Piezo-electric devices

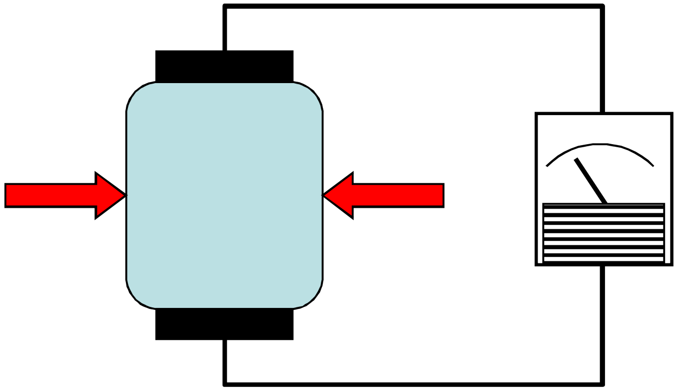
The piezo-electric effect

- The piezo-electric (‘pressure of electricity’) effect couples deformation of a material with electrical output. The effect works in both directions.

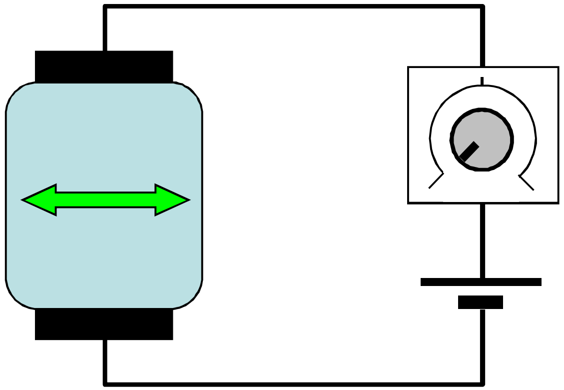
- Quartz is one of the naturally occurring materials to display piezo electric properties, but several man-made piezo electric materials with stronger properties have been developed.

- Piezo-electric materials are solids, the effect arising from their molecular crystal structure. Many are ceramics.

The piezo-electric effect - basic

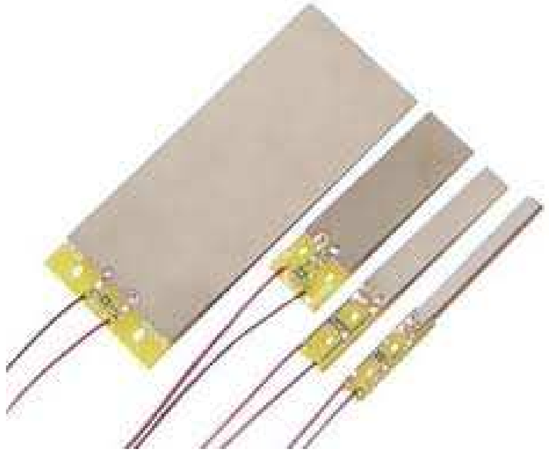


- Compressing (or expanding) the piezo material will produce an electrical output



- Applying an electrical signal will cause the piezo material to deform

Piezo devices

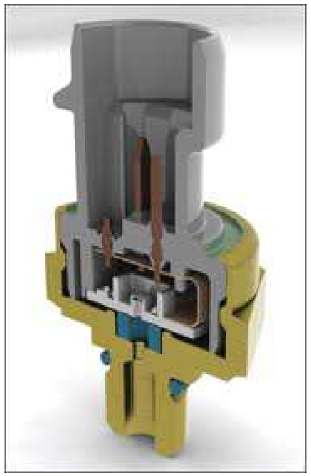


- Piezo electric devices are used in many everyday products, such as buzzers and speakers, microphones, camera lens motors, diesel injectors, accelerometers, etc

