Chapter 27

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Current And Resistance

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Lecture 01

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Current And Resistance

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Electric Current

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Electric current is the rate of flow of charge through some region of space.

The SI unit of current is the **Ampere** (A).

$$1\,A = 1\,C/s$$

The symbol for electric current is I.

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Average Electric Current

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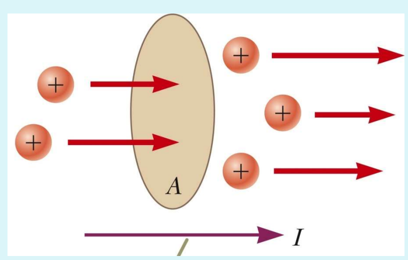
- Assume charges are moving perpendicular to a surface of area A.
- If ΔQ is the amount of charge that passes through A in time Δt, then the **average current** is

$$I_{avg} = \frac{\Delta Q}{\Delta t}$$



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Instantaneous Electric Current

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- If the rate at which the charge flows varies with time, the **instantaneous current**, I, is defined as the differential limit of average current as $\Delta t \to 0$.

$$\boxed{I_{inst.} = \frac{dQ}{dt}}$$

Direction of Current

The charged particles passing through the surface could be positive, negative or both.

It is conventional to assign to the current **the same direction as the flow of positive charges**.

It is common to refer to any moving charge as a *charge carrier.*

Current and Drift Speed

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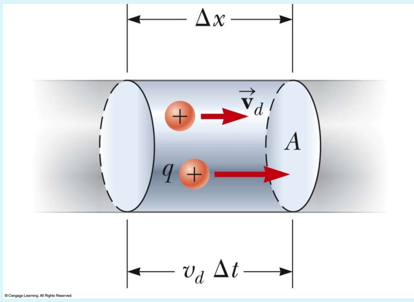
- Charged particles move through a cylindrical conductor of cross-sectional area A.
- (n) is the number of mobile charge carriers per unit volume.

$$Volume = A\Delta x$$

- $(nA\Delta x)$ is the **total number** of charge carriers in a segment.
- The **total charge** is the number of carriers times the charge per carrier, q.

$$\Delta Q = (nA\Delta x)q$$



Current and Drift Speed, cont

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Assume the carriers move with a velocity parallel to the axis of the cylinder such that they experience a displacement in the x-direction.

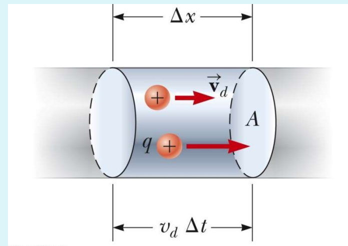
If v_d is the speed at which the carriers move, then

$v_d = \Delta x/\Delta t$ and $\Delta x = v_d \Delta t$

Rewritten: $\Delta Q = (nAv_d\Delta t)q$

Finally, current,

$$I_{avg} = \frac{\Delta Q}{\Delta t} = nqv_dA$$



v_d is an average speed called the **drift speed.**

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Charge Carrier Motion in a Conductor

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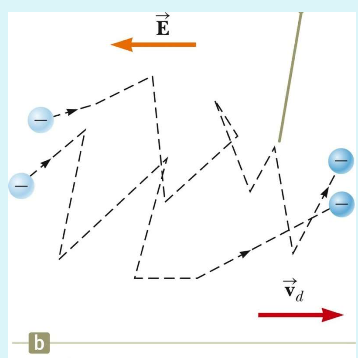
- When a potential difference is applied across the conductor, an electric field is set up in the conductor which exerts an electric force on the electrons.
- The motion of the electrons is no longer random.
- The zigzag black lines represents the motion of a charge carrier in a conductor in the presence of an electric field.
- The sharp changes in direction are due to collisions.
- The net motion of electrons is opposite the direction of the electric field.



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Motion of Charge Carriers, cont.

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- In the presence of an electric field, in spite of all the collisions, the charge carriers slowly move along the conductor with a drift velocity,
- The electric field exerts forces on the conduction electrons in the wire.
- These forces cause the electrons to move in the wire and create a current.
- The electrons are already in the wire, they respond to the electric field set up by the battery.
- The battery does not supply the electrons, it only establishes the electric field.

