Lecture 5 - Dielectrics

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Lecture Summary

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

Introduction

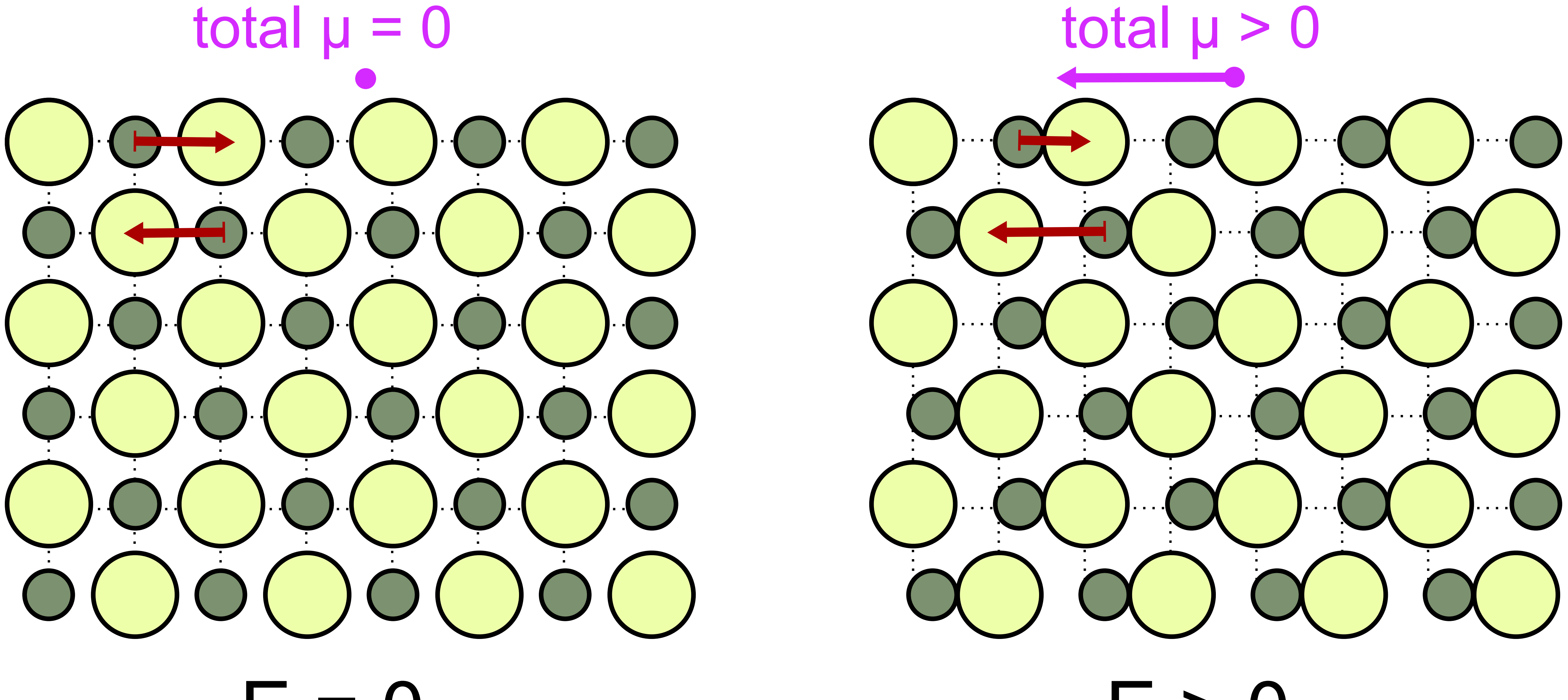
- Ionic conduction is a long-range effect
    - Important in batteries, fuel cells etc.
- In some situations, a highly insulating material is preferred
- Remember, ions are not static with time (e.g. phonons)
    - Short-range atomic motion is important for electrical properties

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



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

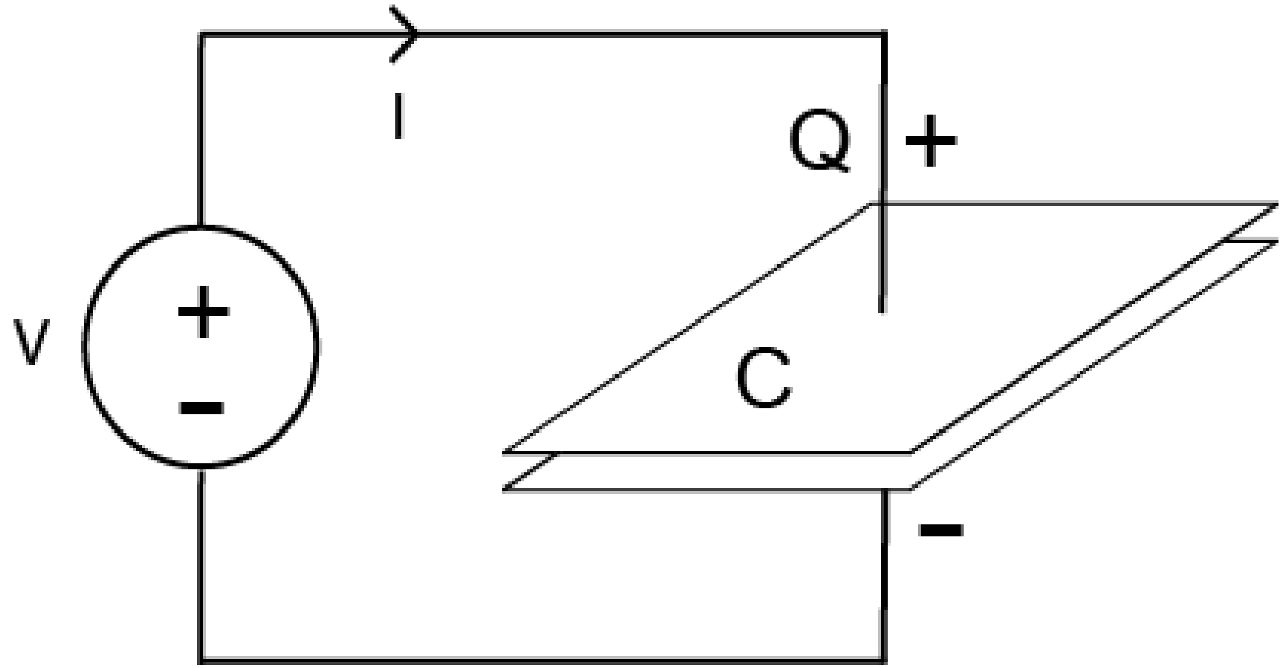
Can use this to screen electric fields

- 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 = 8.854×10^{-12} C^2 J^{-1} m^{-1}

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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.

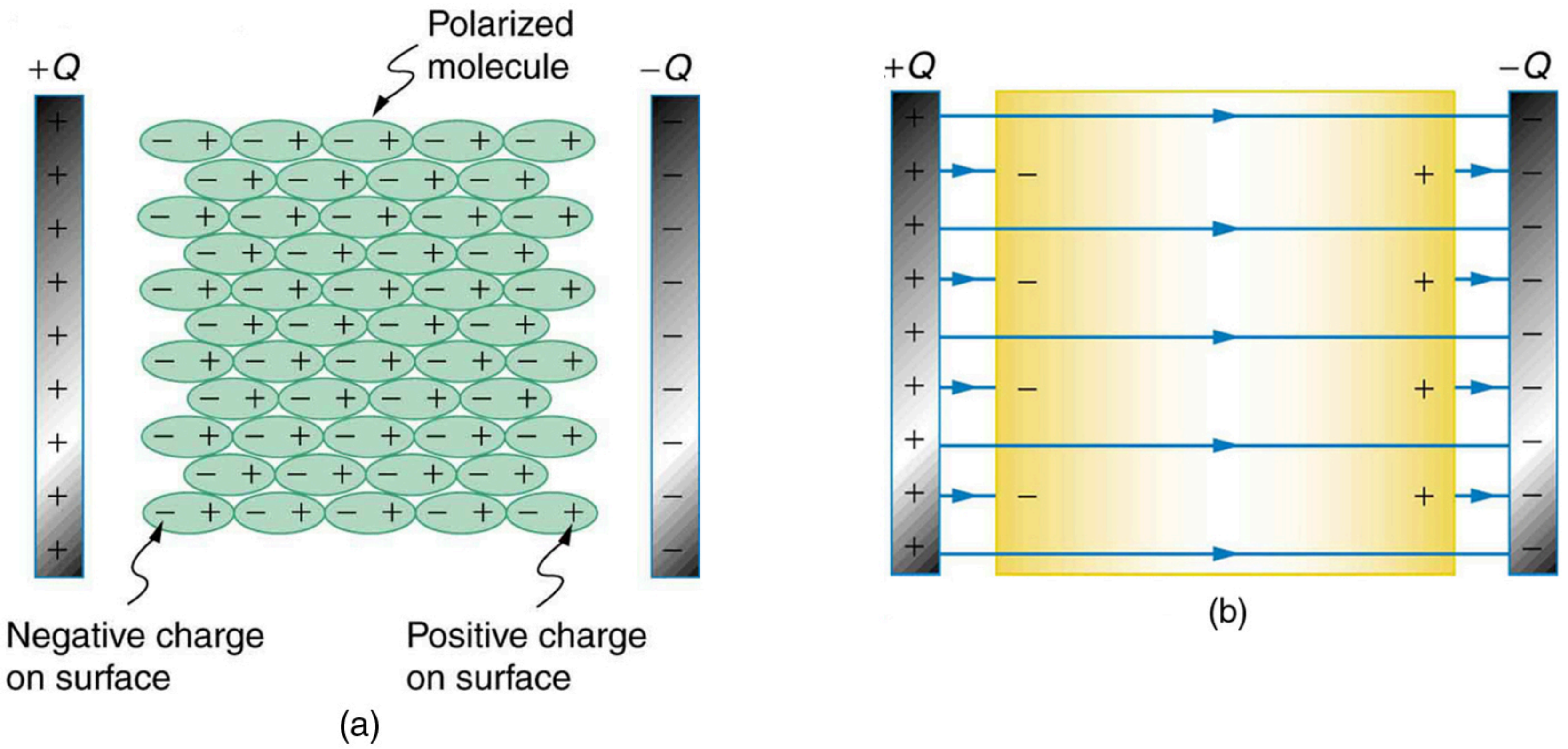
Improving charge stored

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 ($\varepsilon_r = \varepsilon / \varepsilon_0$) and $\varepsilon_r > \varepsilon_0$



