UNIT 1: Introduction to Tribology, Surfaces and Friction

Lecture by

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Plan of Talk

- Tribology, its Historical Development
- Applications
- Basic Concept of Friction
- The various types of friction, laws, modern theories.
- Know about dry sliding friction, temperature of sliding surface.
- Understand mechanism of rolling friction, friction instabilities.

Tribology

(from the Greek word 'tribos' meaning rubbing)

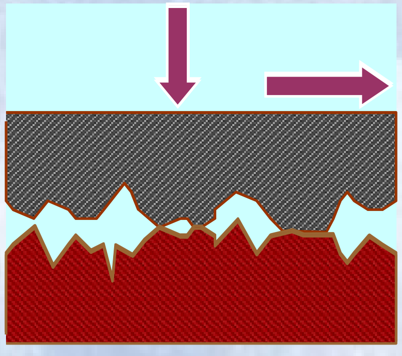
The term *'tribology'* was coined in 1966 and it is defined as *"the science and technology of interacting surfaces in relative motion"*.

It encompasses the study of:

Friction

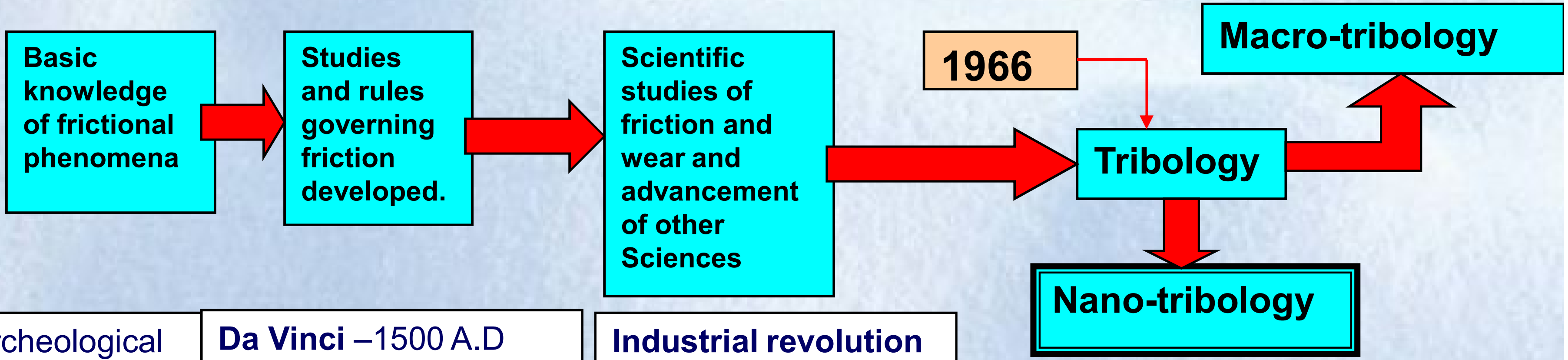
Wear

Lubrication



A Concise History of tribology

1880 BC	1400 – 1800 A.D	1800 – 1950 A.D	20th Century and beyond



Archeological findings from the Ancient **Roman** and **Egyptian** Empires
-water lubricated sleds

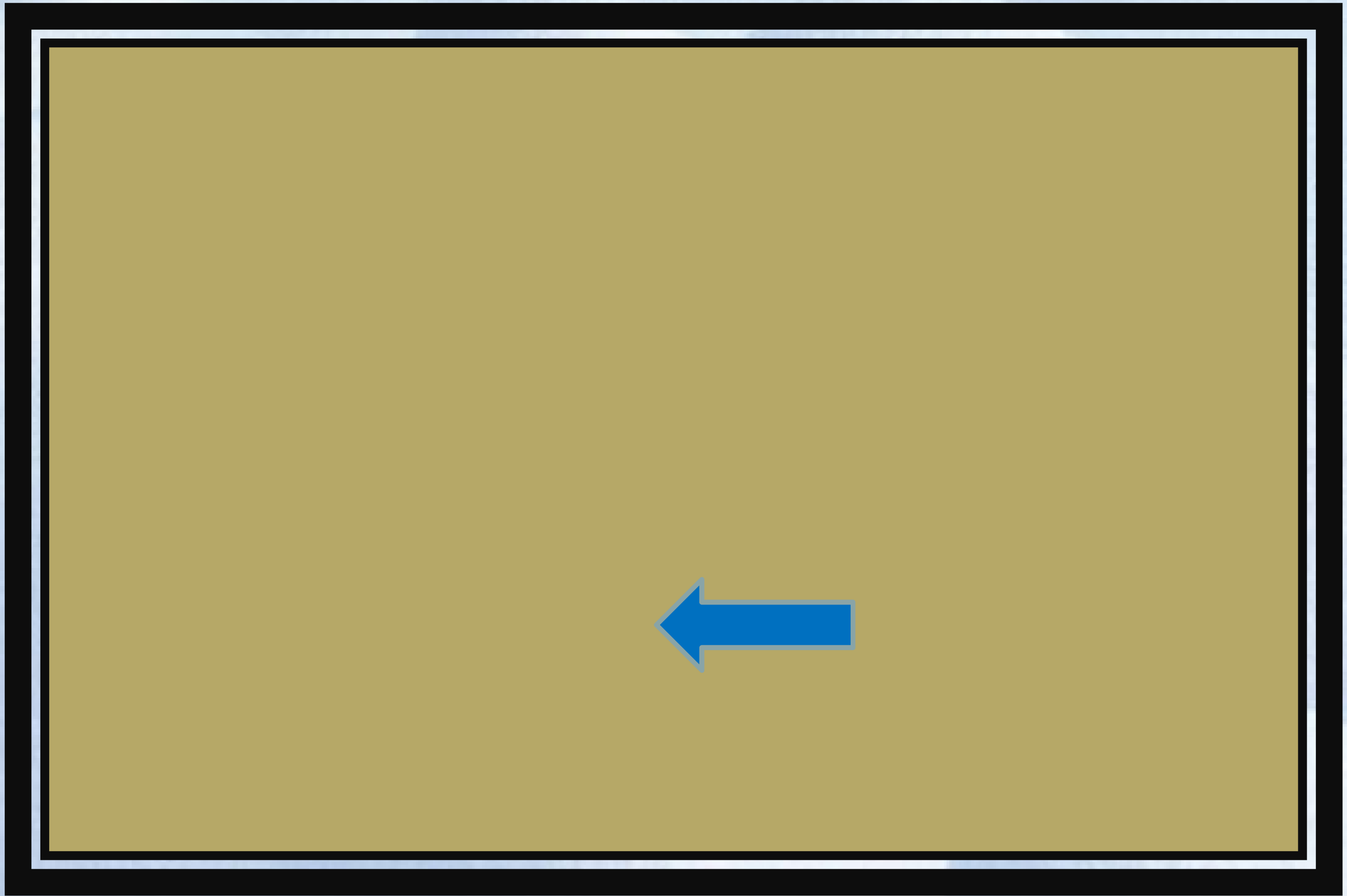
Da Vinci –1500 A.D
-Coefficient of friction
Guillaume **Amontons**
-Friction force of resistance
Coulomb 1785 A.D
-Static and kinetic friction

Industrial revolution 1850 AD
Beauchamp Tower 1886
-Hydrodynamic lubr. (Bearings)
Ragar Holm 1946
-Study of wear

1969 - 2014
Emerging of proximal probes (microscopes and the surface force apparatus), and computational techniques for simulating tip – surface interactions and interfacial properties.

In ancient times, on the order of about 500,000 B.C., early humans learned that by rubbing sticks together with great force they could create fire.

Around 3500 B.C. we learned that rolling motion required less effort than sliding, and the wheel was invented.

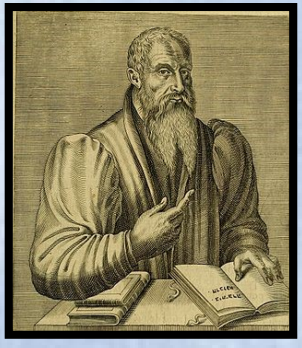


An Egyptian painting dating back to 1880 B.C. depicts workers dragging a sled containing a heavy statue.

One worker pours a liquid on the ground just before the runners to make the going easier.

1495-1950: Laws of friction are developed

- In 1495 **Leonardo** formulated the two basic laws of friction: Friction is independent of contact area, and friction is proportional to load. For years, he never got credit for his work, as he did not formally publish his observations.



- Some 200 years later, in 1699, **Guillaume Amontons** (1663-1705) rediscovered these two basic laws. He reasoned that friction was primarily the result of work done to lift one surface over the roughness of the other, resulting in deformation and wear of the surfaces.

- **Sir Isaac Newton** (1642-1727), in studying and creating the basic laws of motion, added that moving friction was not dependent on speed or velocity, thus formul--ating the third law of friction. All these observations were made in the macro scale.

•In 1950, **Phillip Bowden** and **David Tabor** gave a physical explanation for the observed laws of friction. They determined that the true area of contact, which is formed by the asperities on the surface of a material, is a very small percentage of the apparent area. As the normal force increases, more asperities come into contact and the average area of each asperity contact grows.

•As our ability to analyze surface contacts at the monomolecular level has developed, we are learning that the "macro" laws don't necessarily hold and that the processes of interaction are quite complex.

•"*Amontons Laws of Friction are the first quantitative description of a tribological process. Attempts (theories, mechanisms, models) to explain these laws have been central to the development of tribology*." —**Bill Needelman**, Filtration Science Solutions.

1883-1905: Principles of hydrodynamic lubrication are elaborated

•In 1883, the elucidation of hydro-dynamic lubrication began in England, with testing done by **Beauchamp Tower**. He used a specially constructed test rig for journal bearings, simulating the conditions found in railway axle boxes.

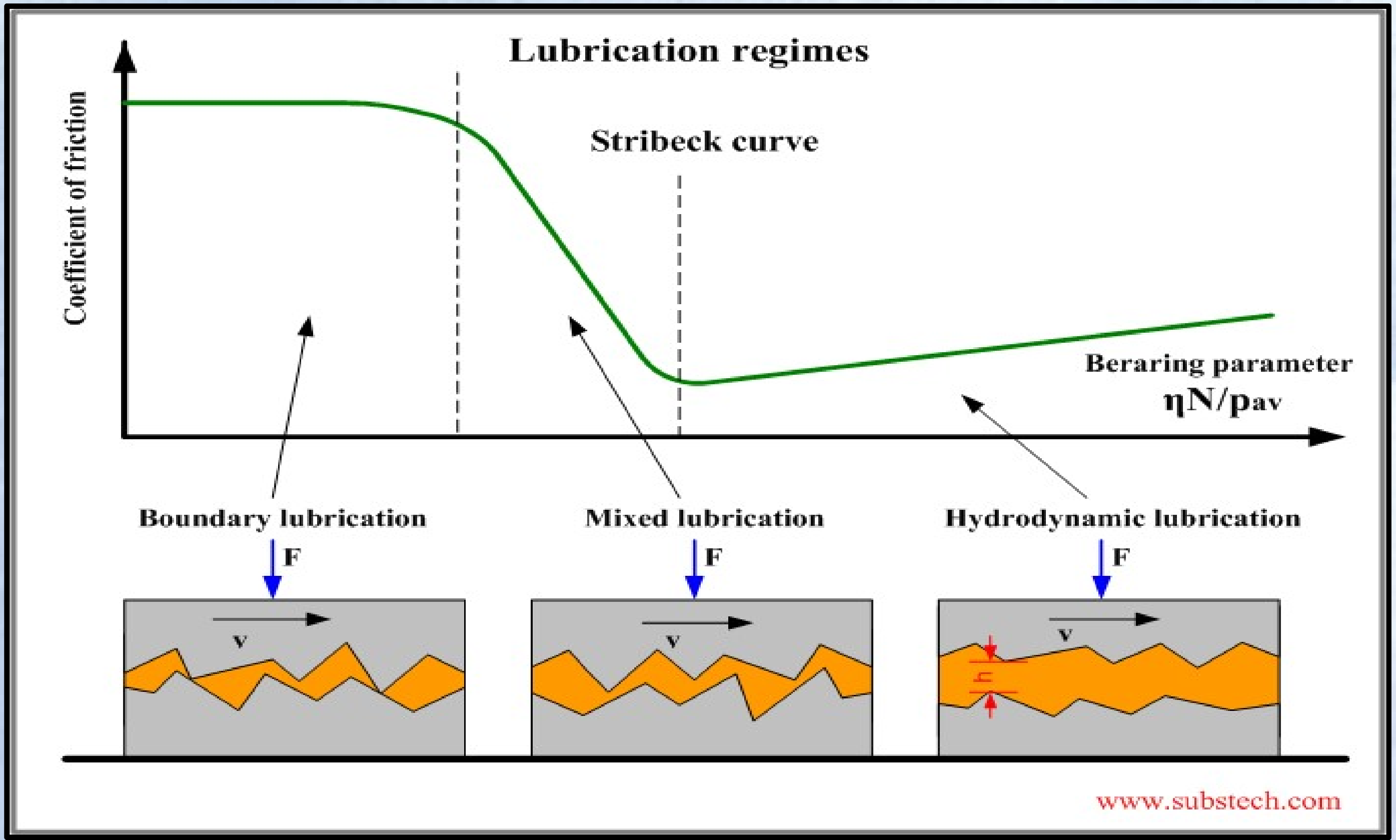
•In the final phase of his research, Tower decided to drill an oil feed hole in the bearing. The oil was found to rise upwards in the feed hole and leak over the top of the bearing cap. He then installed a pressure gauge and found it to be inadequate for measuring the high pressure levels. This result proved the existence of a fluid film that could carry significant loads.

•In 1886 **Osborne Reynolds** published a differential equation describing this pressure buildup of the oil in the narrow converging gap between journal bearing surfaces. This equation, a variation of the Navier-Stokes equations resulting in a second-order differential equation, was so complex that many years passed before it was solved for journal bearings.

•In 1902 **Richard Stribeck**, published the Stribeck curve, a plot of friction as it relates to viscosity, speed and load.

•After the work of Tower and Reynolds, **Arnold Sommerfeld** refined the work into a formal theory of hydrodynamic lubrication in about 1905.

•A surface have tiny asperities that will contact if two plates are placed together. If one of the plates were to slide over the other, then friction would increase, the asperities would break and the surfaces would wear. In hydrodynamic lubrication, a fluid film separates the surfaces, prevents wear and reduces friction.

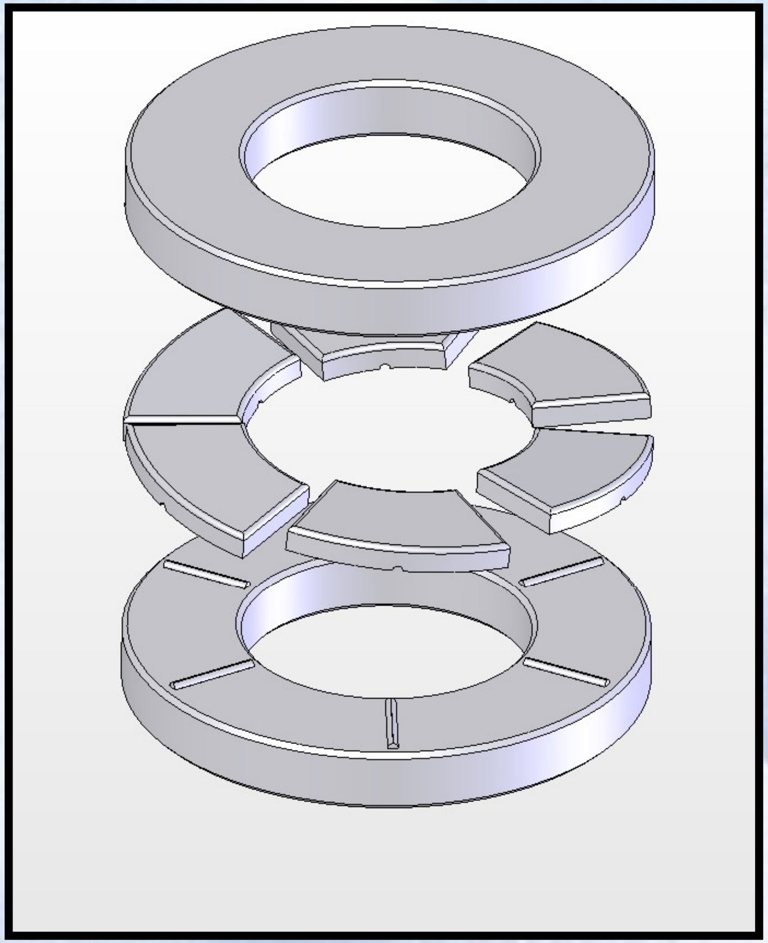


•The hydrodynamic film is formed when the geometry, surface motion and fluid viscosity combine to increase the fluid pressure enough to support the load. The increased pressure forces the surfaces apart and prevents surface contact. This is called hydrodynamic lift. Hydrodynamic bearings get load support by hydrodynamic lift.

•The most recognizable hydrodynamic bearings are slider bearings and journal bearings, both used extensively in machinery and vehicles—thanks to the development of hydrodynamic lubrication theory.

•“*The experiments of Beauchamp Tower formed the basis of modern-day hydrodynamic lubrication and inspired Osborne Reynolds to develop the Reynolds equation, which has remained at the center of fluid film lubrication to this day*.” —**Martin Webster**, ExxonMobil R&E

•In 1905 fluid-film thrust bearings patented by Australian engineer **George Michell**. Michell bearings contain a number of sector-shaped pads, arranged in a circle around the shaft, and which are free to pivot. Michell's invention was notably applied to the thrust block of propellor driven ships. Their small size (one-tenth the size of old bearing designs), low friction and long life enabled the development of more powerful engines and propellers.

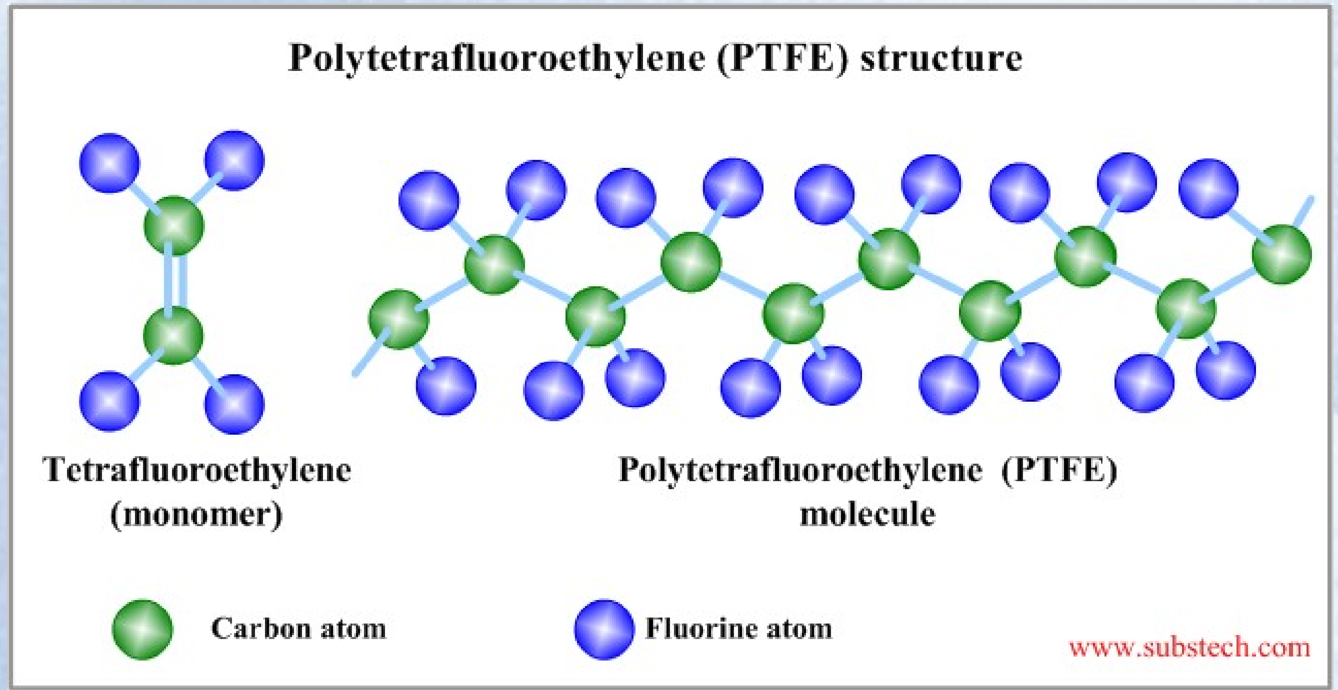


•In 1912 Dr. Albert Kingsbury invented the **hydrodynamic thrust bearing**.

