TRIBOLOGY TODAY

French - German - Turkish
Spring school 2026

April 13-17, 2026
Istanbul - Turkey

https://tribotoday2026.sciencesconf.org

ATM Association de TriboMécanique

Université franco-allemande Deutsch-Französische Hochschule

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES LYON

KIT Karlsruher Institut für Technologie

İTÜ

LaMCoS
UMR 5259

Benyebka Bou-Saïd
Laboratoire de Mécanique des Contact et des Structures (LaMCoS)

Friction, Wear, and Lubrication

LaMCoS
Laboratoire de Mécanique des Contacts et des Structures
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UNIVERSITÉ DE LYON

INSTITUT CARNOT Ingénierie@Lyon

INTRODUCTION

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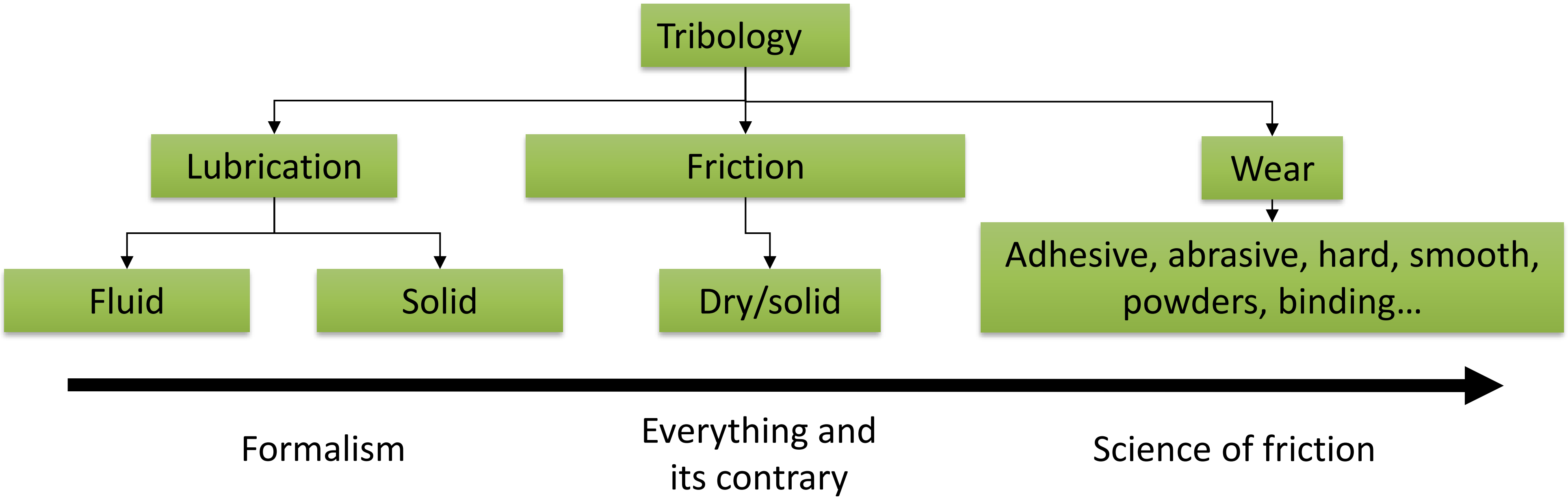
Etymology: *tribein*, to rub and *logos*, discussion, study.

1910, Tribométrie, Larousse dictionary

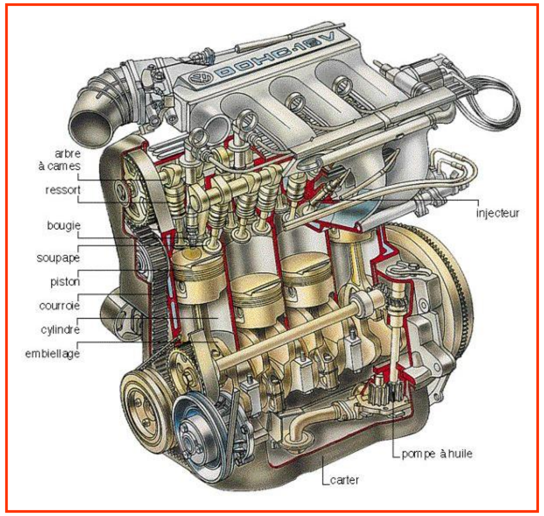
1968, Tribology, G. Salomon, P. Jost ...

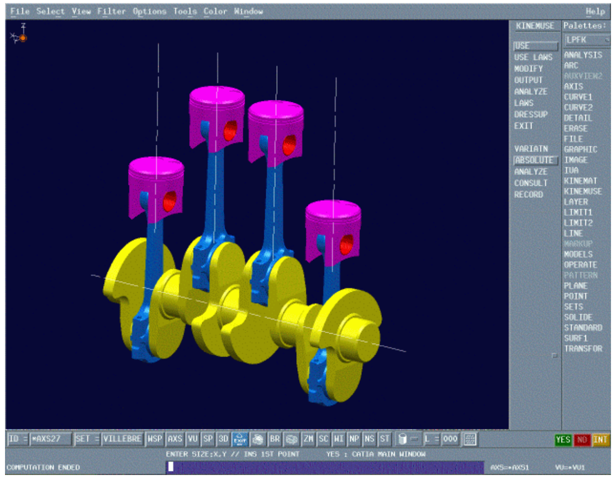
1974, Bio-tribology, D. Dowson, D. Wright

1978, Tribology appears into the dictionary.



	Mechanical actions	Motion
DESIGN	N	N
STATICS	Y	N
KINEMATICS	N	Y
DYNAMICS	Y	Y
TRIBOLOGY	Y and …	Y and…





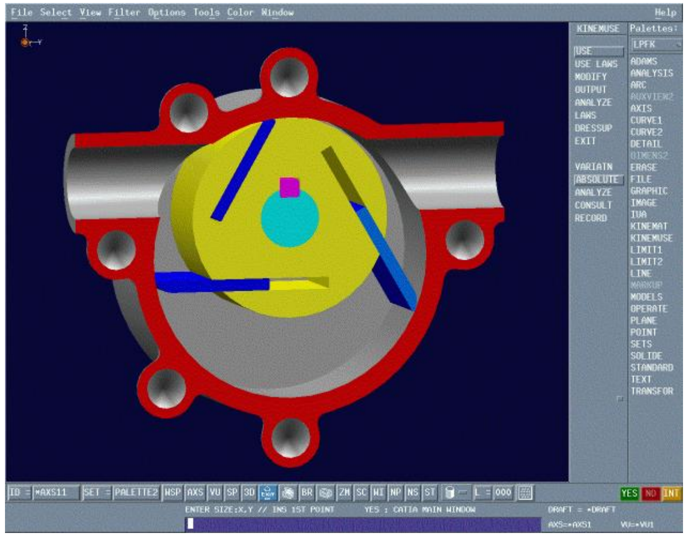
- **Statics** deals with equilibrium and mechanical actions of a system without motion;
- **Kinematics** deals with all the possible motions of a mechanical system;
- **Dynamics** deals with the actual external mechanical actions and the unique motion of the system under such mechanical actions;

