

# Electromagnetism IV: Lorentz Force

The problems here mostly use material covered in previous problem sets, though chapter 5 of Purcell covers relativistic field transformations. For further interesting physical examples, see chapter II-29 of the Feynman lectures. There is a total of **84** points.

## 1 Electrostatic Forces

### Idea 1: Lorentz Force

A charge  $q$  in an electromagnetic field experiences the force

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}).$$

In particular, a stationary wire carrying current  $I$  in a magnetic field experiences the force

$$\mathbf{F} = I \int d\mathbf{s} \times \mathbf{B}.$$

### Example 1: PPP 183

A small charged bead can slide on a circular, frictionless insulating ring. A point-like electric dipole is fixed at the center of the circle with the dipole's axis lying in the plane of the circle. Initially the bead is in the plane of symmetry of the dipole, as shown.



Ignoring gravity, how does the bead move after it is released? How would the bead move if the ring weren't there?

### Solution

Set up spherical coordinates so that the dipole is in the  $\hat{\mathbf{z}}$  direction. Then

$$V(r, \theta) = \frac{kp \cos \theta}{r^2}.$$

Since the ring fixes  $r$ , the potential on the ring is just proportional to  $\cos \theta$ , which is in turn proportional to  $z$ . But a potential linear in  $z$  is equivalent to a uniform downward field, so the bead oscillates like the mass of a pendulum, with amplitude  $\pi/2$ .

The answer remains the same when the ring is removed! Conservation of energy states that

$$\frac{kqp \cos \theta}{r^2} + \frac{1}{2}mv^2 = 0.$$

Let  $N$  be the normal force. Then accounting for radial forces gives

$$N + q \frac{\partial V}{\partial r} = \frac{v^2}{r}.$$

However, plugging in our conservation of energy result for  $v^2$  shows that  $N = 0$ , so the ring doesn't actually do anything, and it may be removed without effect.

### Example 2

A parallel plate capacitor with separation  $d$  and area  $A$  is attached to a battery of voltage  $V$ . Suppose the plates are moved together with speed  $v$ . Verify that energy is conserved.

### Solution

The capacitance is  $C = A\epsilon_0/d$ . The power supplied by the battery is

$$P_{\text{batt}} = IV = V \frac{dQ}{dt} = V^2 \frac{dC}{dt}.$$

On the other hand, the rate of change of the energy stored in the battery is

$$P_{\text{cap}} = \frac{d}{dt} \left( \frac{1}{2} CV^2 \right) = \frac{1}{2} V^2 \frac{dC}{dt}.$$

At first glance, there seems to be a problem. But then we remember that there is an attractive force between the plates, so the plates do work on whatever is moving them together,

$$P_{\text{mech}} = Fv = \frac{QE}{2} v = \frac{QV}{2d} v = \frac{1}{2} CV^2 \frac{v}{d} = \frac{1}{2} V^2 \frac{dC}{dt}.$$

where  $E$  is the electric field inside the capacitor. Thus,  $P_{\text{batt}} = P_{\text{cap}} + P_{\text{mech}}$  as required.

- [2] **Problem 1** (PPP 193). Two positrons are at opposite corners of a square of side  $a$ . The other two corners of the square are occupied by protons. All particles have charge  $q$ , and the proton mass  $M$  is much larger than the positron mass  $m$ . Find the approximate speeds of the particles much later.
- [3] **Problem 2** (PPP 114). A small positively charged ball of mass  $m$  is suspended by an insulating thread of negligible mass. Another positively charged small ball is moved very slowly from a large distance until it is in the original position of the first ball. As a result, the first ball rises by  $h$ .



How much work has been done?

- [3] **Problem 3** (PPP 71). Two small beads slide without friction, one on each of two long horizontal parallel fixed rods a distance  $d$  apart.



