Smart Materials and Structures

- What ?
  - Possess the capability to sense and actuate in a controlled manner in response to variable ambient stimuli
  - Involve combinations of actuators, sensors, and controllers (muscles, nerves, and brains)
  - Also referred to as *adaptive* or *intelligent* materials
  - Very active field in research and applications
  - One of the key technologies for the 21st century [Scientific American]

- Several Types of Smart Materials
  - Piezoelectric Materials
  - Electrostrictive Materials
  - Magnetostrictive Materials
  - Electro-Rheological (ER) Fluids
  - Magneto-Rheological (MR) Fulids
  - Shape Memory Alloys (SMAs)
  - Optical Fibers

- *Applications*
  - Automation: actuators/sensors/motors; robots
  - Biomedicine: surgical tools, microsensors
  - Precision machinery: computer hard disk drives
  - Transportation: cars, trains, airplanes
  - Infrastructures: bridges and buildings
  - Daily life applications: temperature control valves; toys
- *How ?*
  - This is why we offer this course …

Actuated Structures – structures have distributed actuators (may not have sensors)

Sensory Structures – structures configured with distributed sensors, to monitor characteristics of the system

Controlled Structures – integration of sensory and actuated structures with a closed-loop control system

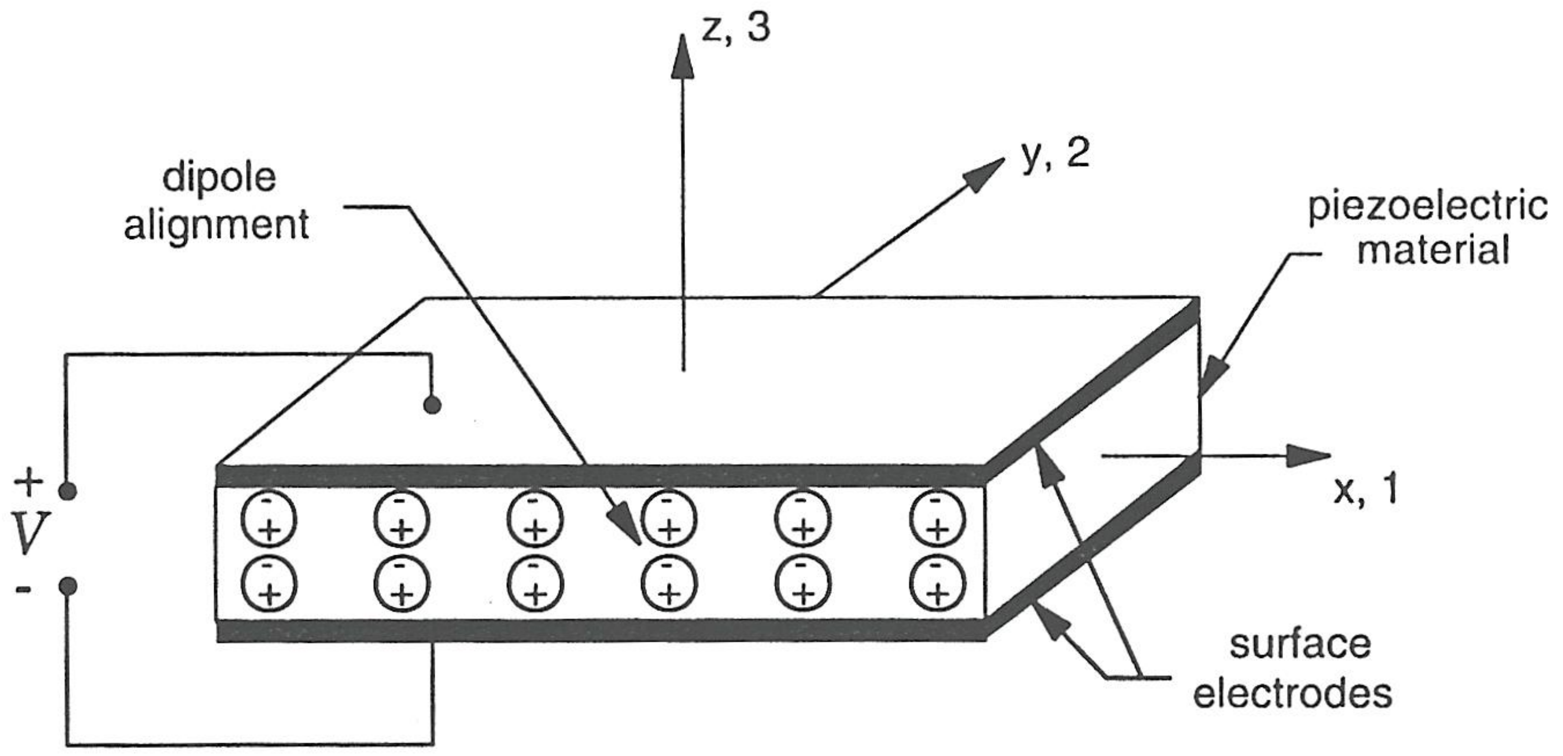
Active Structures – structures with embedded components serving some function in the load bearing properties of the system

Intelligent Structures (**Smart Structures**) – those which incorporate actuators and sensors that are highly integrated into the structure and have structural functionality, as well as highly integrated control logic, signal conditioning and power amplification electronics

- Piezoelectric Materials
  - Most commonly used in smart structures
  - Produce voltage when subject to mechanical strain

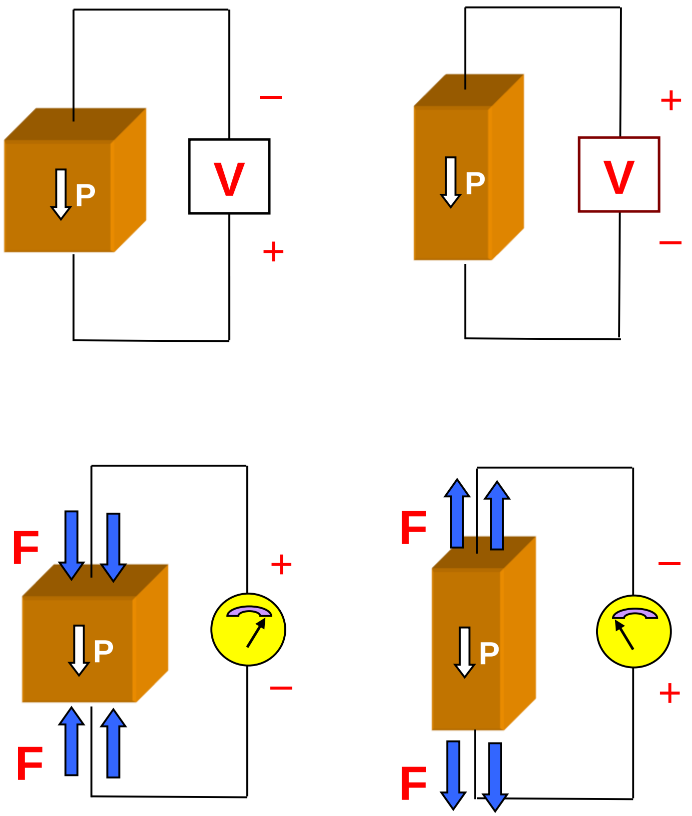
    direct piezoelectric effect
  - Induce strain when electric field applied