Aim of tribology

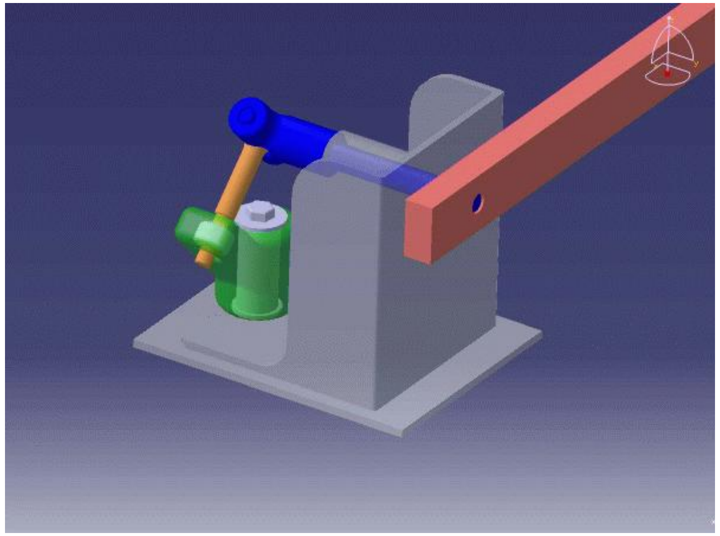
- **Tribology** deals with all the contacts where the system components transmit power, motions and stresses … *tribology is the science that allow for the system motion.*
- Other than time, positions, velocities, accelerations (needed in kinematics), mechanical actions, masses stiffness

(needed in dynamics), **Tribology** needs several other information such as surface properties (roughness, harshness, lubricant, …), material properties, etc…

Vane pumpe

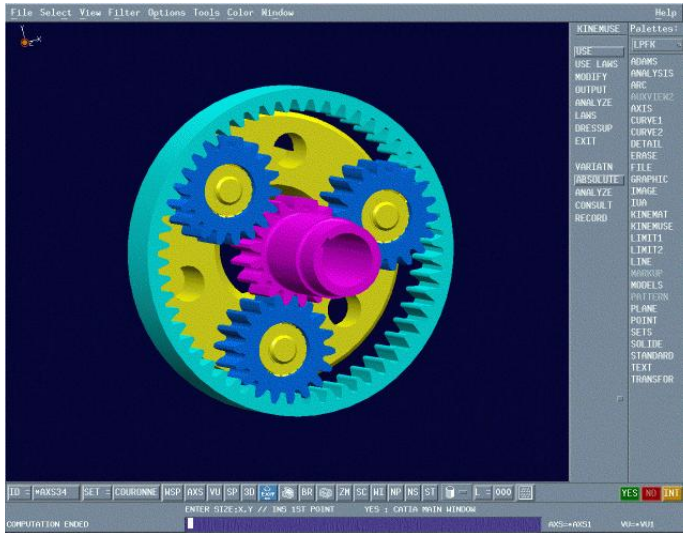


Highway barrier

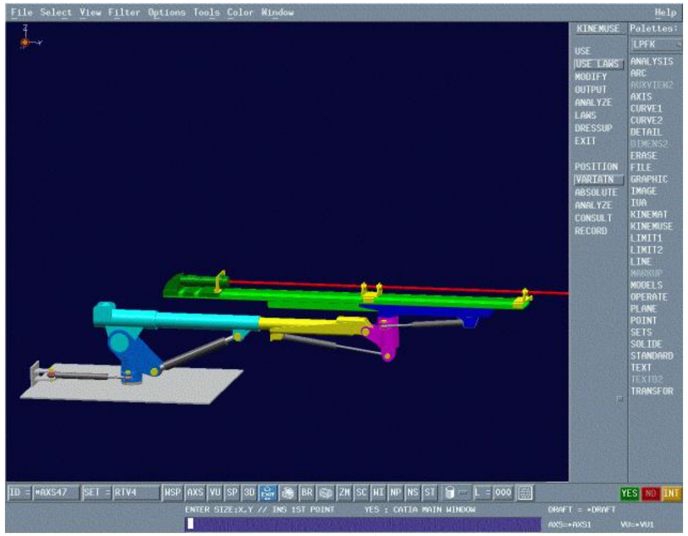


Examples of contacts in mechanical systems

Planetary gear



Robotic harm



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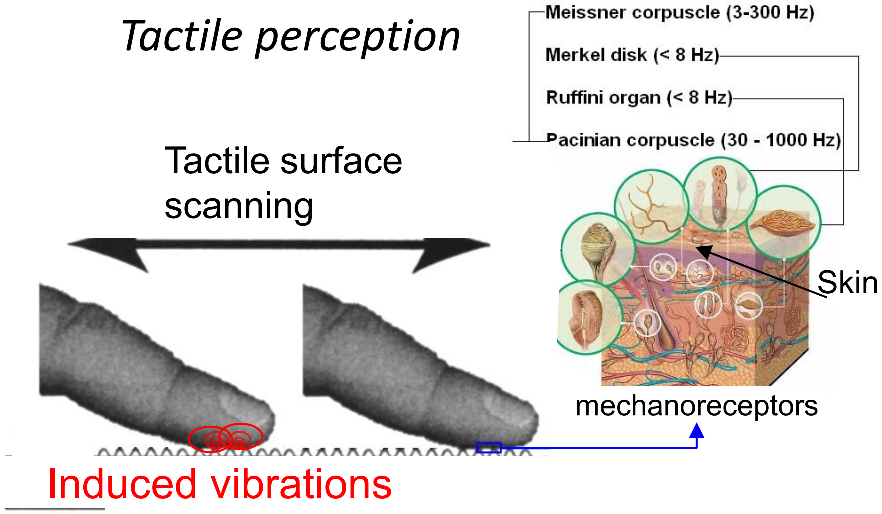
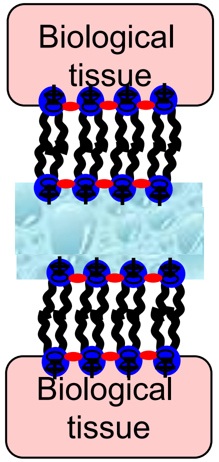
Contacts in bio-mechanical systems