•In 1922 understanding of **Boundary lubrication refined** by W.B. Hardy and I. Doubleday.

•1930s to 1940s The first **zinc dialkyldithiophosphates (ZDDPs)** began to be developed as anticorrosion agents and oxidation inhibitors. The antiwear activity of these molecules was recognized only later, in the 950s, at which point they became an integral part of many oil chemistries. To this day ZDDPs remain the backbone of antiwear additive technology.

•**PTFE**, the most famous of the self-lubricating coating materials, was discovered fortuitously during a project looking at tetrafluoroethylene as a refrigerant.



•In 1942 **Lithium grease** invented & rapidly became widely used multi-purpose grease

•In 1950 **Synthetic oils** introduced for usage in aviation.

•In 1950s **Fire Resistant Hydraulic Fluids** developed.

•In 1962 **Aluminium Complex grease** invented for high temperature applications.

•In 1960s **Multi-grade motor oils** introduced.

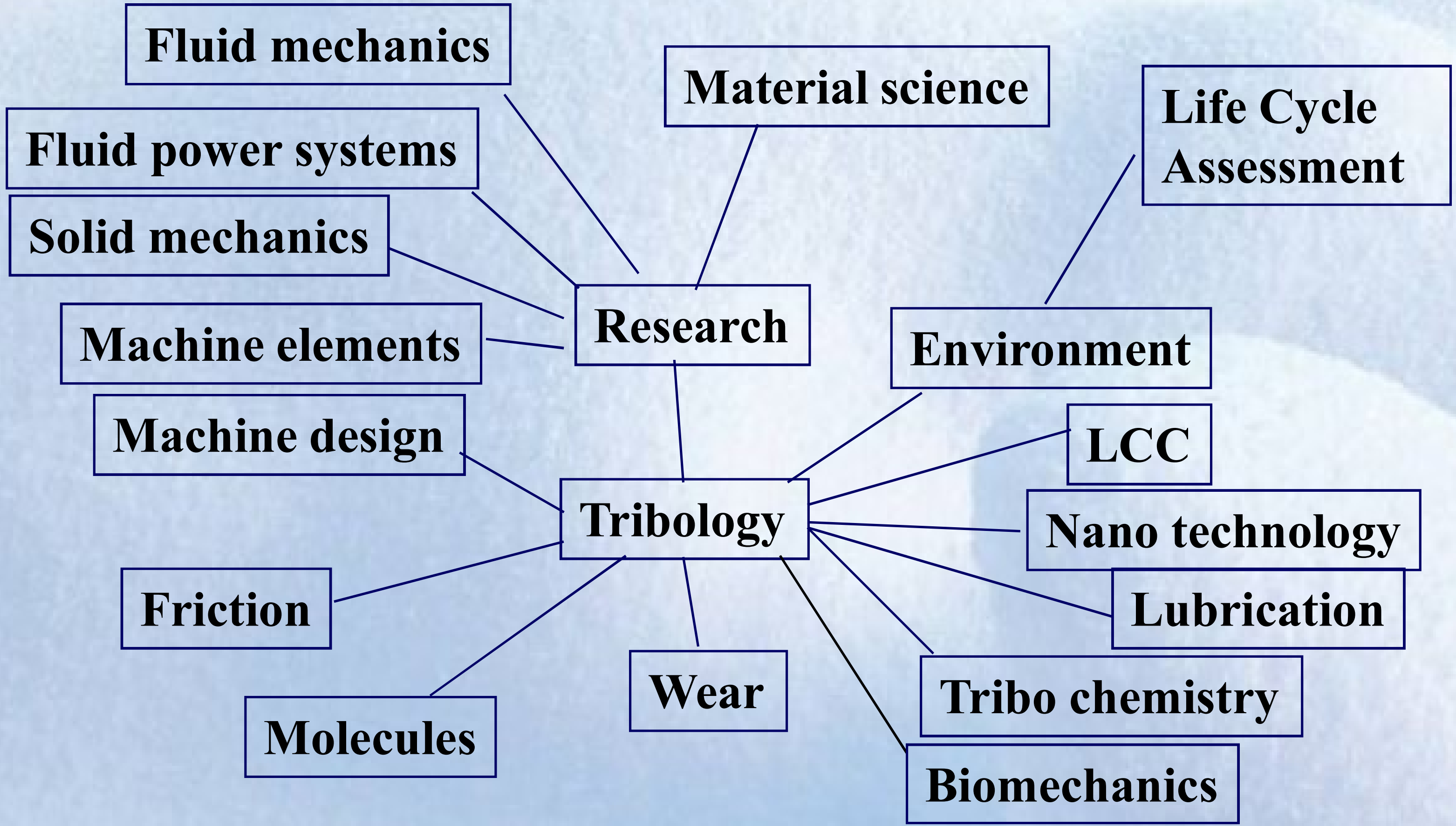
•In 1960s **Synthetic oils** used for motor oils.

•In 1986 the development of the **Atomic Force Microscope** enabled scientists to study & understand friction at the atomic scale.

•1980 onwards **Biolubricants** developments begin.

•1990 onwards **Nanotribolgy, Biotribology** developments begin.

Tribology is a Multi-Disciplinary Subject



Tribology is Everywere- Few Examples

- Tyre-road (high friction required)
- Bearings (low friction and wear required)
- Screw joints (low friction in threading, no wear in contact)
- Ski-snow (low friction for gliding but high in the grip zone)
- Shoe-floor (medium friction for easy walking and dancing)
- Brake-disc (controlled, stable friction, not too low or too high)
- Cam-follower (no wear, low friction)
- Piston ring-cylinder (no wear, low friction)
- Chalk-board (controlled wear process)
- Pen-paper (controlled wear process)
- Artificial joints and
- Many more

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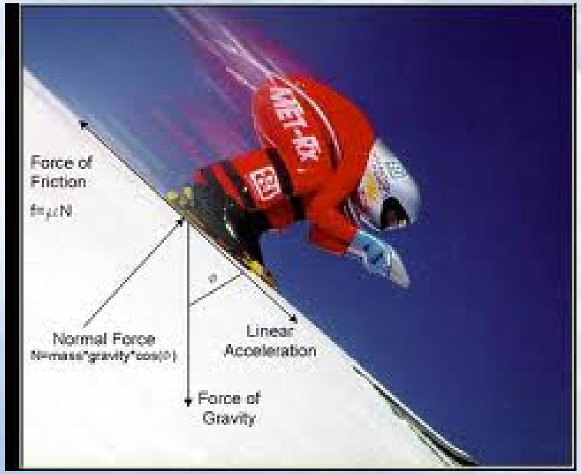

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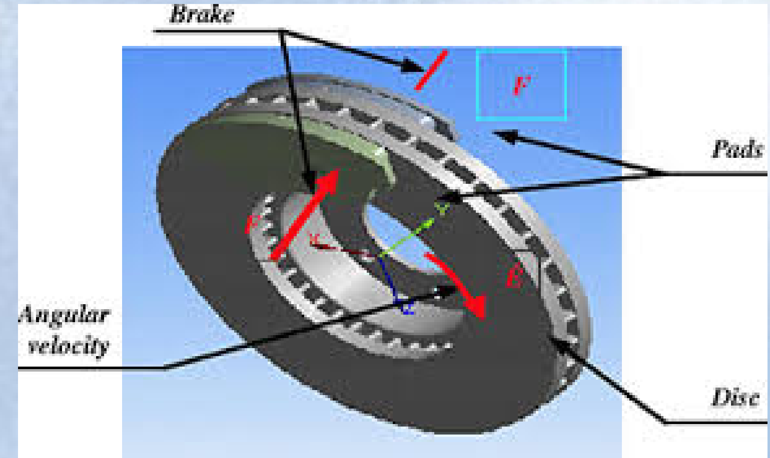

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- Cam-follower (no wear, low friction)

- Piston ring-cylinder (no wear, low friction)

Tribology is Everywere- Few Examples

- Chalk-board (controlled wear process)

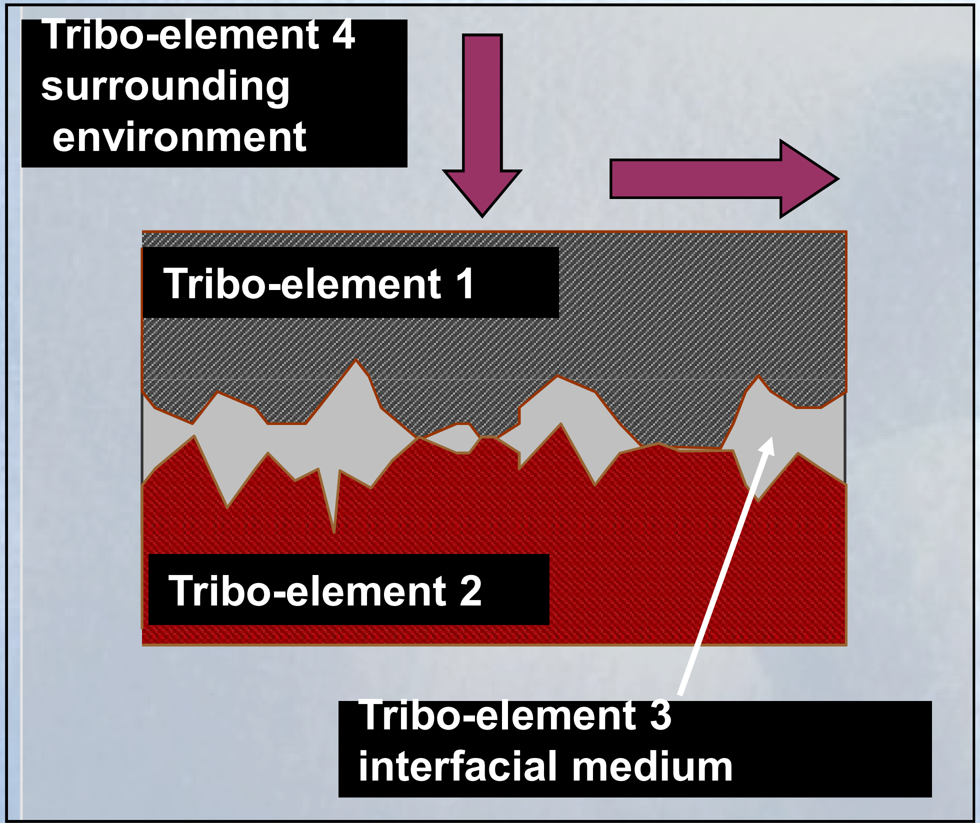
- Pen-paper (controlled wear process)

Tribology is Everywere- Few Examples

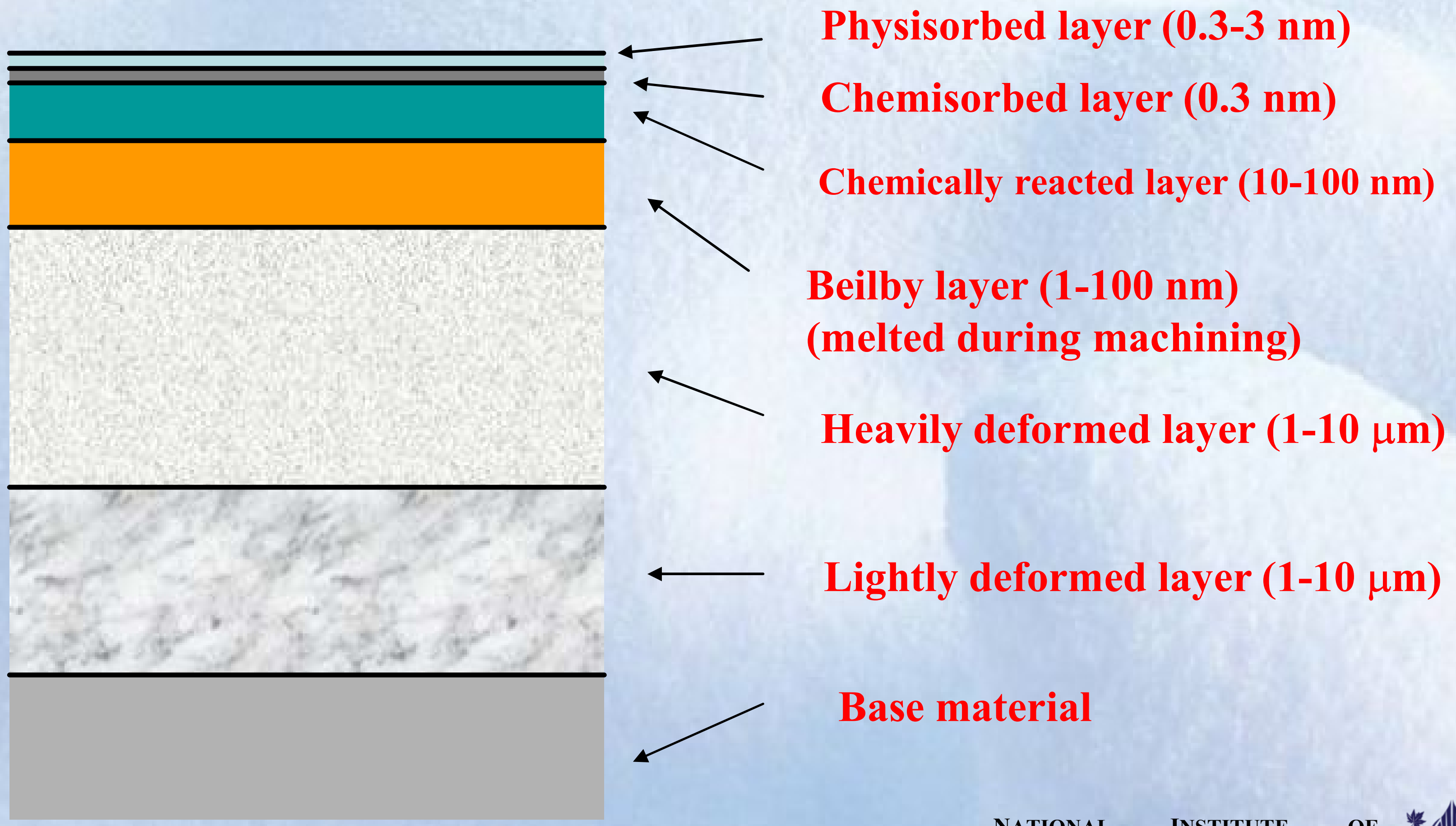
- Artificial joints

- **And Many more....**

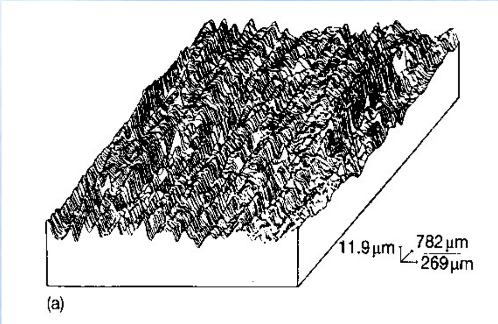
Tribo-system

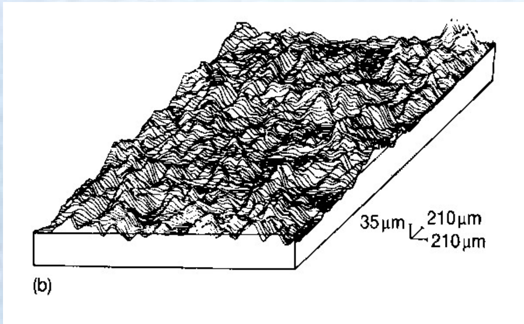


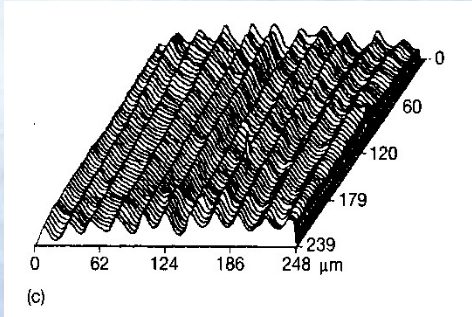
The Nature of Solid Surfaces



Contact of Rough Surfaces



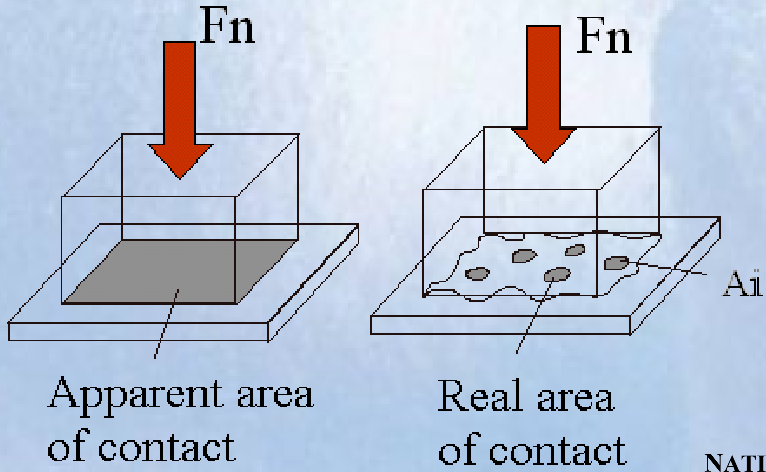




Ground steel surface

Shot-blasted steel surface

Diamond turned surface



General Remarks

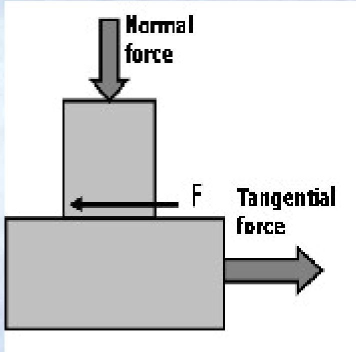
Considering the complexity of the tribological system, it may be pertinent to point out that friction and wear characteristics of materials are not their intrinsic or inherent properties but are highly system dependent.