The masses of the beads are  $m$  and  $M$  and they carry charges  $q$  and  $Q$ . Initially, the larger mass  $M$  is at rest and the other one is far away approaching it at a speed  $v_0$ . For what values of  $v_0$  does the smaller bead ever get to the right of the larger bead?

- [2] **Problem 4** (PPP 192). Classically, a conductor is made of nuclei of positive charge fixed in place, and electrons that are free to move.
- Consider a solid conductor in a gravitational field  $\mathbf{g}$ . Argue that the electric field inside the conductor is *not* zero; find out what it is.
  - Now suppose a positron is placed at the center of a hollow spherical conductor in a gravitational field  $\mathbf{g}$ . Find its initial acceleration.
- [3] **Problem 5**. ⌚ USAPhO 2008, problem B2. You may ignore part (c), which was removed in the final version of the exam, though you can also do it for extra practice.
- [3] **Problem 6**. ⌚ USAPhO 2019, problem B1.
- [5] **Problem 7**. ⌚ IPhO 2004, problem 1. A nice question on the dynamics of a multi-part system.

## 2 The Lorentz Force

### Idea 2

The Lorentz force

$$\mathbf{F} = \frac{d\mathbf{p}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}).$$

In some problems below, you might worry that this relation is modified due to relativistic effects, but it isn't. The Lorentz force expression is always correct, and it's all you need for almost all the problems in this section.

What does change in relativity is the relation between  $\mathbf{p}$  and  $\mathbf{v}$ ,

$$\mathbf{p} = \gamma m \mathbf{v}, \quad \gamma = \frac{1}{\sqrt{1 - v^2/c^2}}.$$

The relativistic energy is also modified to

$$E = \gamma mc^2 = mc^2 + \frac{1}{2}mv^2 + \dots$$

We will return to this subject in more detail in **R2**.

### Example 3: Kalda 163

A beam of electrons, of mass  $m$  and charge  $q$ , is emitted with a speed  $v$  almost parallel to a uniform magnetic field  $\mathbf{B}$ . The initial velocities of the electrons have an angular spread of  $\alpha \ll 1$ , but after a distance  $L$  the electrons converge again. Neglecting the interaction between the electrons, what is  $L$ ?

### Solution

Consider an electron initially traveling at an angle  $\alpha$  to the magnetic field. This electron has a speed  $v_{\parallel} = v \cos \alpha \approx v$  parallel to the field, and a speed  $v_{\perp} = v \sin \alpha \approx v\alpha$  perpendicular to the field. The component  $v_{\parallel}$  always stays the same, while  $v_{\perp}$  rotates, so the electron spirals along the field lines.

The acceleration of the electron is

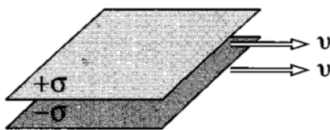
$$a_{\perp} = \frac{F}{m} = \frac{qv_{\perp}B}{m}.$$

The perpendicular velocity component rotates through a circle in velocity space of circumference  $2\pi v_{\perp}$ . After one such circle, the total perpendicular displacement is zero, so the beam refocuses. Thus we have

$$L = \frac{2\pi v_{\perp}}{a} v_{\parallel} \approx \frac{2\pi mv}{qB}.$$

In other words, this setup acts like a magnetic “lens”.

