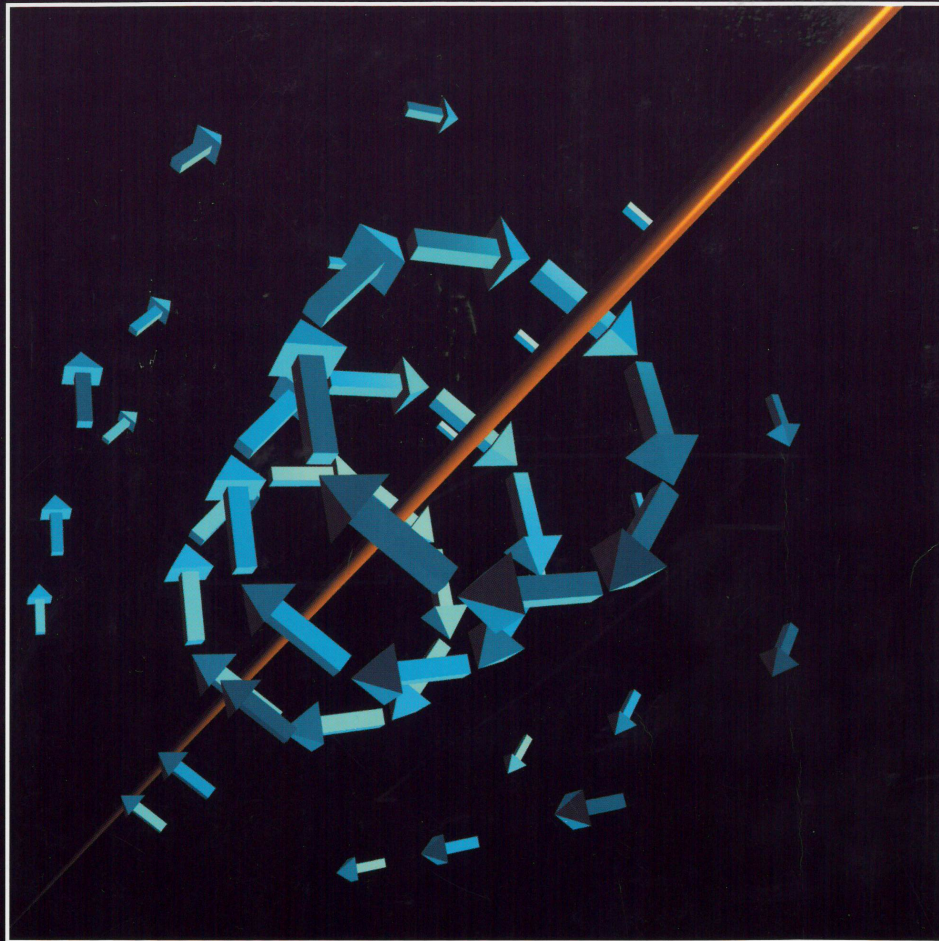


Chabay | Sherwood



# **MATTER & INTERACTIONS II**

ELECTRIC AND MAGNETIC INTERACTIONS

Second Edition

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## **ELECTRIC & MAGNETIC INTERACTIONS**

**SECOND EDITION**

**RUTH W. CHABAY**  
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North Carolina State University



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$$I = \frac{1}{\epsilon_0 \mu_0} \frac{Q}{36\pi R v}$$

This quantity can be shown to have units of C/s, or amperes.

## 20.4 THE HALL EFFECT

Magnetic forces on moving charged particles inside a conductor can cause the conductor to polarize. This is the basis of the Hall effect.

### The initial transient: polarization develops

Mobile electrons moving inside a metal wire can be deflected to the surface of the wire by a magnetic field that is perpendicular to the wire. In Figure 20.18, large coils (not shown) apply a uniform magnetic field of magnitude  $B$  throughout the region of the circuit. As usual, mobile electrons move through the wire in a direction opposite to the electric field driving the current. We will call this electric field  $\vec{E}_{\parallel}$ , because it is parallel to the wire, as we saw in Chapter 18.

Verify for yourself that the moving electrons will be deflected toward the bottom surface of the wire (shown as a rectangular bar for simplicity). This will make the bottom surface negatively charged and the top surface positively charged (due to a deficiency of electrons). These charges are in addition to the usual surface charges, which for clarity we don't show on the diagram.