Friction

- ***We encounter friction in all aspects of everyday lives:***
- ***Walking***
- ***Moving***
- ***Stopping or turning a car***
- ***Since the dawn of time we have been preoccupied with friction, be it:***

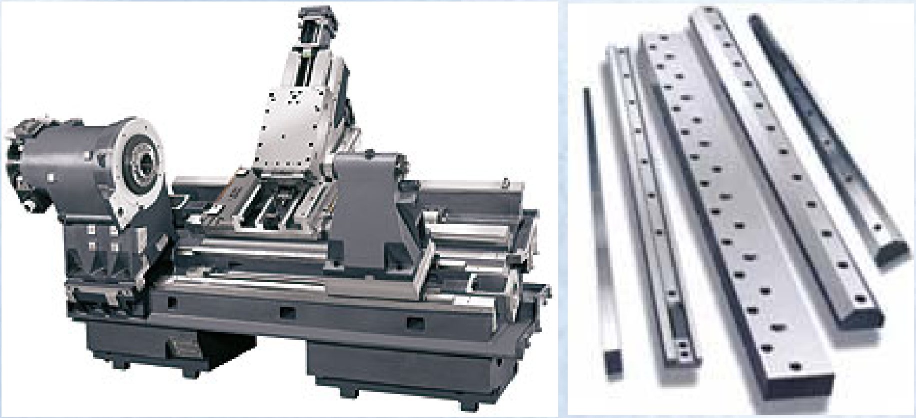
  - the Egyptian pyramids and tombs and

  - the invention of wheel



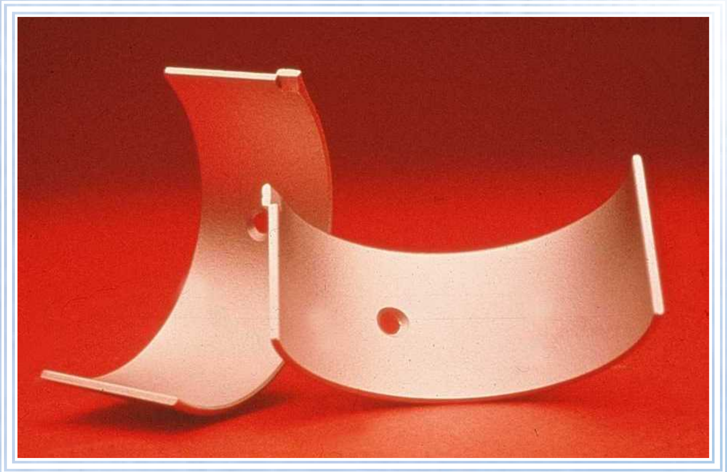
- ***Consequences of friction:***
  - ***Major cause of energy dissipation***
  - ***Frictional heat generation and temperature rise***

Examples of Occurrence of Sliding Friction



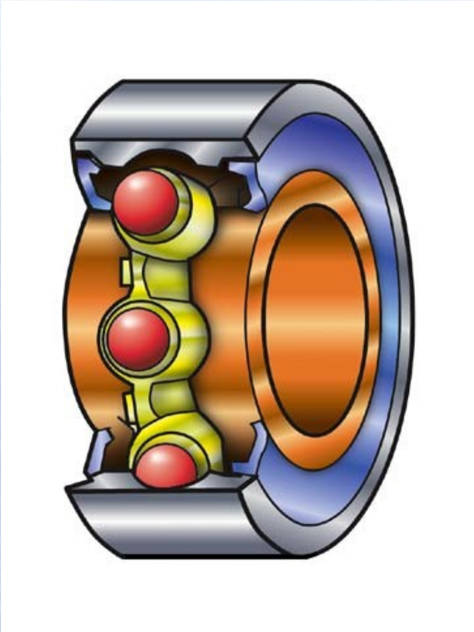
Machine tool slideways

Clutch

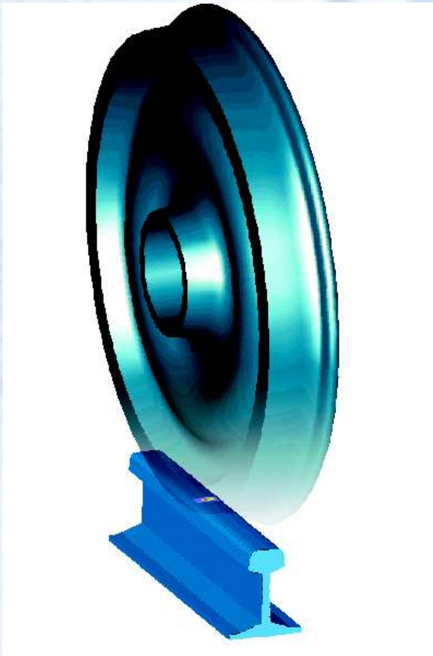


Engine bearings

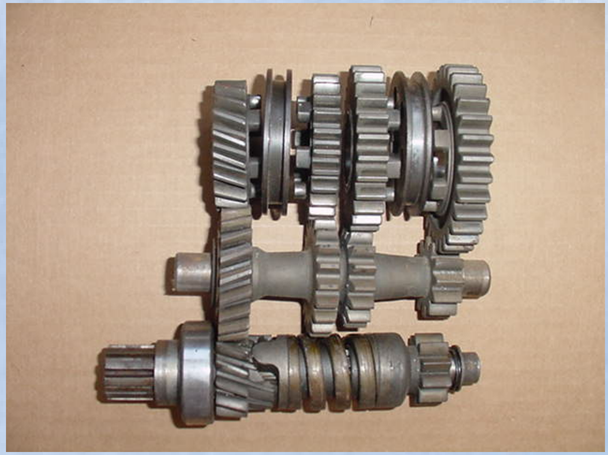
Examples of Occurrence of Rolling Friction



Ball bearing

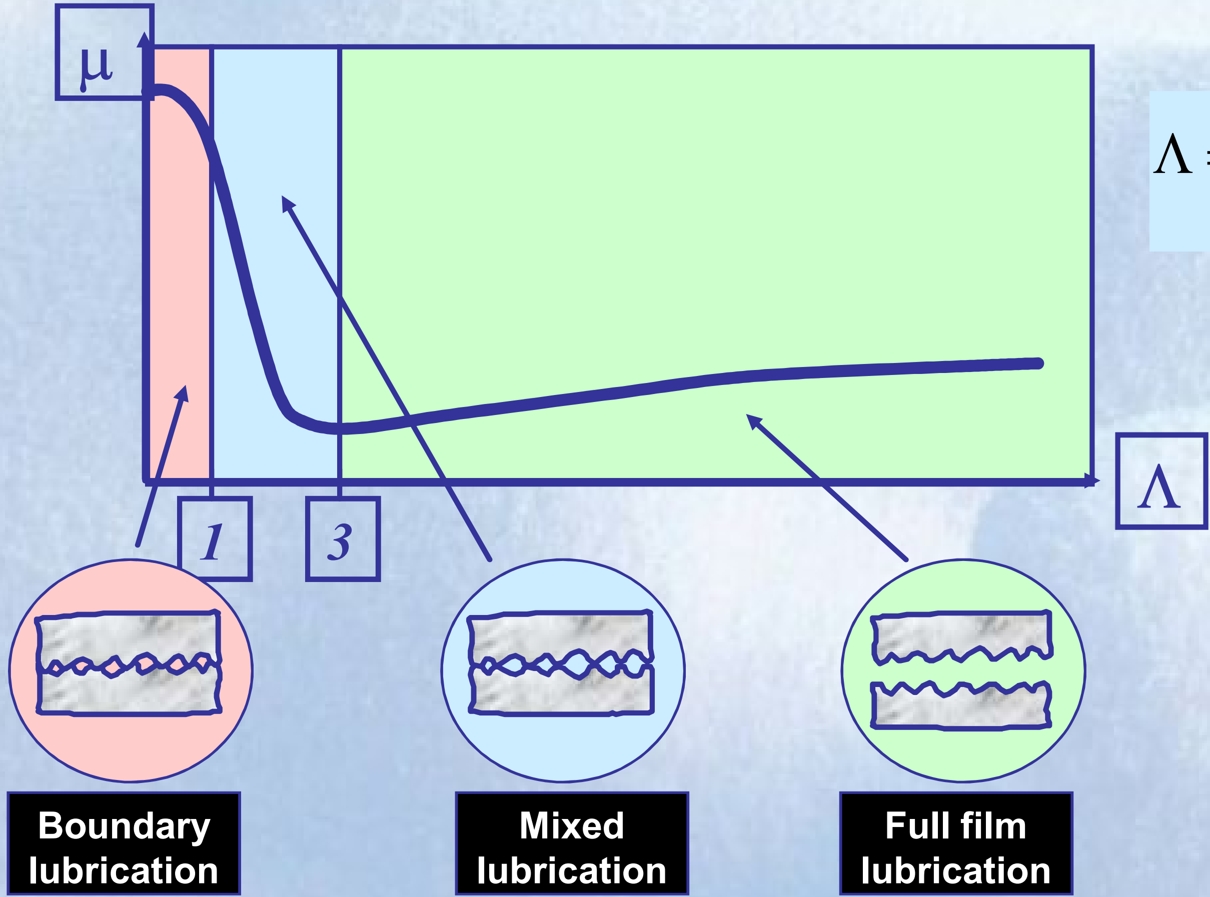


Wheel/rail



Gear transmission

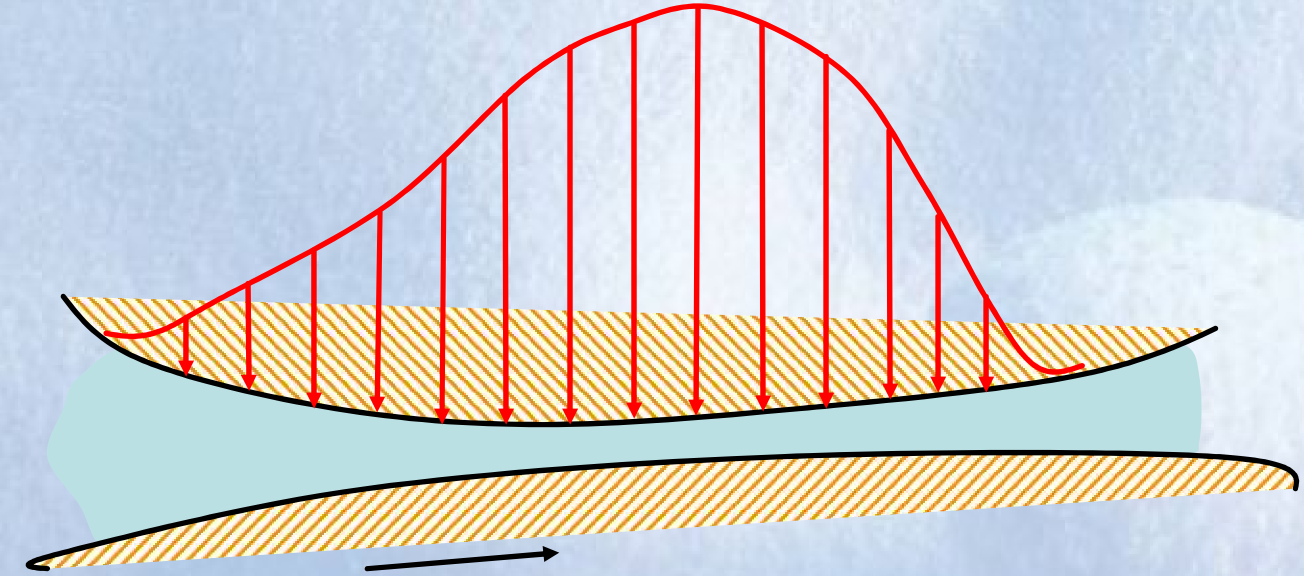
Lubricated Friction Classification



$$\Lambda = \frac{h_{min}}{\sqrt{R_{q1}^2 + R_{q2}^2}}$$

Full film lubrication: The lubricant film separates the surfaces

A hydrodynamic pressure is formed due to the converging gap → surface separation!



EHL - What is that?

Elastohydrodynamic lubrication (EHL)

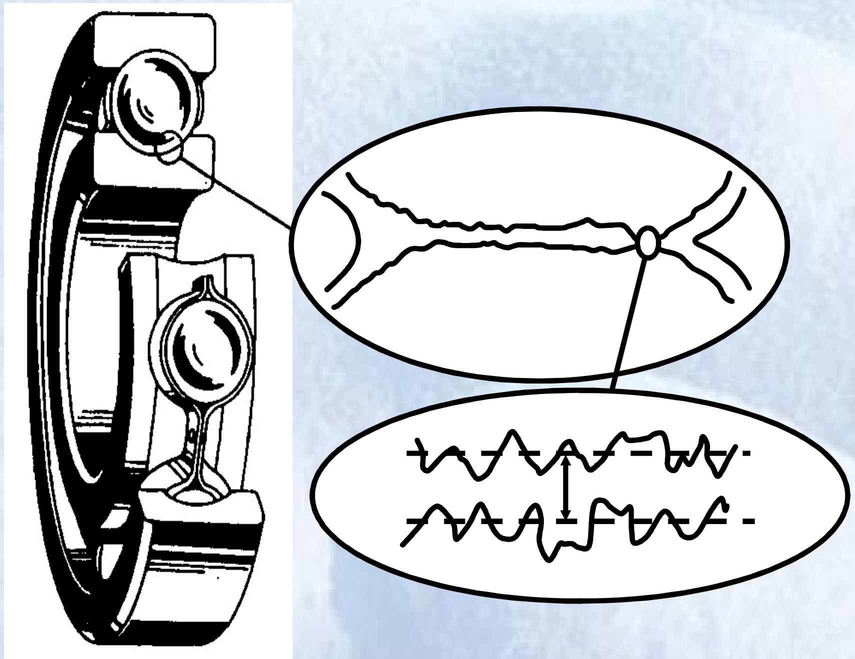
Non-conformal surfaces → small contact region

High contact pressures, 1-3 GPa (1000-3000 N/mm^2)

