Precision Engineering is a sub-discipline of electrical engineering, electronics engineering, mechanical engineering, and optical engineering concerned with designing machines, fixtures, and other structures that have exceptionally low tolerances, are repeatable, and are stable over time. These approaches have applications in machine tools, MEMS, NEMS, optoelectronics design, and many other fields.

A fundamental principle in precision engineering is that of determinism. System behavior is **fully predictable** even to nanometer-scale motions.

The basic idea is that machine tools obey cause and effect relationships that are within our ability to understand and control and that there is nothing random or probabilistic about their behavior. Everything happens for a reason and the list of reasons is small enough to manage.

By this we mean that machine tool errors obey cause-and-effect relationships, and do not vary randomly for no reason. Further, the causes are not uncontrollable, but can be explained in terms of familiar engineering principles.

Micro-electro-mechanical systems (MEMS) is the technology of the very small, and merges at the nano-scale into nanoelectromechanical systems (NEMS) and nanotechnology. MEMS are also referred to as micro machines (in Japan), or *Micro Systems Technology* - *MST* (in Europe). MEMS are made up of components between 1 to 100 µm in size (i.e. 0.001 to 0.1 mm) and MEMS devices generally range in size from 20 µm to a mm. They usually consist of a central unit that processes data, the microprocessor and several components that interact with the outside such as micro-sensors.

MEMS became practical once they could be fabricated using modified semiconductor device fabrication technologies, normally used to make electronics. These include molding and plating, etching, electro discharge machining (EDM), and other technologies capable of manufacturing very small devices.

Semiconductor device fabrication is the process used to create the integrated circuits (silicon chips) that are present in everyday electrical and electronic devices. It is a multiple-step sequence of photographic and chemical processing steps during which electronic circuits are gradually created on a wafer made of pure semi-conducting material *[substance as germanium or silicon whose electrical conductivity is intermediate between that of a conductor and an insulator; its conductivity increases with temperature and in the presence of impurities]*. Silicon is the most commonly used semiconductor material today, along with various compound semiconductors.

[A **wafer** is a thin slice of semiconductor material, such as a silicon crystal, used in the fabrication of integrated circuits and other microdevices. The wafer serves as the substrate for microelectronic devices built in and over the wafer and undergoes many micro-fabrication process steps such as *doping*, etching and deposition of various materials.

Etching is used in micro-fabrication to chemically remove layers from the surface of a wafer during manufacturing. Etching is a critically important process module, and every wafer undergoes many etching steps before it is complete. For many etch steps, part of the wafer is protected from the etchant by a "masking" material which resists etching.

Doping In semiconductor production, doping is the process of intentionally introducing impurities into an extremely pure semiconductor to change its electrical properties.

Cleanliness in fabrication

Microfabrication is carried out in clean rooms, where air has been filtered of particle contamination and temperature, humidity, vibrations and electrical disturbances are under stringent control. Smoke, dust, and bacteria presence will destroy the functionality of a microfabricated device.

Clean room, in manufacturing and research, is a dust-free working area with strict temperature and humidity control that is of vital importance in the manufacture of equipment sensitive to environmental contamination, such as components for electronic and aerospace systems. Seamless plastic walls and ceilings, rounded corners, external lighting and wiring, a continuous flux of dust-free air, and daily cleaning are characteristic features. Clean-room workers wear special clothing, including head coverings, and, on entering, pass through an air blast, or air shower, to remove particles.

More accurately, a cleanroom has a *controlled* level of contamination that is specified by the number of particles per cubic meter at a specified particle size. To give perspective, the ambient air outside in a typical urban environment contains

35,000,000 particles per cubic meter, 0.5 µm and larger in diameter, corresponding to an ISO 9 clean room.

Cleanrooms can be very large. Entire manufacturing facilities can be contained within a cleanroom with factory floors covering thousands of square meters. They are used extensively in semiconductor manufacturing, biotechnology, the life sciences and other fields that are very sensitive to environmental contamination.