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

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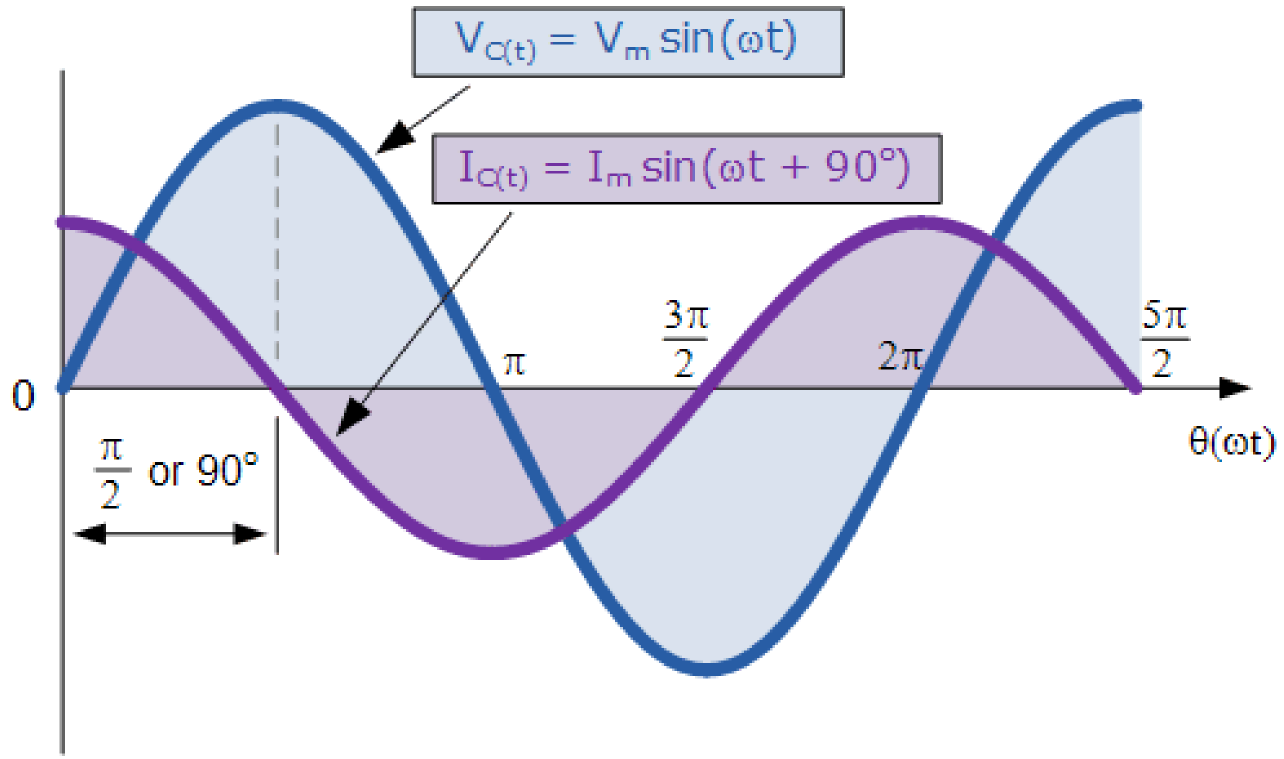
Impedance spectroscopy applies an alternating (sinusoidal) field at different frequencies f, and measures the resulting current

- 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:

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

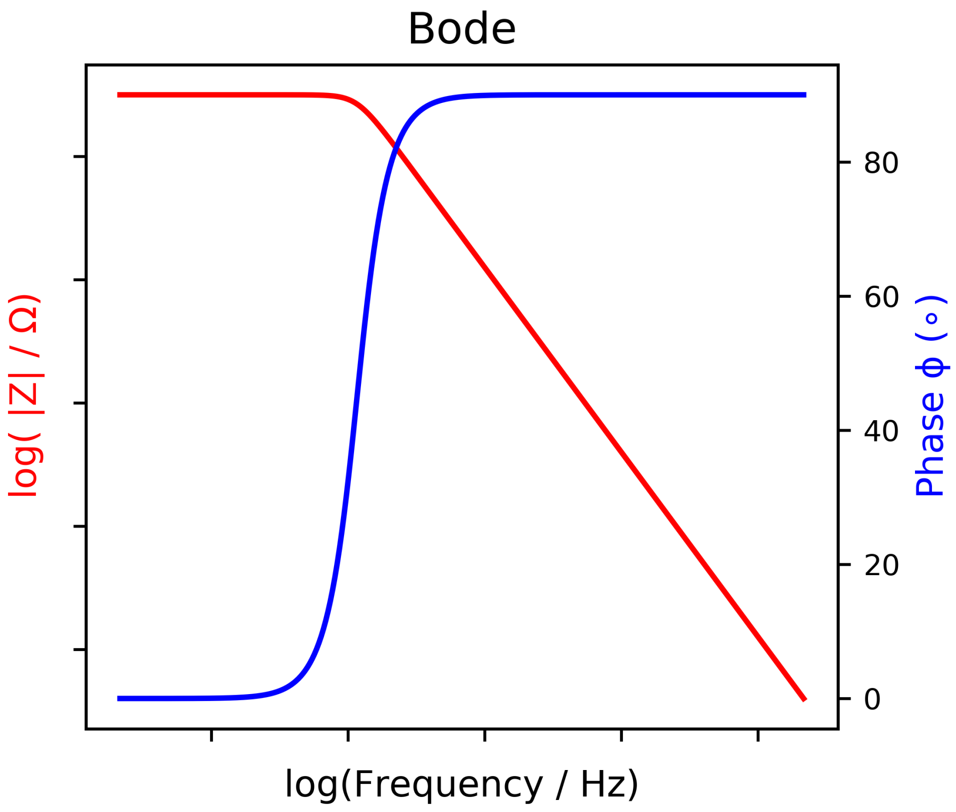
- ϕ is the 'phase-shift' between voltage and current.

Useful introduction to impedance [here]

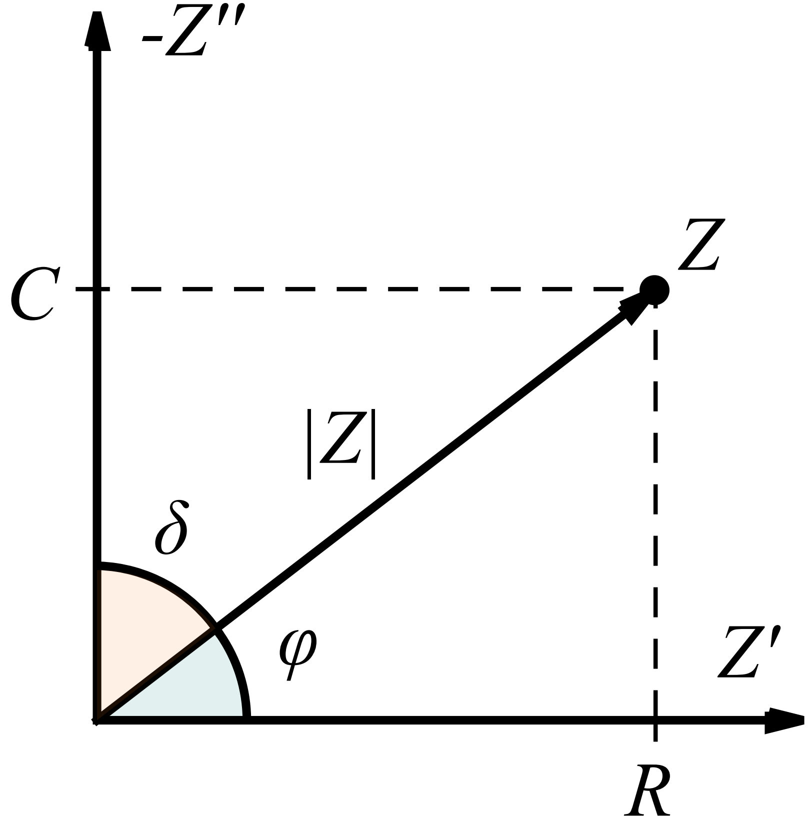
Impedance analysis

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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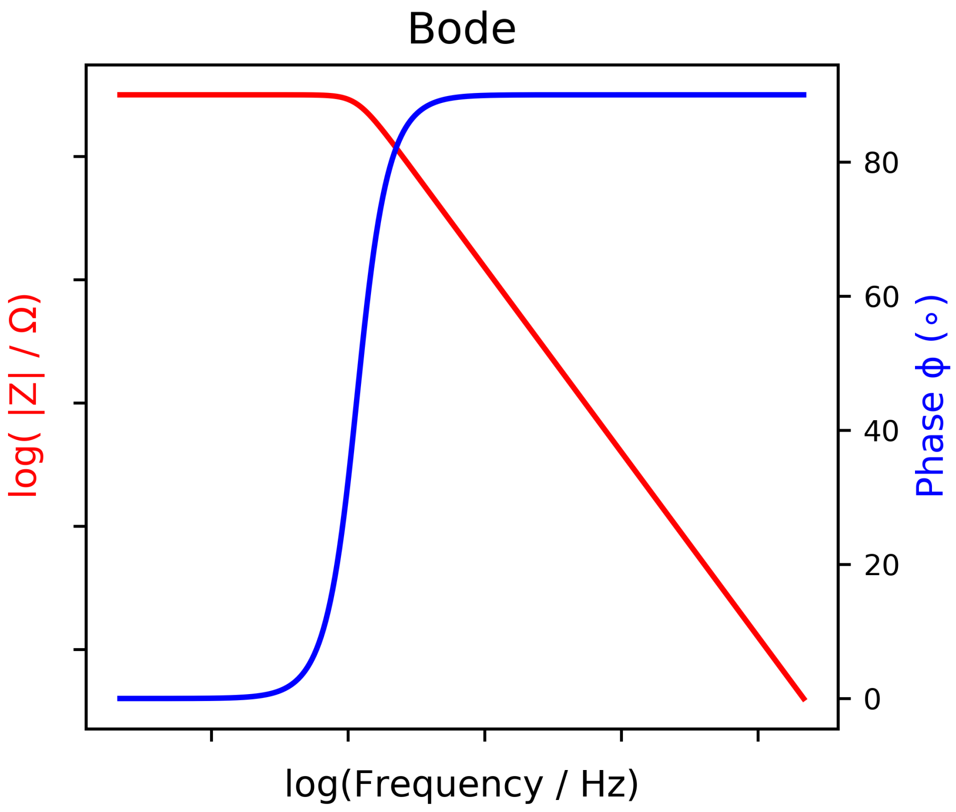