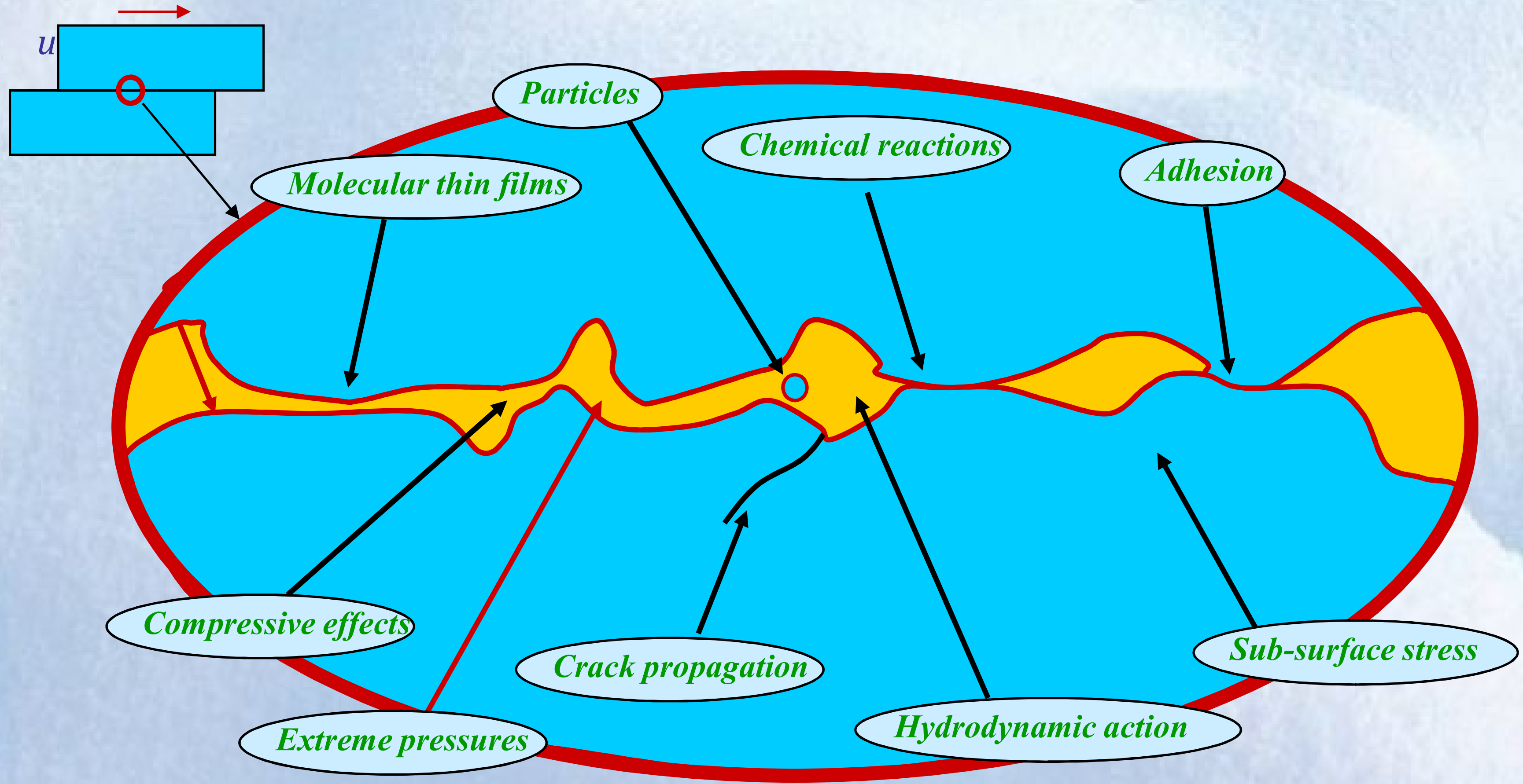
The surfaces are deformed

Thin lubricant films <1µm

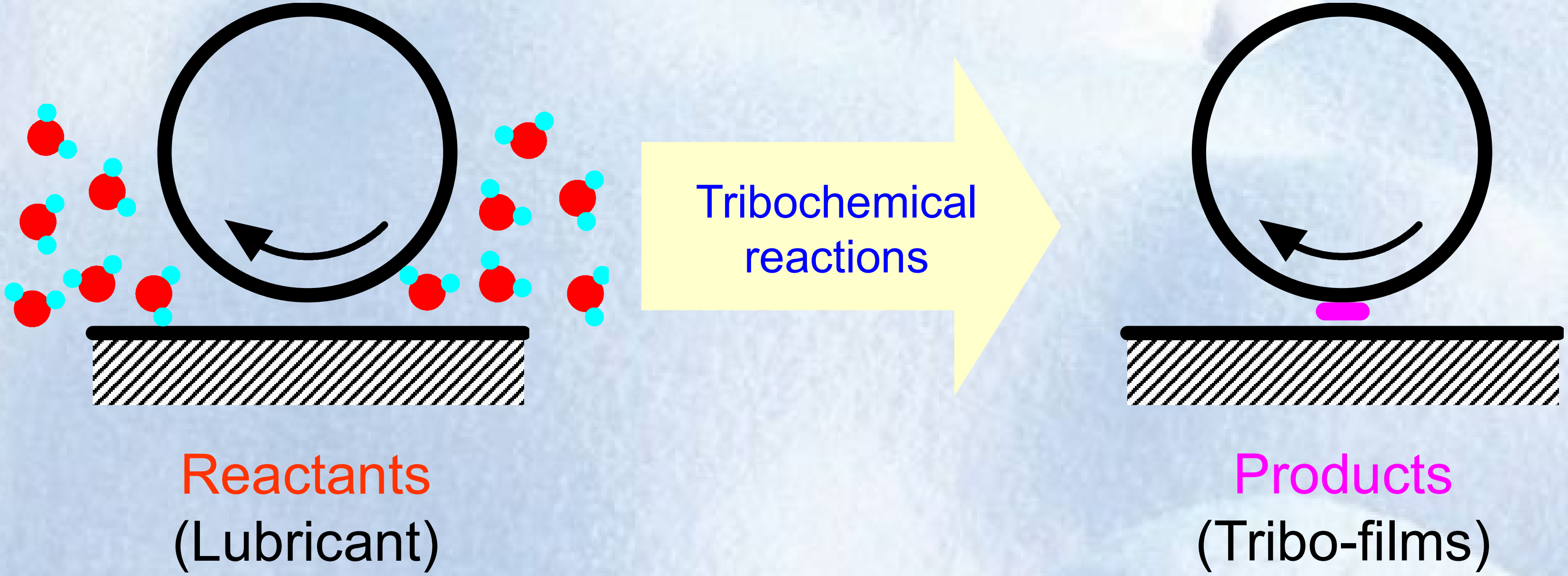
Example: the ball bearing

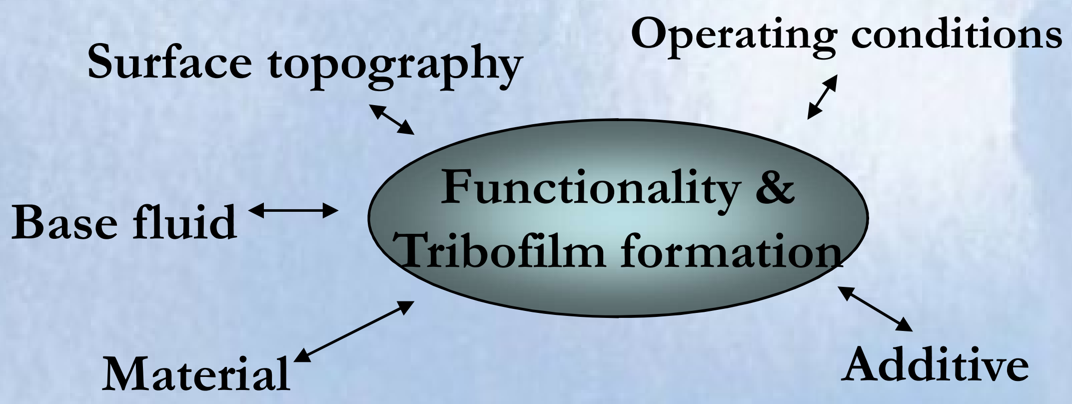


Lubricated Contacting Surfaces



Boundary Lubrication



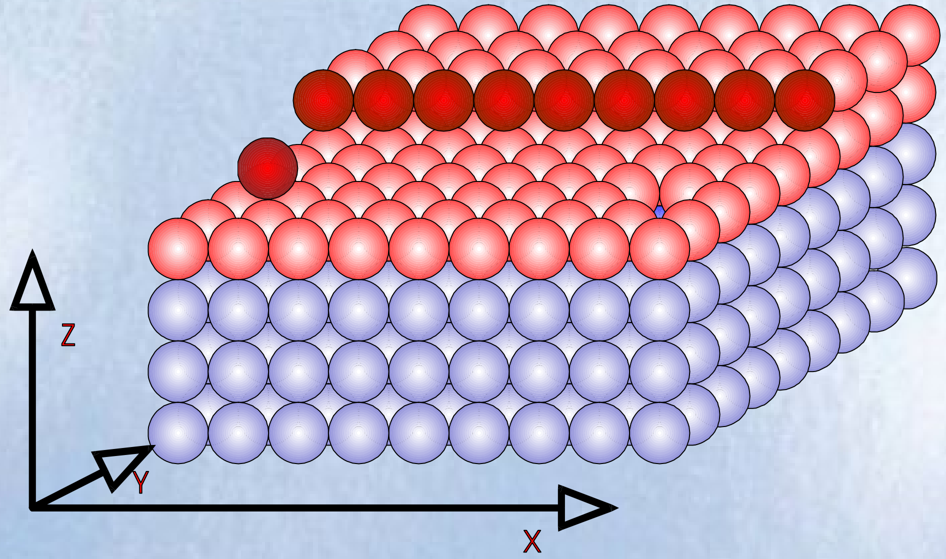


Future challenges in tribology

- **Light weight machines/high power densities**
- **Lubricants for extreme operating temperature (low and high temp.)**
- **Environmental protection**
- **Predictability**
- **Controllability**
- **Profitability**
- **Sustainability**

Surfaces

A surface is made by a sudden termination of the bulk structure. The bonding that was involved in the bulk lattice (for a solid) or liquid is severed to produce the interface.



Since it requires energy to terminate the bonding, the surface is **energetically** less stable than the bulk.

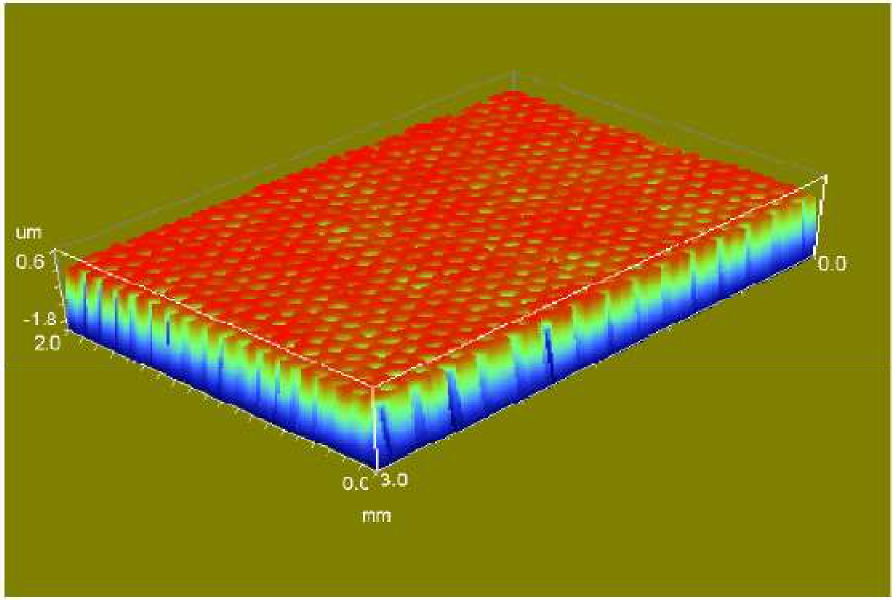
This energy is known as the **surface free energy**. In the case of liquid interfaces, this energy is called **surface tension**.

Why Surfaces?

- Properties different from that of the bulk
- Have major impact on several areas including semiconductors, corrosion, detergent, and *TRIBOLOGY*
- Specialised techniques required to study topography, composition and chemistry of surfaces

Significance of Surfaces in Tribology

- friction
- wear
- effectiveness of lubricants
- surface defects and initiation of cracks
- thermal and electrical conductivities



Ra= 0.1987 μm, Rq= 0.304 μ m, Rz= 10.04 μ m

Surface Defects Caused During Manufacturing

- Crack
  internal/external
- Craters
- Folds/Seams/Laps
- Heat Affected Zone
  thermal cycling w/o melting
- Inclusions
- Residual stresses
- Splatter

- Intergranular attack
- Metallurgical transformations
  temp., press., cycling
- Plastic deformation
  worn tools
- Pits
  shallow surface depressions

Surface Characterisation

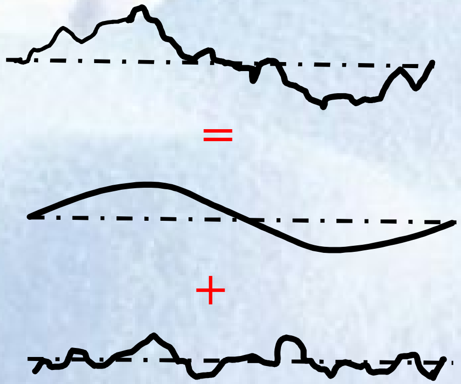
- General features of surface
  - Appearance
  - Shape of surface
  - – Anisotropy ?
- Mechanical properties
  - Modulus
  - Yield Strength
  - Hardness
  - Toughness....
  - Stresses and strains
- Chemistry of surface
  - Elements present
  - Phase distribution

- **Localised defects**
  - Any local changes in
    - Shape
    - Mechanical properties
    - Chemistry
  - Cracks

The Origin of Surface Irregularities

- The production process
  - Turning
  - Grinding
  - Polishing
- The material structure
  - Brittleness
  - Atomic structure
- The use of the surfaces
  - Wear
  - Running-in
  - Corrosion

The Spectrum of Wavelengths

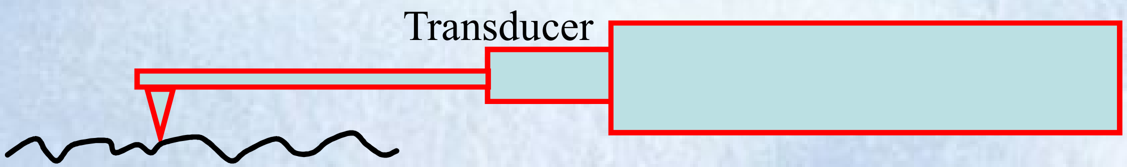


- Form
  - long wavelengths
  - >1000 times its amplitude
- Waviness
  - intermediate wavelengths
  - ratio between wavelength and its amplitude 100:1 - 1000:1
- Roughness
  - Short wavelengths

There is no clear limit between waviness and roughness – it depends on the measurement's sampling length and the filtering technique!

Surface Topography Measurement Methods

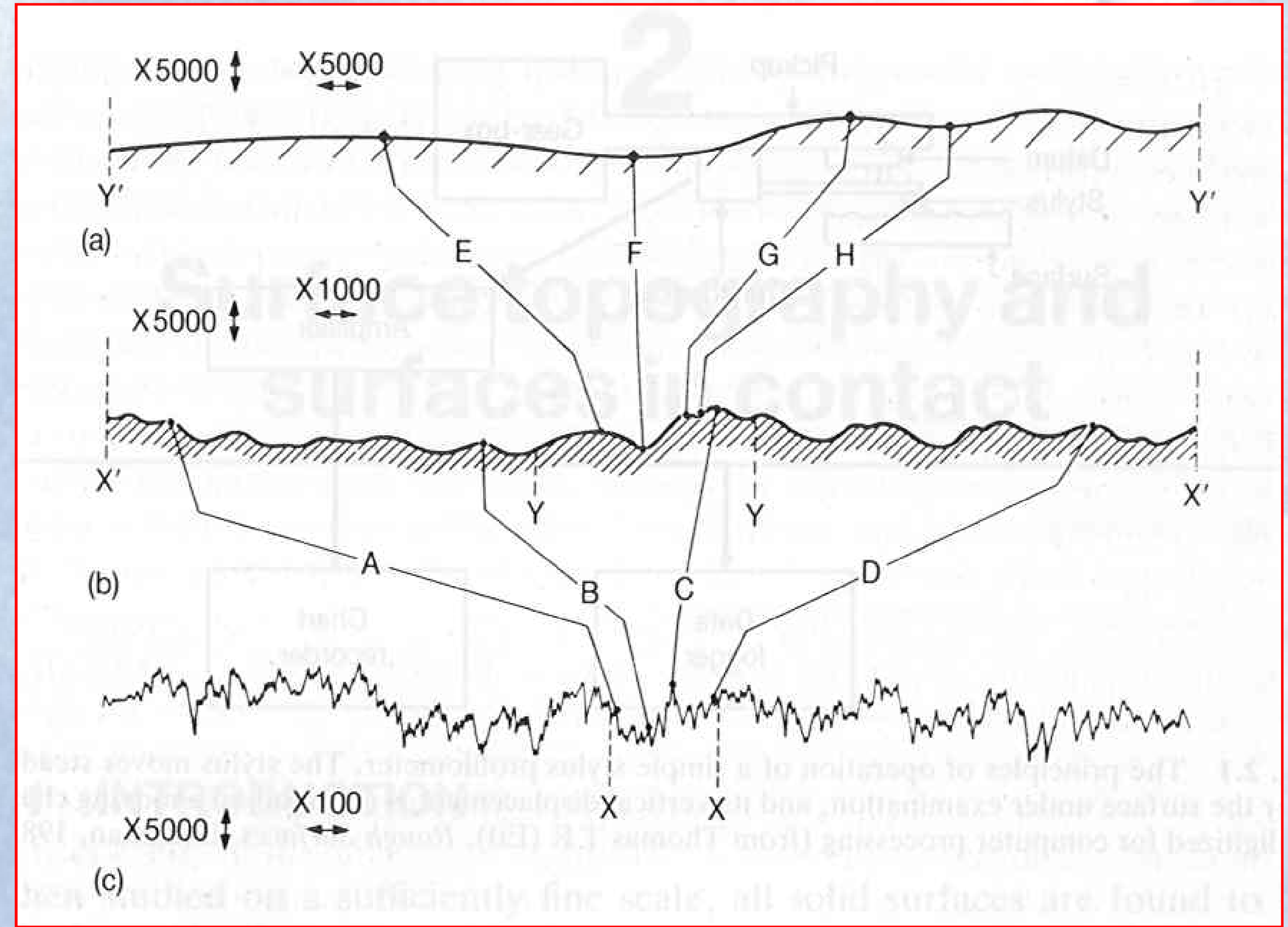
- Stylus profilometers (2D+1D)



- Optical methods (3D)
  - Interferrometry
- Scanning probe microscopy (2D+1D)
  - Scanning tunneling microscopy (STM)
  - Atomic force microscopy (AFM)

Surface topography measurements are never exact. All different Techniques give different answers. Even the use of the same technique at different laboratories!

Surfaces are Flatter Than One Expect

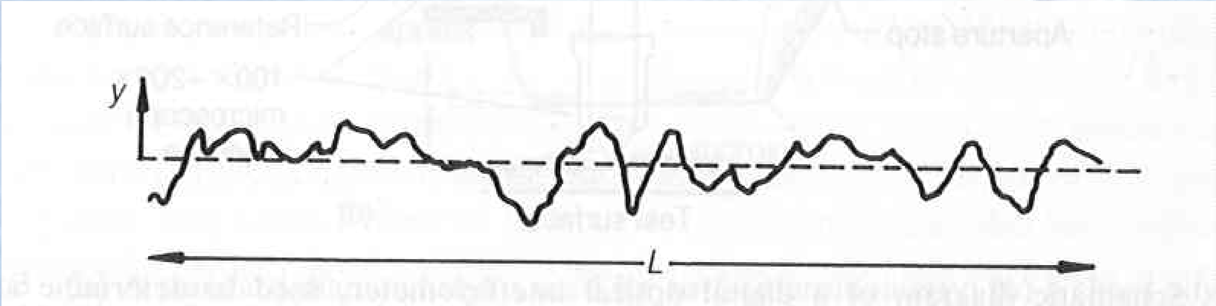


Asperity slopes are rarely steeper than 10°

Problems Encountered in Surface Topography Measurements

- **Stylus profilometers**
  - The tip radius (a few μm) is too large to resolve very fine irregularities
  - Might damage the surface (replication might be the solution)
- **Optical methods**
  - Expensive equipment
  - Thin films on the surface might cause errors
- **Scanning probe microscopy**
  - Expensive and sensitive equipment
  - Measurement on very small areas might lead to mis-interpretations

Average Roughness Parameters



- Average roughness, R_a:

$$R_a = \frac{1}{L}\int_0^L |y(x)|\,dx$$

- R.M.S roughness, R_q:

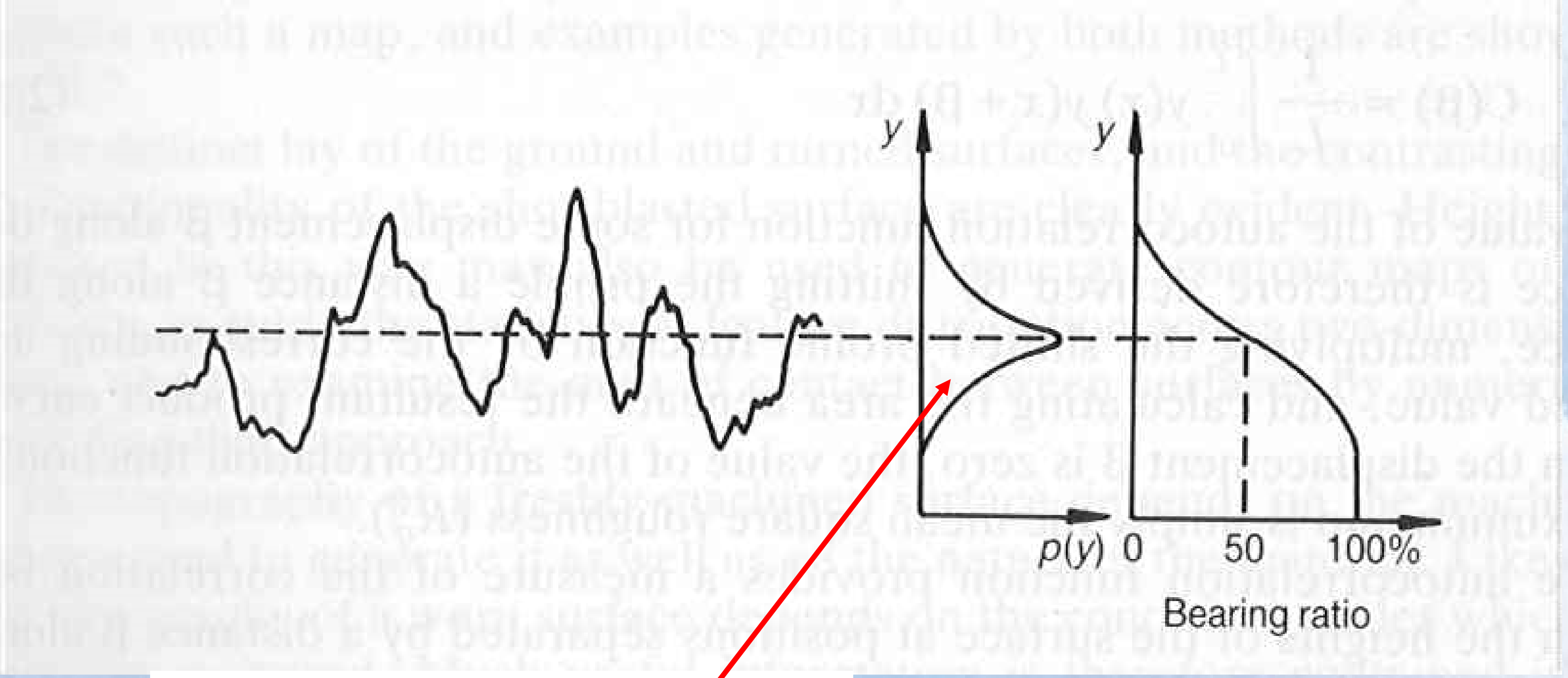
$$R_q = \sqrt{\frac{1}{L}\int_0^L y(x)^2\,dx}$$

- R.M.S slope, Δ_q:

$$\Delta_q = \sqrt{\frac{1}{L}\int_0^L \left(\theta(x) - \bar{\theta}\right)^2 dx} \qquad \bar{\theta} = \frac{1}{L}\int_0^L \theta(x)\,dx$$

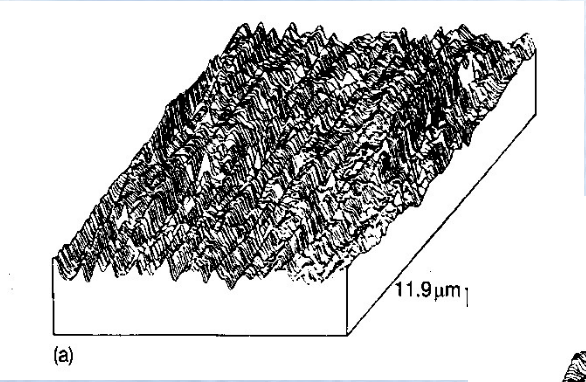
The Amplitude Density Function

Describes the probability to find a point on the surface at height '*y*' above the mean line

