Additional Example

EXAMPLE 21–8 **Force on the rod.** To make the rod of Fig. 21–12a move to the right at speed v, you need to apply an external force on the rod to the right. (*a*) Explain and determine the magnitude of the required force. (*b*) What external power is needed to move the rod? (Do not confuse this external force on the rod with the upward force on the electrons shown in Fig. 21–12b.)

APPROACH When the rod moves to the right, electrons flow upward in the rod according to right-hand-rule-3 (p. 562). So the conventional current is downward in the rod. We can see this also from Lenz's law: the outward magnetic flux through the loop is increasing, so the induced current must oppose the increase. Thus the current is clockwise so as to produce a magnetic field into the page (right-hand-rule-1). The magnetic force on the moving rod is $F = IlB$ for a constant B (Eq. 20–2). Right-hand-rule-2 tells us this magnetic force is to the left, and is thus a "drag force" opposing our effort to move the rod to the right.

SOLUTION (*a*) The magnitude of the external force, to the right, needs to balance the magnetic force $F = IlB$. The current $I = \mathscr{E}/R = Blv/R$ (see Eq. 21–3), and the resistance R is that of the whole circuit: the rod and the U-shaped conductor. The force F required to move the rod is thus

$$F = IlB = \left(\frac{Blv}{R}\right)lB = \frac{B^2l^2}{R}\,v.$$

If B, l, and R are constant, then a constant speed v is produced by a constant force. (Constant R implies that the parallel rails have negligible resistance.)
(*b*) The external power needed to move the rod for constant R is

$$P_{\text{ext}} = Fv = \frac{B^2l^2v^2}{R}.$$

The power dissipated in the resistance is $P = I^2R$. With $I = \mathscr{E}/R = Blv/R$,

$$P_{\text{R}} = I^2R = \frac{B^2l^2v^2}{R},$$

so the power input equals that dissipated in the resistance at any moment.

21–4 Changing Magnetic Flux Produces an Electric Field

We have seen that a changing magnetic flux induces an emf; there also is an induced current. This implies there is an electric field in a wire, causing the electrons to start moving. Indeed, this and other results suggest the important conclusion that

a changing magnetic field induces an electric field.

This applies not only to wires and other conductors, but is a general result that applies to any region in space: an electric field will be induced at any point in space where there is a changing magnetic field.

We can get a simple formula for E in terms of B for the case of electrons in a moving conductor, as in Fig. 21–12. The electrons feel a force (upwards in Fig. 21–12b); and if we put ourselves in the reference frame of the conductor, this force accelerating the electrons implies that there is an electric field in the conductor. Electric field is defined as the force per unit charge, $E = F/q$, where here $F = qvB$ (Eq. 20–4). Thus the effective field E in the rod must be

$$E = \frac{F}{q} = \frac{qvB}{q} = vB. \qquad \textbf{(21–4)}$$