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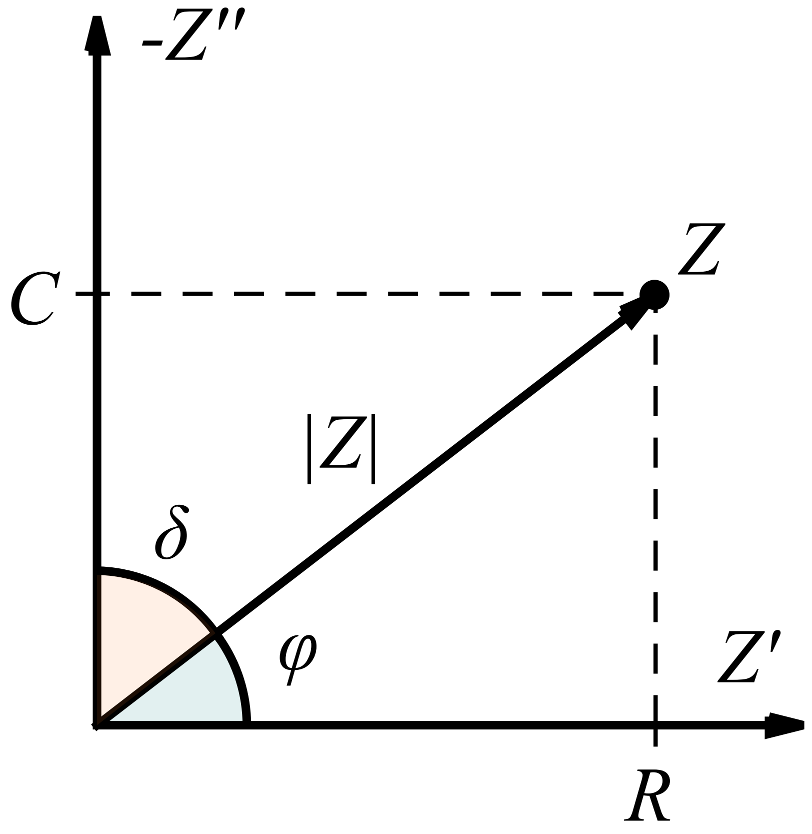
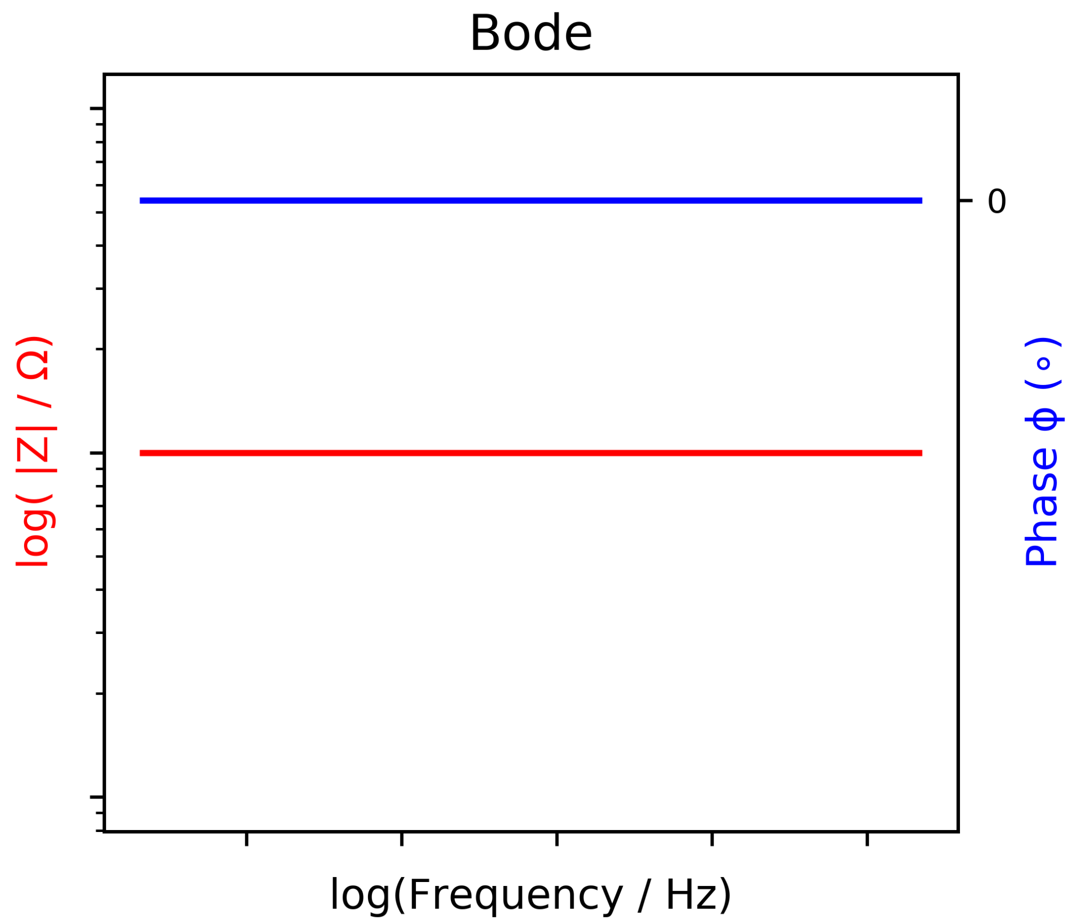


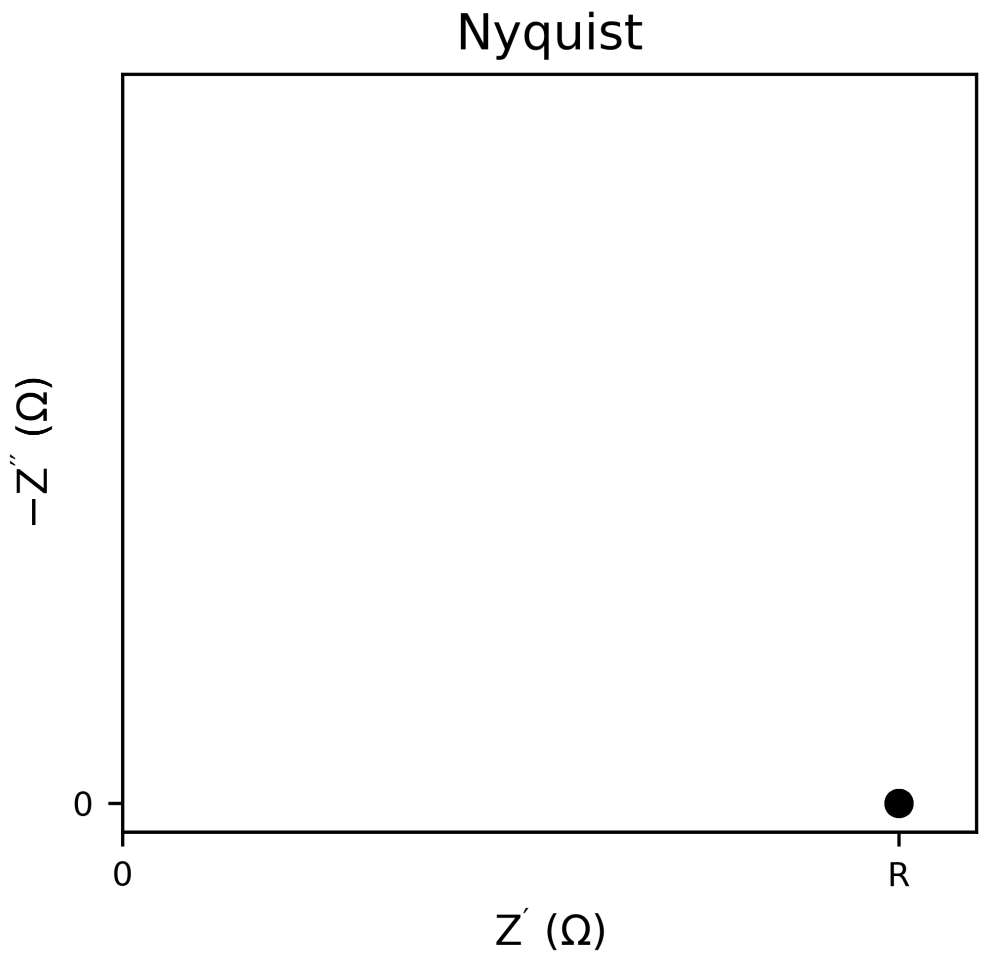
In order to analyse these data, it is useful to fit an electrical circuit that gives the same behaviour