    converse piezoelectric effect
  - Used as both actuators/sensors

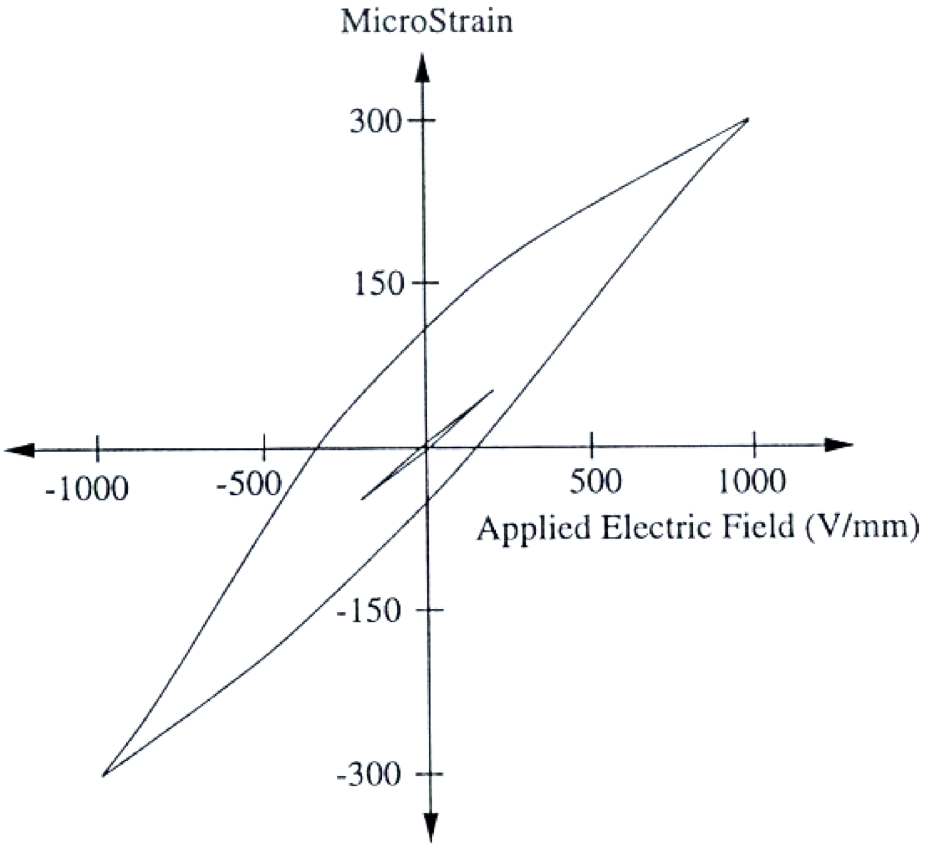


Schematic diagram of dipole effect induced in piezoelectric material

Piezoelectric Materials



Mechanical Response to Electrical Input
and Electrical Response to Mechanical Input



Strain distribution of G-1195 for moderate and large electric fields

- For smaller electric field, strain-field relation is nearly linear
- For higher fields, shown significant hysteresis and strain-based nonlinearities

- Constitutive relations (linear)

  Elastic materials

  $$T = C\,S$$

  where T mechanical stresses

  S mechanical strains

  C material stiffness matrix

Piezoelectric materials

$$D = \varepsilon^{S} E + eS$$
$$T = -e^{t} E + c^{E} S$$

where D electrical displacements (charge/area)

E electric fields (voltage/meter)

ε^{S} dielectric constants obtained at constant strain (permittivity matrix)

e piezoelectric constants relating voltage to stress

c^{E} stiffness matrix measured at constant electric field

More often, an alternate form of constitutive equations:

$$D = dT + \varepsilon^{T} E$$
$$S = s^{E} T + d^{t} E$$

where d piezoelectric constants indicating the strength of the piezoelectric effect

ε^{T} dielectric constants for constant *T*

s^{E} elasticity matrix for constant *E*

The coefficients appearing in the constitutive equations can be obtained. (IEEE 176-1987, IEEE Standard on Piezoelectricity)

With the coordinate system,

voltage applied in *i* direction

strain developed in *j* direction

Induced strain in *x* direction

Piezoelectric Material Properties

Property	Symbols	Values		Units
		PVDF	PZT	
Strain constant	d_{31}	23×10^{-12}	166×10^{-12}	(m/V)
	d_{32}	3×10^{-12}	166×10^{-12}	(m/V)
	d_{33}	-30×10^{-12}	360×10^{-12}	(m/V)
Relative dielectric constant	K_3	12	1700	
Young's modulus	E_{11}	2×10^9	6.3×10^{10}	(N/m^2)
Density	ρ	1780	7600	(kg/m^3)

Comparisons:

PZT times as dense compared to PVDF

PZT times stiffer compared to PVDF

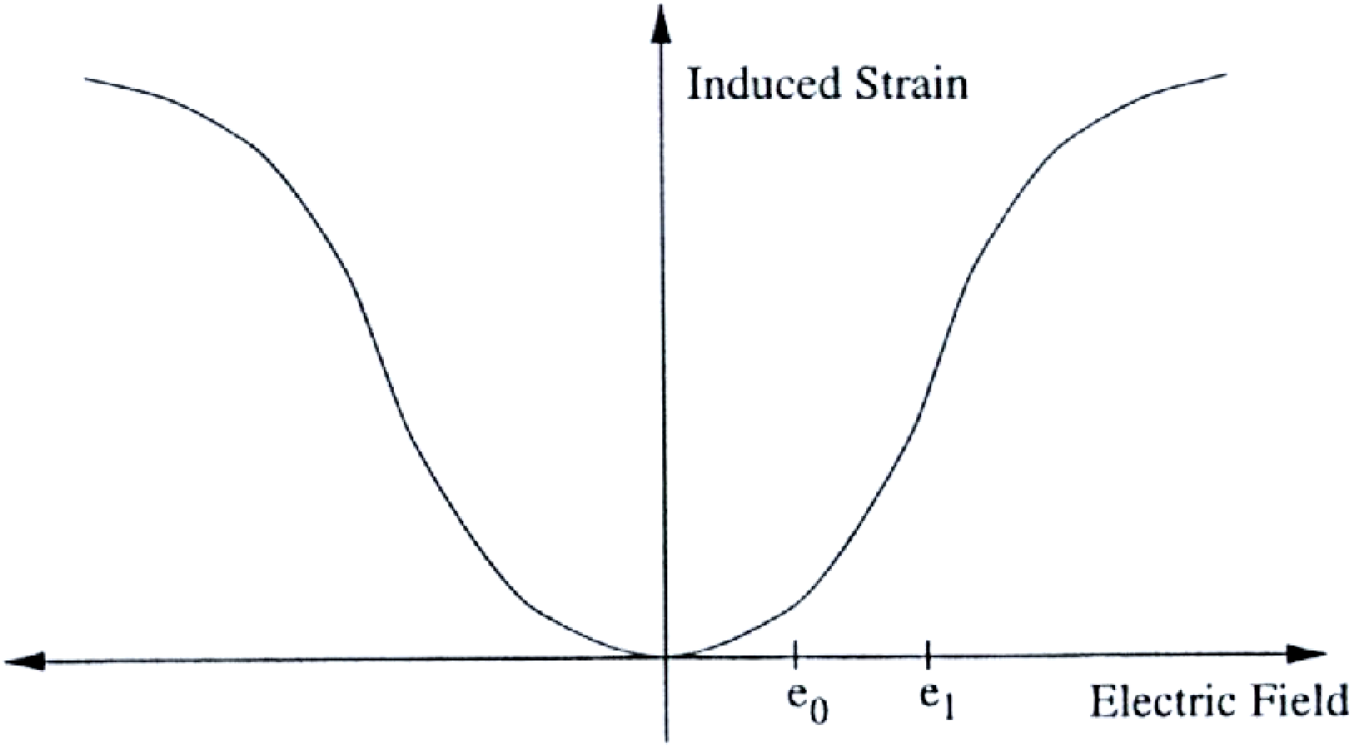
PZT times compared to PVDF

- PZT (Lead Zirconate Titanate)
  - Ceramic based
  - Brittle and stiff
  - Most commonly used as actuators
- PVDF (Polyvinylidene Fluoride)
  - Polymer based
  - Soft (compliant)
  - Readily cut and shaped
  - Suitable for sensing applications

