

Lecture 5 - Dielectrics

Lecture Summary

- Origin of ionic polarisation
- Capacitor operation and definitions
- Impedance spectroscopy
 - definitions
 - ideal responses
- piezoelectricity
- ferroelectricity

Introduction

- Ionic conduction is a long-range effect
 - Important in batteries, fuel cells etc.
- In some situations, a highly insulating material is preferred
- Remember, ions are not static with time (e.g. phonons)
 - Short-range atomic motion is important for electrical properties

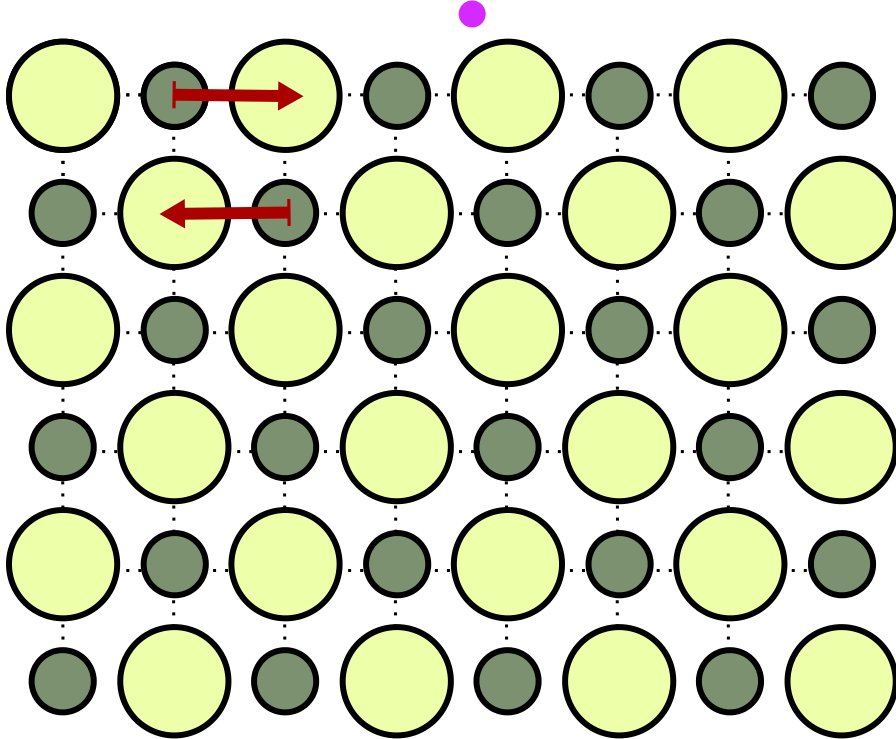
Polarisation

Ionic solids are made up of cations and anions

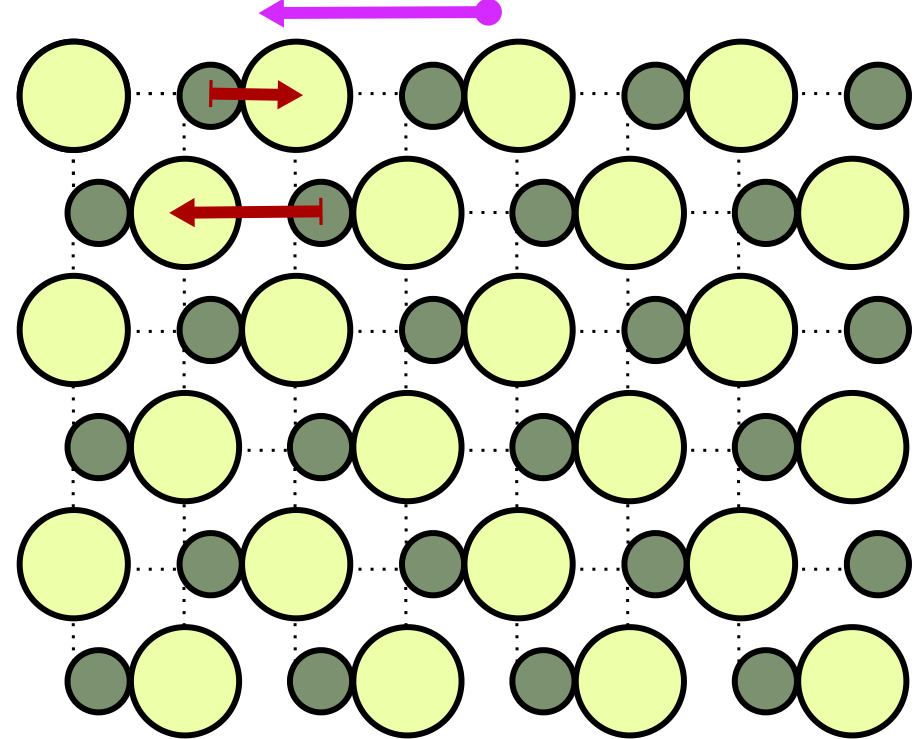
- locally, this creates dipoles (μ)
- across a whole crystal at equilibrium, these dipoles normally cancel

Under an applied electric field (E), ions displace from equilibrium

total $\mu = 0$



total $\mu > 0$



Is this useful?

If the dipoles do not cancel under an applied field, the crystal will develop an overall dipole moment

- can occur if e.g. number of cations \neq number of anions

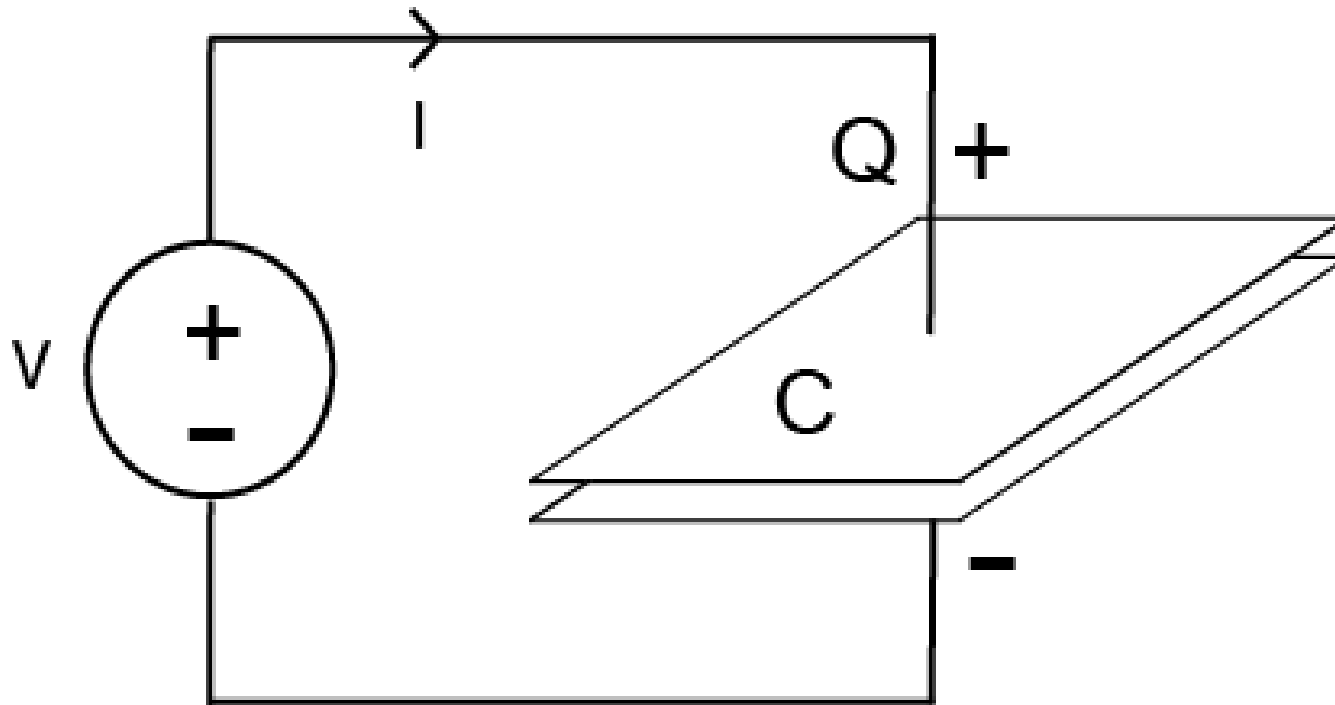
Can use this to screen electric fields

- Useful in e.g. wireless communication filters, sensor devices, transformers, and **capacitors**

Capacitors

- Vital component of most electronic devices
 - Used to store charge, smooth signals, filter, etc...
 - \$20bn per year industry

Essentially, a capacitor is an arrangement of two electrodes of area A , separated by a distance d .



The maximum charge stored, $Q = CV$ where C is the capacitance (in Farads).

Capacitance

Two electrodes separated by vacuum have a capacitance C ;

$$C = \frac{\epsilon_0 A}{d}$$

where ϵ_0 is the permittivity of free space = $8.854 \times 10^{-12} \text{ C}^2 \text{ J}^{-1} \text{ m}^{-1}$

Capacitance

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To increase C (and therefore Q):

- decrease d or increase A , **but**
- electrons will tunnel from one plate to the other if d gets too small.