Ideal resistor response

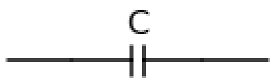
Ideal resistor has no dependence on ω

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

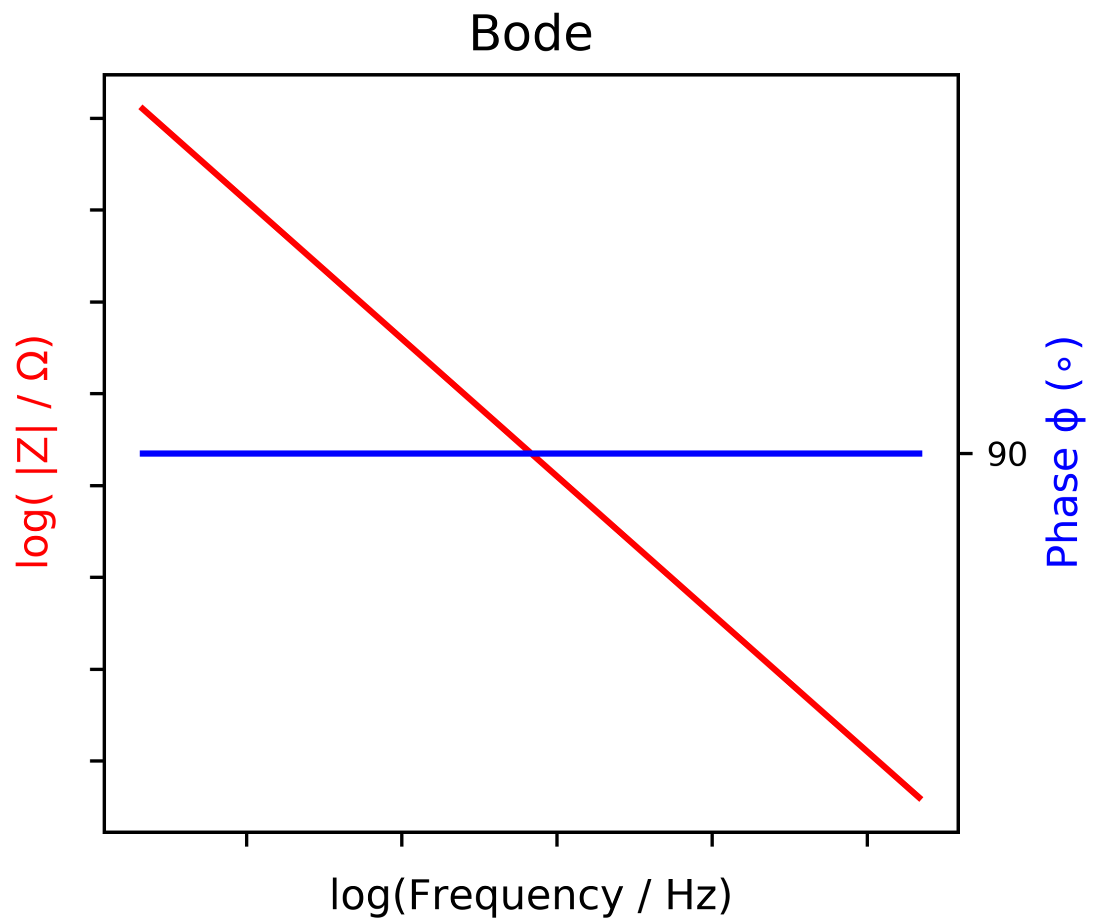


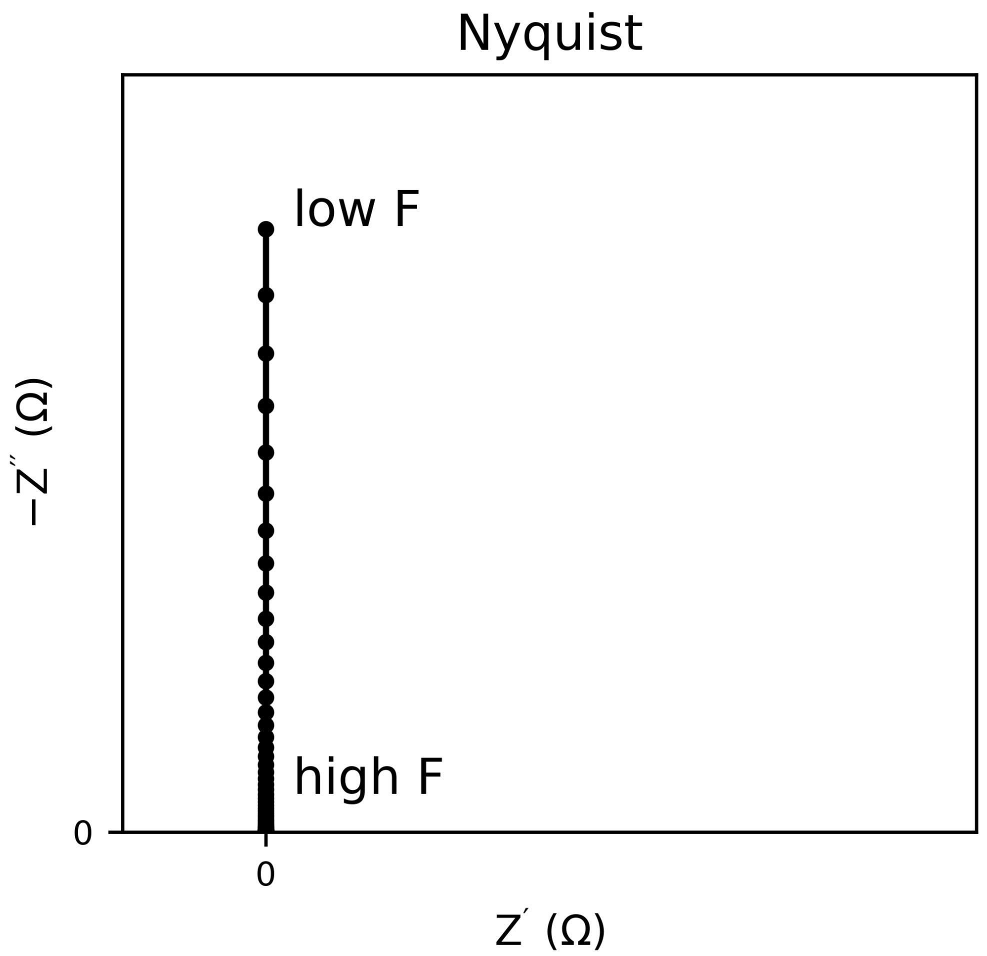


'Ideal' capacitor response

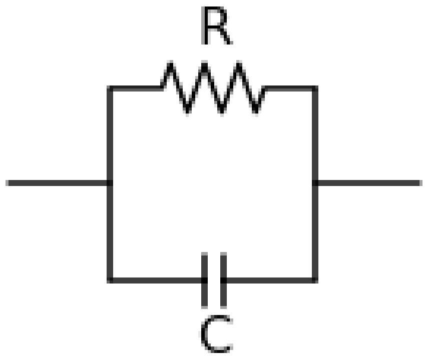


- Current I increases with ω, approaching 0
- I is always out-of-phase with E by $\phi = 90^\circ$
    - The maximum $I(t)$ occurs when $E(t) = 0$
- Represents stored charge building up, for instance ions accumulating on a surface