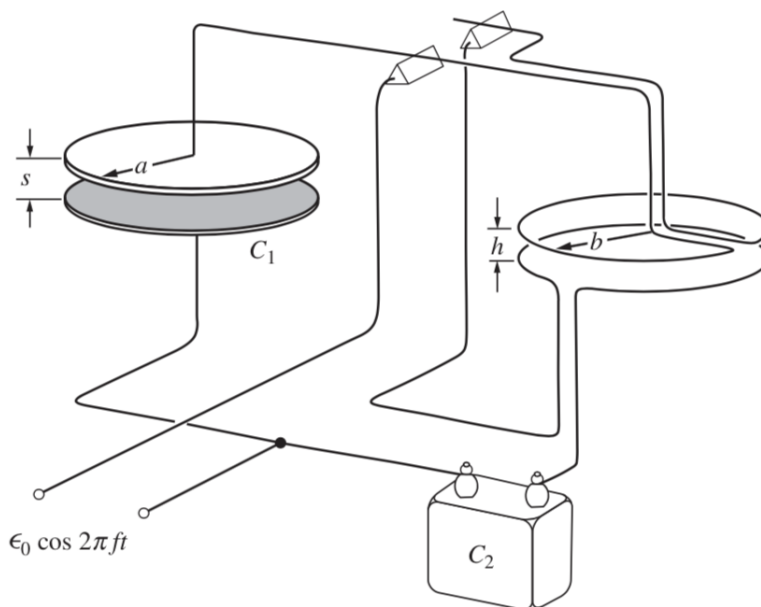
- [3] **Problem 8** (Griffiths 5.17). A large parallel plate capacitor with uniform surface charge  $\sigma$  on the upper plate and  $-\sigma$  on the lower is moving with a constant speed  $v$  as shown.



- Find the magnetic field between the plates and also above and below them.
- Find the magnetic force per unit area on the upper plate, including its direction.

(c) What happens to the net force between the plates in the limit  $v \rightarrow c$ ? Explain your result using some basic ideas from special relativity.

- [3] **Problem 9.** EFPhO 2012, problem 7. An elegant Lorentz force problem with wires. (If you enjoy this problem, consider looking at IdPhO 2020, problem 1B, which has a similar setup but requires three-dimensional reasoning. The official solutions are [here](#).)
- [4] **Problem 10** (Purcell 6.35/INPhO 2008.6). Consider the arrangement shown below.



The force between capacitor plates is balanced against the force between parallel wires carrying current in the same direction. A voltage alternating sinusoidally with angular frequency  $\omega$  is applied to the parallel-plate capacitor  $C_1$  and also to the capacitor  $C_2$ , and the current is equal to the current through the rings. Assume that  $s \ll a$  and  $h \ll b$ .

Suppose the weights of both sides are adjusted to balance without any applied voltage, and  $C_2$  is adjusted so that the time-averaged downward forces on both sides are equal. Show that

$$\frac{1}{\sqrt{\mu_0 \epsilon_0}} = \sqrt{2\pi} a \omega \sqrt{\frac{b}{h}} \frac{C_2}{C_1}.$$

The left-hand side is equal to  $c$ , as we'll show in **E7**, so this setup measures the speed of light.

- [3] **Problem 11.** An electron beam is accelerated from rest by applying an electric field  $E$  for a time  $t$ , and subsequently guided by magnetic fields. These magnetic fields are produced with a series of coils, which carry currents  $I_i$ .

Now suppose the apparatus is repurposed to shoot proton beams. Suppose a proton beam is accelerated from rest by applying an electric field  $E$  for a time  $t$  (in the opposite direction). Let an electron have mass  $m$  and a proton have mass  $M$ .

- (a) Find the currents  $I_i$  needed so that the proton follows the same trajectory the electron did, assuming  $V$  is small enough that both the electron and proton are nonrelativistic.
- (b) How does the answer change if relativistic corrections are accounted for?

- [5] **Problem 12.** ⌚ IPhO 2000, problem 2. A solid question on the Lorentz force with real-world relevance. Requires a little relativity, namely the expressions for relativistic momentum/energy.
- [4] **Problem 13.** ⌚ IPhO 1996, problem 2. An elegant problem on particles in a magnetic field.

### 3 Permanent Magnets

- [3] **Problem 14.** Consider a current loop  $I$  in the  $xy$  plane in a constant magnetic field  $\mathbf{B}$ .

(a) Show that the net force on the loop is zero.

