IDX G10 Physics H
Study Guide Issue S1 Final
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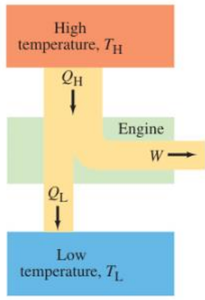
Contents:

15.5 Heat Engines

Key Concepts

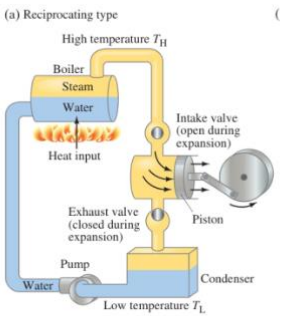


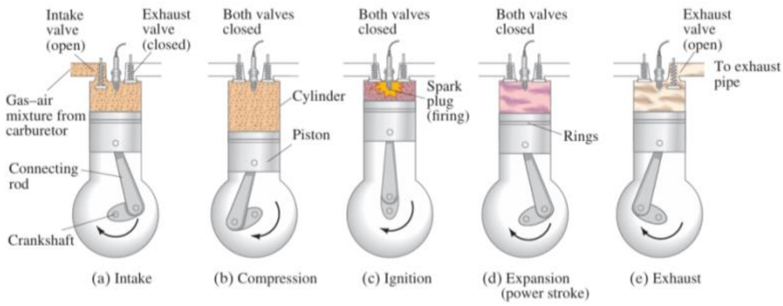
- **Heat Engine:** Device that converts thermal energy into mechanical work by operating between a hot reservoir (T_H) and a cold reservoir (T_L) using a working substance in a cyclic process
- **Cyclic Process:** System returns to initial state → $\Delta U = 0$ → Net heat absorbed equals net work done: $Q_H = W + Q_L$ (all quantities positive)
- **Efficiency (e):** Fraction of heat input converted to useful work:

$$e = \frac{W}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H}$$

Always less than 1 (100%)

- **Types:**
    - Steam engines (reciprocating or turbine)
    - Internal combustion engines (e.g., gasoline engines)

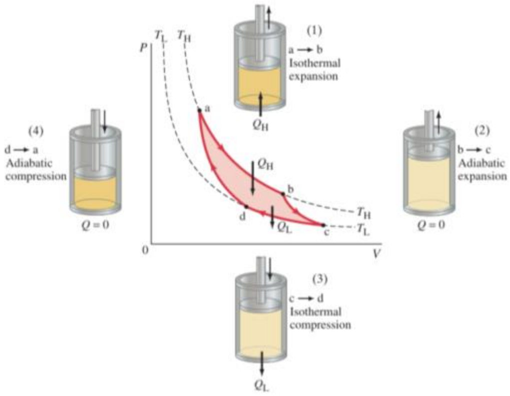




Carnot Engine – The Ideal Heat Engine

- **Carnot Engine:** A heat engine that operates on the Carnot thermodynamic cycle, which serves as the theoretical standard for the efficiency of all heat engines
    - Named after Sadi Carnot (1796-1832), a French physicist
    - Proposed in 1824 as an idealized heat engine model
    - Establishes the maximum efficiency possible for any heat engine

- **Carnot Cycle:** Two reversible isothermal + two reversible adiabatic processes



- **Carnot Efficiency:** Maximum possible efficiency for given T_H and T_L:

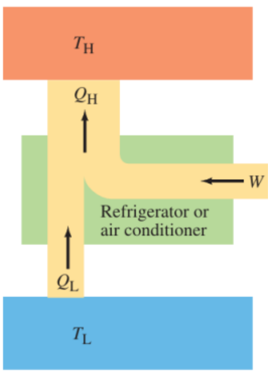
$$e_{Carnot} = 1 - \frac{T_L}{T_H}$$

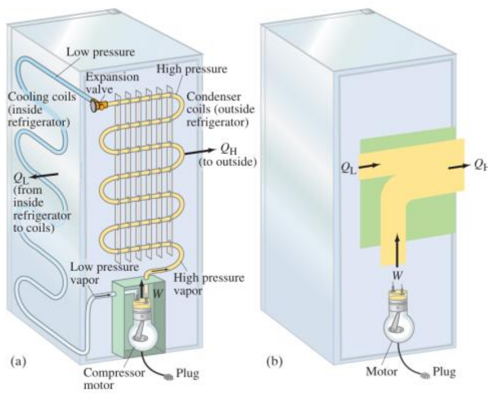
Temperatures must be in Kelvin

- **Carnot's Theorem:**
  - No real engine can exceed Carnot efficiency
  - Efficiency depends only on reservoir temperatures, not on working substance
  - 100% efficiency would require $T_L = 0K$ (impossible per Third Law)
- **Real Engines:** usually achieve 60–80% of Carnot efficiency due to friction, heat loss, and irreversibility