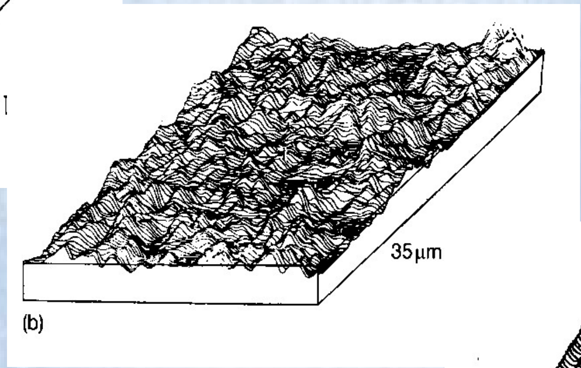


(Gaussian distribution)

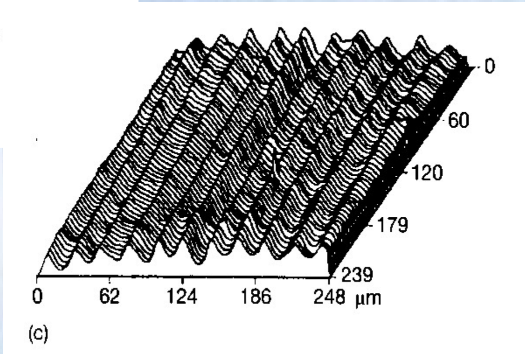
The topography of Engineering Surfaces



Ground steel surface



Shot-blasted steel surface



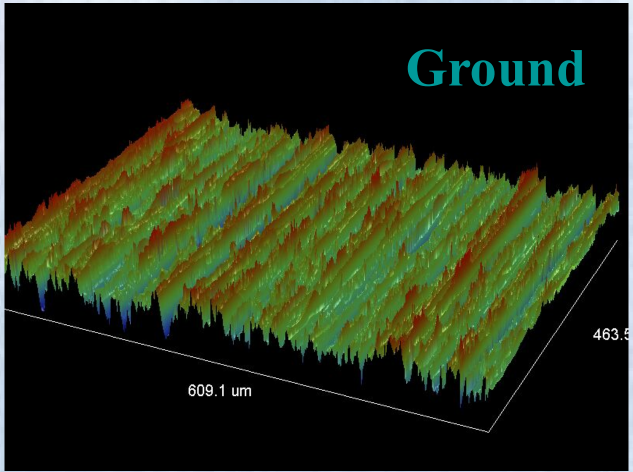
Diamond turned surface

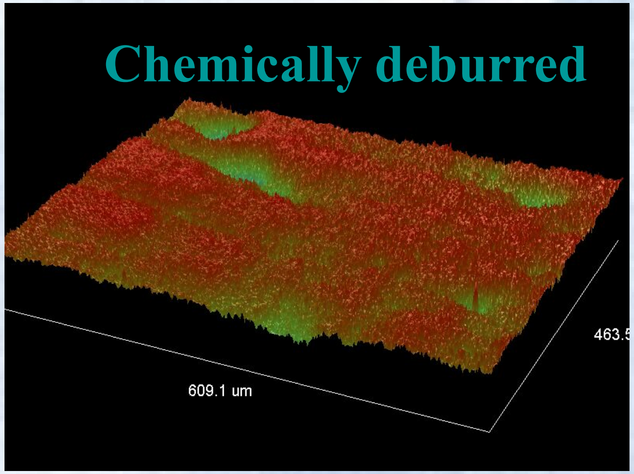
Typical Ra values for Engineering Surfaces

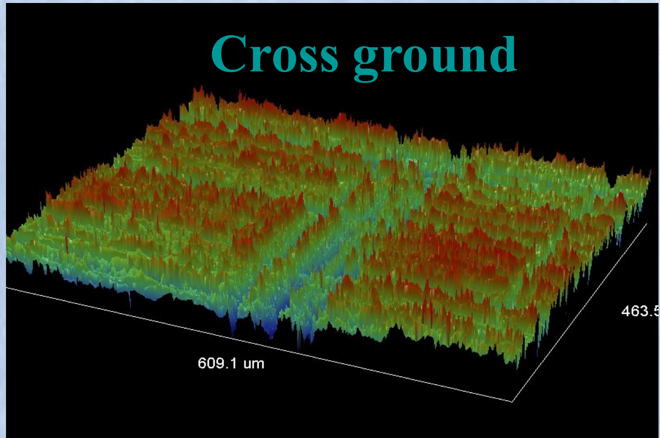
Process	Ra (μm)
Planing, shaping	*1-25*
Milling	*1-6*
Drawing, extrusion	*1-3*
Turning, boring	*0.4-6*
Grinding	*0.1-2*
Honing	*0.1-1*
Polishing	*0.1-0.4*
Lapping	*0.05-0.4*

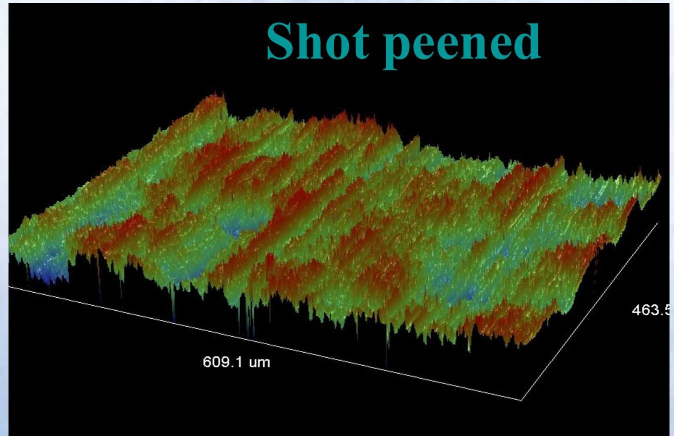
(I.M. Hutchings)

Surfaces Manufactured in Different Ways









Source: John Lord, LTU

Some Remarks about Surface Topography

•Surface topography plays an important role in determining the performance of various tribological machine components.

•There is a need to establish a correlation between surface topography and tribological performance in order to establish optimal surface topography specifications for different moving machine components.

As someone has said:

"The surfaces should be as smooth as possible but as rough as necessary".

It is, of course easier said than done.

Future challenges are to produce the surfaces having specified topographical parameters for optimal tribological performance.

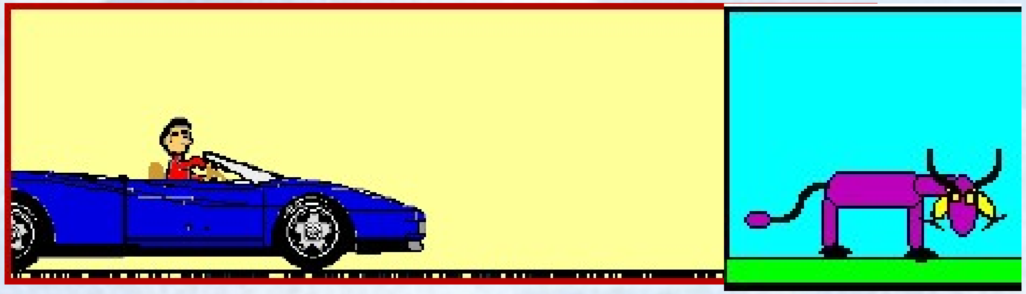
Basic Concept of Friction

INTRODUCTION

- Friction is the resistance to motion during sliding or rolling that is experienced when one solid body moves tangentially over another with which it is in contact .The occurrence of friction is a part of everyday life.

- It is needed so that we have control on our walking.

The Lucky Cow…



- **In this animation, the driver of the car applies the brakes to avoid hitting the cow.**
- **But how does this cause the car to slow down and stop?**
- **The brakes cause the wheels to stop turning and to slide on the road surface.**
- This action produces a force that resists the forward movement of the car.
- This force is called **Friction**

Friction is a force…

- **<u>that acts to resist the motion of one object sliding over another</u>**.
- You may be used to seeing moving objects slow down and stop once the force pushing or pulling the objects is removed.
- For example a wagon will stop moving once you stop pulling it.
- A ball will stop moving once it is caught.

Friction is a force…

- What you may not realize is that there are many forces acting upon objects that affect movement.
- Friction is one of these.
- Friction occurs when two objects are rubbed together.
- The bumps of one surface catch and hook into the bumps of the other surface.

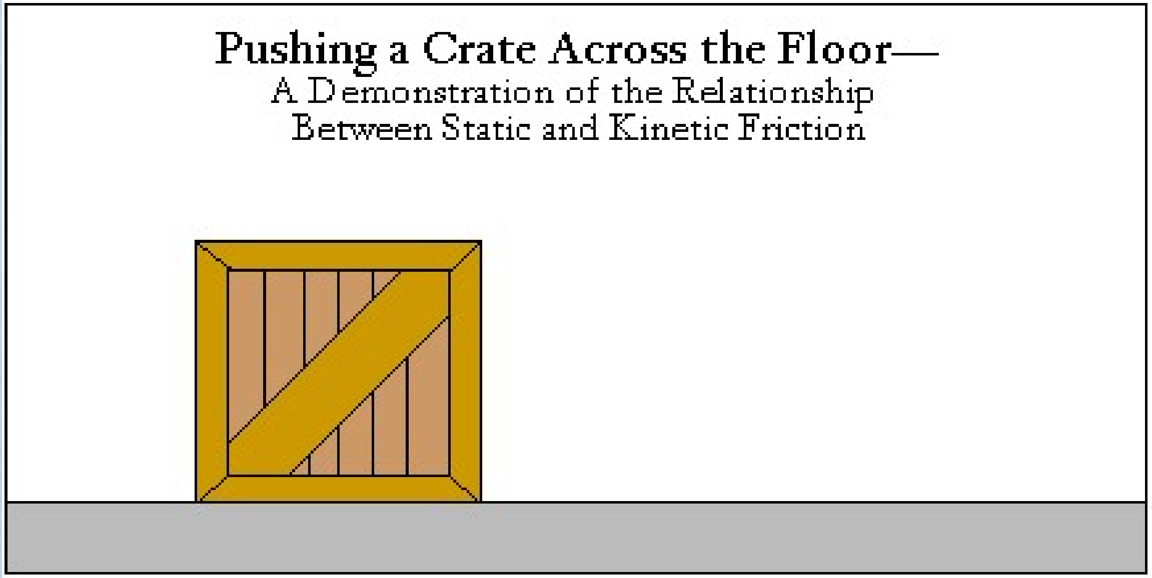
- When the surfaces stick together, the motion between the objects slows down and stops.

- Frictional forces make it possible for us to walk, hold balls, open jars, and ride bikes.

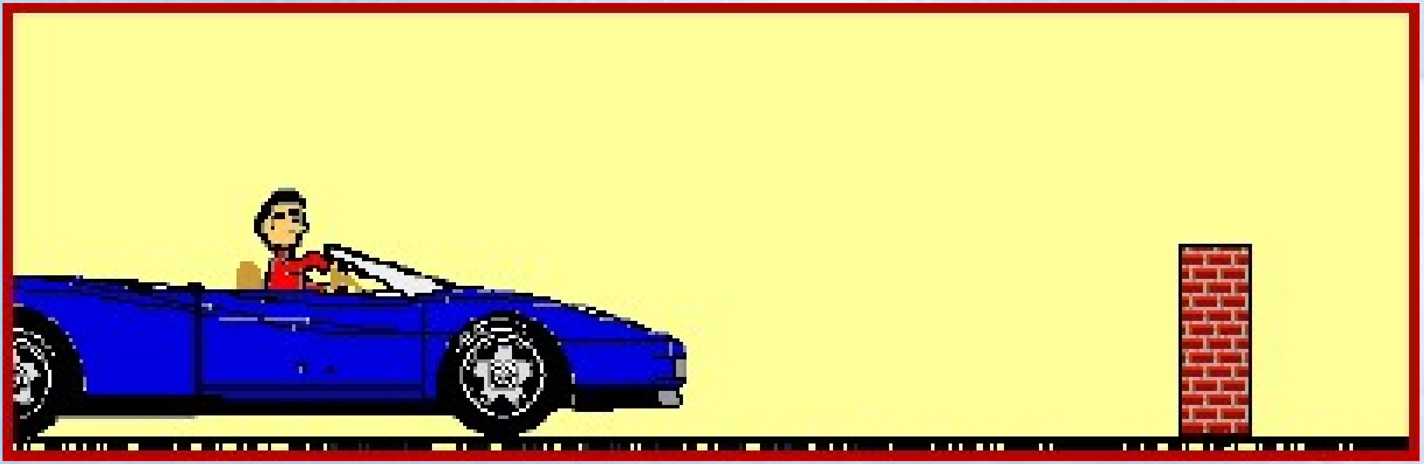
- Lots of friction helps **keep things in place** (cleats on soccer shoes help the shoes grip the ground),
- while little friction **can make motion easy** (moving over a smooth surface like a slide).

- Most motion on earth involves friction.
- A ball rolling on a level floor will eventually stop because the floor pushes against the ball and creates friction.
- When you play baseball and slide into a base, you stop because of friction between you and the earth.
- If there were no friction you would slide right on over the base.

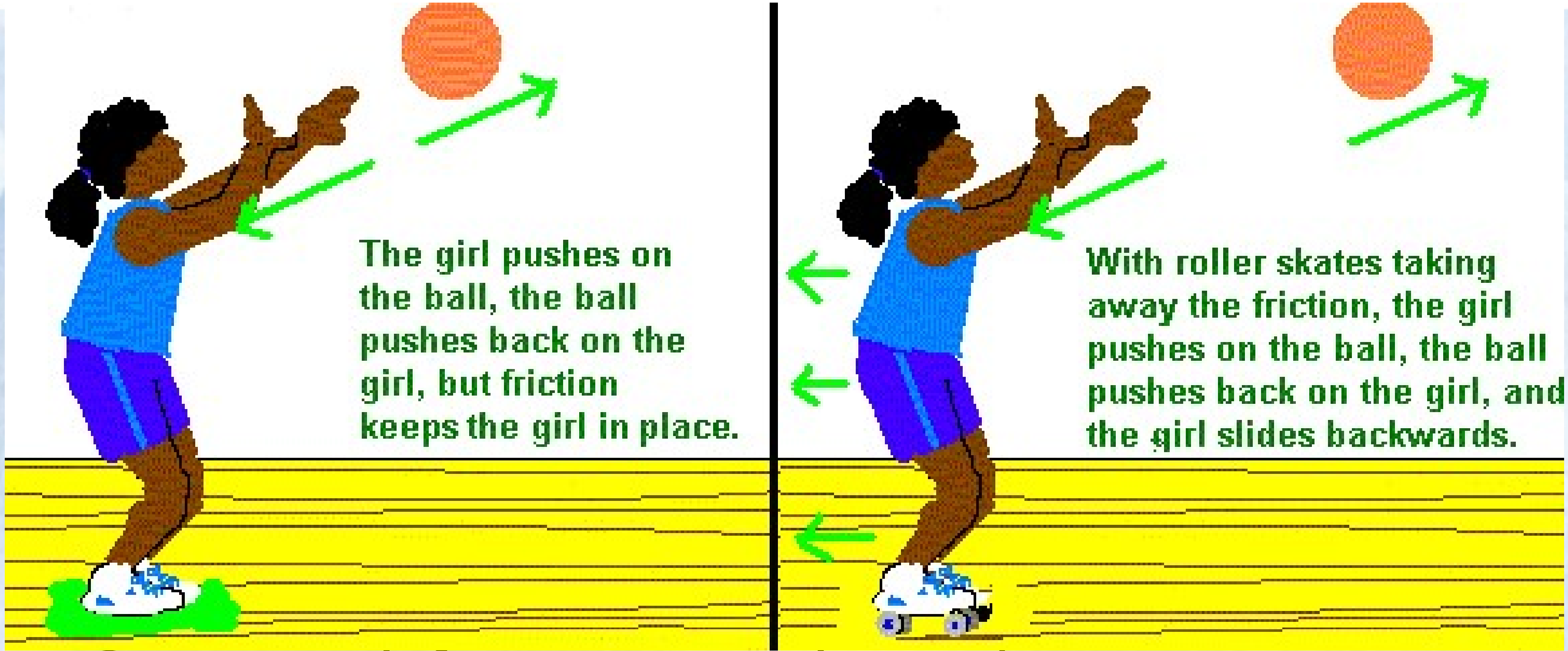
- It is the force of friction that **opposes an object moving**.
- Many people think that it is a nuisance because it has causes us to apply a greater force to move an object.
- But in fact, it is of great help to us.



- If there is no friction, then cars cannot move on the road and we can hardly even walk.



- Imagine when you go skiing, is it very hard to walk on ice?
- How about those penguins?

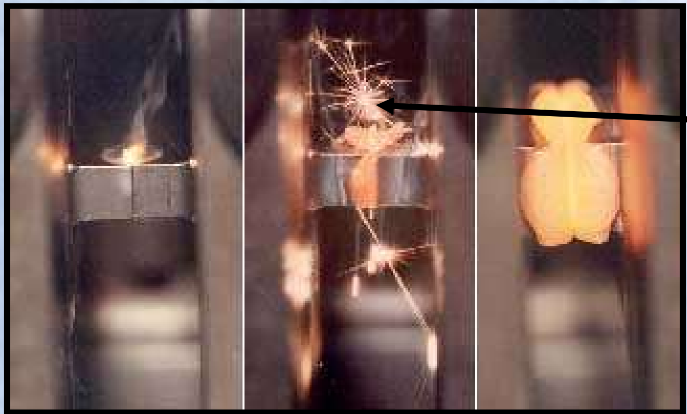


- Frictional forces act along the common surfaces between two bodies in contact so as to resist the relative motion of the two bodies.
- The frictions involved form an **action-reaction pair.**

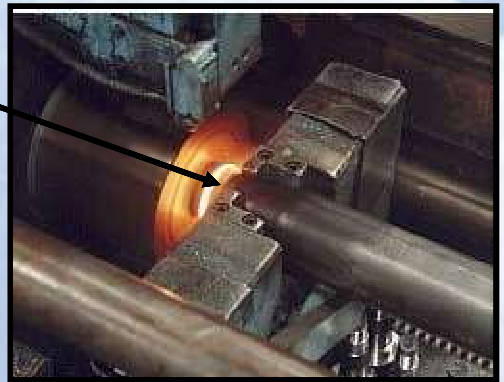
Friction

INTRODUCTION…..(Cont…)

- On the other hand, in most of running machines friction is undesirable (energy loss, leading to wear of vital parts, deteriorating performance due to heat generation) and all sorts of attempts (i.e. using low friction materials, lubricating surfaces with oil or greases, changing design so that sliding can be reduced) have been made to reduce it.



Heat generated due to Friction



Friction

INTRODUCTION…..(Cont..)

- Often coefficient of friction(μ) is considered a constant value for a pair of material. In addition, the value of μ is accounted much lesser than 1.0. In practice μ greater than 1.0, as shown in Table, has been observed. Generally coefficients of friction depend on parameters such as temperature, surface roughness and hardness.

Table : Coefficient of friction for various metals sliding on themselves.