(b) Show that the torque is

$$\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B}$$

where the magnetic moment is

$$\mathbf{m} = IA\hat{\mathbf{z}}$$

where  $A$  is the area of the loop. For simplicity, you can show this in the case where the current loop is a square of side length  $L$ , whose sides are aligned with the  $x$  and  $y$  axes. (The proof for a general loop shape requires some vector calculus, but you can attempt it for a challenge. You'll need the double cross product identity,  $\mathbf{a} \times (\mathbf{b} \times \mathbf{c}) + \mathbf{b} \times (\mathbf{c} \times \mathbf{a}) + \mathbf{c} \times (\mathbf{a} \times \mathbf{b}) = 0$ .)

#### Idea 3

The force on a small current loop is

$$\mathbf{F} = (\mathbf{m} \cdot \nabla)\mathbf{B}$$

but this requires some tricky vector calculus to derive, shown [here](#). The same force and torque results hold for electric dipoles, if we replace  $\mathbf{m}$  with  $\mathbf{p}$  and  $\mathbf{B}$  with  $\mathbf{E}$ .

Both the force and torque expressions can also be found by differentiating the energy

$$U = -\mathbf{m} \cdot \mathbf{B}.$$

However, this expression can be highly misleading, because when a current loop is moved through a nonuniform magnetic field, two sources of work are necessary: mechanical work against the force on the dipole, and electrical work to keep the current in the loop the same. The latter appears because the changing flux through the loop induces an emf, which would otherwise change the current. The expression  $U = -\mathbf{m} \cdot \mathbf{B}$  only counts the mechanical work, which means it can lead you astray in problems we'll consider later, where the total energy of the dipole matters. You won't need to use this expression in any of the problems here. Some further discussion of this point is in chapter II-15 of the Feynman lectures.

#### Example 4

If a bar magnet is held over a table, it can pick up a paper clip. If the paper clip is removed, it can pick up another paper clip just as well, and this process can seemingly continue forever without any effect on the magnet. Since the magnet does work on each paper clip, doesn't

this mean a permanent magnet is an infinite energy source?

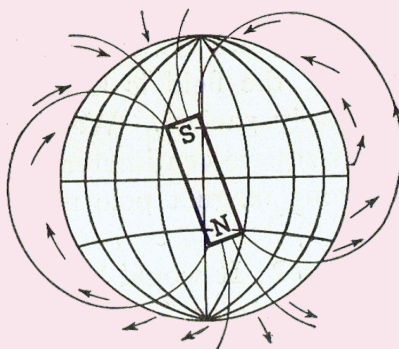
### Solution

This is the kind of question that makes magnets feel so mysterious. They're basically the only everyday example of a long range force besides gravity (in fact, Kepler once thought the Sun acted on the planets like a giant magnet), and as such they've inspired countless attempts at perpetual motion machines. Many people have spent years of their lives trying to get elaborations of this example to work.

To see why it doesn't work, just replace the word "magnet" with "charge". It's true that a positive charge can attract a negative charge to it. And if the negative charge is then removed, the positive charge can then attract another negative charge to it. But conservation of energy isn't violated, because the force from the positive charge is conservative: the work it does on the negative charge to draw it close is precisely the opposite of the work an external agent needs to do to pull it away. The force of a magnet on a paper clip is also conservative.

### Remark

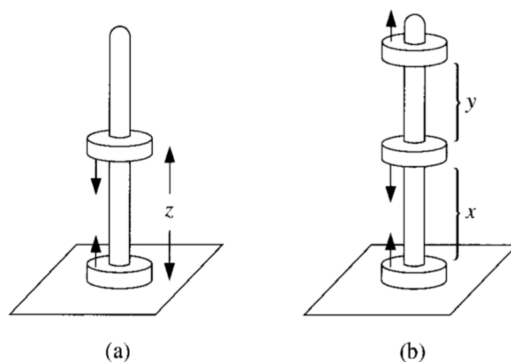
A compass needle is essentially a small magnetic dipole, whose dipole moment points towards the end painted red. We can also approximate the Earth's magnetic field as a dipole field.