15.6 Refrigerators, Air Conditioners, and Heat Pumps

- **Key Concepts**
  - Principle: Heat engines in reverse - use work input to transfer heat from cold to hot region
  - Refrigerator/Air Conditioner: Removes heat Q_L from cold interior, exhausts Q_H to warm exterior





  - Coefficient of Performance (COP): Measures effectiveness; higher COP = more efficient.
    - Refrigerator/AC:

$$COP_{ref} = \frac{Q_L}{W} = \frac{Q_L}{Q_H - Q_L}$$

- Carnot (ideal) refrigerator:

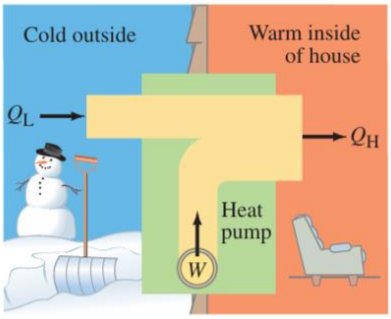
$$COP_{Carnot,ref} = \frac{T_L}{T_H - T_L}$$

- Heat Pump (used for heating):

$$COP_{hp} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_L}$$

$$COP_{Carnot,hp} = \frac{T_H}{T_H - T_L}$$

Note: *COP can be >1; for heat pumps,* $COP_{hp} = COP_{ref} + 1$



Second Law Implications

- Clausius Statement: Heat cannot flow spontaneously from cold to hot; work input is required → a perfect refrigerator (infinite COP) is impossible
- Kelvin-Planck Statement: No cyclic process can convert heat entirely into work

Problem-Solving Strategy

1. Identify the device and sketch energy flow: hot/cold reservoirs, Q_H, Q_L, W direction
2. Apply First Law for cyclic process: $\Delta U = 0\Delta U = 0 \rightarrow Q_{net} = W_{net}$
   (1) Engine: $Q_H - Q_L = W$
   (2) Refrigerator/Heat Pump: $Q_H = Q_L + W$
3. Calculate efficiency or COP using the appropriate formula
4. For maximum (Carnot) values, use $e_{Carnot} = 1 - \frac{T_L}{T_H}$ or corresponding COP formulas
5. Convert temperatures to Kelvin when using Carnot formulas

16.1 Static Electricity; Electric Charge & Its Conservation

- Experiments for Static Electricity
  - Objects can be charged by rubbing (e.g., rub a glass rod with a piece of silk and it can pick up small pieces of paper)
- Electric Charge
  - Definition: A discrete quantity that can be acquired or transferred
  - Benjamin Franklin: 2 types of charges (arbitrary choice)
    - Positive
    - Negative
  - Objects with no charge —> Neutral
  - **Unlike charges attract, like charges repel**
  - Charge transfer separates existing charges —> charges are not "created" alone but in pairs
    - E.g., Glass rubbed with silk (glass +, silk -)
- Law of Conservation of Electric Charge
  - The net amount of electric charge produced in any process is **zero**
  - No net electric charge can be **created** or **destroyed**

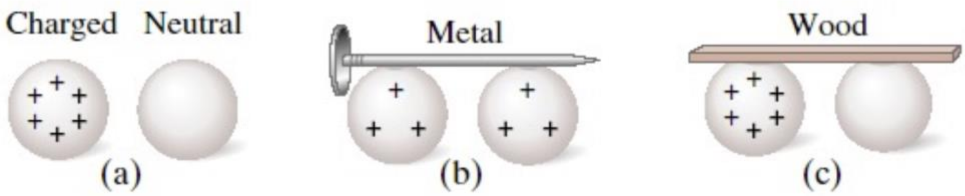
16.2 Electric Charge in an Atom

- Structure of Atoms
  - 1897: J.J. Thomson — **electrons**
    - **Light, negatively** charged particle.
  - 1909 ~1911: Ernest Rutherford — nucleus
    - **Protons: Massive, positively** charged particle
    - **Neutrons**: have **no** net electric charge
  - **Atoms are neutral**
    - Positive charge = negative charge
- Electric Charges in the Atom
  - Ion: An atom may lose one or more of its electrons, or may gain extra electrons (a net positive or negative charge)
  - In solid material —> Nucleus tends to **remain close** to fixed position, some electrons may **move quite freely**
  - In liquids and gases —> **Nuclei or ions** can move as well as **electrons**
- Static Discharge

