EMT 3101
Precision Engineering and Nanotechnology

- Concepts of Precision Engineering: Meso-scale systems, Micro-engineering, Nano-engineering.
- Precision measurements: Nanotribology. Classical laser interferometry: Michelson interferometry, laser dopler interferometry, Young's fringes, in-plane motion measurements, heterodyne interferometry, diffraction and Fourier optics, micro- and nano-displacement measurements, nanopositioning. X-ray interferometry.
- Micro Electro Mechanical Systems (MEMS): Advanced sensors and actuators design and fabrication: Microelectronic fabrication process, MEMS Fabrication process. Micro manufacturing, Nano manufacturing, Micro-machines and Nano machines.
- Micromachining: micromilling, Micro wire-Electro Discharge Machining (EDM), Laser micromachining abrasive polishing, nano-abrasion machining. Micro and Nano deposition: Chemical vapour deposition (CVD), Nano Layer Deposition (NLD), Atomic layer Deposition (ALD), Physical Vapour Deposition (PVD).
- Practical Applications. Recent trends in nanotechnology.

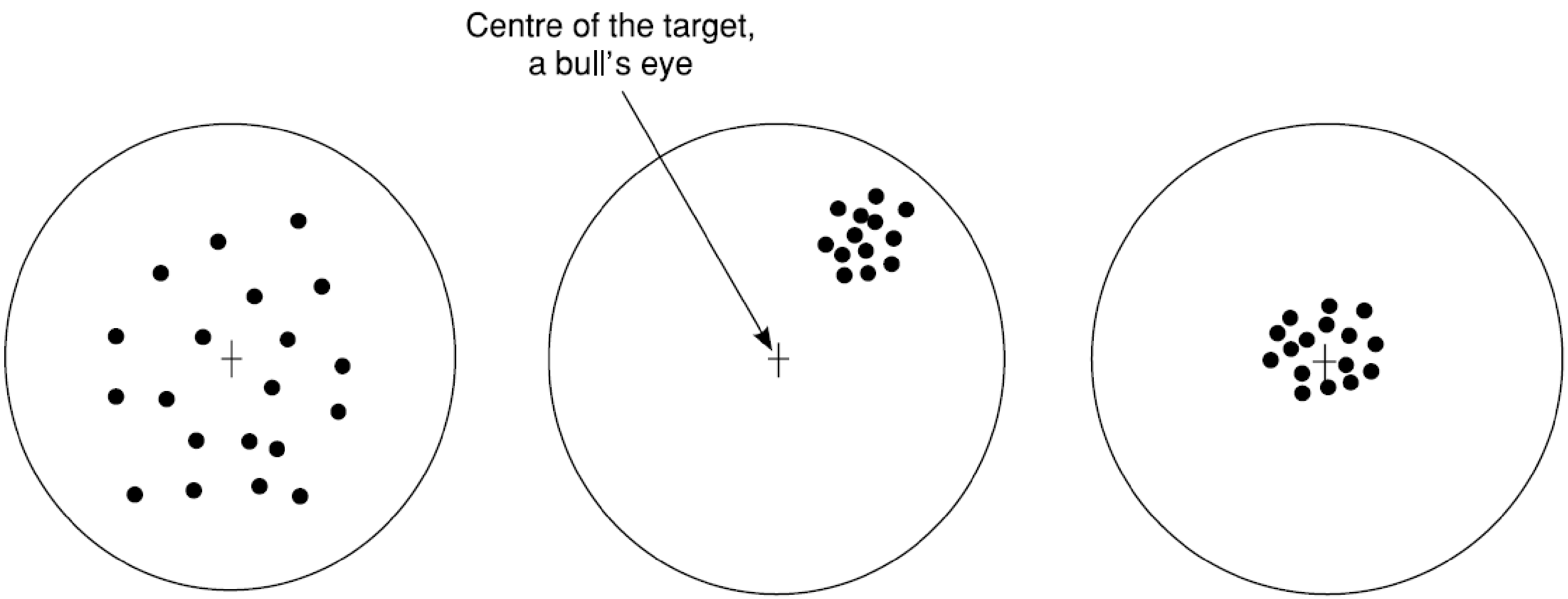
Precision Engineering

Definitions

- Precision engineering concerns the creation of **high-precision machine tools** (design, fabrication and measurement).
- Precision **processing** of materials, information processing systems, control systems and unmanned manufacturing systems containing CAD and CAM systems
- Manufacture of items that have a **wide range of sizes**, from those that are as large as the satellite rocket launcher to ones that are as small as the microchip
- **Goal of precision engineering** - to achieve a high relative accuracy (ratio of tolerance to dimension).