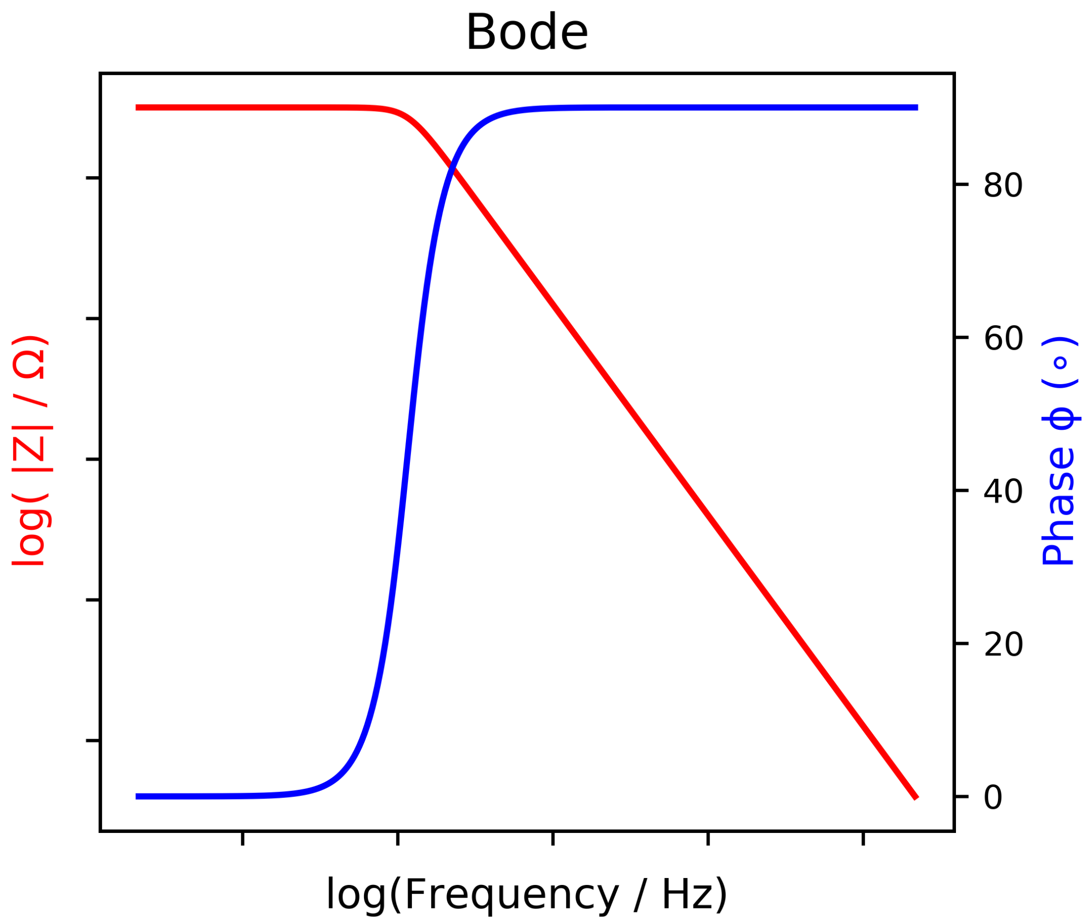


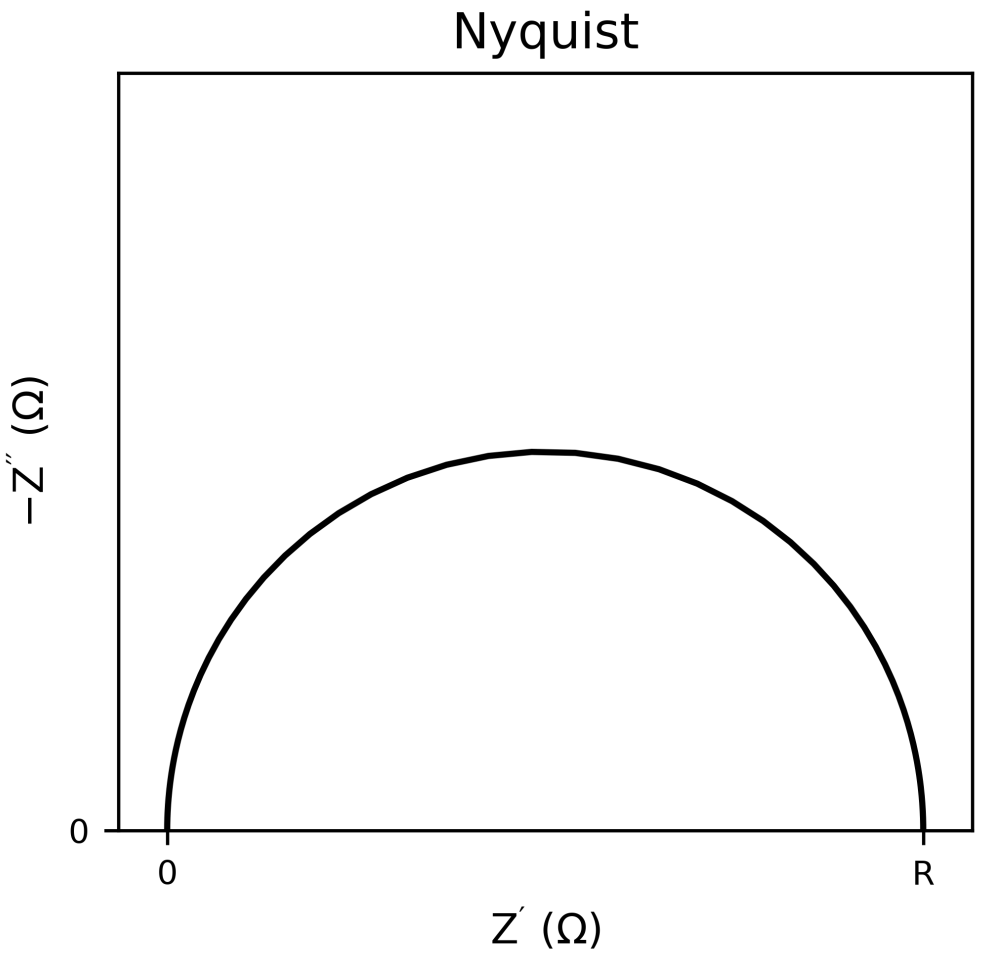


'Real' Impedance



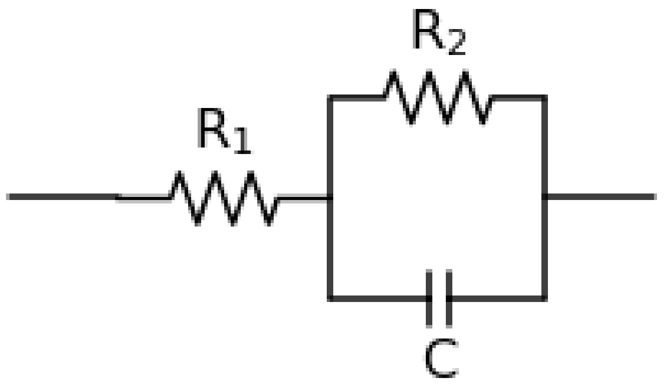
- Many materials behave like a parallel RC circuit:
  - Ions moving due to E, but motion is limited to a maximum displacement
  - Ionic conduction in a ceramic forming a charge gradient on the electrode surface





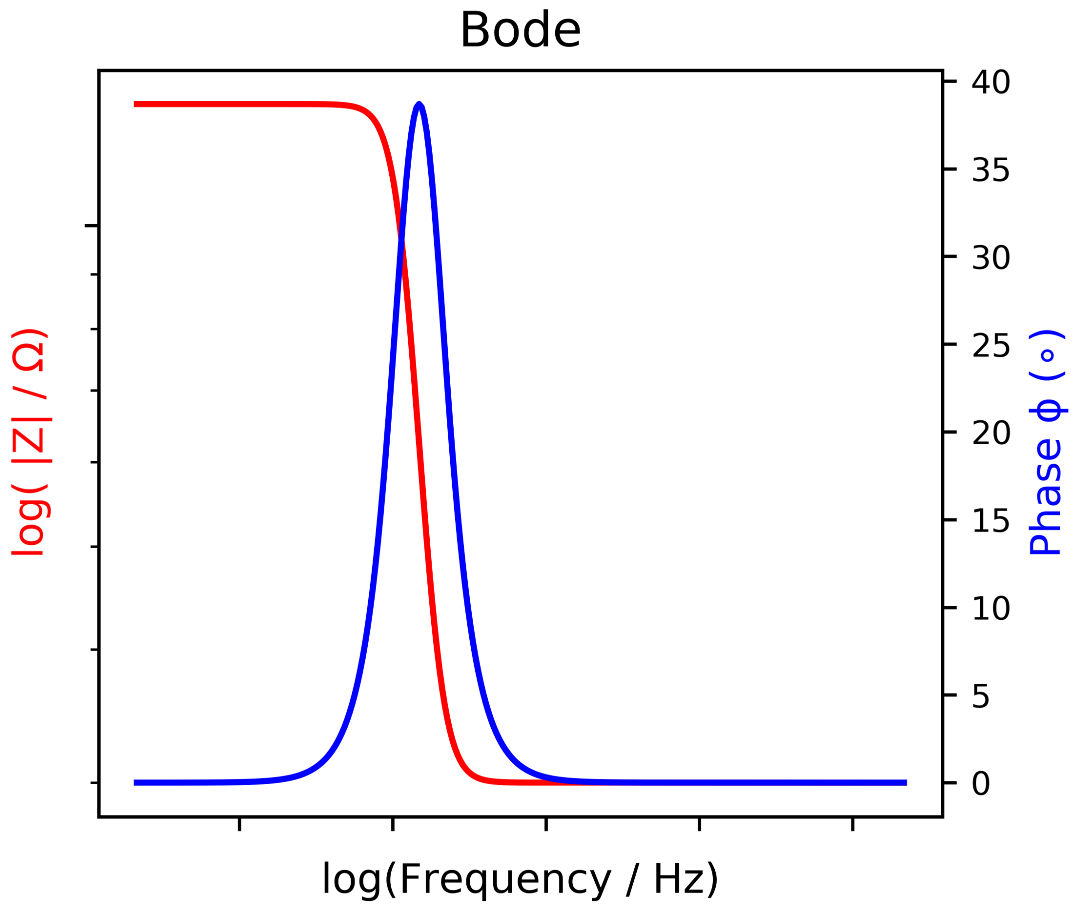
More complex behaviour is often observed, and can be modelled using *equivalent circuits*

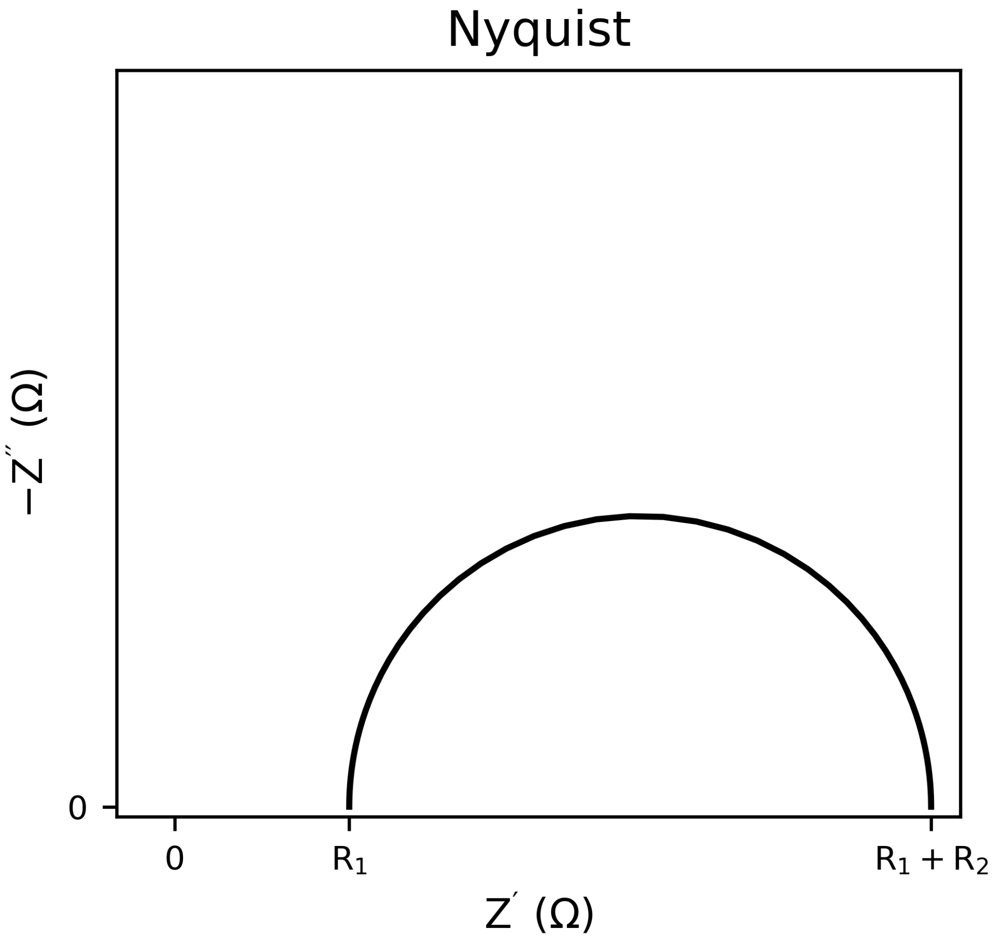
Real dielectric response



Dielectrics are not ideal-they leak!