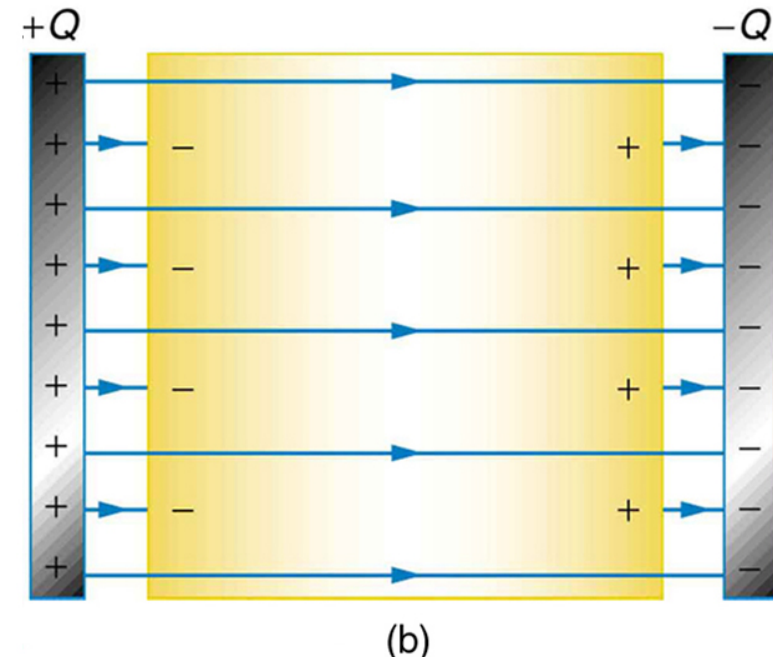
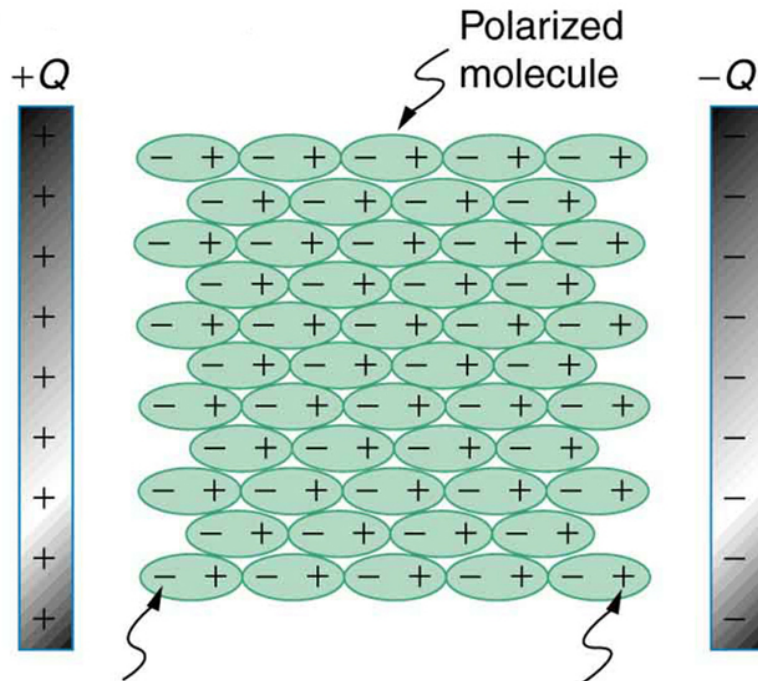
Improving charge stored

Alternatively, we can use a **dielectric**

- opposing electric field stabilises charge on capacitor plates

$$C_{\text{dielec}} = \frac{\epsilon_r \epsilon_0 A}{d}$$

where ϵ_r is the relative permittivity of the dielectric ($\epsilon_r = \epsilon / \epsilon_0$) and $\epsilon_r > \epsilon_0$



Example permittivities

Material	Relative Permittivity, ϵ_r
Vacuum	1
Paper	2.0 - 6.0
Polymers	2.0 - 6.0
Silicon oil	2.7 - 2.8
Quartz	3.8 - 4.4
Glass	4 - 15
Al_2O_3	10
Ta_2O_5	26
TiO_2	100
CaTiO_3	130
SrTiO_3	285
BaTiO_3	1000 - 10000

Characterising dielectrics

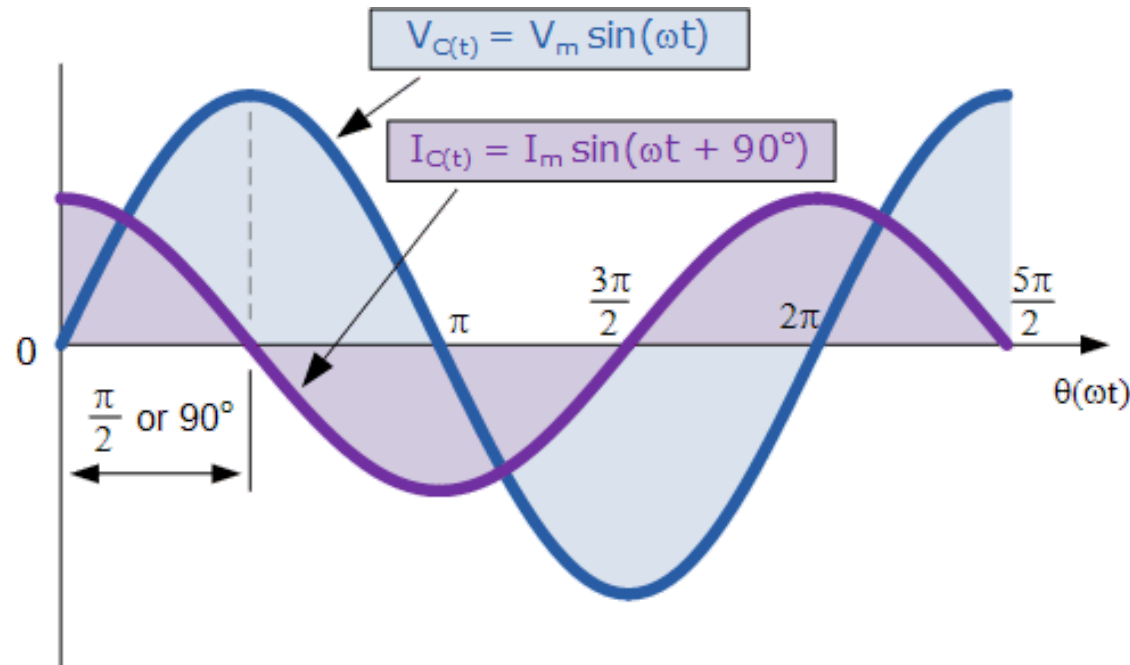
- Because dielectrics are insulating, conductivity measurements are not very useful
- Alternatively, oscillate between +ve and -ve potentials to change polarisation direction

Characterising dielectrics

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Impedance spectroscopy applies an alternating (sinusoidal) field at different frequencies f , and measures the resulting current

- Applied field, $E_t = E_0 \sin(\omega t)$, where $\omega = 2\pi f$
- Response current, $I_t = I_0 \sin(\omega t + \phi)$



Impedance

Similar to Ohm's law ($R = \frac{V}{I}$) for constant voltages, we can define *impedance* as the 'resistance' to an alternating voltage

$$Z(\omega) = \frac{E_t}{I_t}$$

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$$Z(\omega) = \frac{E_t}{I_t}$$

The total impedance can be represented as a complex number:

$$Z(\omega) = Z_0 e^{i\phi} = Z_0 (\cos \phi + i \sin \phi)$$

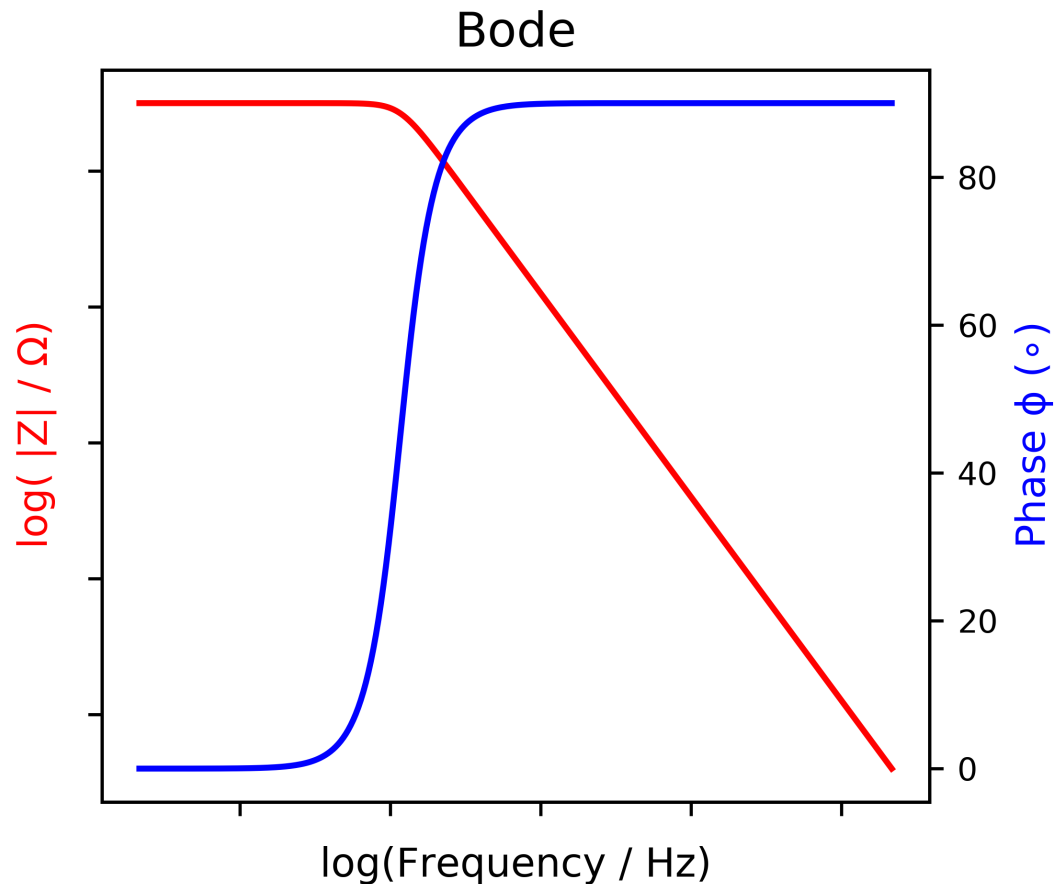
- ϕ is the 'phase-shift' between voltage and current.