Accuracy versus Precision

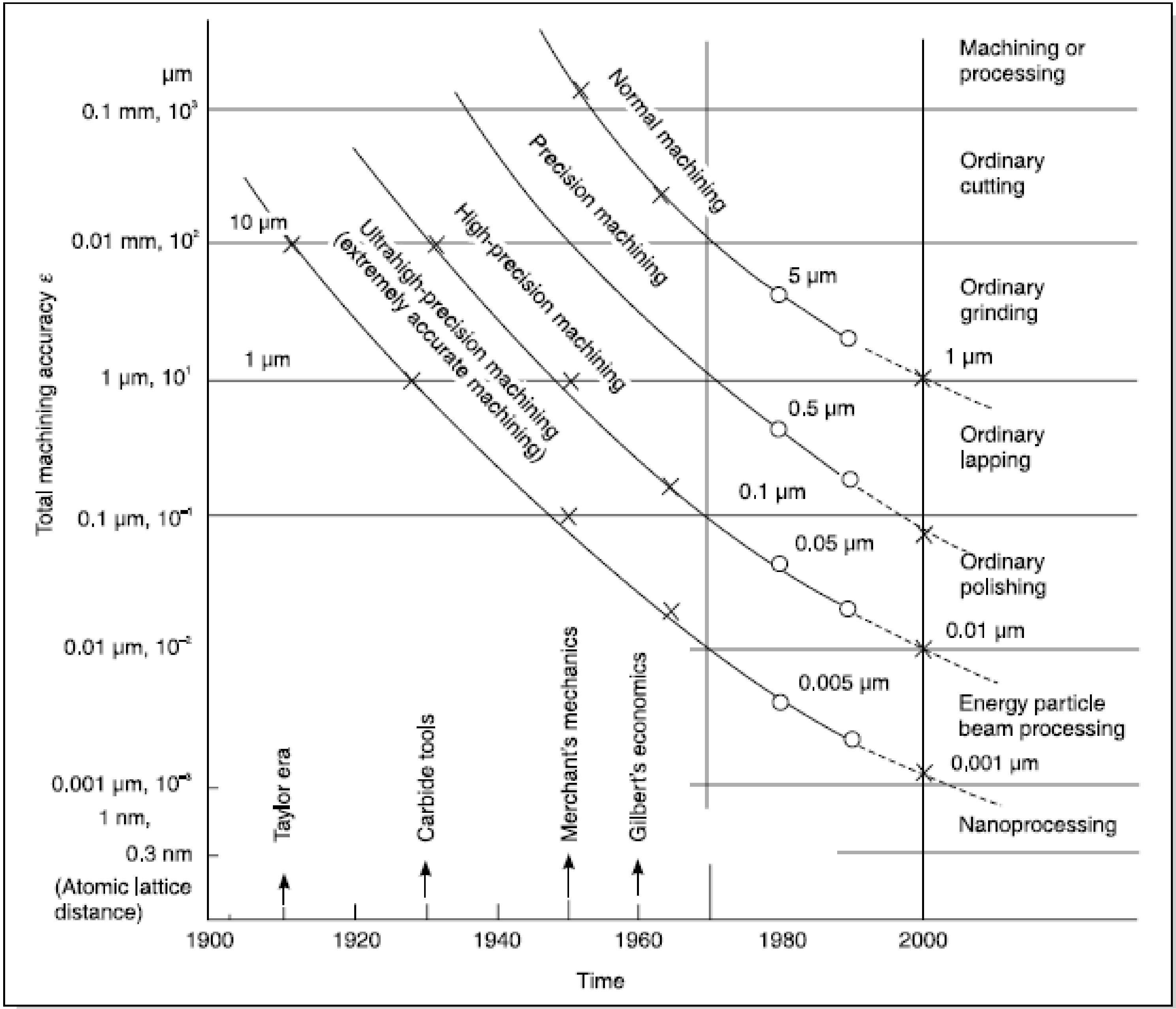
- The goal of precision engineering: To achieve a higher precision in the manufacture of a part.



(a) Accurate, not precise (b) Precise, not accurate (c) Accurate and precise

Objectives of precision engineering

- Create highly precise movements
- **Improve interchangeability** of components so that corresponding parts made by other factories
- Improve quality control through **higher machine accuracy** capabilities and hence reduce scrap, rework, and conventional inspection
- Reduce the dispersion of the product's or part's function
- Eliminate fitting and **promote assembly** especially automatic assembly
- Enable the design safety factor to be lowered
- Make functions independent of one another
- Achieve greater miniaturization and packing densities



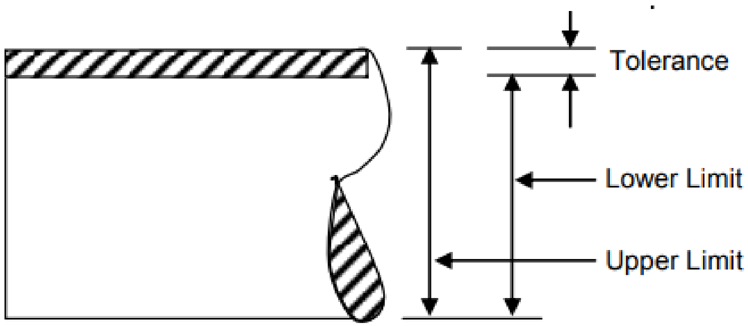
Machining or processing
Ordinary cutting
Ordinary grinding
Ordinary lapping
Ordinary polishing
Energy particle beam processing
Nanoprocessing
Normal machining
Precision machining
High-precision machining
Ultrahigh-precision machining (extremely accurate machining)
µm
0.1 mm, 10^3
0.01 mm, 10^2
1 µm, 10^1
0.1 µm, 10^{-1}
0.01 µm, 10^{-2}
0.001 µm, 10^{-3}
1 nm,
0.3 nm
(Atomic lattice distance)
10 µm
1 µm
5 µm
0.5 µm
0.1 µm
0.05 µm
0.01 µm
0.005 µm
0.001 µm
Total machining accuracy ε
Taylor era
Carbide tools
Merchant's mechanics
Gilbert's economics
1900
1920
1940
1960
1980
2000
Time

Classes of achievable accuracy

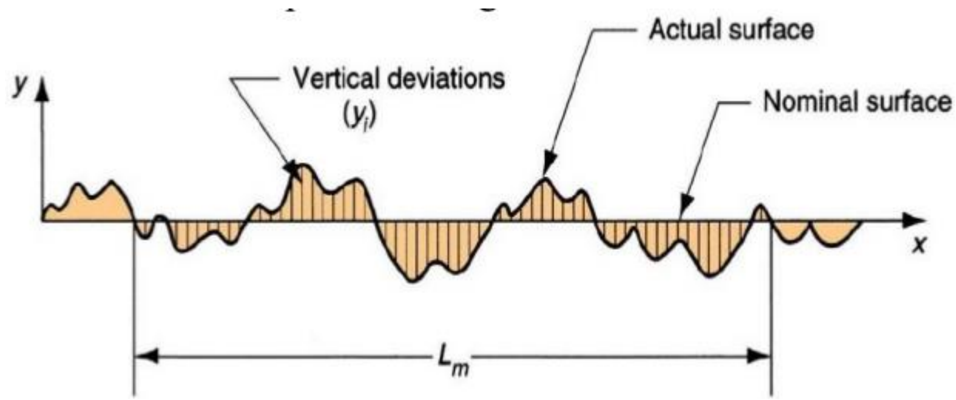
1. Normal machining
2. Precision machining
3. High-precision machining, and
4. Ultra-precision machining