### The steady state: magnetic force balanced by electric force

As time goes on, more and more electrons will pile up on the bottom of the wire. However, this piling-up won't continue forever. When enough electrons have piled up on the bottom (with a corresponding depletion of electrons on the top surface), these extra surface charges will produce a new electric field that applies a vertical electric force to the moving electrons inside the wire.

? What is the direction of this new electric field?

Inside the metal wire, the new electric field points down, pointing away from the positive charge on the top and towards the negative charge on the bottom. We'll call this the "transverse" electric field,  $\vec{E}_{\perp}$ .

? When no more electrons pile up on the bottom, what is the magnitude  $E_{\perp}$  of the transverse (perpendicular) electric field, in terms of the drift speed  $\bar{v}$  of the free electrons and the magnetic field  $B$ ? (Hint: If no more electrons are piling up, what do you know about the electric and magnetic forces on the moving electrons?)

Pile-up will cease when the electric force grows to be as large as the magnetic force, at which time the net vertical force becomes zero, and the electrons move horizontally through the wire, with no vertical deflection. When this happens we know the vertical force on an electron is zero, so the magnetic force must equal the perpendicular electric force:

$$|\vec{F}_{\text{el}\perp}| = |\vec{F}_{\text{mag}}|$$

$$eE_{\perp} = e\bar{v}B\sin 90^{\circ}, \text{ so } E_{\perp} = \bar{v}B$$

Note the similarity between this analysis and the analysis of the velocity selector on page 707.

? Suppose you attach the leads of a digital voltmeter to the top and bottom surfaces as shown in Figure 20.19. Determine the magnitude and sign of the voltage displayed on the voltmeter (the wire has height

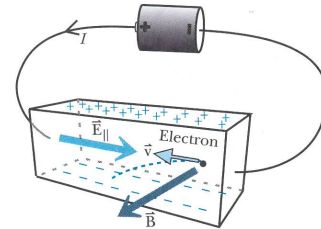


**Figure 20.18** Magnetic deflection of electrons in a conducting bar.  $\vec{E}_{\parallel}$  is the electric field due to the battery and surface charge on the bar (not shown), which drives the current. Polarization shown is due to magnetic deflection of electrons during the transient phase.

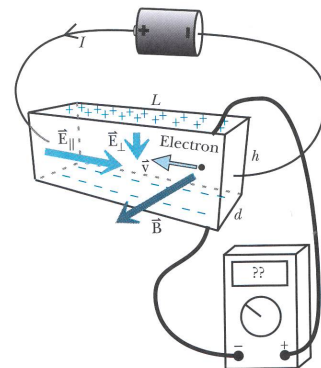


**Figure 20.19** Measuring the transverse potential difference. The voltmeter leads are directly across from each other on the top and bottom surfaces.

$h$ , depth  $d$ , and length  $L$ ; there is a uniform magnetic field of magnitude  $B$ ).

Since the electric field points down inside the wire, the electric potential is higher on top. The electric field has the uniform value  $E_{\perp} = \bar{v}B$  throughout the wire, so the voltmeter will read a positive value  $+E_{\perp}h = +\bar{v}Bh$ .

**?** How big is this voltage if there is no magnetic field?

Since the potential difference is  $\bar{v}Bh$ , the voltage will be zero if  $B = 0$ .

The appearance of a sideways or transverse potential difference across a current-carrying wire in the presence of a magnetic field is called the “Hall effect,” named for its discoverer.

Let’s see approximately how big the Hall voltage is in a metal. Consider a bar of iron of length 5 cm, height 2 cm, and depth 0.5 mm, carrying a conventional current of 15 A to the right in the presence of a perpendicular magnetic field of magnitude 2 T, as shown in Figure 20.19. There are about  $8.4 \times 10^{28}$  mobile electrons per cubic meter in iron.

The magnetic force involves the speed of the moving charge:

$$v = \frac{I}{|q|nA} = \frac{15 \text{ A}}{(1.6 \times 10^{-19} \text{ C})(8.4 \times 10^{28} \text{ m}^{-3})(0.02 \text{ m})(5 \times 10^{-4} \text{ m})} \\ = 1.11 \times 10^{-4} \text{ m/s}$$

In the steady state the vertical force (the force perpendicular to current flow) on a moving charge is zero:

$$F_{\text{mag}} = F_{\text{el}\perp} \text{ and therefore } evB = eE_{\perp}$$

$$E_{\perp} = vB = (1.11 \times 10^{-4} \text{ m/s})(2 \text{ T}) = 2.22 \times 10^{-4} \text{ V/m}$$

$$\Delta V_{\text{Hall}} = E_{\perp}h = (2.22 \times 10^{-4} \text{ V/m})(0.02 \text{ m}) = 4.5 \times 10^{-6} \text{ V}$$

This is a very small voltage, but it can be measured with a sensitive voltmeter whose leads are carefully aligned vertically across the bar.

