Surprising as it may seem, the power of a computer is achieved simply by the controlled flow of charges through tiny wires and circuit elements.

**Chapter Goal:** To understand the fundamental physical principles that govern electric circuits.
How many laws are named after Kirchhoff?

A. 0
B. 1
C. 2
D. 3
E. 4

What property of a real battery makes its potential difference slightly different than that of an ideal battery?

A. Short circuit
B. Chemical potential
C. Internal resistance
D. Effective capacitance
E. Inductive constant

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In an $RC$ circuit, what is the name of the quantity represented by the symbol $\tau$?

A. Period
B. Torque
C. Terminal voltage
D. Time constant
E. Coefficient of thermal expansion
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Which of the following are *ohmic* materials:

A. batteries.
B. wires.
C. resistors.
D. Materials a and b.
E. Materials b and c.

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The equivalent resistance for a group of parallel resistors is

A. less than any resistor in the group.
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C. equal to the average resistance of the group.
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Tactics: Using Kirchhoff’s loop law

1. Draw a circuit diagram. Label all known and unknown quantities.

2. Assign a direction to the current. Draw and label a current arrow $I$ to show your choice.
   - If you know the actual current direction, choose that direction.
   - If you don’t know the actual current direction, make an arbitrary choice. All that will happen if you choose wrong is that your value for $I$ will end up negative.

3. Analysis of the basic circuit using Kirchhoff’s loop law.

   - $I$ flows clockwise.
   - The orientation of the battery indicates a clockwise current, so assign a clockwise direction to $I$.
   - $\Delta V = +\mathcal{E}$
   - $\Delta V_{\text{bat}} = -\mathcal{E}$
   - $\Delta V_{\text{bat}} = -\mathcal{E}$

4. Determine $\Delta V$ for each circuit element.

   - $\Delta V_{\text{bat}} = +\mathcal{E}$
   - $\Delta V_{\text{bat}} = -\mathcal{E}$
   - $\Delta V_{\text{bat}} = -\mathcal{E}$

5. Apply the loop law:

   $\sum (\Delta V) = 0$
Energy and Power

The power supplied by a battery is

\[ P_{\text{out}} = IE \quad \text{(power delivered by an emf)} \]

The units of power are J/s, or W.

The power dissipated by a resistor is

\[ P_R = \frac{dE_{\text{th}}}{dt} = \frac{dq}{dt} \Delta V_R = I \Delta V_R \]

Or, in terms of the potential drop across the resistor

\[ P_R = I \Delta V_R = I^2 R = \frac{(\Delta V_R)^2}{R} \quad \text{(power dissipated by a resistor)} \]

EXAMPLE 32.4 The power of light

**QUESTION:**

EXAMPLE 32.4 The power of light

How much current is “drawn” by a 100 W lightbulb connected to a 120 V outlet?

**MODEL** Most household appliances, such as a 100 W lightbulb or a 1500 W hair dryer, have a power rating. The rating does not mean that these appliances always dissipate that much power. These appliances are intended for use at a standard household voltage of 120 V, and their rating is the power they will dissipate if operated with a potential difference of 120 V. Their power consumption will differ from the rating if they are operated at any other potential difference.

**SOLVE** Because the lightbulb is operating as intended, it will dissipate 100 W of power. Thus

\[ I = \frac{P_R}{\Delta V_R} = \frac{100 \text{ W}}{120 \text{ V}} = 0.833 \text{ A} \]
EXAMPLE 32.4 The power of light

ASSESS A current of 0.833 A in this lightbulb transfers 100 J/s to the thermal energy of the filament, which, in turn, dissipates 100 J/s as heat and light to its surroundings.

Series Resistors
- Resistors that are aligned end to end, with no junctions between them, are called series resistors or, sometimes, resistors “in series.”
- The current \( I \) is the same through all resistors placed in series.
- If we have \( N \) resistors in series, their equivalent resistance is

\[
R_{eq} = R_1 + R_2 + \cdots + R_N \quad \text{(series resistors)}
\]

The behavior of the circuit will be unchanged if the \( N \) series resistors are replaced by the single resistor \( R_{eq} \).

EXAMPLE 32.7 Lighting up a flashlight

QUESTION:

EXAMPLE 32.7 Lighting up a flashlight
A 6 Ω flashlight bulb is powered by a 3 V battery with an internal resistance of 1 Ω. What are the power dissipation of the bulb and the terminal voltage of the battery?
EXAMPLE 32.7 Lighting up a flashlight

**MODEL** Assume ideal connecting wires but not an ideal battery.

**VISUALIZE** The circuit diagram looks like Figure 32.20. $R$ is the resistance of the bulb’s filament.

**SOLVE** Equation 32.19 gives us the current:

$$I = \frac{\mathcal{E}}{R + r} = \frac{3 \text{ V}}{6 \Omega + 1 \Omega} = 0.43 \text{ A}$$