- Normally when objects are charged by rubbing, they hold their charge only for a limited time and eventually return to the neutral state.
  - Charges leak off into the air.
- Usually the charges "leak off" onto water molecules in the air.
  - **Water molecules are polar.** —> Even they are neutral, their charge is not distributed uniformly. (There is a **charge difference** between parts of the water molecule, even though the overall charge is zero.)
  - **Extra electrons** on the negatively charged objects are **attracted** to the positive end of water molecules.
  - The **positively charged objects** can be **neutralized** by transfer of loosely held electrons from molecules in the air.

16.3 Insulators and Conductors

- The ability of a material to be influenced by external charge depends on the **mobility of its electrons.**

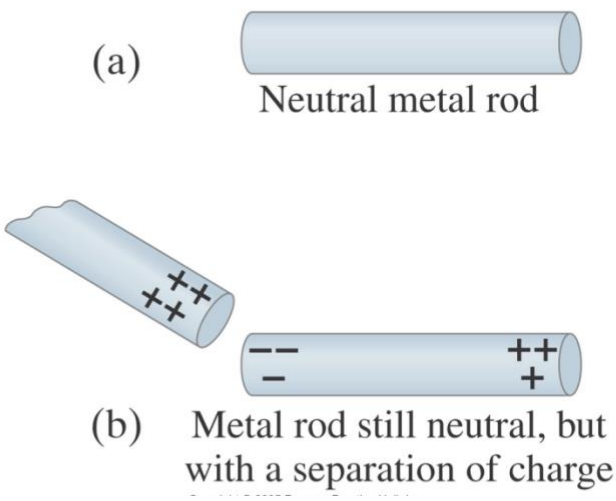


- Conductors
  - Definition: materials that **readily allow charge** to cross them.
    - Some of the electrons (free electrons, conduction electrons) are bound very loosely and can move about freely within the material.
    - E.g., Metals (especially silver; copper; aluminum; iron), plasma (a highly ionized gas), carbon graphite, human body, Earth, impure water (acid/ base/salt solution)
  - Temperature increases, resistance increases
- Insulators
  - Definition: Material whose electrons are **less fluid** and consequently **do not allow charge** to cross them.
    - The electrons are bound **very tightl**y to the nuclei (almost no free electrons)
    - E.g., Nonmetal, glass, rubber, plastic, pure water, etc.
- Semiconductors

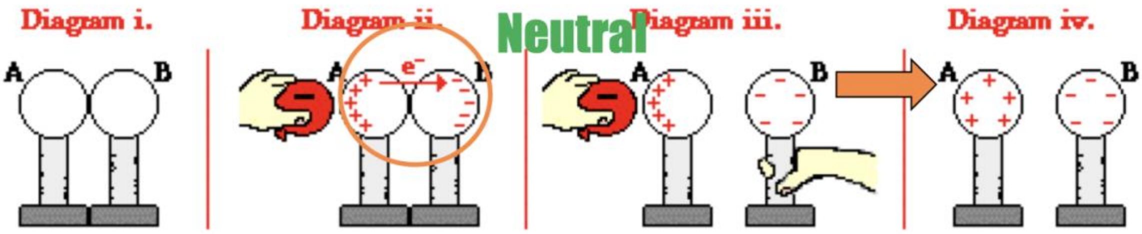
- Definition: materials conduct electricity better than insulator but not as well as conductors.
    - Fewer free electrons
    - E.g., Silicon and germanium
- Pure form: extremely high resistance —> Add other types of atoms (dopant): to decrease resistance.
- Temperature increases, more free electrons —> resistance decreases.