Impedance analysis

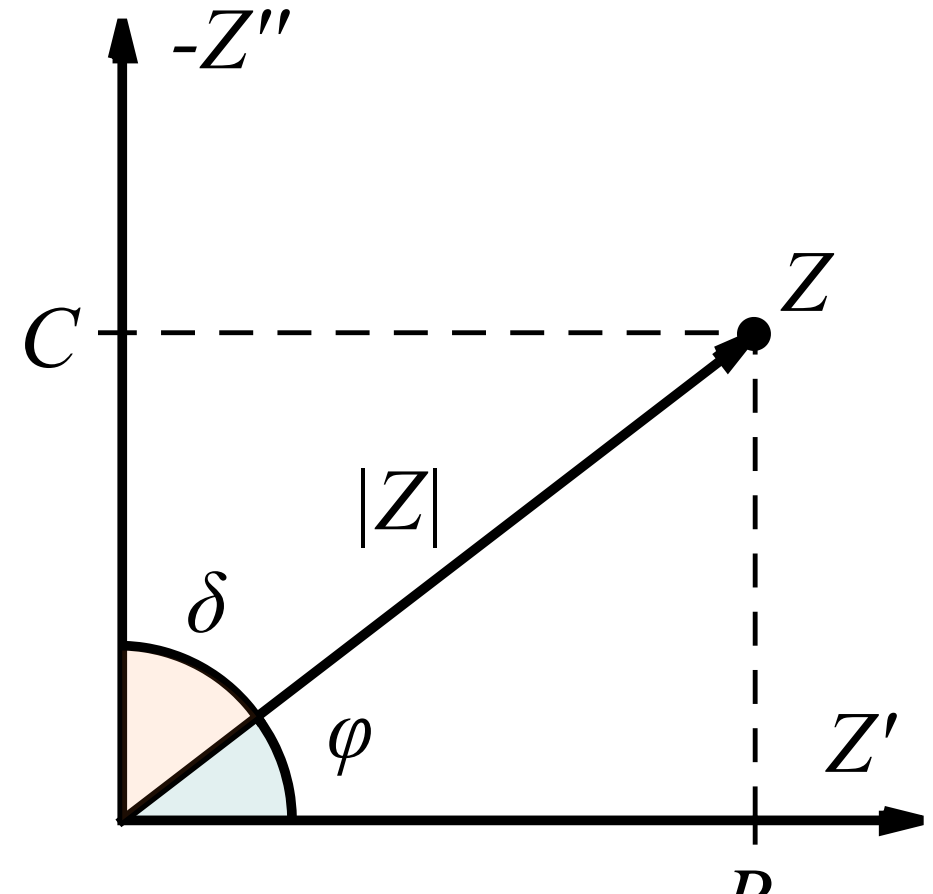
ϕ , Z and ω (or f) are all important features of impedance.

Two 'standard' ways to display data:

Bode plot: $|Z|$ and ϕ plotted vs frequency



Nyquist plot: Z plotted in a 2D plane



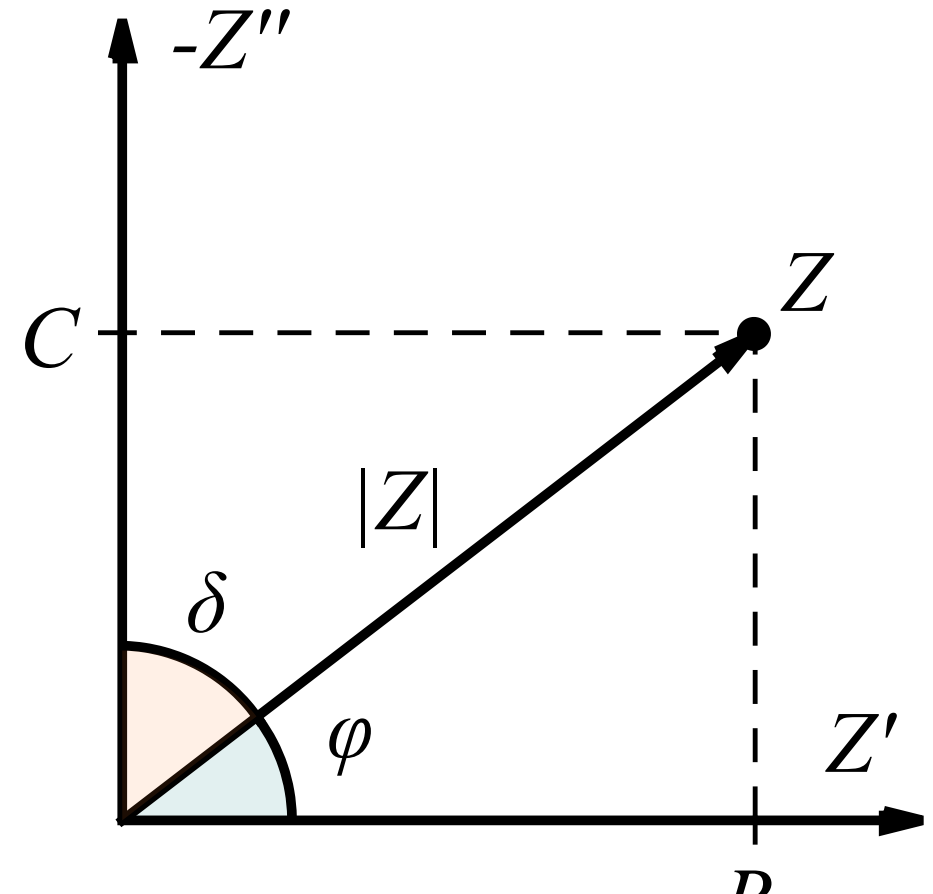
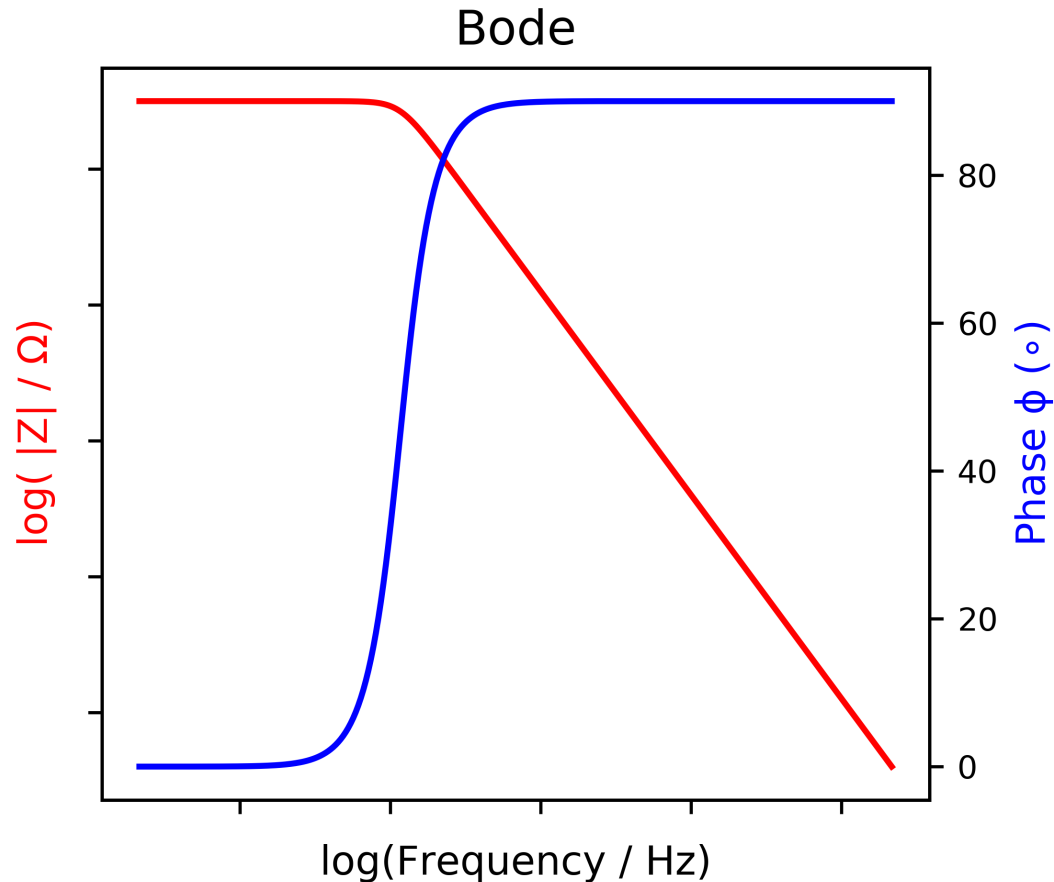
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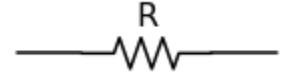
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In **Nyquist plot:** Z plotted in a 2D plane