The air entering a cleanroom from outside is filtered to exclude dust, and the air inside is constantly re-circulated through high efficiency particulate air (HEPA) and/or ultra low particulate air (ULPA) filters to remove internally generated contaminants.

Staff enter and leave through airlocks (sometimes including an air shower stage), and wear protective clothing such as hats, face masks, gloves, boots and coveralls.

Equipment inside the cleanroom is designed to generate minimal air contamination. Cleanroom furniture is also designed to produce a minimum of particles and to be easy to clean.

Common materials such as paper, pencils, and fabrics made from natural fibers are often excluded; however, alternatives are available. Cleanrooms are not sterile (i.e., free of uncontrolled microbes) and more attention is given to airborne particles. Particle levels are usually tested using a particle counter.

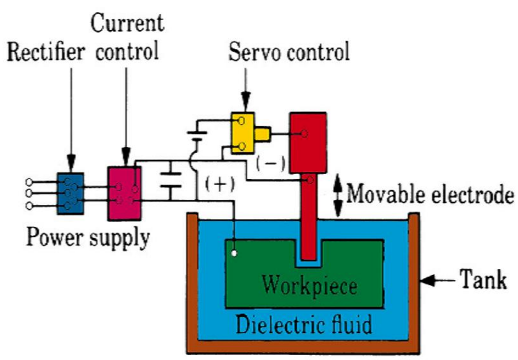
Some clean room systems control the humidity to low levels, such that extra equipment ("ionizers") is necessary to prevent electrostatic discharge (ESD) problems.

Low-level clean rooms may only require special shoes, ones with completely smooth soles that do not track in dust or dirt. However, shoe bottoms must not create slipping hazards (safety always takes precedence). Entering a clean room usually requires wearing a clean room suit.

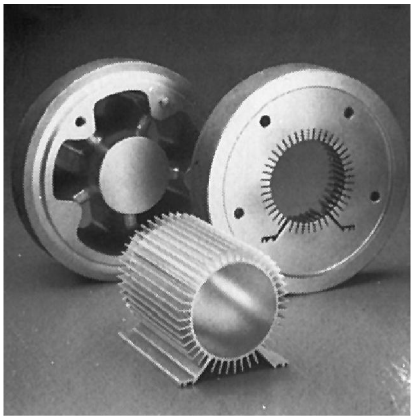
In other clean rooms, in which the standards of air contamination are less rigorous, the entrance to the clean room may not have an air shower. There is an anteroom (known as a "gray room"), in which the special suits must be put on, but then a person can walk in directly to the room (as seen in the photograph on the right).

Some manufacturing facilities do not use fully classified clean rooms, but use some clean room practices together to maintain their cleanliness requirements.

Electric discharge machining (**EDM**), sometimes referred to as **spark eroding**, is a manufacturing process whereby a wanted shape of a work piece, is obtained using electrical discharges (sparks). The material removal from the work piece occurs by a series of rapid current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. One of the electrodes is called tool-electrode and is sometimes simply referred to as 'tool' or 'electrode', whereas the other is called work piece-electrode. When the distance between the two electrodes is reduced, the intensity of the electric field in the volume between the electrodes is expected to become larger than the strength of the dielectric and therefore the dielectric breaks allowing some current to flow between the two electrodes. A collateral effect of this passage of current is that material is removed from both the electrodes.