### Determining the density of mobile charges

We can use measurements of the Hall voltage and the conventional current to determine the density of mobile charges in a metal.

$$\Delta V_{\text{Hall}} = E_{\perp}h = vBh = \left( \frac{I}{|q|nA} \right) (Bh)$$

$$n = \frac{I}{|q|\Delta V_{\text{Hall}}A} (Bh)$$

For some monovalent metals such as sodium, Hall effect measurements show  $n$  to be the same as the number of atoms per cubic meter, indicating that each atom gives up one electron into the free-electron sea. In other metals there may be more than one electron contributed per atom.

### Determining the sign of the mobile charges

The Hall effect offers a very special insight into the nature of the “charge carriers” (mobile charges) responsible for a current. Most electrical measurements come out the same whether electrons are moving inside the wire or positive particles (holes in a metal) are moving in the opposite direction. But the Hall effect differs in the two cases.

Consider what would happen if *positive* particles (holes in the case of aluminum or zinc) were moving to the *right* in the wire as in Figure 20.20, instead of electrons moving to the left.

? On a diagram like Figure 20.20, show the charge pile-up on the top and bottom surfaces and the electric field due to that pile-up. What would be the sign of the voltage displayed on the voltmeter?

Now it is the bottom of the wire that has additional positive surface charge, rather than the top being positive as it was with negative charge carriers. The transverse electric field now points up, and the voltmeter reads a negative voltage.

### HALL EFFECT AND THE SIGN OF CHARGE CARRIERS

By measuring the Hall effect for a particular material, we can determine the sign of the moving particles that make up the current.

In the steady state, the Hall effect is an example of the straight-line motion of charged particles through crossed electric and magnetic fields. Remember that the surface charges which accumulate due to the Hall effect are not the only charges on the wires; there are also the usual surface charges responsible for the longitudinal electric field in the wires. The distinction is that the ordinary surface charges produce electric fields inside the wire in the direction of the conventional current, whereas the Hall-effect surface charges produce a transverse electric field  $\vec{E}_\perp$ , perpendicular to the current.

**20.X.9** Calculate the Hall voltage  $\Delta V_{\text{Hall}}$  for the case of a ribbon of copper 5 mm high and 0.1 mm deep, carrying a current of 20 amperes in a magnetic field of 1 tesla. For copper,  $q = -e$ , and  $n = 8.4 \times 10^{28}$  free electrons per  $\text{m}^3$  (one per atom).

This is a very small voltage, but it can be measured with a sensitive voltmeter. In semiconductors the density of charge carriers  $n$  may be quite small compared to a metal, in which case the Hall-effect voltage can be quite large, since it is inversely proportional to  $n$ .

**20.X.10** It is instructive to compare this transverse Hall voltage in copper with the voltage you would measure *along* the copper ribbon. Calculate the potential difference you would measure along 5 mm of the ribbon; the conductivity of copper is:

$$\sigma = 6 \times 10^7 \frac{\text{A/m}^2}{\text{volt/m}}$$

Since this voltage is much larger than the Hall voltage, experimenters must take special precautions to place their voltmeter leads exactly across from each other, to avoid a spurious reading due to the potential difference along the bar. One way to check for this problem is to remove the magnetic field, in which case the Hall voltage should go to zero.

### Practical applications of the Hall effect

Measuring the Hall effect potential difference for a material can provide information about the sign of the mobile charges and about the number of them per unit volume. For example, Hall effect measurements have confirmed that in some metals and semiconductors, it is positive holes in the electron sea rather than the electrons themselves that are the dominant charge carriers. Hall effect measurements of mobile electron density for some monovalent metals such as sodium and copper shows  $n$  to be the same as the number of atoms per cubic meter, which shows that each atom gives up one electron into the free-electron sea. In other metals there may be more than one electron contributed per atom.