Current Density (J)

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- The **current density** of a conductor is defined as the **current per unit area**.

$$J = \frac{I}{A} = nqv_d$$

  - J has SI units of A/m^2
  - The current density is in the **direction** of the positive charge carriers.

Conductivity and resistivity

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- A current density and an electric field are established in a conductor whenever a potential difference is maintained across the conductor.
- For some materials, the current density is directly proportional to the field.
- The constant of proportionality, σ, is called the **conductivity** of the conductor.
- The inverse of the conductivity is the **resistivity**:

$$\rho = \frac{1}{\sigma}$$

Resistivity has SI units of ohm-meters $(\Omega.m)$

Conductivity has SI units of (ohm-meters)$^{-1}$ $(\Omega.m)^{-1}$

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Ohm's Law

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Ohm's law states that for many materials, **the ratio of the current density to the electric field is a constant, σ, that is independent of the electric field producing the current.**

Most metals obey Ohm's law

Mathematically,

$$J = \sigma E = \frac{E}{\rho}$$

Materials that obey ohm's law are said to be ohmic

Materials that do not obey ohm's law are said to be nonohmic.

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Resistance

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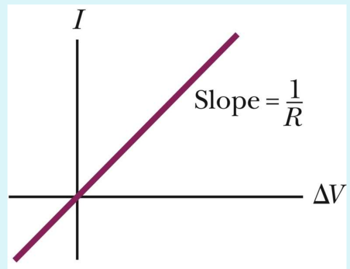
- In a conductor, the voltage applied across the ends of the conductor is proportional to the current through the conductor.
- The constant of proportionality is called the **resistance** of the conductor.

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

- SI units of resistance are **Ohms** (Ω).

$$1\,\Omega = 1\ V/A$$

- Resistance in a circuit arises due to collisions between the electrons carrying the current with the fixed atoms inside the conductor.



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Resistance

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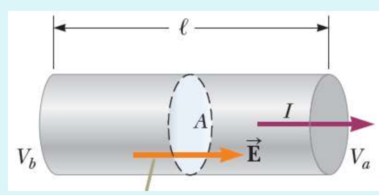
$$J = \sigma E = \frac{E}{\rho}$$

$$\frac{I}{A} = \frac{1}{\rho}\frac{\Delta V}{L}$$

$$\Delta V = \frac{\rho\, L}{A}\, I$$

$$R = \frac{\Delta V}{I} = \frac{\rho\, L}{A}$$



ρ: Resistivity ($\Omega.m$)

L: length (m)

A: cross sectional area (m^2)

R: resistance (Ω)

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Resistivity Values

Table 27.2 Resistivities and Temperature Coefficients of Resistivity for Various Materials

Material	Resistivity[a] ($\Omega \cdot m$)	Temperature Coefficient[b] α [$(°C)^{-1}$]
Silver	1.59×10^{-8}	3.8×10^{-3}
Copper	1.7×10^{-8}	3.9×10^{-3}
Gold	2.44×10^{-8}	3.4×10^{-3}
Aluminum	2.82×10^{-8}	3.9×10^{-3}
Tungsten	5.6×10^{-8}	4.5×10^{-3}
Iron	10×10^{-8}	5.0×10^{-3}
Platinum	11×10^{-8}	3.92×10^{-3}
Lead	22×10^{-8}	3.9×10^{-3}
Nichrome[c]	1.00×10^{-6}	0.4×10^{-3}
Carbon	3.5×10^{-5}	-0.5×10^{-3}
Germanium	0.46	-48×10^{-3}
Silicon[d]	2.3×10^{3}	-75×10^{-3}
Glass	10^{10} to 10^{14}	
Hard rubber	$\sim 10^{13}$	
Sulfur	10^{15}	
Quartz (fused)	75×10^{16}	

[a] All values at 20°C. All elements in this table are assumed to be free of impurities.
[b] See Section 27.4.
[c] A nickel–chromium alloy commonly used in heating elements. The resistivity of Nichrome varies with composition and ranges between 1.00×10^{-6} and 1.50×10^{-6} $\Omega \cdot m$.
[d] The resistivity of silicon is very sensitive to purity. The value can be changed by several orders of magnitude when it is doped with other atoms.