(a)



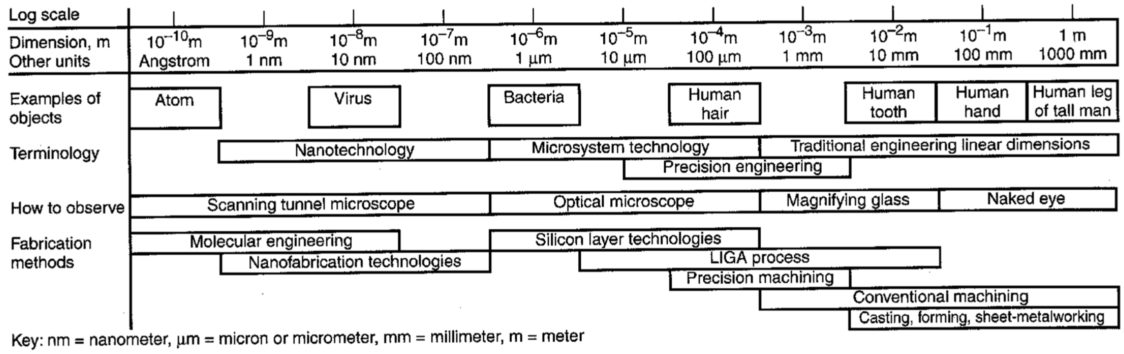
(b)

(a) Schematic illustration of the EDM process. (b) Examples of cavities produced by the electrical-discharge machining process, using shaped electrodes.

The term **Nano-electro-mechanical systems** or **NEMS** is used to describe devices integrating electrical and mechanical functionality on the nanoscale. NEMS form the logical next miniaturization step from so-called microelectromechanical systems, or MEMS devices. NEMS typically integrate transistor-like nanoelectronics [**Nanoelectronics** refer to the use of nanotechnology on electronic components, especially transistors. The term *nanotechnology* is generally defined as *utilizing technology less than 100 nm in size*] with mechanical actuators, pumps, or motors, and may thereby form physical, biological, and chemical sensors. The name derives from typical device dimensions in the nanometer range, leading to low mass, high mechanical resonance frequencies, potentially large quantum mechanical effects such as zero point motion, and a high surface to volume ratio useful for surface-based sensing mechanisms. Uses include accelerometers, or detectors of chemical substances in the air.

MICRO FABRICATION TECHNOLOGIES

An important trend in product design and manufacturing involves products and/or components of products whose features sizes are measured in microns (10^{-3} mm or 10^{-6} m). Several terms have been applied to these miniaturized items. **Micro-electro-mechanical systems (MEMS)** emphasize the miniaturization of systems consisting of both electronic and mechanical components. The word ***micro-machines*** is sometimes used for these systems. Microsystem technology (MST) is a more general term that refers to the products (not necessarily limited to electromechanical products) as well as the fabrication technologies used to produce them. A related term is **nanotechnology**, which refers to even smaller devices whose dimensions are measured in nanometers (10^{-9} m). The figure shown below indicates the relative sizes and other factors usually associated with these terms. The figure also provides an overview of the processes described in this context.



Terminology and relative sizes for Microsystems and related technologies.

MICROSYSTEM PRODUCTS

Designing products that are smaller and are comprised of smaller components and subassemblies means **less material usage, lower power requirements, greater functionality per unit space,** and **accessibility to regions that are forbidden to larger products.** In most cases, smaller products should mean lower prices because less material is used; **however**, the price of a given product is influenced by the costs of research, development, and production, and how these costs can be spread over the number of units sold. The economies of scale that result in lower-priced products have not yet fully been realized in microsystems technology, except for a limited number of cases that we shall examine in this section.