Since the tangential component of this dipole field points north, the red end of the compass points towards the geographic north pole, which is the Earth's magnetic south pole.

By the way, a cheap compass calibrated to work in America or Europe won't work well in Australia. The reason is that the Earth's magnetic field also has a radial component, which acts to tip the compass needle up or down. The needle needs to be appropriately weighted to stay horizontal, so that it can freely rotate, but the side that needs to be weighted differs between the hemispheres.

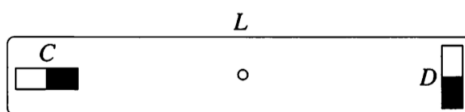
- [3] **Problem 15** (Griffiths 6.23). A familiar toy consists of donut-shaped permanent magnets (magnetization parallel to the axis) which slide frictionlessly on a vertical rod.



Treat the magnets as dipoles with mass  $m_d$  and dipole moment  $\mathbf{m}$ .

- (a) If you put two back-to-back magnets on the rod, the upper one will “float”. At what height  $z$  does it float?
- (b) If you now add a third magnet parallel to the bottom one as shown, find the ratio  $x/y$  of the two heights, using only a scientific calculator. (Answer: 0.85.)

- [3] **Problem 16.** [AuPhO 2019, problem 13](#). An elegant series of visual exercises on permanent magnets, with practical applications. It will be useful to consult the [answer sheet](#).
- [3] **Problem 17** (PPP 89). Two identical small magnets are placed on opposite ends of a rod of length  $L$  as shown.



- (a) Show that the torques the magnets exert on each other are *not* equal and opposite.
- (b) If the rod is fixed but the magnets are each free to spin, will they? Does this violate conservation of angular momentum?
- (c) Now suppose the magnets are glued to the rod, and the rod is pivoted at its center so that only the rod and the magnets as a whole can spin. Will the rod spin? Does this violate conservation of angular momentum? How about conservation of energy?

## 4 Point Charges

In this section we’ll give a sampling of classic problems involving just point charges in fields; these will be a bit more mathematically advanced than the others in this problem set.

- [3] **Problem 18.** A point charge  $q$  is released from rest a distance  $d$  from a grounded conducting plane. Find the time until the point charge hits the plane. (Hint: consider Kepler’s laws.)
- [3] **Problem 19.** A point charge of mass  $m$  and charge  $q$  is released from rest at the origin in the fields  $\mathbf{E} = E\hat{\mathbf{x}}$ ,  $\mathbf{B} = B\hat{\mathbf{y}}$ . Find its position as a function of time by solving the differential equations given by Newton’s second law,  $\mathbf{F} = m\mathbf{a}$ .



- [3] **Problem 20** (Wang). Two identical particles of mass  $m$  and charge  $q$  are placed in the  $xy$  plane with a uniform magnetic field  $B\hat{\mathbf{z}}$ . The particles have paths  $\mathbf{r}_1(t)$  and  $\mathbf{r}_2(t)$ . Neglect relativistic effects, but account for the interaction between the charges.

- (a) Write down a differential equation describing the evolution of the separation  $\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$ .
- (b) Suppose that the initial conditions have been set up so that the particles orbit each other in a circle in the  $xy$  plane, with constant separation  $d$ . What is the smallest  $d$  for which this motion is possible?

- [4] **Problem 21.** [A] Consider a point charge of mass  $m$  and charge  $q$  in the field of a magnetic monopole at the origin,

$$\mathbf{B} = \frac{g}{r^2} \hat{\mathbf{r}}.$$

In this problem we'll investigate the strange motion that results.

- (a) Argue that the speed  $v$  is constant.
- (b) Show that the angular momentum  $\mathbf{L}$  of the charge is *not* conserved, but that

$$\mathbf{V} = \mathbf{L} - qg\hat{\mathbf{r}}$$

is. The second term is the angular momentum stored in the fields of the charge and monopole.