Piezoelectric Materials

- Advantages:
  - Relative temperature insensitivity
  - Linear response at low excitation levels
  - Broadband frequency response
- Disadvantages:
  - Significant hysteresis at large electric field levels
  - Brittleness and small tensile strength of PZTs
  - Weak electromechanical coupling coefficients for PVDFs

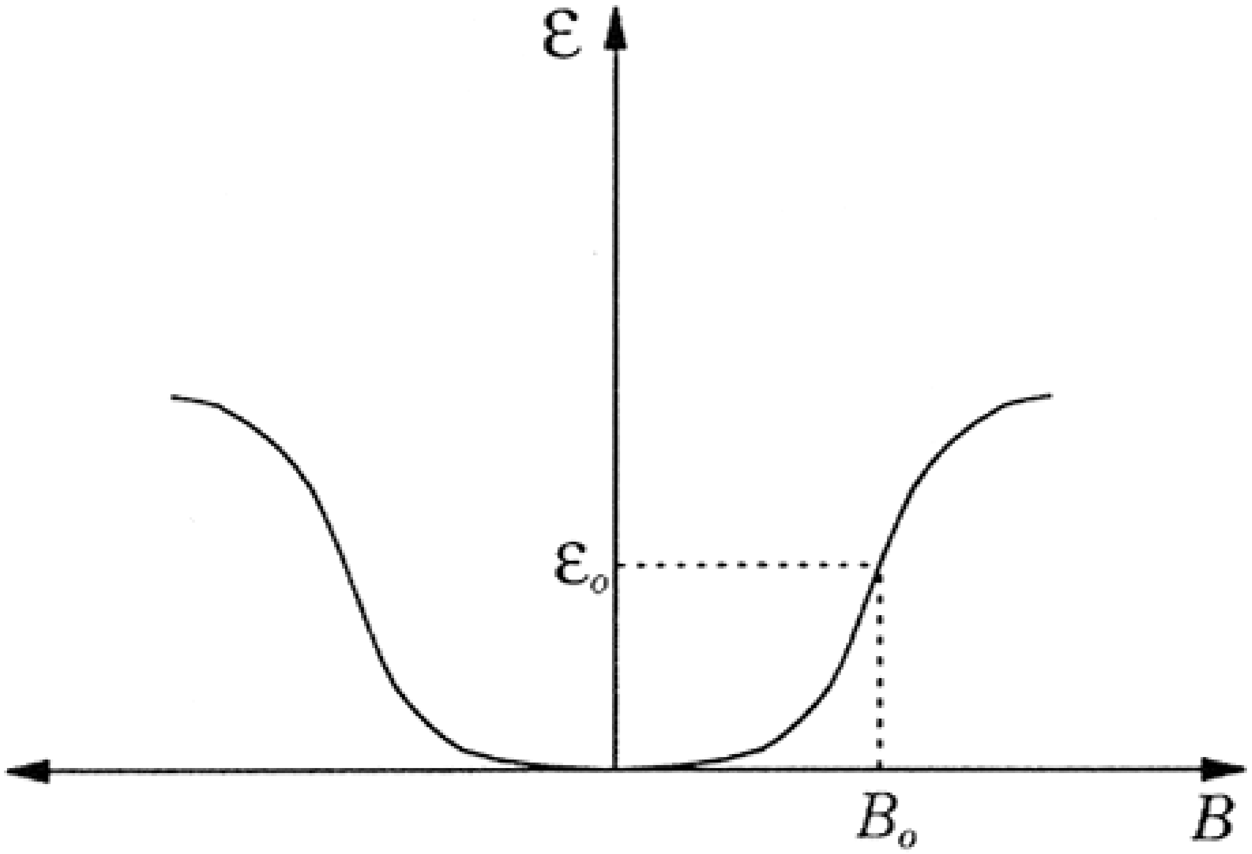
- Electrostrictive Materials
  - Similar to piezoelectric materials with slightly higher free strain
  - Nonlinear strain-field relations
  - Very sensitive to temperature



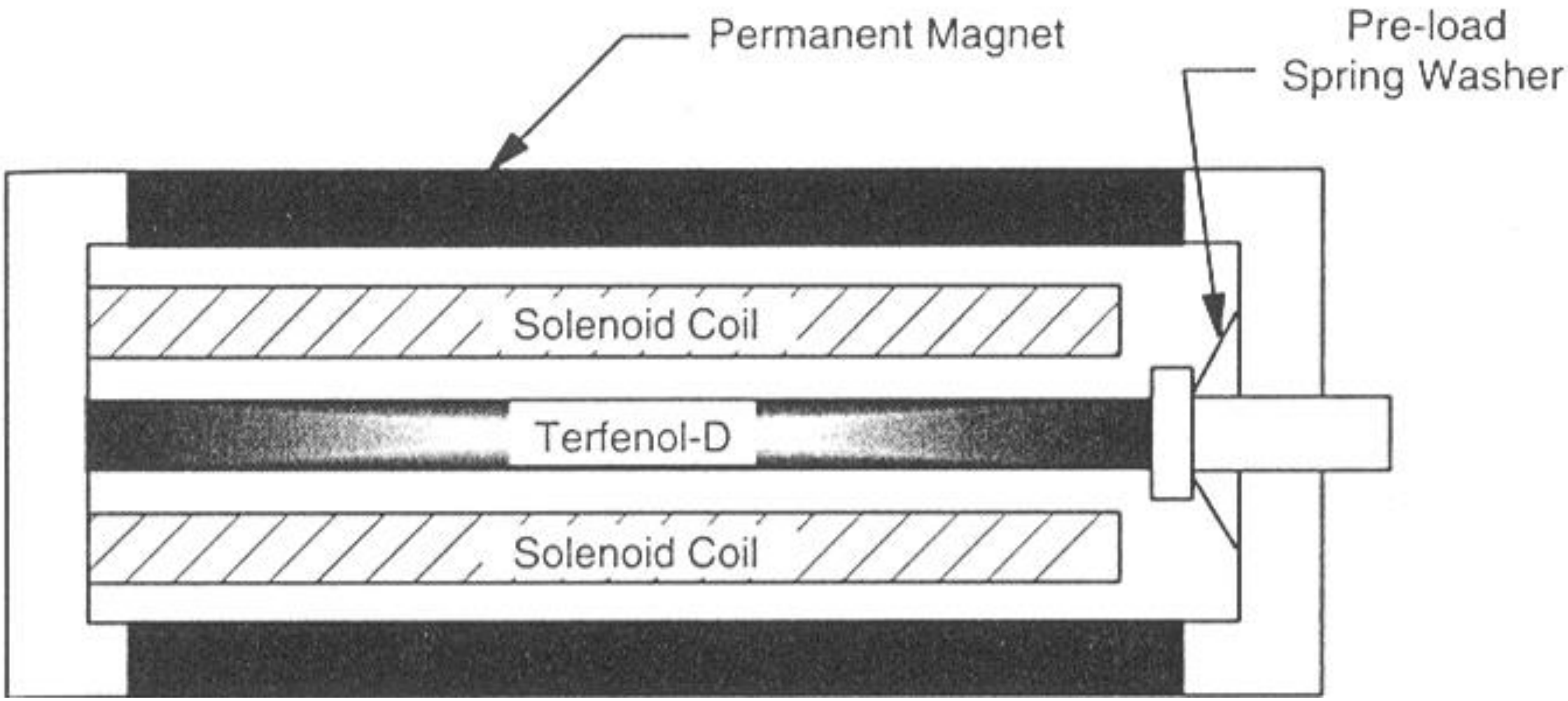
Strain-electric field distribution for an electrostrictive element