- Ions have mass, so cannot move instantly
- At high ω, some resistance remains
- peak in ϕ vs ω corresponds to the maximum energy loss.





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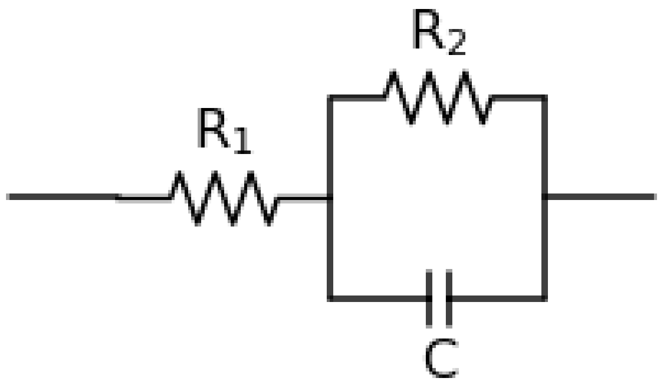

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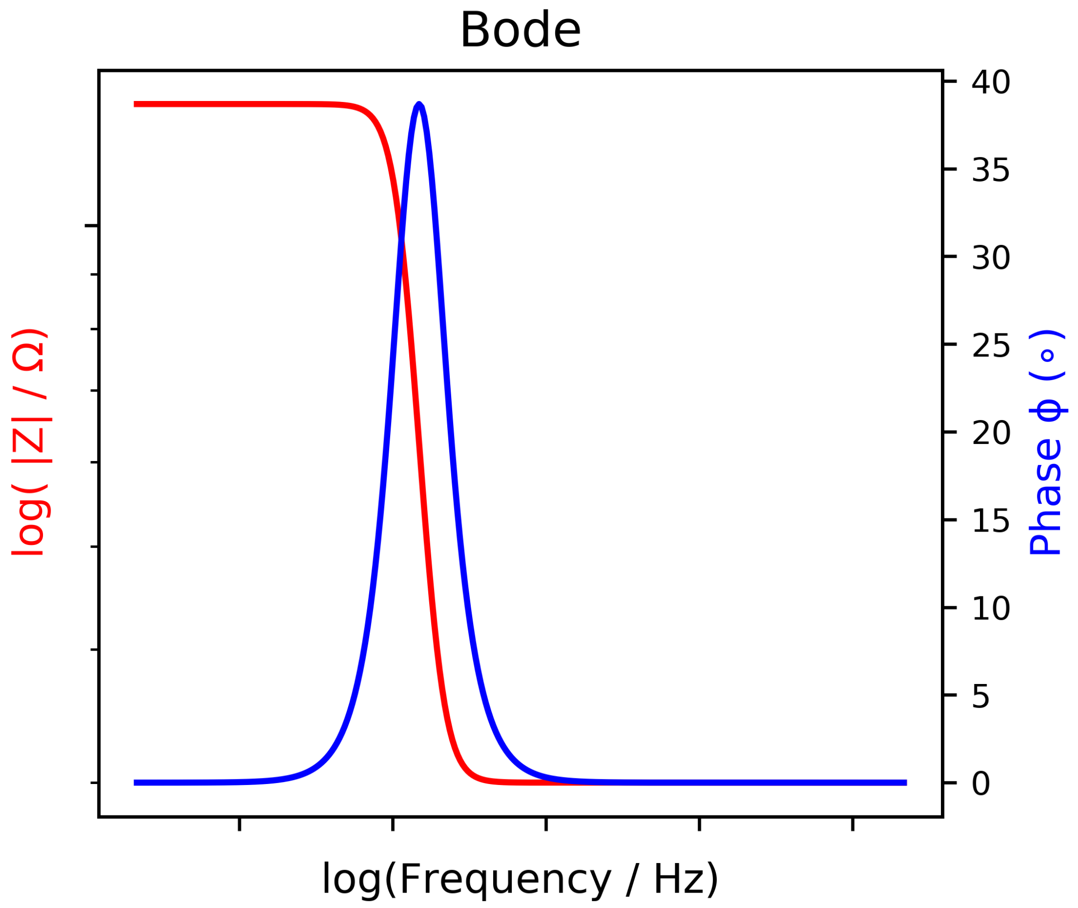
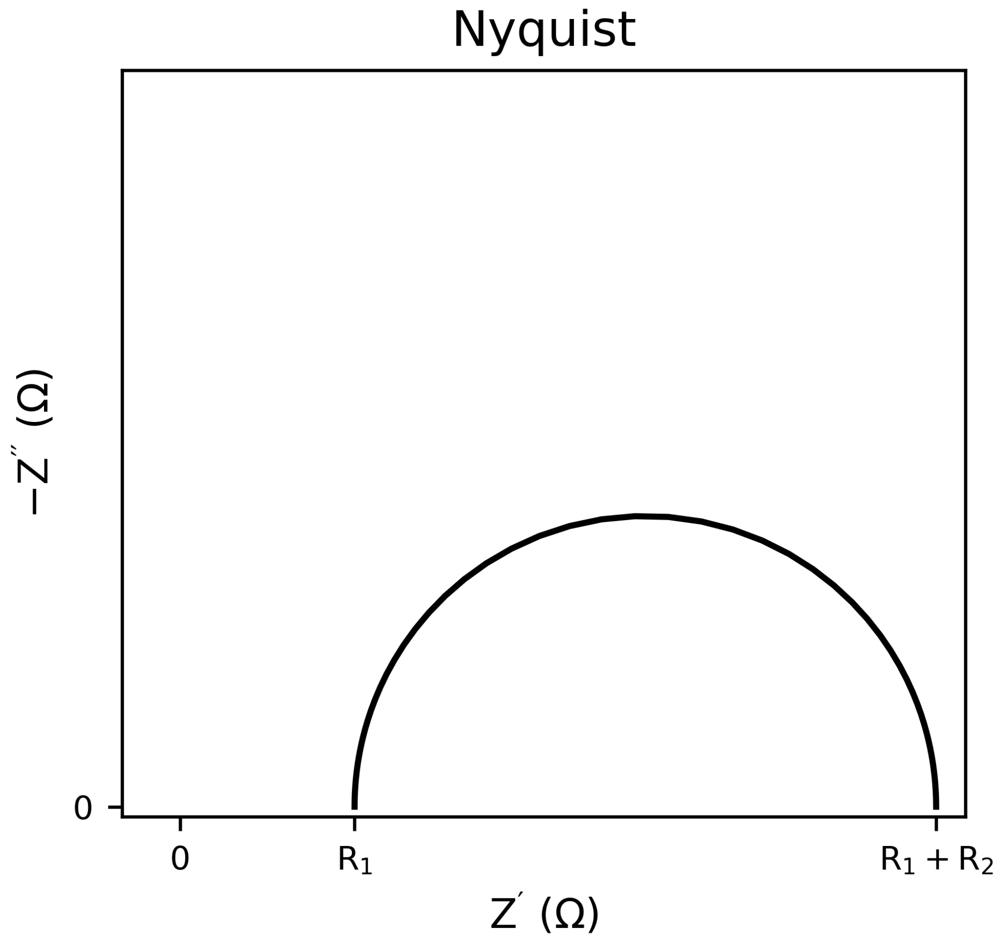
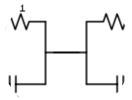




Real materials usually consist of closely packed ceramic grains

Question



What impedance response might you expect from the equivalent circuit shown?

