UNIT – I

OVERVIEW OF MEMS & SCALING LAWS IN MINIATURIZATION

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COURSE OUTCOMES (COs)

- CO1: Interpret the micro systems, micro electronics& miniaturization technique.
- CO2: Apply the scaling laws to micro systems for providing information of downscaling.
- CO3: Illustrate the Bulk and Surface micromachining techniques.
- CO4: Classify and discuss the properties of different materials.
- CO5: Analyze design aspects, working principles and limitations of MEMS based devices.

UNIT – I:OVERVIEW OF MEMS & SCALING LAWS IN MINIATURIZATION

CONTENTS:

- MEMS and Microsystems
- Working Principles of Microsystems with examples
- Microsystems and Microelectronics
- Applications of Microsystems
- Benefits of miniaturization
- Introduction to Scaling
- Scaling in -Geometry,Electrostatic forces
- MEMS Design Considerations.

MEMS

MEMS – a pioneer technology for Miniaturization

MEMS = MicroElectroMechanical System

Any engineering system that performs *electrical* and *mechanical* functions with *components* in *micrometers* is a MEMS. (1 μm = 1/10 of human hair)

HOW SMALL ARE MEMS DEVICES?

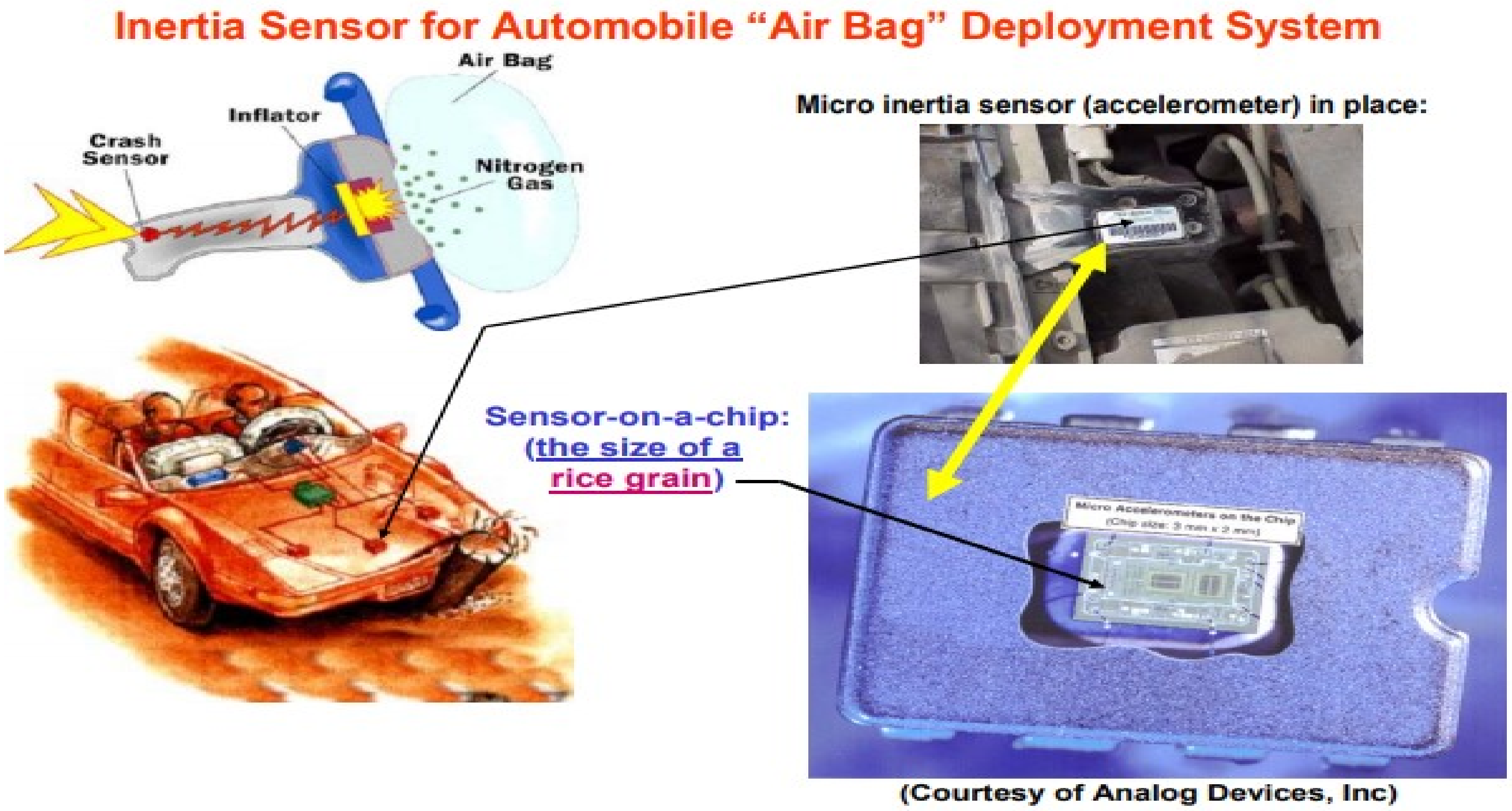
MEMS components are of sizes in 1 micrometer (μm) to 1millimeter (mm).

They can be of the size of a rice grain, or smaller!

Two examples:

- Inertia sensors for air bag deployment systems in automobiles
- Microcars

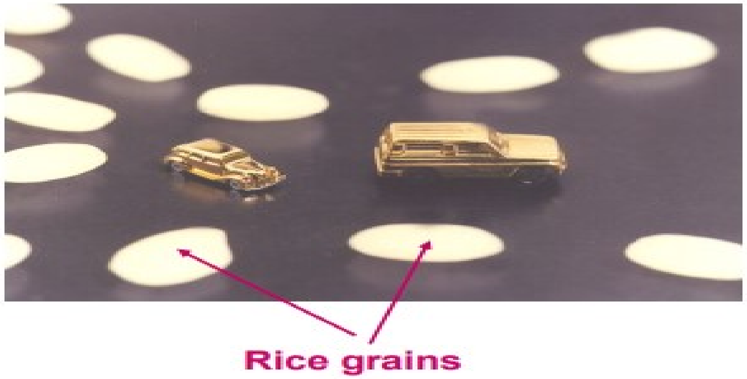
Air Bag Deployment System



Micro Cars

Micro Cars

(Courtesy of Denso Research Laboratories, Denso Corporation, Aichi, Japan)



MICROSYSTEM

A *microsystem* is an engineering system that contains MEMS components that are designed to perform specific engineering functions.