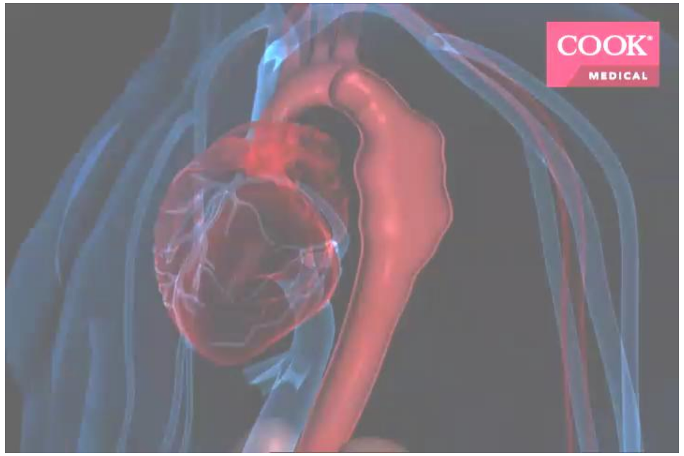
Human joints

Tactile perception

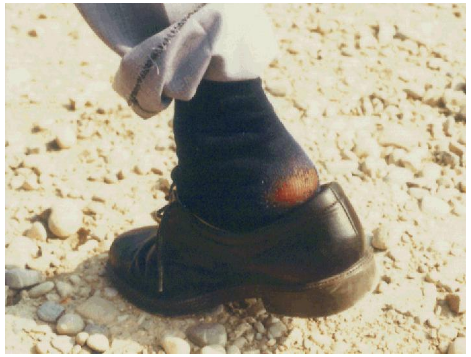


Biological lubricants





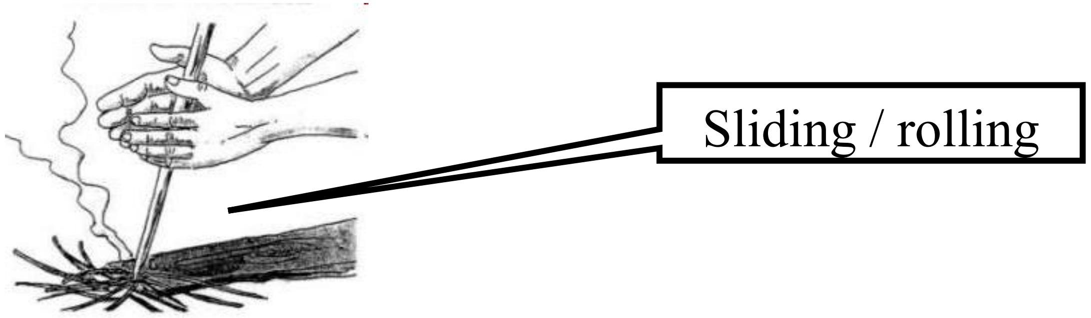
Skin and tissues



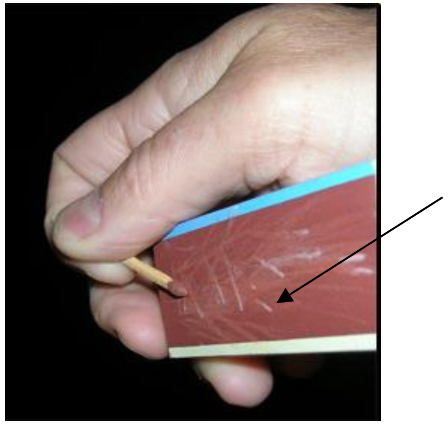
3 TRIBOLOGICAL FUNDAMENTAL INVENTIONS FOR HUMANITY

Fire

- Energy dissipation by friction → heating → lighting



- Friction → heating → chemical reaction → lighting



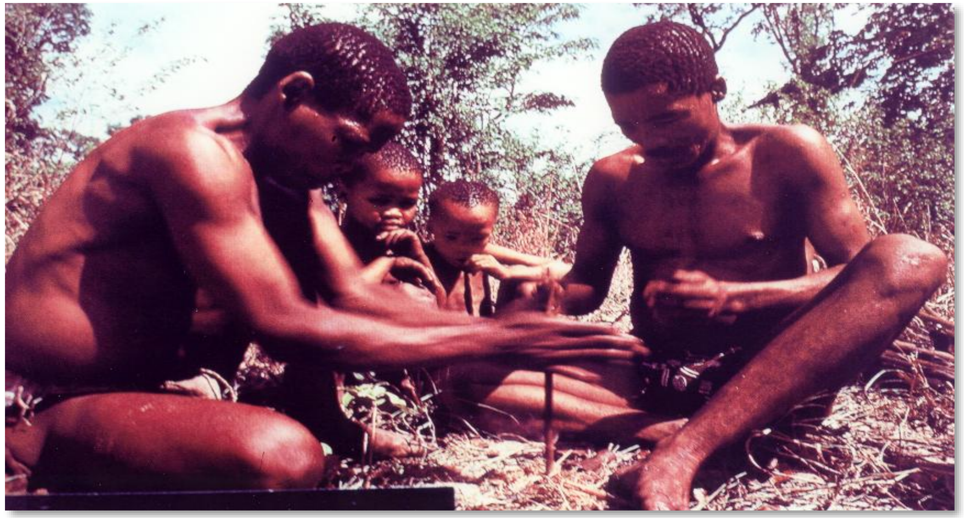
special scraper*, whose chemical elements interact with those of the head of the matchstick to ignite

** The safety match, also called "Swedish Match" because of the Swedish nationality of its inventor Gustaf Erik Pasch, date of 1844. The "safety" comes from the fact that it requires a special scraper, whose chemical elements interact with those of the end of the matchstick to ignite. The scraper is made of glass powder and red phosphorus, while the end of the match is coated with antimony sulfide, manganese and potassium chlorate dioxide. The heat generated by the friction transforms the red phosphorus into white phosphorus, which in turn contributes to the ignition of the match.*

Course of « Tribologie pour l'ingénieur », Y. Berthier, INSA of Lyon.

Tribological fundamental inventions for humanity

Energy delivered to overcome the resistance due to friction is essentially dissipated as heat

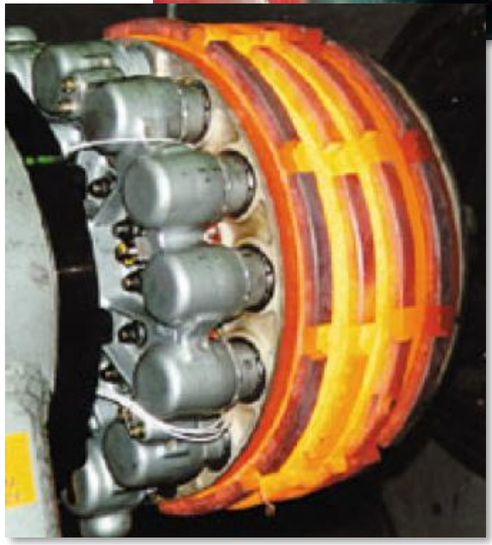


Rotation of a hardwood stick in a hollow of softwood

Egyptian « lighter » (XVIth - XIth century BC, museum of Louvre, Paris)

