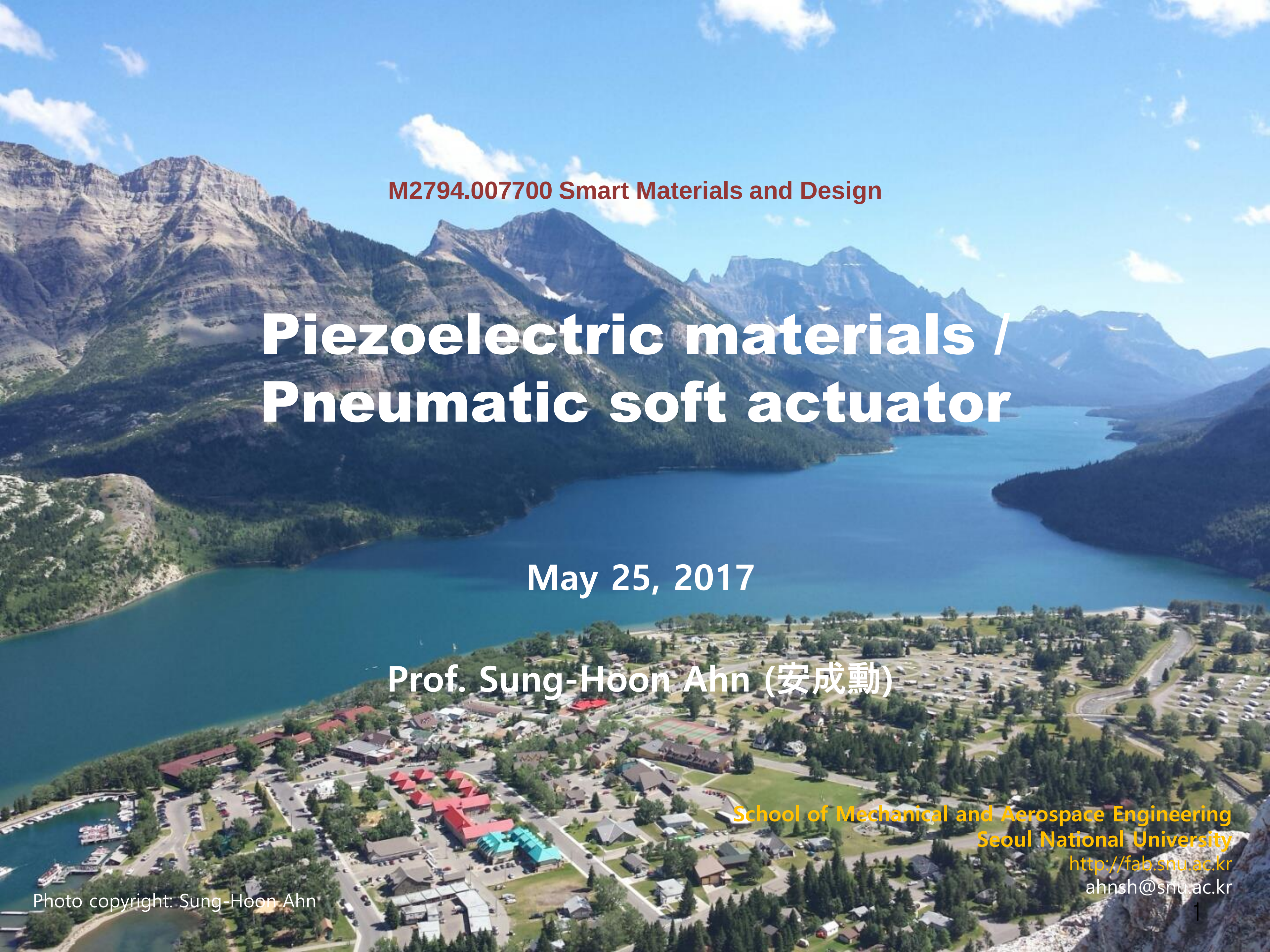

M2794.007700 Smart Materials and Design

Piezoelectric materials / Pneumatic soft actuator

May 25, 2017

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Outline

Introduction to piezoelectricity

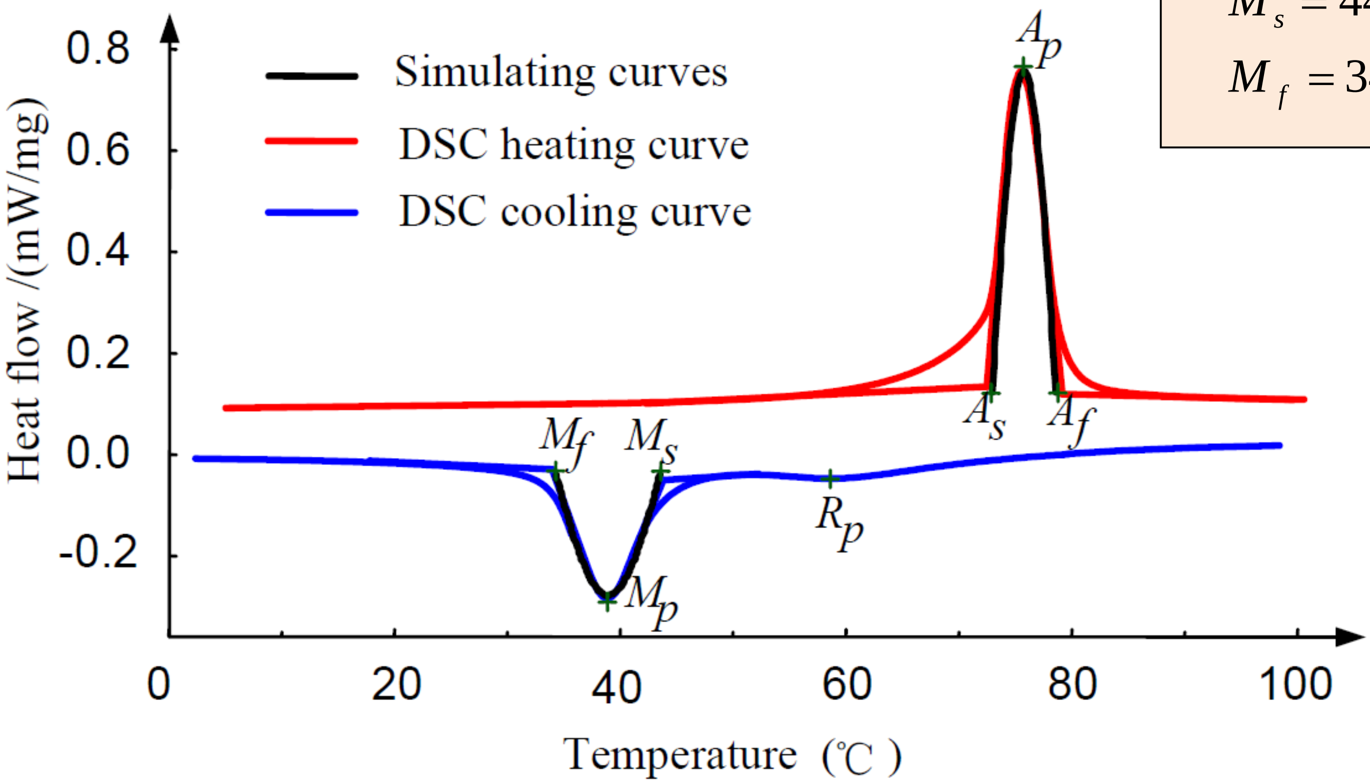
Piezoelectric materials

Applications of piezoelectric material

Pneumatic actuator

Application of Pneumatic actuator

DSC curve of SMA



$A_s = 73$℃

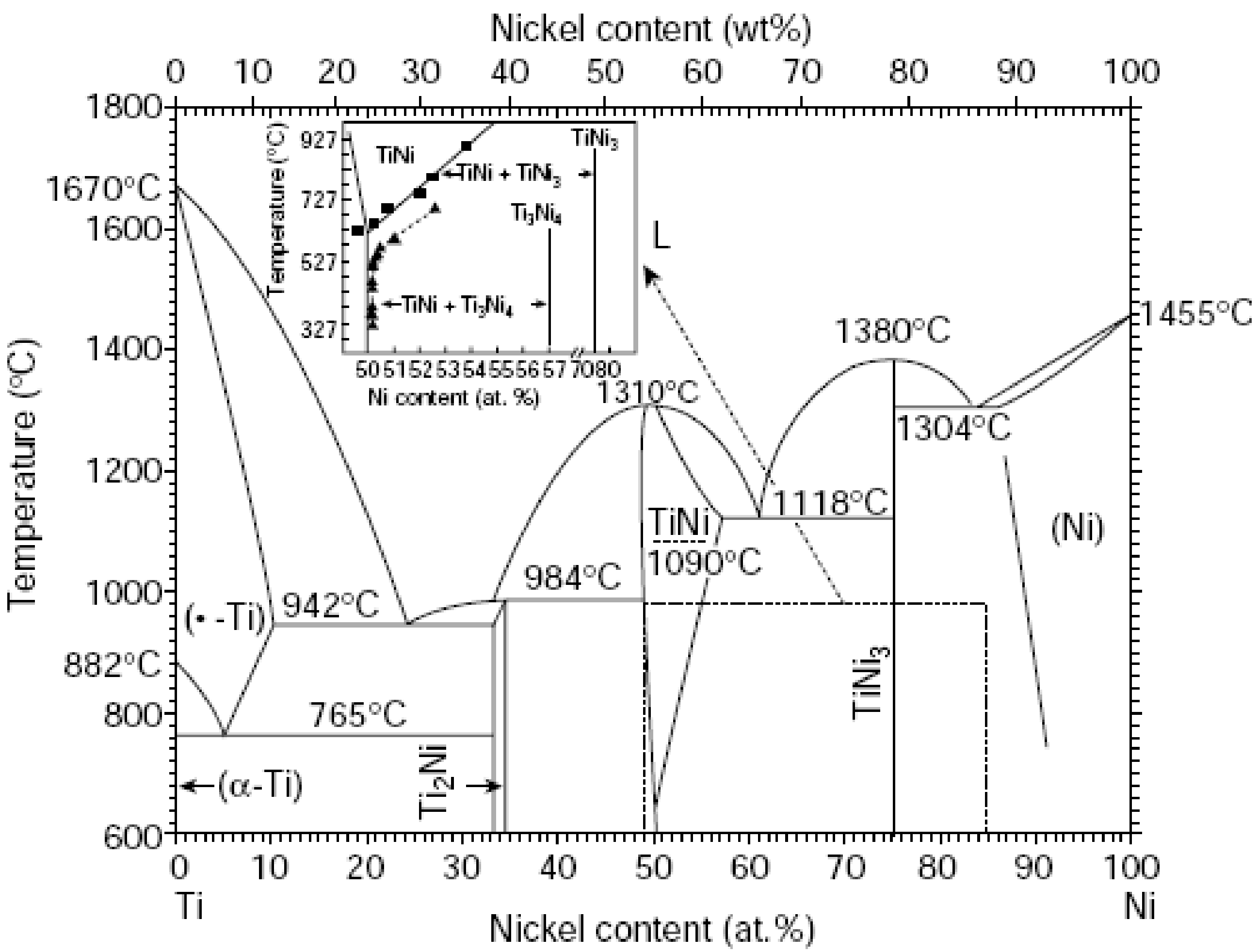
$A_f = 79$℃

$M_s = 44$℃

$M_f = 34$℃

J.-J. Zhang, Y.-H. Yin, and J.-Y. Zhu, "Electrical resistivity-based study of self-sensing properties for shape memory alloy-actuated artificial muscle," *Sensors,* vol. 13, pp. 12958-12974, 2013.

Phase Diagram of SMA



Phase diagram of a Ti-Ni alloy and details of the TiNi and TiNi3 phases

http://thehealthscience.com/showthread.php?850197-Shape-Memory-Alloys

Crystallography of Smart Materials

Prof. Versha Khare
Innovetive Design and Integrated Manufacturing Lab
Institute of Advanced Materials and Design
Seoul National University

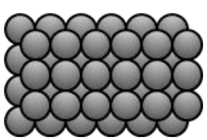
Crystallography

Crystallography : Science dealing with the understanding of arrangements of atoms in solid

Crystal Structure: A regular atomic arrangements in a solid

Solids

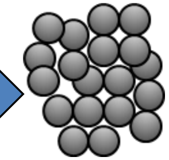
Crystalline



- Long Range order
- Defined arrangement of atoms
- Crystal Structure

Amorphous

- Short Range order
- No Defined arrangement of atoms
- No Crystal Structure



Essentials of Crystal Structure

Crystal Structure

14 Bravais Lattice

Miller indices

Lattice Planes

7-Crystal Systems

Inter-axial Angle

Crystal Axis

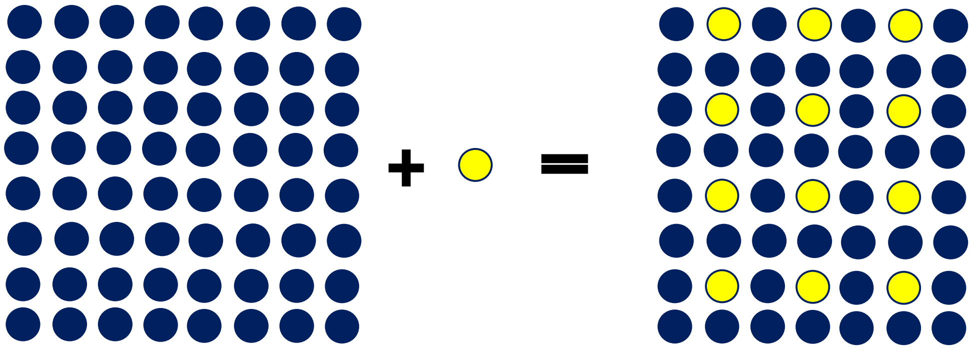
Symmetry Elements

Translation
Rotation
Reflection
Inversion

Auguste Bravais
(1811-1863)

Lattices

Lattices + Basis = Crystal Structure

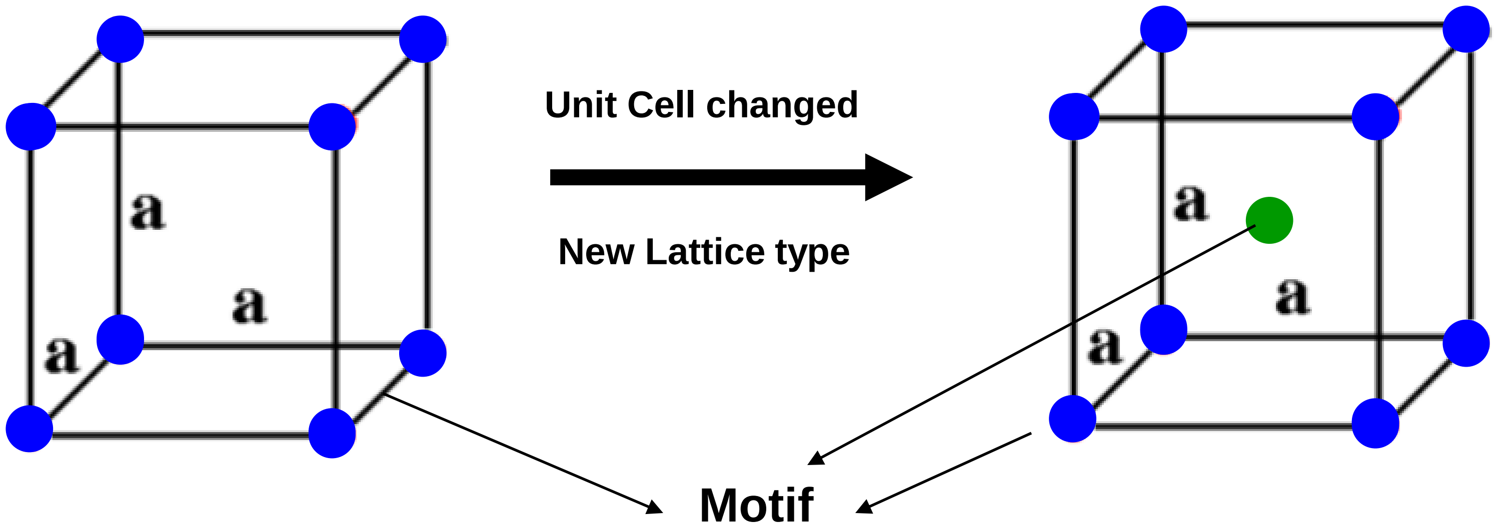


- *An infinite array of discrete points with identical environment*
- *In 3-dimensional system there are fourteen possible ways to get identical environment*
- *Lattices are characterized by translation symmetry*

Lattice : Involvement of Geometry and Mathematics

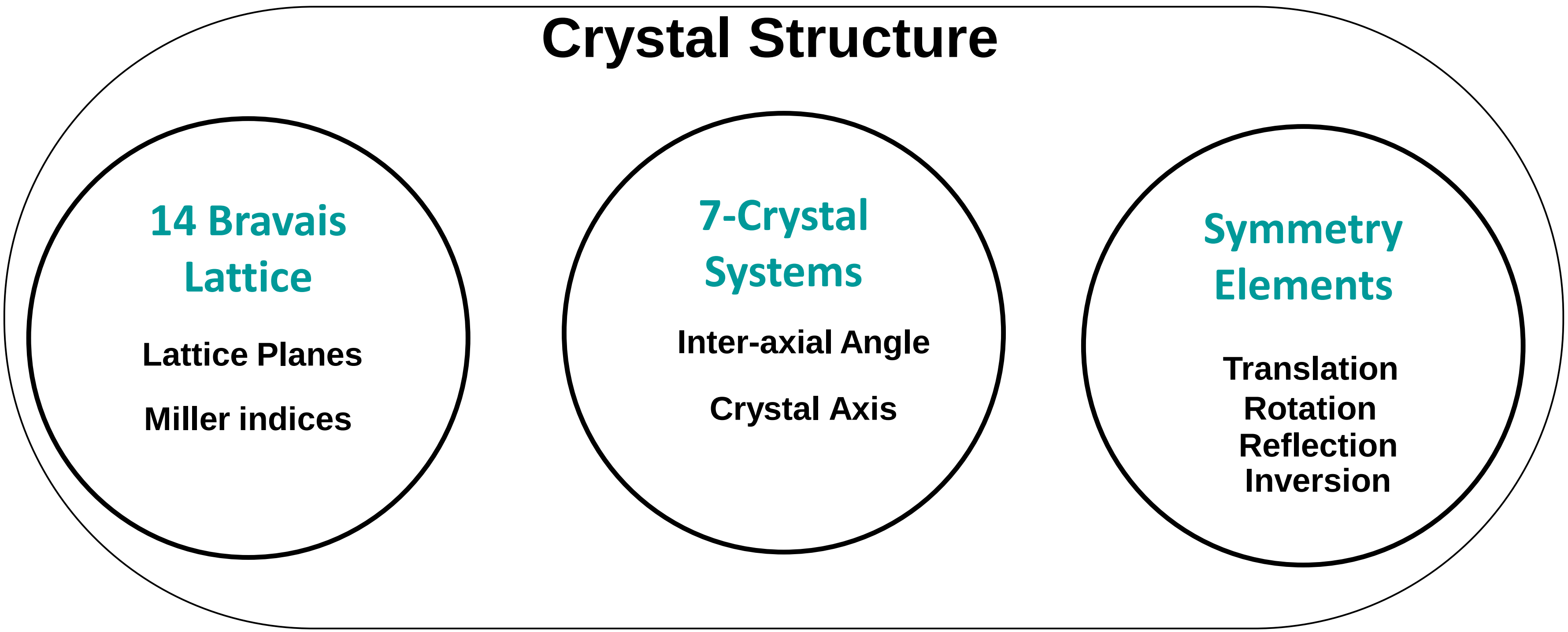
Crystal System has array of atoms arranged systematically

Translation, removal or insertion of these atoms????????????



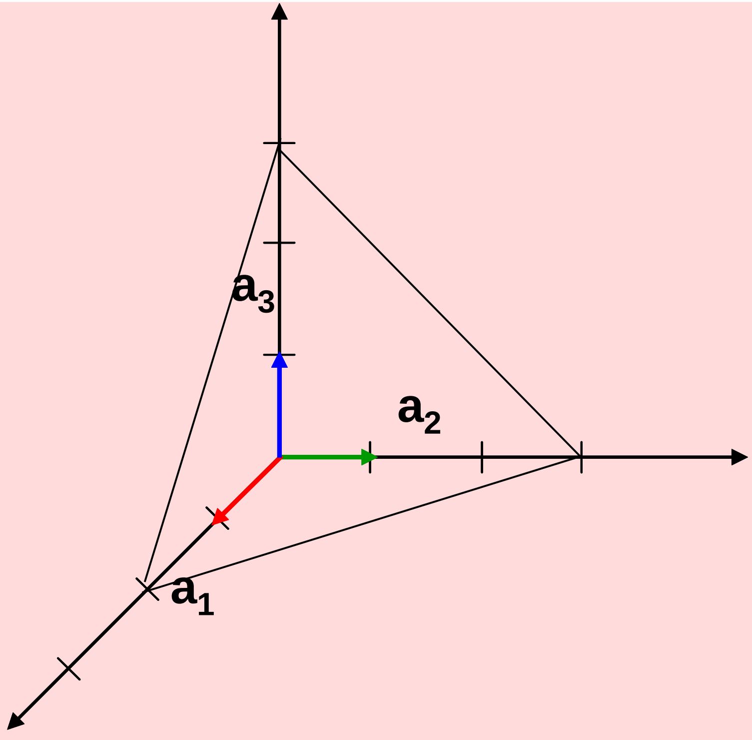
Lattice + Basis/Motif = Unit cell →Crystal structure

Essentials of Crystal Structure



Miller Indices

Miller Indices are the notation system for Crystallographic Planes



Step 1: Determine the Intercept

- a_1 intercepts at 2
- a_2 intercepts at 3
- a_3 intercepts at 3

Step 2: Calculate the reciprocal of intercepts

$\rightarrow$1/2
$\rightarrow$1/3
$\rightarrow$1/3

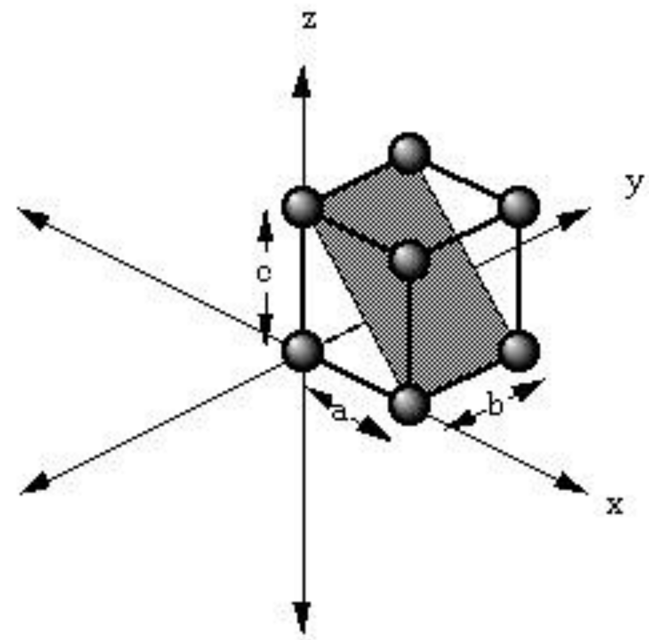
Step 3: Reduced them to smallest integers having the same ratio

