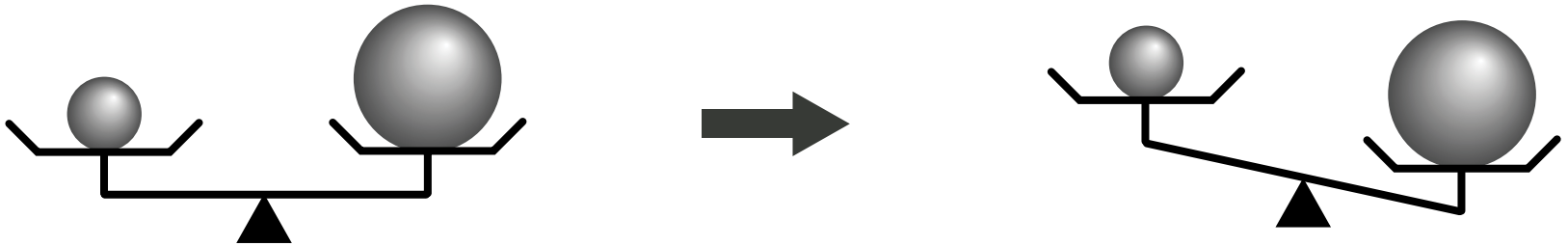
DENSITY

Density is a materials mass/unit volume.

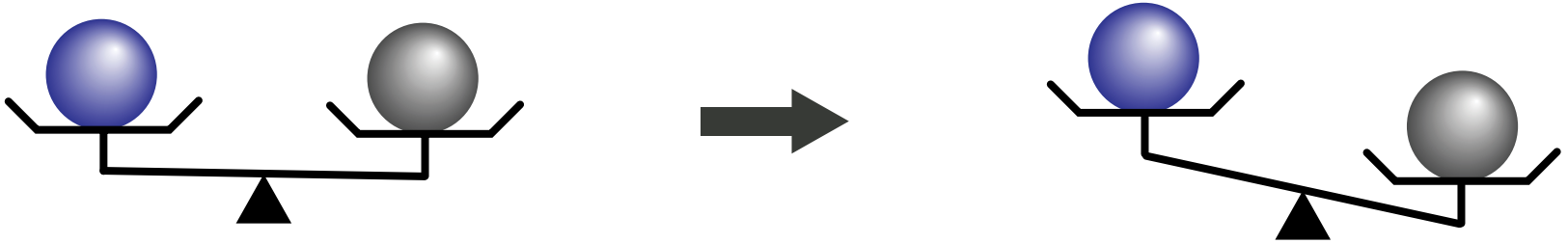
Why are some materials heavier than others?

If the objects are the same *material*, ***size*** matters!



A larger steel ball is heavier than a smaller one

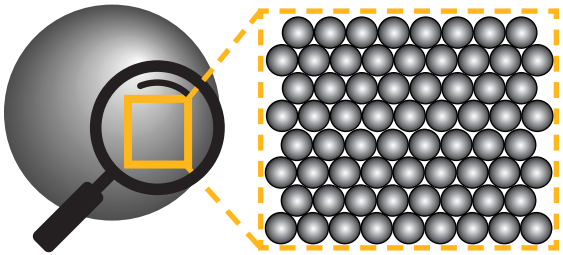
If the objects are the same *size*,
then the material ***density*** matters!



The gray (steel) ball is heavier than
the blue (plastic) one

What causes materials to have different densities?

If we look inside a solid material, we will see that it is made of trillions of atoms.
There are ***two*** important details about these atoms that influence density.



1

Atomic Mass

All atoms on the Periodic Table of Elements have different atomic masses. For example, Copper has an atomic mass of 63.5 g/mol, while Titanium only has an atomic mass of 47.9 g/mol.

2

Atomic Packing

Different materials atoms "pack" or arrange themselves in different ways. ***Crystalline materials*** are highly organized with periodic, repeating 3D arrangement of atoms, ions, or molecules (*i.e.* metals). ***Amorphous materials*** lack this long-range periodic order (*i.e.* glass).

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DENSITY

Density is a materials mass/unit volume.