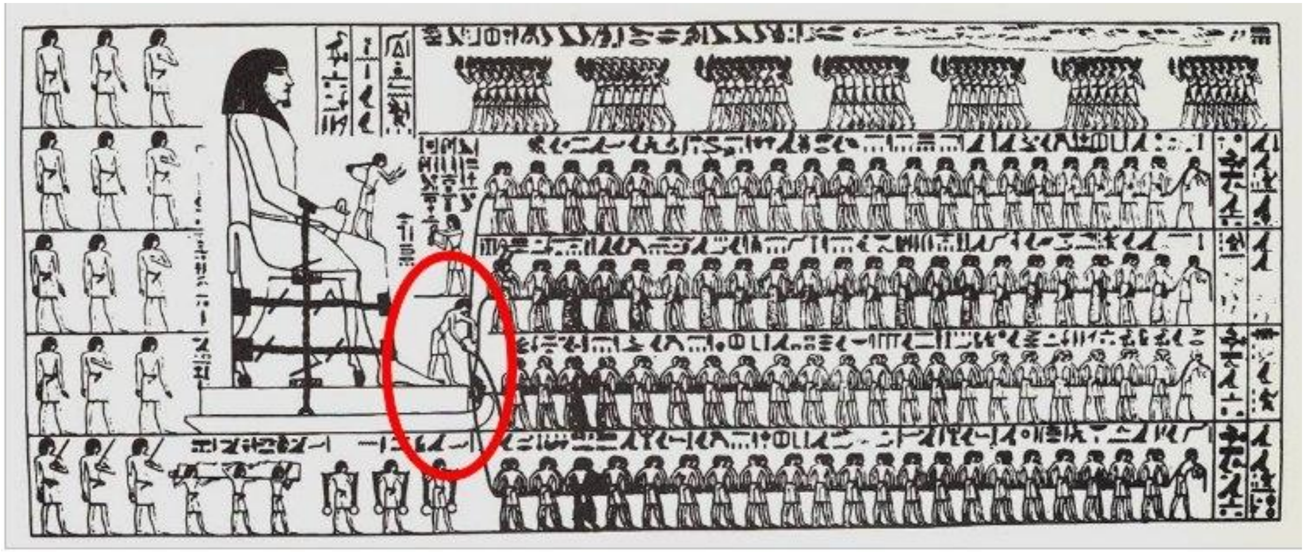
High energy braking

Hot circles during a braking test on a railway rig (Dufrénoy, 1995)



C/C brake of Airbus A 330-A340 (170 tonnes): *emergency braking test (330 km/h, stop in 28 s, temperature 1800°C)*

Wheel



Transportation of a monument, grave of Tchuti Hetep, El-Bersheh, Egypte, 1880 b.c.

The wheel …rolls!
… therefore does not slip on the floor
→ **high local *f*** with the ground, but **low global *f*** (duck traction)

Slides / rolls

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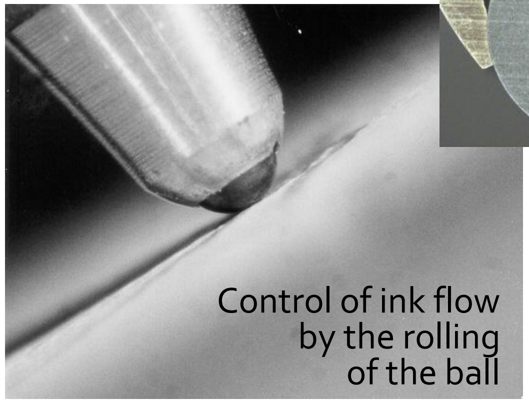
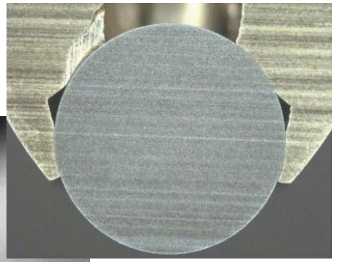
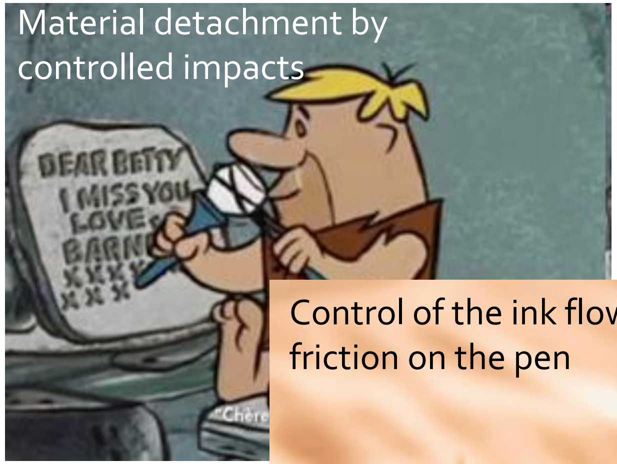
Writing …different tribological processes



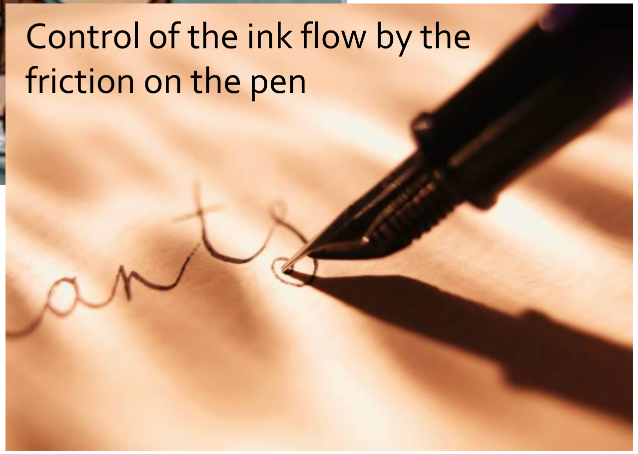


Writing and 3rd body

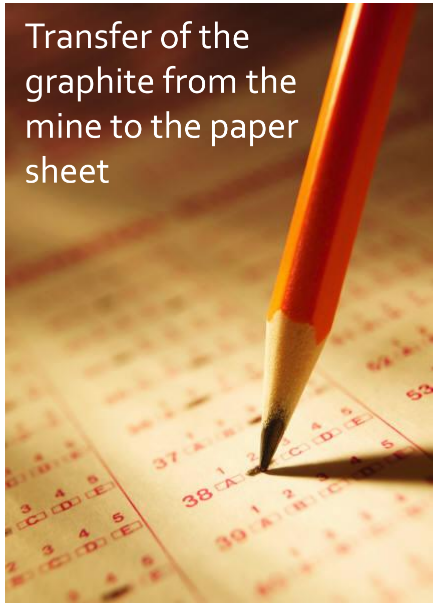
Control of ink flow by the rolling of the ball