Step 3: Bracket the values

Miller Indices – (3,2,2)

Another example:

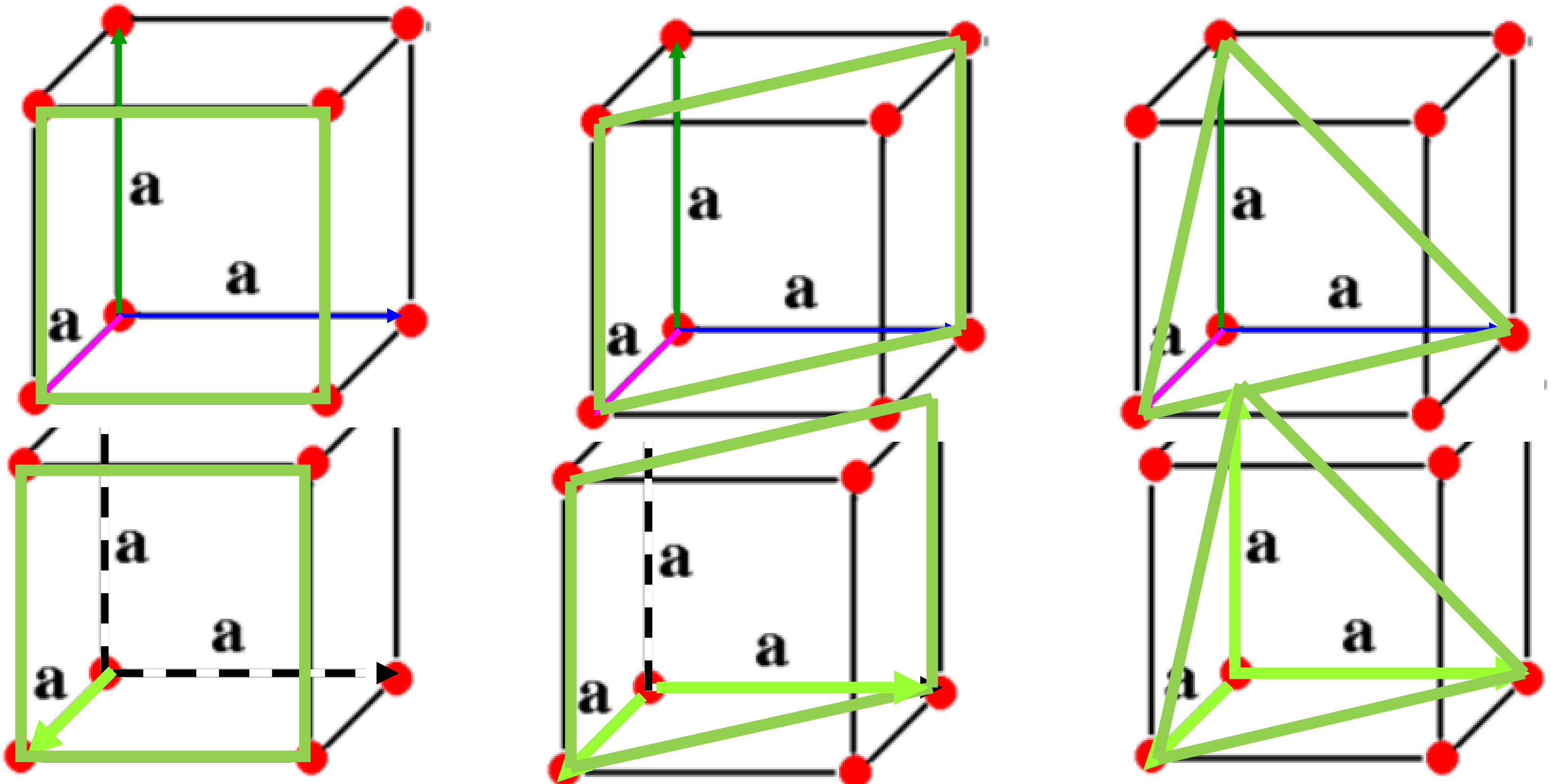
Rules for determining Miller Indices:
1. Determine the intercepts of the face along the crystallographic axes, *in terms of unit cell dimensions.*
2. Take the reciprocals
3. Clear fractions
4. Reduce to lowest terms



	a	b	c
intercept length	1	∞	1
reciprocal	$\frac{1}{1}$	$\frac{1}{\infty}$	$\frac{1}{1}$
cleared fraction	1	0	1

Miller indice (101)

Crystal Planes : Family of Planes

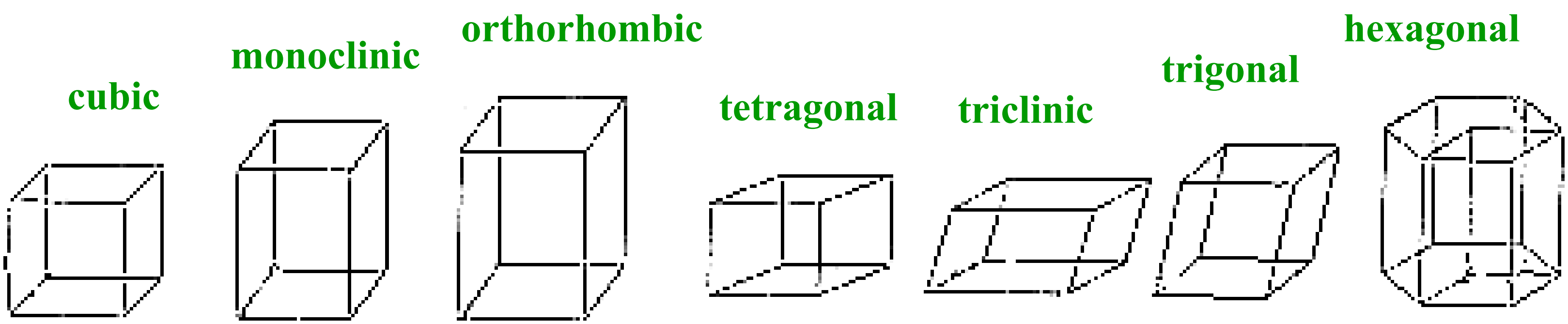


(100) (110) (111)

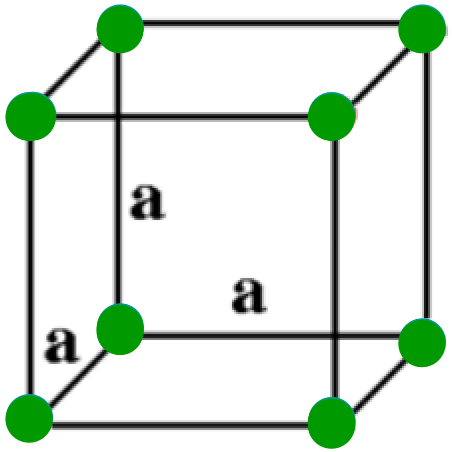
Crystal Systems

Important to define the unit cell shape

Possible shapes which must fill the 3d-space using symmetry operations

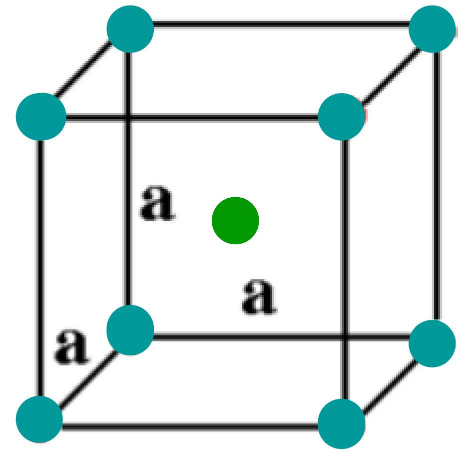


P-Type



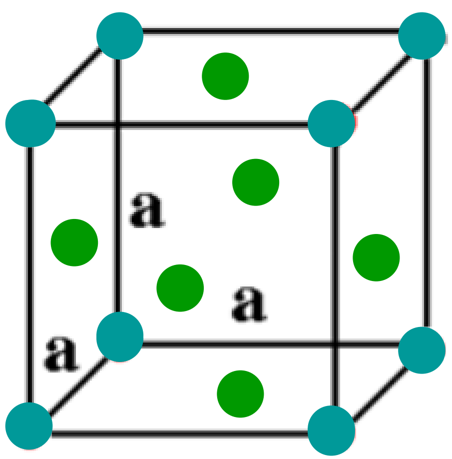
PRIMITIVE

I -Type



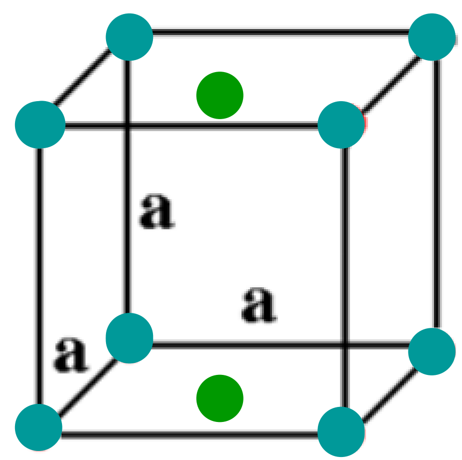
BODY-CENTERED

F-Type



FACE-CENTERED

C-Type



BACE-CENTERED

What is Symmetry

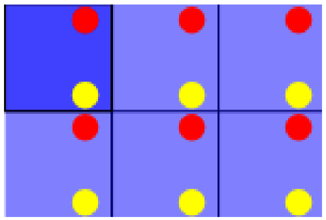
symmetry is the operation that leaves the entire crystal unchanged.

A state in which parts on opposite sides of a plane, line, or point display arrangements that are related to one another via a symmetry operation such as translation, rotation, reflection or inversion.

Symmetry Elements: Macroscopic

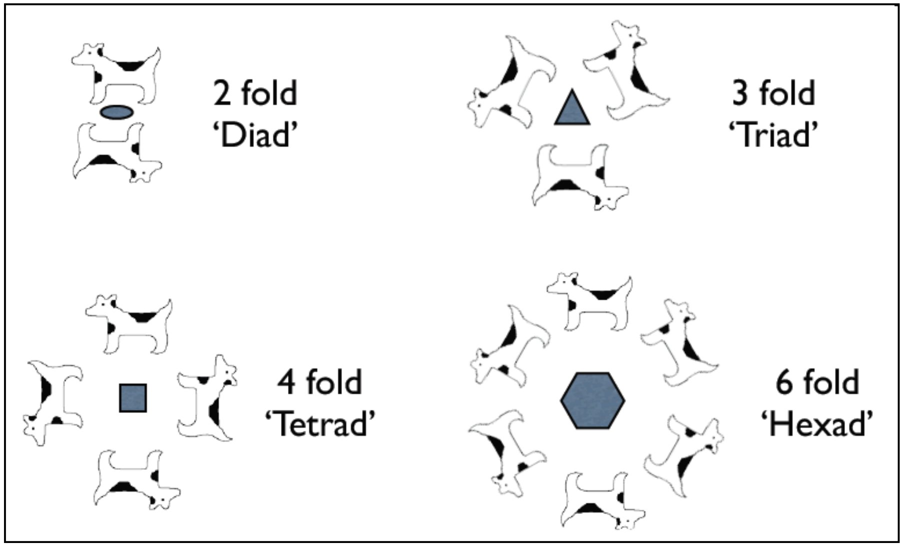
Translation

moves all the points in the asymmetric unit the same distance in the same direction



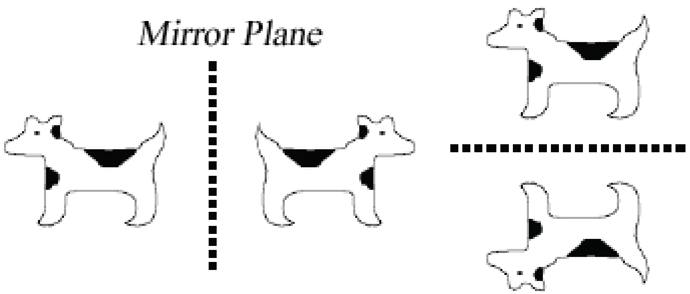
The center of rotation is the only invariant point

Rotation

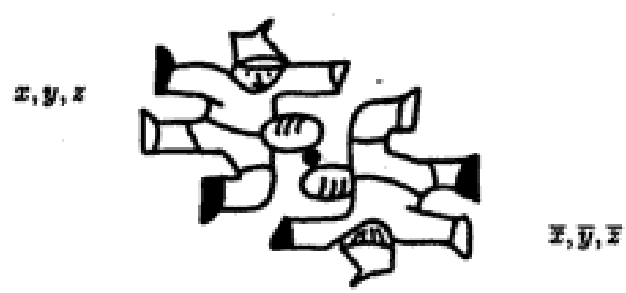


Reflection or Mirror

flips all points in the asymmetric unit over a line, which is called the mirror



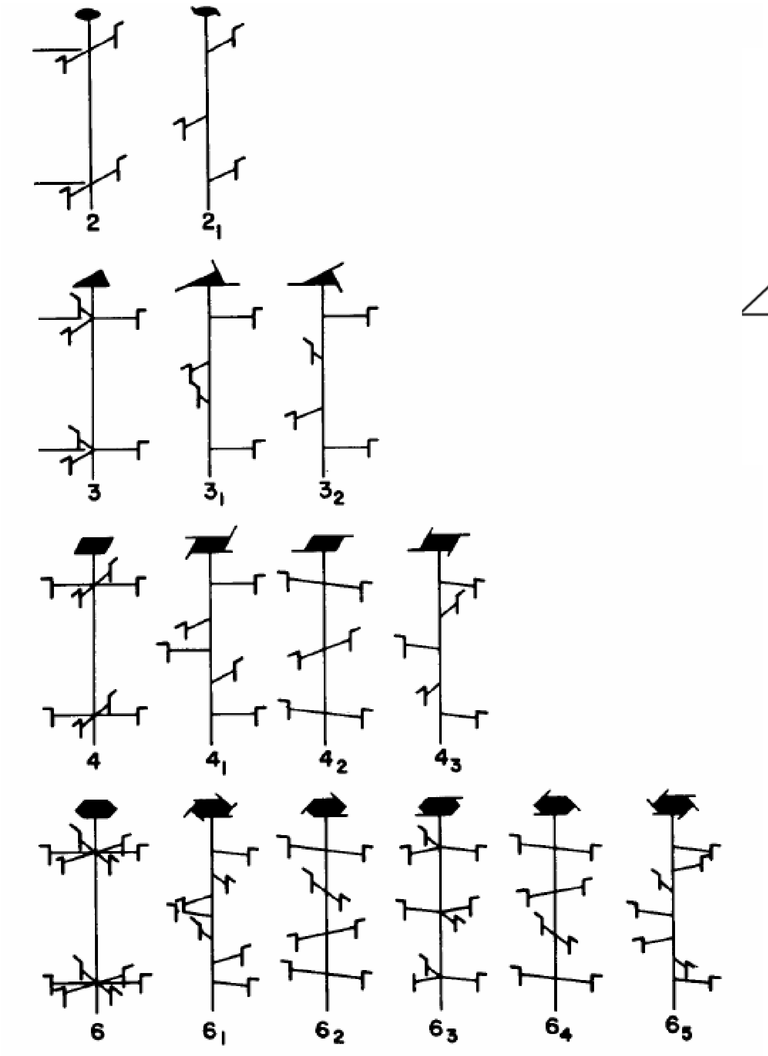
Inversion or centre of Symmetry



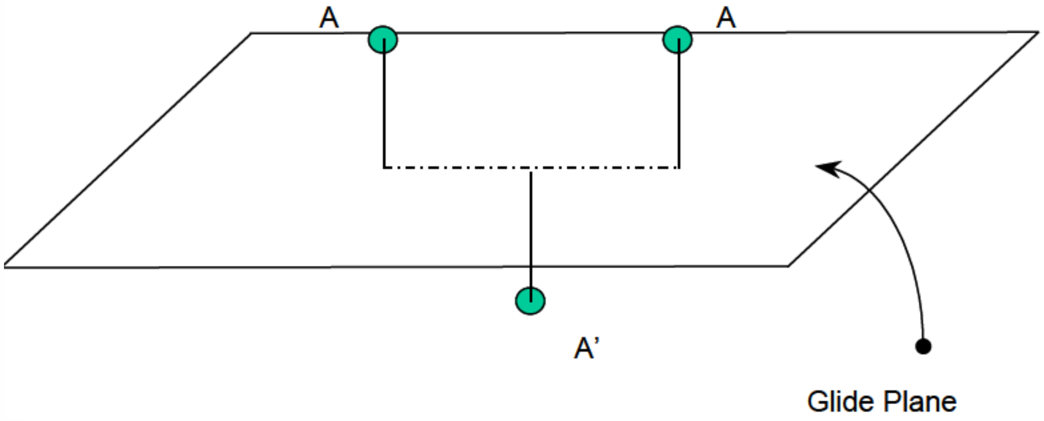
every point on one side of a center of symmetry has a similar point at an equal distance on the opposite side of the center of symmetry.

Symmetry Elements: Microscopic

Screw Axis – Rotation + Translation



Glide plane – Reflection + Translation



Symmetry Classes

Point Group – 32 Point Groups

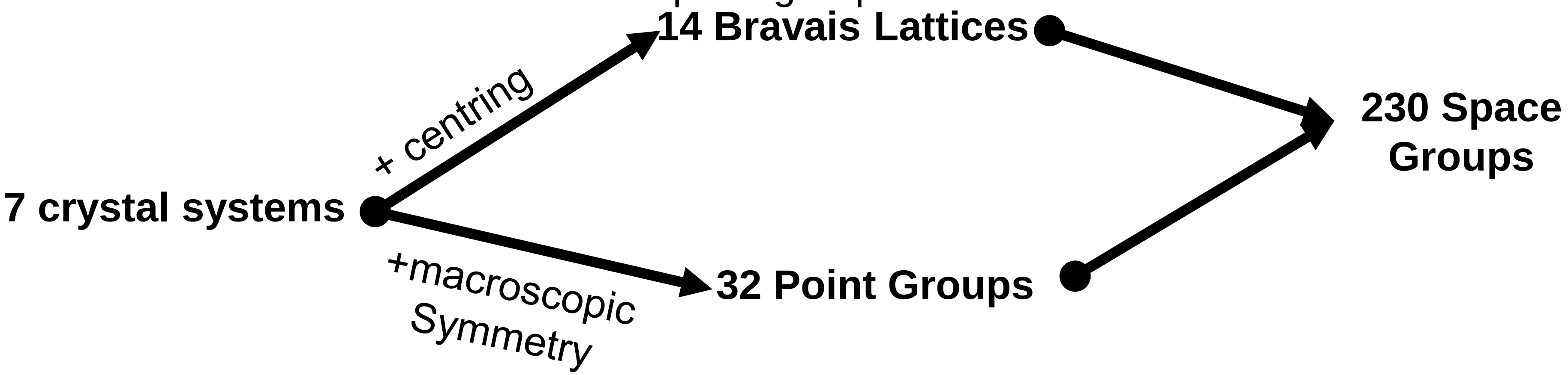
Point group symmetry does not consider translation/centering.

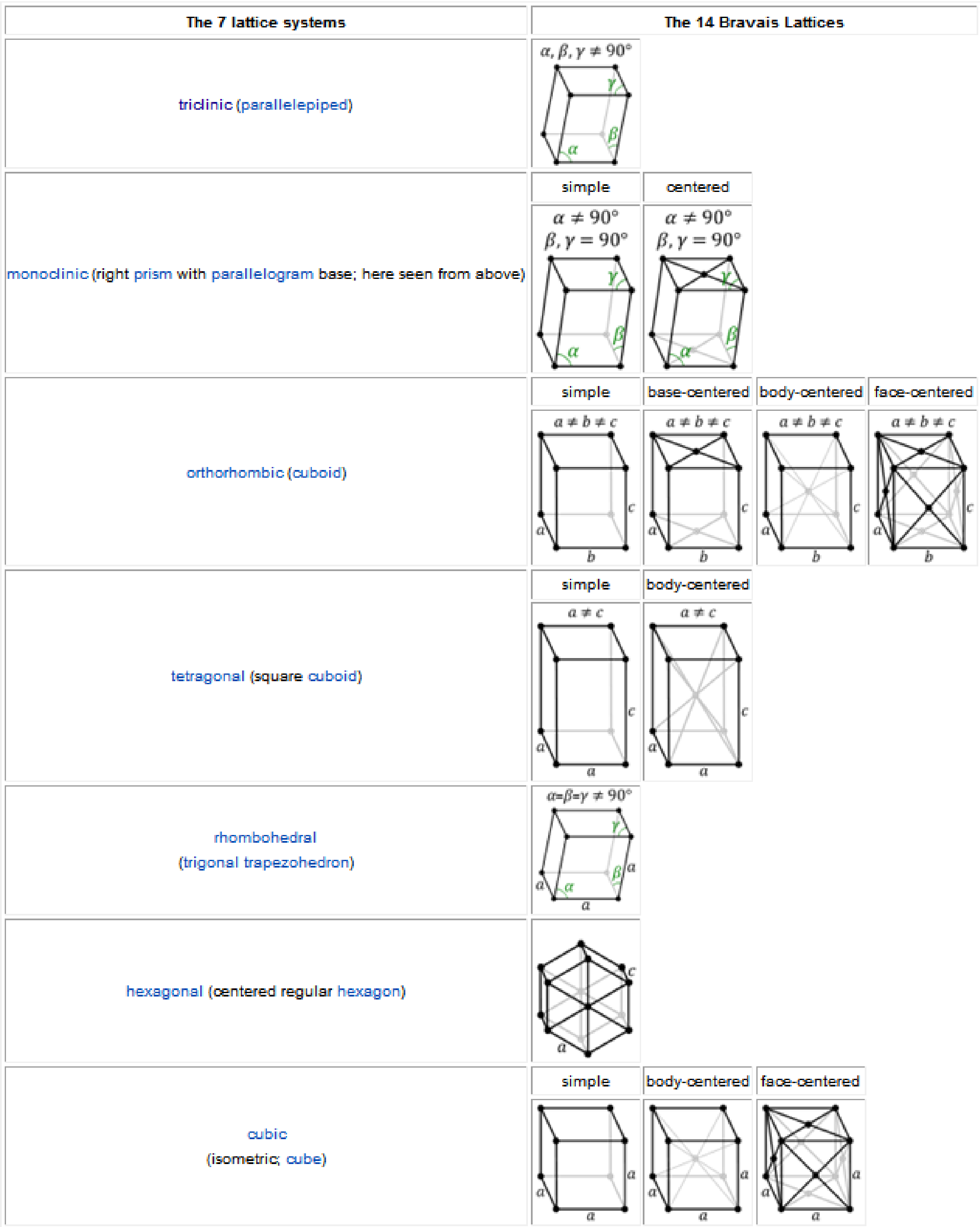
Included symmetry elements are rotation, mirror plane, center of symmetry, rotary inversion.

Space Group – 230 Space Groups

A space group is a representation of the ways that the macroscopic and microscopic symmetry elements (operations) can be self-consistently arranged in space. There are 230 unique manners in which this can be done and, thus, 230 space groups..