Types of Microsystem Devices

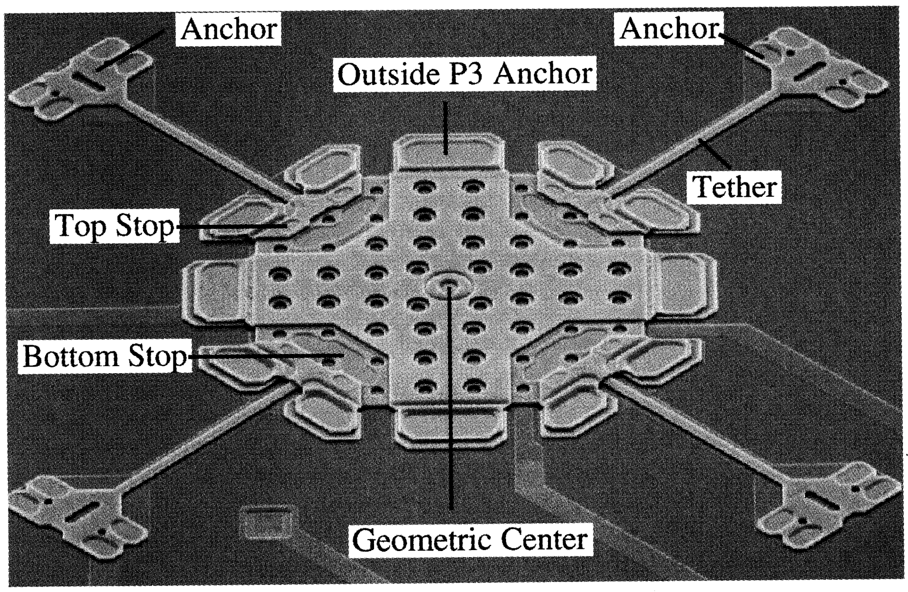
Microsystem products can be classified by type of device (e.g., sensor, actuator) or by application area (e.g., medical, automotive). Device types can be classified as follows:

Micro-sensors

A sensor is a device that detects or measures some physical phenomenon such as heat or pressure. It includes a transducer that converts one of physical variable into another form (e.g., a piezoelectric device converts mechanical force into electrical current) plus the physical packaging and external connections. Most micro-sensors

are fabricated on a silicon substrate using the processing technologies as those used for integrated circuits. Microscopic-sized sensors have been developed for measuring force, pressure, position, speed, acceleration, temperature, flow, and a variety of optical, chemical, environmental, and biological variables.

The term **hybrid micro-sensor** is often used when the sensing element (transducer) is combined with electronics component in the same device. The figure shows a micrograph of a micro-accelerometer developed at Motorola Co.



Micrograph of a micro-accelerometer.
(Photo courtesy of A. A. Tseng, Arizona State University).

Micro-actuators

Like a sensor, an actuator *converts a physical variable of on into another type*, but the converted variable usually involves some mechanical action (e.g., a piezoelectric device oscillating in response to an alternating electrical field). An actuator causes a change in position or the application of force. Examples of micro actuators include valves, positioners, switches, pumps, and rotational and linear motors.

Microsystems and micro-instruments

These terms denote the integration of several of the preceding components together with the appropriate electronics package into

a miniature system or instrument. Microsystems and micro-instruments tend to be very application specific; for example, micro-lasers, optical chemical analyzers, and micro-spectrometers. The economics of manufacturing these kinds of systems have tended to make commercialization difficult.

Industrial Applications

The preceding microdevices and systems have been applied in a wide variety of fields. There are many problem areas that can be approached best using very small devices.

Some important examples are the following:

Ink-Jet Printing Heads This is currently one of the largest applications of MST, because a typical ink-jet printer uses up several cartridges each year. The operation of the ink-jet printing head is depicted in the figure below. An array of resistance heating elements is located above a corresponding array of nozzles. Ink flows between the heaters and nozzles. Each resistor can be independently activated under microprocessor control in microseconds. When activated, the liquid ink immediately beneath the heater boils instantly, bursting through the nozzle opening and hitting the paper, where it dries almost immediately to form a dot that is part of an alphanumeric character or other image.
Today's ink-jet printers possess resolutions of 1200 dots per inch (dpi), which converts to a nozzle separation of only about 21 μm, certainly in the microsystem range.