Material detachment by controlled impacts



Control of the ink flow by the friction on the pen



Transfer of the graphite from the mine to the paper sheet

Control of frictional contact without exchange of matter

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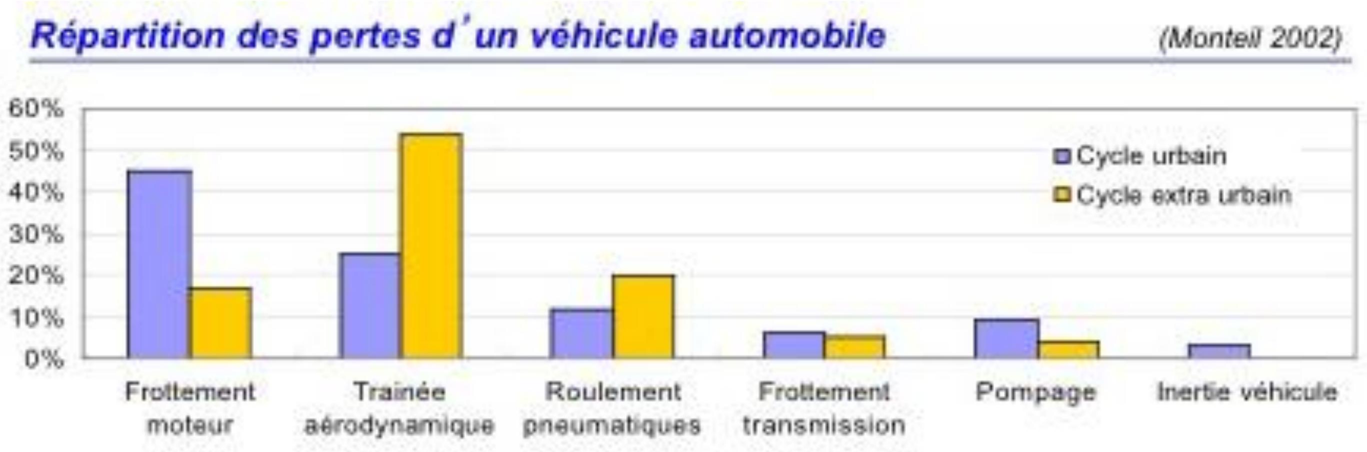
Costs of friction and wear, some data…

- Expenses du to the replacement of worn pieces= 1.6-3% of Gross National Product in France, i.e. between 60 and 90 billions of euro (2022), of which 50% in maintenance;
- 30% of fuel is needed in automotive for contrasting friction, i.e. 200 billions of liters each year;



- **In the USA** recent peer-reviewed analyses estimate that advanced **tribological technologies** could **reduce total energy consumption by** about 8.7% in the long term across transportation, manufacturing, power generation, and residential sectors.;
- In **the UK**, the **annual energy-cost savings** potentially achievable **through improved tribological practices**, estimated at £468–700 million in 1981, are equivalent to roughly £2.33–3.48 billion in 2026 prices (**about €2.69–4.03 billion**).
- **For France**, an energy-consumption-based extrapolation suggests a comparable order of magnitude, around €**2.72–4.06 billion** per year….

Costs of friction and wear, some data…

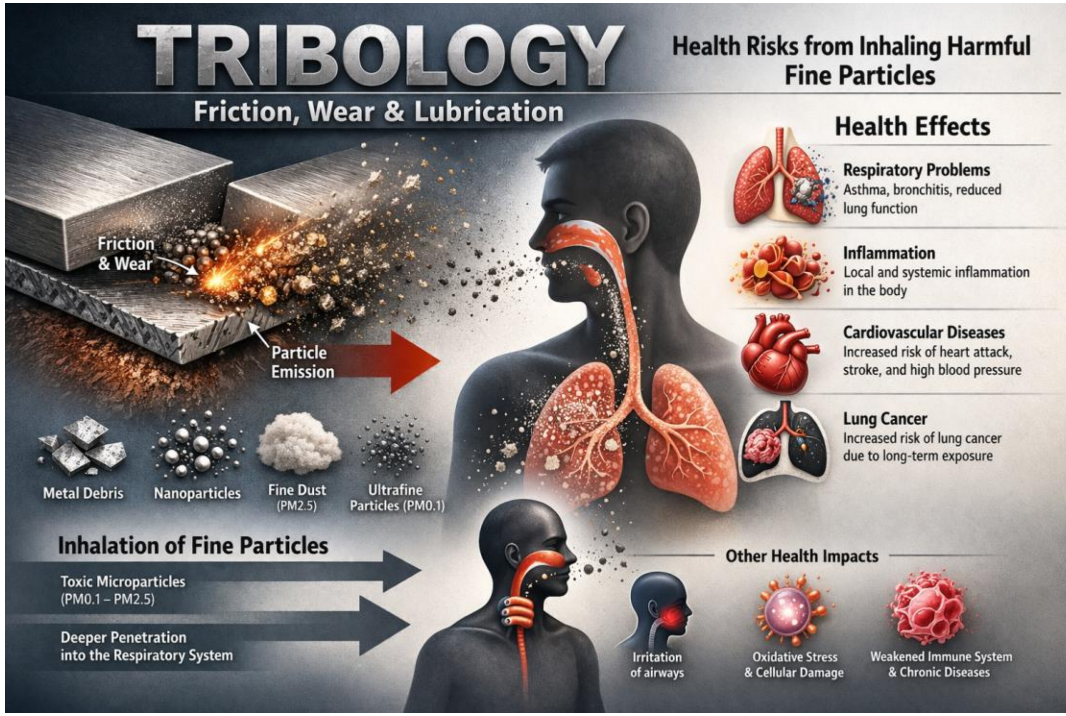
- The tribological issues are nowadays to be considered within the economical context, the sustainable development and the eco-conception

- Tribology and health:
    - Wear particles
      Size <10 µm, health risk, tolerance 50 µg m^{-3}
      (most "polluted" subway station, Stockholm 470 µg m^{-3}! !!!)
    - Passenger cars 20000 tons/year, 9000 tons / year nanoscale and airborne

- For public health need for particles bio-tribo compatible

- Nanobiotribology: contact eyelid cornea, human joints, atherosclerosis, drug targeting, organs ….

- **Engineering Marvels, Tribological Nightmares** : Aircraft, helicopters, space systems, rail contact, brakes, machining, tire wear: same problem, different scale