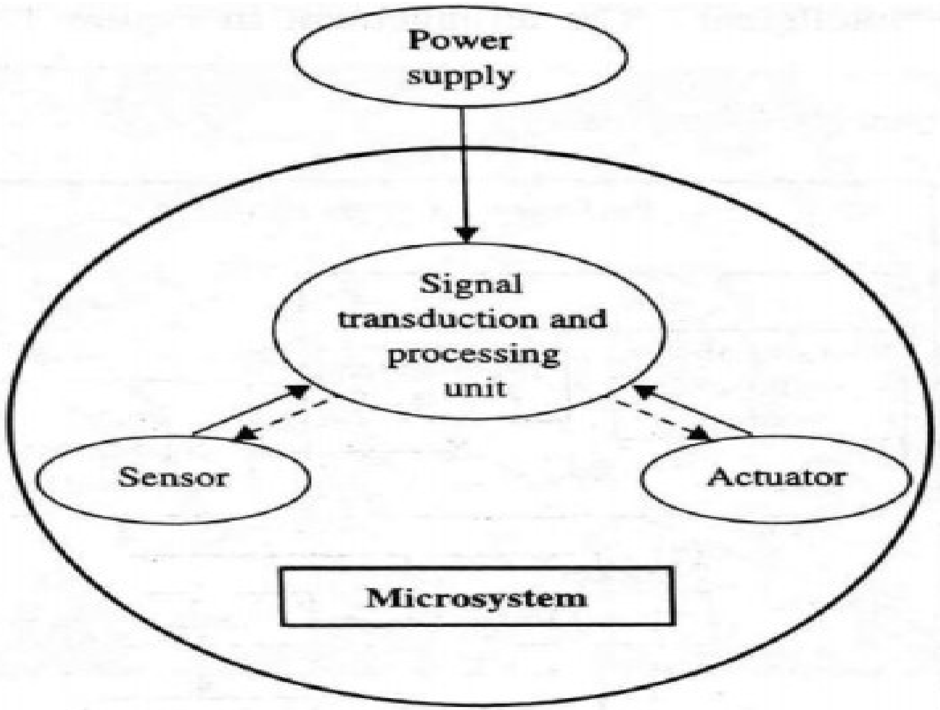


Figure Components of a microsystem.

MEMS COMPONENTS

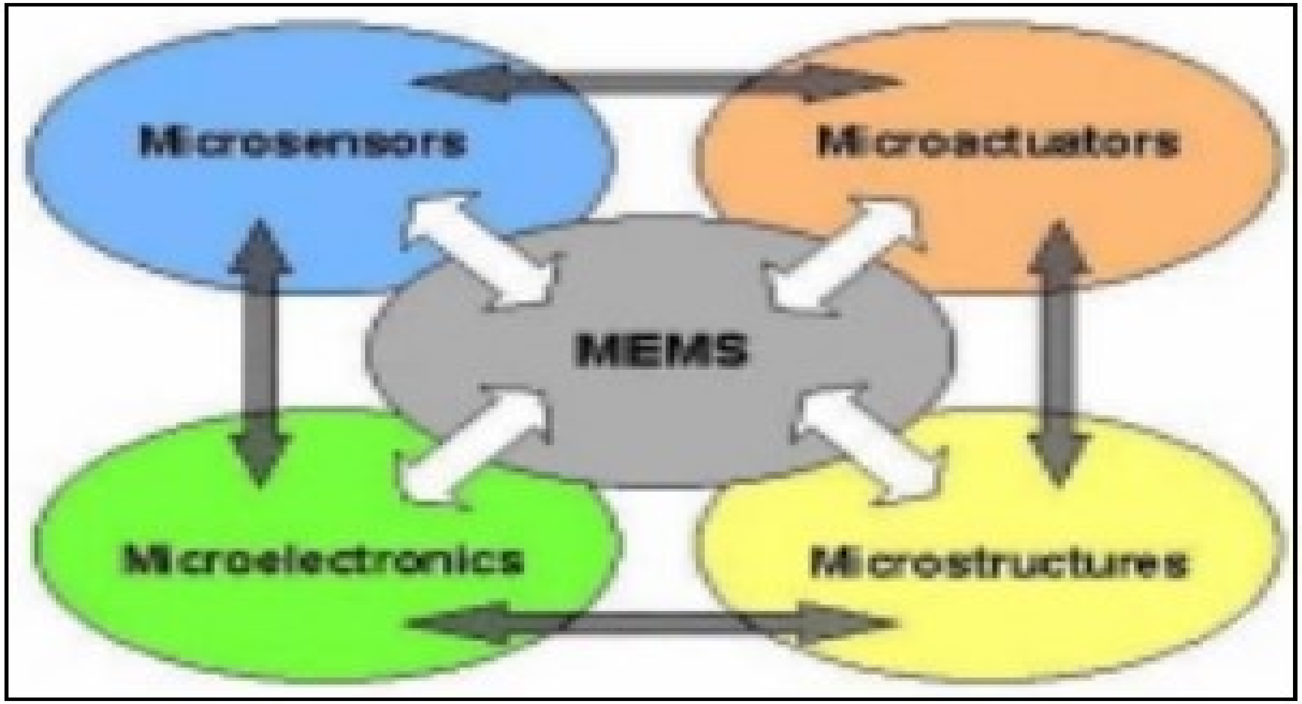


Figure Schematic illustration of MEMS components.

MEMS COMPONENTS

- MEMS consist of mechanical microstructures, microsensors, microactuators and microelectronics, all integrated onto the same silicon chip.
- The two principle components of MEMS:
- i) A sensing or actuating element
- ii) A signal transduction unit

MEMS AS A SENSOR

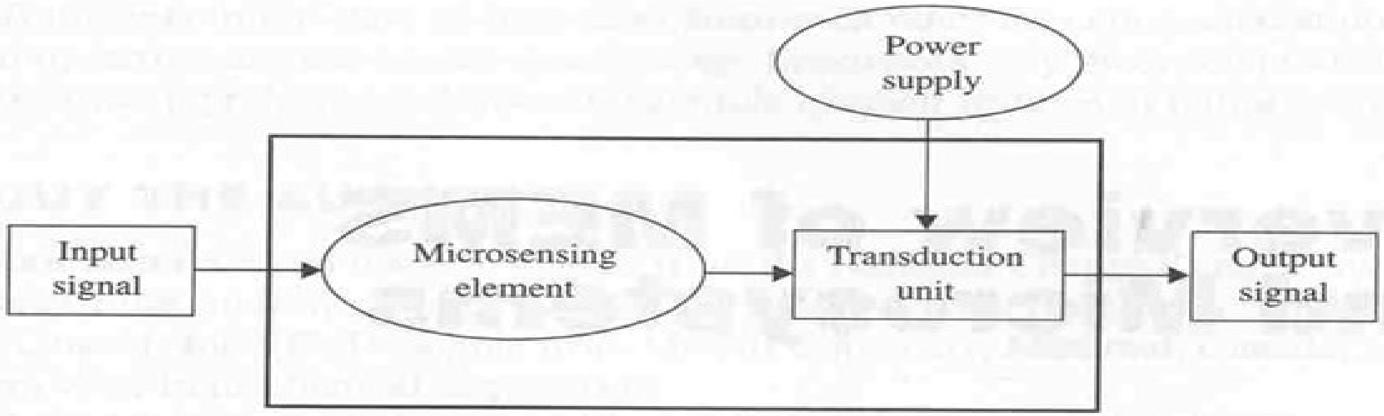


Figure MEMS as a microsensor.

Micro sensors are built to sense the existence and the intensity of certain physical, chemical, or biological quantities, such as temperature, pressure, force, sound, light, nuclear radiation, magnetic flux, and chemical compositions.