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Resistance and Resistivity, Summary

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- Every ohmic material has a characteristic resistivity that depends on the properties of the material and on temperature.
  - Resistivity is a property of substances.
- The resistance of a material depends on its geometry and its resistivity.
  - Resistance is a property of an object.
- An ideal conductor would have zero resistivity.
- An ideal insulator would have infinite resistivity.

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Resistance and Temperature

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Over a limited temperature range, the resistivity of a conductor varies approximately linearly with the temperature.

$$\rho = \rho_\circ[1 + \alpha(T - T_\circ)]$$

- ρ is the resistivity at some temperature T
- $\rho_\circ$ is the resistivity at some reference temperature $T_\circ$
  - $T_\circ$ is usually taken to be 20 °C
  - α is the temperature coefficient of resistivity
    - SI units of α are $°\mathrm{C}^{-1}$

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Temperature Variation of Resistance

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- Since the resistance of a conductor with uniform cross sectional area is proportional to the resistivity, you can find the effect of temperature on resistance.

$$R = R_\circ[1 + \alpha(T - T_\circ)]$$

- R is the resistance at some temperature T
- $R_\circ$ is the resistance at some reference temperature $T_\circ$
  - $T_\circ$ is usually taken to be 20 °C
  - α is the temperature coefficient of resistivity
    - SI units of α are $°\mathrm{C}^{-1}$

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Current density and drift velocity in a wire

Thursday, 15 April, 2021 23:47

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

- ☐ R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.
- ☐ J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.
- ☑ H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.
- ☐ H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

A copper wire, with a diameter of $1.02\ mm$, carries a constant current of $1.67\ A$ to a $200\ W$ lamp. The free-electron density in the wire is $8.5 \times 10^{28}\ m^{-3}$. Find:

- the current density and
- the drift speed.

The radius of the wire is:

$$r = \frac{1.02 \times 10^{-3}}{2} = 0.51 \times 10^{-3} m$$

The cross-sectional area is:

$$A = \pi r^2 = \pi(0.51 \times 10^{-3})^2 = 8.17 \times 10^{-7} m^2$$

The magnitude of the current density is then

$$J = \frac{I}{A} = \frac{1.67}{8.17 \times 10^{-7}} = 2.04 \times 10^6\ A/m^2$$

the drift velocity is:

$$v_d = \frac{I}{nqA} = \frac{1.67}{8.25 \times 10^{28} \times 1.6 \times 10^{-19} \times 8.17 \times 10^{-7}}$$

$$= 1 \cdot 5 \times 10^{-4}\ m/s$$

Charge, Current and Current density-1

Thursday, 15 April, 2021 23:47

The current through a cross-sectional area of a wire is given by the relation $i(t) = 2 + 3t^{-3}$; where I is in Amperes and t is in seconds.

- Find the total charge that passes through this area between $t = 2\ s$ and $t = 8\ s$.
- Find the average current needed to pass the same quantity of charge during the same time interval.

The total charge is:

$$Q = \int_{t_i}^{t_f} i(t)\,\mathrm{d}t = \int_{2}^{8} (2 + 3t^{-3})\,\mathrm{d}t = 12.4C$$

The average current is:

$$I_{\text{avg}} = \frac{Q}{\Delta t} = \frac{12 \cdot 4}{8 - 2} = 2.1A$$

Charge, Current and Current density-2

Thursday, 15 April, 2021 23:47

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

- [ ] R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.
- [ ] J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.
- [ ] H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.
- [x] H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

The charge that passes a cross-sectional area $A = 1 \times 10^{-4} m^2$ varies with time according to the relation $q(t) = 4 + 2t + t^2$, where q is in Coulombs and t is in seconds.

- Find the current at time $t = 2\ s$.
- Find the current density at time $t = 2\ s$.

The current at any time is:

$$\mathrm{I} = \frac{\mathrm{d}q}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}(4 + 2t + t^2) = 2 + 2t$$

At $t = 2s$:

$$I(t = 2) = 2 + 2 \times 2 = 6A$$

The current density at t=$2s$:

$$J = \frac{I}{A} = \frac{6}{1 \times 10^{-4}} = 6 \times 10^4\ A/m^2$$

The Resistance of Nichrome Wire

Tuesday, 2 February, 2021 20:55

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

- R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.
- J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.
- H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.
- H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

The radius of 22-gauge Nichrome wire is $0.32\ mm$. ($\rho = 1.00 \times 10^{-6}\ \Omega.m$)

- Calculate the resistance per unit length of this wire.
- If a potential difference of $10\ V$ is maintained across a $1.0\ m$ length of the Nichrome wire, what is the current in the wire?

