Solid state (one of five states of matter)

We will concentrate on crystals: materials in which atoms form a periodic structure called crystal lattice.

There are many types of lattices (check the web for pretty pictures). The actual configuration for a particular material is determined by minimal potential energy. Each atom/ion in a crystal experiences both attractive (Coulomb) potential and repulsive potential

\[ U_{\text{attr}} = -\lambda \frac{ke^2}{r} \quad [r = \text{nearest-neighbour distance}] \]

\[ \lambda = \text{Madelung parameter, determined by a geometry of the lattice.} \]

\[ U_{\text{rep}} = \lambda e^{-r/r_0} \quad \text{mainly due to Pauli exclusion principle} \]
Types of bonding

1. **Ionic** - electron hops from one atom to another to create two ions with completed electron shells. Then lattice is held together by coulomb attraction b/w ions (NaCl, LiBr, etc.)

2. **Covalent** - electrons are shared b/w two similar atoms, and atoms are held together by coulomb attraction to same electrons (C, Ge, etc.)

   Since in both kinds of lattices electrons are localized, these are usually **isolators**

3. **Dipole - dipole (van-der-Vaals)** - bonding b/w separate tight-bound molecules or atoms with complete electron shells. Electrostatic attraction b/w two induced or internal dipole moments

   ![Diagram of dipole]

4. **Metallic bond** - somewhat similar to covalent, but all electrons are shared between all atoms, while positively charged ions (nucleus + closed electron shells) form a crystal lattice.

   Free electrons can carry electric current, thus metallic bonding is usual for conductors.
Semiclassical Drude model
Conducting electrons are treated as a free gas, moving b/w lattice atoms

\[\begin{align*}
\text{Ohm's law } & \quad V = I \cdot R \quad \text{(bulk)} \\
\text{or (since } & \quad V = E \cdot l, \quad I = J / A \text{)}
\end{align*}\]

\[E \cdot l = j \cdot A \cdot R\]

where conductivity \[\sigma = \frac{E}{R \cdot A}\]

Apparent contrarversy
If electrons are free to move, electric field accelerates them from one end of the conductor to the other
\[a = \frac{\mathbf{F}}{m} = \frac{(-e) \mathbf{E}}{m} = \frac{eE}{m} \quad V_e^2 = 2a \cdot l = \frac{2el}{m} \cdot E\]

\text{electron density}

But \[j = n \cdot e \cdot V_e \implies V_e = j / ne\]

Thus \[j^2 = \left( \frac{2ne^2l}{m} \right) E\]
or \[j^2 \propto E\]

What's wrong?!
Electrons cannot move freely along the conductor, they actually move randomly in all directions with relatively high speeds, bumping into ions in the lattice. Electric current provides a slow drift, and

\[V_{\text{drift}} = a \cdot t \quad \text{where } t \text{ is time b/w consecutive collisions.}\]
Thus \[ j = ne \nu_{\text{drift}} = \frac{2ne^2E}{m} \]

One can estimate that \( \nu_{\text{drift}} \approx 1 \text{ mm/s} \)