An Electrostrictive Polymer Actuator (EPAM)
for manipulation in MRI devices

- Magnetostrictive Materials
  - Produce strains when exposed to magnetic field
  - Highly nonlinear between applied magnetic field and induced strains
  - Magnetostrictive transducers are large in size
  - Actuators generate very large strains compared to piezoelectric and electrostrictive actuators
  - Far from fragile once housed and prestressed



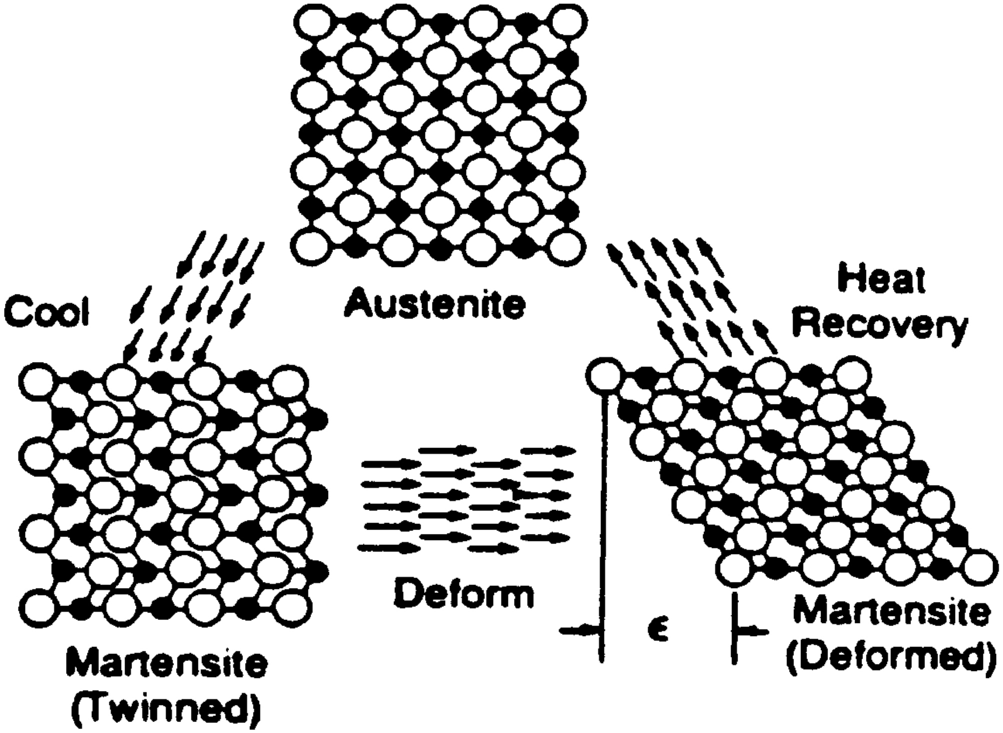
Schematic diagram of strain versus magnetic field for a magnetostrictive material



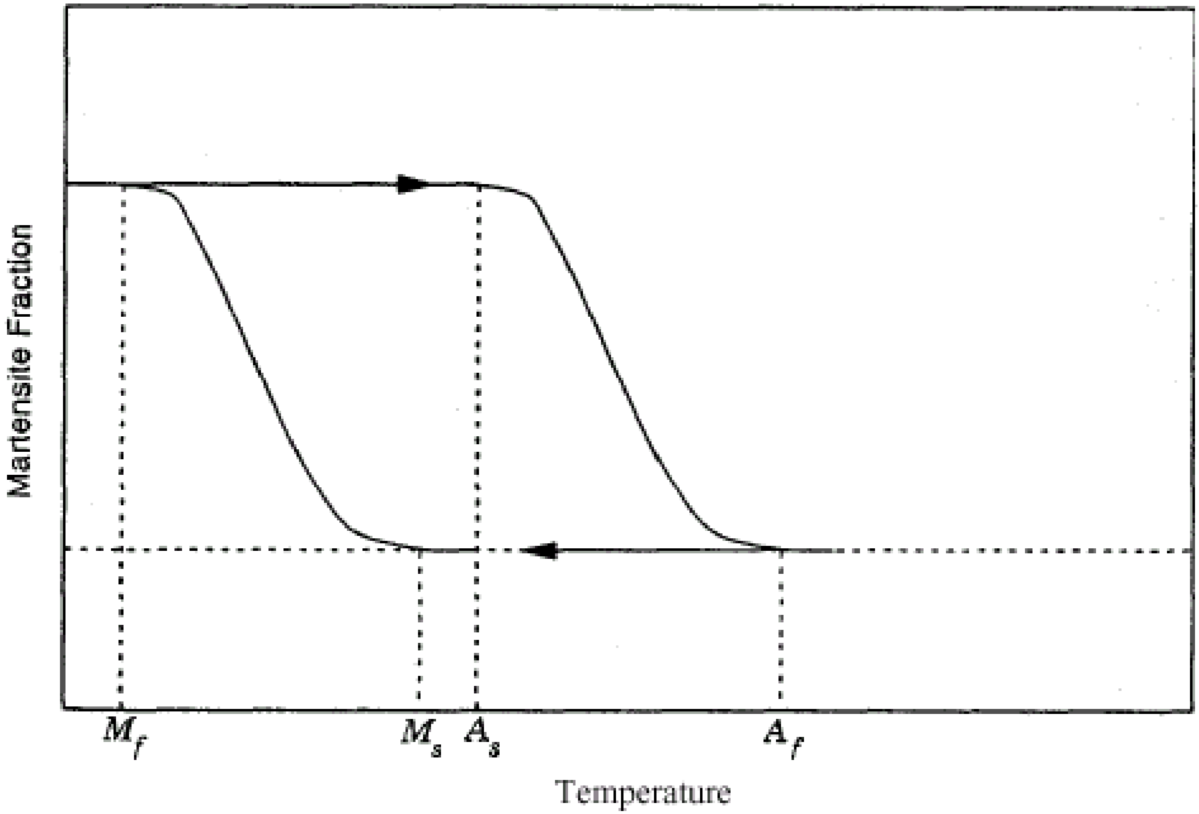
Schematic diagram of a Terfenol-D actuator

- Shape Memory Alloys (SMAs)
  - Capable of memorizing its original configuration after heated above the characteristic transition temperature
  - Can produce large displacements and forces
  - Most common SMA is *Nitinol*
  - Heat may be internal
  - Slow response time
  - Nonlinear hysteresis
  - Modeling is quite difficult