Piezo devices

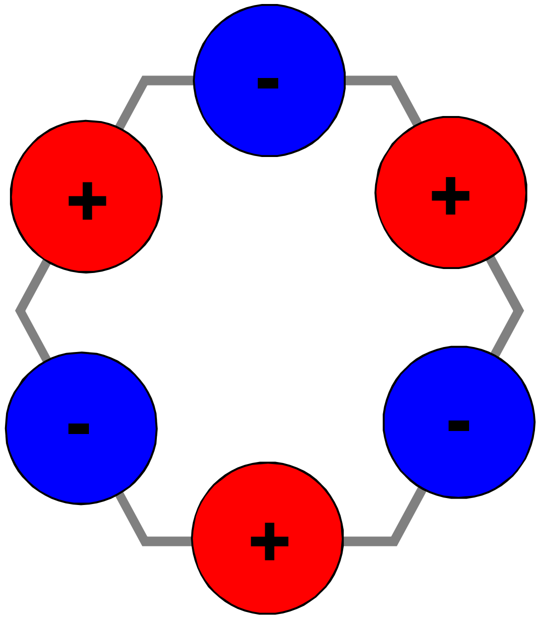
Piezo accelerometers

Piezo diesel injector



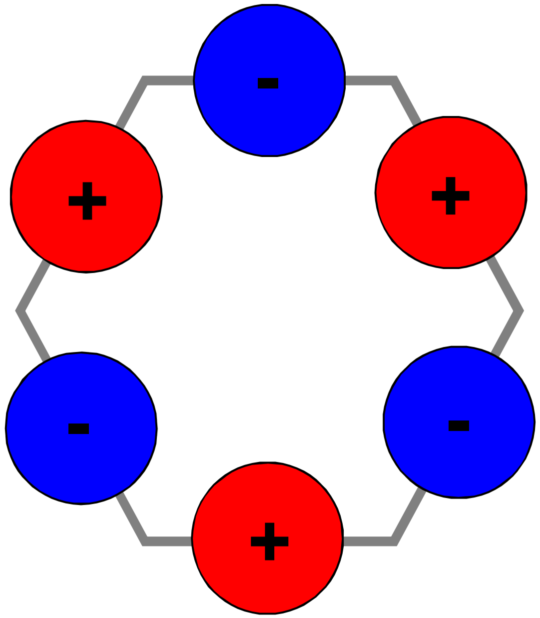
Piezo pressure sensor

Simplified physics – crystal structure



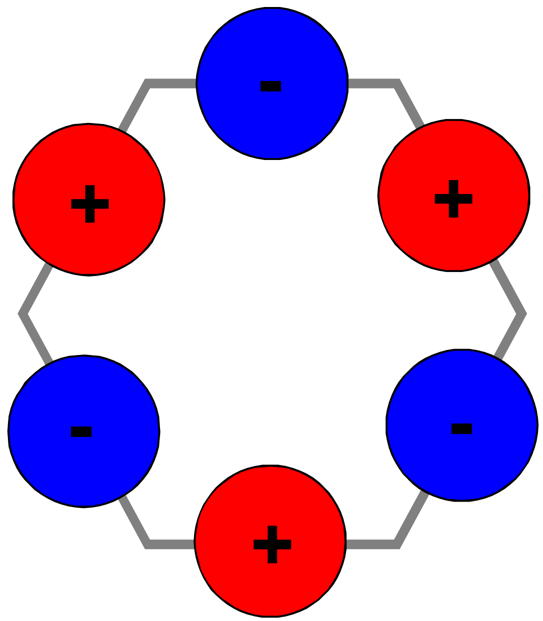
- The bonds of the crystal structure result in the constituent elements becoming polarised locally.
- Although the crystal structure has overall charge neutrality, deformation of the structure causes movement of individual charged elements within the structure.

Simplified physics – crystal structure



- When piezo electric materials are deformed there is a net movement of elements with a particular charge in a particular direction.
- Movement of charged particles = electric current.

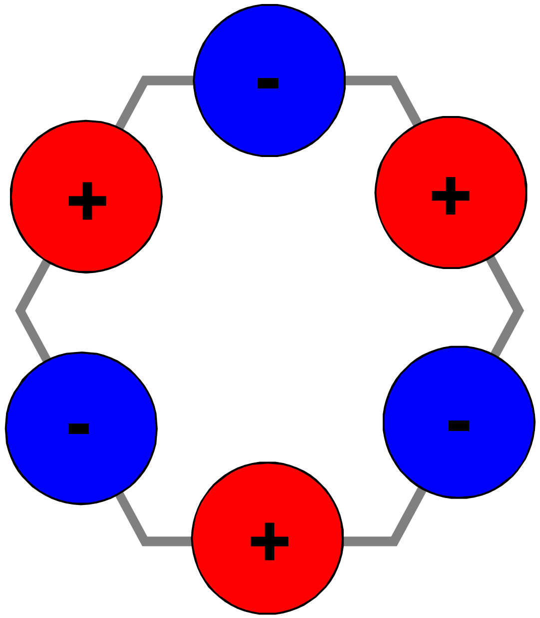
Simplified physics – crystal structure



- Applying an electric field will result in charged elements attempting to migrate in the direction of the field, hence the crystal structure will deform.

- The particular crystal structure is vital in producing a strong piezo electric effect. Hence a large research effort is dedicated to developing new piezo materials.

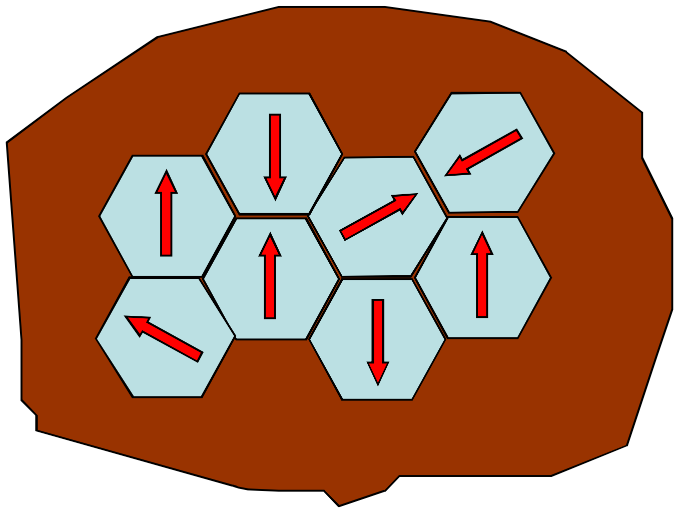
Simplified physics – crystal structure



- The particular crystal structure is vital in producing a strong piezo electric effect. Hence a large research effort is dedicated to developing new piezo materials.