Another practical use of the Hall effect turns the relationship around. There are commercial devices that measure the magnitude and direction of

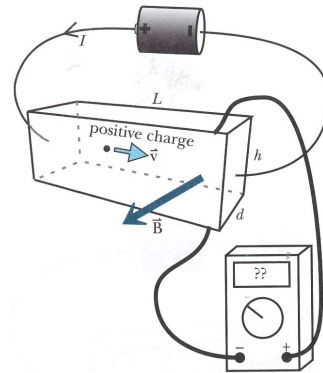


**Figure 20.20** What happens if the charge carriers are positive? The voltmeter leads are directly across from each other on the top and bottom surfaces.

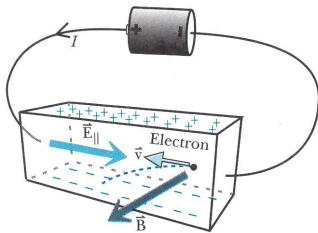


**Figure 20.21** Deflected electrons drag the wire along too.

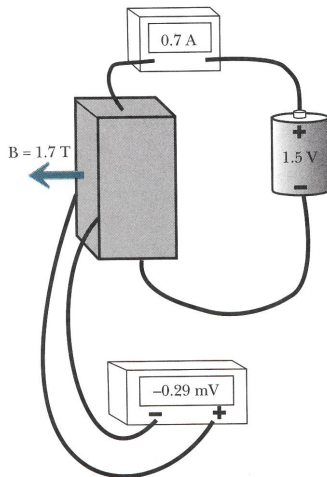


**Figure 20.22** Measuring electrical properties of a new material.

an unknown magnetic field by observing the Hall voltage in a material in which the sign and number density of the mobile charges are known.

### Why does a current-carrying wire move?

There is a subtle point about the magnetic force that a magnetic field exerts on a current-carrying wire. The magnetic force only acts on moving particles, which in the case of a copper wire are the drifting electrons. The stationary positive atomic cores do not experience a magnetic force. So why does the entire wire move?

The answer to this puzzle is closely related to the Hall effect. In Figure 20.21, consider again a current-carrying metal wire in a magnetic field, with a growing number of electrons piling up on the bottom surface (and a deficiency of electrons accumulating on the top surface). Again, for clarity we don't show the usual surface charges along the wire; we just show the extra surface charges due to the magnetic deflection of the electrons.

The extra surface charges exert an electric force  $eE_{\perp}$  upward on the moving electrons which in the steady state just balances the magnetic force  $e\mathbf{v} \times \mathbf{B}$ . The extra surface charges also exert an electric force  $eE_{\perp}$  on the positive atomic cores, and this is an unbalanced force, because the atomic cores initially are not moving and hence are not subject to a magnetic force.

**?** What is the direction of this electric force exerted by the surface charges on the atomic cores?

Evidently the positively charged atomic cores are pulled downward. The electric force due to the Hall-effect surface charges forces the wire as a whole to move in the direction of  $\Delta \vec{F}_{\text{magnetic}} = I \Delta \vec{l} \times \vec{B}$ , and the magnitude of the electric force is equal to this force. The overall effect is that in Figure 20.21 the atomic cores are dragged downward as the electrons are dragged downward. The motion of the wire is an electric side effect of the magnetic force on the moving electrons.

Another way of thinking about this is to say that the electrons are bound electrically to the metal wire—they can't simply fall out of the wire. So when the electrons are pushed down by the magnetic force, they drag the wire along with them.

### Example: Determining electrical properties

A bar made out of a new conducting material is 9 cm long with a rectangular cross section 4 cm wide and 2 cm deep. The bar is inserted into a circuit with a 1.5-volt battery and carries a constant current of 0.7 ampere (Figure 20.22). The resistance of the copper connecting wires and the ammeter, and the internal resistance of the battery, are all negligible compared to the resistance of the bar.

Using large coils not shown in the diagrams, a uniform magnetic field of 1.7 tesla is applied perpendicular to the bar (to the left, as shown in Figure 20.22). A voltmeter is connected across the bar, with the connections across the bar carefully placed directly across from each other as shown. The voltmeter reads  $-0.29$  millivolts. Remember that a voltmeter reads positive if the positive lead is connected to a higher potential location than the negative lead. There is only one kind of mobile charge in the bar material.

(a) What is the sign of the mobile charges in the bar, and which way do they move? Explain carefully, using diagrams to support your explanation.

(b) How long does it take for a mobile charge to go from one end of the bar to the other?

(c) What is the mobility  $u$  of the mobile charges?

(d) If each mobile charge is singly charged ( $|q| = e$ ), how many mobile charges are there in  $1 \text{ m}^3$  of this material?