Example-Pressure Sensor

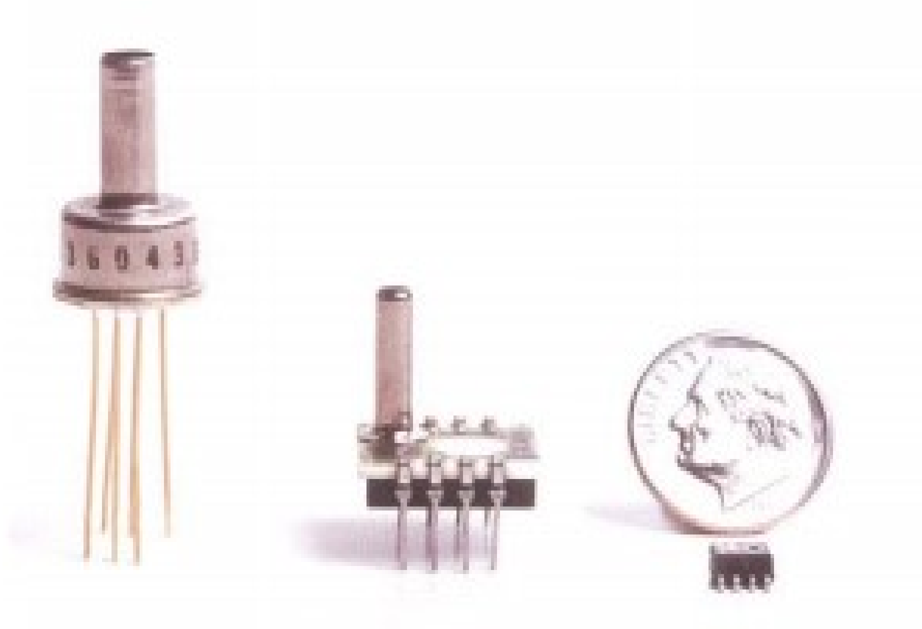


Fig.Pressure sensor

Pressure Sensor

- Pressure Sensor: In a pressor sensor an input signal such as pressure from a sourse is sensed by a microsensing element ,which may include simply a silicon diaphragm only a few micrometers thick.
- The deflection of the diaphragm induced by the applied pressure is converted into a change of electrical resistance by micropiezoresistors that are implanted in the diaphragm.
- The piezoresistors constitute the part of transduction unit.

Pressure Sensor

- The change of electrical resistance in the resistors induced by the change of crystal structure geometry can further be converted into corresponding voltage changes by a micro Wheatstone bridge circuit also attached to the sensing element as another part of transduction unit.
- The ouput of this micosensor is voltage change according to the input pressure

MEMS AS AN ACTUATOR

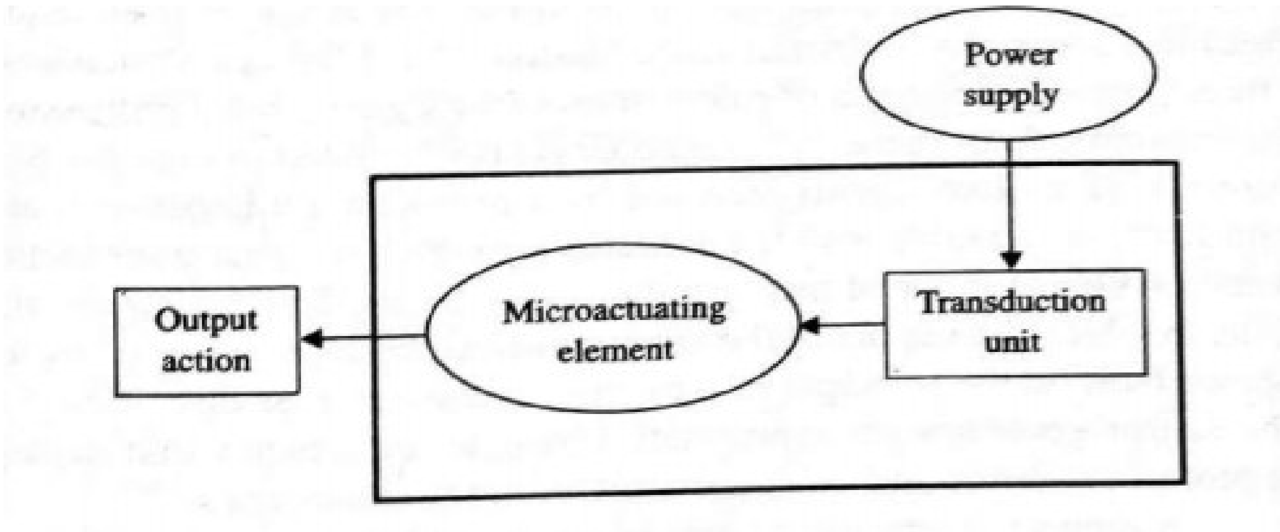
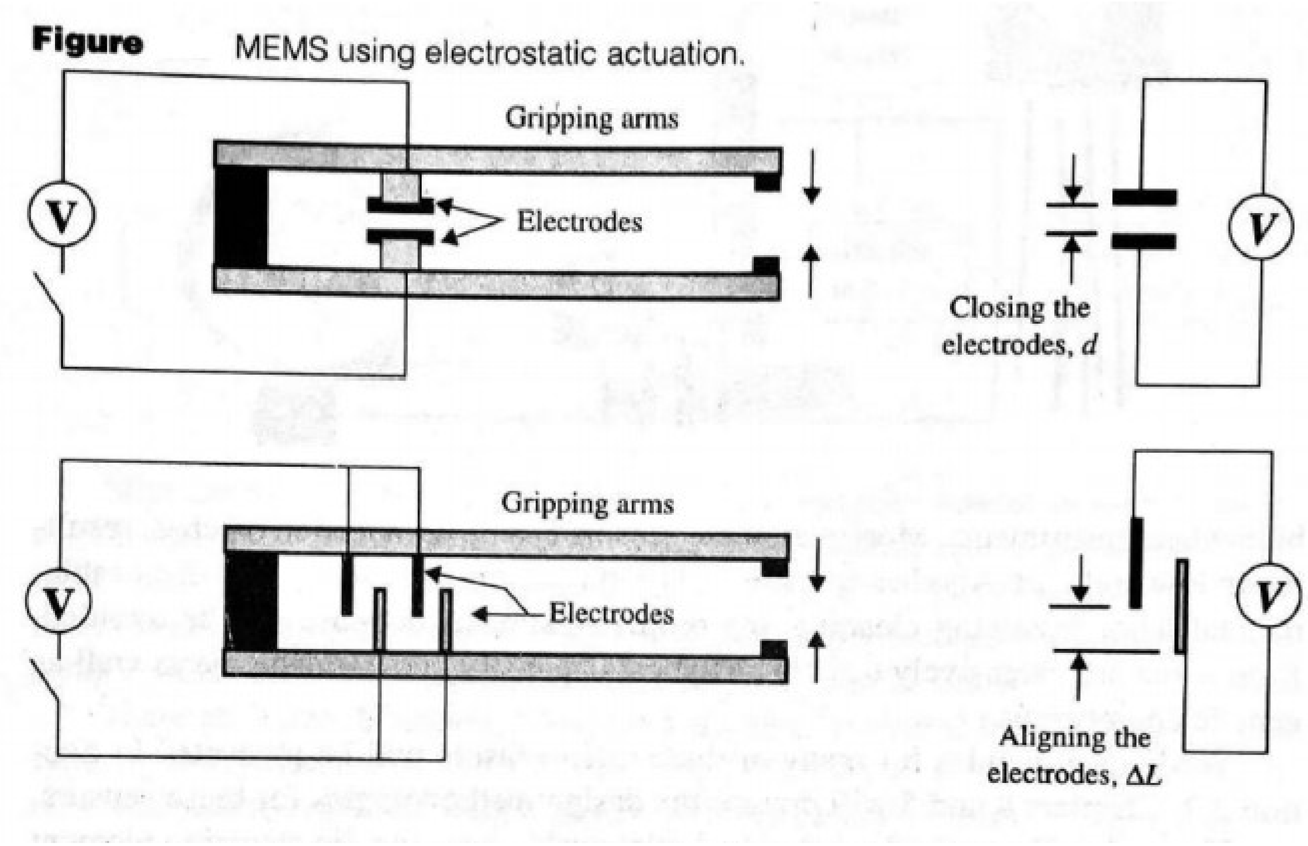