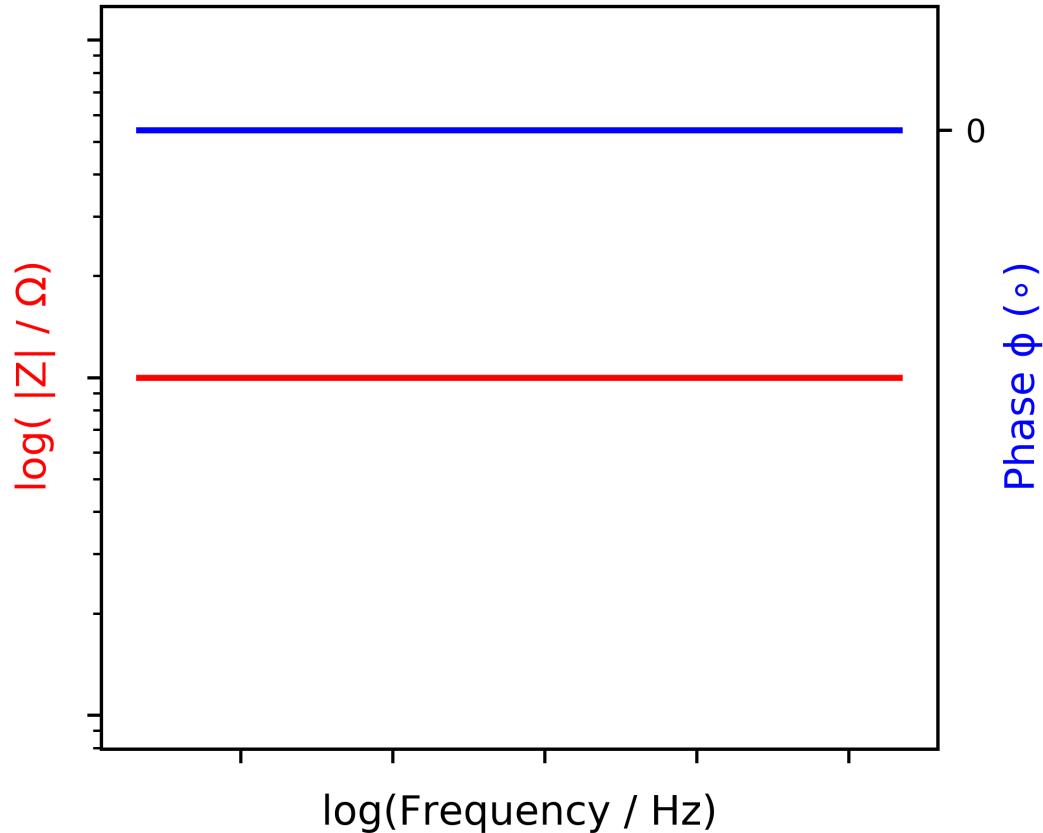
Ideal resistor response



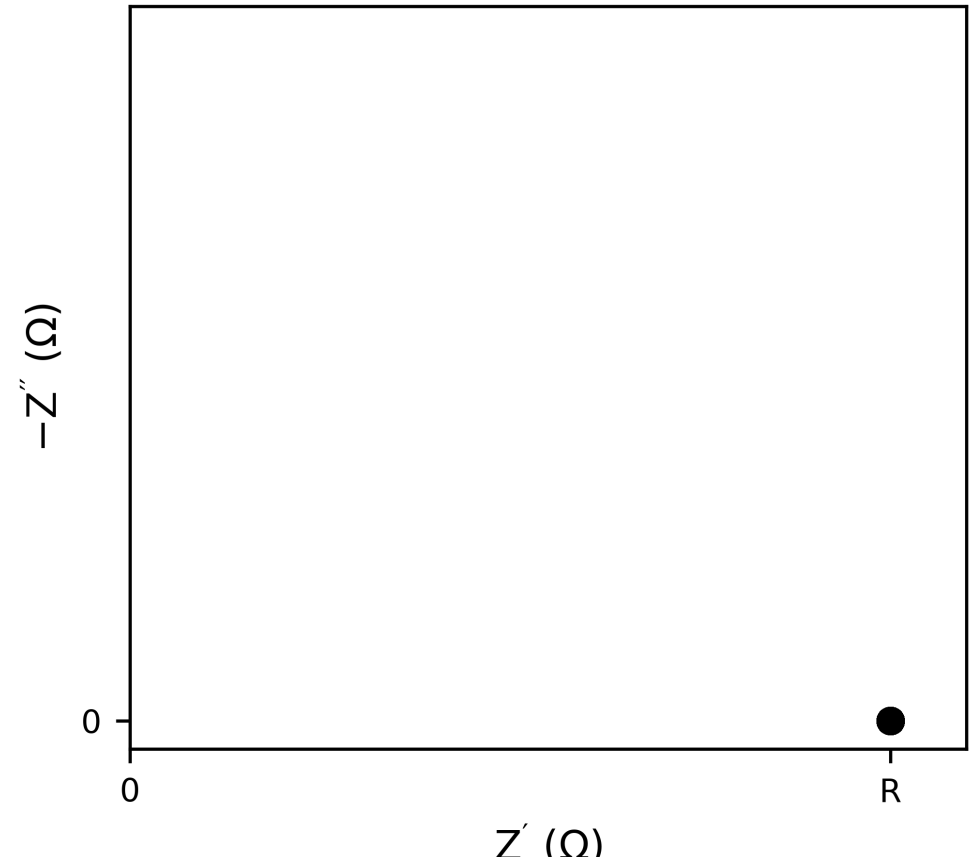
Ideal resistor has no dependence on ω

- Current is instantaneous on applying potential E
- e.g. ions moving with a constant "drag" due to interactions between them

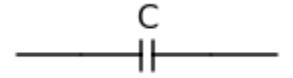
Bode



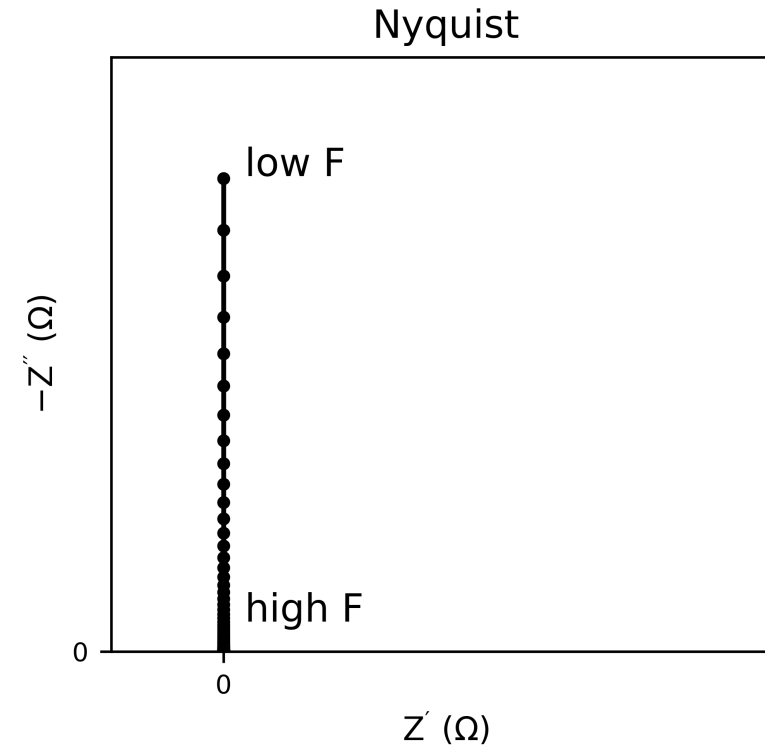
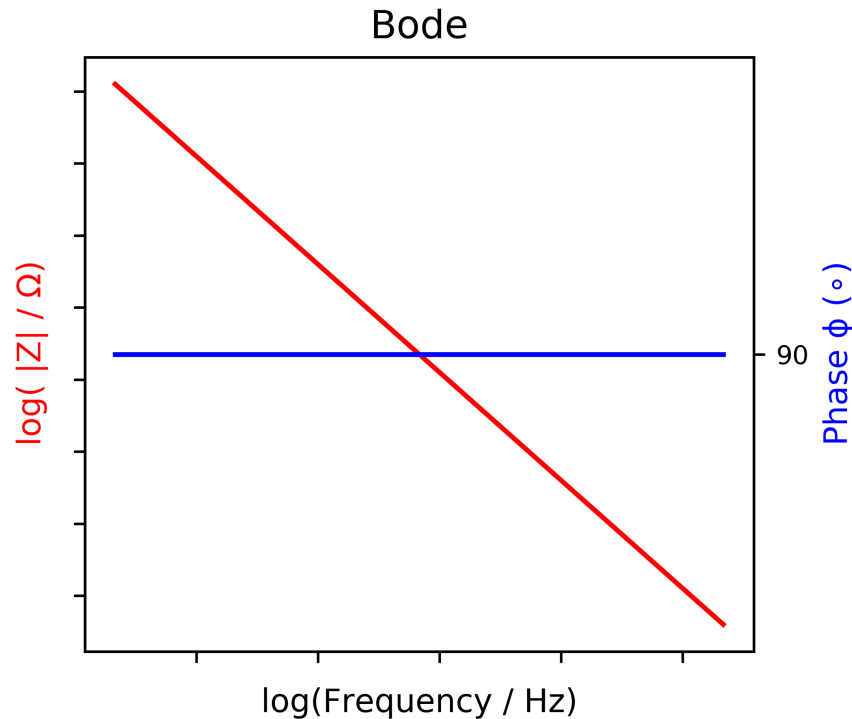
Nyquist