Experimental Density Calculation

In the lab, density of materials can be calculated using the following equation: $$\rho = \frac{m}{V}$$

where:

ρ = density [kg/m^3] m = mass [kg] V = volume [m^3]

Intrinsic Material Property Density Calculation

Two intrinsic material properties influence density: ***Atomic Mass*** and ***Atomic Packing***

Therefore, we can calculate density using atomic mass and atomic structure for ***crystalline materials*** using the equation shown here:

$$\rho = \frac{nW}{V_{cell}N_A}$$

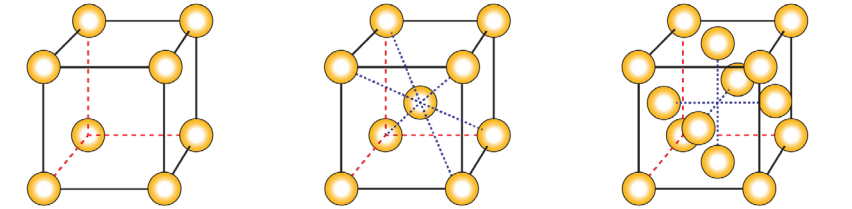
where:

n = number of atoms per crystal unit cell [atoms]
W = atomic mass of material [g/mol]
V_{cell} = volume of unit cell [m^3]
N_A = Avogadro's number [6.022 x10^{23} atoms/mol]

How do we count the number of atoms per crystal unit cell?

For crystalline materials, there exist different ***crystal structures.*** These crystal structures can have different packing arrangements, *e.g.* body-centred cubic (BCC) and face-centred cubic (FCC). A Unit Cell is the smallest repeating unit within these crystalline materials. Examples of BCC, FCC, and a Simple Cubic* unit cell are shown below.

less densely packed → more densely packed



Simple Cubic Unit Cell | Body-Centered Cubic Unit Cell | Face-Centered Cubic Unit Cell

We use these models to help us count the number of atoms per unit cell.

Simple Cubic has 1 atom, BCC has 2 atoms, and FCC has 4 atoms.

Try counting for yourself! Remember, these unit cells have neighbors on all six cube faces.

The degree of atomic packing influences the density of the material. For example, copper is FCC while β-titanium is BCC. This means more copper atoms fit in the same volume, so we expect copper to be more dense.

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*Simple Cubic is not a unit cell found in nature. It is however used to help illustrate atomic packing

THERMAL CONDUCTIVITY

Thermal conductivity is the rate at which heat is conducted or moved through a material from regions of high to low temperature.

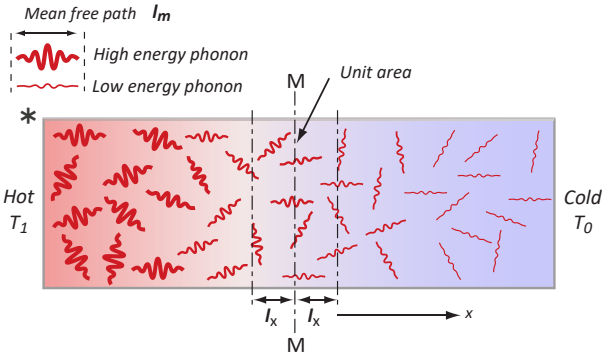
Materials with ***high*** thermal conductivity dissipate heat quickly,
while materials with ***low*** thermal conductivity will take a long time to normalize in temperature. ***Why?***

How does heat move through materials?

Heat moves through solid materials via ***two*** main methods:

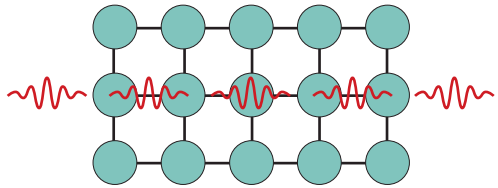
1 Lattice Vibrations

Heat enters the materials as *phonons,* which travel via vibrational waves across the atomic lattice in the system.



Phonons are elastic waves and move at the speed of sound, but heat doesn't diffuse at the same speed- **why?**

If materials were perfect lattices, the phonons would travel across the lattice without any scattering, maintaining their original speed

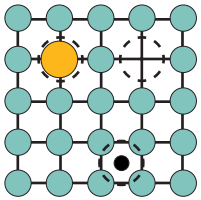


But no material is perfect!