- (c) Show that the charge moves on the surface of a cone. (Hint: in spherical coordinates where the  $z$ -axis is parallel to  $\mathbf{V}$ , consider  $\mathbf{V} \cdot \hat{\phi}$ .) Sketch some typical trajectories.

One can do problem 19 slickly using field transformations, an advanced subject we will cover in **R3**.

#### Idea 4: Field Transformations

If the electromagnetic field is  $(\mathbf{E}, \mathbf{B})$  in one reference frame, then in a reference frame moving with velocity  $\mathbf{v}$  with respect to this frame, the components of the field parallel to  $\mathbf{v}$  are

$$E'_{\parallel} = E_{\parallel}, \quad B'_{\parallel} = B_{\parallel}$$

while the components perpendicular are

$$\mathbf{E}'_{\perp} = \gamma(\mathbf{E}_{\perp} + \mathbf{v} \times \mathbf{B}), \quad \mathbf{B}'_{\perp} = \gamma\left(\mathbf{B}_{\perp} - \frac{\mathbf{v}}{c^2} \times \mathbf{E}\right).$$

#### Remark

The nonrelativistic limit of the field transformation is useful, but one has to be careful in deriving it. You might think, what's the need for care? Can't we just send  $c \rightarrow \infty$ , Taylor expand the above expressions, and call it a day? The problem with this reasoning is that there's no such thing as setting  $c \rightarrow \infty$ . You can't change a fundamental constant, and moreover this statement isn't even dimensionally correct, as noted in **P1**. What we really mean by the nonrelativistic limit is restricting our attention to some subset of possible situations, within which relativistic effects don't matter.

For example, if we have a bunch of point charges with typical speed  $v$ , then the nonrelativistic

limit is considering only situations where  $v/c$  is small. In other words, we are taking  $v/c \rightarrow 0$ , not  $c \rightarrow \infty$ . Since the magnetic field of a point charge is  $v/c^2$  times the electric field, the magnetic field ends up small. Now if we also consider boosts with small speeds  $v$ , then expanding the field transformations to lowest order in  $v/c$  gives

$$\mathbf{E}' = \mathbf{E}, \quad \mathbf{B}' = \mathbf{B} - \frac{\mathbf{v}}{c^2} \times \mathbf{E}.$$

This is the nonrelativistic limit for situations where  $E/B \gg c$ , also called the electric limit.

However, there's another possibility. Suppose that we have a bunch of neutral wires. In this case, it's the electric fields that are small,  $E/B \ll c$ . Using this in the transformations above, we arrive at the distinct result

$$\mathbf{B}' = \mathbf{B}, \quad \mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B}$$

which apply for situations where  $E/B \ll c$ , also called the magnetic limit.

You might think we could improve the approximation by combining the two,

$$\mathbf{E}' = \mathbf{E} + \mathbf{v} \times \mathbf{B}, \quad \mathbf{B}' = \mathbf{B} - \frac{\mathbf{v}}{c^2} \times \mathbf{E}.$$

You'll even see this occasionally used in problems, but it isn't self-consistent. For example, if you apply a Galilean boost with speed  $v$ , and then a boost with speed  $-v$ , you don't get back the same fields you started with! A sensible Galilean limit is only possible if  $E/B \gg c$  or  $E/B \ll c$ , which are called the electric and magnetic limits. It's only in special relativity that the two are treated on an equal footing.

**[3] Problem 22.** Using the Galilean field transformations to solve problem 19.

- (a) In the magnetic limit, show that the Lorentz force stays the same between frames, as it should. Then use the field transformations to solve the problem.
- (b) In the electric limit, show that the Lorentz force stays the same up to terms that are order  $(v/c)^2$  smaller, where  $B/E \sim v/c^2$ . (This is fine, since at second order relativity has to come in anyway.) Then use the field transformations to solve the problem.
- (c) The solutions you found in parts (a) and (b) should look very different, even though you should have found only one type of behavior in problem 19. In fact, there is a critical value of  $E/B$  separating the two kinds of behavior. What is this critical value, and why didn't you run into it when solving problem 19?