**Solution**

(a) This requires trial and error—we assume that the mobile charges have a particular sign, and see if this would lead to the observed polarization. First we need to draw  $\vec{E}_{\parallel}$ , the field established by the batteries and surface charge on the bar, which drives the current in the bar (see Figure 20.23).

If the mobile charges are positive, they will move in the direction of  $\vec{E}_{\parallel}$ . As is shown in Figure 20.23, this would lead to positive charge buildup on the back of the bar (magnetic force into the page). The voltmeter would give a positive reading, because  $\vec{E}_{\perp}$  would point out of the page. This is not what is observed, so the mobile charges must not be positive.

If the mobile charges are negative, they will move opposite to  $\vec{E}_{\parallel}$ , as shown in Figure 20.24. The magnetic force would again be into the page, making the back of the bar negative, and creating  $\vec{E}_{\perp}$  pointing into the page. The voltmeter reading would be negative, as is observed. We can conclude that the mobile charges are negative.

(b) We need to find the drift speed of the mobile charges, which we can find from the magnetic force on an electron. In the steady state, the transverse magnetic and electric forces balance, so  $eE_{\perp} = evB$ . We have  $E_{\perp} = (\Delta V_{\perp})/d = vB$ , where  $d = 2$  cm, so

$$v = \frac{\Delta V_{\perp}}{Bd} = \frac{0.29 \times 10^{-3} \text{ volt}}{(1.7 \text{ T})(0.02 \text{ m})} = 8.5 \times 10^{-3} \text{ m/s}$$

$$\Delta t = \frac{0.09 \text{ m}}{8.5 \times 10^{-3} \text{ m/s}} = 10.6 \text{ s}$$

(c)  $v = uE_{\parallel}$ , where  $E_{\parallel} = (1.5 \text{ V})/(0.09 \text{ m}) = 16.7 \text{ V/m}$  is the longitudinal electric field in the direction of the current.

$$u = v/E_{\parallel} = (8.5 \times 10^{-3} \text{ m/s})/(16.7 \text{ V/m}) = 5 \times 10^{-4} \text{ (m/s)/(V/m)}$$

(d)  $I = enAv$ , so  $n = I/(eAv)$

$$n = \frac{(0.7 \text{ A})}{(1.6 \times 10^{-19} \text{ C})(0.02 \text{ m})(0.04 \text{ m})(8.5 \times 10^{-3} \text{ m/s})} = 6.4 \times 10^{23} \text{ m}^{-3}$$

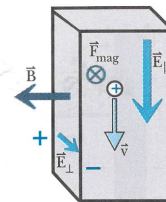


**Figure 20.23** If the mobile charges are positive their velocity will be in the direction of  $\vec{E}_{\parallel}$ . The magnetic force will be into the page, so the back of the bar will become positive.

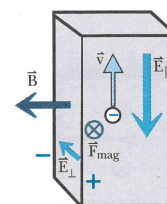


**Figure 20.24** If the mobile charges are negative, their velocity will be opposite to  $\vec{E}_{\parallel}$ . The magnetic force will again be into the page, so the back of the bar will become negative.

## 20.5 MOTIONAL EMF

A magnetic field exerts a force on a current-carrying wire. This effect can be reversed: moving a wire through a magnetic field makes a current run in the wire, which provides a way to generate electricity from mechanical work.

### The initial transient: Polarization develops

Consider a metal bar of length  $L$  that is moving through a region of uniform magnetic field, into the page, with magnitude  $B$  (Figure 20.25). Because a mobile electron inside the moving metal bar is moving to the right, it experiences a magnetic force.

? If the bar is moving at a speed  $v$ , what are the magnitude and direction of the magnetic force on this electron?

The magnetic force  $\vec{F} = (-e)\vec{v} \times \vec{B}$  points downward, and the magnitude of the force is  $evB \sin(90^\circ) = evB$ . As a result of this magnetic force, the mobile-electron sea will shift downward.

? What will the resulting approximate charge distribution on the metal bar be? What is the direction of the electric field  $\vec{E}$  produced by this charge distribution inside the metal?

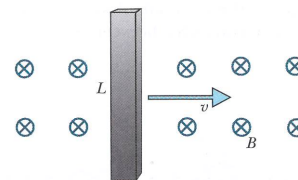


**Figure 20.25** A metal bar moving at constant velocity through a region of uniform magnetic field into the page.

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