Parameters of interest,

Tolerance:

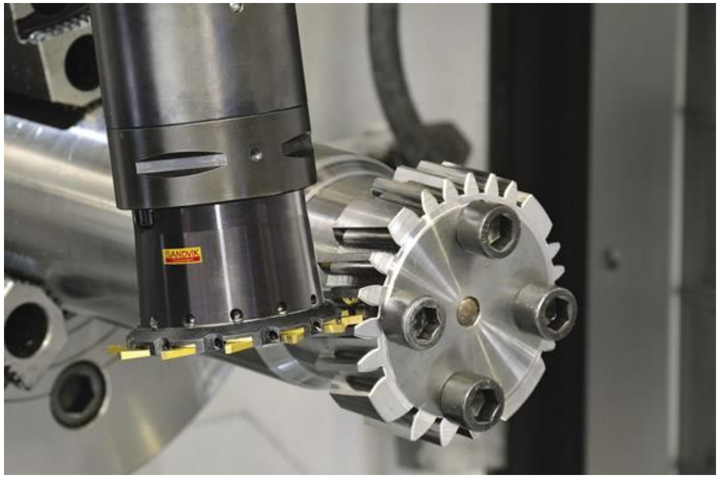


Surface roughness, R_a – Average of vertical deviations from nominal surface over specified length surface.



1. Normal Machining

- **Tolerance band**: 50 μm – 200 μm
- Normal mechanical parts, transistors, diodes, camera shutters
- Surface finish, R_a
  - Shaping: 12.5 – 16 μm
  - Milling: 6.3 – 0.8 μm
  - Turning: 6.3 - 0.4 μm
  - Drilling: 6.3 – 0.8 μm



2. Precision machining

- **Tolerance band**: 5 µm – 0.5 µm
- Surface Roughness, R_a:
  - Boring: 6.3 – 0.4 µm
  - Laser: 6.3 -0.8 µm
  - Electrochemical Machining: 3.2 – 0.2 µm
  - Grinding: 3.2 – 0.1 µm
  - Honing: 0.8 – 0.1 µm
- Products:
  - IC Chips: End milling
  - Ball and roller bearings, magnetic scales, quartz oscillators
  - Spherical and aspherical surfaces on plastics and glass (Moulds)

3. High precision machining

- High-precision CNC diamond turning machines are available for diamond mirror machining of components such as:
  a) Computer magnetic memory disc substrates
  b) Convex mirrors for high output carbon dioxide laser resonators
  c) Spherical bearing surfaces made of beryllium, copper, etc.
  d) Infrared lenses made of germanium for thermal imaging systems
  e) Scanners for laser printers
- Lapping and polishing are considered to be high-precision machining operations

4. Ultra-precision machining

- Dimensional tolerances: of the order of 0.01 µm (10nm)
- Surface roughness of 0.001 µm - (1 nm).
- Dimensions of the parts as small as 1 µm,
- Example: Integrated circuit (IC) - ultra-precision **machining accuracy** capability of the order of **0.005 µm (5 nm).**
- Machining processes :
  - Single-point diamond and cubic boron nitride (CBN) cutting
  - Free abrasive (erosion) processes such as lapping, polishing,
  - Chemical (corrosion) processes such as controlled etch machining
  - Energy beam processes : Photon (laser) beam for cutting, drilling, Electron beam for lithography, welding, Electrochemical (current) (ECM) for profiling

Precision Measurements

Nano tribology

- Size of mechanical, electrical and optical components is reducing at a very fast pace.
- Going from macro to nano scale, the **surface area to volume ratio increases considerably** and the **surface forces** such as **friction**, **adhesion**, **meniscus forces**, **viscous drag**, and **surface area** significantly increase.
- "**Tribology**" - combination of two Greek words - "tribo" and "logy". "Tribo" means rubbing and "logy" means knowledge.
- **Nanotribology**: investigations of interfacial processes, on scales ranging in the molecular and atomic scale, occurring during adhesion, friction, scratching, wear, nano-indentation, and thin-film lubrication at sliding surfaces.

Nano tribology (cont.)

- Tribology helps to increase the lifespan of mechanical components. However many industrial processes require a detailed understanding of tribology at the nanometer scale.
- Examples of application areas:
  - Development of lubricants in the automobile industry depends on adhesion of nanometer layers or monolayers to the material surface.
  - Assembly of components can depend critically on the adhesion of materials at the nanometer length scale
  - Fast moving interacting surfaces for rapid actuation
  - Materials with low friction and adhesion are desirable.

Why we need nano-tribology

- New electronic and atomic interactions
- New properties like magnetic and mechanical properties observed at nano-levels for synthesis, assembling and processing of nanoscale building blocks
- Smart materials with in built condition based maintenance and self-repair e.g. Microcraft space exploration
- In-situ lubrication study and control.
- Self replicating biomimetic materials: materials developed using inspiration from nature
- Self cleaning surfaces with reduced and controlled friction, wear and corrosion.
- Advanced health care: to modify surfaces in order to create structures that control interaction between materials and biological systems
- Energy conversion and storage: nanoscale carbide coatings.
- nanoscale devices which can sustain any need for movement of sliding surfaces for long periods under severe conditions.
- Ultra light weight and ultra strong materials with unique properties for required for demanding projects.