This is 15% less than the 0.5 A an ideal battery would supply. The potential difference across the resistor is $\Delta V_R = IR = 2.6 \text{ V}$, thus the power dissipation is

$$P_R = I \Delta V = 1.1 \text{ W}$$

The battery’s terminal voltage is

$$\Delta V_{\text{bat}} = \frac{R}{R + r} \mathcal{E} = \frac{6 \Omega}{6 \Omega + 1 \Omega} 3 \text{ V} = 2.6 \text{ V}$$

**ASSESS** 1 $\Omega$ is a typical internal resistance for a flashlight battery. The internal resistance causes the battery’s terminal voltage to be 0.4 V less than its emf in this circuit.
Parallel Resistors

- Resistors connected at both ends are called **parallel resistors** or, sometimes, resistors “in parallel.”
- The left ends of all the resistors connected in parallel are held at the same potential $V_1$, and the right ends are all held at the same potential $V_2$.
- The potential differences $\Delta V$ are the same across all resistors placed in parallel.
- If we have $N$ resistors in parallel, their **equivalent resistance** is

\[
R_{eq} = \left( \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_N} \right)^{-1} \quad \text{(parallel resistors)}
\]

The behavior of the circuit will be unchanged if the $N$ parallel resistors are replaced by the single resistor $R_{eq}$.

**EXAMPLE 32.10 A combination of resistors**

**QUESTION:**

What is the equivalent resistance of the group of resistors shown in **FIGURE 32.26**?

![Diagram of resistors](image)

**FIGURE 32.26** A combination of resistors.

**SOLVE** Reduction to a single equivalent resistance is best done in a series of steps, with the circuit being redrawn after each step. The procedure is shown in **FIGURE 32.27**. Note that the 10 Ω and 25 Ω resistors are not in parallel. They are connected at their top ends but not at their bottom ends. Resistors must be connected at both ends to be in parallel. Similarly, the 10 Ω and 45 Ω resistors are not in series because of the junction between them. If the original group of four resistors occurred within a larger circuit, they could be replaced with a single 15.4 Ω resistor without having any effect on the rest of the circuit.

**MODEL** This circuit contains both series and parallel resistors.
EXAMPLE 32.10 A combination of resistors

**FIGURE 32.27** The combination is reduced to a single equivalent resistor.

\[
\begin{align*}
10 \Omega & \quad 25 \Omega \quad 30 \Omega \\
\quad 40 \Omega & \quad 25 \Omega \quad = \quad 15.4 \Omega
\end{align*}
\]

Example: Kirchoff’s Rules

\[
l = I_2 + I_3
\]

\[
-l_2R_2 + l_2R_2 = 0
\]

\[
\Delta V_1 - \Delta V_2 - l_2R_2 - l_1R_1 = 0
\]

**RC Circuits**

- Consider a charged capacitor, an open switch, and a resistor all hooked in series. This is an \(RC\) Circuit.
- The capacitor has charge \(Q_0\) and potential difference \(\Delta V_C = Q_0/C\).
- There is no current, so the potential difference across the resistor is zero.
- At \(t = 0\) the switch closes and the capacitor begins to discharge through the resistor.
- The capacitor charge as a function of time is

\[
Q = Q_0e^{-t/\tau}
\]

where the time constant \(\tau\) is

\[
\tau = RC
\]
EXAMPLE 32.14 Exponential decay in an RC circuit

QUESTION:

The switch in **FIGURE 32.37** has been in position a for a long time. It is changed to position b at \( t = 0 \) s. What are the charge on the capacitor and the current through the resistor at \( t = 5.0 \mu s \)?

**FIGURE 32.37** An RC circuit.

![Image of RC circuit](image)

**SOLVE** The time constant of the RC circuit is

\[
\tau = RC = (10 \Omega)(1.0 \times 10^{-6} \text{ F}) = 10 \times 10^{-6} \text{ s} = 10 \mu s
\]

The capacitor is initially charged to 9.0 V, giving \( Q_0 = C \Delta V_C = 9.0 \mu C \). The capacitor charge at \( t = 5.0 \mu s \) is

\[
Q = Q_0 e^{-t/\tau} = (9.0 \mu C) e^{-(5.0 \mu s)/(10 \mu s)} = (9.0 \mu C) e^{-0.5} = 5.5 \mu C
\]

The initial current, immediately after the switch is closed, is \( I_0 = Q_0/\tau = 0.90 \text{ A} \). The resistor current at \( t = 5.0 \mu s \) is

\[
I = I_0 e^{-t/\tau} = (0.90 \text{ A}) e^{-0.5} = 0.55 \text{ A}
\]

**MODEL** The battery charges the capacitor to 9.0 V. Then, when the switch is changed to position b, the capacitor discharges through the 10 \( \Omega \) resistor. Assume ideal wires.