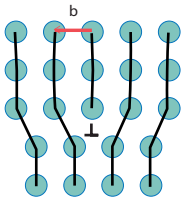
Instead, phonons are scattered by irregularities within the material lattice, causing energy loss and speed reduction.

Many types of lattice irregularities exist

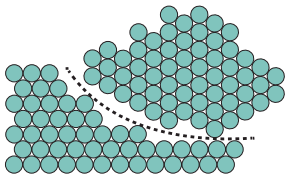
Point/1D



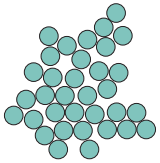
Line/2D



Planar/3D



Amorphous Structure



The more irregular the lattice, the more scattering occurs!

2 Free Electrons

Phonons can also travel via free electrons. The number of free electrons in the system is dependent on the atomic bonding within the material.

most free electrons **Metallic > Ionic > Covalent** *least free electrons*

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*figure adapted from the Ansys Granta EduPack software

THERMAL CONDUCTIVITY

Thermal conductivity is the rate at which heat is conducted or moved through a material from regions of high to low temperature.

Why is thermal conductivity important?

High thermal conductivity materials are important for applications where heat dissipation is important, such as ***heat sinks*** in electronic devices. Low thermal conductivity materials are used for ***thermal insulators***.

Experimental Thermal Conductivity Calculation

In the lab, thermal conductivity can be calculated using the following equation:

$$\lambda = \frac{QL}{A\Delta T}$$

where:

λ = thermal conductivity [W/(m·K)]* | Q = heat transfer rate [W] | L = material length [m]
A = material cross-sectional area [m^2] | ΔT = temperature difference across the material [K]

Intrinsic Material Property Thermal Conductivity Calculation

We can use properties related to a material's microstructure to calculate thermal conductivity using this equation:

$$\lambda = \frac{1}{3}\rho C_p l_m c_o$$

where:

λ = thermal conductivity [W/(m·K)] | ρ = material density [kg/m^3] |
C_p = specific heat capacity (amount of heat required to raise temperature of a unit volume of material by one degree Celsius) [J/(kg·K)]
l_m = mean free path (average distance phonons travel before scattering) [m] | c_o = speed of sound in the material [m/s]

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*sometimes thermal conductivity is denoted by the symbol *k*

ELECTRICAL RESISTIVITY

Electrical Resistivity is the ability for a material to *resist* the flow of electrons from an electric current

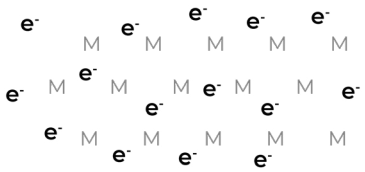
How does electric current move through a material?

Electrons are the primary carriers of electric current and move through solid material via ***two methods:***

1 Free Electrons

To understand how electrons move in materials, we need to consider ***atomic bonding.***

Metallic Bonds

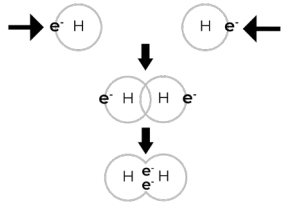


The electrons in metallic bonds delocalize from their original atomic nucleus, giving us electrons that are the most mobile.

Ionic Bonds

Ionic bonds occur when one atom "donates" electrons to another, leaving both atoms with complete electron valence shells that are not as mobile.

Covalent Bonds

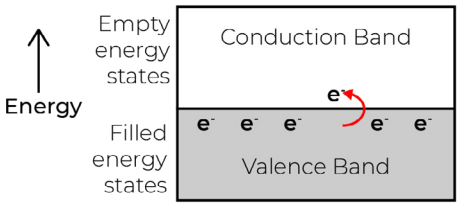


Covalent bonds "share" electrons from the involved atoms, leading to a very strong bond that is difficult to break.