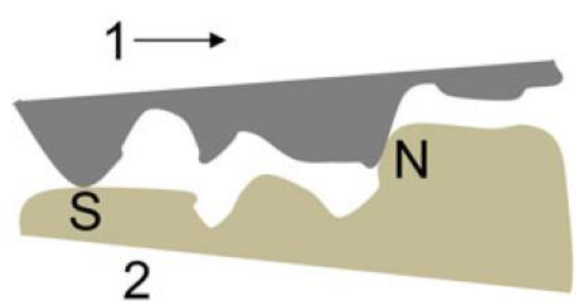
Importance of studying surfaces

- Surface roughness has a huge influence on physical phenomena such as contact mechanics, sealing, adhesion and friction.
- Reasons for studying surfaces especially on the nano-scale:

1. Properties of surface atoms are generally different from those of the same atoms in the bulk material
2. In any interaction of a solid with another phase, the surface atoms are the first to be encountered.

The study of surfaces

- When two solid surfaces come into contact, contact happens at the tips of irregularities which are called as **asperities**.
- As the top surface is moved against the bottom surface, interaction between the asperities takes place.
- Asperities may slide against each other (point S) and in some other places the asperities indent with each other (point N).



- During the interaction of the asperities, asperity region can deform either **elastically** or **plastically** depending on the local contact pressure.
- Adsorbed layers, and oxides, worked area also gets deformed.

Surface characterization

- Tribological properties of surface and surface films are extremely **sensitive to the adsorbed species, surface texture**, and **orientation of the solid surface**.

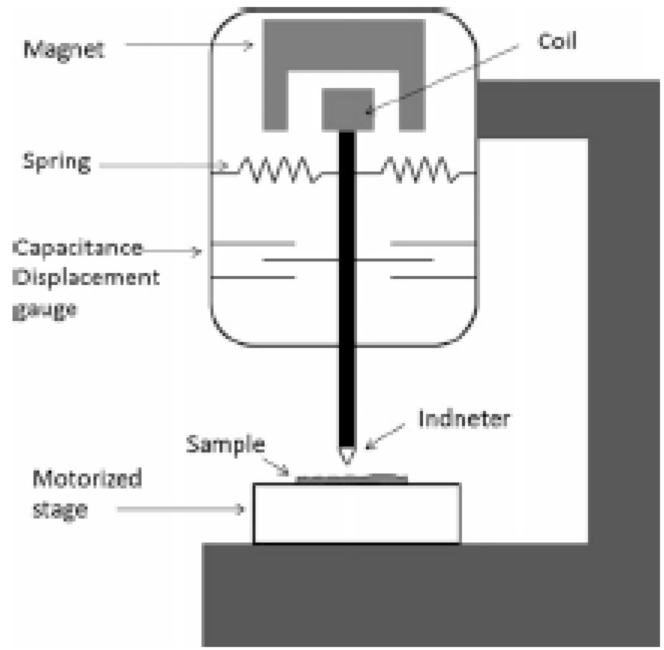
- Three different kinds of probes are used for surface characterization:
  - Mechanical probes
  - Photon (optical and X-rays)
  - Electron

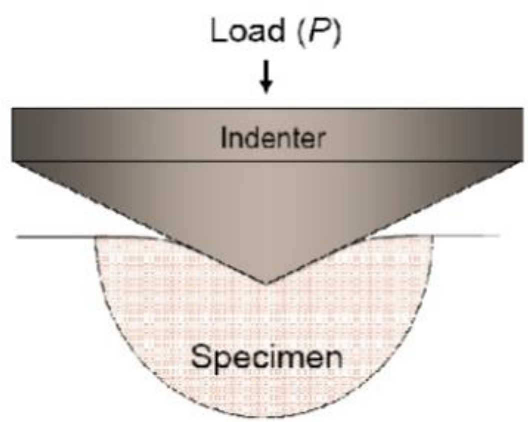
Mechanical Probes

- A sharp tip of known geometry is used to probe the sample.
- Common methods:
  1. **Nanoindentation**: used to determine the mechanical properties of small volume of the materials
  2. **Atomic force microscopy (AFM)**: used to get the topographic information of the surface in nanometer length scale.
  3. **Scanning Tunneling microscopy**

Nanoindentation

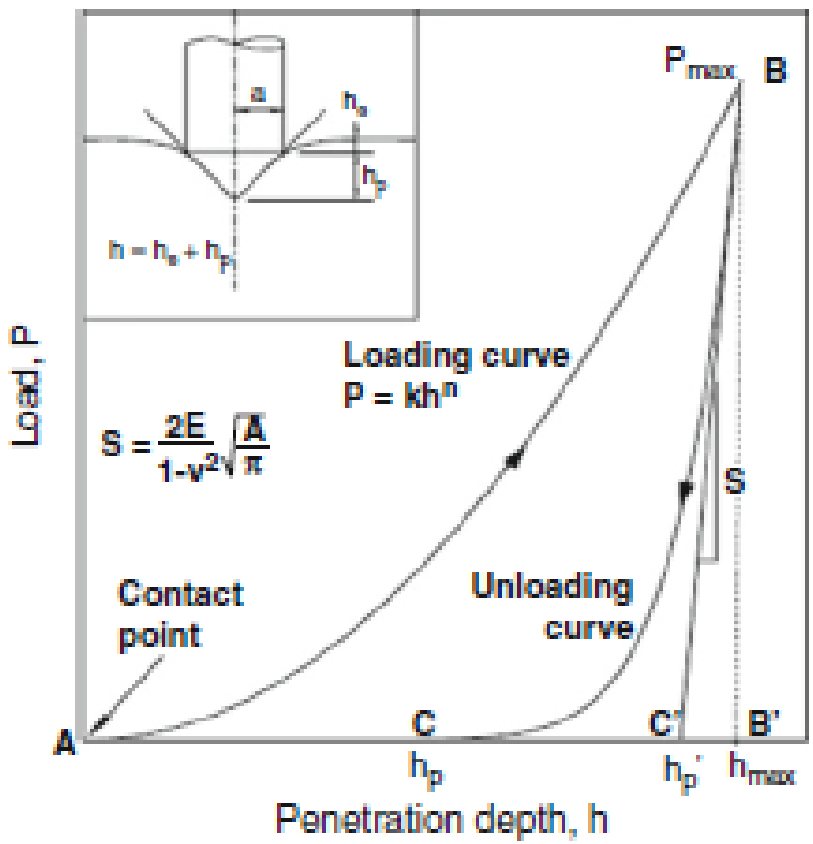
- Mechanical properties of small volumes like thin films and nanostructures
- An indenter of a material with known properties (usually diamond) is brought into contact with the sample surface. The material response to **penetration** is characterized by continuously measuring the load on the indenter and its penetration into the sample.