Aluminum	1.5
Copper	1.5
Gold	2.5
Iron	1.2
Platinum	3
Silver	1.5

Fig. 2.1 indicates that under dry lubricant conditions, μ ranges between 0.1 to 1.0 for most of the materials. Very thin lubrication reduces coefficient by 10 times.

Friction

INTRODUCTION…..(Cont..)

- Fig. indicates that under dry lubricant conditions, μ ranges between 0.1 to 1.0 for most of the materials. Very thin lubrication reduces coefficient by 10 times.

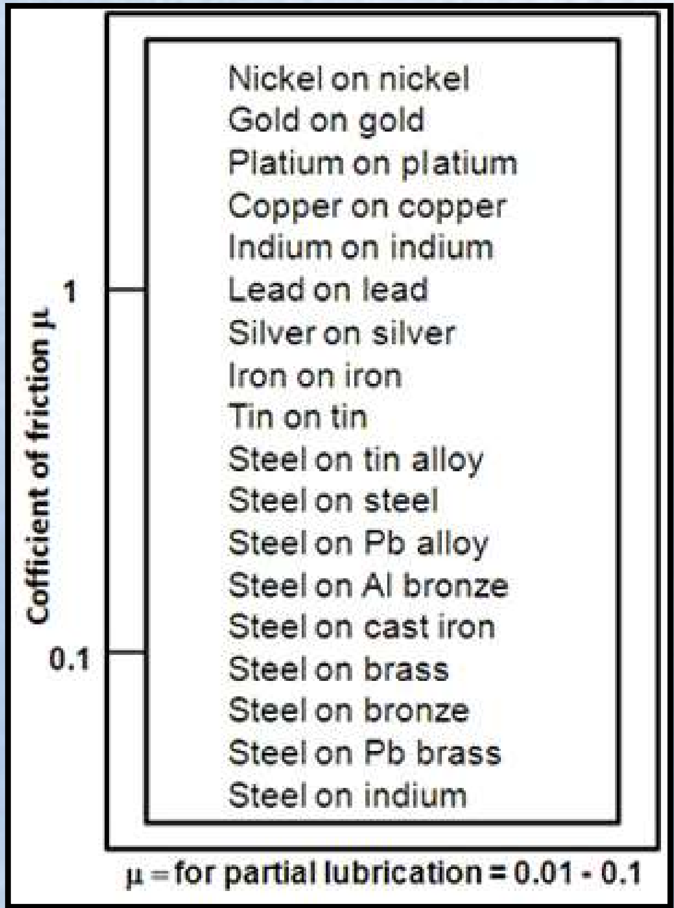


Fig. : Coefficient of friction for various metals.

Friction

INTRODUCTION…..(Cont..)

- Generally, adhesion (ref. Fig.) increases the friction. So, while selecting metal pairs, low adhesion metal pairs must be selected to reduce friction force. Similar material pair must be avoided as similar materials have higher tendency of adhesion.

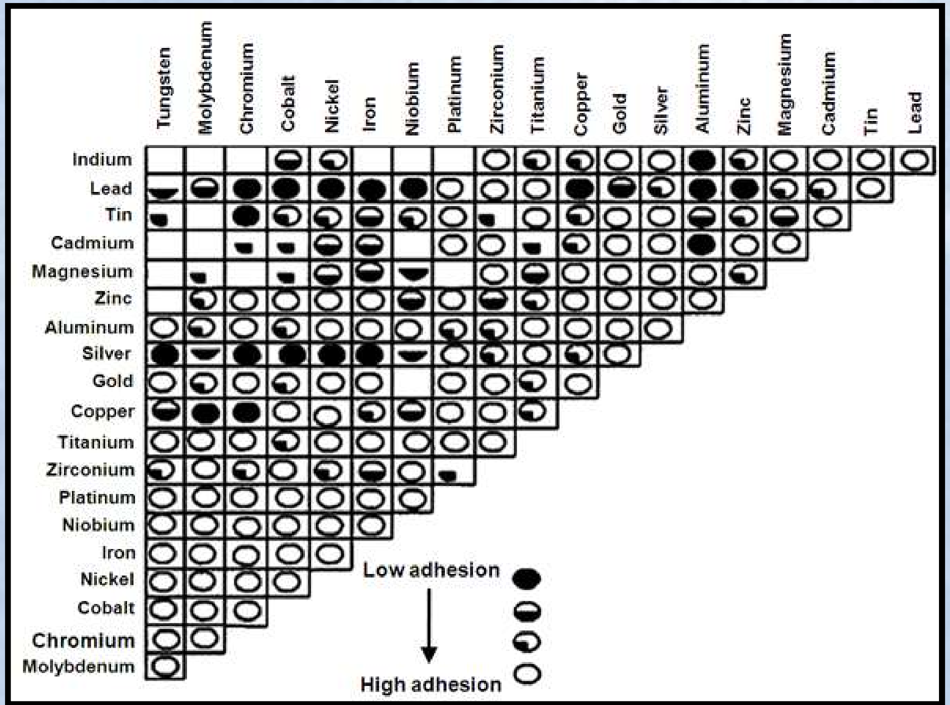


Fig. : Adhesive Friction among various materials

Types of Friction

- Static
- Sliding
- Rolling
- Fluid

Static & Kinetic Frictions

- Before starting friction mechanisms, it is necessary to define static and kinetic friction.
- Let us consider a block on the surface getting pushed by a tangential force F.
- On application of 20 N load, block does not move.
- This second point on the graph(Fig.) shows that on application of 40 N, still block does not move.
- There is static force equilibrium between application force and friction force. On application of 50 N load, block just start sliding. At this point of load application friction force remains equal to 50 N, but friction resistance decreases subsequently to 40 N.

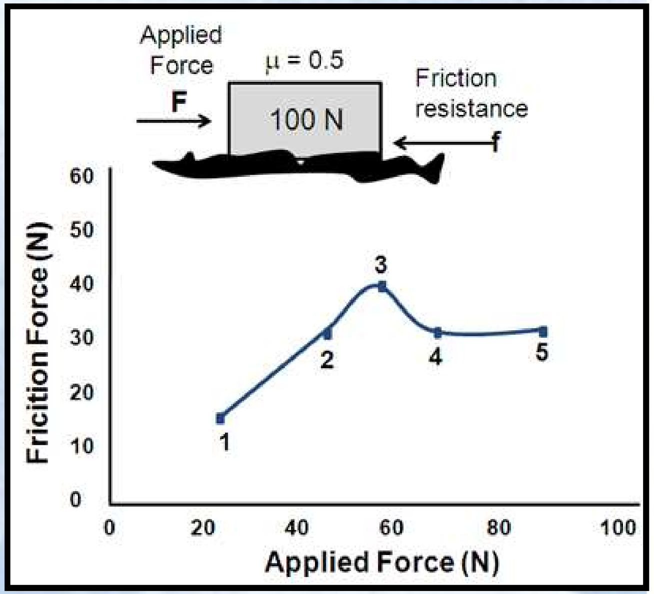


Fig.: Difference between the static and kinetic friction may initiate 'stick-slip'.

Static & Kinetic Frictions (Cont..)

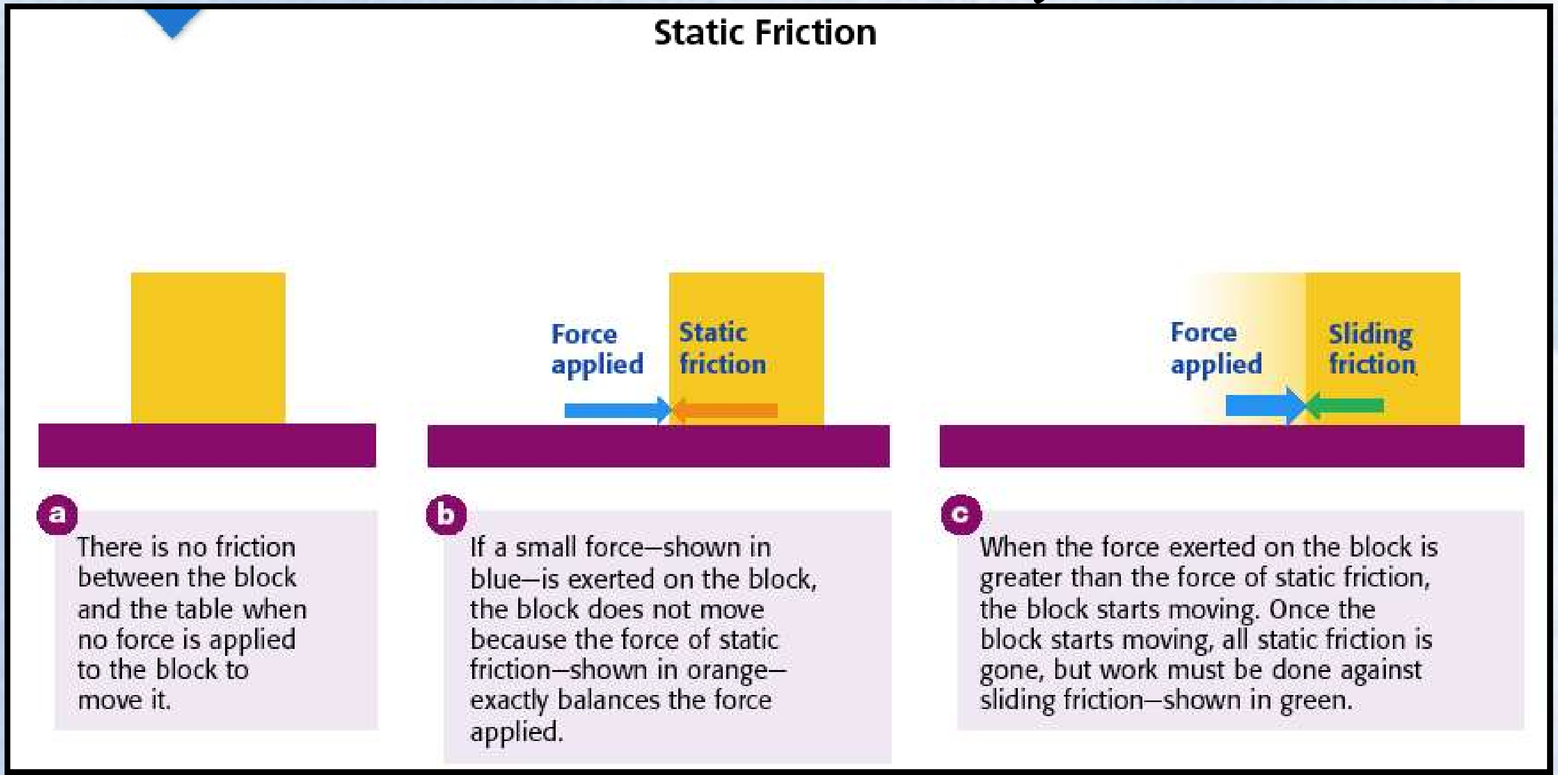
- In other words, static friction is higher than kinetic friction.
- Table shows few published results of static/kinetic coefficient of friction.
- This table indicates that coefficient of friction is statistical parameter.
- It is difficult to obtain same value under various laboratory conditions.
- Further, there is a possibility of substantial decrease in kinetic friction relative to static friction.
- Stick-slip is a phenomenon where the instantaneous sliding speed of an object does not remain close to the average sliding speed.
- Stick-slip is a type of friction instability.

Table: μ for wood-on-wood reported in various articles.

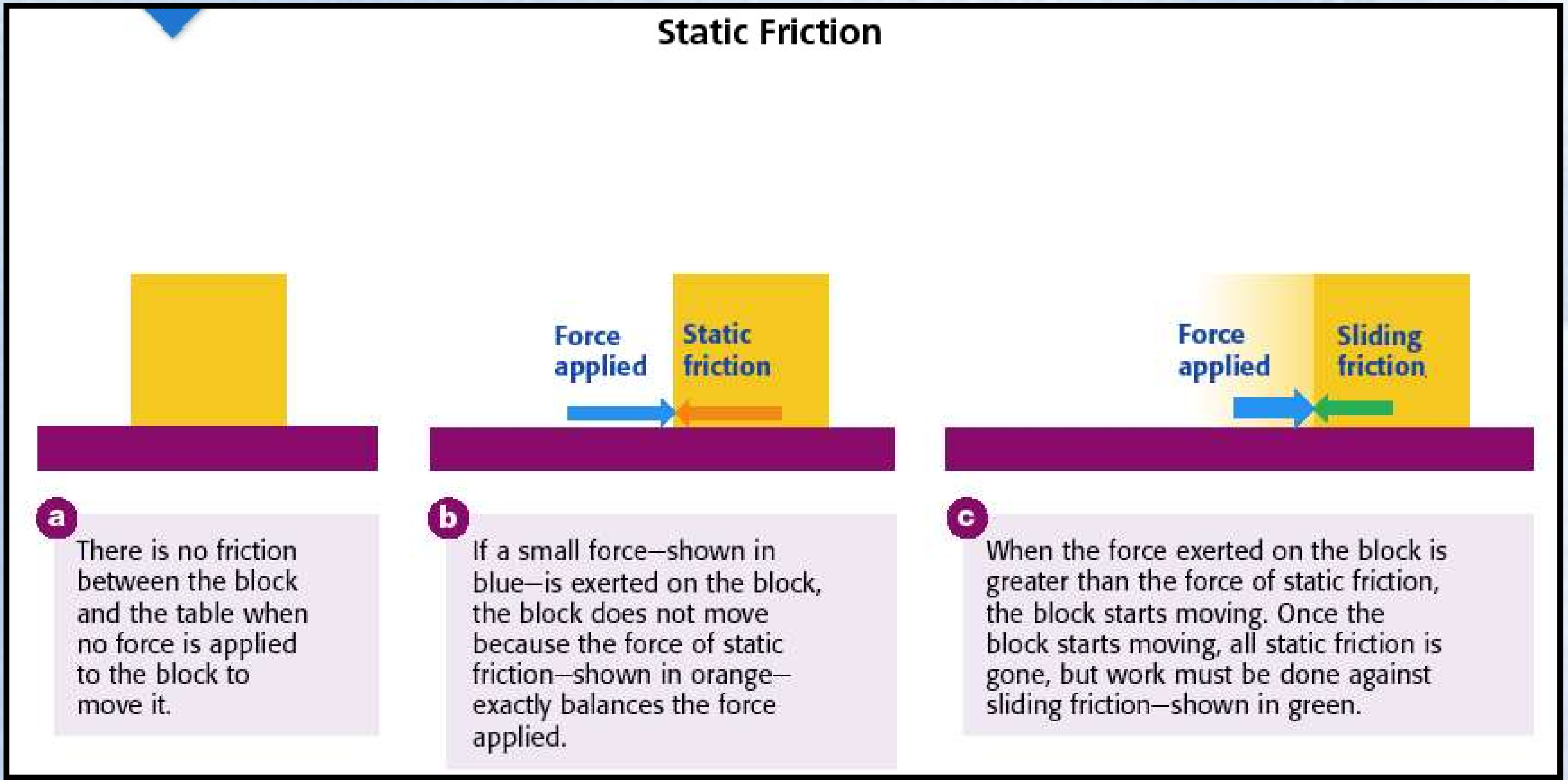
Listed material combination	μ_s	μ_k
Wood on wood	0.25 – 0.5	0.19
Wood on wood (dry)	0.25 – 0.5	0.38
Wood on wood	0.30 – 0.70	---
Wood on wood	0.6	0.32
Wood on wood	0.6	0.5
Wood on wood	0.4	0.2
Oak on oak (para. to grain)	0.62	---
Oak on oak(perp. To grain)	0.54	0.48
Oak on oak(fibers parallel)	0.62	0.48
Oak on oak(fibers crossed)	0.54	0.34
Oak on oak(fibers perpendicular)	0.43	0.19

Static Friction

- **In this figure, a horizontal force is applied to a body with an intention to move it to the right-side. (note: if the force applied is too small the "static friction is greater and the block will not move.)**



- As long as the body is at rest, the frictional force is equal to the applied force and directs to the left-side (opposite direction of motion) resisting the motion.
- The friction is static as there is no motion.



Greater Mass
Creates More Friction

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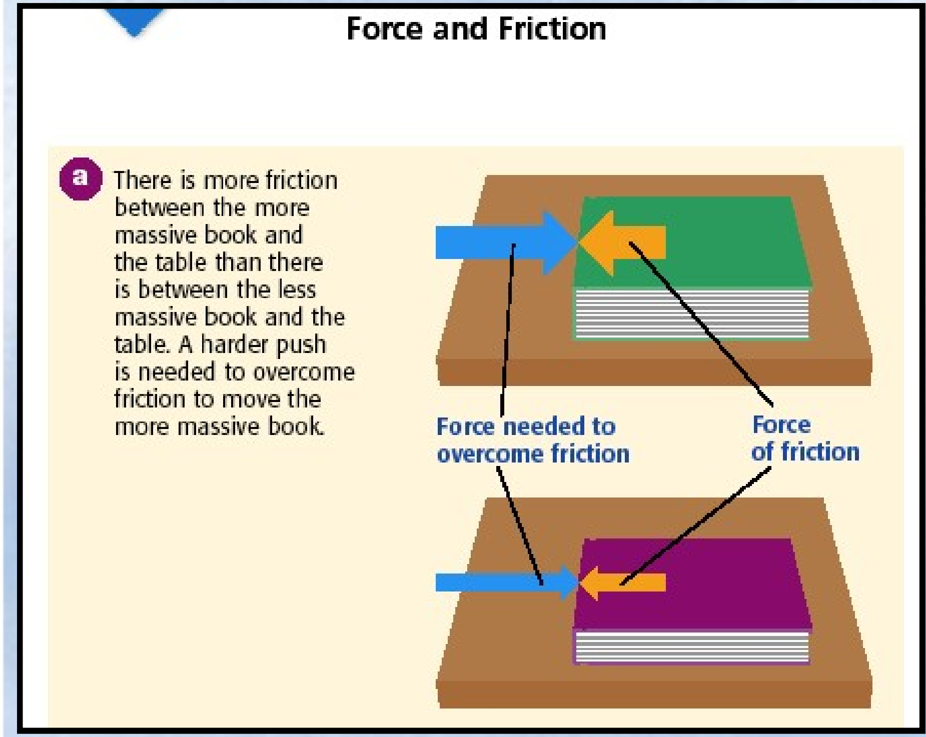
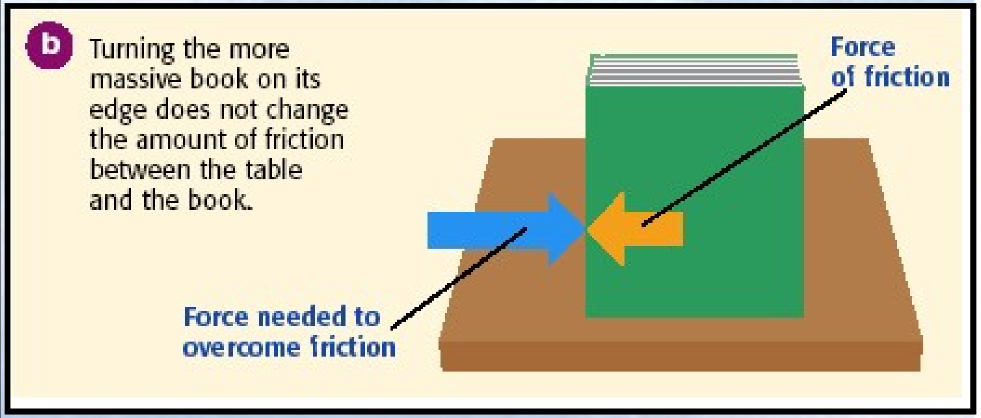
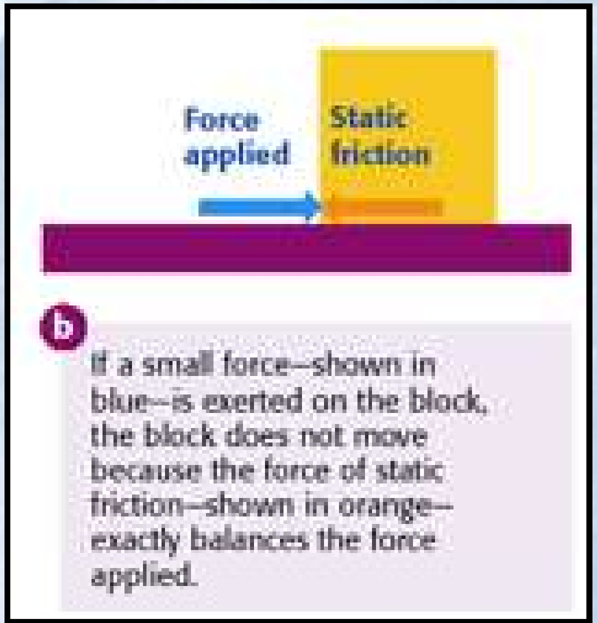
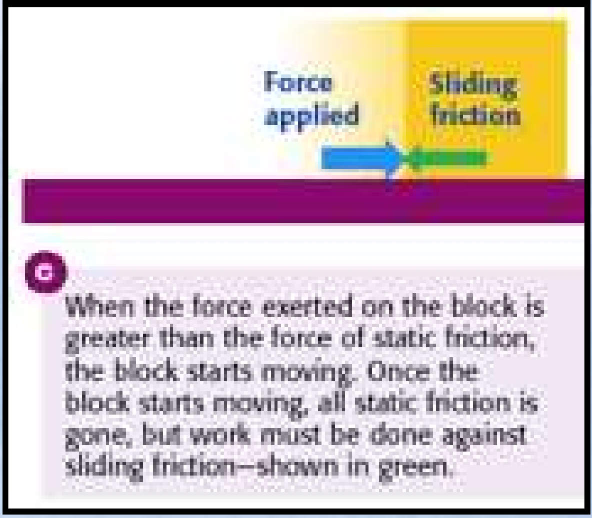
A greater push is needed to overcome the greater mass which has greater (static) friction