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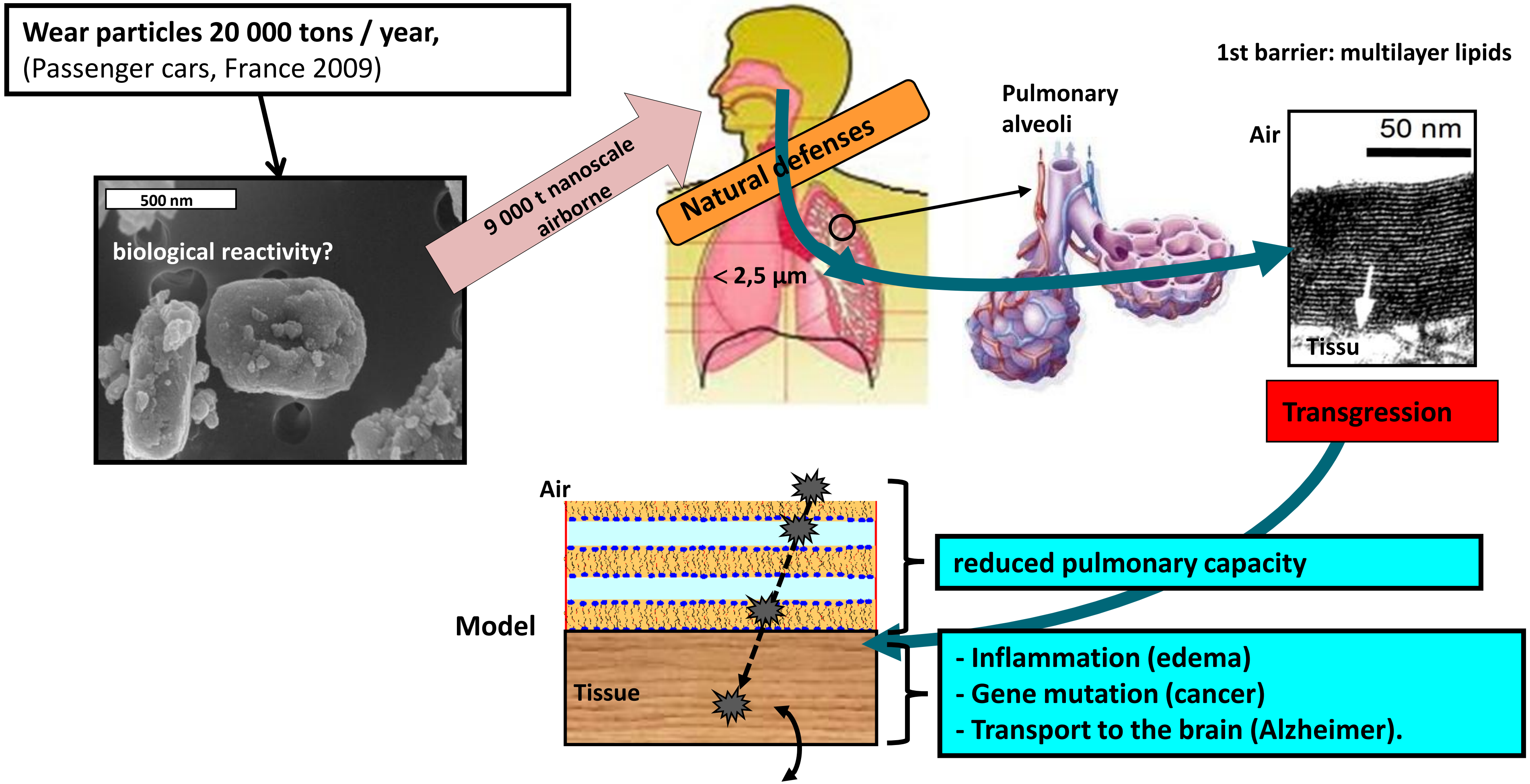
Impact of wear particles on public health



Costs of friction and wear, some data…

114TH CONGRESS
2D SESSION

H. RES. 916

Recognizing the impact of tribology on the United States economy and competitiveness in providing solutions to critical technical problems in manufacturing, energy production and use, transportation vehicles and infrastructure, greenhouse gas emissions, defense and homeland security, health care, mining safety and reliability, and space exploration, among others, and recognizing the need for increased research and development investments in tribology and related fields.

IN THE HOUSE OF REPRESENTATIVES

SEPTEMBER 28, 2016

Mr. RYAN of Ohio (for himself and Mr. LIPINSKI) submitted the following resolution; which was referred to the Committee on Science, Space, and Technology

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RESOLUTION

Recognizing the impact of tribology on the United States economy and competitiveness in providing solutions to critical technical problems in manufacturing, energy production and use, transportation vehicles and infrastructure, greenhouse gas emissions, defense and homeland security, health care, mining safety and reliability, and space exploration, among others, and recognizing the need for increased research and development investments in tribology and related fields.

Whereas tribology is a branch of science and engineering encompassing scientific disciplines related to the controlling of friction, reduction of wear loss, and development and application of novel lubrication strategies;

Whereas almost every aspect of our lives is impacted by technologies that benefit from the ability to control friction and wear loss;

Whereas approximately a third of the world's primary energy consumption is attributed to friction, and about 70 percent of equipment failures is blamed on lubrication breakdown and wear loss;

Whereas loss of energy to friction and material losses due to wear in mechanical systems such as internal combustion and gas turbine engines account for huge economic and environmental burdens;

Whereas finding ways to minimize friction and wear through new technologies in tribology can have an enormous impact on the economy;

Whereas improving durability of goods and equipment has a dramatic impact on reducing our demand for finite resources such as raw materials;

Whereas proper application of tribology principles reduces energy usage, lowers the cost of maintenance and replacement, and increases reliability;

Whereas new solid lubricants and biodegradable and synthetic lubricants developed from fundamental research are critical to a greener and more sustainable future;

Whereas improvements in manufacturing productivity and efficiency enabled by reduction of friction and wear loss are crucial to our economic competitiveness;

•HRES 916 IH

Whereas energy conservation and successful generation of clean energy, such as with wind turbines, rely on principles of tribology;

Whereas reduction of friction is at the very core of improving fuel economy and reducing greenhouse gas emissions;

Whereas safety, reliability, and durability of mechanical products and systems have critical implications on our global reputation with respect to trade and exported goods;

Whereas reduction of friction and increasing durability of artificial joints, prosthetics, and implants are crucial to maintaining quality of life for veterans and the aging population;

Whereas tribology is used to improve everyday personal care products such as toothpaste, skin creams, and hair products;

Whereas tribology principles are crucial to our national defense and homeland security through the use of lighter-weight weapon systems, more efficient and safe operation in a wide range of environments, higher reliability, longer life, and reduced maintenance;

Whereas scientific understanding of friction and wear loss improves maintenance and reliability of the Nation's transportation infrastructure, resulting in a better return on public funding and gains in public safety;

Whereas mining safety and reliability and durability of mining equipment can be improved through proper use of tribology;

Whereas reliability, function, and durability of outer space mechanisms and rockets are essential for future space missions; and

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Costs of friction and wear, some data…

Whereas the enormous potential of tribology in solving global challenges is hampered by limited investments in research, thus limiting innovations in new materials and lubrication technologies: Now, therefore, be it

Resolved, That the House of Representatives—

(1) recognizes the impact of tribology on the United States economy and competitiveness;

(2) recognizes the importance of tribology in providing solutions to critical technical problems in manufacturing, energy production and use, transportation vehicles and infrastructure, greenhouse gas emissions, defense and homeland security, health care, mining safety and reliability, and space exploration, among other sectors;

(3) encourages Federal agencies to develop and implement programs and projects related to tribology;

(4) encourages the formation of public-private partnerships to advance fundamental research and accelerate the development of tribology-related products and technologies;

(5) recognizes the need for increased research and development investments in tribology and related fields; and

(6) encourages the National Academy of Engineering to conduct a comprehensive survey of the