## 5 Continuous Systems

### Example 5: Drude Theory

Model a conductor as a set of electrons, of charge  $q$ , mass  $m$ , and number density  $n$ , which are completely free. Assume that in every small time interval  $dt$ , each electron has a probability  $dt/\tau$  of hitting a lattice ion, which randomizes the direction of its velocity. Under these assumptions, compute the resistivity of the material.

### Solution

First, suppose the electrons have some average momentum  $\langle \mathbf{p} \rangle$  each. Because the collisions randomize the velocity, the average momentum falls exponentially with timescale  $\tau$ ,

$$\frac{d\langle \mathbf{p} \rangle}{dt} = -\frac{\langle \mathbf{p} \rangle}{\tau}.$$

On the other hand, if there is an applied field, a force term appears on the right,

$$\frac{d\langle \mathbf{p} \rangle}{dt} = -\frac{\langle \mathbf{p} \rangle}{\tau} + q\mathbf{E}$$

since  $\mathbf{F} = d\mathbf{p}/dt$  for each individual electron. In the steady state,

$$\langle \mathbf{p} \rangle = q\mathbf{E}\tau.$$

The current density is

$$\mathbf{J} = nq\langle \mathbf{v} \rangle = \frac{nq\langle \mathbf{p} \rangle}{m} = \frac{nq^2\tau}{m}\mathbf{E}.$$

Thus, the resistivity in the Drude model is

$$\rho = \frac{m}{nq^2\tau}.$$

We can also compute the typical drift velocity,

$$v = \frac{qE\tau}{m}.$$

For values of  $m$  that give reasonable  $\rho$ , the value of  $v$  is a literal snail's pace, which is why people say that the electrons themselves move very slowly through a circuit. (Of course, a current can get started in a circuit much faster, because when a battery is attached, each moving electron pushes on the next one along the wire, and this wave of motion travels much faster than the electrons themselves.)

### Remark

Above we assumed there was a given probability of collision per unit time, but usually when a particle flies through a medium, there is a given probability of collision per unit *length* it travels. If we had made the latter assumption, then the typical energy of the electrons would

match the work done on them in the typical length  $\ell$  they travel,  $mv^2/2 \sim qE\ell$ , but that implies an average velocity that scales as  $v \propto \sqrt{E}$ . The analogue of Ohm's law would then be  $I \propto \sqrt{V}$ , completely contrary to observation!

A given probability of collision per unit *time* would be what we expect if the electrons had constant speed, but how is this possible? The answer, as shown in **X1**, involves quantum mechanics. The idea is that, due to the Pauli exclusion principle, the electrons in the conductor have to occupy different quantum states, and the high density of electrons requires most of them to have extremely high velocities, on the order of 1% of the speed of light! The drift velocity is merely the tiny amount by which these velocities are shifted on average, so their speeds are almost constant between collisions.

- [2] **Problem 23.** Consider Drude theory again, but now suppose there is also a fixed magnetic field  $B\hat{z}$ . In this case,  $\mathbf{J}$  is not necessarily parallel to  $\mathbf{E}$ , but the relation between the two can be described by the “tensor of resistivity”. That is, the components are related by

$$E_i = \sum_{j \in \{x,y,z\}} \rho_{ij} J_j.$$

Calculate the coefficients  $\rho_{ij}$ . Express your answers in terms of the quantities

$$\rho_0 = \frac{m}{nq^2\tau}, \quad \omega_0 = \frac{qB}{m}$$

as well as the parameter  $\tau$ .