'Ideal' capacitor response

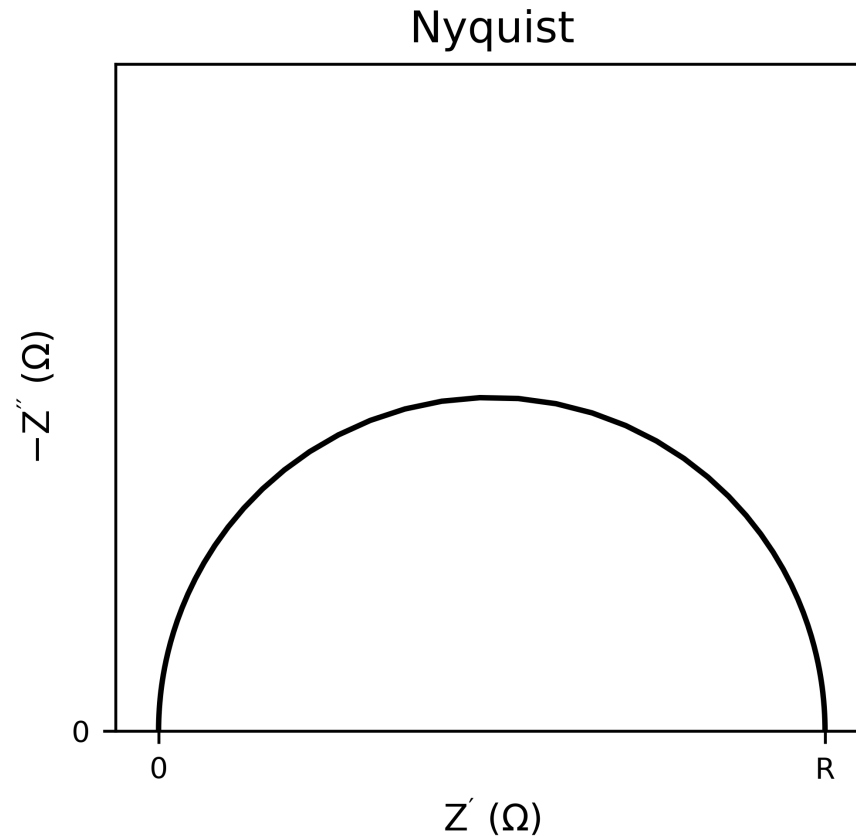
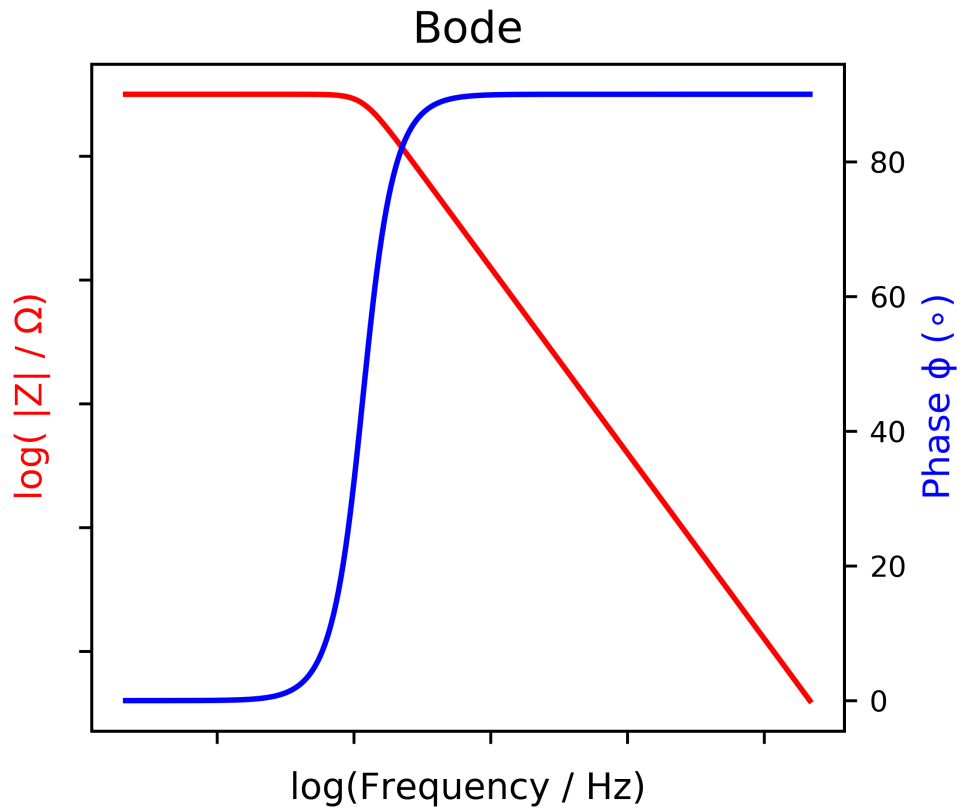
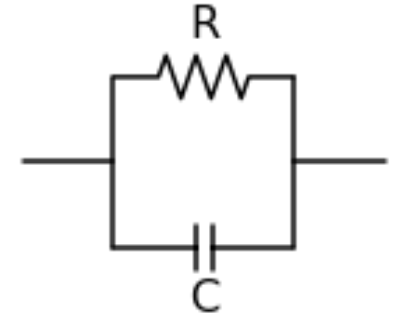


- Current I increases with ω , approaching 0
- I is always out-of-phase with E by $\phi = 90^\circ$
 - The maximum $I(t)$ occurs when $E(t) = 0$
- Represents stored charge building up, for instance ions accumulating on a surface



'Real' Impedance

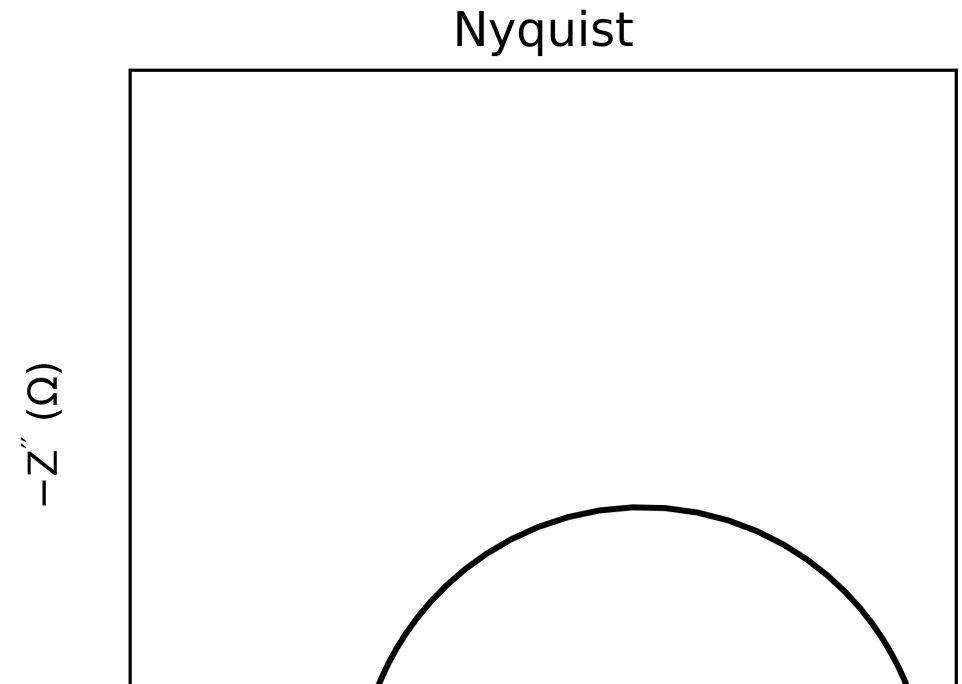
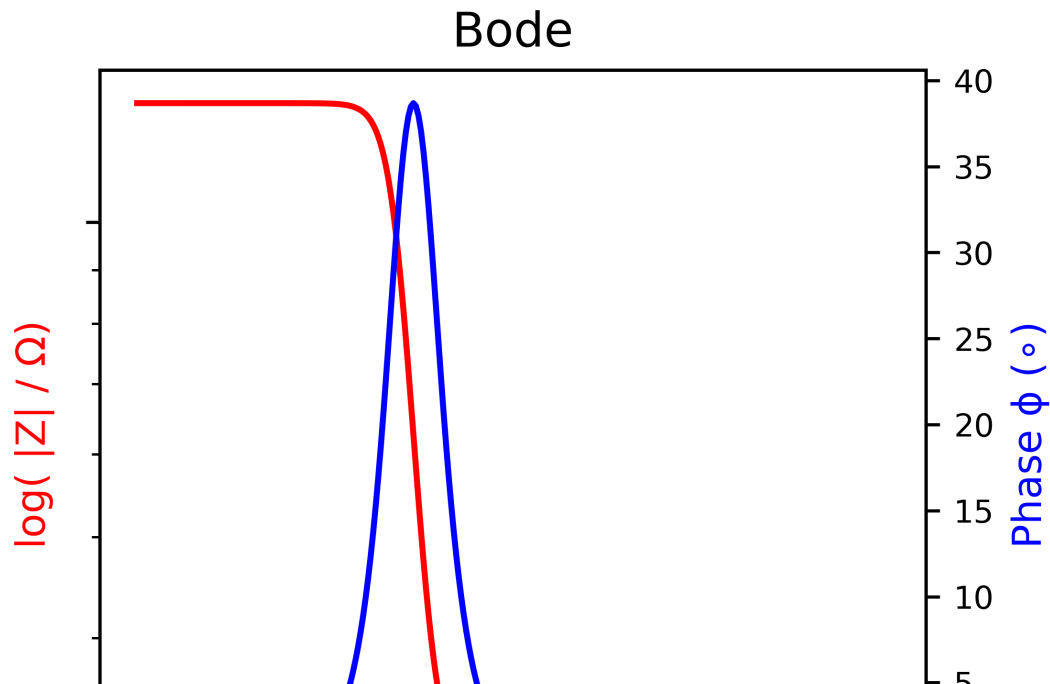
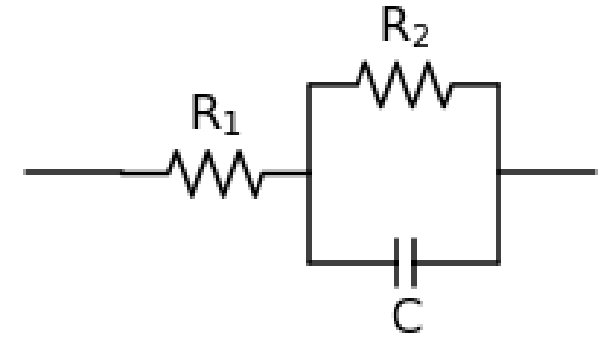
- Many materials behave like a parallel RC circuit:
 - Ions moving due to E , but motion is limited to a maximum displacement
 - Ionic conduction in a ceramic forming a charge gradient on the electrode surface