Data obtained from nanoindentation

- Test involves continuous measurement of **load** supported by the material and the **displacement** of the indenter as the indenter penetrates the material.



AC = permanent deformation

area ABB' = total work done on the material

CBB' = amount of energy that has been recovered elastically

ABC = energy that has been absorbed by the material resulting in the permanent impression.

Nanoindentation data

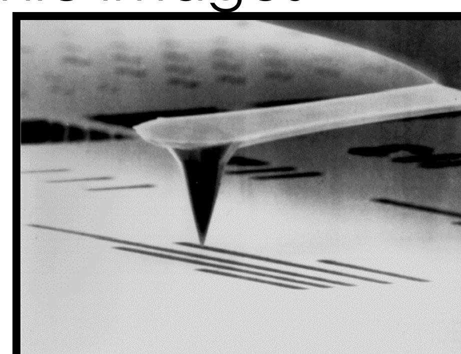
- Hardness of material is defined as the ratio of the load to the projected area of the residual impression (Meyer's hardness).
- Contact stiffness "S" during the nanoindentation test

$$S = \frac{2E}{1-\nu^2}\sqrt{\frac{A}{\pi}}$$

- Modulus of elasticity is being calculated based on the unloading curve which is limited to linear, isotropic materials.
- Advantages of nanoindentation:
  - **Very small penetrations** can be made, allowing automation of the measurement process.
  - Surface **can be probed at various locations** and a spatial map of its mechanical properties created.
  - Enables **measurement of the hardness of very thin films**, but it can also be used to determine the elastic modulus

Atomic Force Microscopy (AFM)

- Atomic force microscope (AFM) consists of a **cantilever with a sharp tip (probe)** at its end that is used to scan the specimen surface.
- The cantilever is typically **silicon or silicon nitride** with a tip radius of curvature on the order of nanometers.
- When the tip is brought into proximity of a sample surface, forces between the tip and the sample cause the cantilever to deflect.
- This deflection is measured with the help of optical beams and is used for obtaining surface topographic images



AFM (cont.)

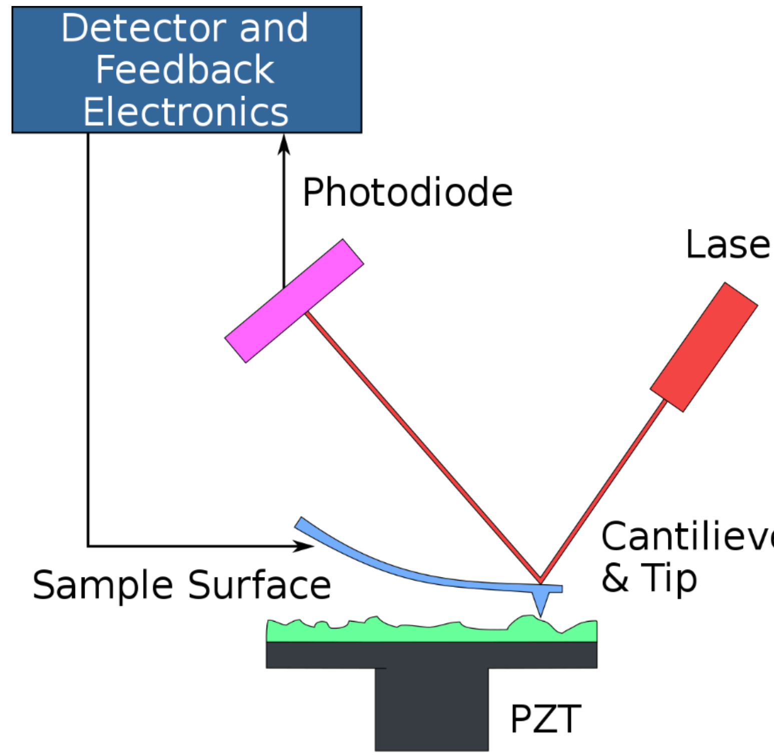
- **Attraction**:
  - When the distance between the surfaces is large, interaction force is close to zero.
  - As the surfaces are brought closer, **van der Waals** attractive interaction takes place (separations of up to 10 nm or more)
  - An instantaneous polarization of an atom induces a polarization in nearby atoms – and therefore an attractive interaction.

AFM (cont.)

- **Repulsion**:
  - At **very small tip-sample distances** (a few angstroms) a very strong repulsive force appears between the tip and sample atoms.
  - Its origin is the so-called exchange interactions due to the overlap of the electronic orbitals at atomic distances (repulsion of electrons from having same energy).
  - When this repulsive force is predominant, the tip and sample are considered to be in “contact”.

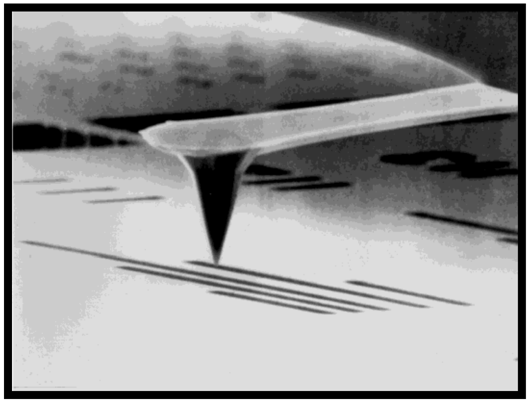
AFM (cont.)