- In real piezo materials the net charge dislocation can occur in several axes, including that of the applied force – more of this later.

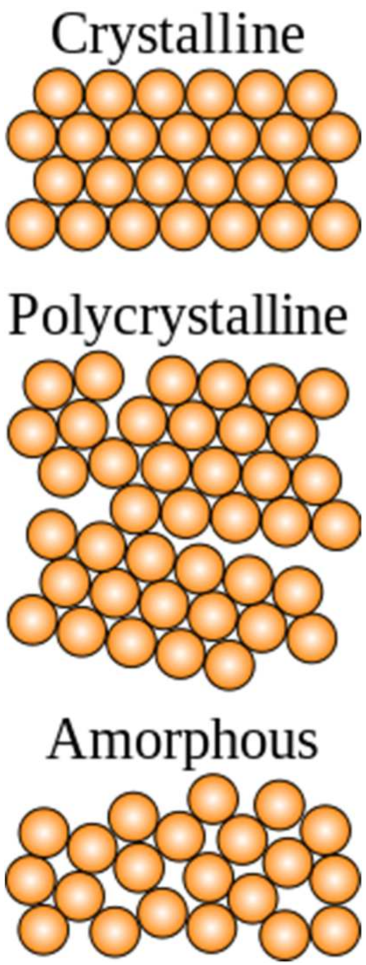
Simplified physics



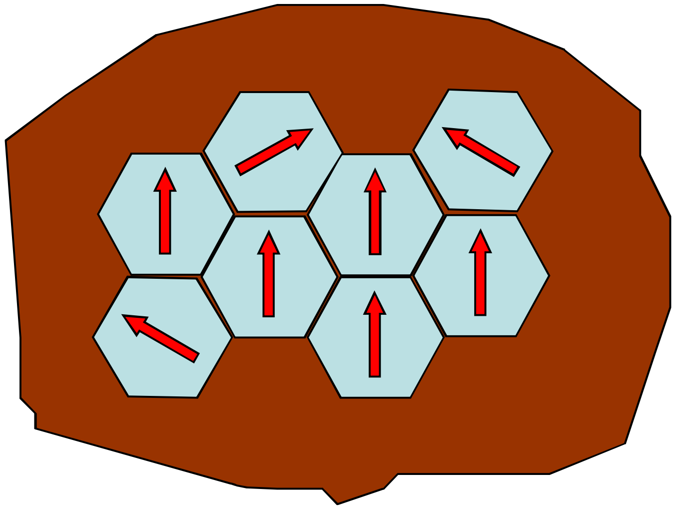
Random crystallite, or grain orientation. These are known as 'Weiss domains'

- At a bulk material level, most piezo materials are polycrystalline.
- This random orientation of crystallite regions produces constructive and destructive summation of the net charge dislocation, reducing or destroying the piezo effect.

Crystal Structures



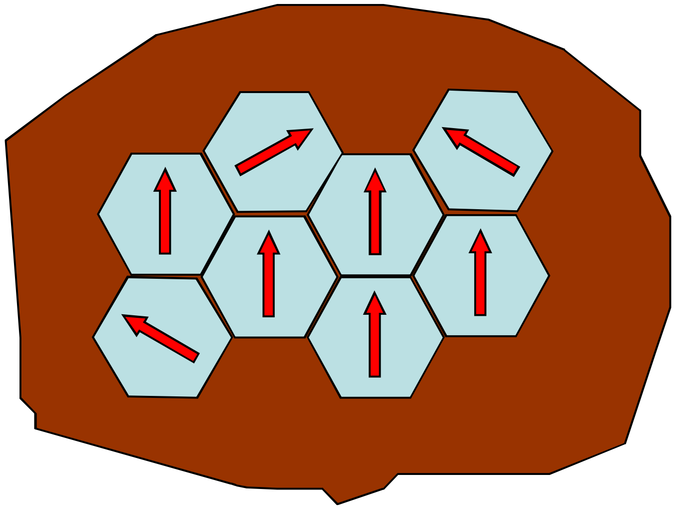
Simplified physics



Grains aligned after polarisation

- Materials naturally tend towards a random orientation of Weiss domains as it minimises internal energy.
- To improve the strength of the piezo electric effect, material is polarised by applying a very high electric field – this tends to align the domains.

Simplified physics

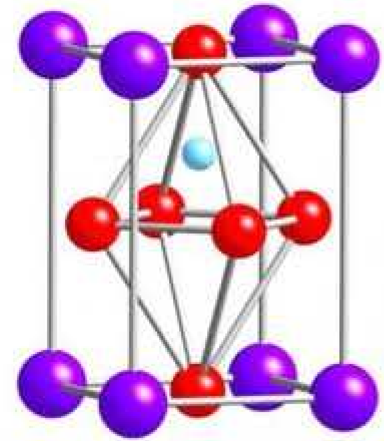


Grains aligned after polarisation

- The alignment can be reversed by;
  - Mechanical overloading
  - Electrical overloading
  - Heating material above Currie temperature.

- An even stronger piezo electric effect can be achieved by growing single crystals of piezo material, but that is a complex business.