Fig.MEMS as an Actuator

Example-Electrostatic Actuation



Electrostatic Actuation

- Electrostatic Actuator: In Electrostatic Actuation the application of input voltage to the plates can result in Electrostatic forces that promt relative motion of these plates in the normal direction of the aligned plates or parallel movement of misaligned plates.These motions are set to accomplish the required actions. Electrostatic Actuating is used in many actuators.

Intelligent Microsystem

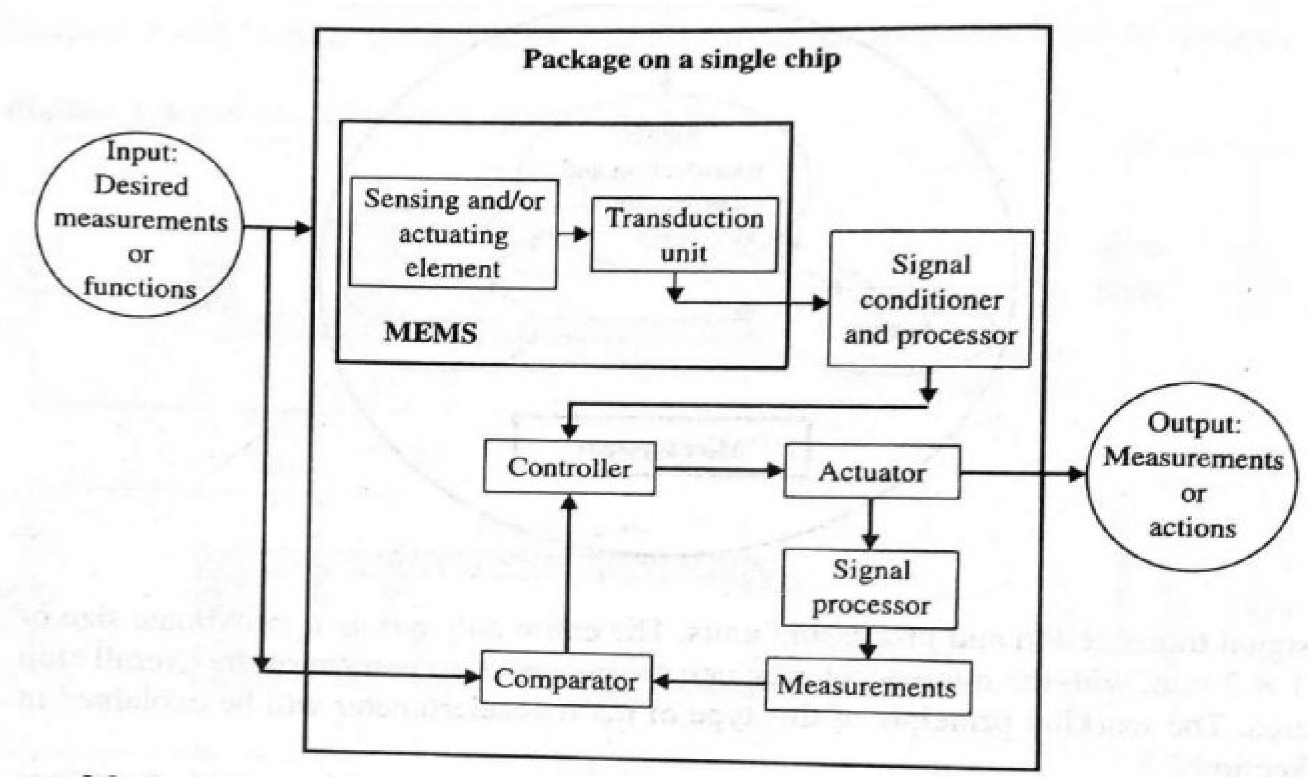


Figure Intelligent microsystems.

Intelligent Microsystem

- Signal processing and closed loop feedback control system in a control system makes the integrated system as Intelligent Microsystem.
- Example: Intertial sensors used in air bag deployment system in automobiles.

Microsystems and Microelectronics

Microelectronics	Microsystems (silicon-based)
Uses single crystal silicon die, silicon compounds, and plastic	Uses single-crystal silicon die and a few other materials, such as GaAs, quartz, polymers, and metals
Transmits electricity for specific electrical functions	Performs a great variety of specific biological, chemical, electromechanical, and optical functions
Stationary structures	May involve moving components
Primarily 2-D structures	Complex 3-D structures
Complex patterns with high density over substrates	Simpler patterns over substrates
Fewer components in assembly	Many components to be assembled
IC die is completely protected from contacting media	Sensor die is interfaced with contacting media
Mature IC design methodology	Lack of engineering design methodology and standards
Large number of electrical feedthroughs and leads	Fewer electrical feedthroughs and leads
Industrial standards available	No industrial standards to follow
Mass production	Batch production or on customer-needs basis
Fabrication techniques are proved and well documented	Many microelectronics fabrication techniques can be used for production
Manufacturing techniques are proved and well documented	Distinct manufacturing techniques
Packaging technology is relatively well established	Packaging technology is at the infant stage