### Example 6: Griffiths 5.40

Since parallel currents attract, the currents within a single wire should contract. To estimate this, consider a long wire of radius  $r$ . Suppose the atomic nuclei are fixed and have uniform density, while the electrons move along the wire with speed  $v$ . Furthermore, assume that the electrons contract, filling a cylinder of radius  $r' < r$  with uniform negative charge density, and that the wire is overall neutral. Find  $r'$ .

### Solution

The contraction of the electrons produces an overall inward electric field, and hence an outward electric force on each electron, which balances the radially inward magnetic force. Specifically, equilibrium occurs when  $E = vB$ .

Let the charge densities of the nuclei and electrons be  $\rho_+$  and  $\rho_-$ . The magnetic field at radius  $r$  is found by Ampere's law, which gives

$$(2\pi r)B = \mu_0(\rho_-v)(\pi r^2), \quad B = \frac{\mu_0\rho_-vr}{2}.$$

The electric field at radius  $r$  is found by Gauss's law, which gives

$$(2\pi r)E = \frac{1}{\epsilon_0}(\rho_+ + \rho_-)\pi r^2, \quad E = \frac{1}{2\epsilon_0}(\rho_+ + \rho_-)r.$$

Note that both  $E$  and  $B$  are proportional to  $r$ . Then  $E = vB$  can be satisfied at all  $r$  simultaneously, which confirms that our assumption that  $\rho_+$  and  $\rho_-$  were uniform is self-consistent.

Plugging these results into  $E = vB$  yields

$$\rho_+ + \rho_- = \rho_-(\epsilon_0\mu_0v^2) = \rho_-\frac{v^2}{c^2}.$$

This can be written in terms of the Lorentz factor of special relativity,

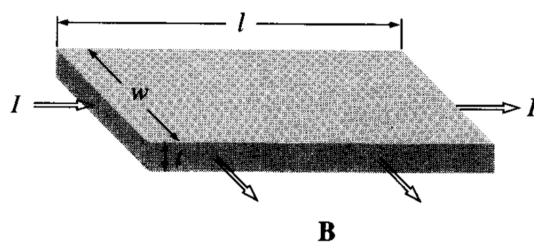
$$\rho_- = -\gamma^2\rho_+, \quad \gamma = \frac{1}{\sqrt{1 - v^2/c^2}}.$$

Since the wire is overall neutral,  $\rho_-r'^2 + \rho_+r^2 = 0$ , so

$$r' = \frac{r}{\gamma}.$$

For nonrelativistic motion, the contraction is extremely small. (However, in plasmas, where the positive charges are also free to move, this so-called pinch effect can be very significant.)

- [2] **Problem 24** (Griffiths 5.41). A current  $I$  flows to the right through a rectangular bar of conducting material, in the presence of a uniform magnetic field  $\mathbf{B}$  pointing out of the page, as shown.



- If the moving charges are positive, in what direction are they deflected by the magnetic field? This deflection results in an accumulation of charge on the upper and lower surfaces of the bar, which in turn produces an electric force to counteract the magnetic one. Equilibrium occurs when the two exactly cancel. (This phenomenon is known as the Hall effect.)
- Find the resulting potential difference, called the Hall voltage, between the top and bottom of the bar, in terms of  $B$ , the speed  $v$  of the charges, and the dimensions of the bar.
- How would the answer change if the moving charges were negative?

When measurements were performed in the early 20th century, some metals were found to have *positive* moving charges! This “anomalous Hall effect” was solved by the quantum theory of solids, as you can learn in any solid state physics textbook. Today, extensions of the Hall effect, such as

the integer and fractional quantum Hall effects, remain active areas of research, and could be used to build quantum computers. We'll return to these effects in **X3**.

[3] **Problem 25.** ⌚ USAPhO 2015, problem B2.

[3] **Problem 26.** ⌚ USAPhO 1997, problem B1.

[3] **Problem 27.** ⌚ USAPhO 2019, problem A3. This is a tough but useful problem. The first half derives the so-called Child–Langmuir law, covered in problem 2.53 of Griffiths.