PZT



- One of the most commonly encountered piezo materials is ‘PZT’ – Lead Zirconate Titanate.
- This ceramic is usually sintered – material in powder form is compressed into a shape and heated to a temperature at which fuses particles together.
- Sintering is done above the Currie temperature so the material must be polarised.

Modelling Piezo

- In the piezo material a mechanical displacement causes electric charge to moved.

By definition; *Current = ΔCharge / time*

So; *Current $\propto$ ΔDisplacement / time*

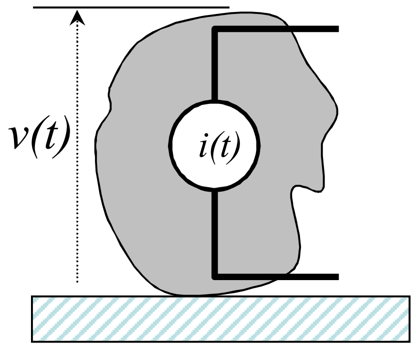
Hence; *Current $\propto$ Velocity*

This points to the impedance analogy, so make everything 'square up' with we set;

Force $\propto$ Voltage

Piezo relations – forward effect

- We can represent the *forward effect* of piezo electric coupling as a current proportional to an applied velocity:



Where; $i(t) \propto v(t)$

$$i(t) = p_f v(t)$$

We can define the forward coupling constant

- But this leaves us with a paradox: current must flow somewhere, so what happens if we deform the piezo element but leave it open circuited?

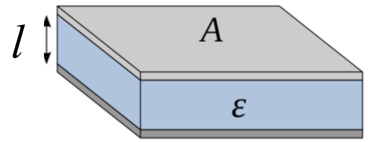
Piezo relations – forward effect

- If the current isn't flowing out of the material then logically charge must be stored internally.
- The ability of a body to store charge is ***Capacitance.***

Electrically: *Capacitance = charge / voltage*

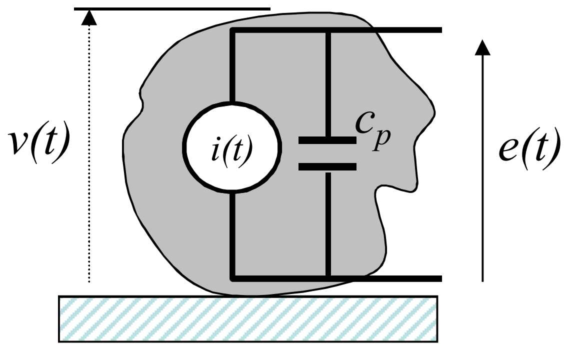
As a material property : *Capacitance = ε * area / length*

Where *'ε' is the permittivity of the material, some times called 'dielectric constant', and often given in the form $\varepsilon_o\ \varepsilon_r$, where ε_o is the permittivity of free space.*



Piezo relations – forward effect

- Thus our basic model of *forward coupling* is a current source proportional to the driving velocity, in parallel with a capacitance formed by the piezo material itself.



Where: $i(t) = v(t)P_f$

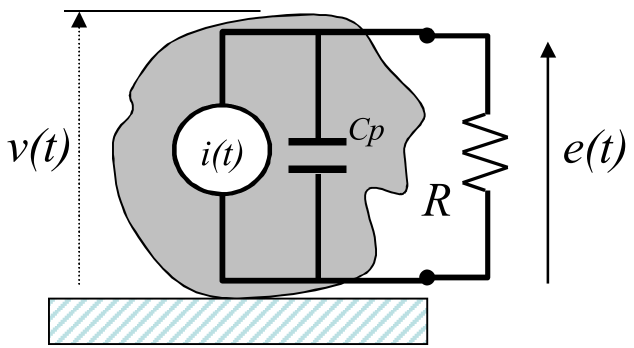
and: $e(t) = \frac{1}{c_p}\int i(t)dt$

so: $e(t) = \frac{p_f}{c_p}\int v(t)dt$

- ***An applied velocity causes a current which in turn generates a voltage across the piezo material's internal capacitance.***

Piezo relations – forward effect

- If we add an electrical load on the output then the current remains the same for a given velocity, but the resultant voltage is different:



Where: $i(t) = v(t)P_f$

but now: $i(t) = \frac{e(t)}{R} + C_p \frac{de(t)}{dt}$

Since we know that this differential equation is easier handled in the frequency domain, we convert:

$$I(s) = V(s)P_f$$

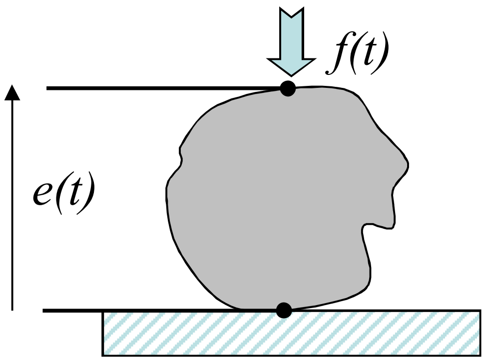
$$I(s) = \frac{E(s)}{R} + C_p sE(s)$$

$$V(s)P_f = \frac{E(s)}{R} + C_p sE(s)$$

so: $\frac{E}{V} = \frac{p_f}{\frac{1}{R} + j\omega C_p} = \frac{p_f/C_p}{\frac{1}{RC_p} + j\omega}$

Piezo relations – converse effect

- But we also know that applying an electrical field to piezo material produces a mechanical force – the *converse effect*.