Space groups add the centring information and microscopic elements to the point groups





The 7 lattice systems	The 14 Bravais Lattices			
triclinic (parallelepiped)	$\alpha, \beta, \gamma \neq 90°$			
monoclinic (right prism with parallelogram base; here seen from above)	simple: $\alpha \neq 90°$ $\beta, \gamma = 90°$	centered: $\alpha \neq 90°$ $\beta, \gamma = 90°$		
orthorhombic (cuboid)	simple: $a \neq b \neq c$	base-centered: $a \neq b \neq c$	body-centered: $a \neq b \neq c$	face-centered: $a \neq b \neq c$
tetragonal (square cuboid)	simple: $a \neq c$	body-centered: $a \neq c$		
rhombohedral (trigonal trapezohedron)	$\alpha=\beta=\gamma \neq 90°$			
hexagonal (centered regular hexagon)				
cubic (isometric; cube)	simple	body-centered	face-centered	

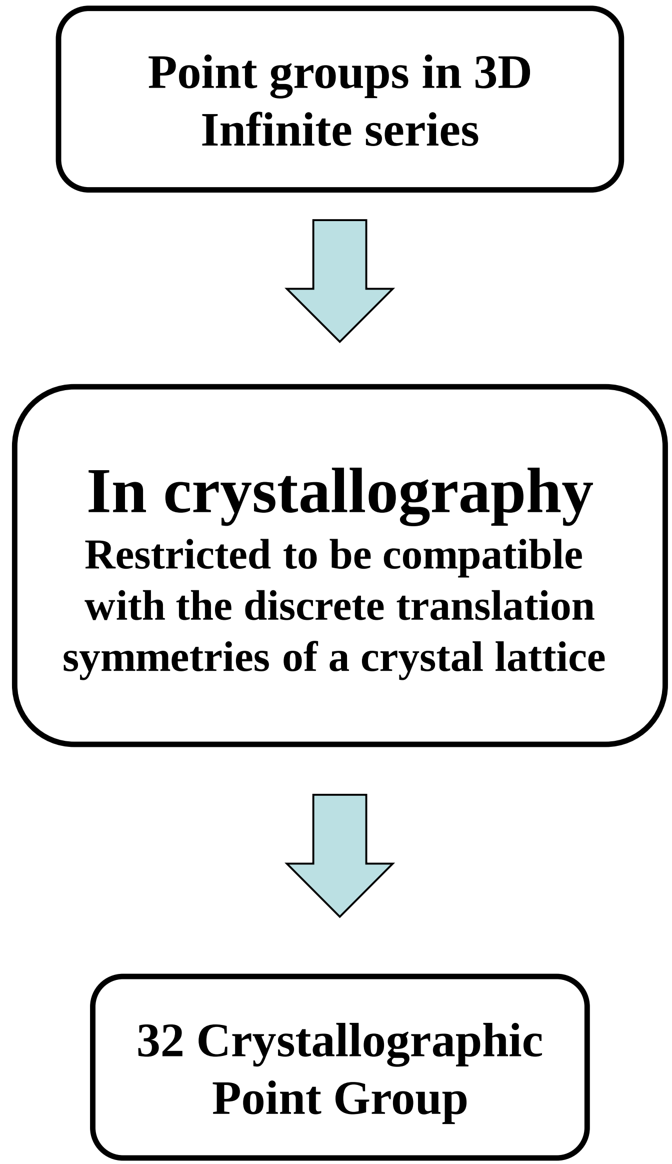


Table 3.1. Graphic Symbols for Symmetry Elements[a]

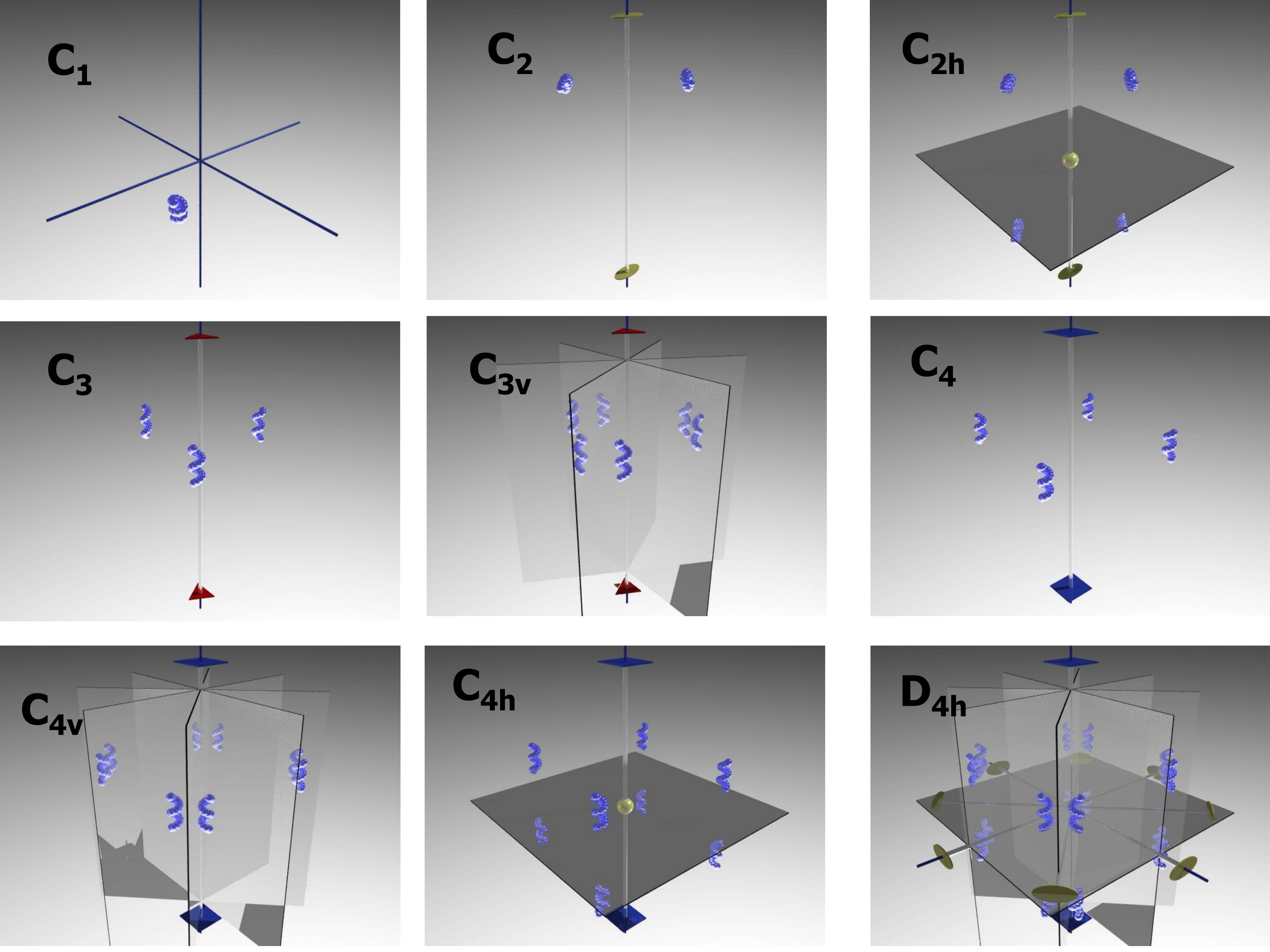
Symmetry axis or symmetry point	Graphic symbol	Screw vector of a right-handed screw rotation in units of the shortest lattice translation vector parallel to the axis	Printed symbol
Symmetry axes normal to the plane of projection (three dimensions) and symmetry points in the plane of the figure (two dimensions)			
Identity	None	None	1
Twofold rotation axis; Twofold rotation point (two dimensions)		None	2
Twofold screw axis: "2 sub 1"		$\frac{1}{2}$	2_1
Threefold rotation axis; Threefold rotation point (two dimensions)		None	3
Threefold screw axis: "3 sub 1"		$\frac{1}{3}$	3_1
Three fold screw axis: "3 sub 2"		$\frac{2}{3}$	3_2
Fourfold rotation axis; Fourfold rotation point (two dimensions)		None	4
Fourfold screw axis: "4 sub 1"		$\frac{1}{4}$	4_1
Fourfold screw axis: "4 sub 2"		$\frac{1}{2}$	4_2
Fourfold screw axis: "4 sub 3"		$\frac{3}{4}$	4_3
Sixfold rotation axis; Sixfold rotation point (two dimensions)		None	6

(continued)

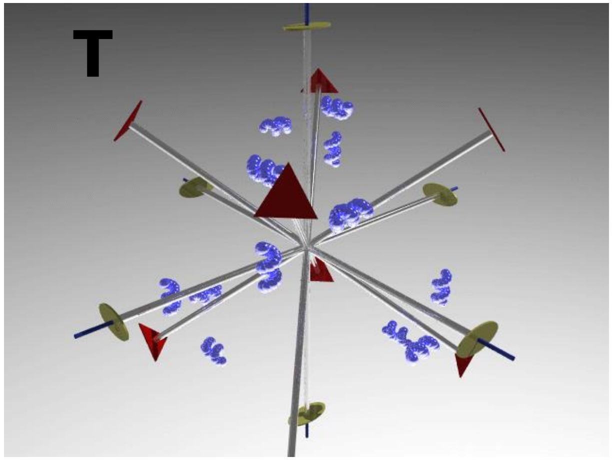
Crystallographic Point Group

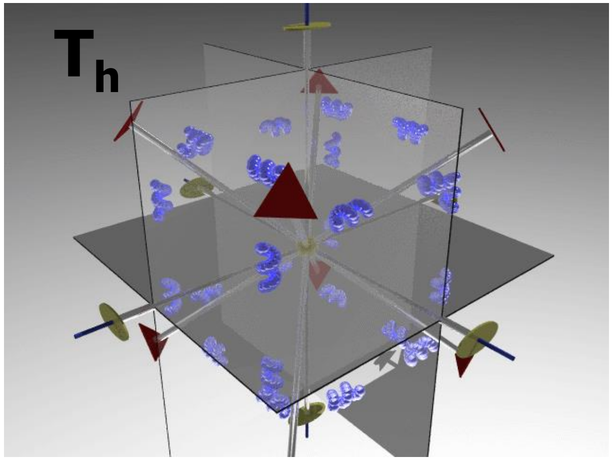
- **A set of symmetry operations (such as rotations or reflections)**
- **Infinitely many three dimensional point groups**
- **But in crystallography, they are restricted to be compatible with the discrete translation symmetries of a crystal lattice → Finite 32 crystallographic point groups**

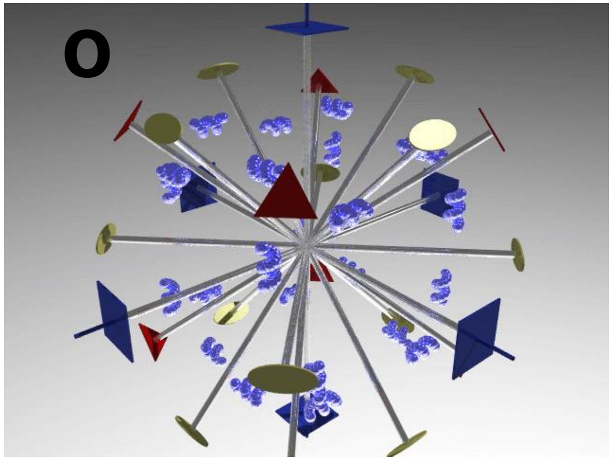
- **In Schönflies notation**
  - ***C_n* (for cyclic)**
    - The group has an n-fold rotation axis
      - C_{nh} includes a mirror (reflection) plane perpendicular to the axis of rotation
      - C_{nv} includes a mirror plane parallel to the axis of rotation
  - ***O* (for octahedron)**
    - The group has the symmetry of an octahedron (or cube)
      - O_h includes improper operations
      - *O* excludes improper operations
  - ***T* (for tetrahedron)**
    - The group has the symmetry of a tetrahedron
      - T_d includes improper operations
      - *T* excludes improper operations
      - T_h includes an inversion to *T*
  - ***S_n* (for Spiegel, German for mirror)**
    - The group that contains only an n-fold rotation-reflection axis
  - ***D_n* (for dihedral, or two-sided)**
    - The group has an n-fold rotation axis plus a two-fold axis perpendicular to that axis
    - D_{nh} includes a mirror plane perpendicular to the n-fold axis
    - D_{nv} includes mirror planes parallel to the n-fold axis

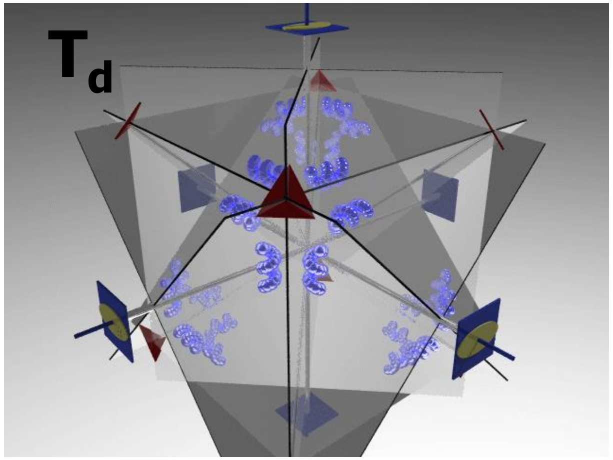


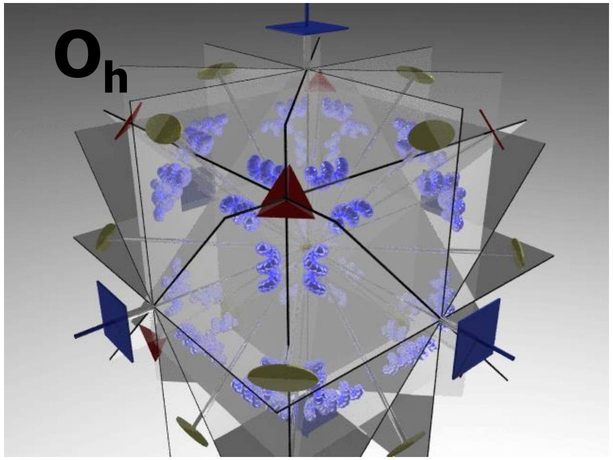
C_1
C_2
C_{2h}
C_3
C_{3v}
C_4
C_{4v}
C_{4h}
D_{4h}


T


T_h


O


T_d


O_h

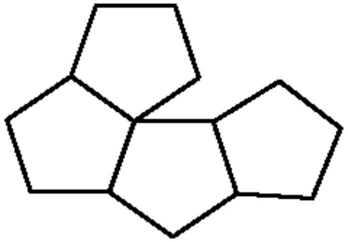
Crystallographic Point Group

- **By the crystallographic restriction theorem**
  - n = 1, 2, 3, 4, or 6 in 2 or 3 dimension space

n	1	2	3	4	6
C_n	C_1	C_2	C_3	C_4	C_6
C_{nv}	$C_{1v}=C_{1h}$	C_{2v}	C_{3v}	C_{4v}	C_{6v}
C_{nh}	C_{1h}	C_{2h}	C_{3h}	C_{4h}	C_{6h}
D_n	$D_1=C_2$	D_2	D_3	D_4	D_6
D_{nh}	$D_{1h}=C_{2v}$	D_{2h}	D_{3h}	D_{4h}	D_{6h}
D_{nd}	$D_{1d}=C_{2h}$	D_{2d}	D_{3d}	D_{4d}	D_{6d}
S_n	$S_1=C_{1h}$	S_2	$S_3=C_{3h}$	S_4	S_6

Fill the 2D Space by Pentagon using any symmetry operation

Not possible



27 point groups

Note : D_{4d} and D_{6d} are actually forbidden because they contain improper rotations with n = 8 and 12

T, T_d, T_h, *O*, O_h

(5 additional point groups)

Total 32 Crystallographic Point Group

Smart Materials

A Smart System ⇨ Predictivity + Adaptivity + Repetivity

Smart Materials: Respond to a stimulus with a predictable action in a systematic pattern

Response Stimuli	Mechanical	Thermal	Electrical	Optical	Magnetic
Mechanical	Negative Poisson R atio		Piezoelectric Electrostrictive	Mechanochromic	Magnetostrictive
Thermal	Shape Memory	Thermoelectri c		Thermochromic Thermoluminescent	
Electrical	Piezoelectric Electrostrictive ER Fluids			Electrochromic Electroluminescent Electro-optic	
Optical			Photoconductor	Photochromic	
Magnetic	MR Fluids			Magneto-optic	

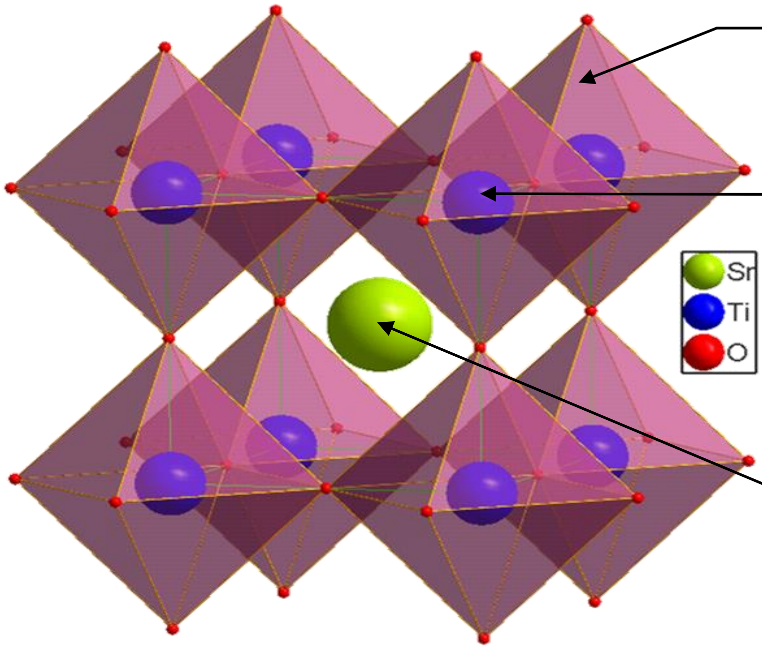
Smart Materials : Pervoskite

General Formula- ABX_3
A – Larger Cation
B – Smaller Cation
X – Anion (In most cases O)

Atomic Cordination (CN)-
A – 12
B – 6
X – Anion (In most cases O)

$Pm\overline{3}m$

Ideal Pervoskite Structure (SrTiO3)



Anion (O) Octahedra

Corner Sharing Octaedral site B cations :
Nb, Ta, Ti, Zr, Fe, Mn, ….

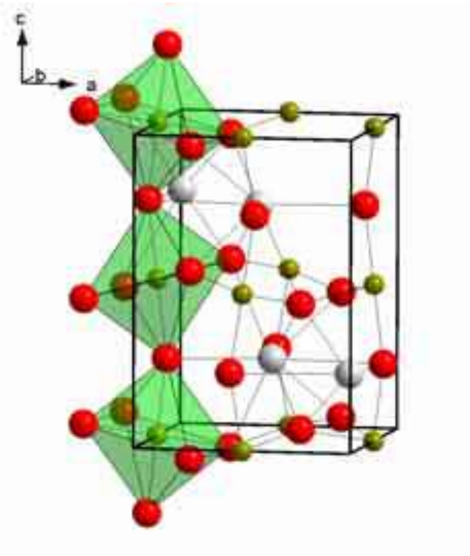
Tweleve-fold Cavities Dodecaedral site A cations :
K, Na, Ca, Sr, Ba, Pb, Bi, Y, La, …

Deformation in Pervoskite : Size factor

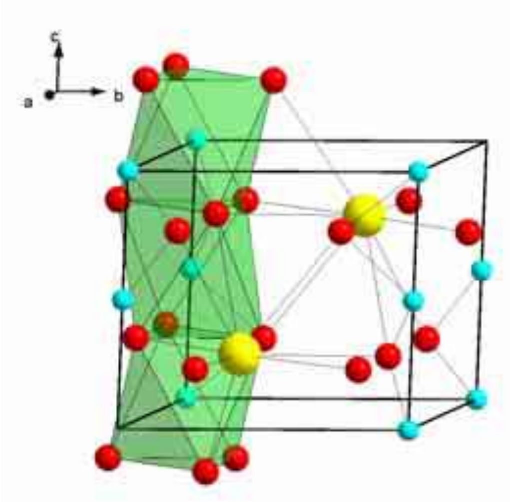
Stability Range of Pervoskite :
Goldschmidt's Tolerance factor

$$t = \frac{(r_A + r_X)}{\sqrt{2}(r_B + r_X)}$$

- The perovskite structure is stable when $0.89 \le t \le 1.06$ (taking r_X = 0.14 nm)
- Low value of t will lower the symmetry



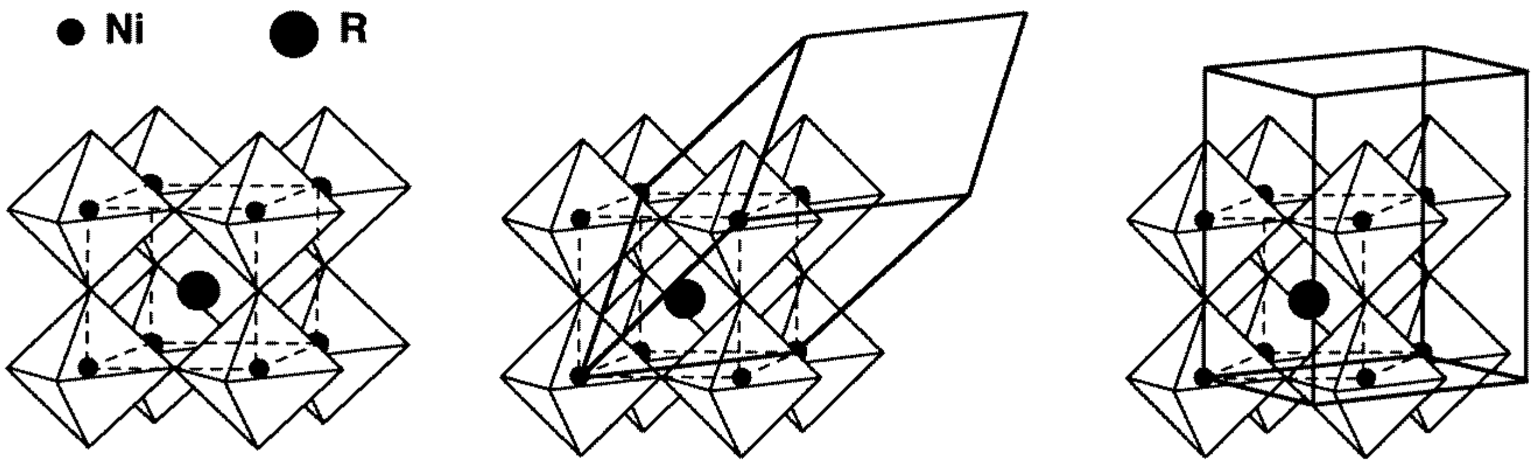
Orthorhombic $GdFeO_3$ (t=0.81)



Hexagonal $BaNiO_3$ (t=1.13)

Deformation in Pervoskite : Rotation or tilting effect

Ideal Pervoskite | Rotation effect | Tilting effect



a) | b) | c)

Cubic Pm3m

Rhombohedral (R3c)

Rotation along [111] cubic axis

Orthorhombic (Pbnm)