Microsystems and Microelectronics

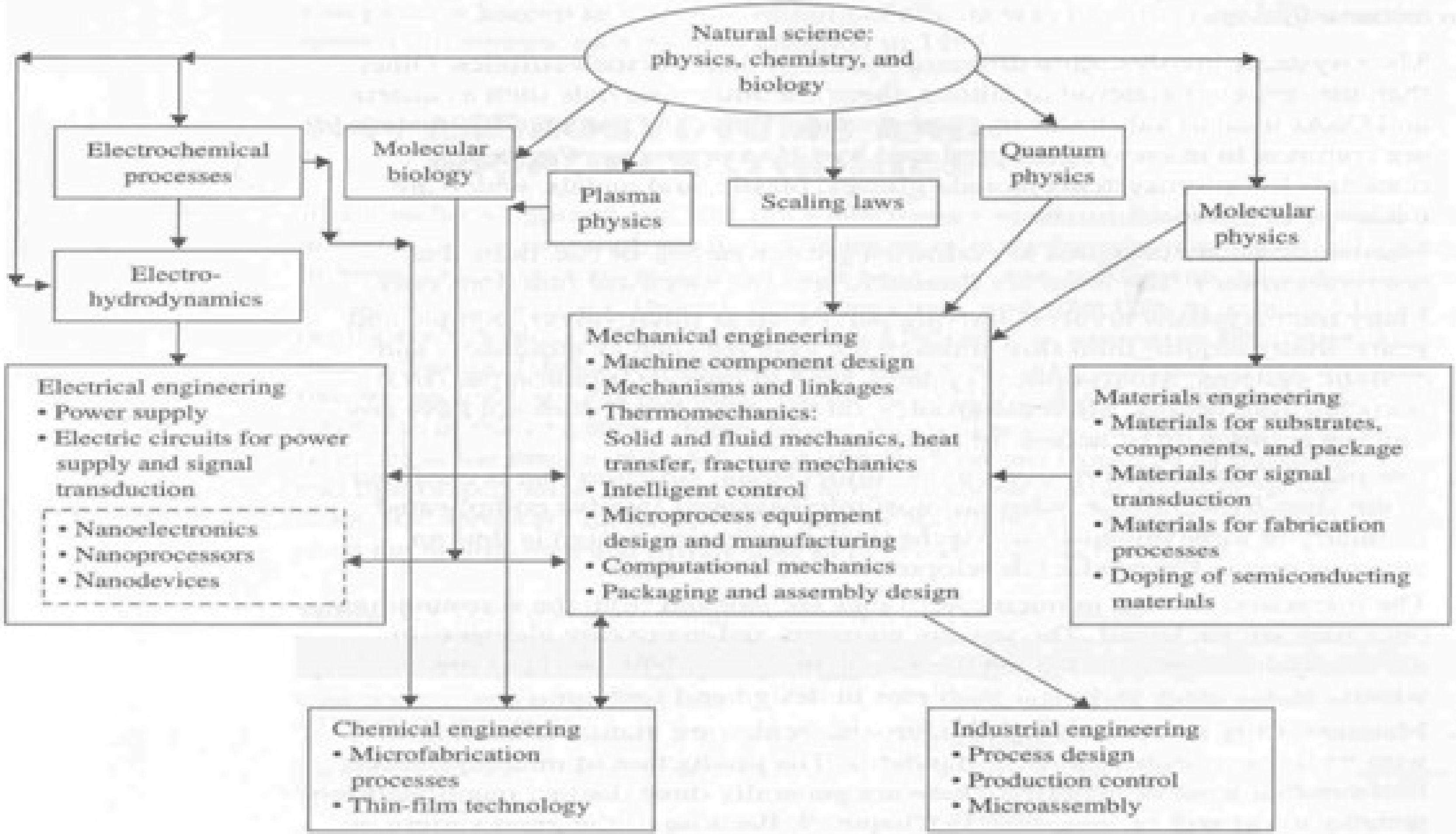
1. Microsystems involve more different materials than microelectronics. Other than the common material of silicon, there are other materials such as quartz and GaAs used as substrates in microsystems. Polymers and metallic materials are common in microsystems produced by LIGA processes. Packaging materials for microsystems include glasses, plastic, and metals, which are excluded in microelectronics.
2. Microsystems are designed to perform a greater variety of functions than microelectronics. The latter are limited to specific electrical functions only.
3. Many microsystems involves moving parts such as microvalves, pumps, and gears. Many require fluid flow through the systems such as biosensors and analytic systems. Micro-optical systems need to provide input/output (I/O) ports for light beams. Microelectronics, on the other hand, does not have any moving component or access for lights or fluids.
4. Integrated circuits are primarily a two-dimensional structure that is confined to the silicon die surface, whereas most microsystems involve complicated geometry in three dimensions. Mechanical engineering design is thus an essential part in the product development of microsystems.

Microsystems and Microelectronics

5. The integrated circuits in microelectronics are isolated from the surroundings once they are packaged. The sensing elements and many core elements in microsystems, however, are required to be in contact with working media, which creates many technical problems in design and packaging.
6. Manufacturing and packaging of microelectronics are mature technologies with well-documented industry standards. The production of microsystems is far from that level of maturity.

The Multidisciplinary Nature of Microsystem Design and Manufacturing

Figure Principal science and engineering disciplines involved in microsystem design and manufacture.



Natural sciences involved in Micro system Design and Manufacture

1. Electrochemistry is widely used in electrolysis to ionize substances in some micromanufacturing processes. Electrochemical processes are also used in the design of chemical sensors.
2. Electrohydrodynamics principles are used as the driving mechanisms in fluid flows in microchannels and conduits, such as those for capillary fluid flow
3. Molecular biology is intimately involved in the design and manufacture of biosensors and biomedical equipment
4. Plasma physics involves the production and supply of ionized gases with high energy. It is required for etching and deposition in many microfabrication

Natural sciences involved in Micro system Design and Manufacture

5. Scaling laws provide engineerswith a sense for the scaling down of physical quantities involved in the design of microdevices.

6. Quantum physics is used as the basis for modeling certain physical behaviors of materials and substances in microscales, as will be described in regard to microfluid flow and heat transportation in solids

7. Molecular physics provides many useful models in the description of materials at microscales, as well as the alteration of material properties and characteristics used in microsystems

   Molecular dynamics theories are the principal modeling tool for describing mechanical behavior of materials in nanoscale.

Engineering disclipines involved in Micro system Design and Manufacture

1. Mechanical engineering principles are used primarily in the design of microsystem structures and the packaging of the components. These would involve many aspects of design analyses as indicated in the central box in Figure Intelligent control of microsystems has not been well developed, but it is an essential part of *micromechatronics systems*, which are defined as intelligent microelectromechanical systems.
2. Electrical engineering involves electrical power supplies and the functional control and signal processing circuit design. For integrated microsystems, e.g., "laboratory-on-a-chip," the IC and microelectronic circuitry that integrates microelectronics and microsystems makes electrical engineering a major factor in the design and manufacturing processes.
3. Chemical engineering is an essential component in microfabrication and micromanufacturing

Engineering disclipines involved in Micro system Design and Manufacture

4. Materials engineering offers design engineers a selection of available materials that are amenable to microfabication and manufacturing ,as well as packaging.

   Materials engineering plays a key role in the development of chemical ,biological and optical sensors.