Submit

Results

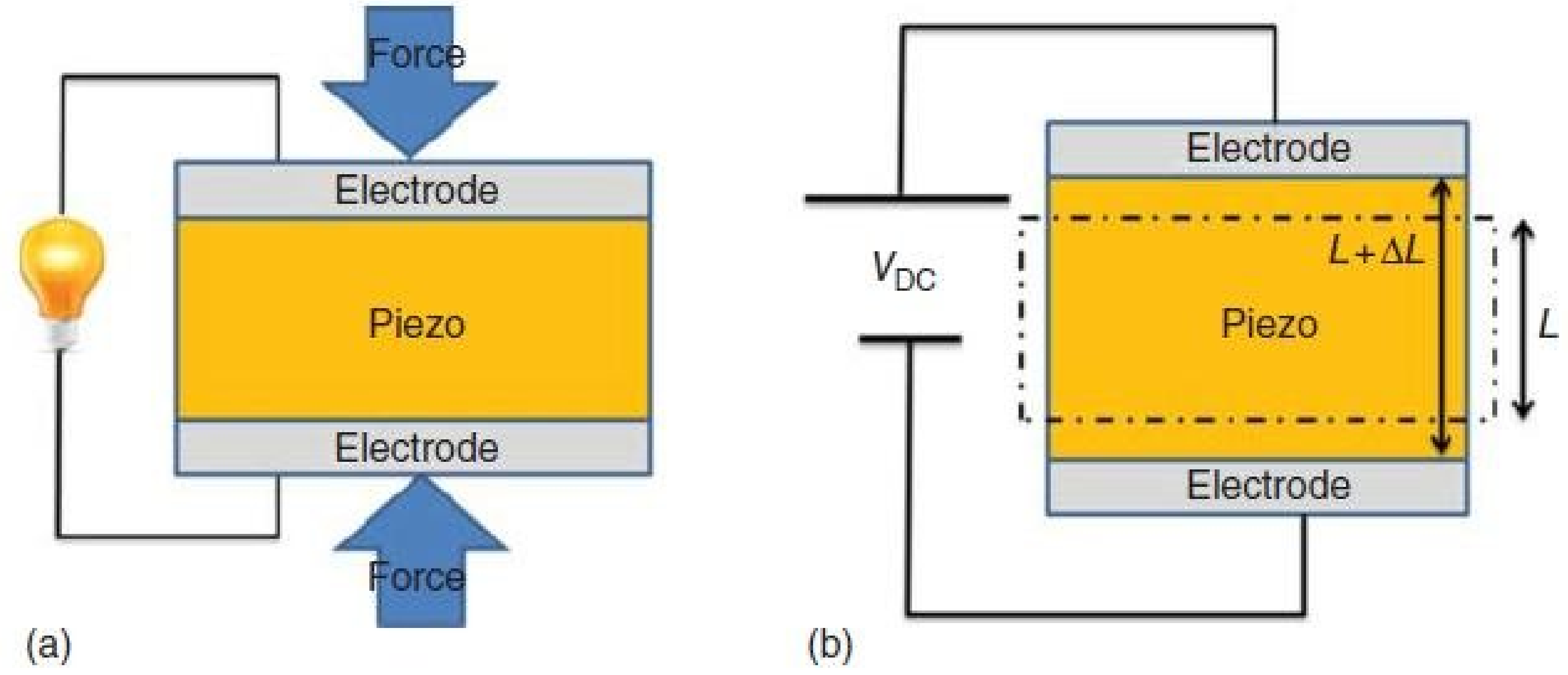
wooclap

Quiz results will be available here
after the lecture

Piezoelectricity

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

- Stress = change in lattice parameters



Direct effect

- pressure sensors
- ultrasonic imaging

Converse effect

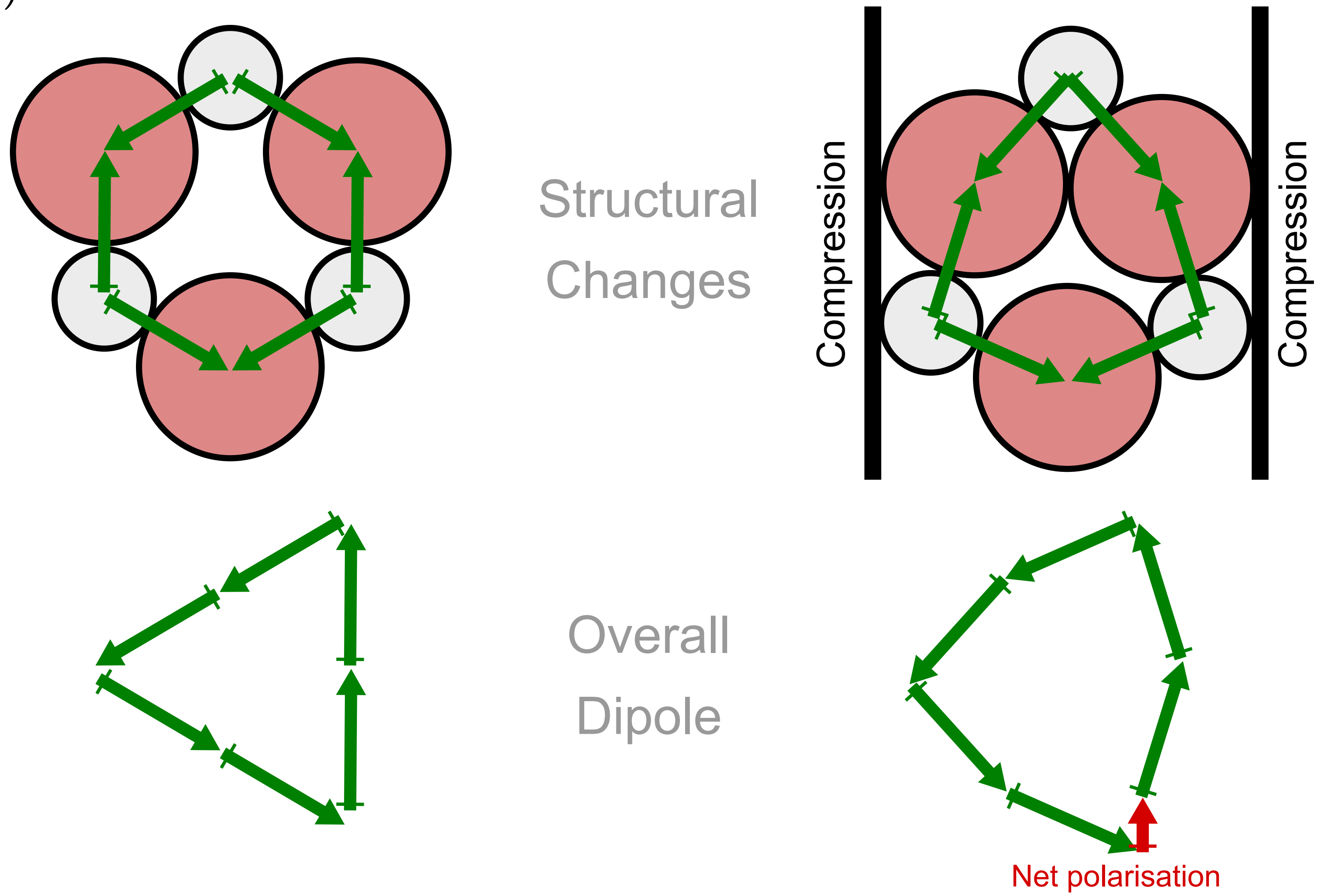
- Actuators/motors
- crystal oscillator (watches)

Structural Aspects

Stresses arise due to unbalanced dipoles

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

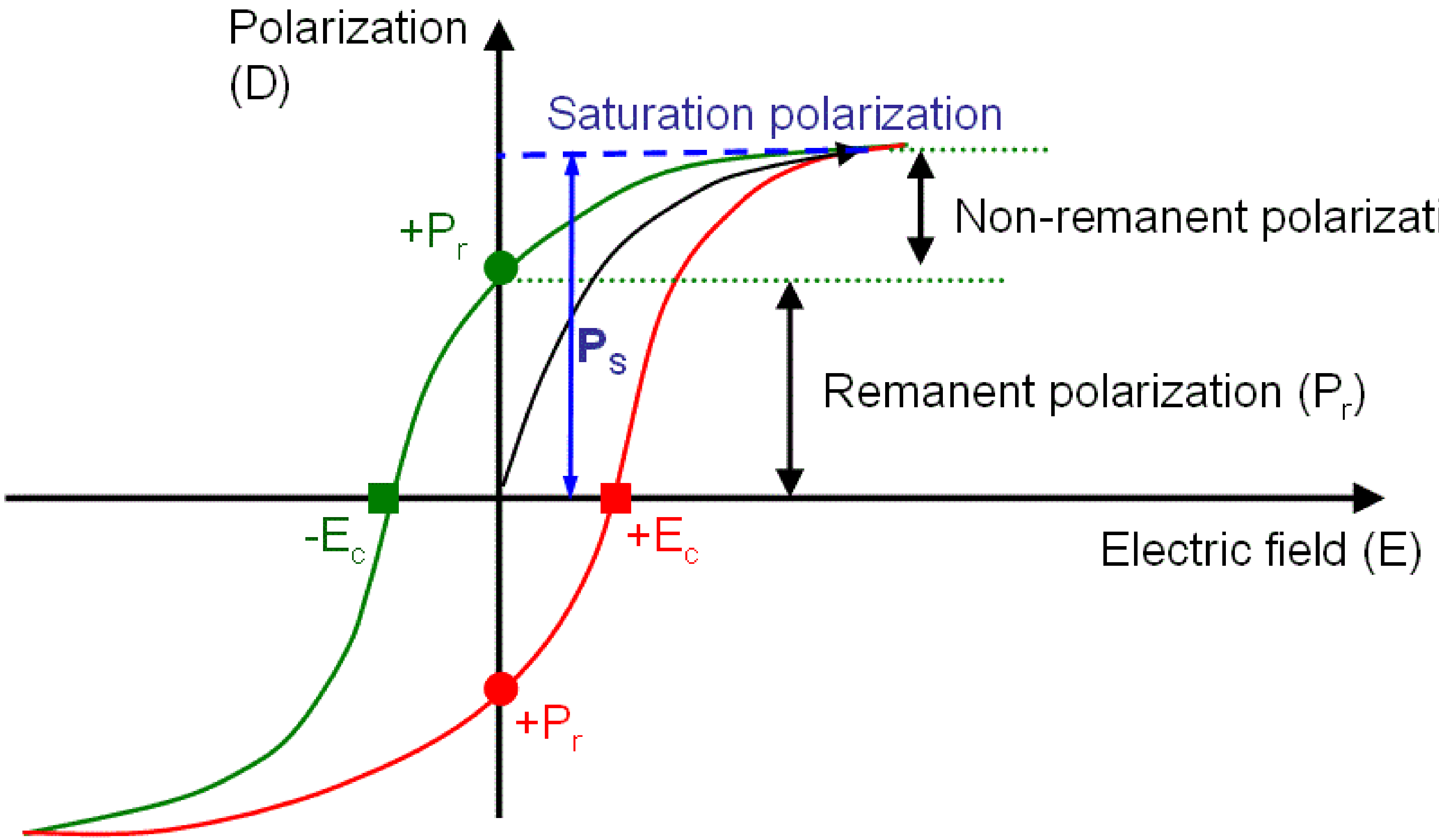
Example: Quartz (SiO_2)