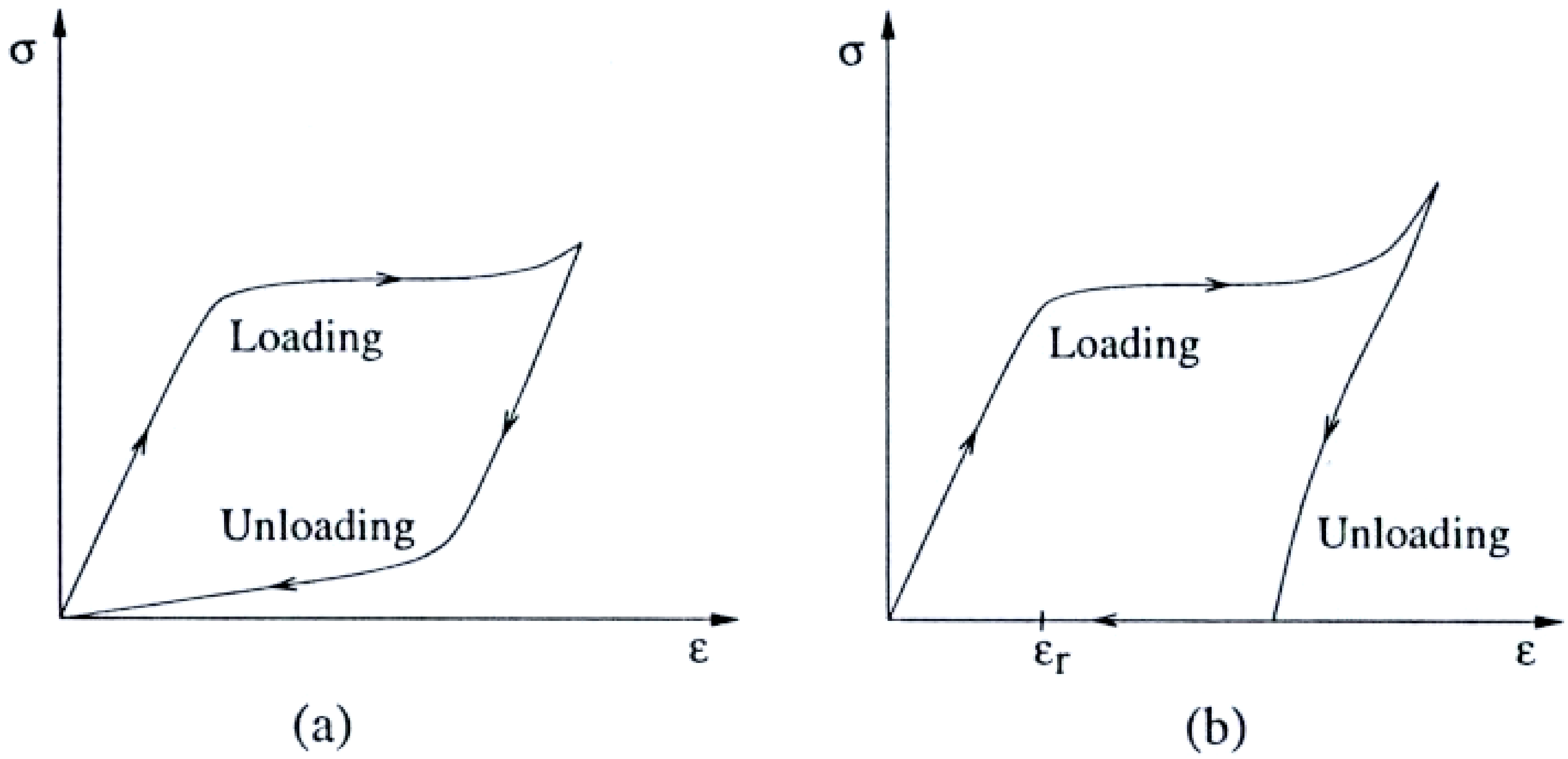
Shape Memory Alloys (SMAs)



Representation of the changes in the crystal form of SMAs which leads to the shape memory effect



Schematic diagram of transformation of a shape memory alloy

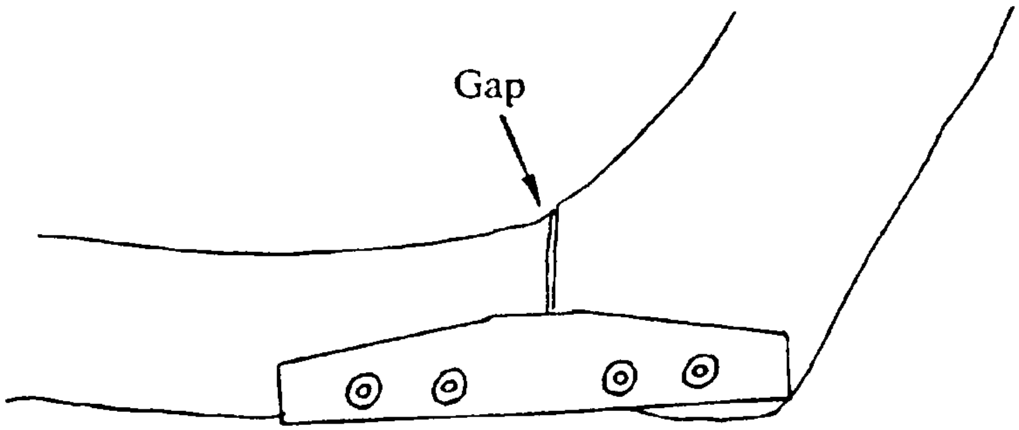


(a) Pseudoelasticity: stress-strain hysteresis loop ($T > A_f$)
(b) Shape memory effect: residual strain ε_r ($T < A_s$)

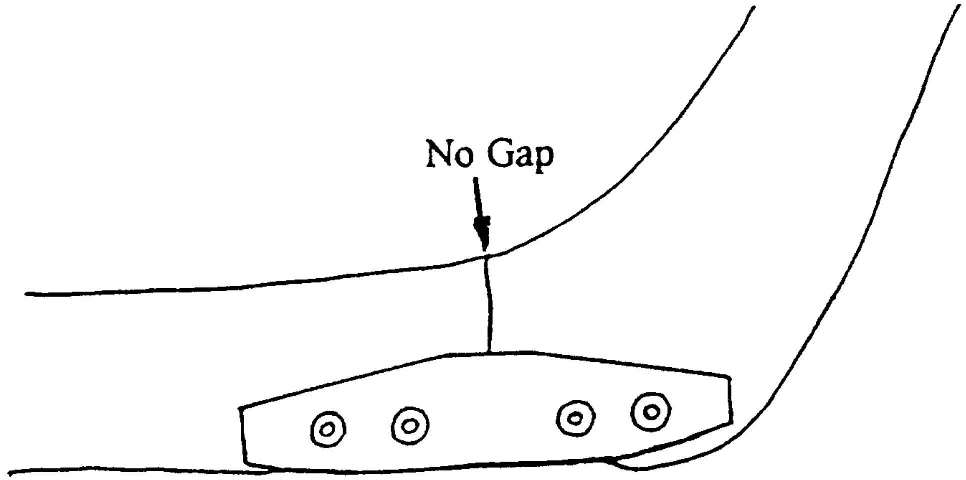
- *Pseudoelastic:* When an SMA is in the austenite phase ($T > A_f$), a plastic strain is achieved under stress loading, the full strain can be recovered upon unloading

- *Shape memory effect:* when $T < A_s$ during the stress-induced martensite phase transformation, a large residual strain ε_r remains after unloading. This strain can be recovered by heating SMA to $T > A_f$