Where: $f(t) \propto e(t)$

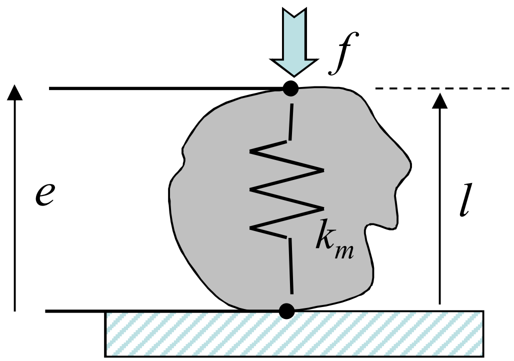
$$f(t) = p_c e(t)$$

converse constant

- Applying thinking similar to forward case, what happens if we apply a force to an mechanically unconstrained piezo element?

Piezo relations – converse effect

- Simple - it deforms!



Where; $f(t) = p_c e(t)$

And $\Delta l = \dfrac{f(t)}{k_m}$

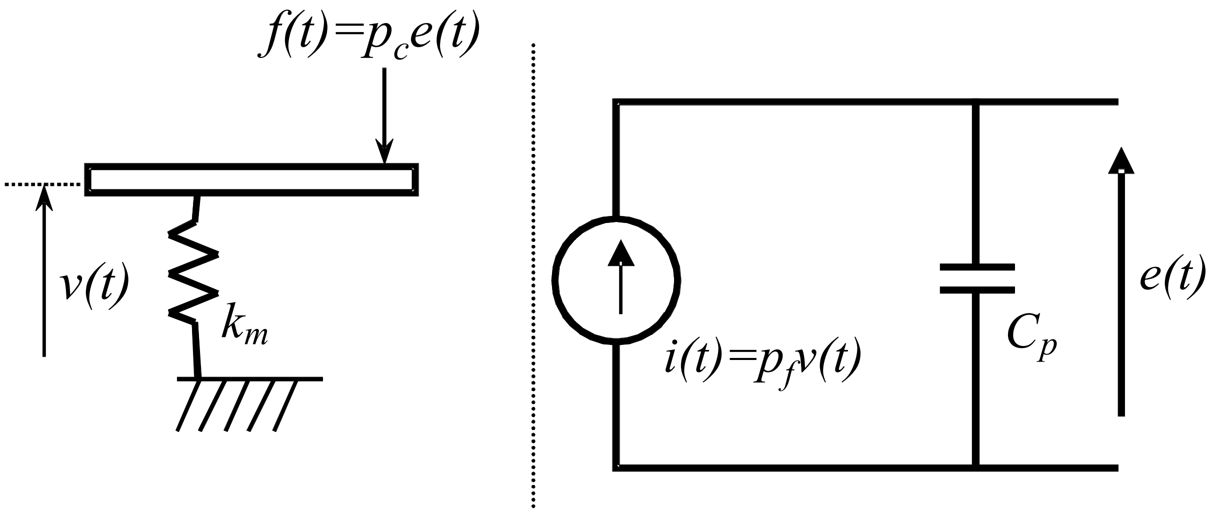
so $\Delta l = \dfrac{p_c e(t)}{k_m}$

- *Applying an electric field creates a force which deforms the piezo material against it's own stiffness.*

- If we add additional mechanical structure then, similar to adding more components on the electrical side, the force is applied to the new structure and a differing deformation occurs.

Piezo model

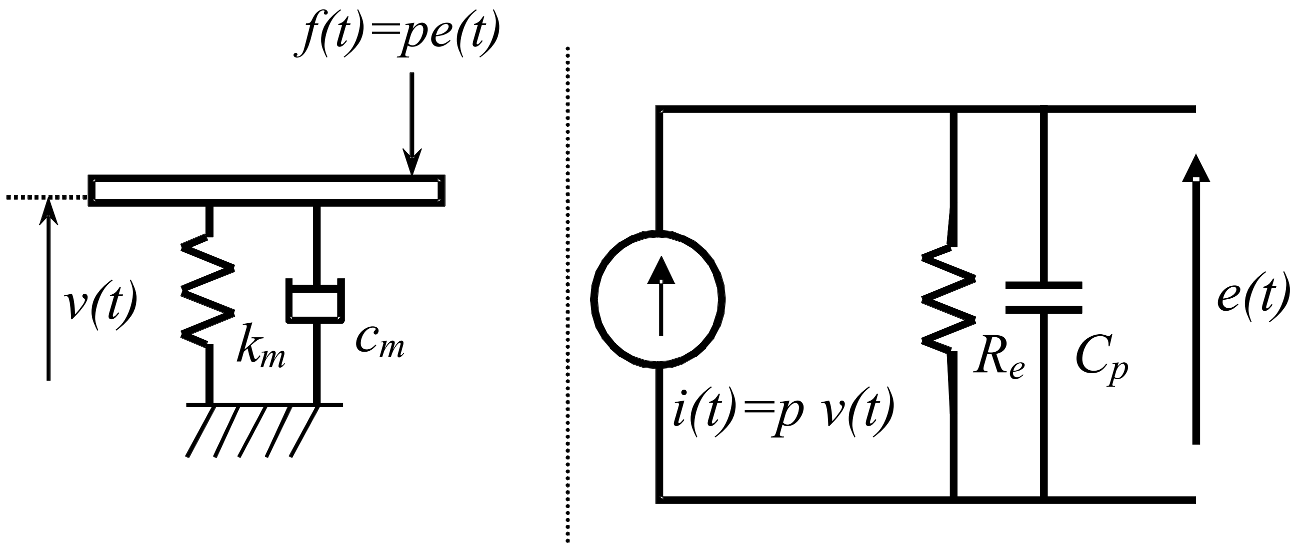
- Both the forward and converse effects happen together, so we can build a complete model of our piezo device