Spontaneous polarisation

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

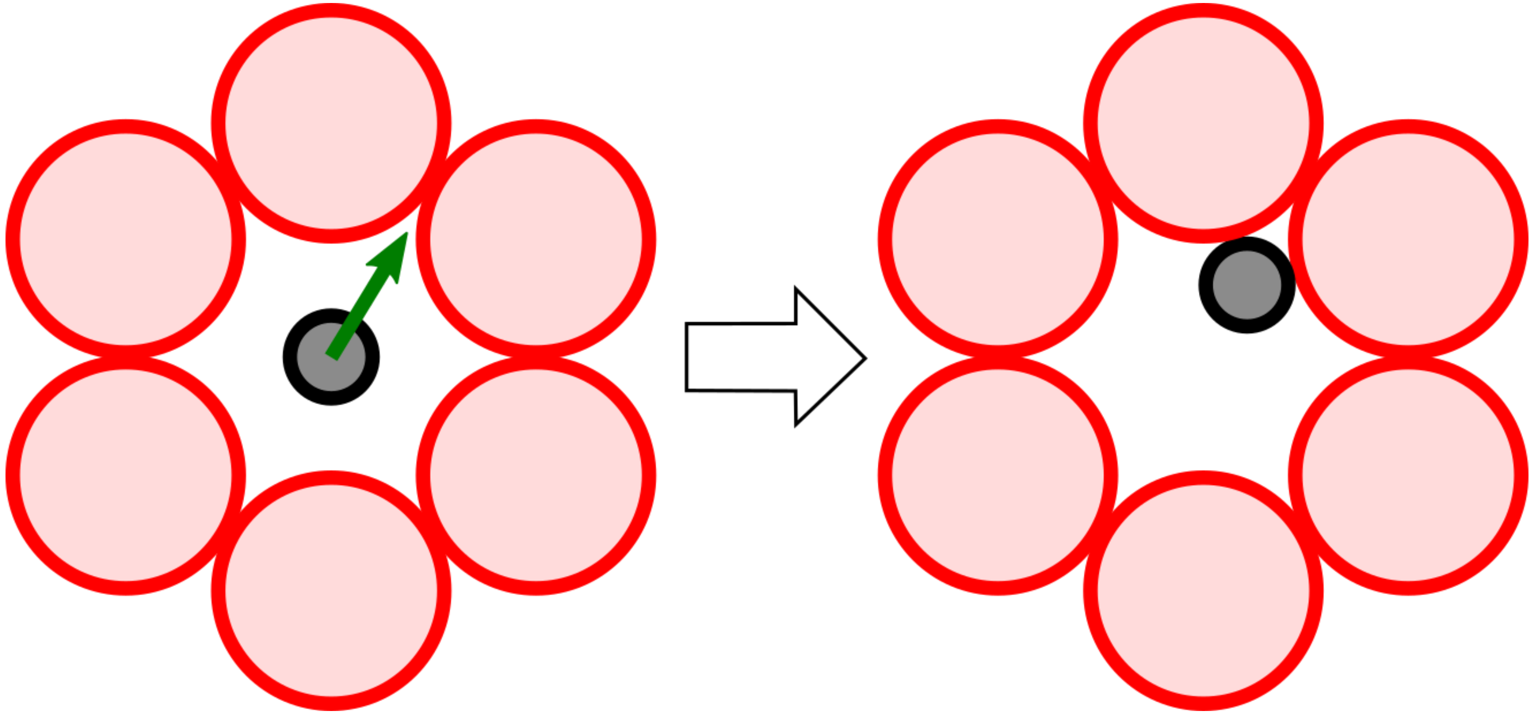
If the polarisation can be switched with an electric field - **Ferroelectric**

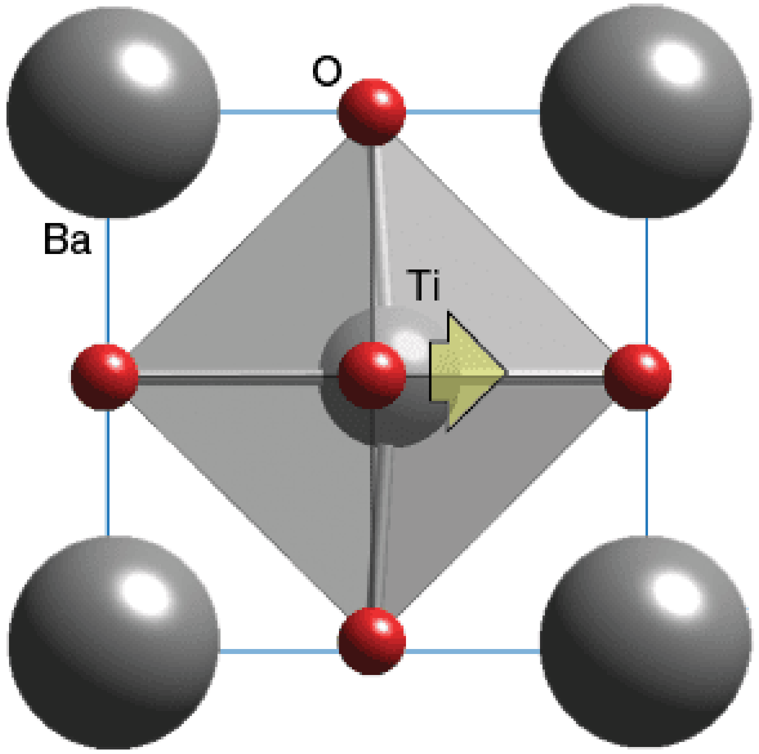


Structural origin

Precise origin of ferroelectricity is unknown!
Often, displacement of small ion in a large 'cavity' is partly reponsible

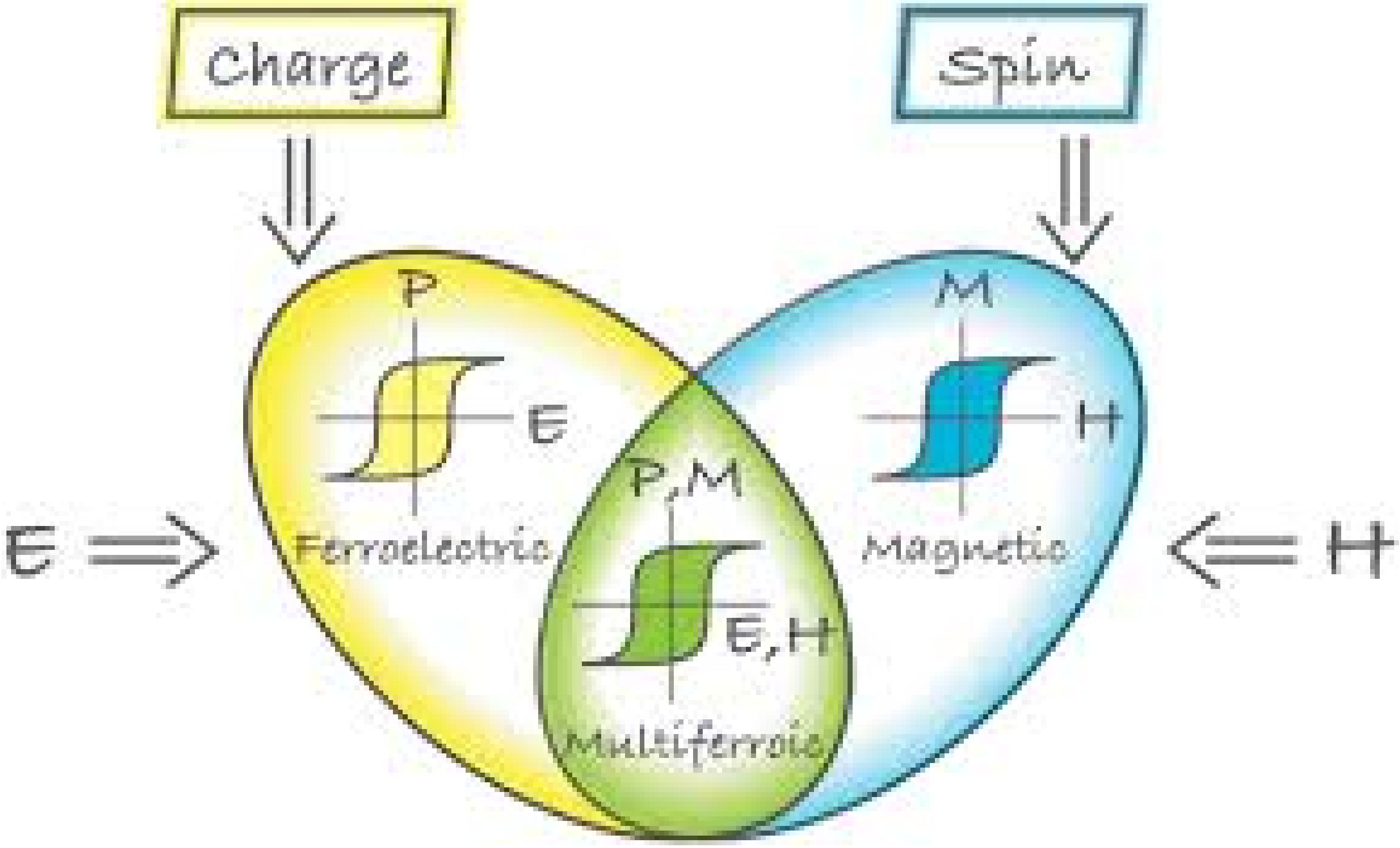
- Driven by anharmonicity or pseudo-Jahn-Teller effects
- *sometimes* this results in long-range order of dipoles...
- Many perovskites are ferroelectric (e.g. $\mathrm{BaTiO_3}$)





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)



Nice summary of ferroelectric mechanisms and multiferroics

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 lecture 5?

Write your answer...

Submit