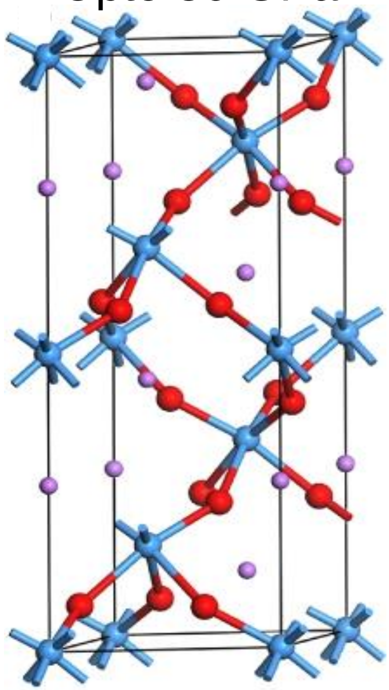
Tilt along [110] and [001] cubic axis

J. Phys.: Condens. Matter **9** (1997) 1679–1707

Pressure induced Deformation in Pervoskite

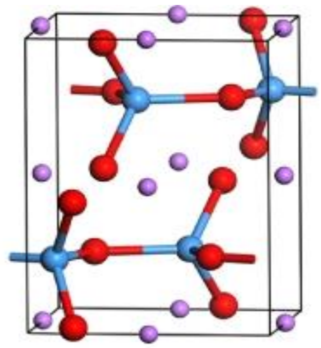
$LiTaO_3$

Upto 36 GPa



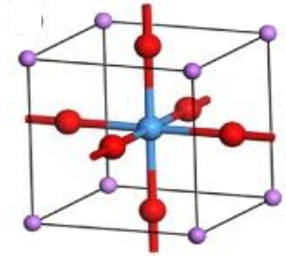
Rhombohedral (R3c)

at 56.1 GPa



Orthorhombic (Pnma)

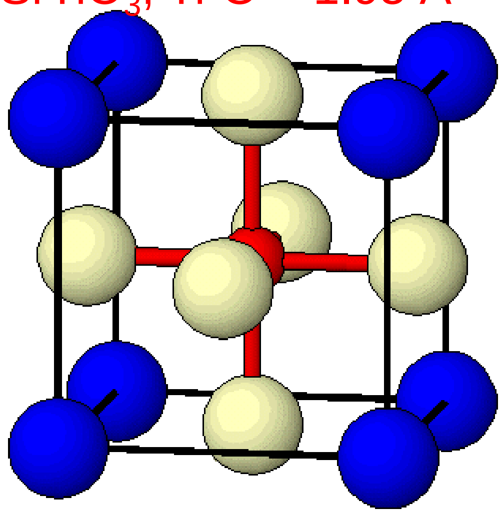
Ideal



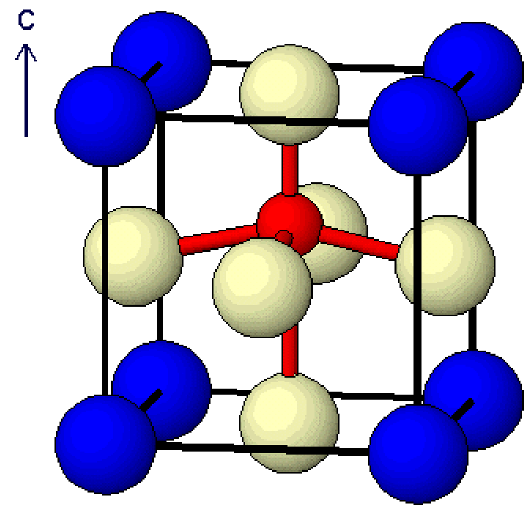
Cubic Pm3m

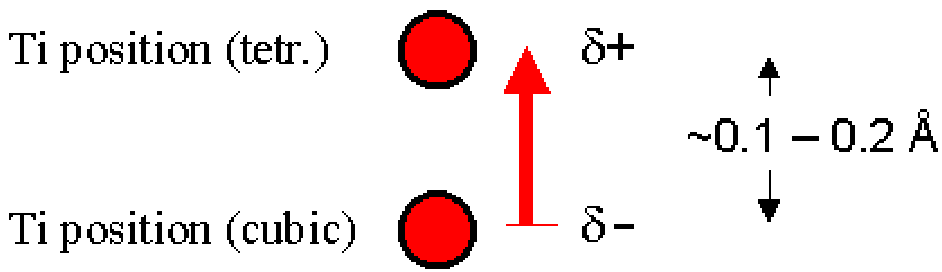
Polarisation effect in Pervoskite

$SrTiO_3$, Ti-O ~ 1.95 Å



$BaTiO_3$, Ti-O is stretched, > 2.0 Å





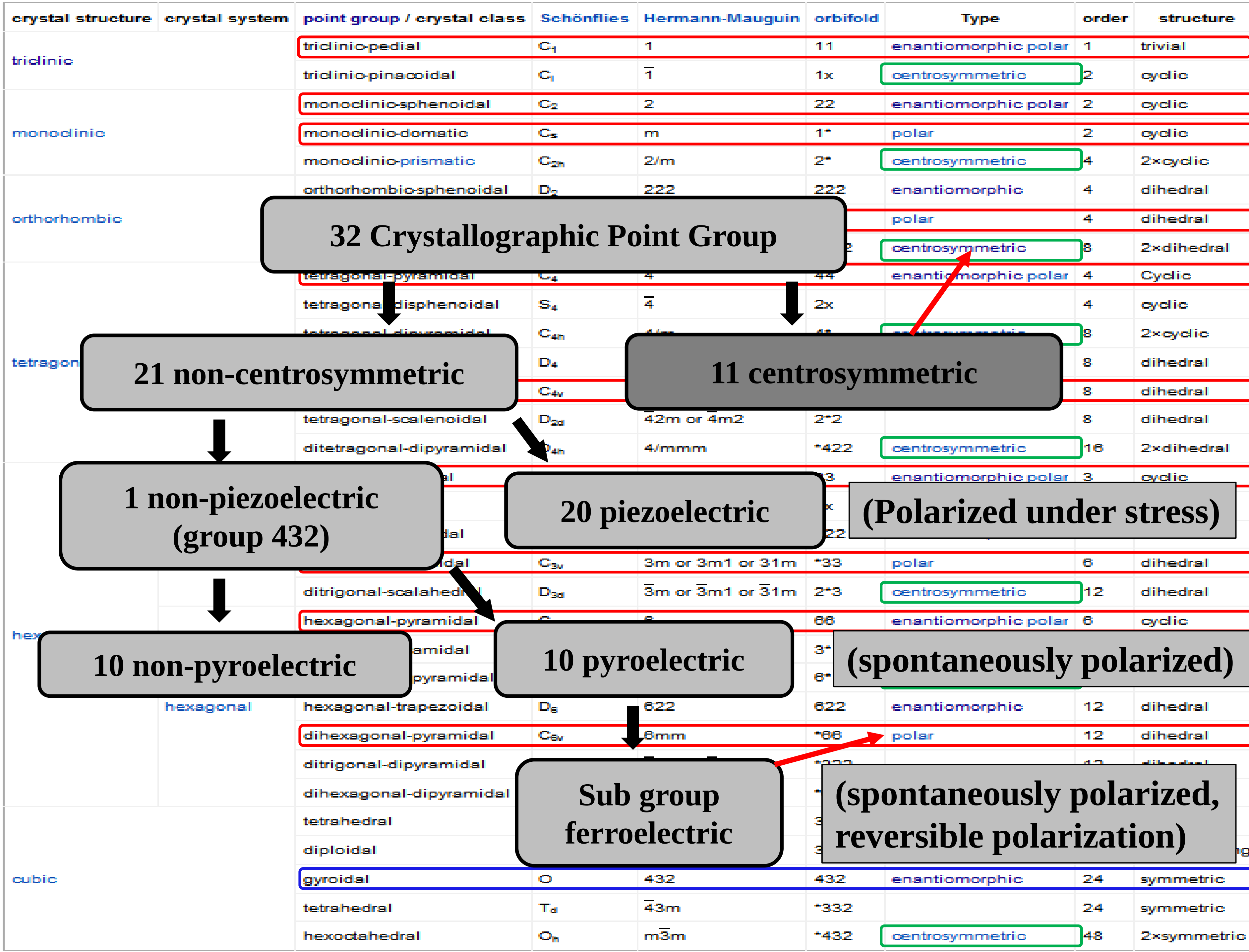
Displacement by 5-10% Ti-O bond length

Random dipole orientations- Paraelectric

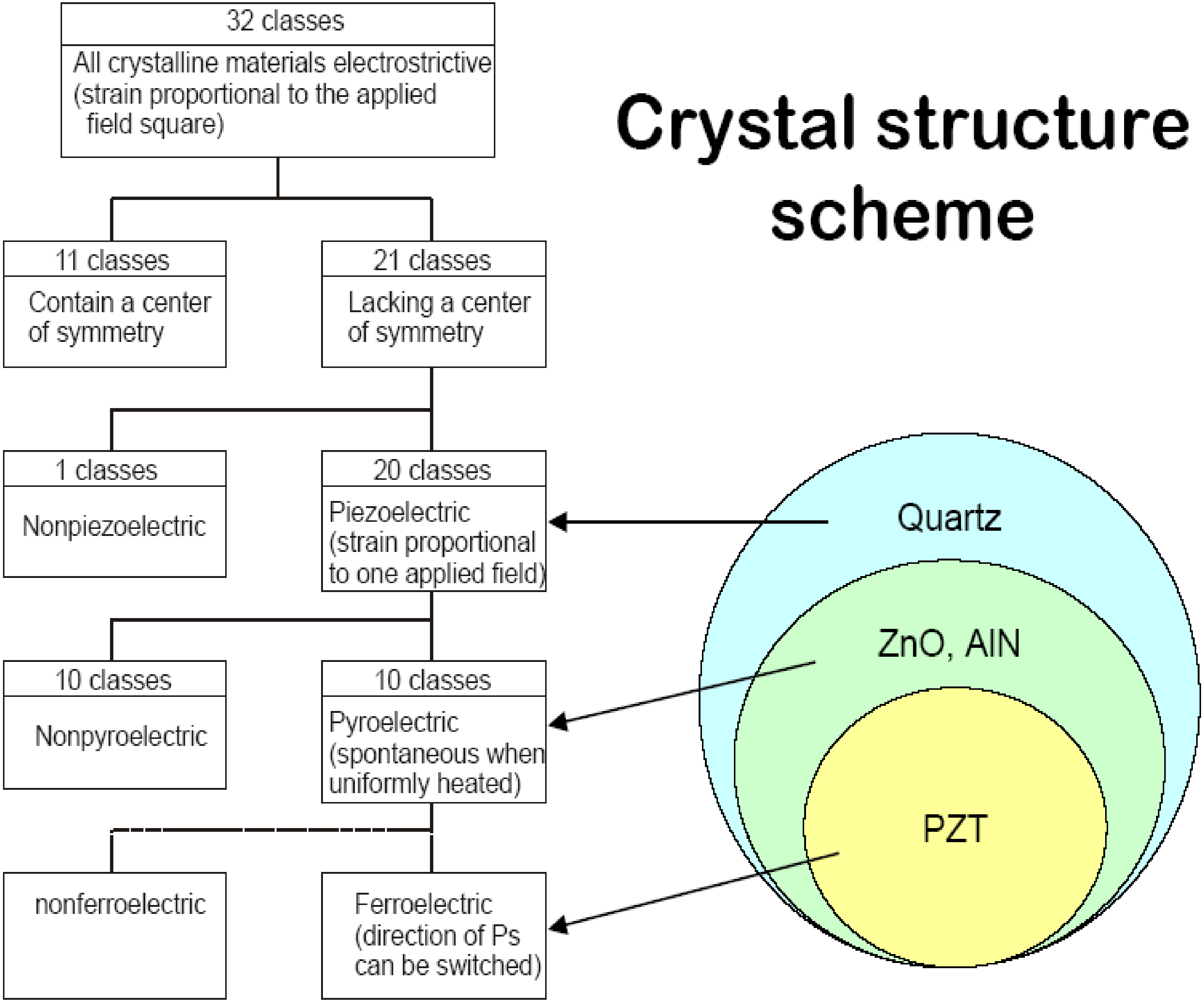
Aligned dipole orientations - Ferroelectric

Deformation in Pervoskite

- Deformation will lead to Structural transformation
- Mainly BX_6 Octahedra is responsible for the Structural transformation
- Size variation in cation is also responsible for the structural variation
- Adaptability of various size ions is key for categories pervoskite as smart materials
- Pressure also have effect on structural transformation


32 Crystallographic Point Group
21 non-centrosymmetric
11 centrosymmetric
1 non-piezoelectric (group 432)
20 piezoelectric
(Polarized under stress)
10 non-pyroelectric
10 pyroelectric
(spontaneously polarized)
Sub group ferroelectric
(spontaneously polarized, reversible polarization)
crystal structure
crystal system
point group / crystal class
Schönflies
Hermann-Mauguin
orbifold
Type
order
structure
triclinic
triclinic-pedial C1 1 11 enantiomorphic polar 1 trivial
triclinic-pinacoidal Ci 1̄ 1x centrosymmetric 2 cyclic
monoclinic
monoclinic-sphenoidal C2 2 22 enantiomorphic polar 2 cyclic
monoclinic-domatic Cs m 1* polar 2 cyclic
monoclinic-prismatic C2h 2/m 2* centrosymmetric 4 2×cyclic
orthorhombic
orthorhombic-sphenoidal D2 222 222 enantiomorphic 4 dihedral
tetragonal-disphenoidal S4 4̄ 2x 4 cyclic
tetragonal-scalenoidal D2d 4̄2m or 4̄m2 2*2 8 dihedral
ditetragonal-dipyramidal D4h 4/mmm *422 centrosymmetric 16 2×dihedral
C3v 3m or 3m1 or 31m *33 polar 6 dihedral
ditrigonal-scalahedral D3d 3̄m or 3̄m1 or 3̄1m 2*3 centrosymmetric 12 dihedral
hexagonal-pyramidal 66 enantiomorphic polar 6 cyclic
hexagonal
hexagonal-trapezoidal D6 622 622 enantiomorphic 12 dihedral
dihexagonal-pyramidal C6v 6mm *66 polar 12 dihedral
ditrigonal-dipyramidal
dihexagonal-dipyramidal
tetrahedral
diploidal
cubic
gyroidal O 432 432 enantiomorphic 24 symmetric
tetrahedral Td 4̄3m *332 24 symmetric
hexoctahedral Oh m3̄m *432 centrosymmetric 48 2×symmetric

Crystal structure scheme



Piezoelectric materials

- Single crystals

  - quartz
  - $LiTaO_3$
  - $GaPO_4$
  - $La_3Ga_5SiO_{14}$ (Langasite)

  d = 2-20 pC/N

- Used mostly as resonant and high frequency devices and mechanical sensors (pressure, force and acceleration sensors)

- Ceramics

  - PZT
  - modified $PbTiO_3$
  - $Bi_4Ti_3O_{12}$ based materials
  - PMN-PT (relaxor composition)
  - $PbTiO_3$-Pb(Zn,Nb)O_3

  d= 20-2000 pC/N

- Used as sensors, acutators, resonant devices and transducers;
- Relatively easy and inexpensive to fabricate;
- Easy to modify and to achieve a wide range of properties

Piezoelectric materials

- Polymers

- PVDF(polyvinylidene fluoride)

d = 30 pC/N

- Limited use where flexibility and low acoustic impedence are important (headphones, speakers, hydrophones, vibration and pressure sensors)

- Composites

- polymer-ceramic (PZT-polymer)

- metal-ceramic (PZT-metal)

- polymer-ceramics

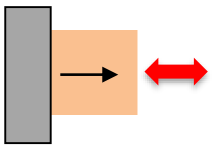
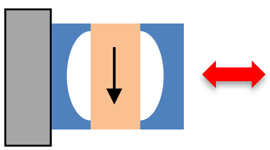
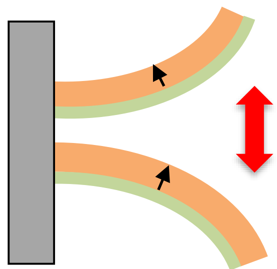
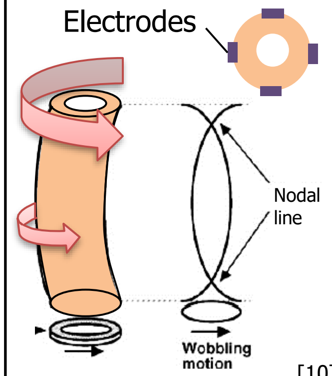
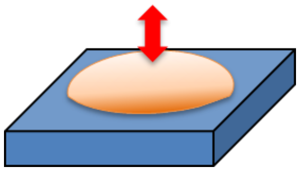
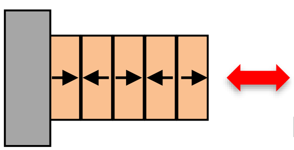
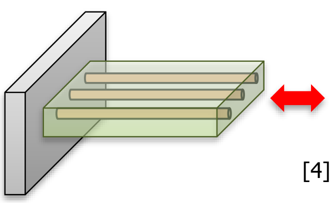
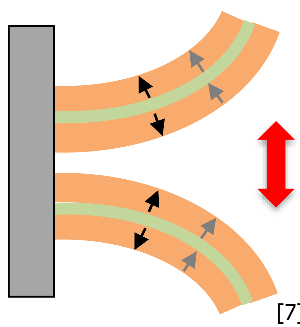
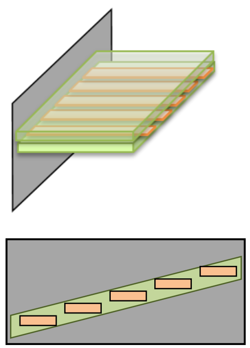
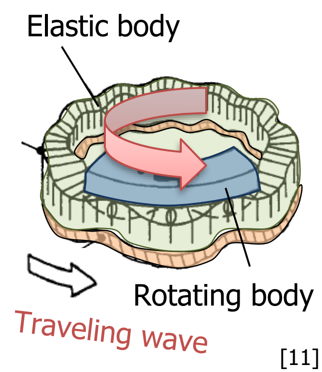
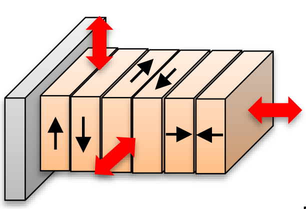
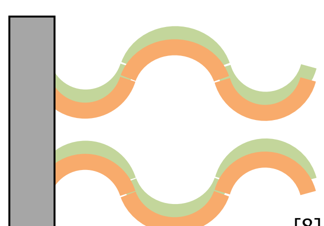
Special applications where a good acoustical impedence matching is essential (hydrophones, medical ultrasonic imaging)

- metal-ceramics

For very large displacement, but low force devices

Outline – PZT actuator

- → Poling direction
- PZT material
- Soft polymer
- Rigid structure

		Linear	Bending	Twisting	Rotation	Diaphragm
Bi-direction	Single material	 [1]  [2]	 [6]		 [10]	 [12]
	Multiple materials	 [3]  [4]	 [7]	 Front view [9]	 [11]	
Multi-direction		 [5]	 [8]			

Outline – PZT actuator

[1] K. Uchino and S. Takahashi, "Multilayer ceramic actuators," Current Opinion in Solid State and Materials Science, vol. 1, pp. 698-705, 1996.

[2] R. Newnham, A. Dogan, Q. Xu, K. Onitsuka, J. Tressler, and S. Yoshikawa, "Flextensional “moonie” actuators," in Ultrasonics Symposium, 1993. Proceedings., IEEE 1993, 1993, pp. 509-513.

[3] Q.-M. Wang and L. E. Cross, "Performance analysis of piezoelectric cantilever bending actuators," Ferroelectrics, vol. 215, pp. 187-213, 1998..

[4] G. A. Rossetti Jr, A. Pizzochero, and A. A. Bent, "Recent advances in active fiber composites technology," in Applications of Ferroelectrics, 2000. ISAF 2000. Proceedings of the 2000 12th IEEE International Symposium on, 2000, pp. 753-756.

[5] K. Uchino and S. Takahashi, "Multilayer ceramic actuators," Current Opinion in Solid State and Materials Science, vol. 1, pp. 698-705, 1996.

[6] M. Y. Yasin, N. Ahmad, and M. N. Alam, "Finite element analysis of actively controlled smart plate with patched actuators and sensors," Latin American Journal of Solids and Structures, vol. 7, pp. 227-247, 2010.

[7] Q.-M. Wang and L. E. Cross, "Performance analysis of piezoelectric cantilever bending actuators," Ferroelectrics, vol. 215, pp. 187-213, 1998.

[8] I. Chopra, "Review of state of art of smart structures and integrated systems," AIAA journal, vol. 40, pp. 2145-2187, 2002.

[9] D. Cadogan, T. Smith, F. Uhelsky, and M. MacKusick, "Morphing inflatable wing development for compact package unmanned aerial vehicles," AIAA Paper, vol. 1807, p. 2004, 2004.

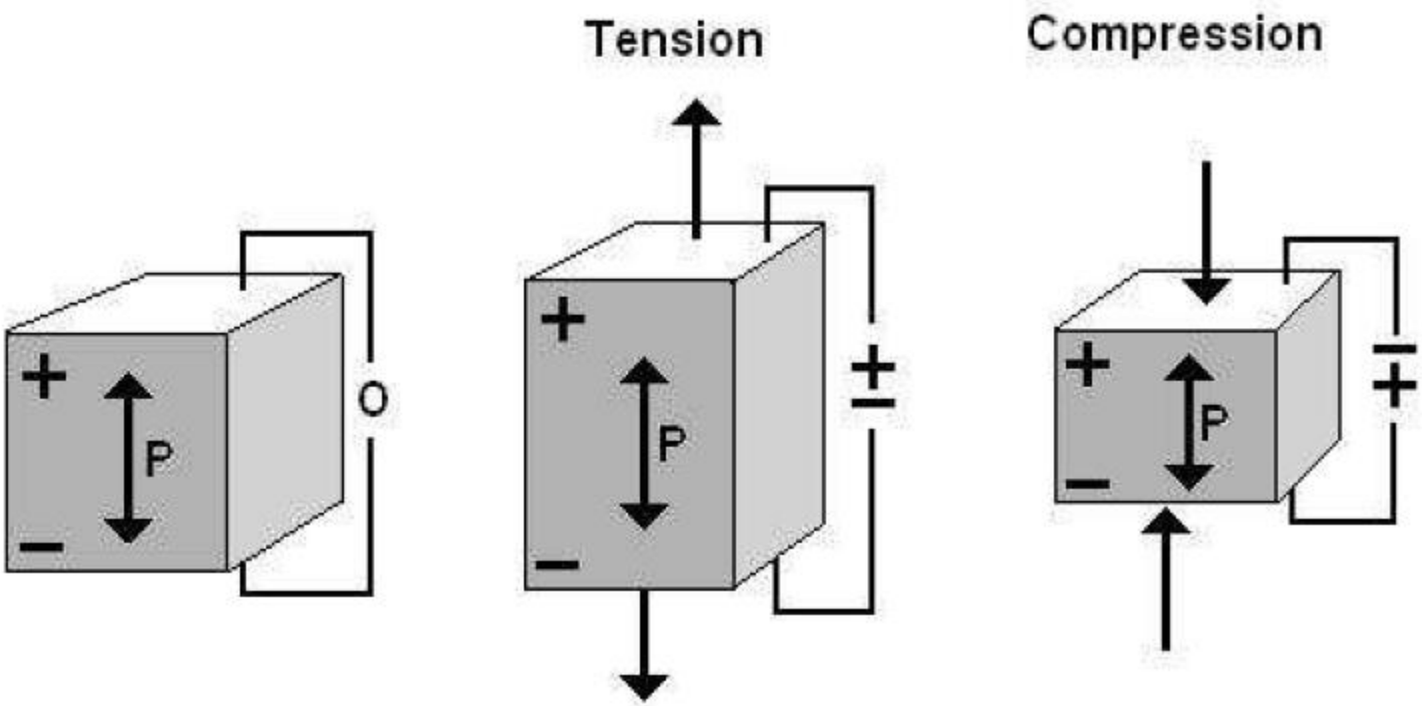
[10] I. Chopra, "Review of state of art of smart structures and integrated systems," AIAA journal, vol. 40, pp. 2145-2187, 2002.