5. Industrial engineering relates to production and assembly of Microsystems.

Applications of Microsystems in Automotive Industry

Safety:

- Air bag depolyment system
- Antilock breaking system
- Suspension system
- Object avoidance
- Navigation

Engine and power train

A few of these sensors are:

- Manifold control with pressure sensors.
- Airflow control
- Exhaust gas analysis and control
- Crankshaft positioning
- Fuel pump pressure and fuel injection control
- Transmission force and pressure control
- Engine knock detection for higher power output

Comfort and Convenience

- Seat control (displacement sensors and microvalves)
- Rider's comfort (sensors for air quality, airflow, temperature, and humidity controls)
- Security (remote status monitoring and access control sensors)
- Sensors for defogging of windshields
- Satellite navigation sensors

Vehicle Diagnostics and Health Monitoring

- Engine coolant temperature and quality
- Engine oil pressure, level. and quality
- Tire pressure
- Brake oil pressure
- Transmission fluid
- Fuel pressure

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Vehicle Diagnostics and Health Monitoring

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- Brake oil pressure
- Transmission fluid
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Applications in the Aerospace Industry

- Cockpit instrumentation

  Pressure sensors for oil, fuel, transmission, and hydraulic systems

  Airspeed measurement

  Altimeters
- Safety devices, e.g., ejection seat controls
- Wind tunnel instrumentation (e.g., shear stress sensors)
- Sensors for fuel efficiency and safety
- Microgyroscopes for navigation and stability control
- Microsatellites

Applications in health care

- Sphygmomanometers
- Respirators
- Lung capacity meters
- Kidney dialysis equipment
- Medical process monitoring

Applications in Telecommuncations

- Optical switching and fibre optic couplings
- RF switches
- Tunable Resonators

MINIATURIZATION

- According to Webster's dictionary, the word miniature means a copy on a much-reduced scale. In essence, miniaturization is an art that substantially reduces the size of the original object yet retains the characteristics of the original (and more) in the reduced copy.

Benifits of miniaturization

- Smaller systems tend to move more quickly than larger systems because of lower inertia of the mass.
- The minute sizes of small devices encounter fewer problems in thermal distortion and vibration because resonant vibration of a system is inversely proportional to the mass. Smaller systems with lower masses have much higher natural frequencies than those expected from most machines and devices in operations.
- In addition to the more accurate performance of smaller systems, their minute size makes them particularly suitable for applications in medicine and surgery and in microelectronic assemblies in which miniaturized tools are necessary.
- Miniaturization is also desirable in satellites and spacecraft engineering to satisfy the prime concerns about high precision and payload size.
- The high accuracy of miniaturized systems in motion and dimensional stability make them particularly suitable for telecommunication systems.

SCALING LAWS IN MINIATURIZATION

- Introduction to Scaling
- Scaling in Geometry
- Scaling in Electrostatic forces
- MEMS Design Considerations

WHY SCALING LAWS?

- Miniaturizing machines and physical systems is an ongoing effort in human civilization.
- Intelligent, Robust, Multi-functional and Low cost
- consumer products has become more strong than ever. The only solution to produce these consumer products is to package many components into the product – making it necessary to miniaturize each individual components.
- Miniaturization of physical systems is a lot more than just scaling down device components in sizes. Some physical systems either cannot be scaled down favorably, or cannot be scaled down at all!

SCALING LAWS

- Scaling laws thus become the very first thing that any engineer would do in the design of MEMS and microsystems.

Scale sizes

Three general scale sizes:

(a) Astronomical objects

(b) Macro-objects

(c) micro-objects.

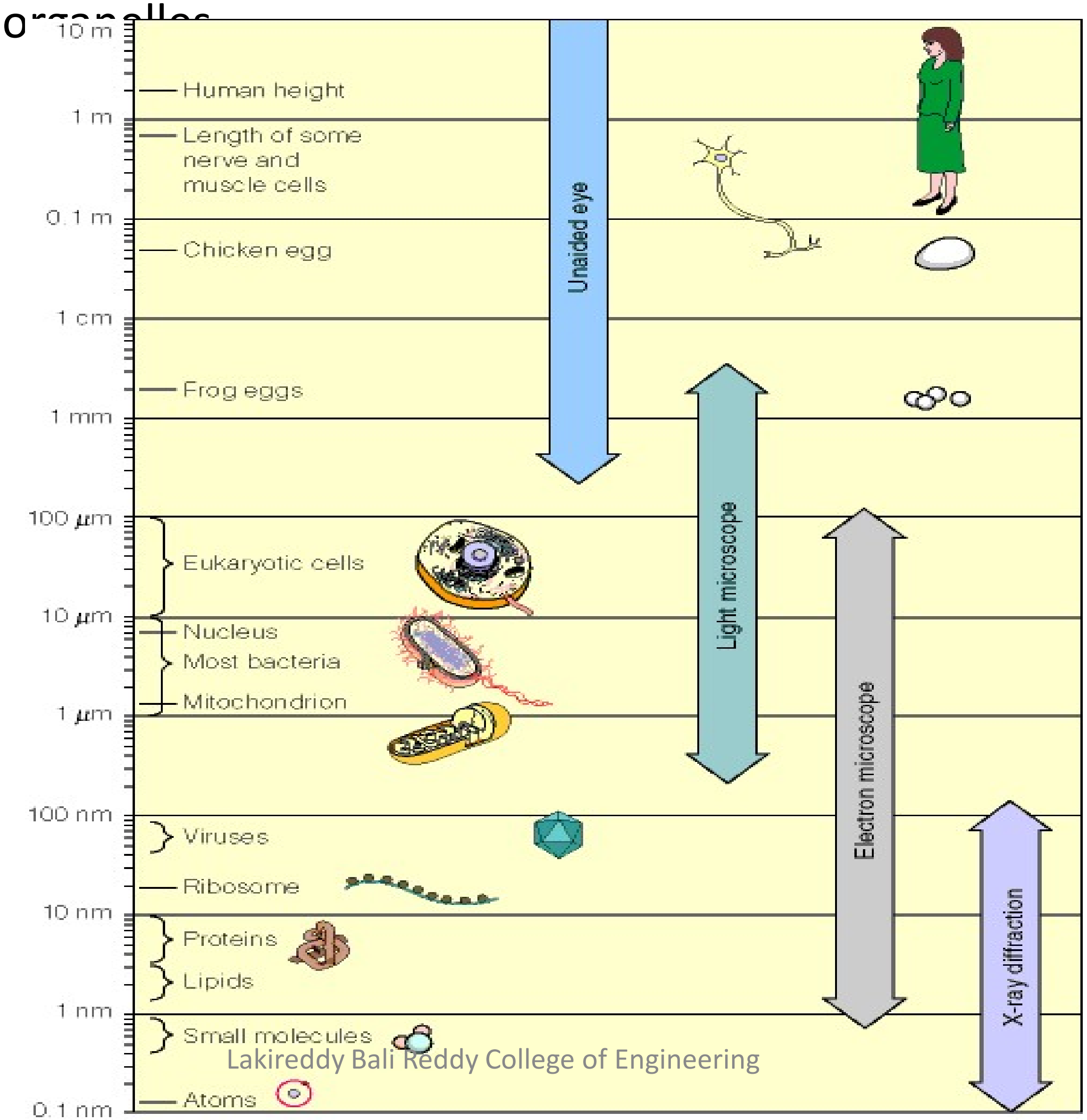
- Things effective at one of these scale sizes often are insignificant at another scale size.