Real dielectric response

Dielectrics are not ideal-they leak!

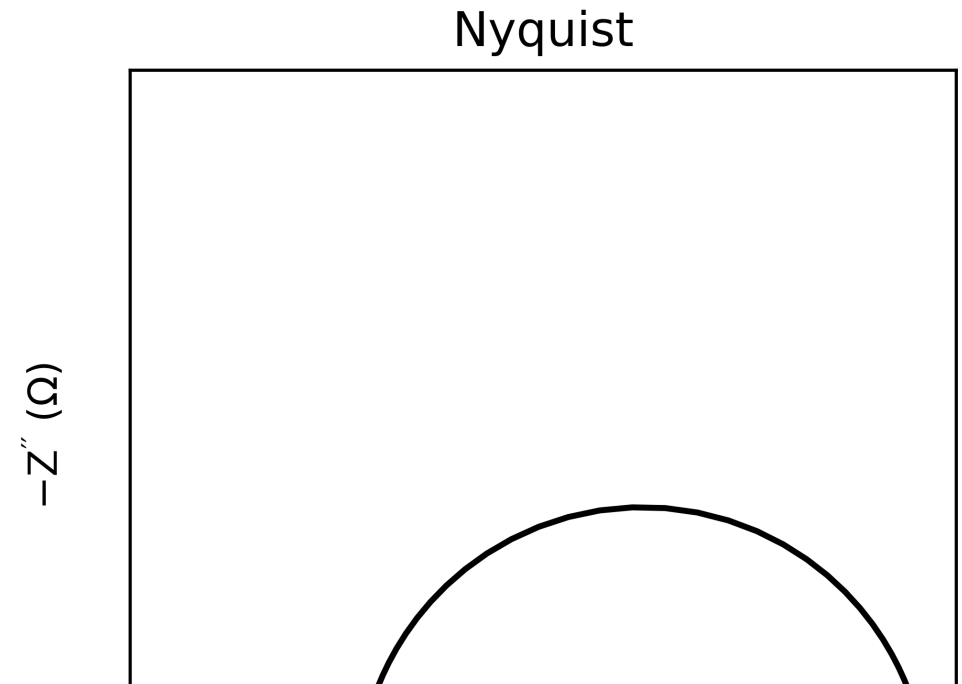
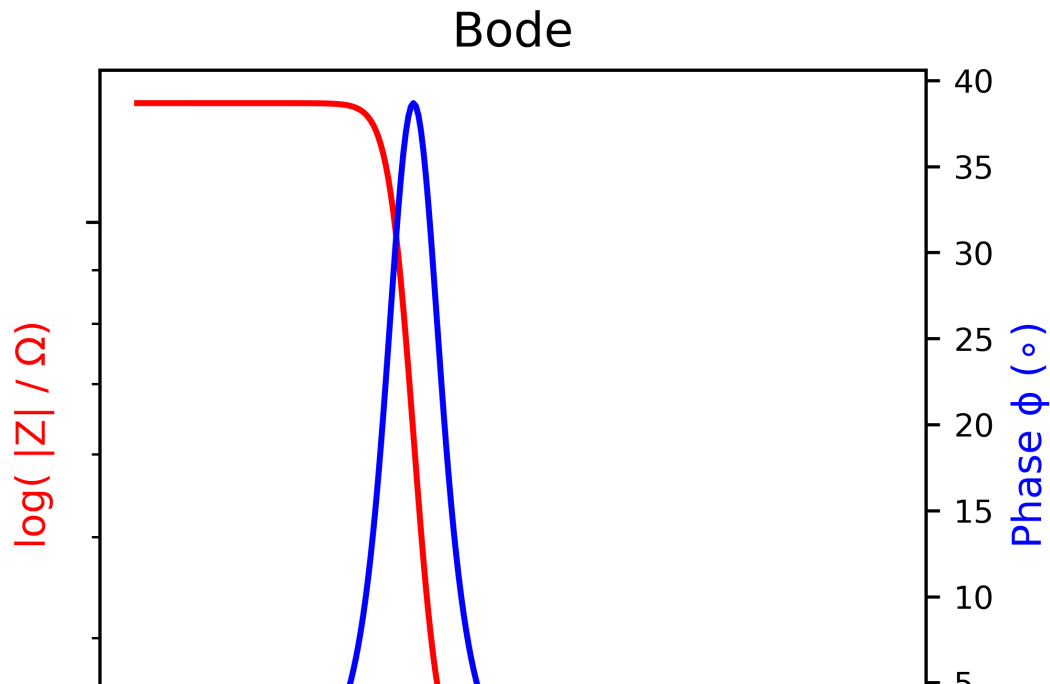
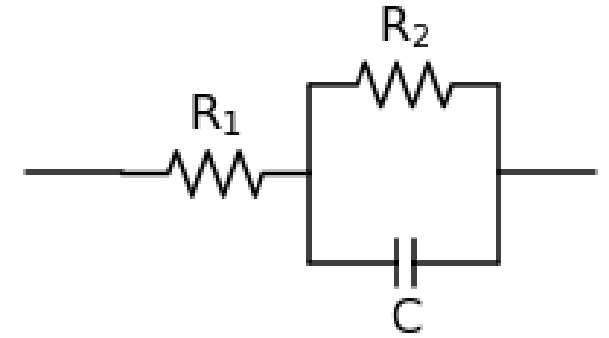
- Ions have mass, so cannot move instantly
- At high ω , some resistance remains
 - energy lost as heat
- peak in ϕ vs ω , corresponding to the maximum energy loss.
 - often reported as $\tan \delta$ (where $\delta = 90^\circ - \phi$)



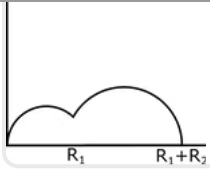
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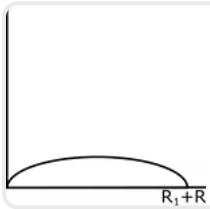
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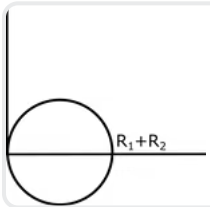
Question