[11] T. King, M. Preston, B. Murphy, and D. Cannell, "Piezoelectric ceramic actuators: A review of machinery applications," Precision Engineering, vol. 12, pp. 131-136, 1990.

[12] P. Muralt, A. Kholkin, M. Kohli, and T. Maeder, "Piezoelectric actuation of PZT thin-film diaphragms at static and resonant conditions," Sensors and Actuators A: Physical, vol. 53, pp. 398-404, 1996.

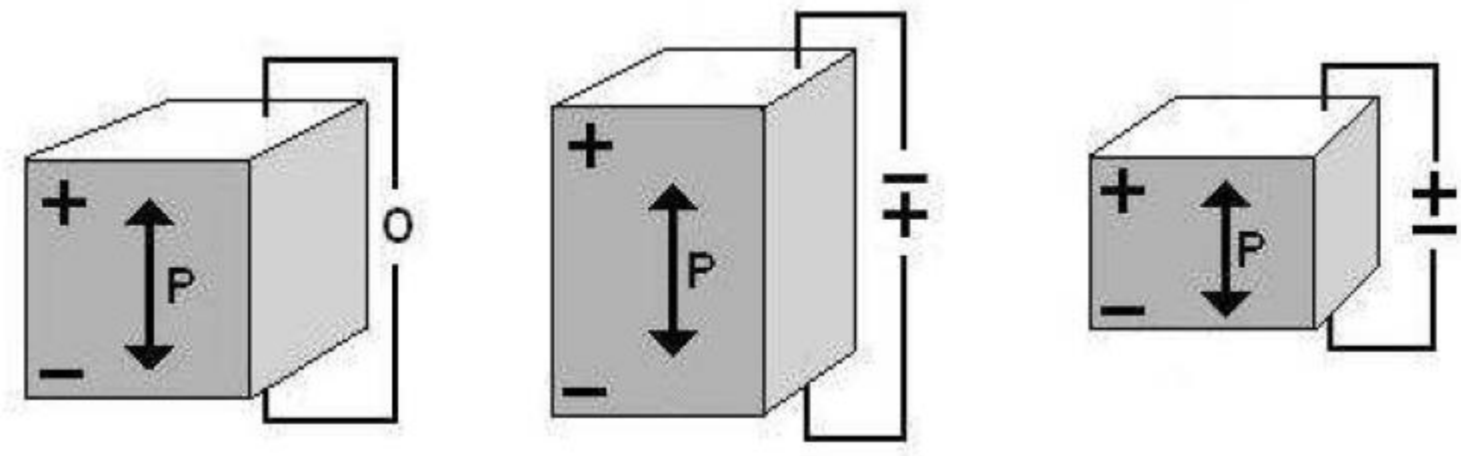
Piezoelectric effect

- **Direct piezo effect**
  - A mechanical stress on a material produces an electrical polarization



Piezoelectric effect

- **Converse (inverse) piezo effect**
  - An applied electric field in a material produces dimensional changes and stresses within a material



Piezoelectric actuator

compliance; piezoelectric strain coefficients

$$S = s^E T + d E$$

strain; stress; electric field

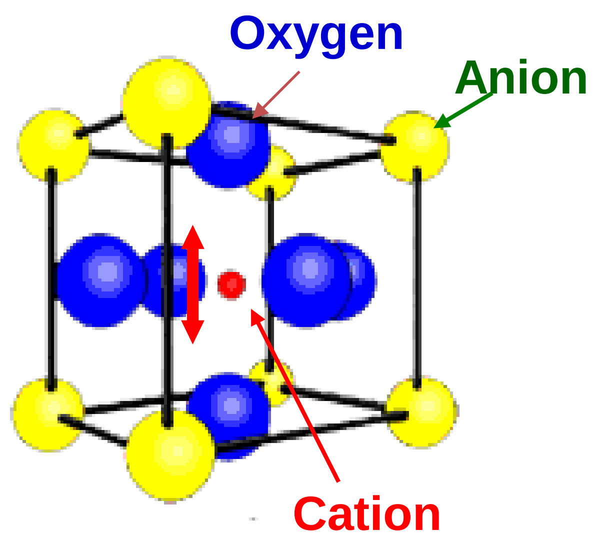
piezoelectric strain coefficients (transpose); dielectric permittivity

$$D = d^{Tr} T + \varepsilon^T E$$

electric displacement; stress; electric field

Mechanical Energy ⟷ Electronic Signals

Piezoelectric effect



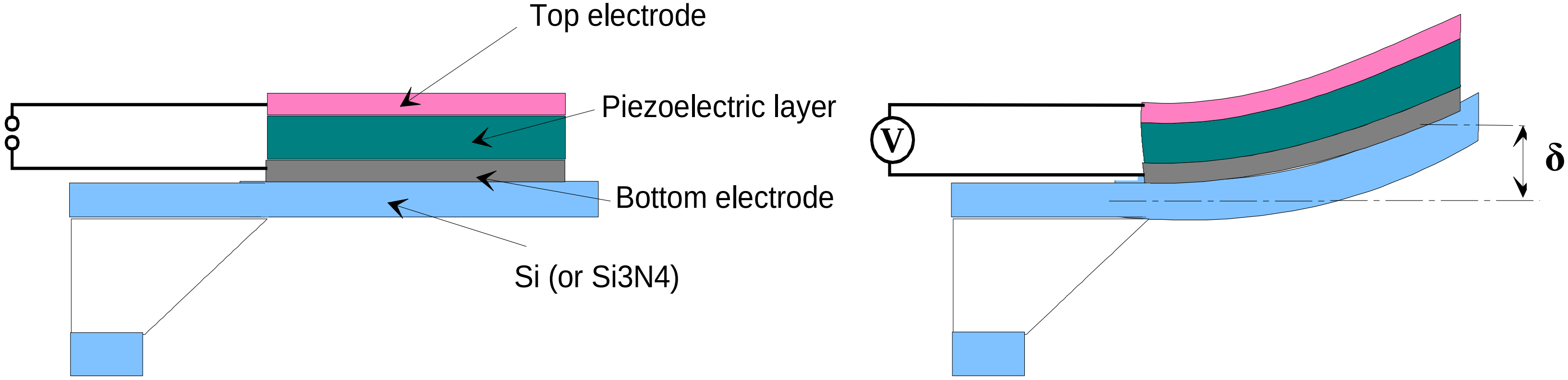
Piezoelectric actuator

Piezoelectric ?

Electric Field ⇒ Displacement (d_{31} : m/V)

Stress ⇒ Charge (d_{31} : C/N)

δ (displacement) ∝ d_{31}* V



Free standing **After applying voltage**

Mechanical effect of Piezoelectric

Typical Materials for Piezoelectric MEMS

- PZT
  - High piezoelectric (pyroelectric) constant, Low leakage current
  - Process issues (deposition, etching)
  - Operational frequency : < ~ 700 MHz
- ZnO
  - Low piezoelectric constant, High leakage current
  - Easy Process (deposition, etching)
  - Operational frequency : High (PCS, IMT2000) (> *GHz)*
- AlN
  - Low piezoelectric constant, Low leakage current, Low dielectric loss
  - Process : High vacuum
  - Operational frequency : High (PCS, IMT2000) (> *GHz)*
- PVDF
  - Low piezoelectric constant, Low dielectric constant
  - Easy to fabricate large area → ex) Speaker, Sensor

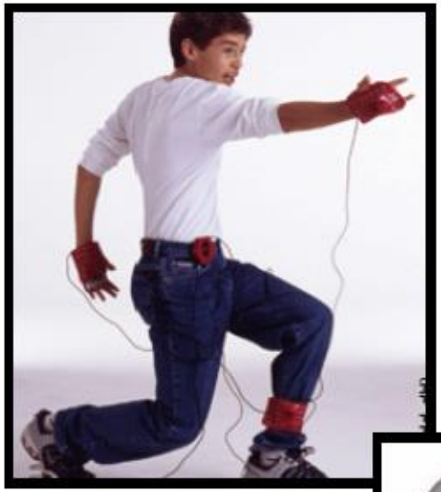
Piezoelectric materials

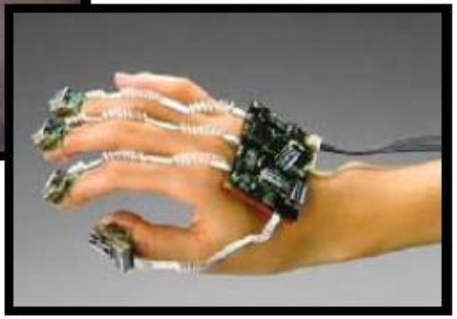
	Stiffness (10^{10} N / m²)	Strain Coefficient (10^{-12} C / N)	Relative Permittivity	Coupling Coefficient K^2 (%)	Velocity (m / s)	Density (kg / m_3)
Aluminum Nitride (AlN)	33.0	5.6 (d_{33})	8.6	6.0	11,300	3.26
Barium Titanate ($BaTiO_3$) *	11.0 - 27.5	82-145 (d_{33})	625-1350	39 – 46	4460	5.85
Lithium Niobate ($LiNbO_3$)	24.5	19.2 (d_{33})	44	17.2 †	4379 †	4.64
Lithium Tantalate ($LiTaO_3$)	23.3	8.0 (d_{33})	41	4.7 †	4112 †	7.64
P(VDF–TrFE)	0.3	-12.0 (d_{31})	13	0.18	2400	1.88
Quartz (SiO_2)	10.7	2.3 (d_{11})	4.5	0.11 †	3948 †	2.65
PZT (PbZrTiO3)*	4.8 – 13.5	240-550 (d_{33})	1100- 3200	66 - 73	4600	7.55
Zinc Oxide (ZnO)	21.0	10-12 (d_{33})	8.5	7.5	6,080	5.60

$$k = \sqrt{\frac{\text{mechanical energy stored}}{\text{electrical energy applied}}}$$

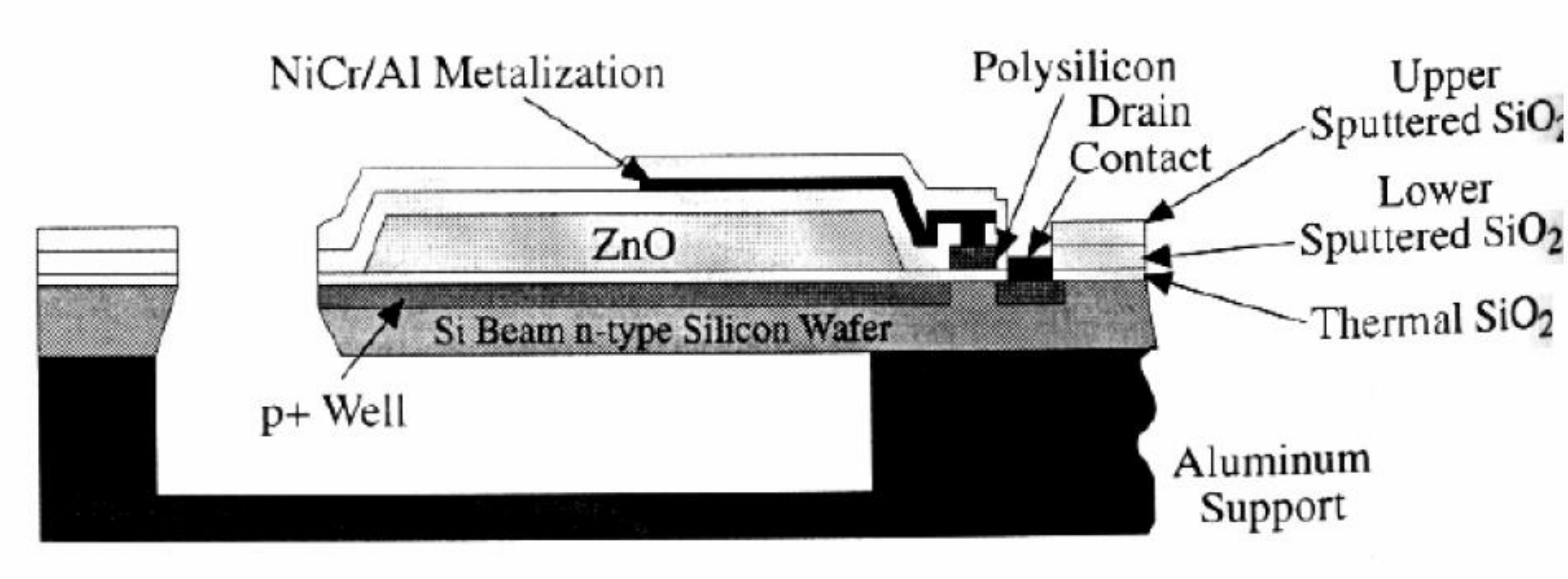
Inertial sensors for Car

Inertial sensors for Motion sensing



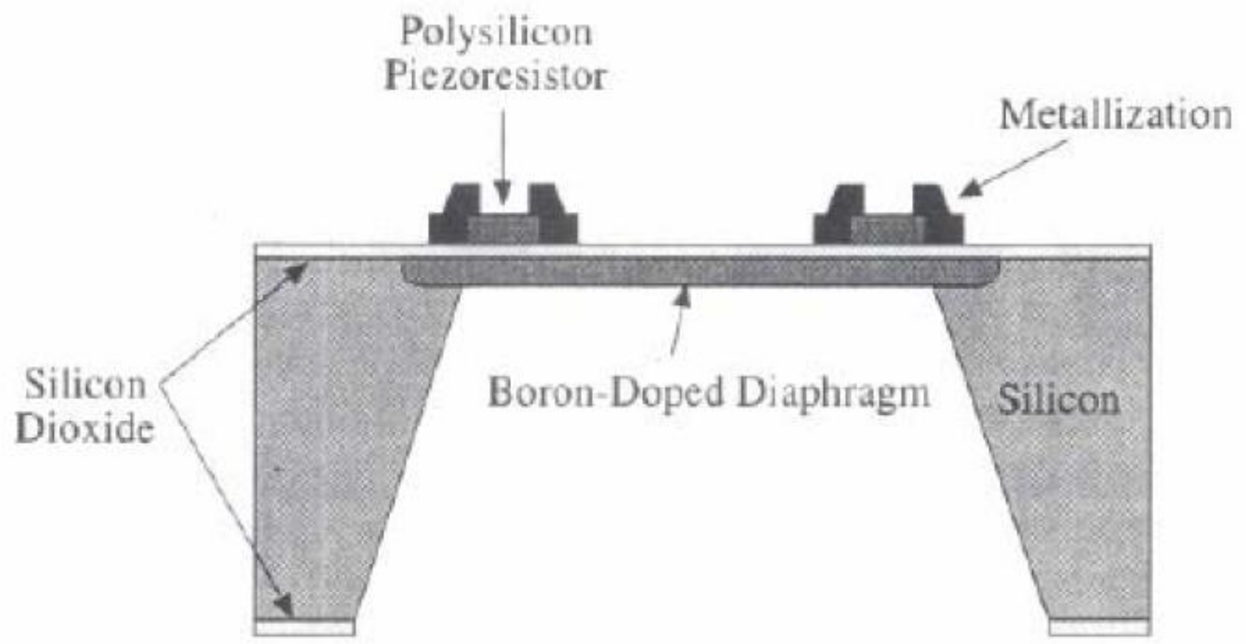


Accelerometer with Piezoelectric sensing



Side view piezoelectric accelerometer

Piezoresistive Microphones



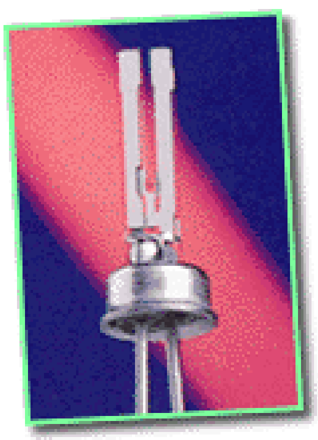
- Compansation with Wheatstone bridge configuration
- Low sensitivity, but piezoresistive transduction has relatively low output impedance

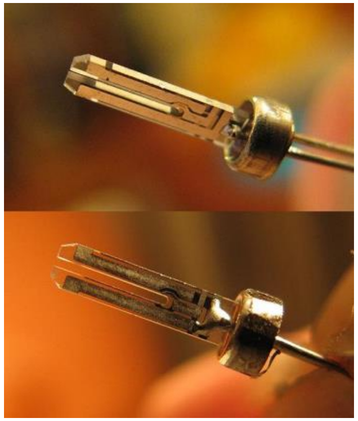
Brief history of piezoelectricity

- **Greek ancient:**
  Greek term "piezin" means "to press"
- **1880 :**
  The Curie brothers found that Rochelle salt crystals produce electricity when pressure is applied in certain crystallographic directions (piezoelectric effect)
- **1881 :**
  Lippman predicted that an applied electric potential would produce a mechanical deformation (reverse piezoelectric effect)
- **1881 :**
  Lord Rayleigh published "On waves propagating along the plane of an elastic solid"
- **1917 :**
  Langevin – quartz crystals used as transducers / receivers of ultrasound in water (SONAR)
- **1919 :**
  First demonstrations of loud speakers, microphones…
- **1921:**
  Cady : quartz resonator for stabilizing electronic oscillations
- **1946 :**
  Cady: "Piezoelectricity"
  →Electric polarization produced by mechanical strain in crystals belonging to certain classes, the polarization being proportional to the strain and changing sign with it"
- **1959 :**
  Sauerbrey – the frequency shift of a quartz crystal resonator is directly proportional to the added mass
- **1965 :**
  White, Voltmer – "Direct piezoelectric coupling to surface acoustic waves"
- **Today:**
  Piezoelectric devices in watches, TVs, radios, radar, communication satellites, mobile phones, car sensors, …biosensors !!

Quartz resonator

- **Quartz resonator for timing standard**
  - The frequency of the quartz oscillator is determined by the cut and shape of the quartz crystal.
  - miniature encapsulated tuning forks which vibrate 32,768 times per second



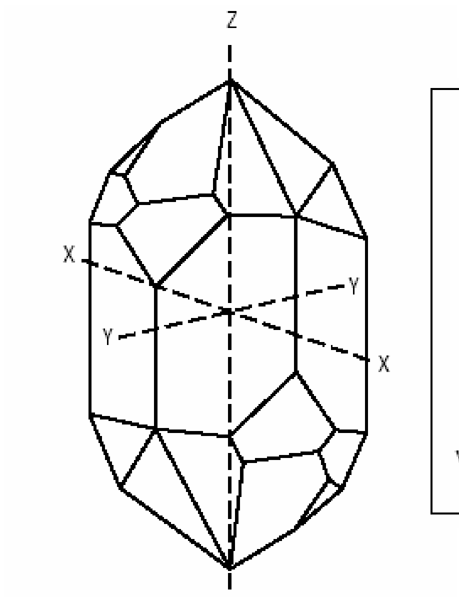


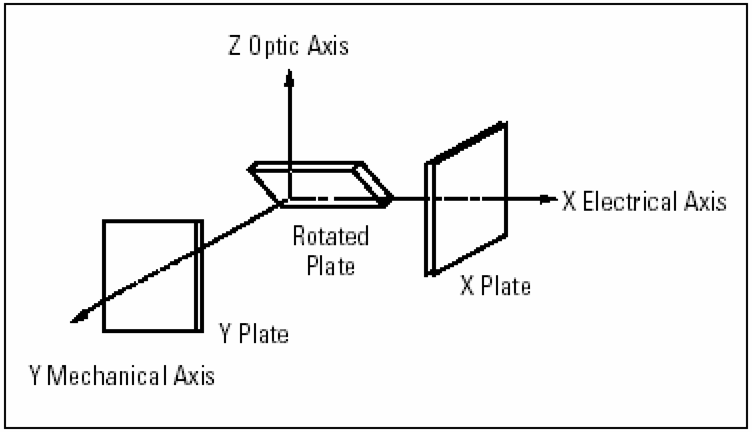
Tuning fork quartz resonator

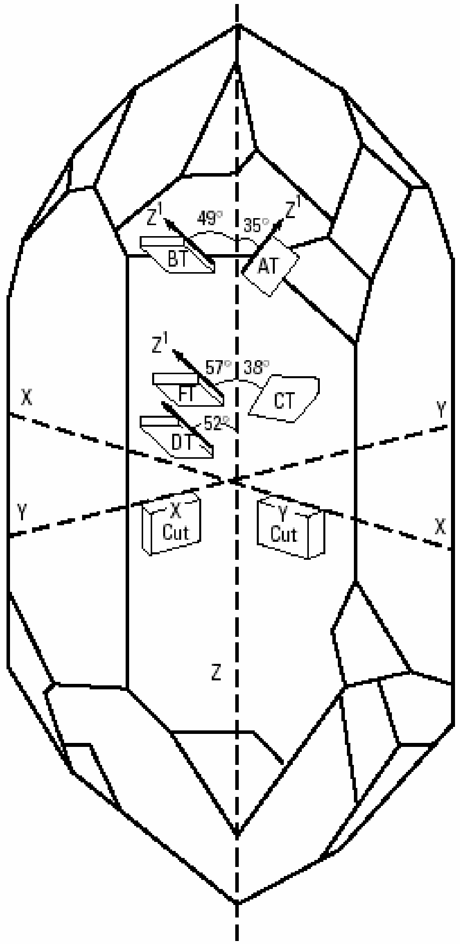
Walter Cady (1874-1973)