- AFMs optical lever techniques are employed to **measure the deflection of the cantilever** to obtain the force interaction between the tip and the sample
- A mirrorlike surface at the back of the cantilever is used to reflect a laser beam onto a position-sensitive photodetector.
- Depending on the force experienced by the tip, the cantilever deflection varies, and hence the beam shifts its position in the detector.
- **Displacements** of the tip are obtained as a function of "x" and "y" coordinates resulting in a **topographical image** of the sample surface.

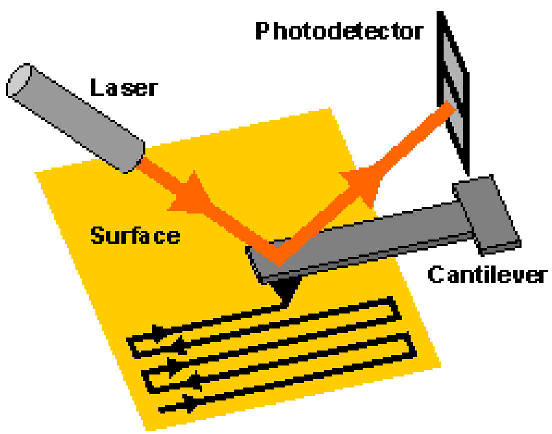


Generating an Image

Scanning Tip



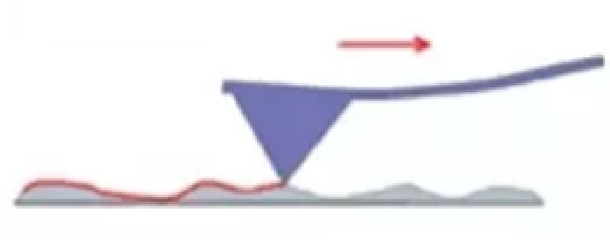
Raster Motion



- The tip passes back and forth in a straight line across the sample (think old typewriter or CRT)
- In the typical imaging mode, the tip-sample force is held constant by adjusting the vertical position of the tip (feedback).
- A topographic image is built up by the computer by recording the vertical position as the tip is rastered across the sample.

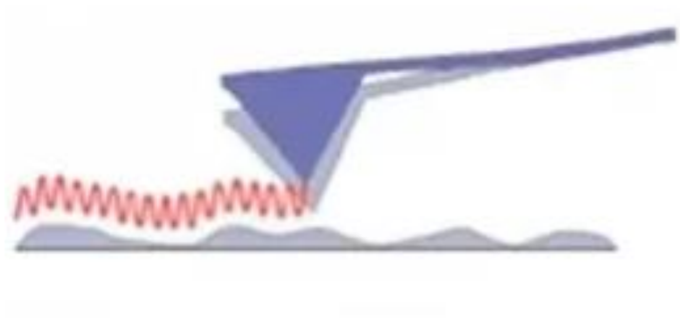
AFM: Modes of operation

- **Contact mode**: tip makes the direct contact with the surface examined. Cantilever bends to accommodate the changes in surface topography due to the contact forces acting upon it.



AFM: Modes of operation

- **Noncontact mode**:
  - Tip is separated from the sample by a distance between 50 and 100 Å.
  - A stiff cantilever must be used
  - Attractive forces from the sample are substantially weaker, the tip must be given a small oscillation so that AC detection methods can be used to detect the small forces between the tip and the sample
  - **Change in amplitude, phase, or frequency** of the oscillating cantilever in response to force gradients from the sample.

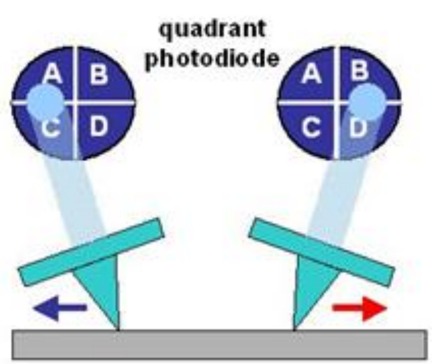


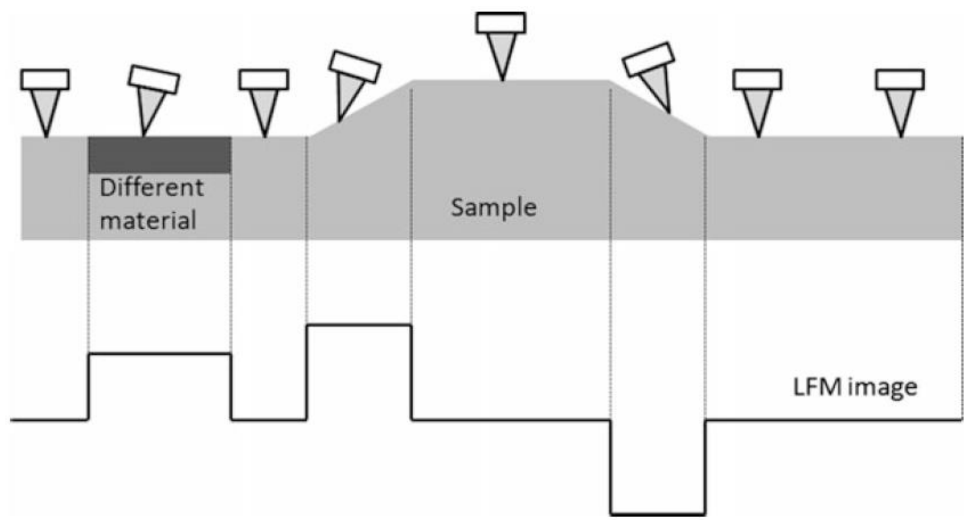
AFM: Modes of operation

- Tapping mode:
  - This technique overcomes problems associated with friction, adhesion, electrostatic forces
  - Tapping mode works by alternately placing the tip in contact with the surface to provide high resolution and then lifting the tip off the surface to avoid dragging the tip across the surface.
  - Implemented in ambient air by oscillating the cantilever assembly at or near the **cantilever's resonant frequency** using a piezoelectric crystal.
  - The **reduction in oscillation amplitude** is used to identify and measure surface features.