- What about p_c and p_f ?
- It is easy to prove that for power balance, they are equal.

Piezo model

- Using a single coupling constant and adding in some mechanical loss and some electrical loss (always inevitable), we can describe the piezo device.



Piezo coefficients – ‘g’ and ‘d’

- Piezo materials are commonly defined by manufacturers with two coefficients – ‘g’ and ‘d’.
- Note they are slightly more than the ‘coupling constant’ we have looked at so far with as they incorporate material properties: the material cannot be separated from the transduction effect, hence it often makes sense to do it this way.
- The coefficients are normalised to the size of the piezo element so comparison can be made of material properties.

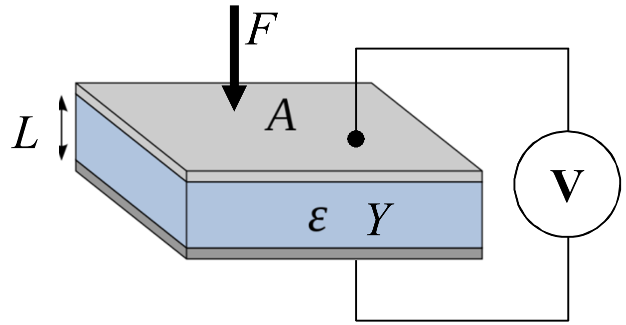
‘Voltage constant’ g;

$$g = \frac{\textit{field}}{\textit{applied stress}} = \frac{\textit{strain}}{\textit{applied charge density}}$$

‘Charge constant’ d;

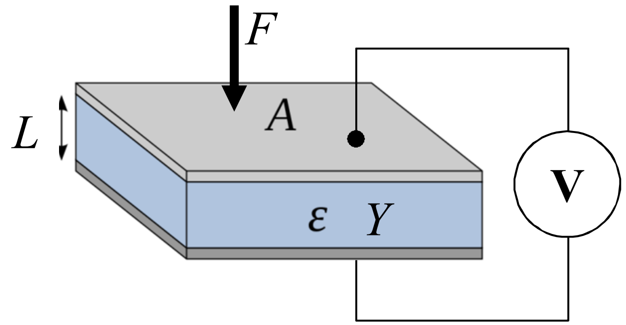
$$d = \frac{\textit{strain}}{\textit{applied field}} = \frac{\textit{charge density}}{\textit{applied stress}}$$

Piezo coefficients – normalised variables



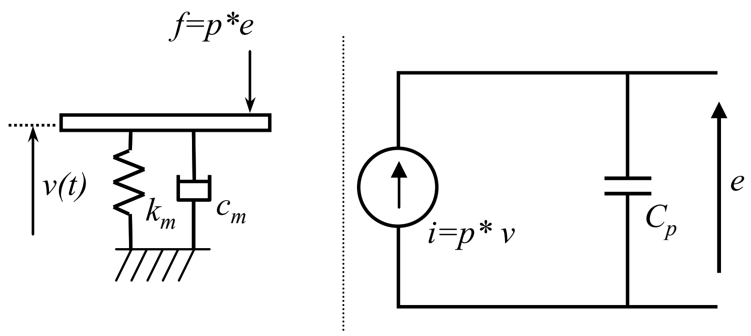
Variable		***Normalised Variable***
Displacement	→	Strain = $\frac{\textit{Change in length}}{\textit{Length}}$
Force	→	Stress = $\frac{\textit{Force}}{\textit{Cross section}}$
Voltage	→	Electric field = $\frac{\textit{Voltage}}{\textit{Length}}$
Charge (Current)	→	Charge density = $\frac{\textit{Charge}}{\textit{Cross section}}$

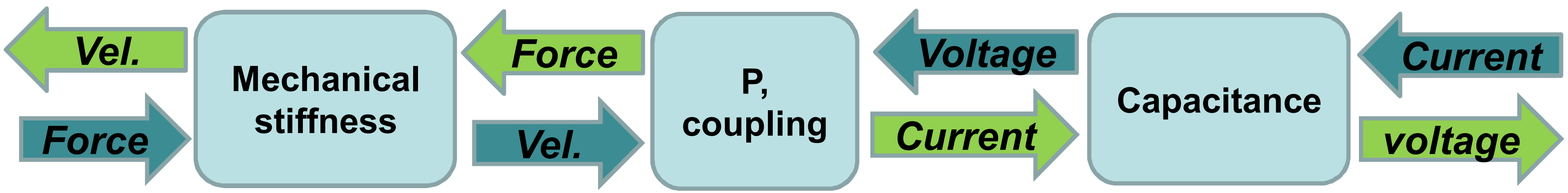
Piezo coupling constants - parameters



Parameter		***Normalised Parameter***
Stiffness = $\dfrac{\textit{Force}}{\textit{Change in length}}$	→	Elastic modulus = $\dfrac{\textit{Stress}}{\textit{Strain}}$
Capacitance = $\dfrac{\textit{Charge}}{\textit{Voltage}}$	→	Permittivity = $\dfrac{\textit{Charge density}}{\textit{Electric field}}$