Static Friction

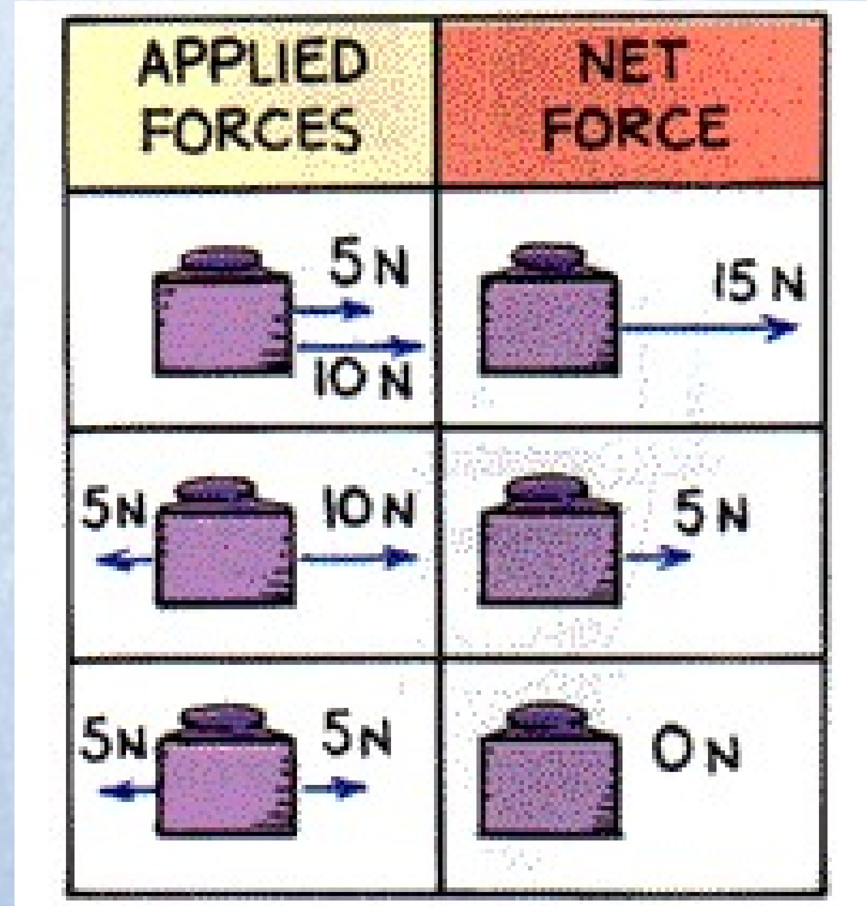




- If applied force is increased, the frictional force will also increase until it reaches the
- **limiting frictional force**.
- As the applied force increases further, the body will begin to move.
- The limiting frictional force is independent of the applied force but depends on the nature of the surfaces and the normal contact force.

What is Net force?

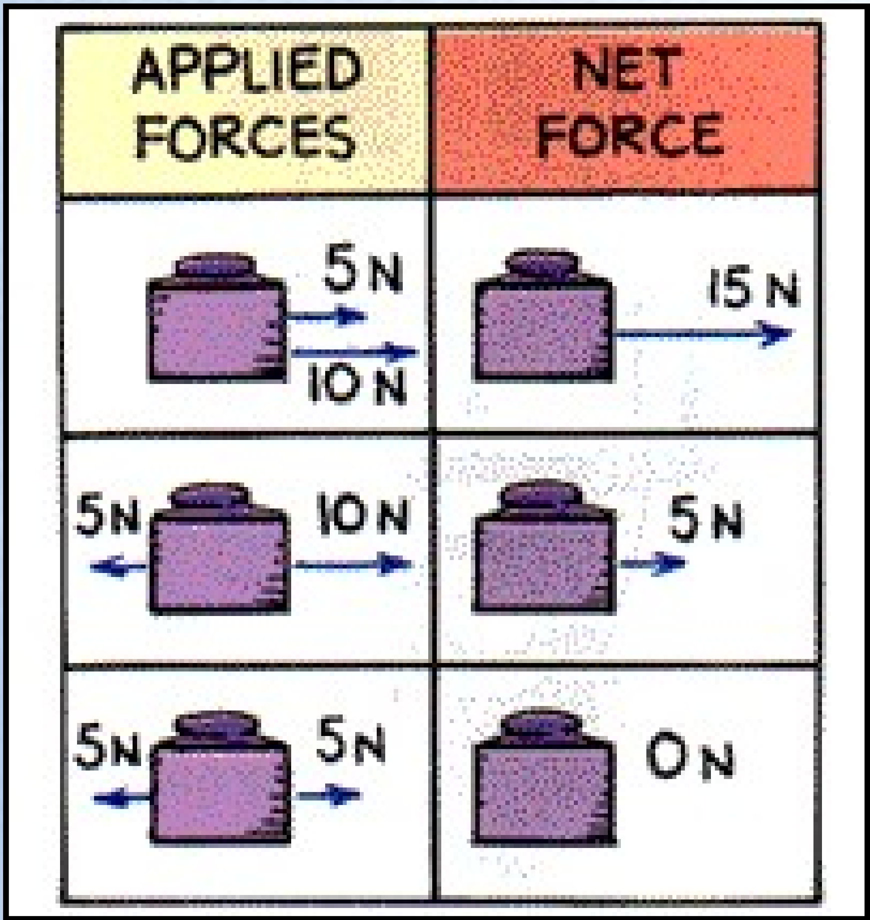
- Combining all forces exerted on an object



Draw this at the bottom
Of the page!

Calculating net force:
Combining all forces exerted on an object

- Forces in the **same** direction
- **Add** forces together

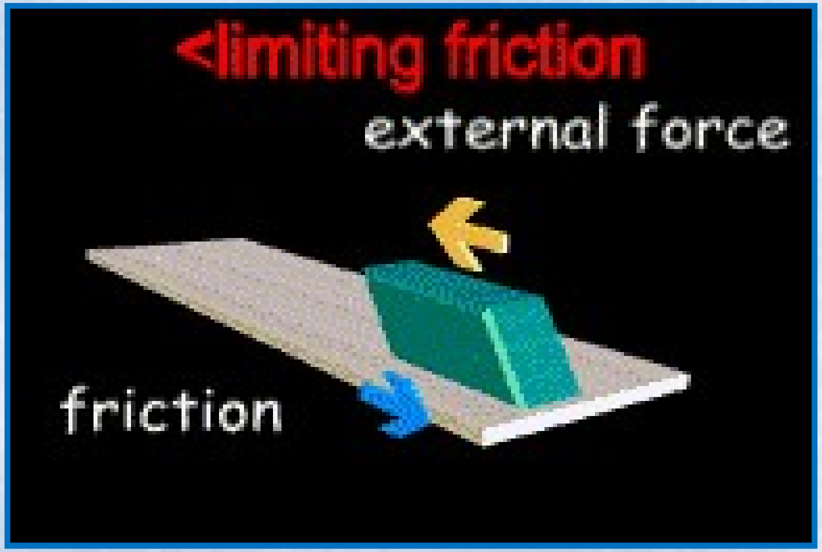


- Forces in the **opposite** direction
- **Subtract** smaller force from the larger force

Static Friction

- This figure shows that object begin to move if the applied force is larger than the limiting friction.
- Before that, the frictional force increased with the applied force.

Static Friction continued



- Once the body starts to move, the frictional force would fall to a smaller value compare with the static frictional force.
- This frictional force remains constant even though the applied force is increased further.

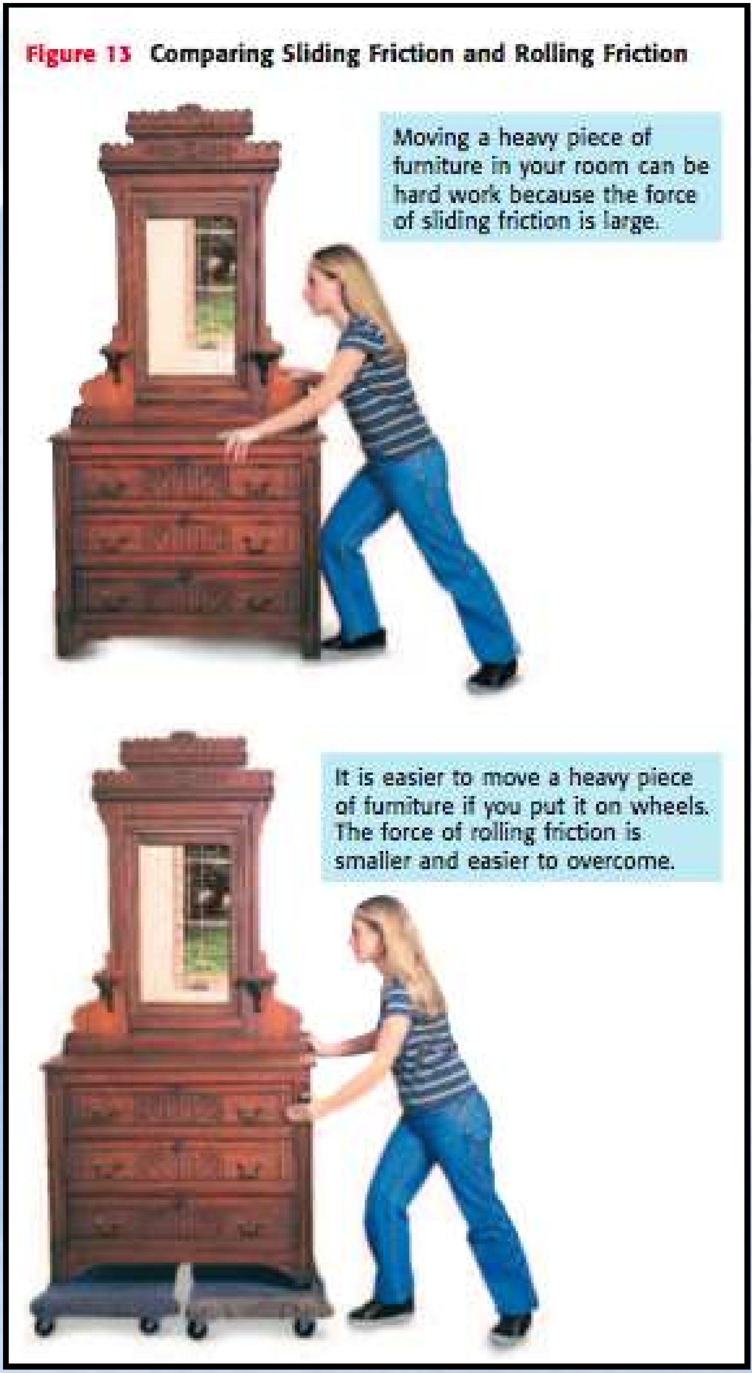
A plane and it's friction experience with "Sliding Friction"

NATIONAL INSTITUTE OF TECHNOLOGY, SRINAGAR, J & K, INDIA

Sliding friction = HEAT

Rolling Friction

- The friction between the wheels and the ground is an example of rolling friction.
- The force of rolling friction is usually less than the force of sliding friction



Rolling Friction

Fluid Friction

❖ Fluid friction opposes the motion of objects traveling through a fluid

❖ Remember that fluids include liquids & gases, water, milk and air are ALL fluids

Figure 14 *Swimming provides a good workout because you must exert force to overcome fluid friction.*

Theories on Friction

- A friction is statistical parameter depends on a number of variable. There is a need to understand science of friction.
- To understand the effect of material pair, role of lubrication, and environmental factors let us start with dry friction.
- The dry friction is also known as solid body friction and it means that there is no coherent liquid or gas lubricant film between the two solid body surfaces.
- Four theories given by Leonardo da Vinci, Amonton, Coulomb and Tomlison for dry lubrication are explained in following slides.

Theories on Friction (Cont..)

- ***Leonardo da vinci(Earliest experimenter, 1452-1519) :***

As per Leonardo, “Friction made by same weight will be of equal resistance at the beginning of movement, although contact may be of different breadths or length”.

“Friction produces the double the amount of effort if weight be doubled”.

In other words, F α W.

Theories on Friction (Cont..)

❖ ***G. Amontons, 1699 :*** The friction force is independent of the nominal area (F ≠ A) of contact between two solid surfaces. The friction force is directly proportional F α N to the normal component of the load. He considered three cases (Fig.) and showed that friction force will vary as per the angle of application of load. As per Amontons μ = 0.3 for most of materials.

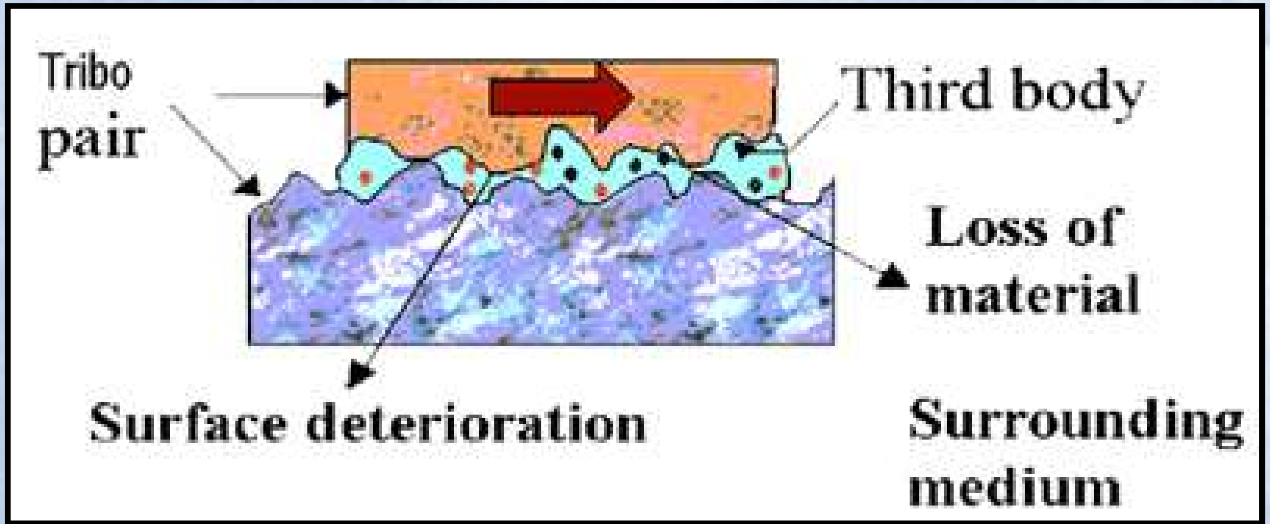


Fig. : Amonton`s work.

Theories on Friction (Cont..)

❖ ***C.A. Coulomb 1781 (1736-1806) :***

- ✓ Clearly distinguished between static & kinetic frictions. Friction due to interlocking of rough surfaces.

  Contact at discrete points μstatic ≥ μkinetic.

  $f \neq func(A)$.

  $f \neq func(v)$.

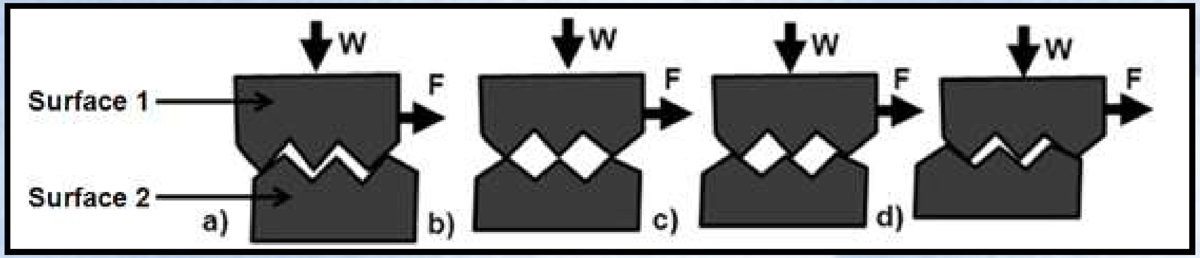


Fig. : Coulomb friction model.

- ✓ As per coulomb friction force is independent of sliding speed. But this law applies only approximately to dry surfaces for a reasonable low range of sliding speeds, which depends on heat dissipation capabilities of tribo-pairs.

Theories on Friction (Cont..)

- ***TOMLINSON's Theory of Molecular attraction, 1929 :***

  Tomlison based on experimental study provided relation between friction coefficient & elastic properties of material involved.

- As per Tomlison due to molecular attraction between metal, cold weld junctions are formed. Generally load on bearing surface is carried on just a few points. These are subjected to heavy unit pressure, and so probably weld together. Adhesion force developed at real area of contact.

$$f = 1.07 * [\theta_I + \theta_{II}]^{2/3}$$

where E is young modulus, Mpsi

Where θ is

$$\theta = \frac{3.E + 4.G}{G(3.*E + G)}$$

where G is modulus in shear, Mpsi

Clean Steel E = 30 Mpsi, G=12 Mpsi → 0.6558
Aluminum E = 10 Mpsi, G=3.6 Mpsi → 0.742
Titanium E = 15.5 Mpsi, G=6.5 Mpsi → 0.5039

Fig. : Examples on Tomlison formula.