Examples:

- Gravitational forces dominate on an astronomical scale (e.g., the earth moves around the sun), but not on smaller scales.
- Macro-sized motors use magnetic forces for actuation, but micro-sized ones usually use electrostatic fields instead of magnetic.

Range of sizes of objects studied by biochemists and biologists

Eukaryotes - Organisms whose cells are compartmentalized by internal cellular membranes to produce 3 a nucleus and organelles



Types of Scaling Laws

1. Scaling in Geometry:

   Scaling of physical size of objects

2. Scaling of Phenomenological Behavior :

   Scaling of both size and material characterizations

Scaling in Geometry

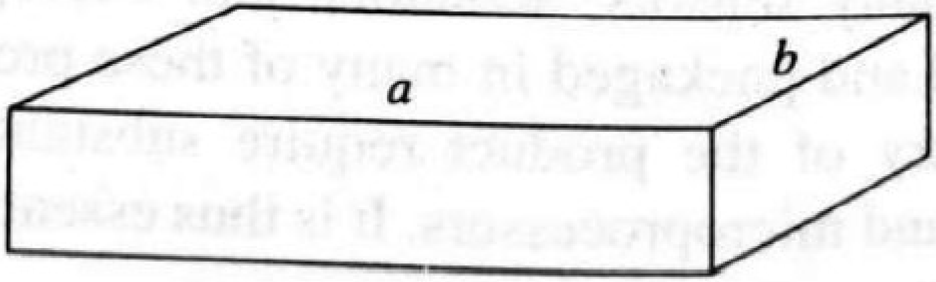
- Volume (V) and surface (S) are two physical parameters that are frequently involved in machine design.
- Volume leads to the mass and weight of device components.
- Volume relates to both mechanical and thermal inertia. Thermal inertia is a measure on how fast we can heat or cool a solid. It is an important parameter in the design of a thermally actuated device.

Scaling in Geometry

- Surface is related to pressure and the buoyant forces in fluid mechanics.
- For instance, surface pumping by using piezoelectric means is a practical way for driving fluids flow in capillary conduits.
- When the physical quantity is to be miniaturized, the design engineer must weigh the magnitudes of the possible consequences from the reduction on both the volume and surface of the particular device.

Scaling in Geometry-Example: A solid of rectangular geometry

Figure I A solid rectangle.



$a > b > c.$

volume $V = abc$ ➔ $V \alpha (l)^3$

surface area is $S = 2 \times (ac + bc + ab)$ ➔ $S \alpha (l)^2$

Where l represents linear dimension of a solid,then

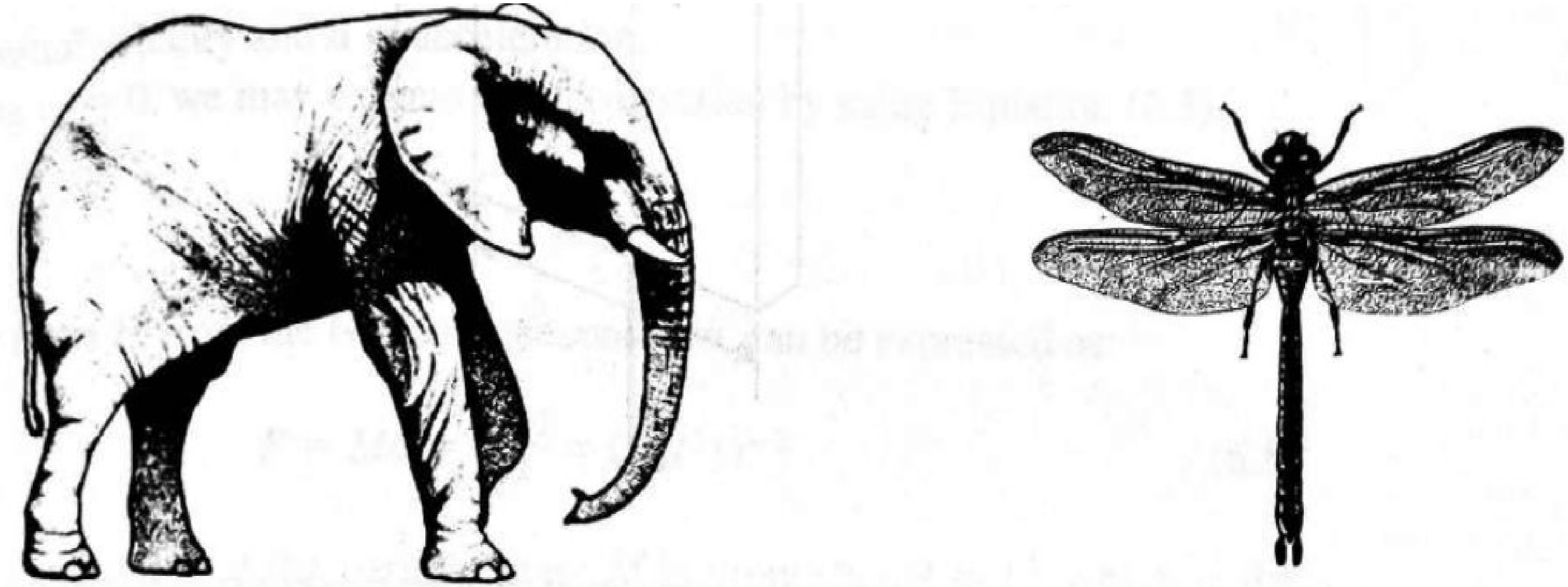
$$S/V = l^{-1}$$

Scaling in Geometry-Example: A solid of rectangular geometry

One may thus conclude from the scaling formula in Equation above that a reduction of size of 10 times (i.e., $l = 0.1$) will mean a $10^3 = 1000$ times reduction in volume, but only $10^2 = 100$ times reduction in surface area. A reduction of volume by 1000, of course, means a 1000 times reduction in weight.

The same scaling relations apply to other geometries of solids.

Scaling in Geometry-An Example of two living objects



(a) An elephant ($S/V \approx 10^{-4}$/mm)

(b) A dragonfly ($S/V \approx 10^{-1}$/mm)

Fig. The distinct surface-to-volume ratios of two objects.