16.4 Induced Charge; The Electroscope

- Charging by Friction
    - The **transfer of electrons** from one object to another by **rubbing**
- Charging by Conduction/Contact
    - **Conduction**: the transfer of electrons from a **charged object** to another object by **direct contact**.
    - When a charged object **touches** a neutral conductive object, electrons are transferred such that two objects have the **same** type (sign) of charge.
        - The direction of electron transfer in such a case depends on the **initial type of charge**.
    - **<u>Identical objects will share charges equally</u>**
    - **<u>Bigger objects will get more charges</u>**
- Charging by Induction
    - Induction: the **movement of electrons** to one part of an object caused by the **<u>electric field</u>** of another object.
        - No contact (a charged object put nearby)
        - Induction involves the rearrangement of electric charges



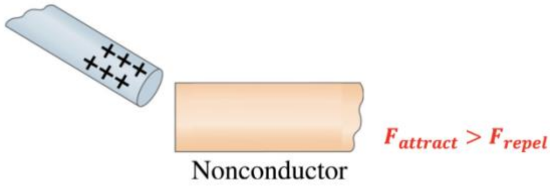
- (1) Bring a **positively (negatively)** charged object **close** to a neutral metal rod, but **does not touch it**.
    - The **free electrons** of the metal rod do not leave the rod, but they still **move within** the rod toward (away from) the external positive (negative) charge, leaving a positive (negative) charge at the opposite end of the rod.
    - A charge is said to have been **induced** at the two ends of the metal rod.
    - **No net charge** has been created in the rod: charges have merely been **separated**.
    - If the metal is broken into two pieces, we would have **two charged objects**: one charged positively and one charged negatively.



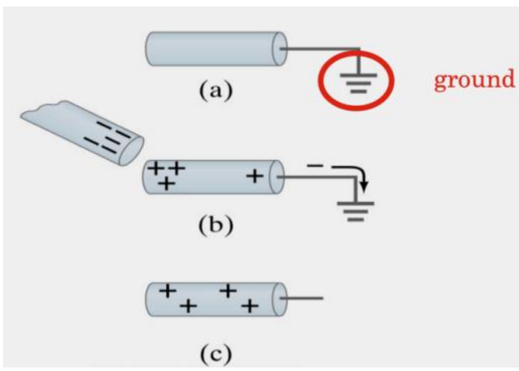
- (2) Another way to induce a net charge on a metal object is to **first connect it with a conducting wire to the ground (or a conducting pipe leading into the ground)**
    - The object is said to be **"grounded" or "earthed"**. (Earth is a charge reservoir)
    - If a charged object (negative) is brought up close to the metal object, f**ree electrons** in the metal are **repelled** and many of them **move down** the wire into the Earth. —> This leaves the metal **positively** charged.
    - If the wire is **now cut**, the metal object will have a positive induced charge.

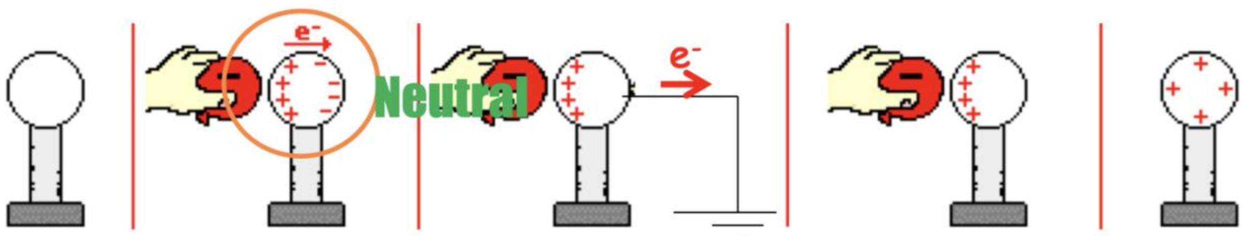
- If the wire were cut **after** the negative object is moved away, the electrons would all have **moved back into the metal object and it would be neutral**.

- Charge Separation in Nonconductor
  - Almost no electrons can move about freely within the nonconductor. But they can **move slightly** within their **own atoms and molecules.**
  - The negatively charged electrons **attracted** to the external positive charge, tend to move in its direction within their molecules.