Inventor of quartz resonator

Piezoelectricity: quartz crystal structure





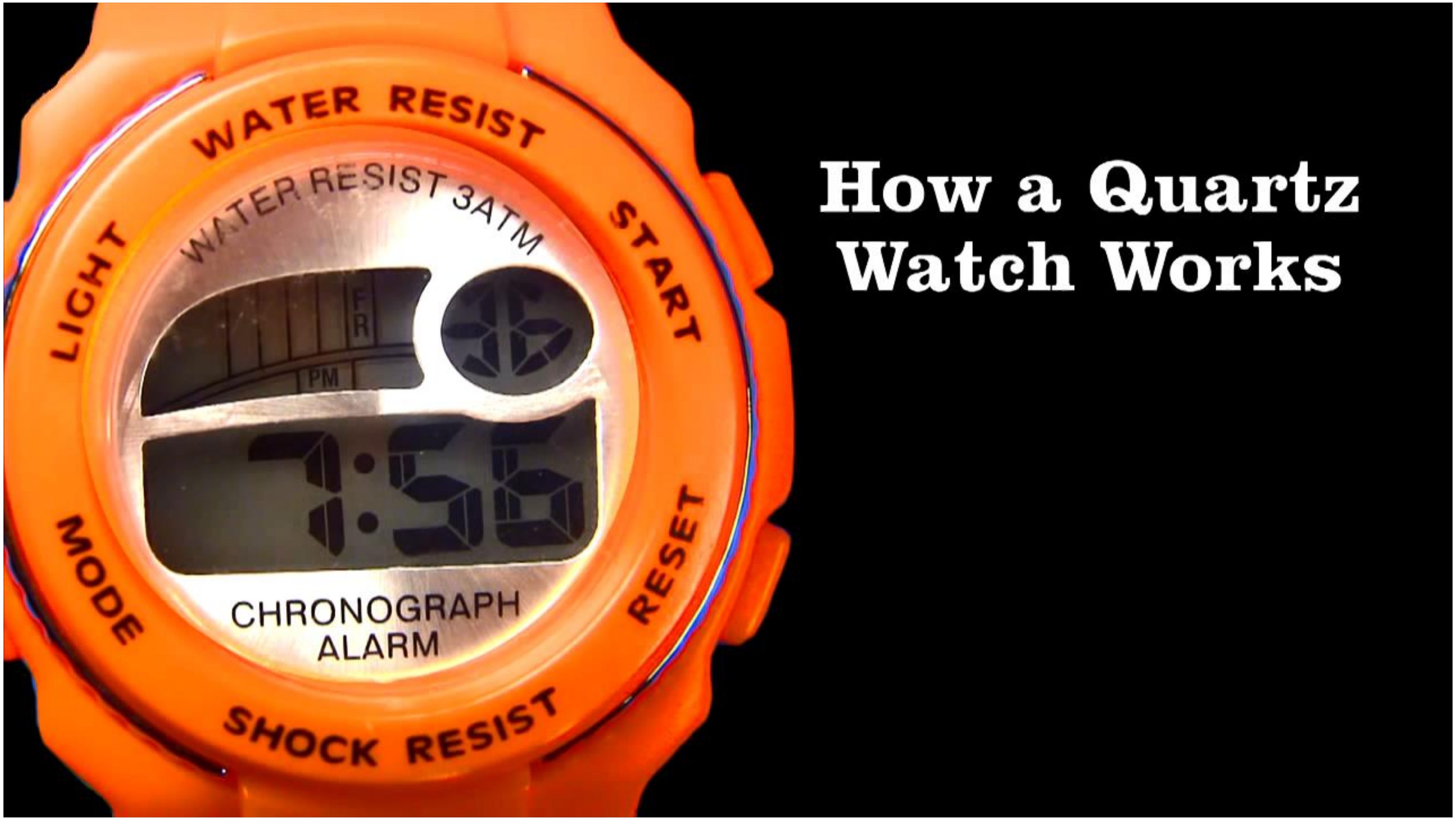


- X plate crystals: large voltage generated when compressed and decrease in frequency with T increases
- Y plate crystals: large voltage generated by shear stress and increase in frequency with T increases

- X cuts exhibits an extensional vibration mode with AC voltage
- AT cuts (35 degrees off the Y axis) vibrates in the thickness shear mode

Quartz resonator

- **Quartz watch**



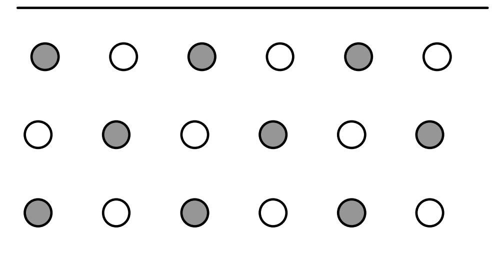
https://www.youtube.com/watch?v=1pM6uD8nePo

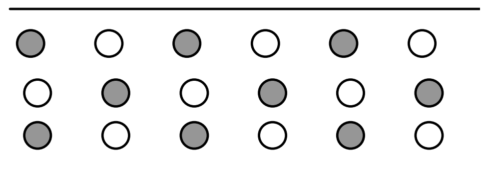
Piezoelectric materials

- **What material can show piezoelectric effect??**
  - Symmetry requirements:
    - Noncentrosymmetric materials can be piezoelectric.
  - Polycrystalline materials with randomly oriented grains must be ferroelectric to exhibit piezoelectric effect
  - Ferroeletrcicity : direction of the spontaneous polarization within grains may be re-oriented by external electric field
  - Texture materials behave differently.

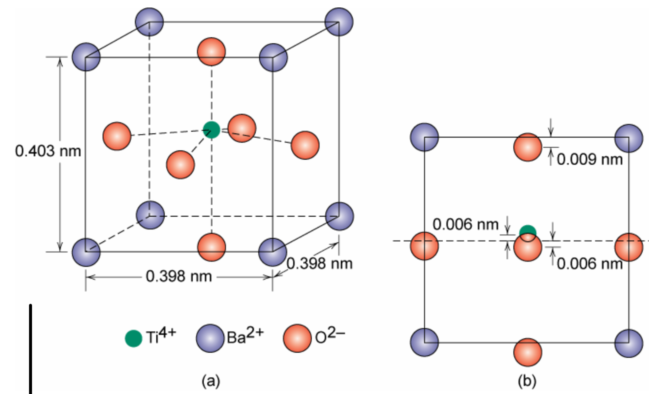
Asymmetric Crystal Produces Piezoelectric Effect

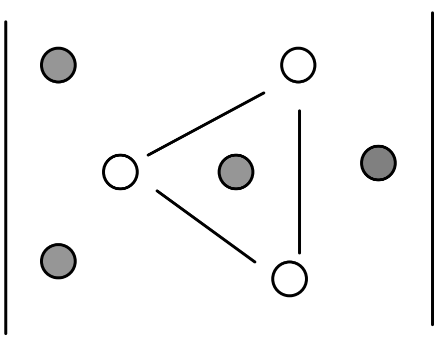
- **Symmetric (centrosymmetric) lattice structure does not produce piezoelectricity when deformed.**

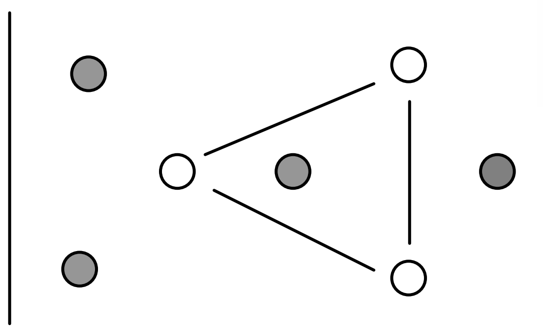




- **Asymmetic lattice structures do!**







Constitutive equations of piezoelectric materials

$$\{D\} = [d]\{T\} + \left[\varepsilon^T\right]\{E\}$$
$$\{S\} = \left[s^E\right]\{T\} + [d^t]\{E\}$$

- D is the electric displacement, ε is permittivity and E is electric field strength
- S is strain, s is compliance and T is stress
- [d] is the matrix for the direct piezoelectric effect and [d^t] is the matrix for the converse piezoelectric effect. The superscript t stands for transposition of a matrix.

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{21}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 \\ s_{31}^E & s_{32}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E = 2\left(s_{11}^E - s_{12}^E\right) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Unit of piezoelectric coefficient

- **Unit of d_{33} is the unit of electric displacement over the unit of the stress. Thus**

$$[d_{33}] = \frac{[D]}{[T]} = \frac{[\varepsilon][E]}{[T]} = \frac{\frac{F}{m}\frac{V}{m}}{\frac{N}{m^2}} = \frac{Columb}{N}$$

Reverse piezoelectricity

- **Strain as a function of applied field is governed by**

$$\begin{pmatrix} \varepsilon 1 \\ \varepsilon 2 \\ \varepsilon 3 \\ \varepsilon 4 \\ \varepsilon 5 \\ \varepsilon 6 \end{pmatrix} = \begin{pmatrix} 0 & 0 & d31 \\ 0 & 0 & d31 \\ 0 & 0 & d33 \\ 0 & d15 & 0 \\ d15 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} E1 \\ E2 \\ E3 \end{pmatrix}$$

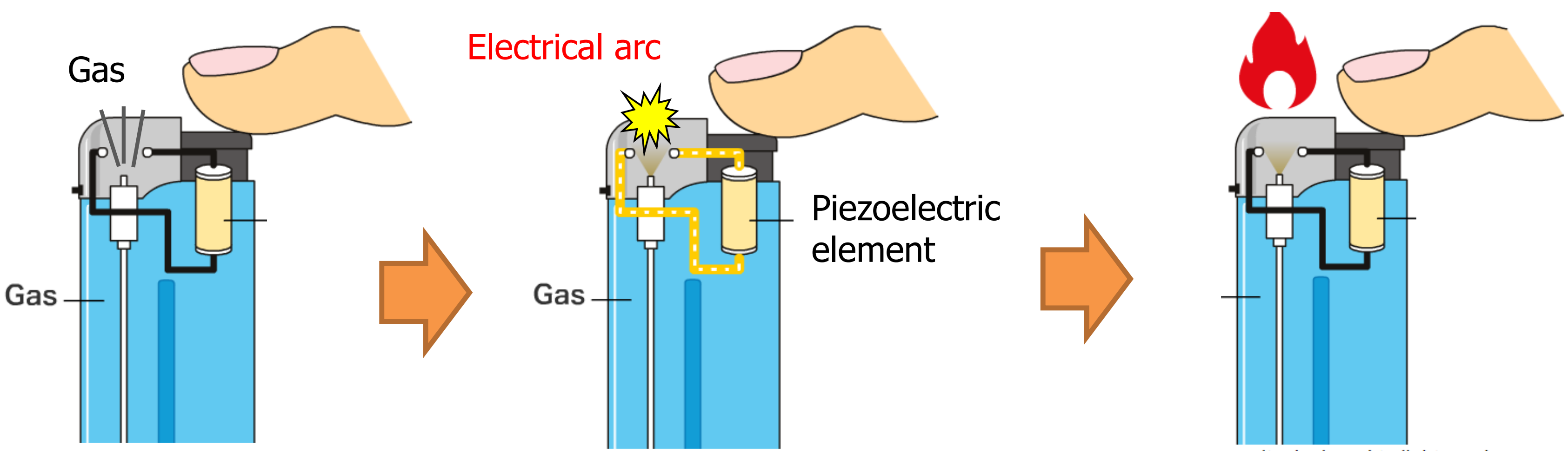
- **Verify the unit** $[d] = \dfrac{[\varepsilon]}{[E]} = \dfrac{1}{\frac{V}{m}} = \dfrac{c}{c \cdot (\frac{V}{m})} = \dfrac{C}{N}$
  - charge multiplied by electric field is force.

PZT APPLICATIONS

Piezo Ignition

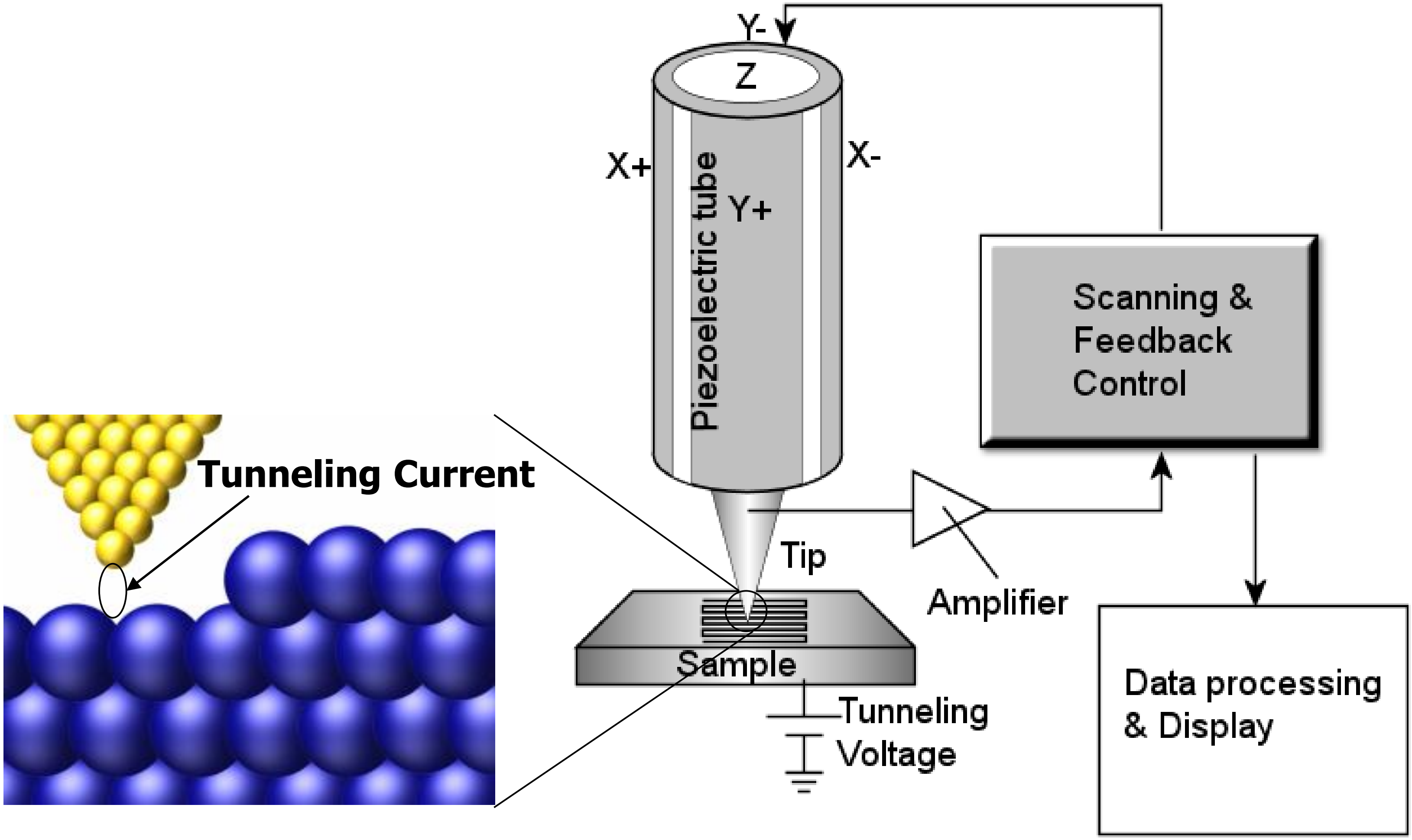
- **Convert mechanical shock into electrical signals**
  - Sudden forceful deformation in piezo material produces a high voltage and subsequent electrical discharge, which ignites the gas

Mechanical shock is converted to electricity

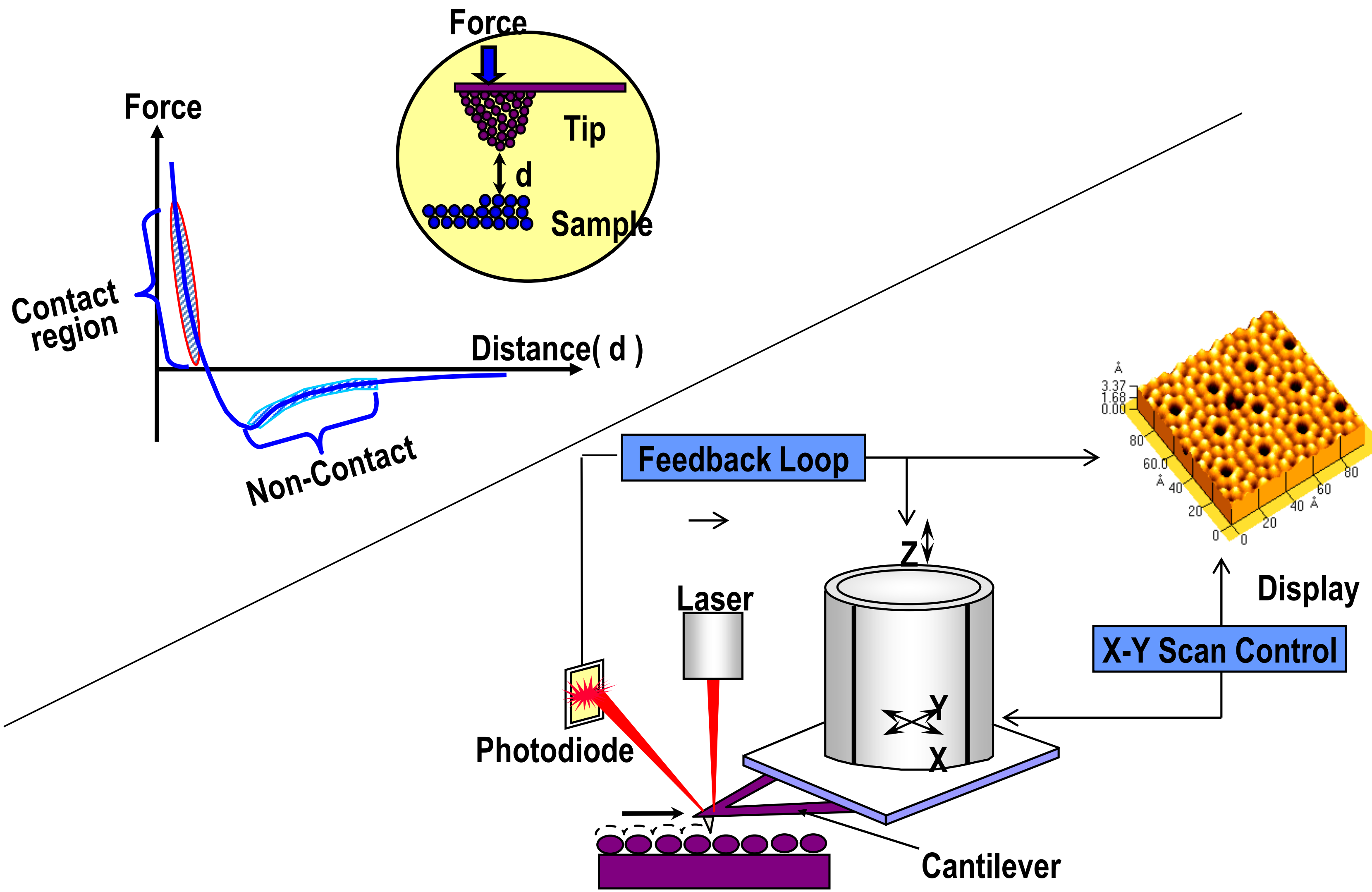


Scanner for scanning probe microscopy

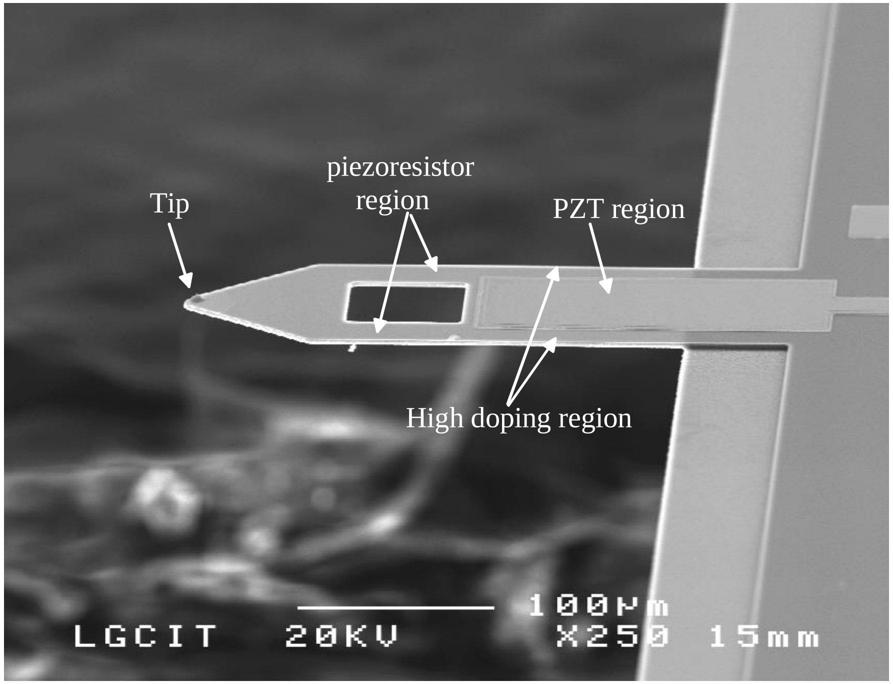
Basic configuration of tube scanner for SPM applications

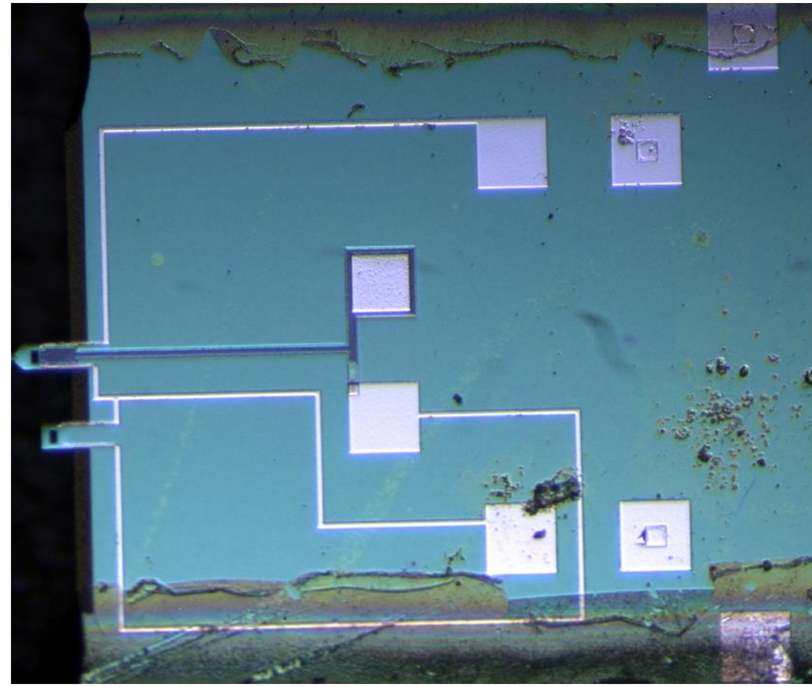


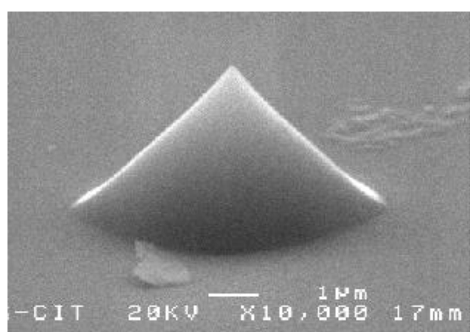
Atomic Force Microscope (AFM)