Piezo coupling constants - definitions



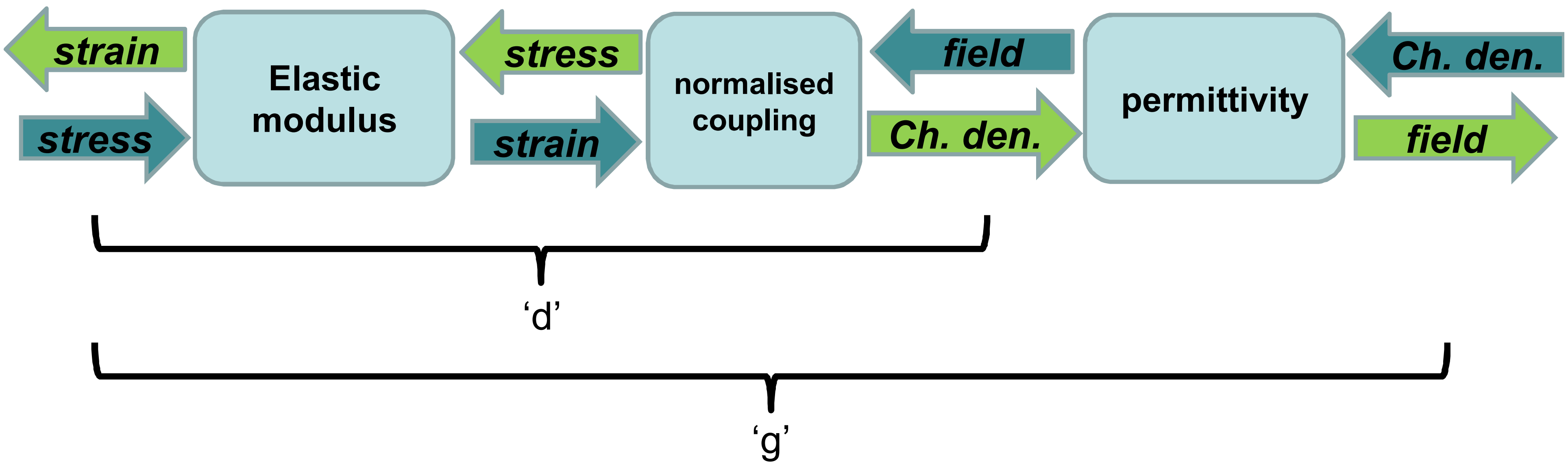


Note: this diagram is not implying that applying a force to a stiffness gives a velocity (it produces displacement), nor current to capacitance a voltage etc. It is drawn to preserve power producing couplets

Piezo coupling constants - definitions

$$g = \frac{\textit{field}}{\textit{applied stress}} = \frac{\textit{strain}}{\textit{applied charge density}}$$

$$d = \frac{\textit{strain}}{\textit{applied field}} = \frac{\textit{charge density}}{\textit{applied stress}}$$



Piezo coupling constants

- As ‘d’ and ‘g’ are normalised to the area and length, they provide a good comparison of materials (as opposed to a particular device which is materials + geometry)

- By introducing the relations between stress and strain (elastic modulus) plus field and charge density (permittivity) it is possible to derive relations between d, g and the constant we defined in our model:

$$p = \frac{A}{l} Y d = \frac{A}{l} Y \varepsilon g$$

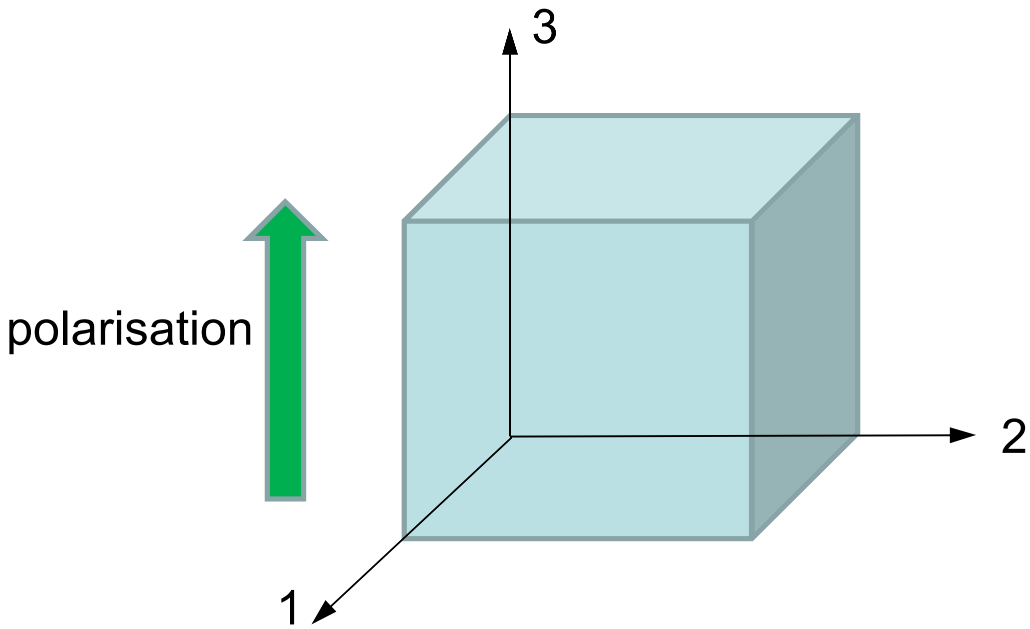
Piezo coupling constants

- ‘d’ and ‘g’ give a guide to behaviour in common applications, although it should be noted they are sometimes invalidated by additional mechanical or electrical components.

- The ‘d’ constant considers cases where we have applied a voltage, or the result is charge. Neither of these scenarios requires knowledge of the capacitance. Hence the ‘d’ constant only takes mechanical compliance into account. *This is useful when the piezo device is used as a sensor for instance to measure force.*

- The ‘g’ constant consider the cases where we need to convert both input and outputs via compliance and capacitance and vice-versa. Hence it takes both into account. *This is useful when the piezo device is used as an actuator.*

Piezo coupling constants - axes



- The piezo electric effect can occur in orthogonal axes, as well as in line with the excitation.
- Coefficient have subscripts which indicate which i.e. d_{11} d_{13} g_{33}

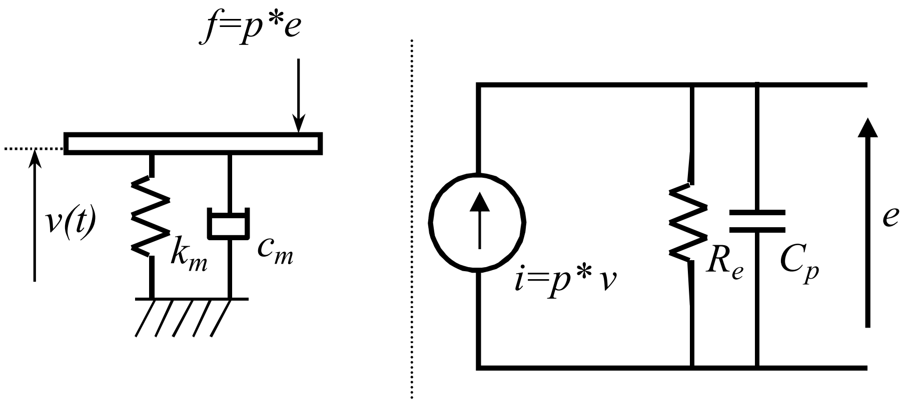
More piezo constants........

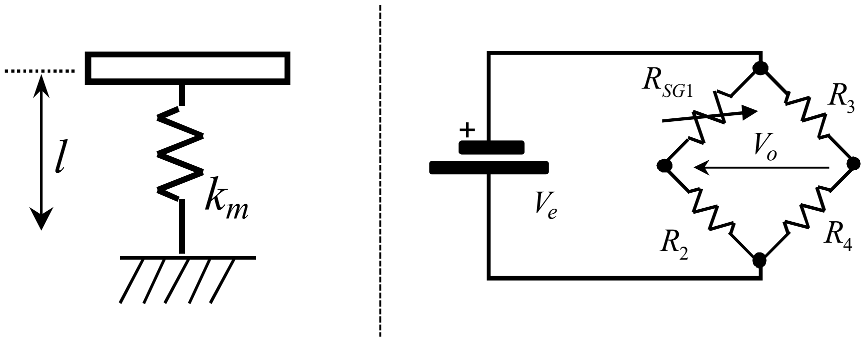
- In addition to the coupling terms, manufactures will often indicate loss.
- Unhelpfully, this is often called the electromechanical coupling coefficient (this is a different definition of the term than we will encounter elsewhere)

$$k = \frac{\sqrt{mech\_energy\_input}}{\sqrt{Electrical\_energy\_ouput}}$$

Piezo compared to foil strain gauge

- What are the key differences between them?





$$R_{SG} = R_n\left(1 + \frac{GF\Delta l}{l}\right)$$

Piezo compared to foil strain gauge

- The mechanical input to the piezo device ‘sees’ the electrical output; The mechanical input to the strain gauge is oblivious to the electrical side.

- The piezo device has reciprocal conversion processes; the strain gauge system only works in one direction.

- Energy flows from one side of the piezo device to the other; No energy passes across the strain gauge mech/electrical interface.

Piezo compared to foil strain gauge

- The piezo device is a transducer:

  "Transducer: converts input energy of one form into output energy of another"

- The strain gauge is a *parametric* system i.e. input energy alters a parameter of another part of the system.

- Important Info

  All transducers can be sensors, but not all sensors are transducers