Artificially Fractured Jaw Model



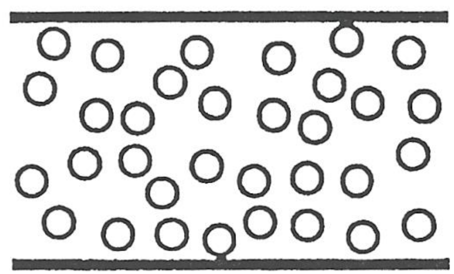
SMA plate attached



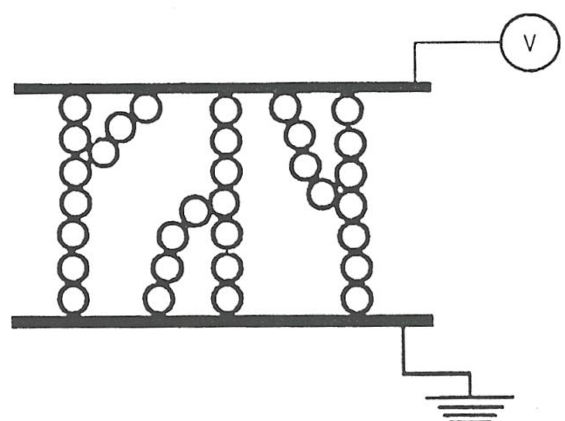
SMA plate activated

- Electro-rheological (ER) Fluids
  - ER fluids are colloidal dispersions of solid particulates in nonconducting or insulating oils
  - Display reversible changes in dynamic yield stress due to an application of an electric field
  - Electric field induce polarization of particles
  - Particle-particle interaction leads to pearl chain formulation
  - Can change device stiffness & damping properties via electric field

Electrorheological (ER) Fluids



No electric field



Electric field applied

- A recipe for a couple of ER fluid

- Newtonian fluid

- Bingham plastic

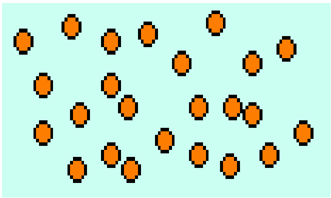
A fluid that behaves as a solid until a minimum yield stress is exceeded and subsequently exhibits a linear relation between stress and shear rate

- Disadvantages (ER fluids):
  - High voltage required
  - Lack of long term stability
  - Complexity of actuator/control design

Magneto-Rheological (MR) Fluids

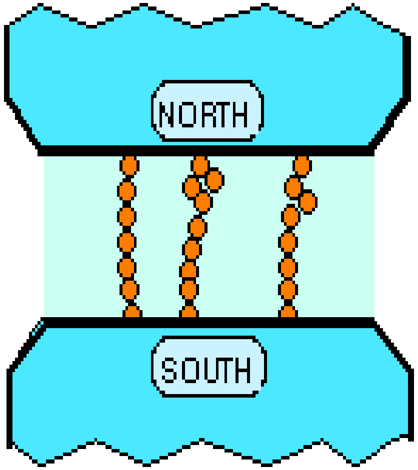
What are they ?

- Micron sized, paramagnetic particles in oil

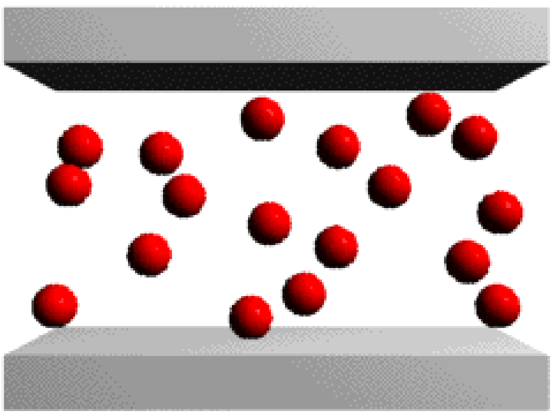


What do they do ?

- Newtonian in absence of applied field
- Develop yield strength when magnetic field applied
- Bingham Model: $\tau = \tau\,(H) + \eta\dot{\gamma}$
- Provide means for a quiet, rapid response interface between electronic controls and mechanical devices



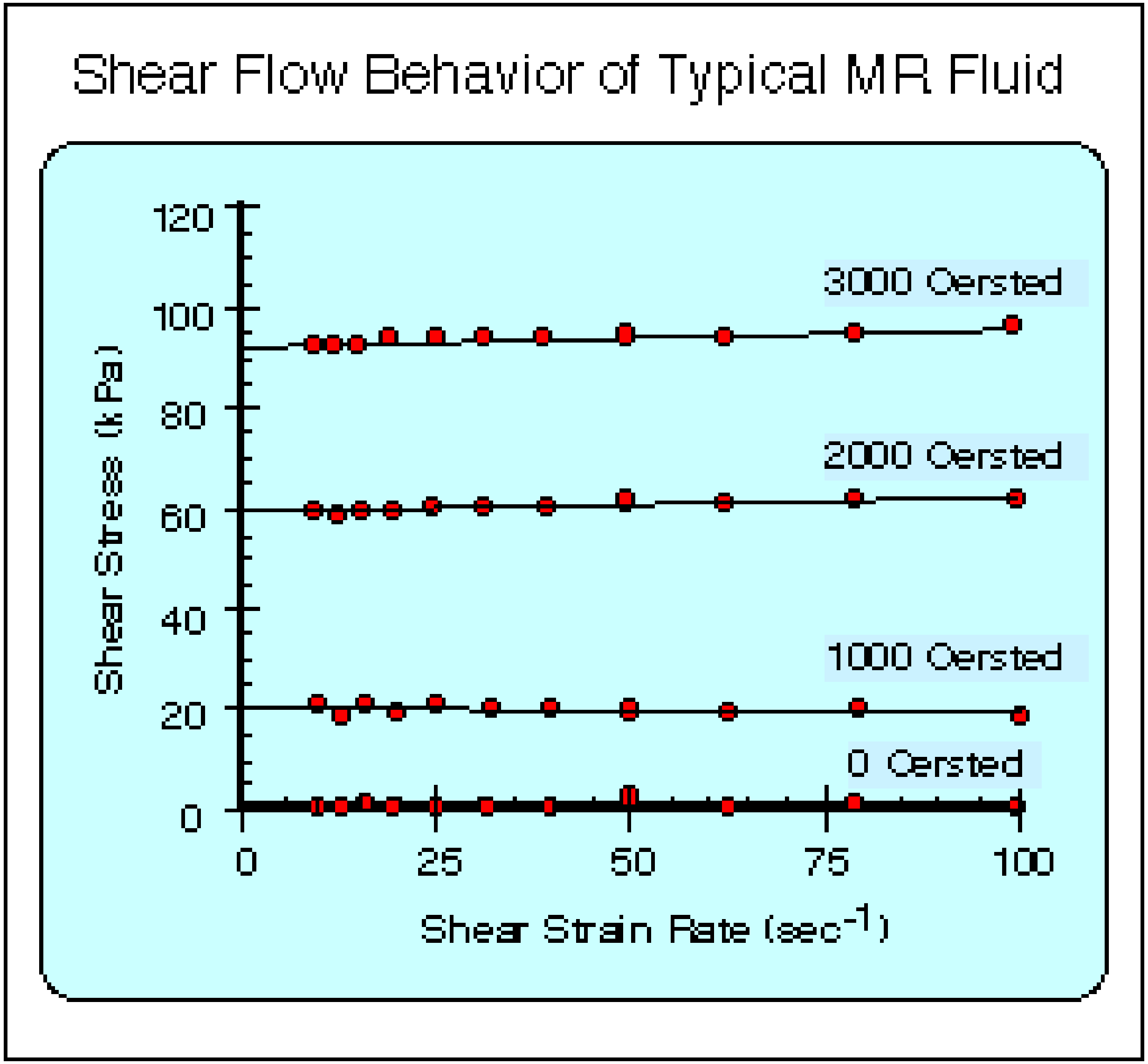
Demonstration of MR fluids



(Courtesy of Lord Company)