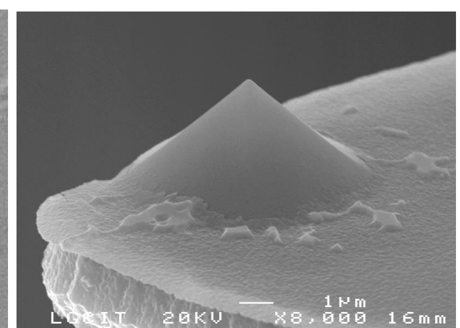
AFM Tip







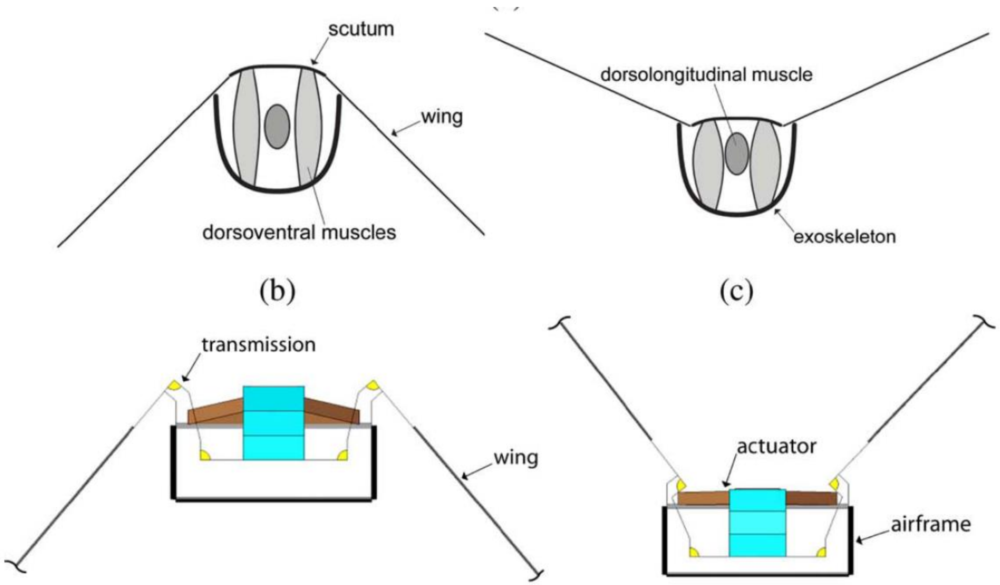
Before PZT process



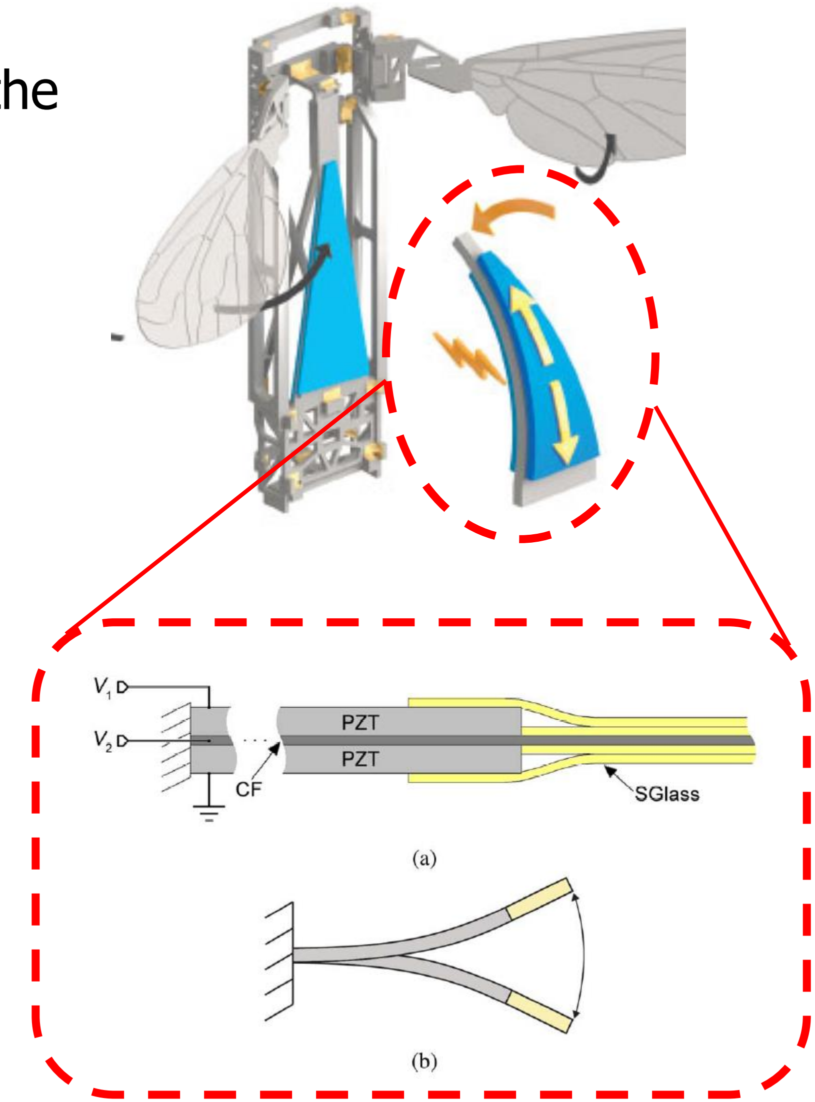
After PZT process

Flying robot

- Harvard Microrobotic fly (Robobee)
  - The wings are driven open loop at the flapping resonance to maximize the stroke amplitude.



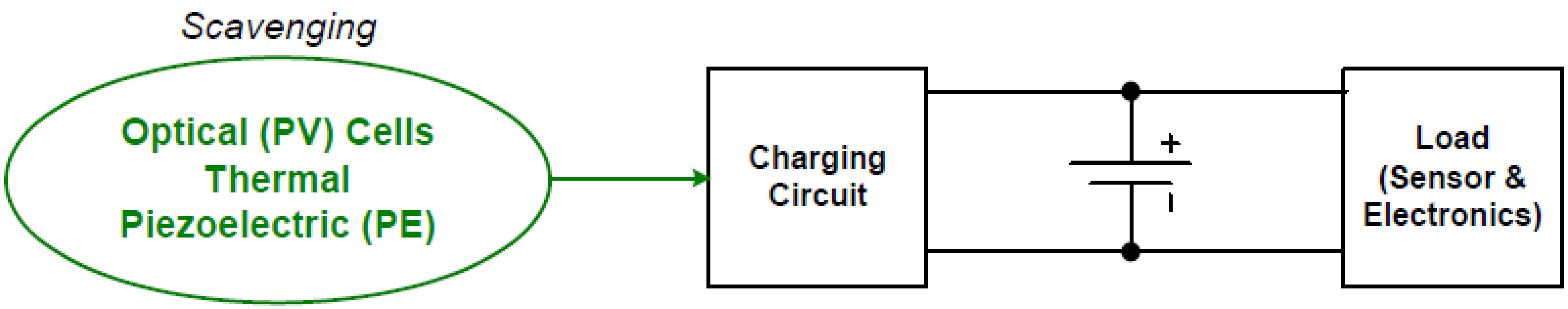
Actuating mechanism



R. J. Wood, "The first takeoff of a biologically inspired at-scale robotic insect," *Robotics, IEEE Transactions on,* vol. 24, pp. 341-347, 2008.

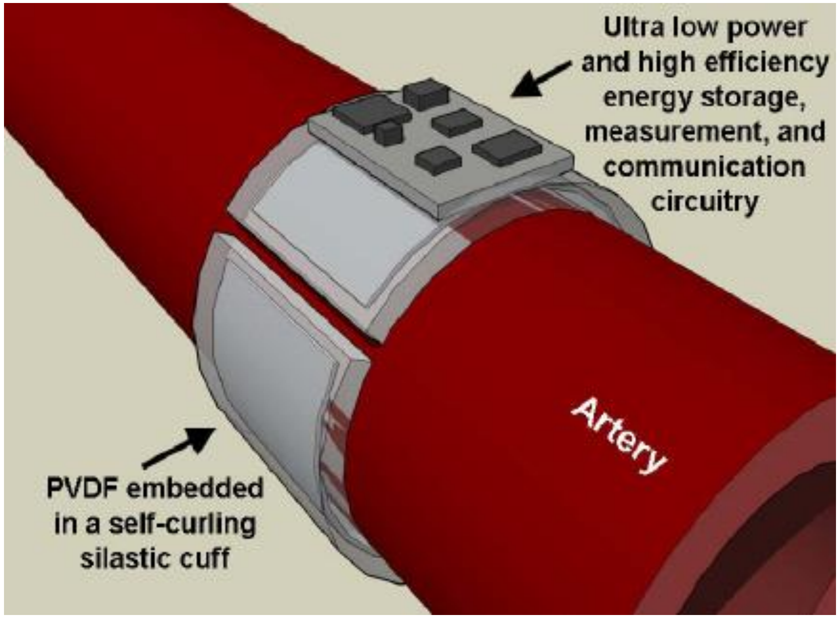
Energy Scavenging

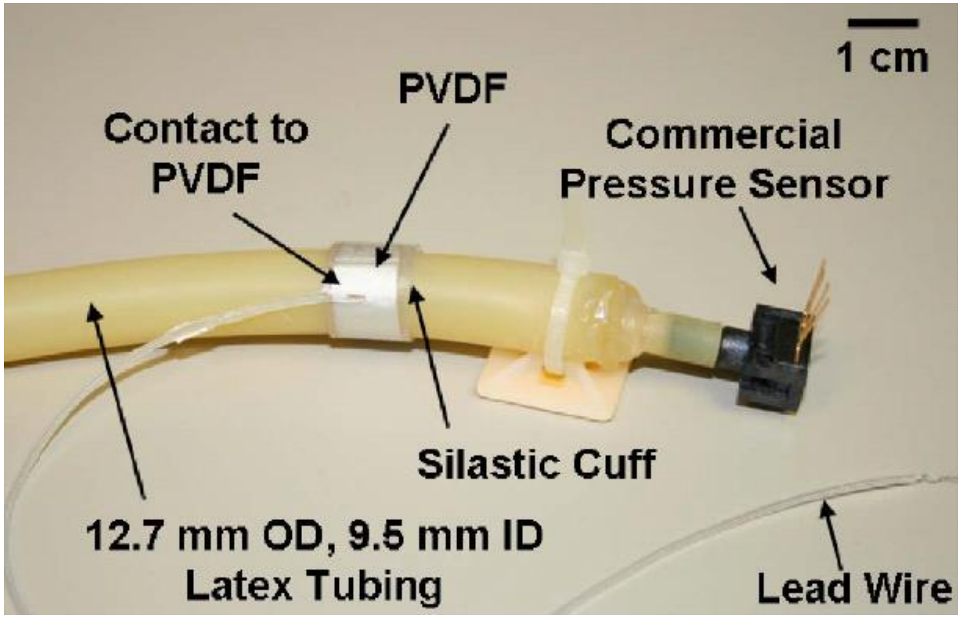
- **PE Energy Scavenging – Applications**
  - Must match energy scavenging method to appropriate application/environment
  - Thermal – heat source and sink
  - PV – Light source
  - PE – source of mechanical strain – vibration, pulsing flow, joint etc.
    - OR environments in which you can use PE as sensor AND energy source



Arterial Cuff Energy Scavenging (ACES)

1. Blood vessel causes expansion of the artery
2. Artery expansion creates strain in the arterial wall ACES
3. Strain converted into power by piezoelectric





Concept of implanted arterial cuff power source integrated into a self-powered blood pressure sensing system

Arterial Cuff Energy Scavenging (ACES)

Open-ended thick-walled cylinder model for artery wall and cuff

$$\Delta P = \frac{E\left[(r_i + t)^2 - r_i^{\,2}\right]}{2r_i^{\,3}\left[(1+\nu)+(1+\nu)\dfrac{(r_i+t)^2}{r_i^{\,2}}\right]}\Delta D$$

where

ΔP is the change in the blood vessel

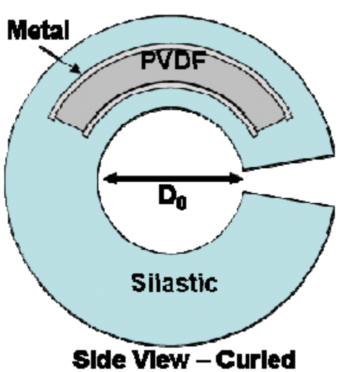
ΔD is the change in diameter

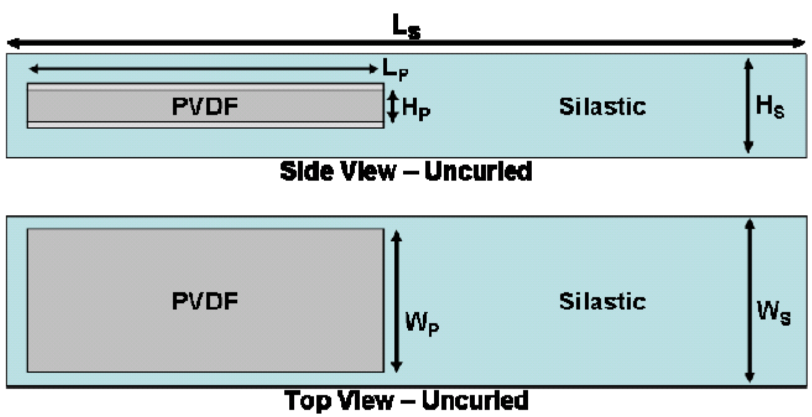
E is the elastic modulus of the material

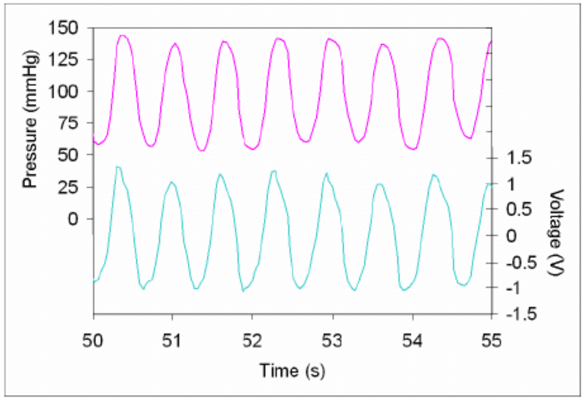
v is the Poisson' ratio

ri is the initail radius

t is the thickness of the layer

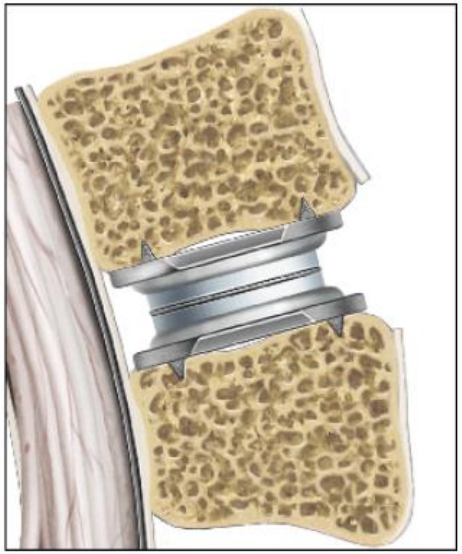






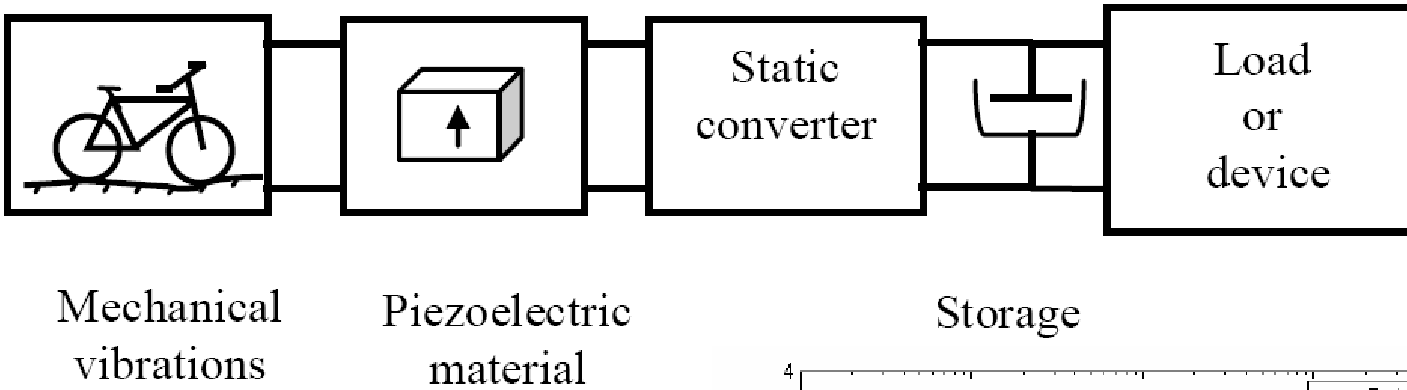
Artificial disc energy scavenging

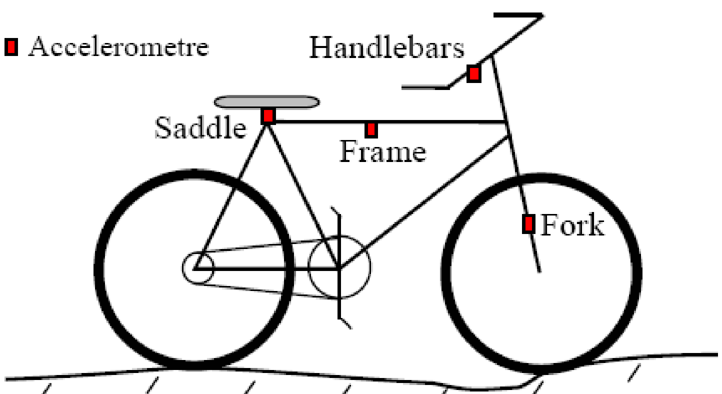
- **Backgroud**
  - Incentive for patients to avoid exposure to WBV (Whole Body Vibration), and learn what environments cause their pain
- **Idea**
  - Include PE sensor/scavenger to record data on alignment, vibration intensity and frequency
  - Doctors could examine data and compare to patient's notes on when back pain was present
- **Design**
  - Between the two metal plates that anchor to the bone is a rudder core made up of polyethylene that allows for motion

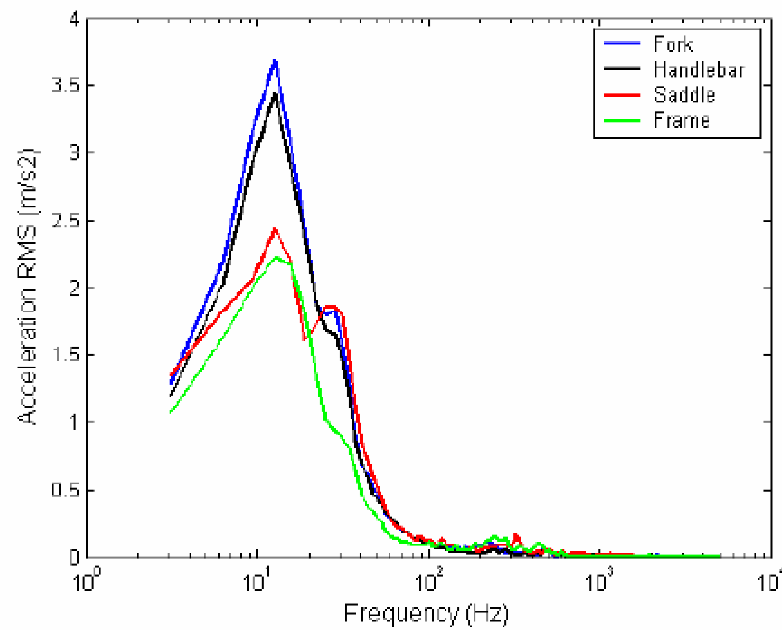


Piezoelectric generator using vibration

- **Power generation using vibration energy harvesting**

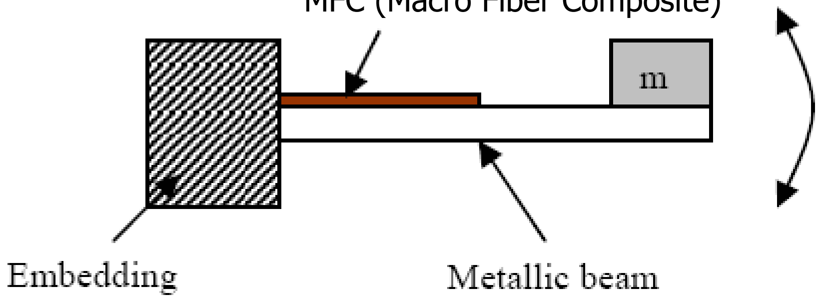




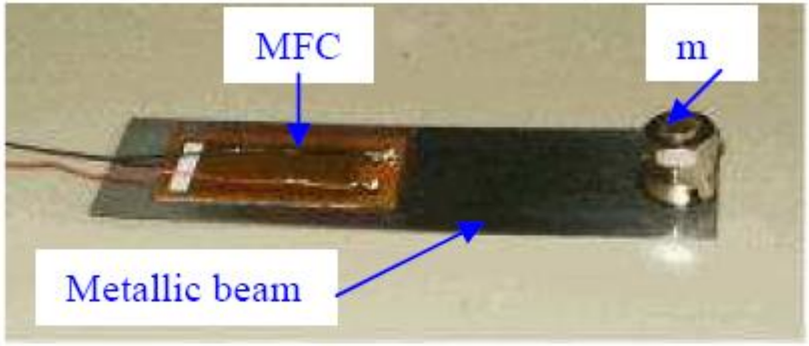


Piezoelectric generator using vibration

- **Fabrication of piezoelectric power generator**



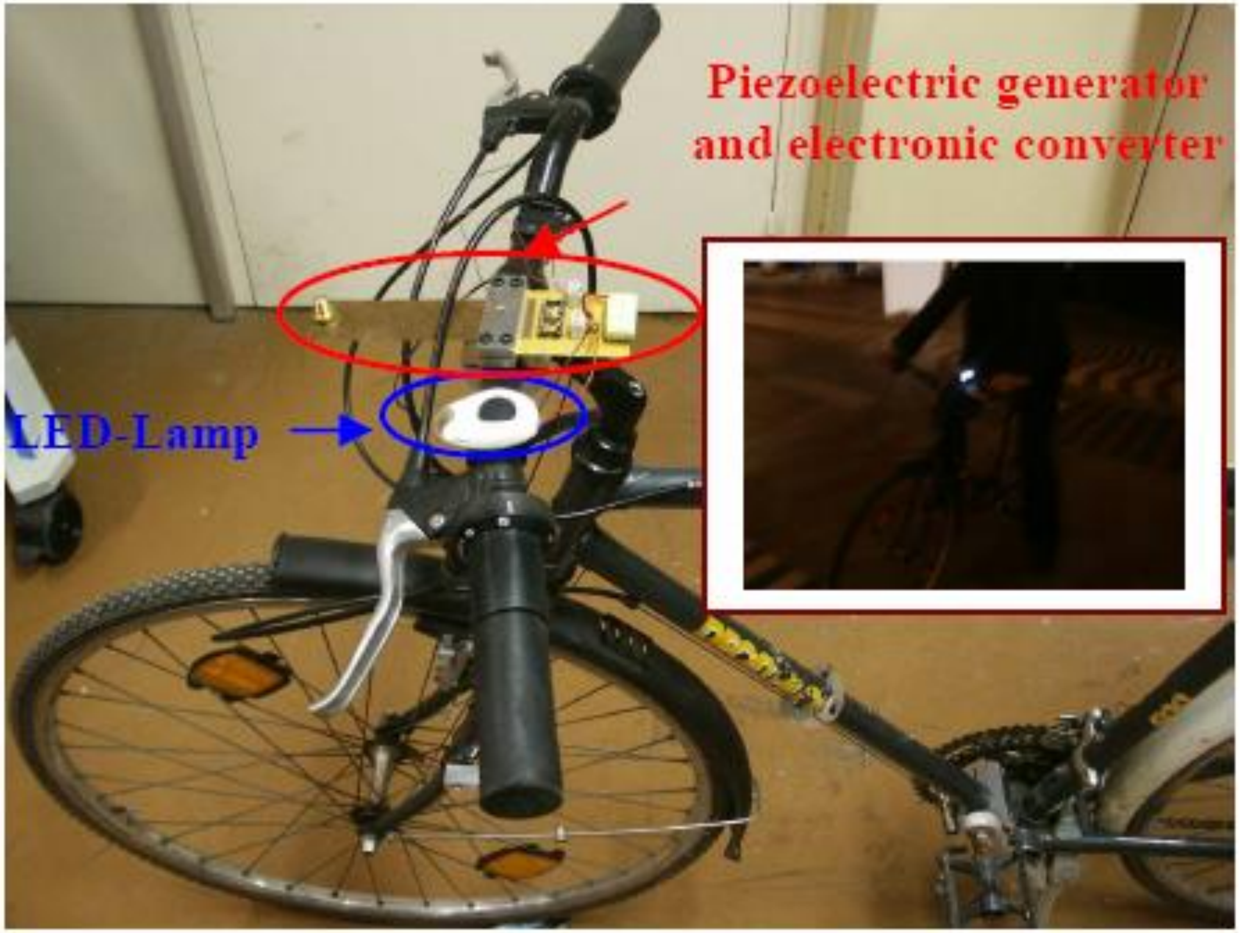
Metallic beam with piezoelectric element