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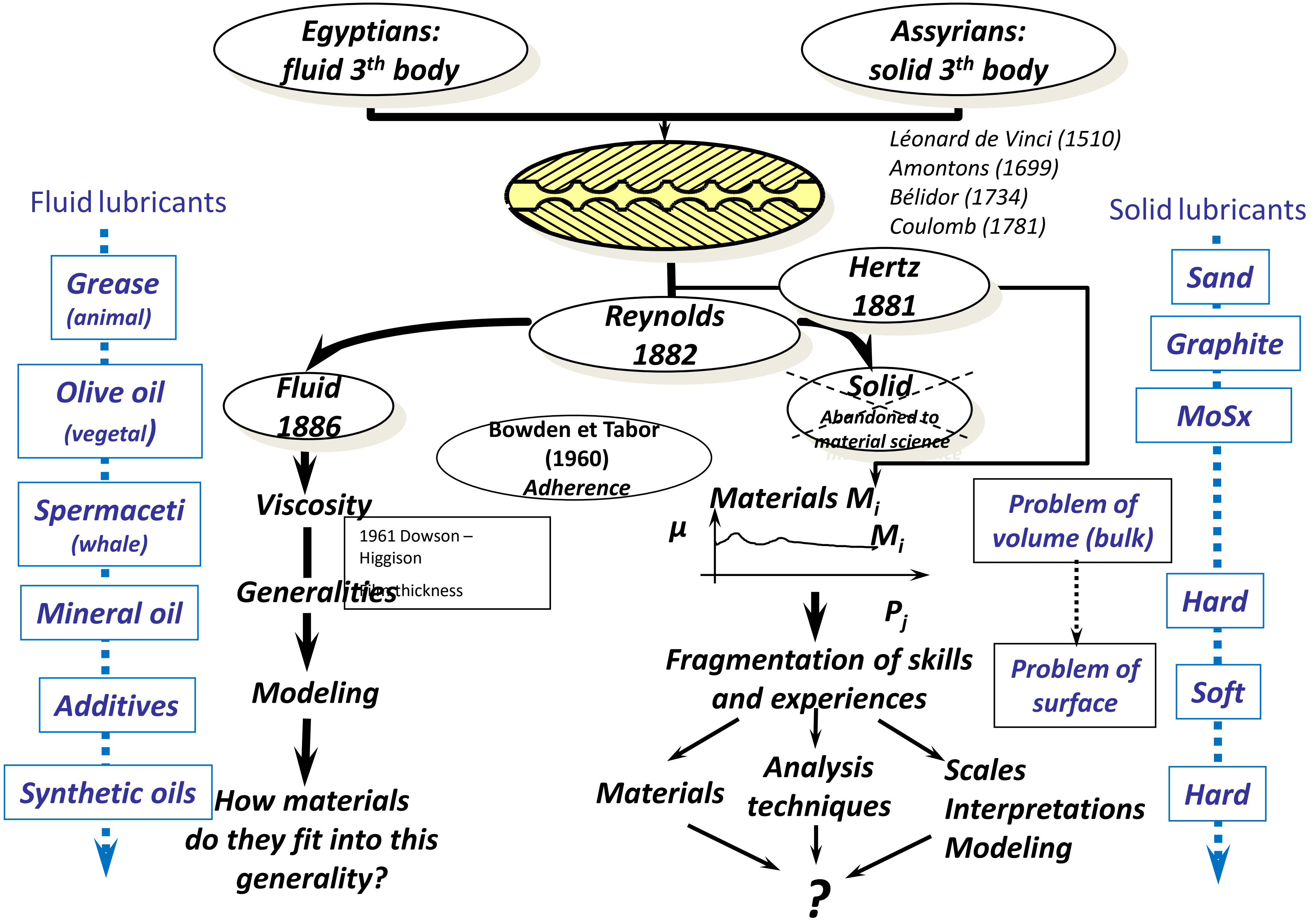
status of research and development in academia and government laboratories and recommend a course of action to accelerate innovations in tribology.

○

SOME HISTORY



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Situation in 2026

Friction and wear

- To live with → "spare parts" : no more possible because of sustainable development
- Change of materials → Empirical solutions without understanding; Intuitions / false evidence

Ongoing developments

Full mechanical analysis

- ***Mechanical advances***
  Local contact stresses and dynamics [s], [e]
- ***Material advances***
  [E], [n], [« Behavior »] (Volume, Surface)
- ***Numerical tribology***
  FEM, DEM, MD, …

→ *Better tribological diagnosis*

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If the mechanics is the science of movement, tribology is the science that allows movement (M. Godet)

Attempt of classification:

1. Continuous Contacts

1.1 Rubbing contacts

Frictional surface contact (braking)

Frictional "punctual, linear" contact (blade / carter, cutting tools…)

1.2 Assemblies under static loads

Prestressed assemblies (bolts, rivets, hooping ...)

2. Alternate Contacts

2.1 Bearings and Transmissions

bearings

rolling contacts under high stress and low lifetimes

gears

2.2 Assemblies under dynamic loads

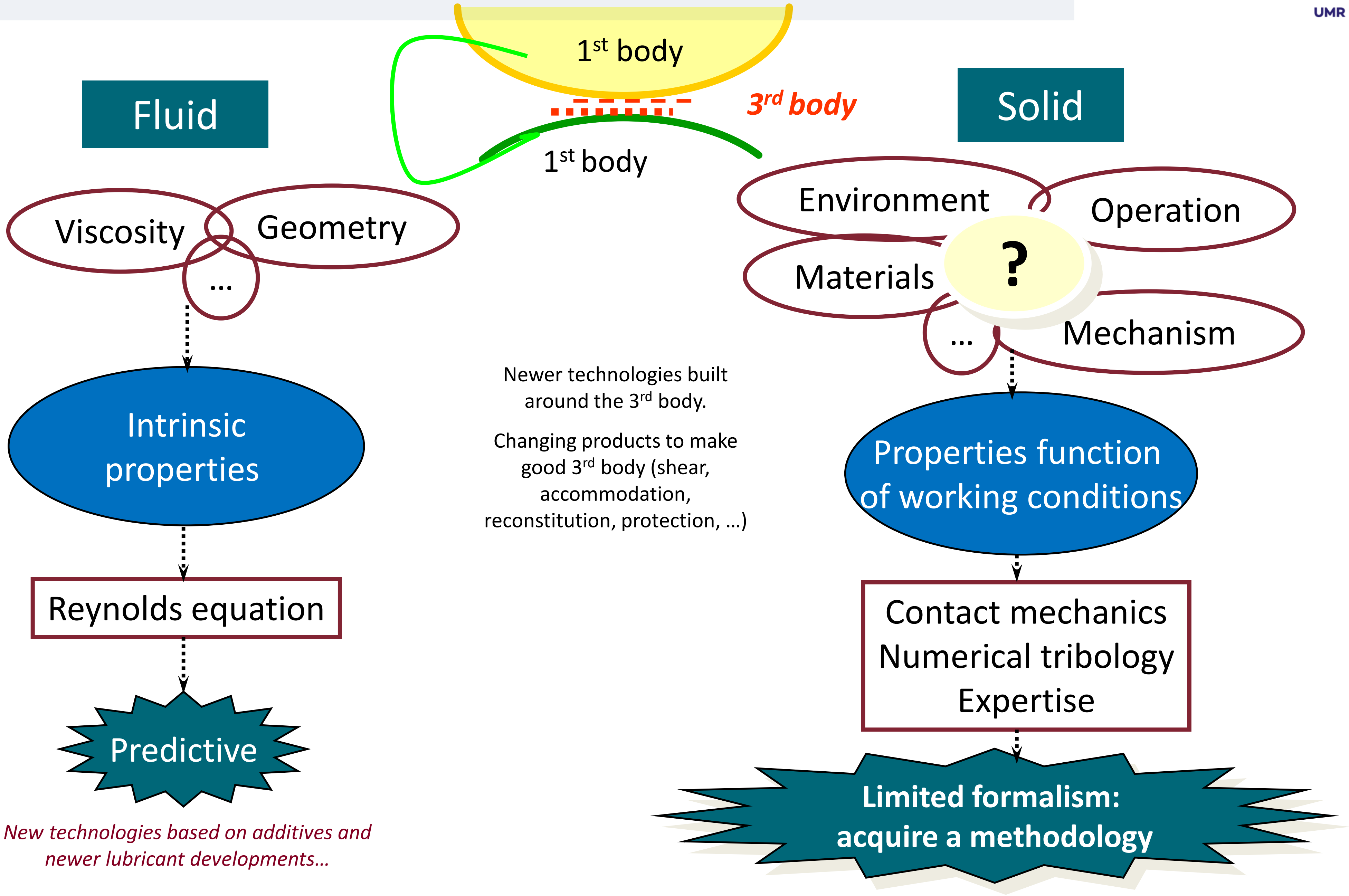
Assemblies with play (grooves, blade roots ...)