Lateral Force Microscopy (LFM)

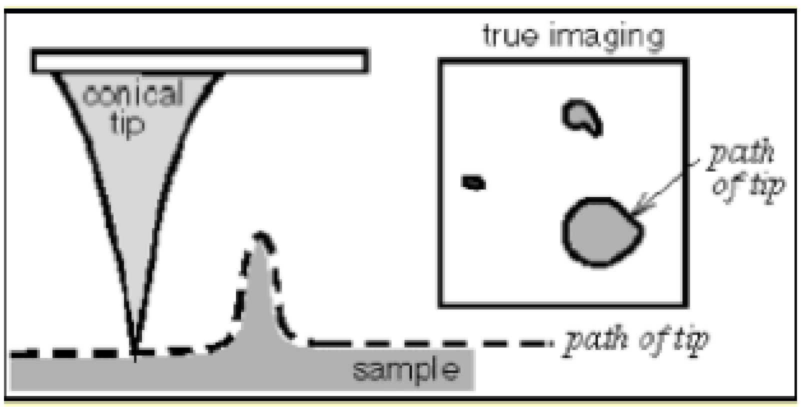
- Also known as friction force microscope (FFM).
- Measure local variations in **surface friction**, from inhomogeneity in surface material and changes in the slope.
- The tip is subjected to lateral forces, which are related to local coefficients of friction, i.e., ratio of the lateral force to the normal force acting on a tip is a coefficient of friction.
- These forces are transmitted to a cantilever**, which twists along its length**. The cantilever deflections and twists, i.e., lateral deflections, are monitored in the same manner as in a traditional AFM using position-sensitive photodetectors.

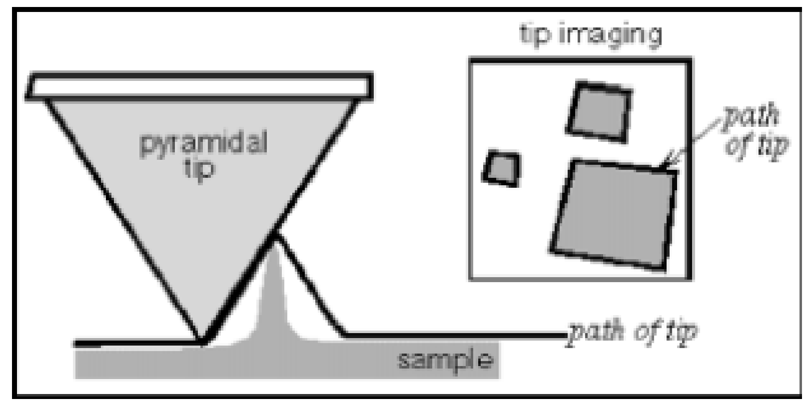




LFM (cont.)

- Lateral resolution depends on tip sharpness

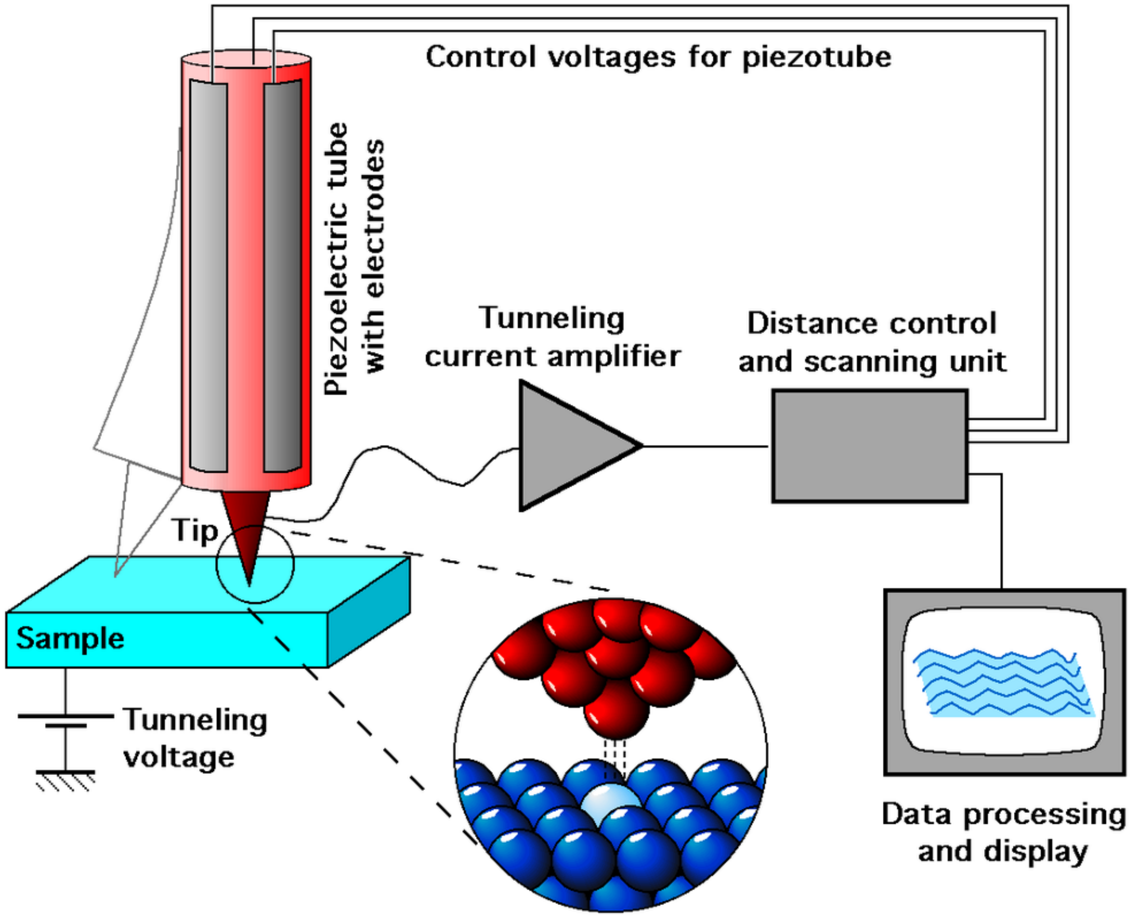




- Larger tip cannot discern two or more adjacent features.
- Higher resolution demands sharper tips.

