the total *electromotive force*, or *emf*, $\mathcal{V}_T$ of the circuit. The field $\mathbf{E}_e$ is produced, in the present example, by chemical action in the battery. If it were absent, no current would flow since an electric field $\mathbf{E}_c$ due to charges is not able to maintain a steady current. The right-hand side of (3) equals the total $IR$ drop around the circuit. Hence (3) becomes

$$\mathcal{V}_T = IR_T \tag{4}$$

where $R_T$ is the total resistance of the circuit (equals $R_0$ if the internal resistance of the battery is zero).

In general, for a closed circuit containing many resistors and sources of emf,

$$\boxed{\sum \mathcal{V} = I \sum R} \tag{5}$$

This is *Kirchhoff's voltage law*. In words it states that *the algebraic sum of the emfs around a closed circuit equals the algebraic sum of the ohmic, or IR, drops around the circuit.*† Kirchhoff's voltage law applies not only to an isolated electric circuit as in Fig. 4-9 but to any single mesh (closed path) of a network.

To distinguish emf from the scalar potential $V$, the symbol $\mathcal{V}$ (script $V$) is used for emf. Both $V$ and $\mathcal{V}$ are expressed in volts, so that either may be referred to as a voltage if one does not wish to make a distinction between potential and emf.

It is to be noted that the scalar potential $V$ is equal to the negative of the line integral of the static field $\mathbf{E}_c$, while the emf $\mathcal{V}$ equals the line integral of $\mathbf{E}_e$. Thus, between any two points $a$ and $b$,‡

$$V_{ab} = V_b - V_a = -\int_a^b \mathbf{E}_c \cdot d\mathbf{l} \tag{6}$$

and

$$\mathcal{V}_{ab} = \int_a^b \mathbf{E}_e \cdot d\mathbf{l} \tag{7}$$

In (6) $V_{ab}$ is independent of the path of integration between $a$ and $b$, but $\mathcal{V}_{ab}$, in (7), is not.

For closed paths, $\oint \mathbf{E}_c \cdot d\mathbf{l} = 0$ and $\oint \mathbf{E}_e \cdot d\mathbf{l} = \mathcal{V}_T$, where $\mathcal{V}_T$ is the total emf around the circuit.

**Example** Let the circuit of Fig. 4-9 be redrawn as in Fig. 4-10*a*. The battery has an internal resistance $R_1$, and it will be convenient in this example to assume that the field $\mathbf{E}_e$ in the battery is uniform between the terminals

† In time-varying situations, where the circuit dimensions are small compared with the wavelength, Kirchhoff's law is modified: The algebraic sum of the *instantaneous* emfs around a closed circuit equals the algebraic sum of the *instantaneous* ohmic drops around the circuit.

‡ An open-circuited battery (no current flowing) has a terminal potential difference $V$ equal to its emf $\mathcal{V}$. The potential $V$ is as given by (6). As explained in the examples that follow, $\mathbf{E}_c$ and $\mathbf{E}_e$ have opposite directions in the battery. Therefore, in order that $V_{ab} = \mathcal{V}_{ab}$ for an open-circuited battery, (7) has no negative sign.