Beam piezoelectric transducer using a MFC

Piezoelectric generator using vibration

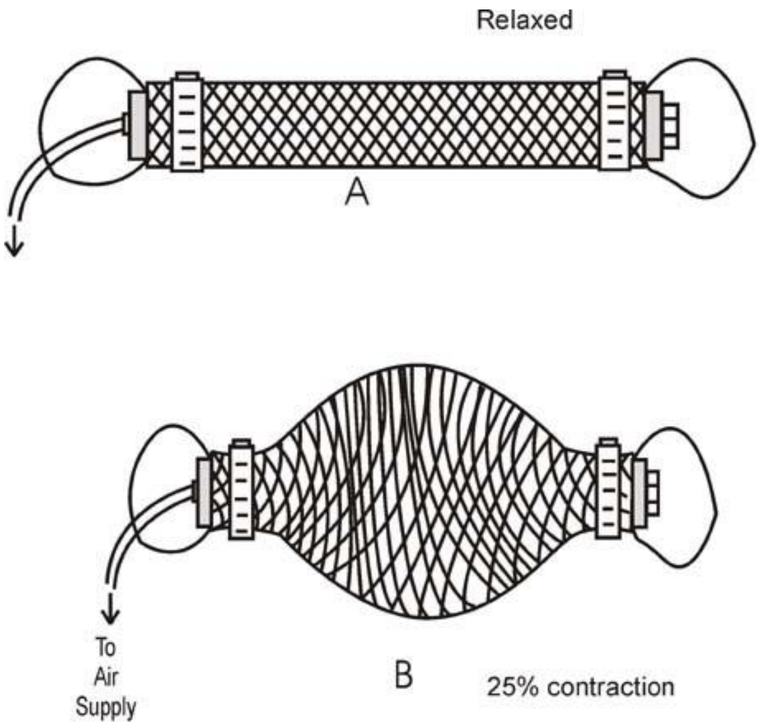
- **Power up the lamp of bike**



PNEUMATIC SOFT ACTUATOR

Pneumatic Artificial Muscle

- **McKibben air muscles (1950s)**
  - Lightweight, easy to fabricate, are self limiting (have a maximum contraction) and have load-length curves similar to human muscle



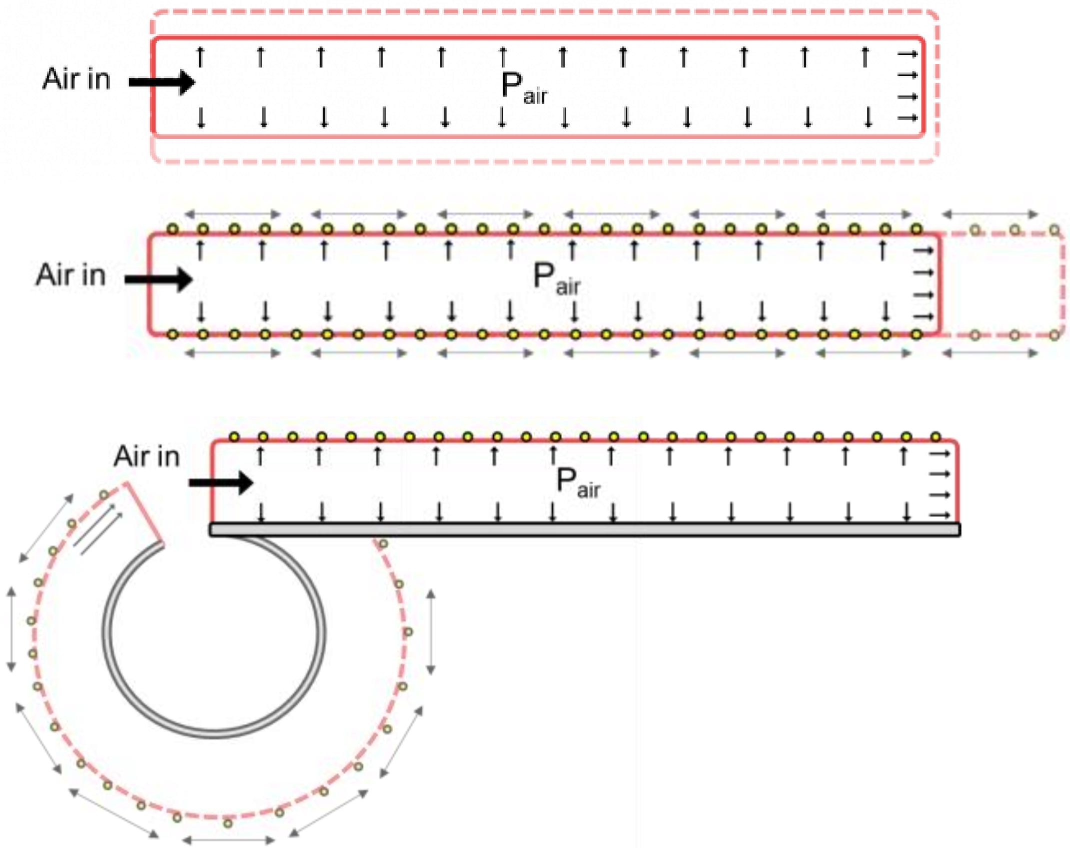
When muscle is pressurized (B), it can contract up to about 75 % of it’s relaxed length

Pneumatic Artificial Muscle

- **Fabrication**

Fiber-Reinforced Actuator

- **Elastomer bladder wrapped with inextensible reinforcements**



Wrapping the bladder with inextensible fibers constrains it from expanding radially - expand in the axial direction

Adding a sheet of inextensible material makes bending

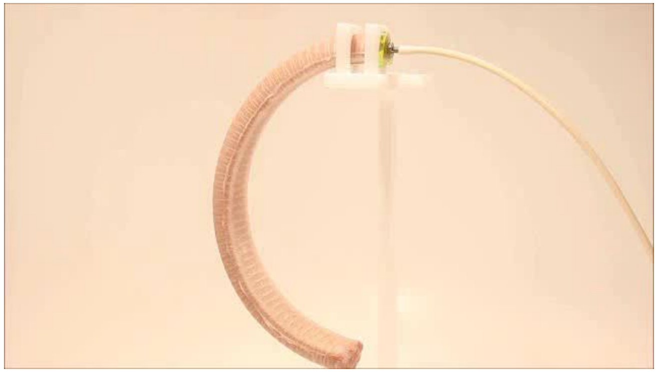
Actuating mechanism

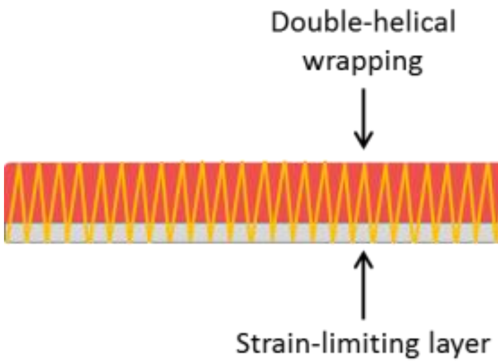
Fiber-Reinforced Actuator

- **Fabrication**

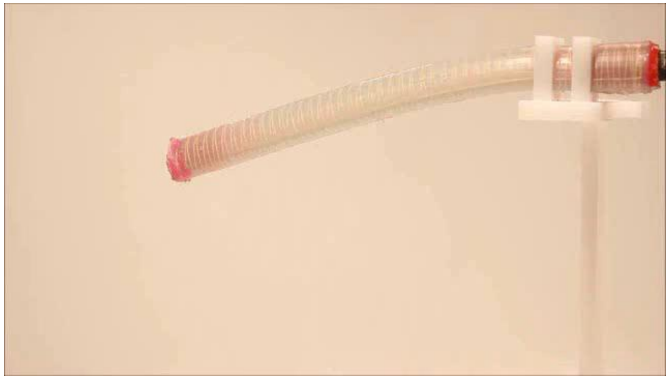
Fiber-Reinforced Actuators

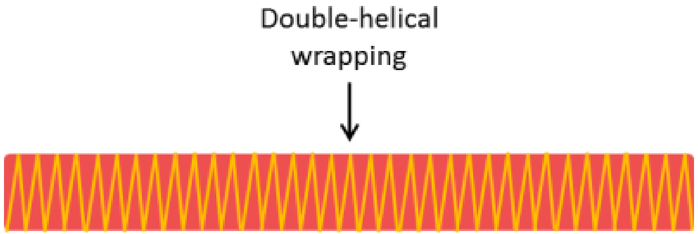
- **Motion design**
  - Bending motion
    - Wrapping the fiber reinforcement in a symmetrical, double-helix configuration





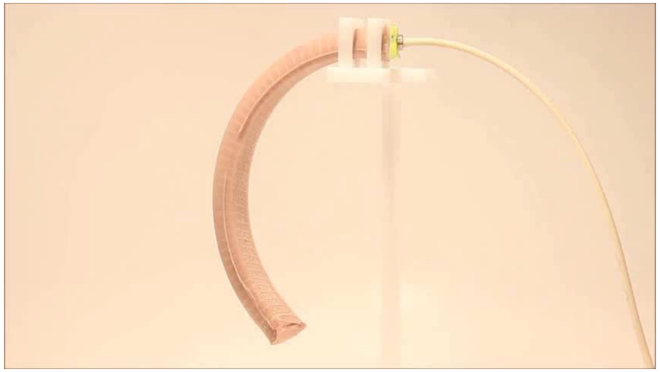
  - Extending
    - Symmetrical, double-helical fiber wrapping without inextensible layer

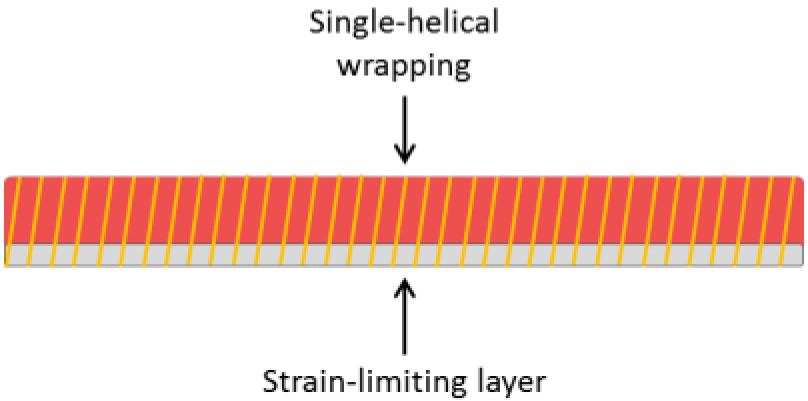




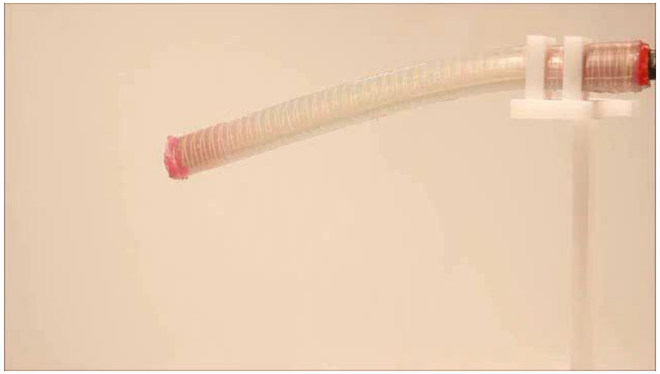
Fiber-Reinforced Actuators

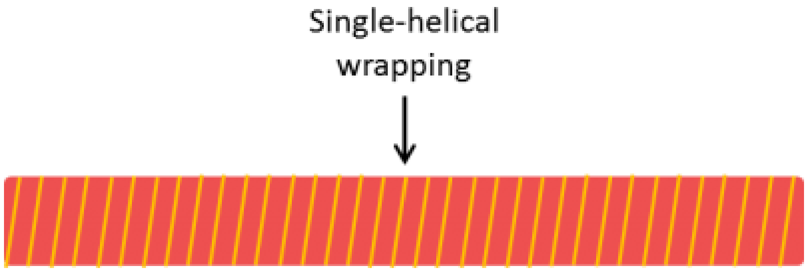
- **Motion design**
  - Twisting and Bending
    - Single-helical fiber wrapping combined with a strain-limiting layer





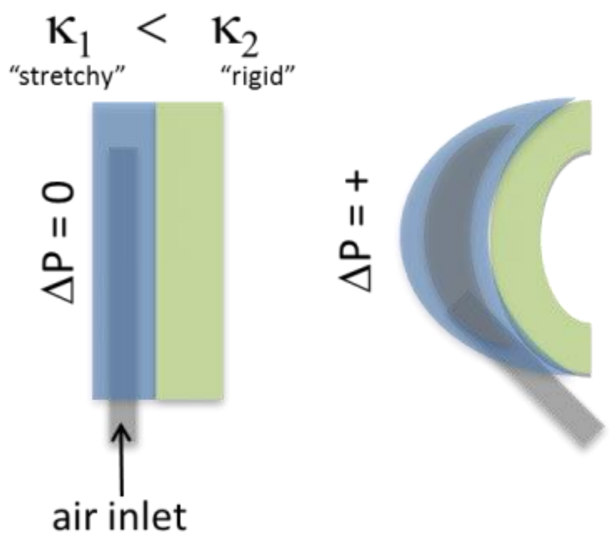
  - Twisting and Extending
    - Single-helical fiber wrapping with no strain-limiting layer



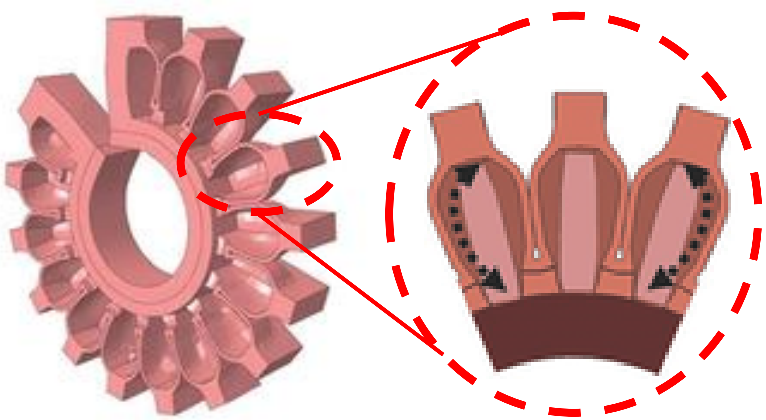


PneuNets Bending actuator

- **A series of channels and chambers inside an elastomer**
  - Inflate when pressurized, creating motion
  - actuator is pressurized, expansion occurs in the most compliant (least stiff) regions
  - Different materials can be used in combination to enable further control over actuator behavior



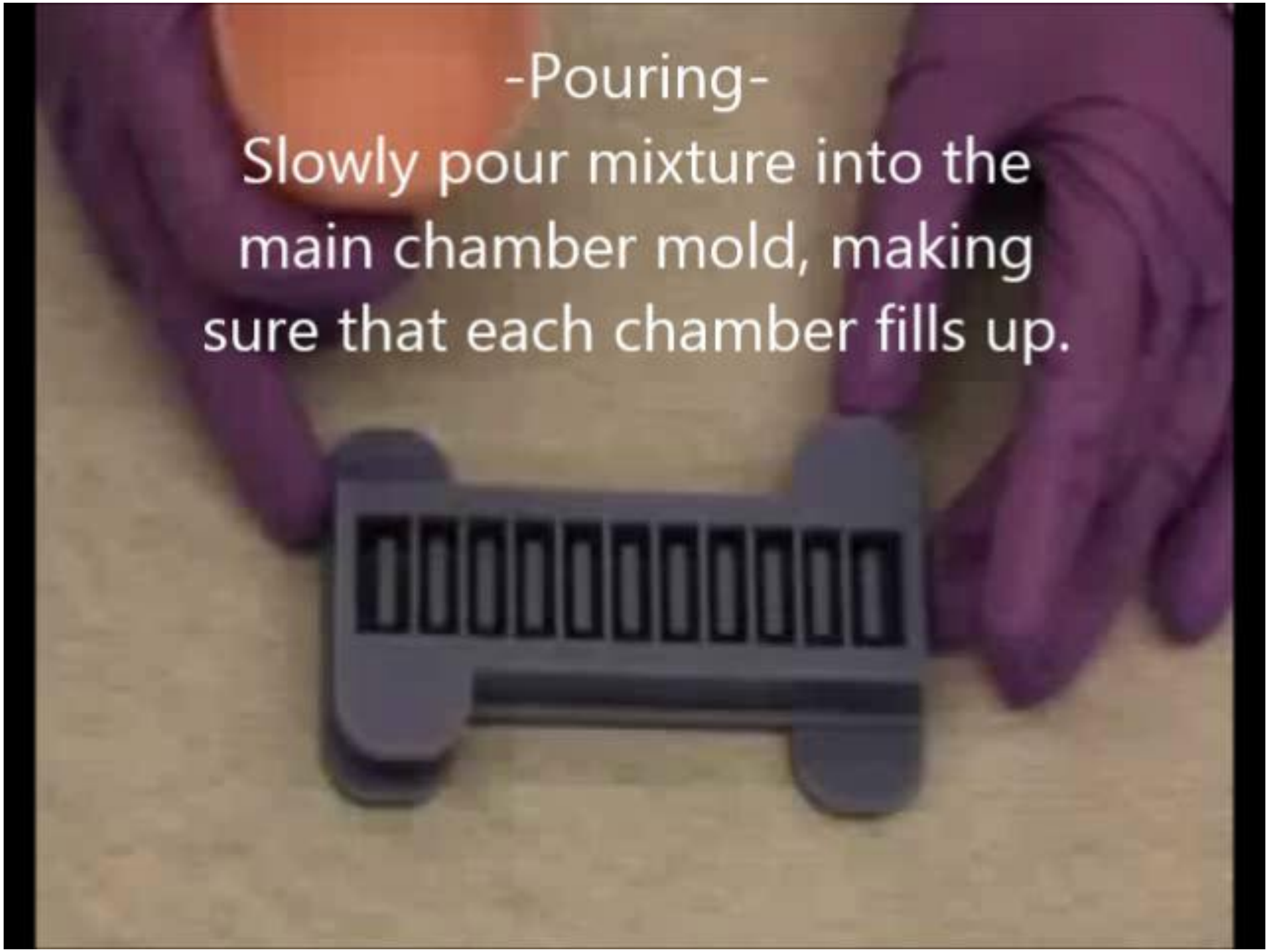
Actuating mechanism of Pneunets actuator



Example of actuating motion

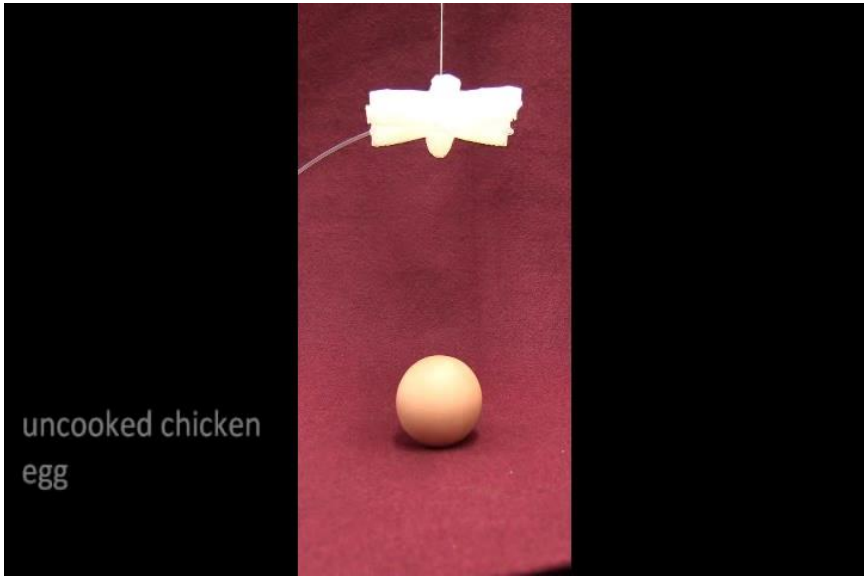
PneuNets Bending actuator

- **Fabrication**

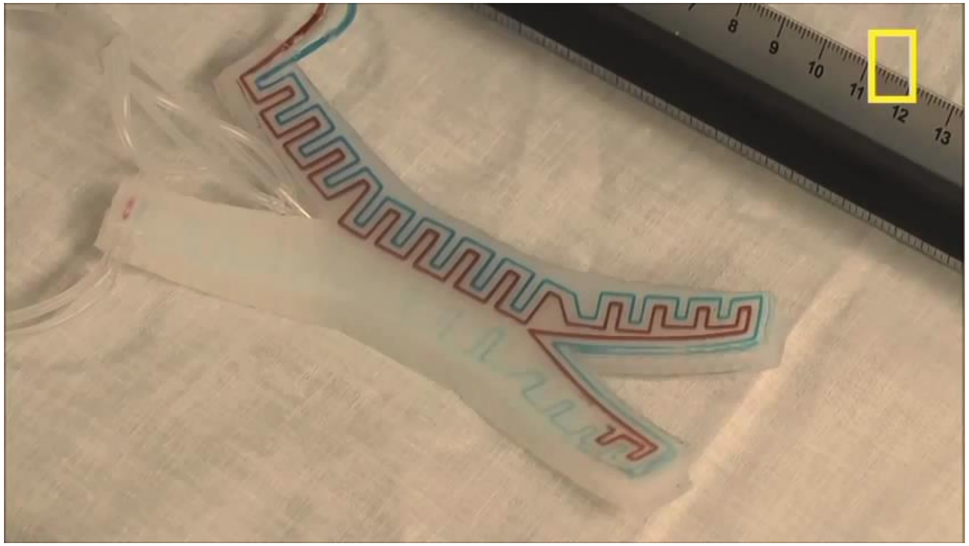


PneuNets Bending actuator

- **Application of PneuNets actuator**



Soft gripper



Soft robot