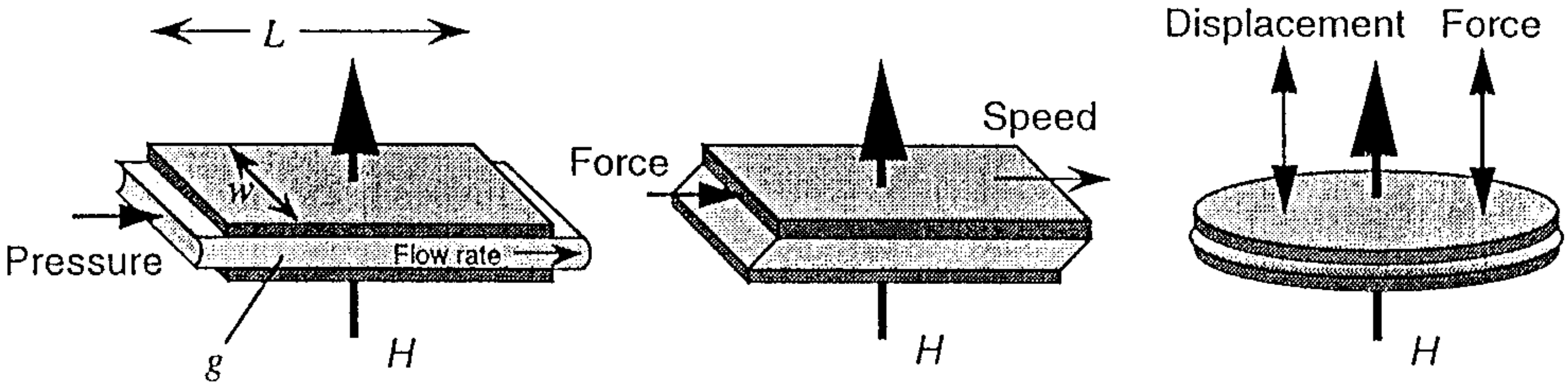
- Magneto-rheological (MR) Fluids

  - High yield stress (50 kPa to 100 kPa)
  - Good stability
  - Fast response time (within milliseconds), can be used for high frequency applications
  - Broad operating temperature range (less than 10 % variation in force output over a temperature range of - 40 to +150 °C)



Shear Flow Behavior of Typical MR Fluid
3000 Oersted
2000 Oersted
1000 Oersted
0 Oersted
120
100
80
60
40
20
0
Shear Stress (k Pa)
0
25
50
75
100
Shear Strain Rate (sec-1)