Scanning Tunneling Microscope

- If a potential difference is applied to two metals separated by a thin insulating film, a current will flow because of the ability of electrons to penetrate a potential barrier (tunneling)
- The two metals must be spaced no more than **10 nm apart**.
- A sharp metal tip (one electrode of the tunnel junction) is brought close enough (0.3–1 nm) to the surface to be investigated (the second electrode) that, at a convenient operating voltage (10mV–1 V), the tunneling current varies from 0.2 to 10 nA which is measurable.
- The tip is scanned over a surface at a distance of 0.3–1 nm, while the tunneling current between it and the surface is measured.



- Tunneling current is measured to obtain surface topography,
- Current is a function of the distance between the specimen and the tip.

STM (cont.)

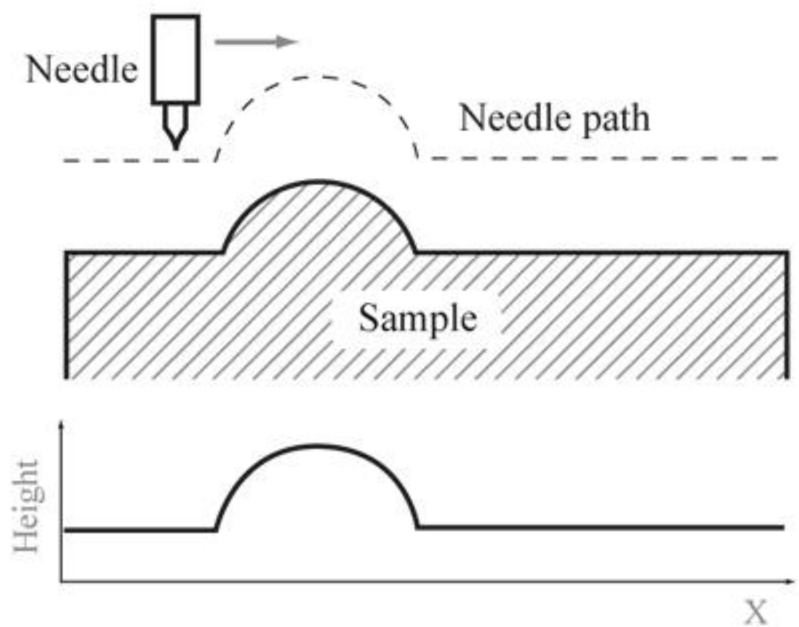
- Tunneling current, I_t varies exponentially depending on the distance between individual specimens.

$$I_t = V\, e^{-kd}$$

- Where
  - V is the potential difference between conductors
  - k is the constant depending on conductors' composition
  - d – distance between the lowest atom on the tip and the highest (nearest) atom on the sample

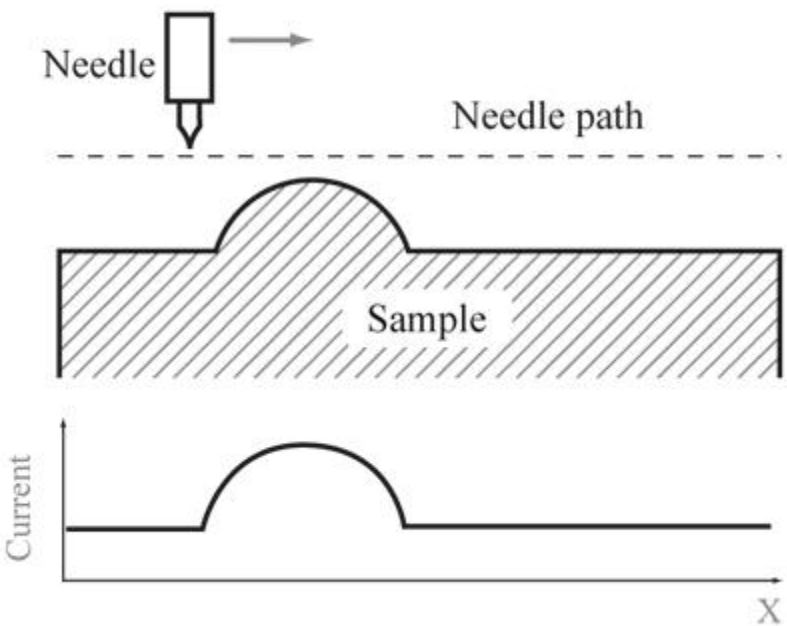
Modes of operation

- **Constant current mode**:
  - Current is kept constant through a feedback network by changing the height of the tip z.
  - Displacement of the tip given by the voltage applied to the piezoelectric drives then yields a topographic map of the surface.



Modes of operation (cont.)

- **Constant height mode**:
- The tip scans above the sample and tunneling current will vary depending on the topography of the sample and local surface electronic properties.
- Tunneling current constitutes the data set.



Limitation of this mode:

Different atomic species produce different tunneling currents for a given bias voltage.

Height data may not be a direct representation of the topography of the surface of the sample

Advantages & Limitations

- Advantages:
  - STM generates mm size length and width, compared to microscale AFM
  - STMs can be used in temperatures as low as 0 K upto a few hundred degrees
  - Faster and has better resolution than AFM
- Limitations:
  - Requires a lot of skill and precision
  - Requires very stable and smooth surfaces, excellent vibration control
  - Only works n conductive materials unlike AFM which uses conductive and insulator materials
  - STM requires vacuum atmosphere, AFM can work in liquid and can be used for biological materials

Next class

- Photon (optical and X-rays) methods
- Electron methods
- Applications of nano-/micro-tribology