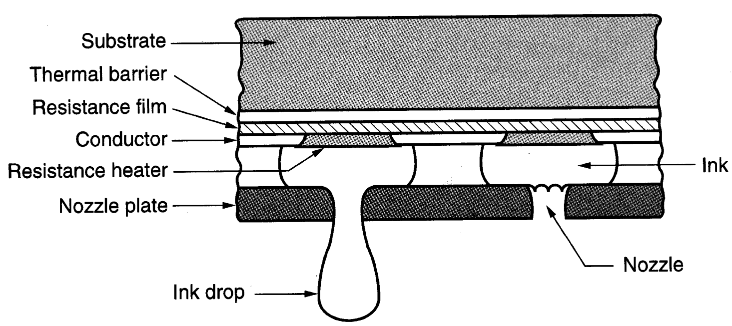


Diagram of an ink-jet printing head.

Thin-Film Magnetic Heads Read-write heads are key components in magnetic storage devices. These heads were previously manufactured from horseshoe magnets that were manually wound with insulated

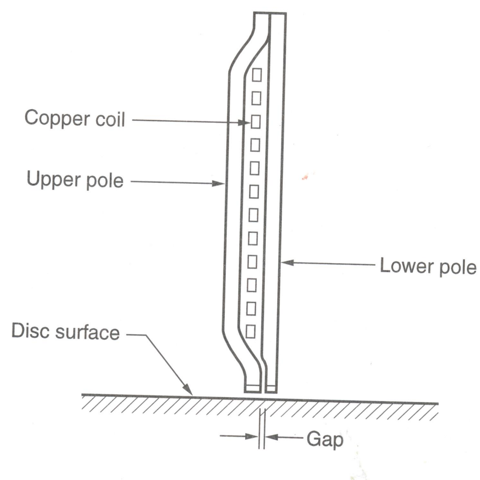
copper wire. Because the reading and writing of magnetic media with higher-bit densities are limited by the size of the read-write head, hand-wound horseshoe magnets were a limitation on the technological trend toward greater storage densities.

Development of thin-film magnetic heads at IBM Corporation was an important breakthrough in digital storage technology as well as significant success story for micro-fabrication technologies. Thin-film read-write heads are produced annually in hundreds of millions of units, with a market of several billions of dollars per year.
A simplified sketch of the read-write head is presented in the figure below, showing its MST parts. The copper conductor coils are fabricated by electroplating copper through a resist mold. The cross section of the coil is about 2 to 3 μm on a side. The thin-film cover, only a few μm thick, is made of nickel-iron alloy. The miniature size of the read-write head has permitted the significant increases in bit densities of magnetic storage media. The small sizes are made possible by microfabrication technologies.

Compact Discs Compact discs (CDs) represent important commercial products today, as storage media for audio, video, and computer software storage applications. CDs are mass-produced by plastic molding. The molds for the process are fabricated using micro-system technology. A master for the mold is made from a smooth, thin layer of polymer coated onto a glass plate. The polymer is exposed to a laser beam that writes the data into the surface. When developed, the data are represented in the form of microscopic pits in the surface. The mold is then made by electroforming metal on this polymer master.

Automotive Micro-sensors and other micro devices are widely used in modern automotive products. Use of these micro-systems is consistent with the increased application of on-board electronics to accomplish control and safety functions for the vehicle. The functions include electronic engine control, cruise control, anti-lock braking systems, air-bag

deployment, automatic transmission control, power steering, all-wheel drive, automatic stability control, on-board navigation systems, and remote locking and unlocking, not to mention air conditioning and radio. These control systems and safety features require sensors and actuators, and a growing number of these are microscopic in size.



Thin-film magnetic read-write head (simplified)

Accuracy and Precision

In the fields of engineering, industry and statistics, the **accuracy** of a measurement system is the degree of closeness of measurements of a quantity to its actual (true) value. The **precision** of a measurement system, also called reproducibility or repeatability, is the degree to which repeated measurements under unchanged conditions show the same results. Although the two words can be synonymous in use, they are deliberately contrasted in the context of scientific method.

A measurement system can be accurate but not precise, precise but not accurate, neither, or both. For example, if an experiment contains a systematic error, then increasing the sample size generally increases precision but does not improve accuracy. Eliminating the systematic error improves accuracy but does not change precision.