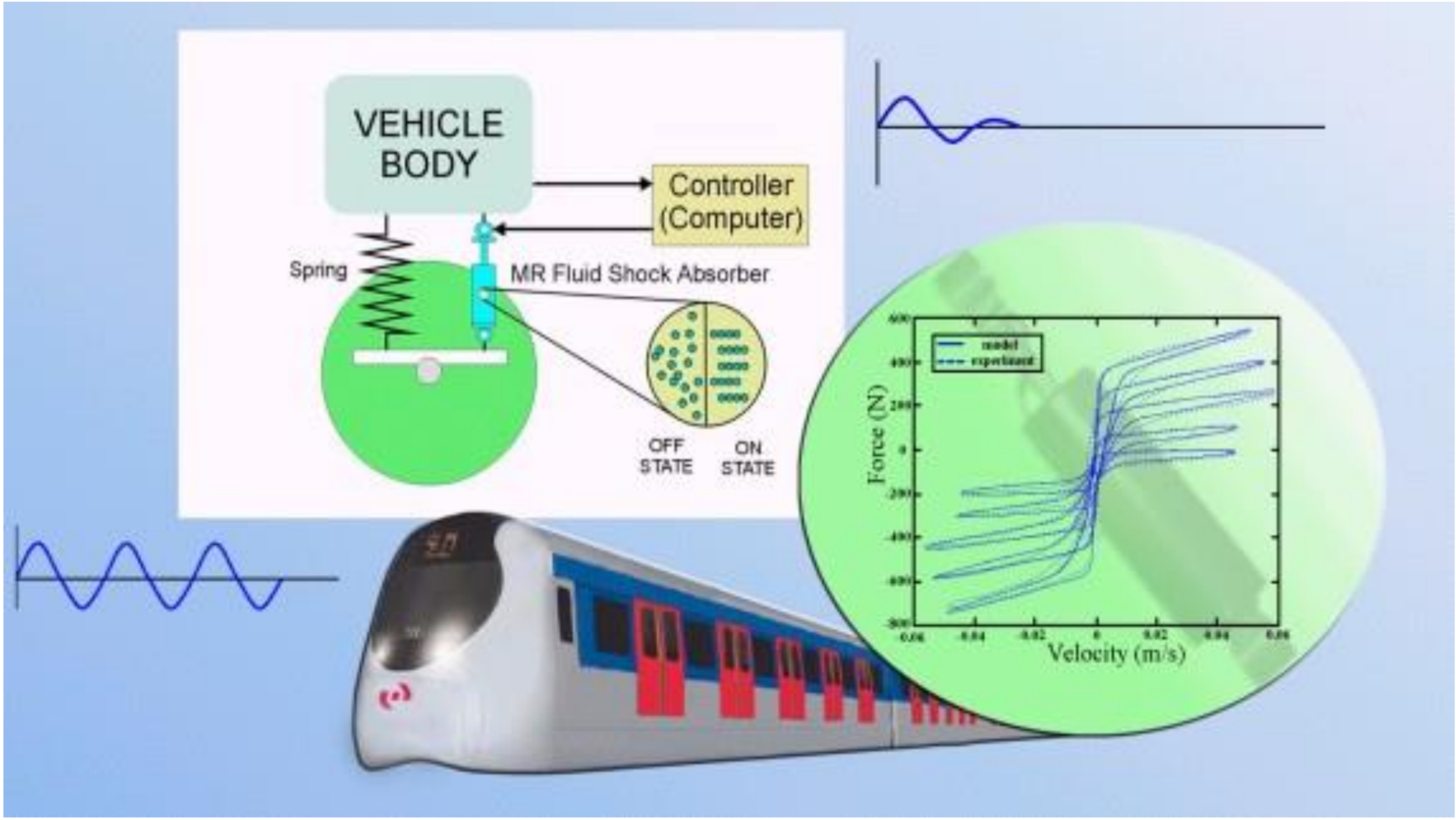
Magnetorheological (MR) Fluids



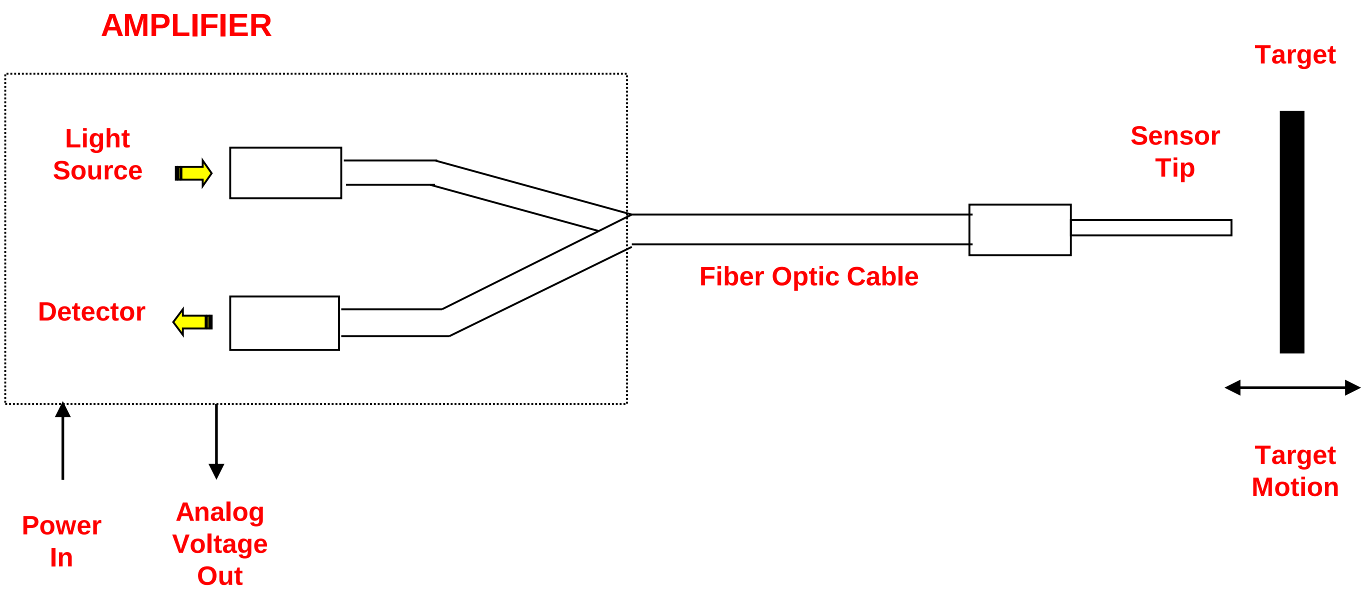
Flow Mode **Shear Mode** **Squeeze Mode**

Three basic modes of operation for MR Fluids

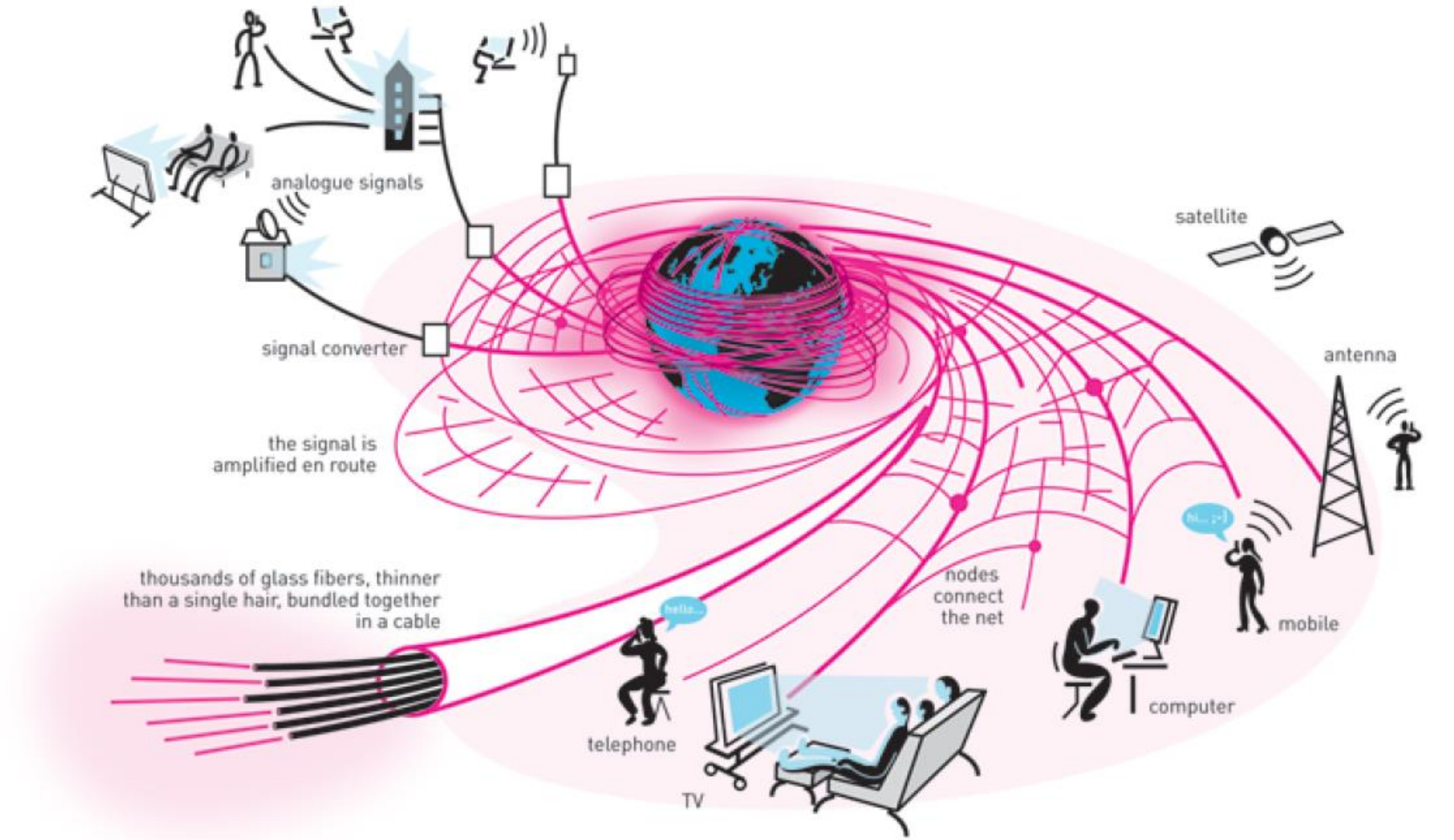
Smart Dampers for Suspension Systems



Fiber Optic Sensors



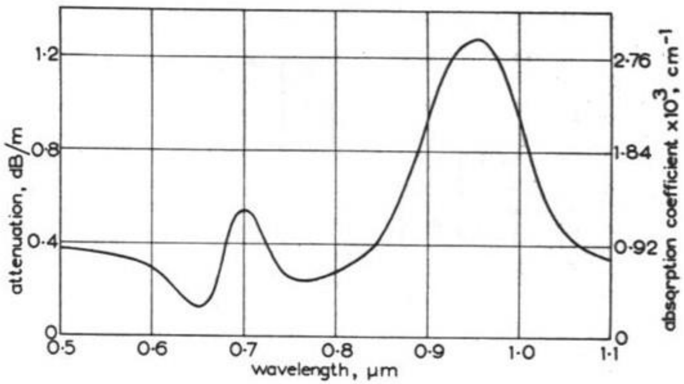
- Fiber Optic Sensors
  - Lightweight
  - Mechanically flexible, diverse geometry possible
  - Low maintenance, high reliability
  - No actuation abilities



Artistic view of global communication

(Scientific Background on the Nobel Prize in Physics 2009)

K.C. Kao & G.A. Hockham,
Proc. IEE **113**, 1151 (1966).
Dielectric-fibre surface waveguides for
Optical frequencies.



Fibre core: λ_0
Fibre diameter : $>>\lambda_0$
Losses : < 20 dB/km