- Fig. provides illustration related to Tomlison`s friction formula. This figure indicates f = 0.6558 for clean steel and aluminium, f = 0.742 for aluminium and titanium, and f = 0.5039 for clean steel and titanium.

Theories on Friction (Cont..)

❖ ***Scientific Explanation of Dry Friction :***

- There are two main friction sources: ***Adhesion and Deformation***. Force needed to plough asperities of harder surface through softer.
- In lubricated tribo-pair case, friction due to adhesion will be negligible, while for smoother surfaces under light load conditions deformation component of friction will be negligible.
- Fig. demonstrates the adhesion (cold weld) between two surfaces. Some force, F_a, is required to tear the cold junction.

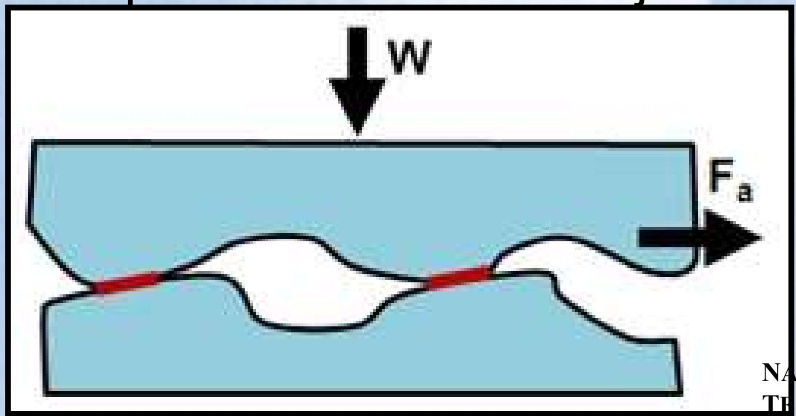


Fig. : Adhesion

Theories on Friction (Cont..)

❖ ***Scientific Explanation of Dry Friction :***

- Fig. demonstrates the deformation process. It shows a conical asperity approaching to a softer surface. To move upper surface relative to lower surface some force is required.

✓ Two friction sources: Deformation and Adhesion.

✓ Resulting friction force (F) is sum of two contributing (F_a & F_d) terms.

✓ Lubricated tribo-pair case -- negligible adhesion.

✓ Smoother surfaces under light load conditions – Negligible deformation.

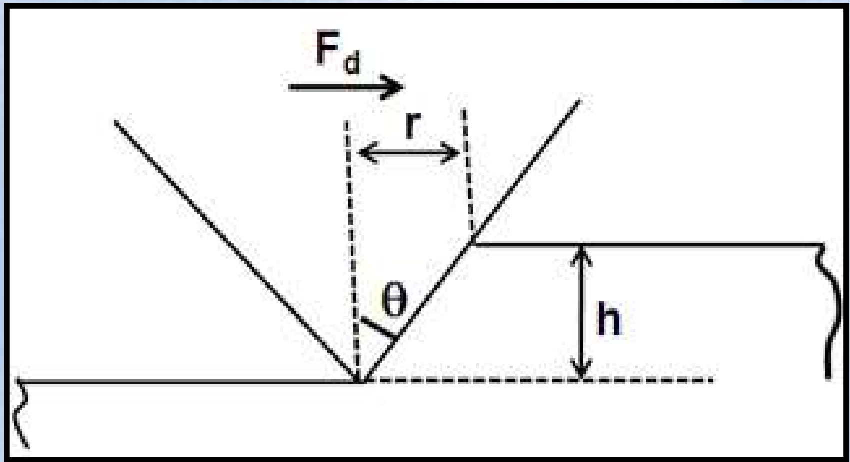


Fig.: Abrasion (Deformation)

Adhesion and Ploughing in Friction

- This theory is based on the fact that all surfaces are made of atoms.
- All atoms attract order one another by attractive force.
- For examples, if we press steel piece over indium piece (as shown in Fig.) they will bind across the region of contact.
- This process is sometimes called "cold welding," since the surfaces stick together strongly without the application of heat.

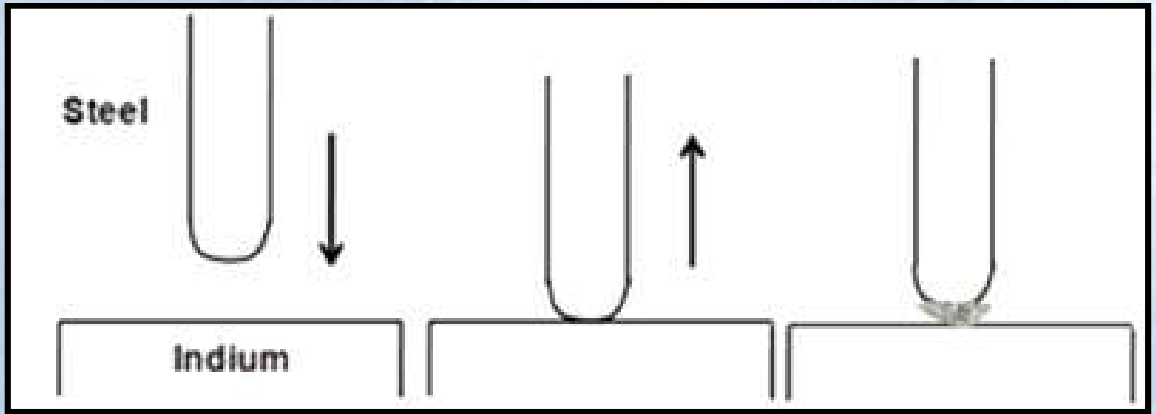


Fig. : Cold welding in steel and indium

Adhesion and Ploughing in Friction (Cont..)

- It requires some force to separate the two surfaces.
- If we now apply a sideways force to one of surfaces the junctions formed at the regions of real contact will have to be sheared if sliding is to take place.
- The force to do this is the frictional force. Fig. shows carbon graphite material adhered to stainless steel shaft.

Fig. : Carbon graphite and stainless steel.

THEORY OF ADHESIVE FRICTION

- Bowden and Tabor developed theory of adhesive friction.
- As per this theory on application of W, initial contact at some of higher asperity tips occurs.
- Due to high stress those asperities suffer plastic deformation, which permits strong adhesive bonds among asperities.
- Such cold formed junctions are responsible for the adhesive friction.
- The real area of contact, A can be estimated by applied load W and hardness of the soft material, H.
- If s is shear stress of softer material, then force F_a required to break these bonds can be estimated by Equation $F_a = A_s$.
- The coefficient of friction due to adhesive friction is given by ratio of friction force to applied load W.

THEORY OF ADHESIVE FRICTION (Cont..)

- Fig. shows the formulation and breakage of cold junctions. •
  - ✓ Two surfaces are pressed together under load W.
  - ✓ Material deforms until area of contact (A) is sufficient to support load W, A = W/H.
  - ✓ To move the surface sideway, it must overcome shear strength of junctions with force Fa.
  - ✓ $\mu = Fa / W = s / H$.
  - ✓ In other words shear strength(s) and hardness(H) of soft material decides the value of μ.
  - ✓ This means whatever properties of the other harder pairing material, μ would not change.

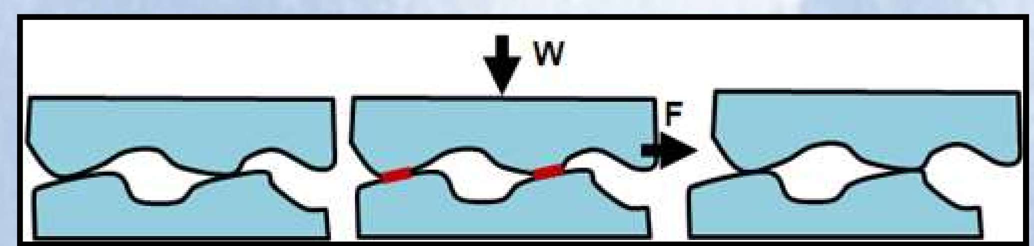


Fig. : Adhesion theory

THEORY OF ADHESIVE FRICTION (Cont..)

- For most of untreated materials H = 3 σy & s = σy/1.7321.
- Expected value of μ = 0.2, as μ = s ⁄ H.
- But for most of the material pair(shown in Fig.) μ is greater than 0.2.
- There is a huge difference between measured values of friction coefficient and estimated by theory of adhesion.
- Theory is unable to estimate different μ for steel on indium and steel on lead alloy. Theory related to deformation needs to be explored.

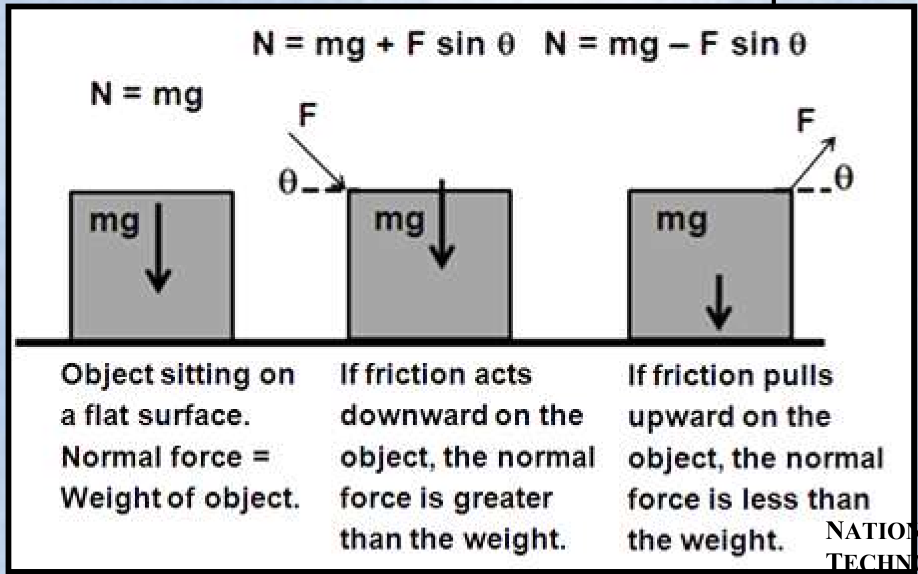


Fig.:Friction coefficients for various material pairs.

FRICTION DUE TO DEFORMATION

- This theory is based on the fact that contact between tribo-pairs only occurs at discrete points, where the asperities on one surface touch the other.
- The slope of asperities governs the friction force.
- Sharp edges cause more friction compared to rounded edges.
- Expression for coefficient of friction can be derived based on the ploughing effect.
- Ploughing occurs when two bodies in contact have different hardness.
- The asperities on the harder surface may penetrate into the softer surface and produce grooves on it, if there is relative motion.

FRICTION DUE TO DEFORMATION (Cont..)

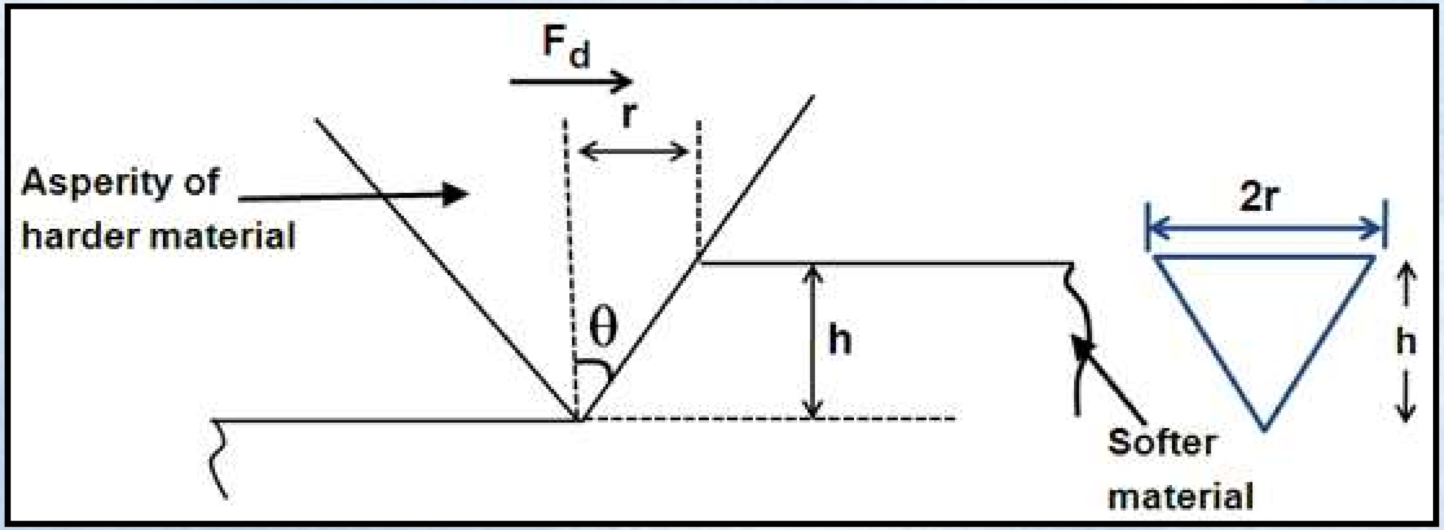


Fig. : Deformation theory[1].

- Contact between tribo-pairs only occurs at discrete points. Assume n conical asperities of hard metal in contact with flat soft metal, vertically project area of contact.

$$W = n(0.5 * \pi r^2)H$$

$$A = n\left(0.5 * \pi r^2\right)$$

$$F = n(rh)H$$

[1]. J Halling, Principles of Tribology, The Macmillan Press Ltd, London, 1975.

FRICTION DUE TO DEFORMATION (Cont..)

- μd = (F/W), substituting the equations of F and W, we get μd = (2/π)cot θ : This relation shows important of cone angle, θ.
- Table lists the μd for various θ values.
- In practice slopes of real surfaces are lesser than 100 (i.e. θ > 800), therefore μd = 0.1. If we add this value(μd = 0.1), total μ, should not exceed 0.3. Total μ, representing contribution for both ploughing and adhesion terms.

Table

θ	μ
5	7.271
10	3.608
20	1.748
30	1.102
40	0.758
50	0.534
60	0.367
70	0.231
80	0.112
85	0.055

PLOUGHING BY SPHERICAL ASPERITY

- If we consider asperities on solid surfaces are spherical, vertical projected area of contact:

$$A = n\left(0.5 * \pi r^2\right)$$

$$or\ A = n\left(0.5 * \pi (0.5\ d)^2\right)$$

$$or\ A = n\ \frac{\pi d^2}{8}$$

$$W = n\frac{\pi d^2}{8}H$$

$$F = n\ \frac{2hd}{3}H$$

$$\mu_d = \frac{2hd8}{3\pi d^2} = \frac{16}{3\pi}\frac{h}{d} = \frac{16}{3\pi}\frac{h}{\sqrt{8hR}} = 0.6\sqrt{\frac{h}{R}}$$

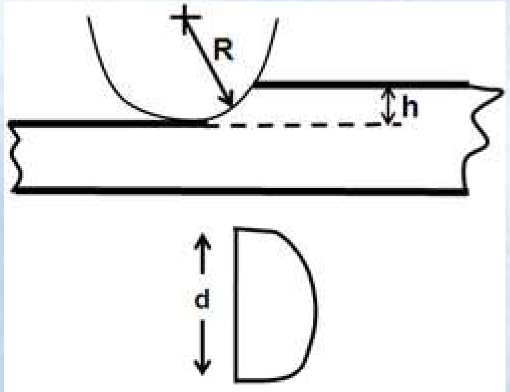


Fig. : Spherical asperity.

- Generally h << R, therefore μd Ξ 0.1. This means total μ, should not exceed 0.3. Summary of theories related to adhesion and ploughing effects.

PLOUGHING BY SPHERICAL ASPERITY (Cont..)

Adhesion, $\mu_a = \frac{s}{H}$

Deformation by Conical Asperities:

$$\mu_d = \frac{2}{\pi}\cot\theta = 0.64\frac{h}{r}$$

Deformation by Spherical Asperities:

$$\mu_d = 0.6\sqrt{\frac{h}{R}}$$

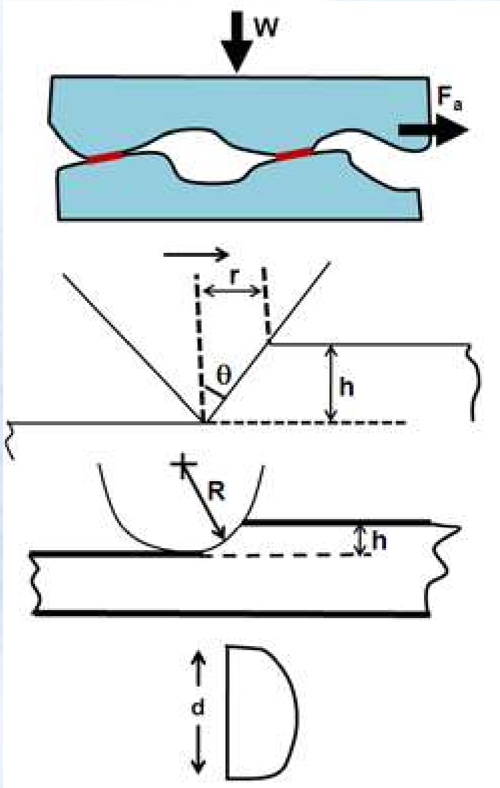


Fig.: Summary of adhesion and ploughing.

PLOUGHING BY SPHERICAL ASPERITY (Cont..)

Three frictional theories were discussed :

- In first expression it is shown that friction depends on the lowest shear strength of the contact tribo-pair. Reducing shear strength and increasing the hardness reduces the coefficient of friction.
- Second expression shows the dependence of coefficient of friction on the angle of conical asperity.
- Third expression indicates lesser sensitivity of coefficient of friction compared to that of conical asperity.
- ✓ None of these expression provides reliable estimation of coefficient of friction which we observe during laboratory tests. Bowden and tabor improved that theory of adhesion and incorporated the limiting shear stress concept.

JUNCTION GROWTH

- Bowden and Tabor were motivated to think that contact area(shown in Fig.) might become much enlarged under the additional shear force and they proposed junction growth theory.
- They considered two rough surfaces subjected to normal load W and friction force at the interface.
- To explain their hypothesis they considered two dimensional stress system(Eq.(1)). If W force is in y-direction and force in x-direction is zero, then principle stresses can be expressed by Eq.(2) and Eq.(3).

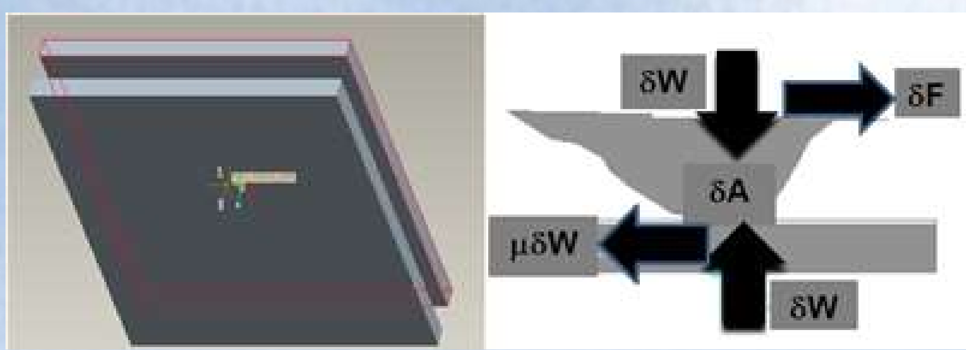


Fig. : Two contacting surfaces.

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Thank You