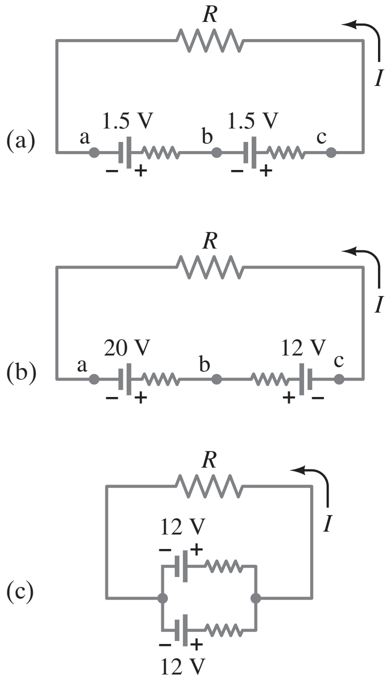


FIGURE 19–14 Batteries in series, (a) and (b), and in parallel (c).

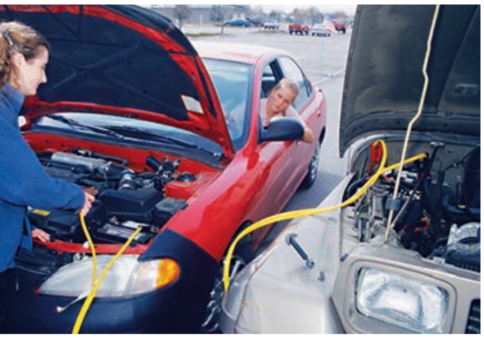
19–4 EMFs in Series and in Parallel; Charging a Battery

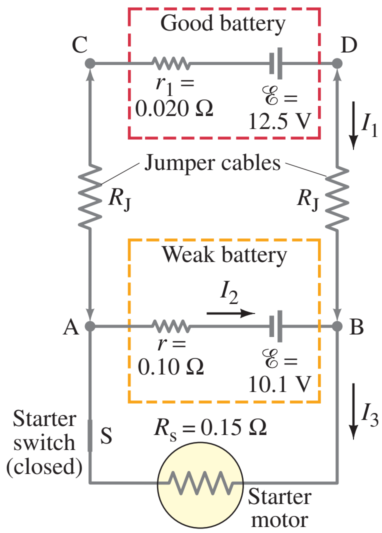
When two or more sources of emf, such as batteries, are arranged in series as in Fig. 19–14a, the total voltage is the algebraic sum of their respective voltages. On the other hand, when a 20-V and a 12-V battery are connected oppositely, as shown in Fig. 19–14b, the net voltage V_{ca} is 8 V (ignoring voltage drop across internal resistances). That is, a positive test charge moved from a to b gains in potential by 20 V, but when it passes from b to c it drops by 12 V. So the net change is 20 V − 12 V = 8 V. You might think that connecting batteries in reverse like this would be wasteful. For most purposes that would be true. But such a reverse arrangement is precisely how a battery charger works. In Fig. 19–14b, the 20-V source is charging up the 12-V battery. Because of its greater voltage, the 20-V source is forcing charge back into the 12-V battery: electrons are being forced into its negative terminal and removed from its positive terminal.

An automobile alternator keeps the car battery charged in the same way. A voltmeter placed across the terminals of a (12-V) car battery with the engine running fairly fast can tell you whether or not the alternator is charging the battery. If it is, the voltmeter reads 13 or 14 V. If the battery is not being charged, the voltage will be 12 V, or less if the battery is discharging. Car batteries can be recharged, but other batteries may not be rechargeable because the chemical reactions in many cannot be reversed. In such cases, the arrangement of Fig. 19–14b would simply waste energy.

Sources of emf can also be arranged in parallel, Fig. 19–14c, which—if the emfs are the same—can provide more energy when large currents are needed. Each of the cells in parallel has to produce only a fraction of the total current, so the energy loss due to internal resistance is less than for a single cell; and the batteries will go dead less quickly.

FIGURE 19–15 Example 19–9, a jump start.





EXAMPLE 19–9 **Jump starting a car.** A good car battery is being used to jump start a car with a weak battery. The good battery has an emf of 12.5 V and internal resistance 0.020 Ω. Suppose the weak battery has an emf of 10.1 V and internal resistance 0.10 Ω. Each copper jumper cable is 3.0 m long and 0.50 cm in diameter, and can be attached as shown in Fig. 19–15. Assume the starter motor can be represented as a resistor $R_s = 0.15\ \Omega$. Determine the current through the starter motor (*a*) if only the weak battery is connected to it, and (*b*) if the good battery is also connected, as shown in Fig. 19–15.

APPROACH We apply Kirchhoff's rules, but in (*b*) we will first need to determine the resistance of the jumper cables using their dimensions and the resistivity ($\rho = 1.68 \times 10^{-8}\ \Omega\cdot\mathrm{m}$ for copper) as discussed in Section 18–4.