The Trimmer Force Scaling Vector

The *force scaling vector* is defined as:

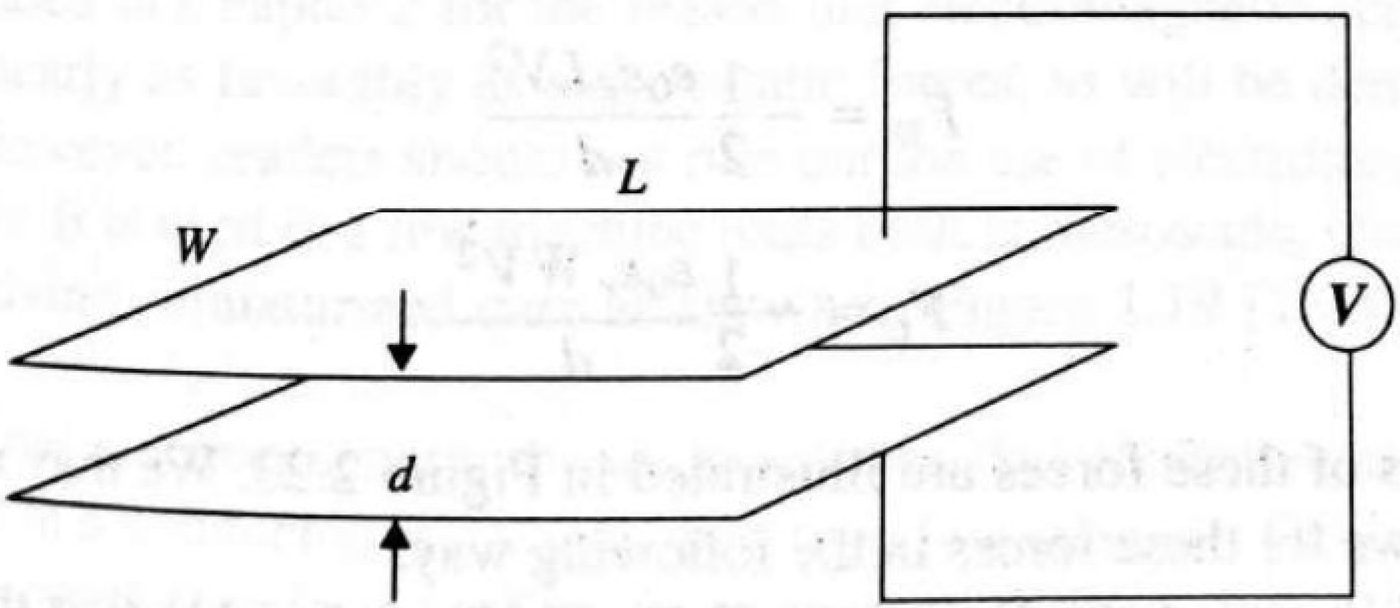
$$F = [l^F] = \begin{bmatrix} l^1 \\ l^2 \\ l^3 \\ l^4 \end{bmatrix}$$

Scaling Laws for a rigid body dynamics

Order	Force Scale -F	Acceleration -a	Time-t	Power density- P/V_0
1	l^{1}	l^{-1}	$l^{1.5}$	$l^{-2.5}$
2	l^{2}	l^{-2}	l^{1}	l^{-1}
3	l^{3}	l^{0}	$l^{0.5}$	$l^{0.5}$
4	l^{4}	l^{1}	l^{0}	l^{2}

Scaling in Electrostatics Forces

Fig. Electrically charged parallel plates.



Scaling in Electrostatics Forces

- The electric potential energy induced in the parallel plate capacitor is
- $U=(1/2)CV^2=((€_0€_rWL)/2d)\ V^2$

Where V is the applied voltage

$€_0$ is the absolute permittivity

$€_r$ is the relative permittivity

d is the distance between the plates

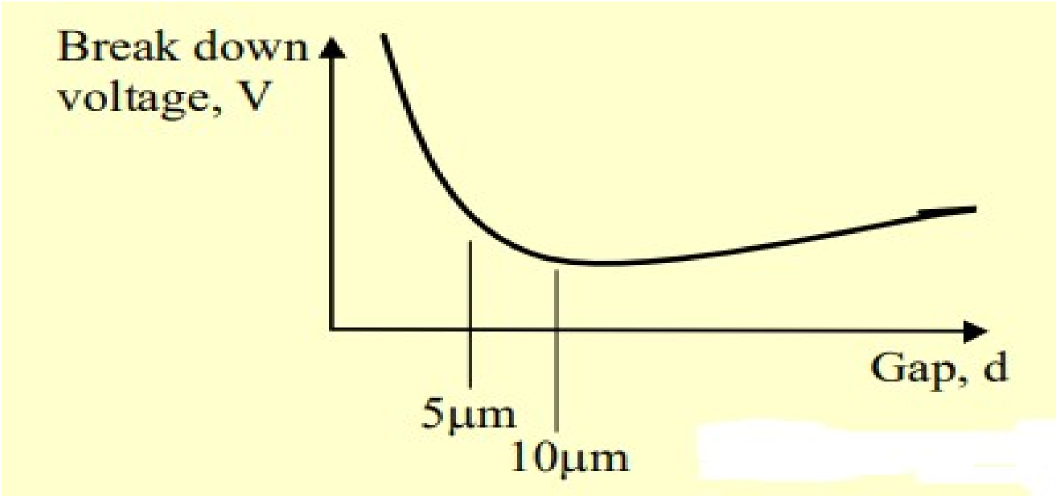
Scaling in Electrostatics Forces

- Applying scaling laws, the electric potential energy induced in the parallel plate capacitor becomes

- $U \alpha ((l^0)(l^0)(l^1)(l^1)(l^1)^2)/(l^1) = (l^3)$

Scaling in Electrostatics Forces

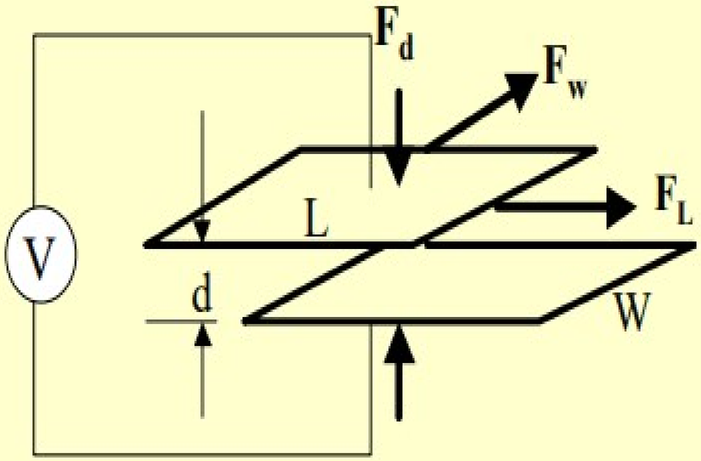
The scaling of voltage, V can be approximated by the Paschen's effect illustrated as:



Scaling: A 10 times reduction of linear size of electrodes → 10 3 = 1000 times reduction in Potential energy!!

Scaling in Electrostatics Forces

Electrostatic forces in misaligned electrodes are obtained by:



$$F_d = -\frac{\partial U}{\partial d} = -\frac{1}{2}\frac{\varepsilon_0 \varepsilon_r W L V^2}{d^2} \propto \ell^2$$

$$F_w = -\frac{\partial U}{\partial W} = \frac{1}{2}\frac{\varepsilon_o \varepsilon_r L V^2}{d} \propto \ell^2$$

$$F_L = -\frac{\partial U}{\partial L} = -\frac{1}{2}\frac{\varepsilon_0 \varepsilon_r W V^2}{d} = \propto \ell^2$$

Scaling in Electrostatics Forces

So, we may conclude that electrostatic forces:

$F_{d,}\ F_{W,}\ F_L\ \alpha\ l^2$

Scaling: A 10 times reduction in electrode linear dimensions → 10^2 = 100 times reduction in the magnitude of the electrostatic forces.

MEMS Design considerations