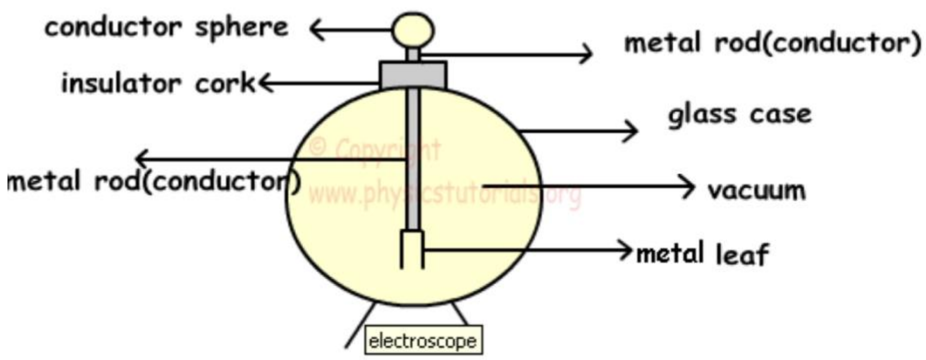
  - Because the negative charges in the nonconductor are **nearer** to the external positive charge, the nonconductor as a whole is **attracted to the external positive charge**.
- Electroscope
  - Definition: A device that can be used for detecting charge.
  - Structure:



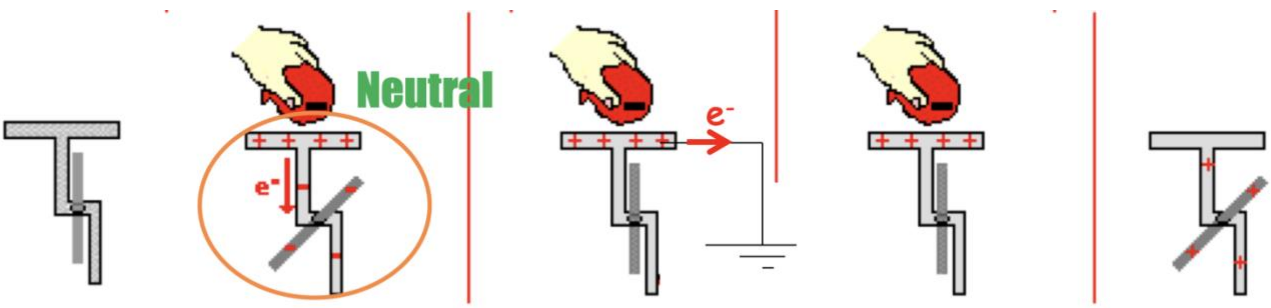


- Inside a case are two movable metal leaves, often made of gold foil, connected to a metal knob on the outside. (Sometimes only one leaf is movable.)

- Electroscope can be charged by conduction or by induction.
  - By conduction: If the knob is charged by conduction, **the whole apparatus acquires a net charge**.
  - By induction: If the positively charged object is brought close to the knob, **a separation of charge is induced:** electrons are attracted up into the knob, leaving the leaves positively charged. The two leaves repel.
- The electroscope can measure **the relative strength** of an electric charge
  - The greater the amount of the charge, **the greater the separation of the leaves.**
- The electroscope **cannot directly determine the type of charge**
- An electroscope can be used to determine the sign of the charge if it is first charged by conduction.
- Grounding a + electroscope



  - Free electrons are attracted and enter the electroscope from the ground.
  - When the electroscope becomes neutral, the electrons are no longer attracted into the electroscope.



- Grounding a - electroscope

- Free electrons are repelled and move into the earth.
- When the electroscope becomes neutral, the electrons are no longer repelled into the ground.

Specific Heat Lab

- **Procedure**
  1. Measure mass of the empty calorimeter cup
  2. Add water and measure total mass
  3. Measure the initial temperature of the water and cup
  4. Heat the metal in hot water, then measure the temperature of the hot water
  5. Quickly transfer the metal to the calorimeter
  6. Stir gently until the temperature stabilizes, then record final temperature
  7. Remove, dry, and measure the mass of the metal
- **Error Analysis**
  - Heat loss during transfer: Q_{gained} too low, causing c_{metal} too low
  - Stirring not enough or early temperature reading: system hasn't reached equilibrium, causing T_{final} too low or too high
  - Thermometer inaccuracy: systematic error
  - Absorption of heat by thermometer/stirrer: they also gain heat but is not included in calculations
  - Water evaporation: mass loss of water during evaporation
- **Short Answers**
  1. Purpose of the lab:
     - Use calorimeter to measure specific heat of an unknown metal
     - Identify the metal by comparing calculated value to known values
  2. Why water is excellent in the calorimeter:
     - High specific heat → absorbs/releases large amounts of heat with minimal temperature change
     - Results in more accurate and sensitive measurements
  3. Meaning of "low specific heat":
     - Heats up and cools down quickly
     - Requires little energy to change temperature
     - Poor heat retention
  4. Other properties for identifying metal:
     - Density, color, hardness, melting point
     - Electrical/thermal conductivity, malleability, reactivity