitch which rides against the decagon. As the motor turns at the rate of one revolution per second, the rotating decagon opens and closes the microswitch ten times per second. The entire assembly is mounted on an aluminum base.

The counting units, mounted on bases of wood, consist of nonresettable counters and momentary contact switches. When the unit is plugged into the circuit being fed by the master, the counter counts its pulses so long as the key is depressed. When a student wishes to time an event he depresses the key and holds it down during the duration of the event, then notes how much the reading of the counter has increased; this increase represents the time in tenths of seconds.

The distribution system in our laboratory is such that all outlet boxes on the tables can be connected together at the control panel, and so we make such connection then set the master timer on the lecture table in sight of the entire laboratory and let it click away during the period. It and the counter are connected to the distribution system with banana plugs.

This method of timing seems to be preferable to stop watches because of the greater accuracy with which intervals of the order of a second can be read, the comparative cost (each counter unit costs less than $6.00), and the greater ruggedness and life expectancy. For the experiments in which it is being used, this system has adequate accuracy. The irreducible uncertainty introduced by the use of pulses rather than a continuous motion to measure time intervals is a source of less inaccuracy than the reaction time of the student. Moreover, it is a source of imprecision which is easily noticed by students, who worry about this but accept the reading of a stop watch with uncritical faith.

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[1] Timing motor, microswitch, and counters can be obtained from Allied Electronics Company, 100 N. Western Avenue, Chicago, 80, Illinois or similar electrical supply houses.

An Electromagnetic Acceleration Correction to the Debye Relaxation Time

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THE Debye relaxation time for molecules of a dipolar liquid was calculated on the assumption that the molecules were not accelerated, but turned with a constant velocity that depends upon the macroscopic viscosity of the liquid. The effect of the viscosity was to limit the minimum time needed for alignment with an external electric field, thus providing an explanation of dispersion at radio frequencies. It is obvious, however, that a suddenly applied