2 Excited Electrons

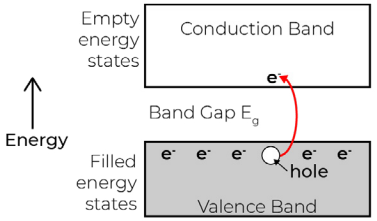
All electrons have energy states in which they exist, which average into two general "bands" within materials: **valence** and **conduction**. Conduction is where electrons move with current. Adding energy to a system can allow for increased electron mobility. How mobile electrons become depends on the type of material:

Conductors



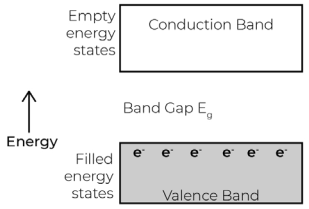
Conductors require the least amount of energy to move electrons to conduction band.

Semiconductors



Semiconductors require energy greater than the band gap E_g to move electrons to conduction band. The hole left behind in the valence band also aids in electron movement.

Insulators



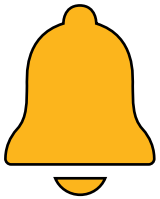
Insulators have too large of a band gap, making it difficult for any electrons to make it into the conduction band.

MECHANICAL LOSS COEFFICIENT

Mechanical loss-coefficient (or damping coefficient, η) measures the degree to which a material dissipates or loses *vibrational energy*

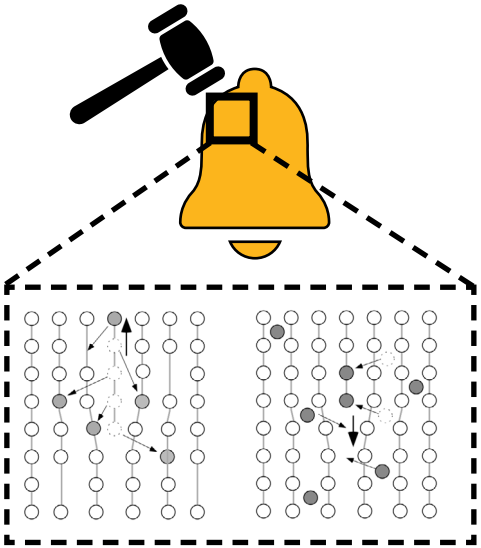
Why do we care about vibrational energy loss in materials?

Think of a bell!



Bells are often made of metal (particularly brass) or even glass and ceramic materials.

But why don't we see bells made of plastic?



When a bell is struck, mechanical energy enters the system and the material undergoes *elastic deformation* (meaning it does not change shape permanently).

This energy needs to be released somehow- it cannot stay within the material. This energy dissipation can occur via vibrations in the atomic structure.

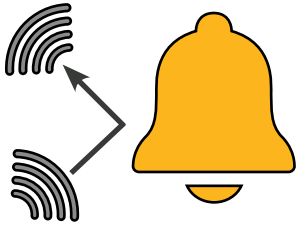
If materials had perfect atomic lattices, the vibrations would travel through the material without losing any energy.

But materials are *not perfect*! Atomic structures can have many irregularities, from single atoms missing (holes) to lack of long range atomic order (amorphous). These irregularities cause the vibrations to lose energy (as heat) as they move through the material. The more irregularities, the more energy lost.

So materials with a low number of irregularities have *low damping coefficients*, and materials with a high number of irregularities have *high damping coefficients*

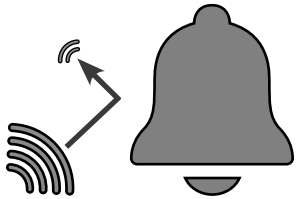
So how does this impact the material choice for a bell?

Metals, such as brass, have *low damping coefficients*, allowing the sound of the bell to ring for longer (instead of the sound being absorbed)



Polymers, on the other hand, have *high damping coefficients*, which would absorb the sound and not ring for as long.

This does make polymers great for sound damping however!



DIELECTRIC CONSTANT

Dielectric constant (or relative permittivity) is a measure of how much electric charge a material can hold when placed in an electric field.

What type of materials are best suited to hold electric charge?

Need a material that resists the flow of charges through the material- we want the material to ***hold*** the charge

~~METALS~~

Metals won't work; their electrical conductivity is too high

✓ INSULATOR

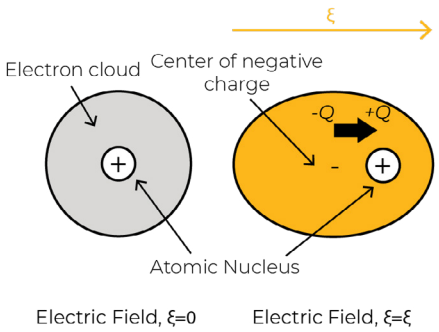
Insulators, like ceramics, would work well. Their low electrical conductivity makes them a good candidate.