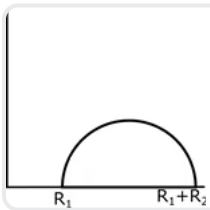
☐ A



☐ B



☐ C



☐ D

Submit

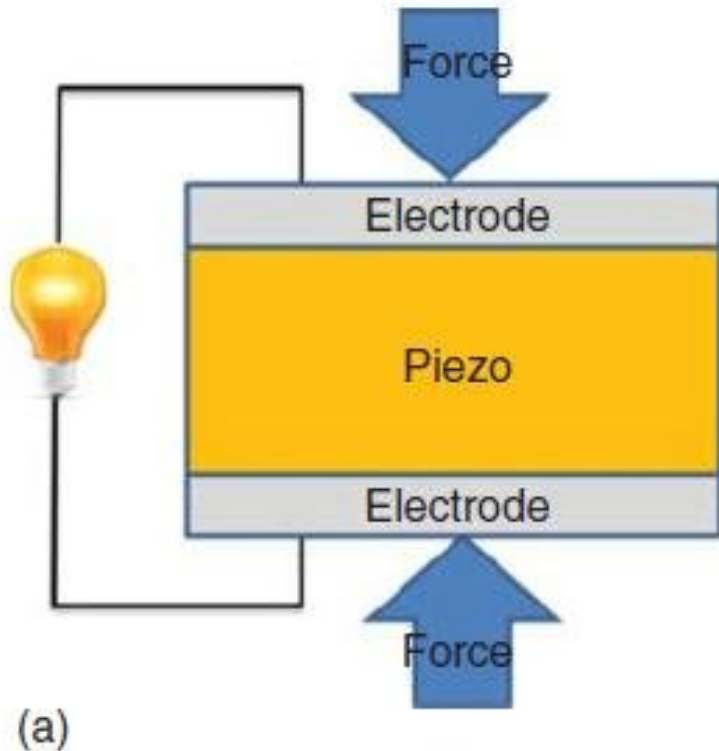
Results

Go to www.menti.com and use the code **73 71 00 6**

Piezoelectricity

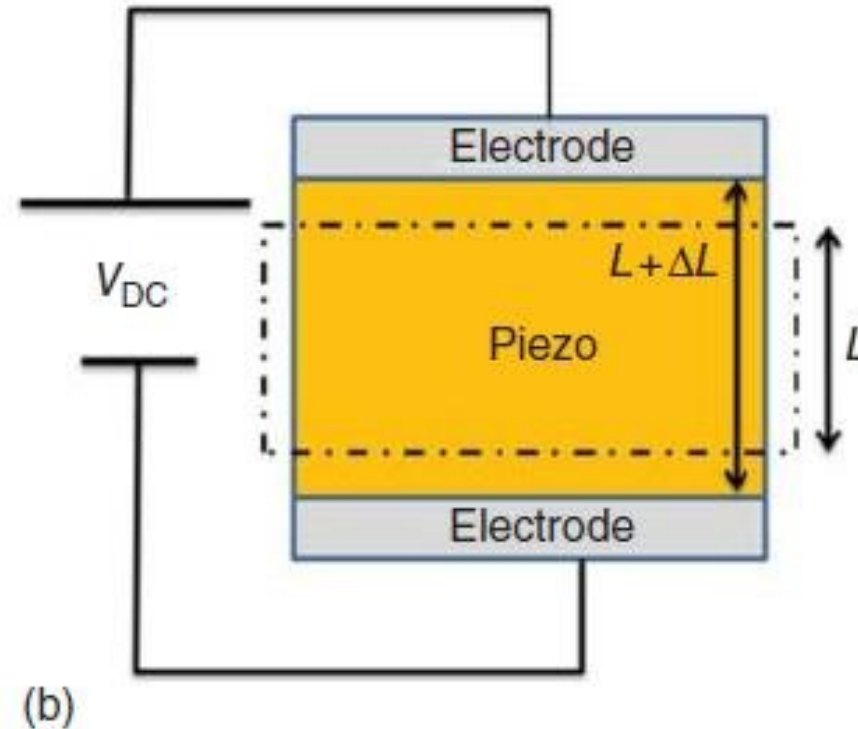
In some dielectric materials, applying E can result in a mechanical stress (or *vice versa*)

- Stress = change in lattice parameters



Direct effect

Applications:



Converse effect

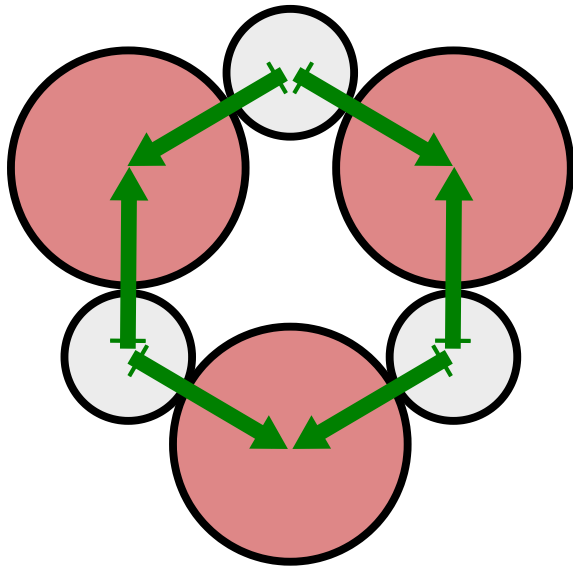
Applications:

Structural Aspects

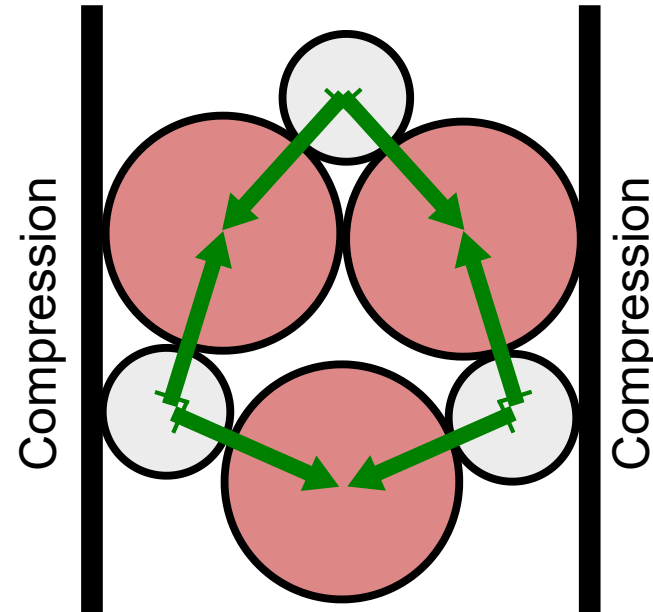
Stresses arise due to unbalanced dipoles

- Can only occur if the structure is **non-centrosymmetric**

Example: Quartz (SiO_2)



Structural
Changes

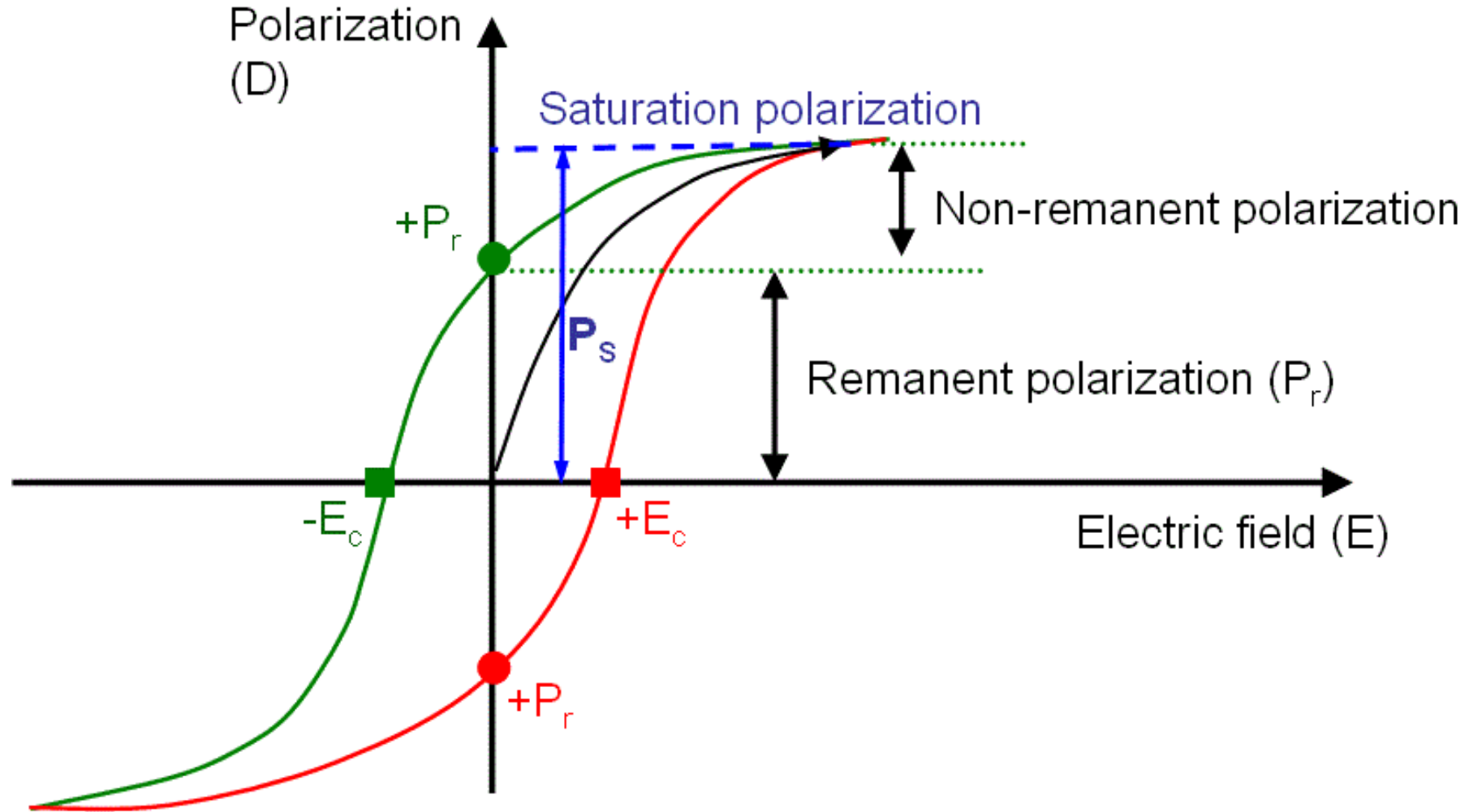


Overall
Dipole

Spontaneous polarisation

Some materials exhibit a net dipole *without* an applied electric field (**pyroelectric**)

