2.12.8: Footnotes

1. For a more practical demonstration of this effect, you can put an ordinary magnet near a computer monitor. The picture will be distorted. Make sure that the monitor has a demagnetizing ("degaussing") button, however! Otherwise you may permanently damage it. Don't use a television tube, because TV tubes don't have demagnetizing buttons.
2. One could object that this is circular reasoning, since the whole purpose of this argument is to prove from first principles that magnetic effects follow from the theory of relativity. Could there be some extra interaction which occurs between a moving charge and *any* other charge, regardless of whether the other charge is moving or not? We can argue, however, that such a theory would lack self-consistency, since we have to define the electric field somehow, and the only way to define it is in terms of F/q, where F is the force on a test charge q which is at rest. In other words, we'd have to say that there was some extra contribution to the *electric* field if the charge making it was in motion. This would, however, violate Gauss' law, and Gauss' law is amply supported by experiment, even when the sources of the electric field are moving. It would also violate the time-reversal symmetry of the laws of physics.
3. The reader who wants to see the full relativistic treatment is referred to E.M. Purcell, *Electricity and Magnetism*, McGraw Hill, 1985, p. 174.
4. Strictly speaking, there is a hole in this logic, since I've only ruled out a field that is purely along one of these three perpendicular directions. What if it has components along more than one of them? A little more work is required to eliminate these mixed possibilities. For example, we can rule out a field with a nonzero component parallel to the wire based on the following symmetry argument. Suppose a charged particle is moving in the plane of the page directly toward the wire. If the field had a component parallel to the wire, then the particle would feel a force into or out of the page, but such a force is impossible based on symmetry, since the whole arrangement is symmetric with respect to mirror-reflection across the plane of the page.
5. If you've taken a course in differential equations, this won't seem like a very surprising assertion. The differential form of Gauss' law is a differential equation, and by giving the value of the field in the midplane, we've specified a boundary condition for the differential equation. Normally if you specify the boundary conditions, then there is a unique solution to the differential equation. In this particular case, it turns out that to ensure uniqueness, we also need to demand that the solution satisfy the differential form of Ampère's law, which is discussed in section 11.4.
6. If you didn't read this optional subsection, don't worry, because the point is that we need to try a whole new approach anyway.
7. Note that the magnetic field never does work on a charged particle, because its force is perpendicular to the motion; the electric power is actually coming from the mechanical work that had to be done to spin the coil. Spinning the coil is more difficult due to the presence of the magnet.
8. If the pump analogy makes you uneasy, consider what would happen if all the electrons moved into the page on both sides of the loop. We'd end up with a net negative charge at the back side, and a net positive charge on the front. This actually would happen in the first nanosecond after the loop was set in motion. This buildup of charge would start to quench both currents due to electrical forces, but the current in the right side of the wire, which is driven by the weaker magnetic field, would be the first to stop. Eventually, an equilibrium will be reached in which the same amount of current is flowing at every point around the loop, and no more charge is being piled up.
9. The wire is not a perfect conductor, so this current produces heat. The energy required to produce this heat comes from the hands, which are doing mechanical work as they separate the magnet from the loop.
10. They can't be blamed too much for this. As a consequence of Faraday's work, it soon became apparent that light was an electromagnetic wave, and to reconcile this with the relative nature of motion requires Einstein's version of relativity, with all its subversive ideas how space and time are not absolute.
11. One way to prove this rigorously is that in a frame of reference where the particle is at rest, it has an electric field that surrounds it on all sides. If the particle has been moving with constant velocity for a long time, then this is just an ordinary Coulomb's-law field, extending off to very large distances, since disturbances in the field ripple outward at the speed of light. In a frame where the particle is moving, this pure electric field is experienced instead as a combination of an electric field and a magnetic field, so the magnetic field must exist throughout the same vast region of space.
12. Even if the fields can't be parallel to the direction of propagation, one might wonder whether they could form some angle other than 90 degrees with it. No. One proof is given on page 703. A alternative argument, which is simpler but more esoteric, is that if there was such a pattern, then there would be some other frame of reference in which it would look like figure i.
13. A young Einstein worried about what would happen if you rode a motorcycle alongside a light wave, traveling at the speed of light. Would the light wave have a zero velocity in this frame of reference? The only solution lies in the theory of relativity, one

of whose consequences is that a material object like a student or a motorcycle cannot move at the speed of light.

14. Actually, this is only exactly true of the rectangular strip is made infinitesimally thin.
15. You may know already that different colors of light have different speeds when they pass through a material substance, such as the glass or water. This is not in contradiction with what I'm saying here, since this whole analysis is for light in a vacuum.
16. What makes them appear to be unrelated phenomena is that we experience them through their interaction with atoms, and atoms are complicated, so they respond to various kinds of electromagnetic waves in complicated ways.
17. This current will soon come to a grinding halt, because we don't have a complete circuit, but let's say we're talking about the first picosecond during which the radio wave encounters the wire. This is why real radio antennas are *not* very short compared to a wavelength!