But how would an insulator hold charge?

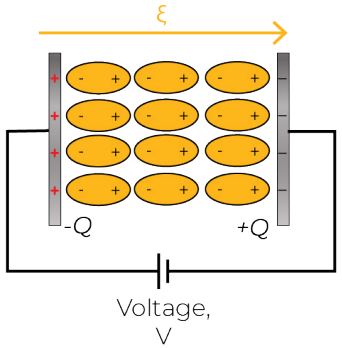
Dielectric Materials, Dipole Moments, and Electrical Polarization

Dielectric Materials are insulators that, when exposed to an electric field, form dipole moments within their atoms.

A **dipole moment** occurs the positive and negative charges within an atom are separated. **Electrical Polarization** can cause a dipole to form in dielectrics, like shown below.



When a dielectric material is placed within an electric field (like shown below), dipole moments occur across the material and lead to opposing charges on the plates generating the field.



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DIELECTRIC CONSTANT

Dielectric constant (or relative permittivity) is a measure of how much electric charge a material can hold when placed in an electric field.

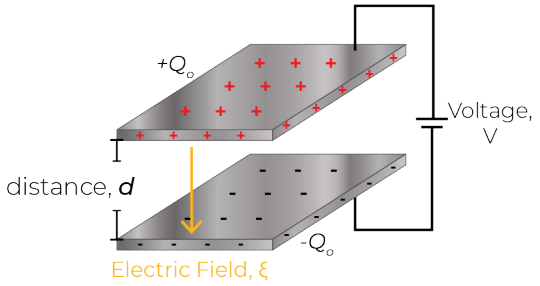
Why do we care how much electric charge a dielectric material can hold?

Electrical circuits! When designing a circuit, unwanted current flow needs to be prevented. What if we had a way to collect extra charge and store it within a circuit...

We can use a capacitor!

When a voltage source is connected to two separated plates, it causes positive charge to accumulate on one plate and negative charge to accumulate on the other plate. This separation of charge creates an electric potential (V) and an electric field (ξ) between the plates- a *capacitor*.

Figure 1: Parallel Plate Free Space Capacitor



We calculate the *Electrical Capacitance* of our capacitor using the equation:
Where C= Capacitance, Ɛ=the permittivity of the space between the plates, A= area of the plates, and d=distance between the plates

$$C = \frac{\varepsilon A}{d}$$

The capacitance is also related to the electric charge and applied voltage in the capacitor by the equation:
where C= Capacitance, Q= electric charge, and V= applied voltage

$$C = \frac{Q}{V}$$

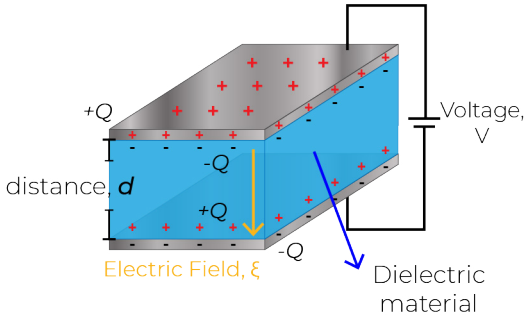
In Figure 1, the capacitor has free space (vacuum) between the plates and the permittivity is ε_0, or the *absolute permittivity*, with charge Q_0 and capacitance C_0.

In Figure 2, the capacitor has a dielectric in between the plates. This dielectric forms the opposing charges on the surface of the plates (as described on earlier on this card). The permittivity of this capacitor is ***increased*** due to these surface charges, leading to our ε_r or ***relative permittivity*** being related to Capacitance and charge by the equation:

$$\varepsilon_r = \frac{Q}{Q_o} = \frac{C}{C_o}$$

where Q= capacitor charge with dielectric
Q_o=absolute charge
C= capacitor charge with dielectric
C_o=absolute capacitance

Figure 2: Parallel Plate Dielectric Medium Capacitor



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