If the polarisation can be switched with an electric field - **Ferroelectric**

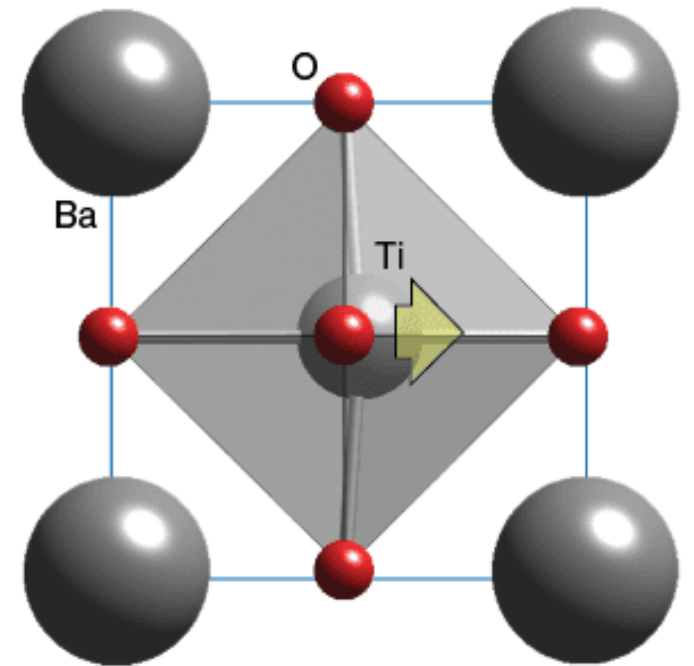
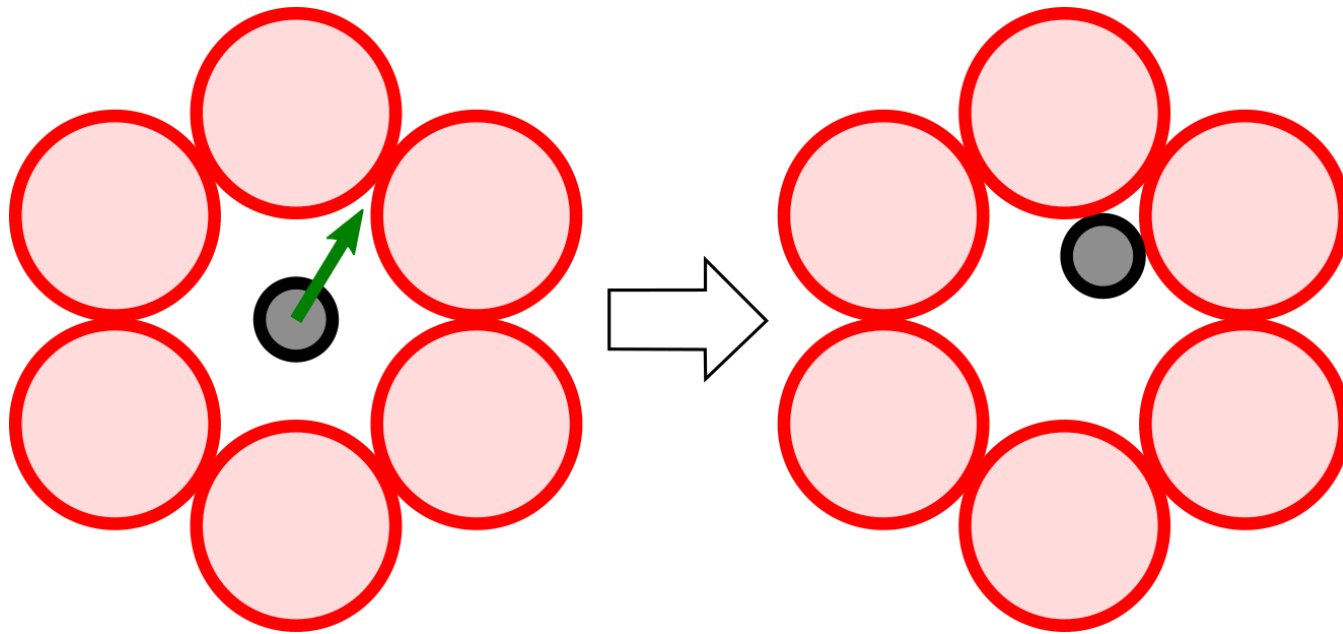


Structural origin

Precise origin of ferroelectricity is unknown!

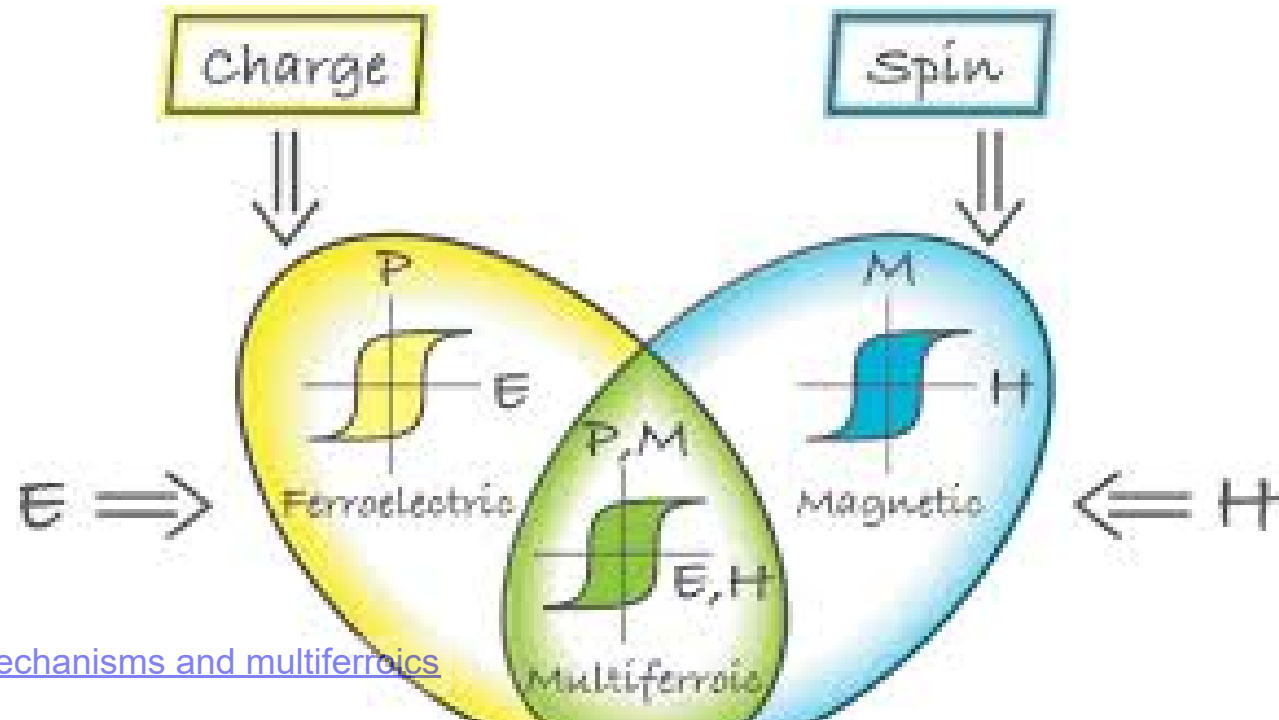
Often, displacement of small ion in a large 'cavity' is partly responsible

- Driven by anharmonicity or pseudo-Jahn-Teller effects
- *sometimes* this results in long-range order of dipoles...
- Many perovskites are ferroelectric (e.g. BaTiO_3)



Applications

- Ferroelectrics often have the largest ϵ_r
 - important for high- C capacitors
- Could be coupled with e.g. ferromagnetism
 - **Multiferroics** are currently popular for electrical control of magnetic fields (e.g. in hard drives)



Hierarchy of dielectrics

Dielectric

Insulators that may change polarisation under an applied electric field
Polar or non-polar

Piezoelectric

Change in polarisation is proportional to mechanical stress
Non-centrosymmetric, polar or non-polar

Pyroelectric

Show spontaneous polarisation
Polar material

Ferroelectric

Exhibit polarisation
switchable by electric field

Lecture recap

- Polarisation arises from cation-anion dipoles
 - Can be modified by external electric field
- Important in capacitors
 - charge stored increased by high ϵ_r dielectric
- Impedance spectroscopy can characterise ionic motion
 - Oscillating potential generates oscillating current
 - Impedance $Z(\omega)$ has both phase (ϕ) and magnitude ($|Z|$)
 - Many materials behave like parallel RC circuits
- Piezoelectricity is the linear relationship between polarisation and mechanical stress
 - requires non-centrosymmetric structures
- Pyro- and ferro-electrics exhibit spontaneous polarisation without applied electric fields
 - used where high permittivity is needed (e.g. capacitors)
 - current interest in multiferroics

Feedback



What did you like or dislike about this lecture?

Short answers are recommended. You have 250 characters left.

250

You can submit multiple answers

Submit