**ASSESS** This capacitor will be almost entirely discharged \( 5\tau = 50 \mu s \) after the switch is closed.
Chapter 32. Summary Slides

General Strategy

**MODEL** Assume that wires and, where appropriate, batteries are ideal.

**VISUALIZE** Draw a circuit diagram. Label all known and unknown quantities.

**SOLVE** Base the solution on Kirchhoff’s laws.
- Reduce the circuit to the smallest possible number of equivalent resistors.
- Write one loop equation for each independent loop.
- Find the current and the potential difference.
- Rebuild the circuit to find \( I \) and \( \Delta V \) for each resistor.

**ASSESS** Verify that
- The sum of potential differences across series resistors matches \( \Delta V \) for the equivalent resistor.
- The sum of the currents through parallel resistors matches \( I \) for the equivalent resistor.

---

Kirchhoff’s loop law

For a closed loop:
- Assign a direction to the current \( I \).
- \( \sum (\Delta V) = 0 \)

Kirchhoff’s junction law

For a junction:
- \( \sum I_{\text{in}} = \sum I_{\text{out}} \)
**Important Concepts**

**Ohm’s Law**

A potential difference $\Delta V$ between the ends of a conductor with resistance $R$ creates a current

$$I = \frac{\Delta V}{R}$$

**Important Concepts**

The energy used by a circuit is supplied by the emf $\mathcal{E}$ of the battery through the energy transformations

$$E_{\text{chem}} \rightarrow U \rightarrow K \rightarrow E_{\text{th}}$$

The battery *supplies* energy at the rate

$$P_{\text{bat}} = I\mathcal{E}$$

The resistors *dissipate* energy at the rate

$$P_R = I\Delta V_R = I^2R = \frac{(\Delta V_R)^2}{R}$$

**Important Concepts**

**Signs of $\Delta V$**

- $\Delta V_{\text{bat}} = +\mathcal{E}$ (Travel $\rightarrow$)
- $\Delta V_{\text{bat}} = -\mathcal{E}$ (Travel $\leftarrow$)
- $\Delta V_R = -IR$

**Applications**

**Series resistors**

$$R_{\text{eq}} = R_1 + R_2 + R_3 + \cdots$$
Applications

RC circuits
The discharge of a capacitor through a resistor satisfies:

\[ Q = Q_0 e^{-t/\tau} \]

\[ I = \frac{dQ}{dt} = \frac{Q_0}{\tau} e^{-t/\tau} = I_0 e^{-t/\tau} \]

where \( \tau = RC \) is the **time constant**.

Chapter 32. Questions

Which of these diagrams represent the same circuit?

A. a and b
B. b and c
C. a and c
D. a, b, and d
E. a, b, and c

Which of these diagrams represent the same circuit?

A. a and b
B. b and c
C. a and c
D. a, b, and d
E. a, b, and c
What is $\Delta V$ across the unspecified circuit element? Does the potential increase or decrease when traveling through this element in the direction assigned to $I$?

A. $\Delta V$ decreases by 2 V in the direction of $I$.
B. $\Delta V$ increases by 2 V in the direction of $I$.
C. $\Delta V$ decreases by 10 V in the direction of $I$.
D. $\Delta V$ increases by 10 V in the direction of $I$.
E. $\Delta V$ increases by 26 V in the direction of $I$.

Rank in order, from largest to smallest, the powers $P_a$ to $P_d$ dissipated in resistors a to d.

A. $P_b > P_a = P_c = P_d$
B. $P_b = P_d > P_a > P_c$
C. $P_b > P_c > P_a > P_d$
D. $P_b > P_d > P_a > P_c$
E. $P_b > P_c > P_a > P_d$

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What is the potential at points a to e?

A. \( V_a = 0 \text{ V} \), \( V_b = -4 \text{ V} \), \( V_c = -10 \text{ V} \), \( V_d = -12 \text{ V} \), \( V_e = -20 \text{ V} \)
B. \( V_a = -20 \text{ V} \), \( V_b = -16 \text{ V} \), \( V_c = -10 \text{ V} \), \( V_d = -8 \text{ V} \), \( V_e = 0 \text{ V} \)
C. \( V_a = -4 \text{ V} \), \( V_b = -6 \text{ V} \), \( V_c = -2 \text{ V} \), \( V_d = -8 \text{ V} \), \( V_e = 0 \text{ V} \)
D. \( V_a = 4 \text{ V} \), \( V_b = 6 \text{ V} \), \( V_c = 2 \text{ V} \), \( V_d = 8 \text{ V} \), \( V_e = 0 \text{ V} \)
E. \( V_a = 20 \text{ V} \), \( V_b = 16 \text{ V} \), \( V_c = 10 \text{ V} \), \( V_d = 8 \text{ V} \), \( V_e = 0 \text{ V} \)

Rank in order, from brightest to dimmest, the identical bulbs A to D.

A. \( C = D > B > A \)
B. \( A > C = D > B \)
C. \( A = B = C = D \)
D. \( A > B > C = D \)
E. \( A > C > B > D \)
The time constant for the discharge of this capacitor is

A. 5 s.
B. 1 s.
C. 2 s.
D. 4 s.
E. The capacitor doesn’t discharge because the resistors cancel each other.