SOLUTION (*a*) The circuit with only the weak battery and no jumper cables is simple: an emf of 10.1 V connected to two resistances in series, $0.10\ \Omega + 0.15\ \Omega = 0.25\ \Omega$. Hence the current is $I = V/R = (10.1\ \mathrm{V})/(0.25\ \Omega) = 40\ \mathrm{A}$.

(*b*) We need to find the resistance of the jumper cables that connect the good battery to the weak one. From Eq. 18–3, each has resistance

$$R_J = \frac{\rho \ell}{A} = \frac{(1.68 \times 10^{-8}\ \Omega\cdot\mathrm{m})(3.0\ \mathrm{m})}{(\pi)(0.25 \times 10^{-2}\ \mathrm{m})^2} = 0.0026\ \Omega.$$

Kirchhoff's loop rule for the full outside loop gives

$$12.5\ \mathrm{V} - I_1(2R_J + r_1) - I_3 R_S = 0$$

$$12.5\ \mathrm{V} - I_1(0.025\ \Omega) - I_3(0.15\ \Omega) = 0 \qquad \textbf{(i)}$$

since $(2R_J + r) = (0.0052\ \Omega + 0.020\ \Omega) = 0.025\ \Omega$.

The loop rule for the lower loop, including the weak battery and the starter, gives

$$10.1\text{ V} - I_3(0.15\,\Omega) - I_2(0.10\,\Omega) = 0. \qquad \textbf{(ii)}$$

The junction rule at point B gives

$$I_1 + I_2 = I_3. \qquad \textbf{(iii)}$$

We have three equations in three unknowns. From Eq. (iii),

$$I_1 = I_3 - I_2$$

and we substitute this into Eq. (i):

$$12.5\text{ V} - (I_3 - I_2)(0.025\,\Omega) - I_3(0.15\,\Omega) = 0,$$
$$12.5\text{ V} - I_3(0.175\,\Omega) + I_2(0.025\,\Omega) = 0.$$

Combining this last equation with Eq. (ii) gives

$$12.5\text{ V} - I_3(0.175\,\Omega) + \left(\frac{10.1\text{ V} - I_3(0.15\,\Omega)}{0.10\,\Omega}\right)(0.025\,\Omega) = 0$$

or

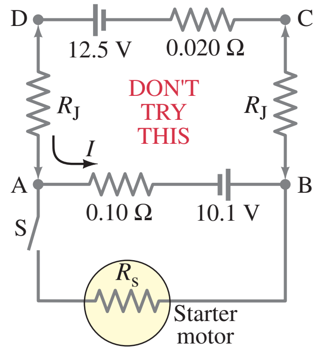
$$I_3 = \frac{12.5\text{ V} + 2.5\text{ V}}{(0.175\,\Omega + 0.0375\,\Omega)} = 71\text{ A},$$

quite a bit better than in part (*a*).
The other currents are $I_2 = -5$ A and $I_1 = 76$ A. Note that $I_2 = -5$ A is in the opposite direction from what we assumed in Fig. 19–15. The terminal voltage of the weak 10.1-V battery when being charged is

$$V_{BA} = 10.1\text{ V} - (-5\text{ A})(0.10\,\Omega) = 10.6\text{ V}.$$

NOTE The circuit in Fig. 19–15, without the starter motor, is how a battery can be charged. The stronger battery pushes charge back into the weaker battery.

FIGURE 19–16 Exercise E.



EXERCISE E If the jumper cables of Example 19–9 were mistakenly connected in reverse, the positive terminal of each battery would be connected to the negative terminal of the other battery (Fig. 19–16). What would be the current I even before the starter motor is engaged (the switch S in Fig. 19–16 is open)? Why could this cause the batteries to explode?

Safety when Jump Starting

Before jump starting a car's weak battery, be sure both batteries are 12 V and check the polarity of both batteries. The following (cautious) procedure applies if the negative (−) terminal is ground (attached by a cable to the metal car frame and motor), and the "hot" terminal is positive (+) on both batteries, as is the case for most modern cars. The + terminal is usually marked by a red color, often a red cover. The safest procedure is to first connect the hot (+) terminal of the weak battery to the hot terminal of the good battery (using the cable with red clamps). Spread apart the handles of each clamp to squeeze the contact tightly. Then connect the black cable, first to the ground terminal of the good battery, and the other end to a clean exposed metal part (i.e., at ground) on the car with the weak battery. (This last connection should preferably be not too close to the battery, which in rare cases might leak H_2 gas that could ignite at the spark that may accompany the final connection.) This is safer than connecting directly to the ground terminal. When you are ready to start the disabled car, it helps to have the good car running (to keep its battery fully charged). As soon as the disabled car starts, immediately detach the cables in the exact reverse order (ground cable first).

In the photo of Fig. 19–15, the above procedure is not being followed. Note the safety error: with ground terminals connected, if the red clamp (+12 V) touches a metal part (= ground), even if dropped by the person, a short circuit with damaging high electric current can occur (hundreds of amps).