SOLUTION

- the resistance per unit length:

$$\frac{R}{\ell} = \frac{\rho}{A} = \frac{\rho}{\pi r^2} = \frac{1.0 \times 10^{-6}\Omega \cdot m}{\pi(0.32 \times 10^{-3} m)^2} = 3.1\Omega/m$$

- the current:

$$I = \frac{\Delta V}{R} = \frac{\Delta V}{(R/\ell)\ell} = \frac{10V}{(3.1\Omega/m)(1.0m)} = 3.2A$$

What if the wire were composed of copper instead of Nichrome?

Calculations show that a copper wire of the same radius would have a resistance per unit length of only $0.053\Omega/m$.
A 1.0-m length of copper wire of the same radius would carry a current of 190 A with an applied potential difference of 10 V.

Electric field, potential difference, and resistance in a wire

Thursday, 15 April, 2021 23:52

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

- [ ] R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.
- [ ] J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.
- [x] H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.
- [ ] H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

A copper wire ($\rho = 1.72 \times 10^{-8}\ \Omega.m$) has a cross-sectional area of $8.20 \times 10^{-7} m^2$. It carries a current of $1.67\ A$. Find:

- the electric-field magnitude in the wire;
- the potential difference between two points in the wire $50.0\ m$ apart;
- the resistance of a $50.0\ m$ length of this wire.

- the electric-field magnitude in the wire is:

$$\sigma = \frac{J}{E} \rightarrow \frac{1}{\rho} = \frac{I}{AE}$$

$$E = \frac{\rho I}{A} = \frac{1 \cdot 72 \times 10^{-8} \times 1 \cdot 67}{8.2 \times 10^{-7}} = 0.035\, V/m$$

- the potential difference between two points in the wire $50.0\ m$ apart is:

$$\Delta V = EL = 0.035 \times 50 = 1.75V$$

- the resistance of a $50.0\ m$ length of this wire is:

$$R = \frac{\rho L}{A} = \frac{1.72 \times 10^{-8} \times 50}{8.2 \times 10^{-7}} = 1.05\Omega$$

Alternatively,

$$R = \frac{\Delta V}{I} = \frac{1 \cdot 75}{1 \cdot 67} = 1.05\Omega$$

We emphasize that the resistance of the wire is defined to be the ratio of voltage to current. If the wire is made of nonohmic material, then R is different for different values of V but is always given by $R = \Delta V/I$. Resistance is also always given by $R = \rho L/A$; if the material is nonohmic, ρ is not constant but depends on E (or, equivalently, on $V = EL$).

Temperature dependence of resistance

Friday, 16 April, 2021 00:00

Lecturer: Mustafa Al-Zyout, Philadelphia University, Jordan.

R. A. Serway and J. W. Jewett, Jr., *Physics for Scientists and Engineers*, 9th Ed., CENGAGE Learning, 2014.

J. Walker, D. Halliday and R. Resnick, *Fundamentals of Physics*, 10th ed., WILEY,2014.

H. D. Young and R. A. Freedman, *University Physics with Modern Physics*, 14th ed., PEARSON, 2016.

H. A. Radi and J. O. Rasmussen, *Principles of Physics For Scientists and Engineers*, 1st ed., SPRINGER, 2013.

Suppose the resistance of a copper wire is $1.05\ \Omega$ at $20\ °C$. Find the resistance at $0\ °C$ and $100\ °C$.
At $T_{\circ} = 20\ ℃$, $\alpha = 0.00393\ ℃^{-1}$.

At $T = 0\ °C$, the resistance is:

$$R = R_{\circ}[1 + \alpha(T - T_{\circ})]$$

$$R = 1.05 \times [1 + 0.00393(0 - 20)]$$

$$R = 0.97\Omega$$

At $T = 100\ °C$, the resistance is:

$$R = R_{\circ}[1 + \alpha(T - T_{\circ})]$$

$$R = 1.05 \times [1 + 0.00393(100 - 20)]$$

$$R = 1.38\Omega$$