Prestressed assemblies (bolts, rivets, hooping ...)

Within each theme, the approach can be structured according to the three following issues:

- **Mechanical behavior of the contact** : Understand and simulate the distribution of stresses at the contacts.
- **Vibrational, thermal and physiochemical phenomena related to friction** : Analysis and modeling.
- **Damage, wear and durability** : Estimate the lifetime of a system knowing the phenomena occurring at the contact.

State of the art



Solving a tribology problem requires ***an integrated understanding of mechanics, physico-chemistry, and sometimes biology****—starting with a rigorous diagnosis and a clear distance from preconceptions.*

Example of preconception:
« The more it's hard, the less it wears»

The integration of knowledge, refined through iterative reflection and expert input, leads to the definition of a methodology for resolving the specific tribological issue.

Dry tribology is marked by several fundamental difficulties:

- *weak knowledge accumulation;*
- *imited mathematical support;l*
- *nsufficient formal training;case-by-case expertise with little generalization;*
- *contact is generally observed only after shutdown and disassembly (post mortem);*
- *the surface modifies the bulk, and the bulk in turn modifies the surface.….*

Friction and wear are not intrinsic properties of materials in contact*; they are working properties, produced by the actual conditions of operation.*

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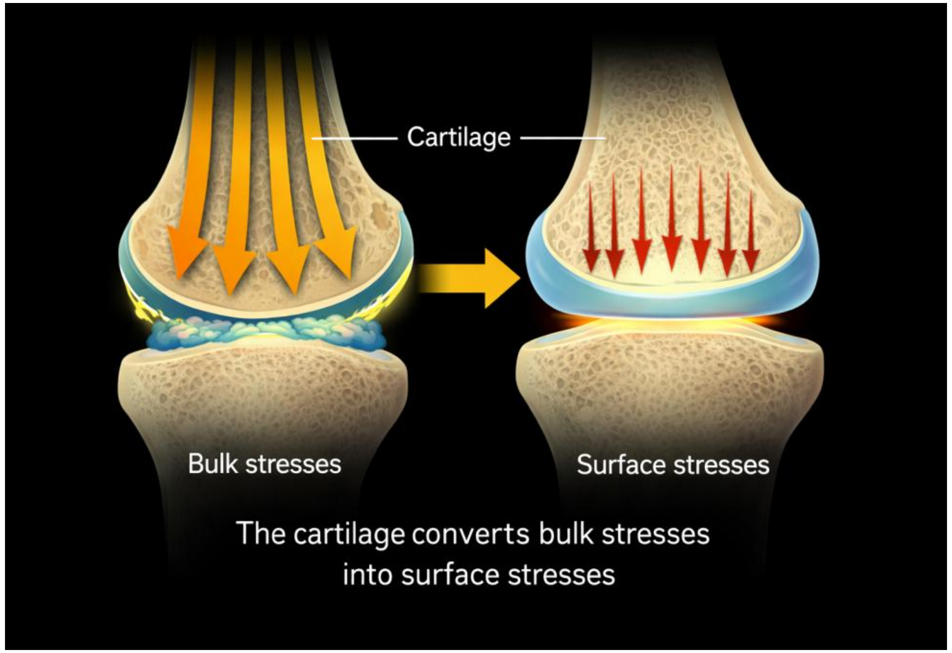
Tribological problem *=*

problem of "surface and interface" =

complex problem!

The volume worn the surface and the surface strains the volume

Ex: the cartilage converts bulk stresses in surface stresses.



Solution *=*

Friction and wear are not intrinsic properties of materials in contact; they are operational properties that emerge from actual service conditions.

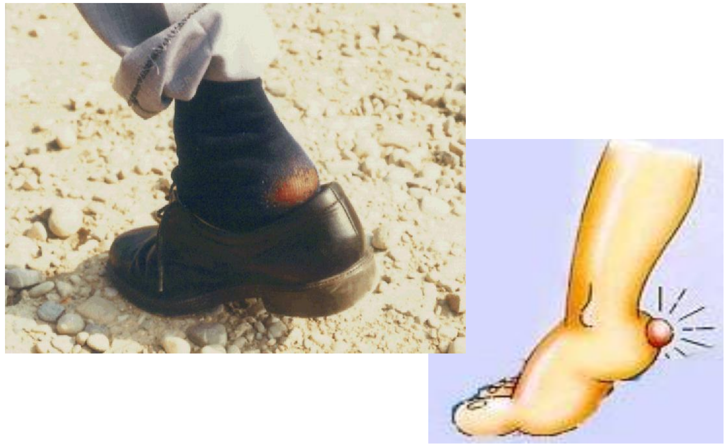
« Mechanism – system » too often forgotten in research of solutions!

…if not introduction of fluid interface…

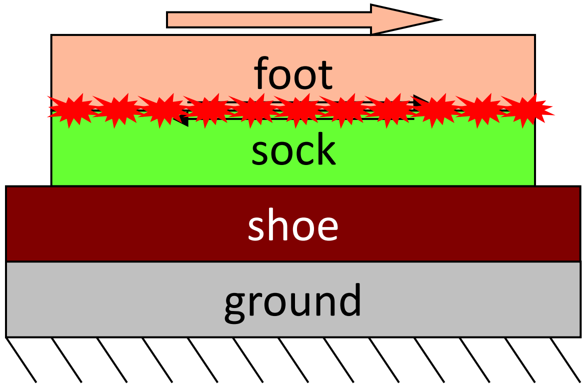
… if not !!!???

FROM SURFACE TO VOLUME PROBLEM: EXAMPLE

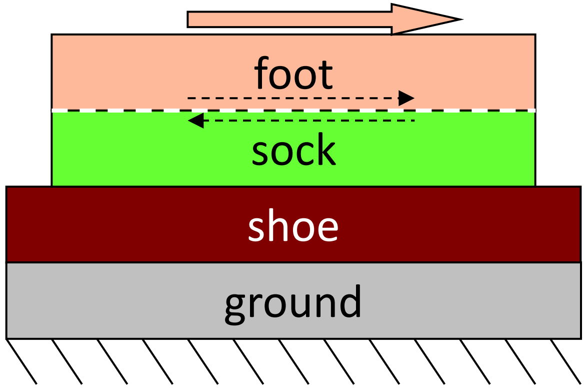
Controlling deformation accommodation, for avoiding the formation of blisters



« The surface sacrifices to protect the volume »

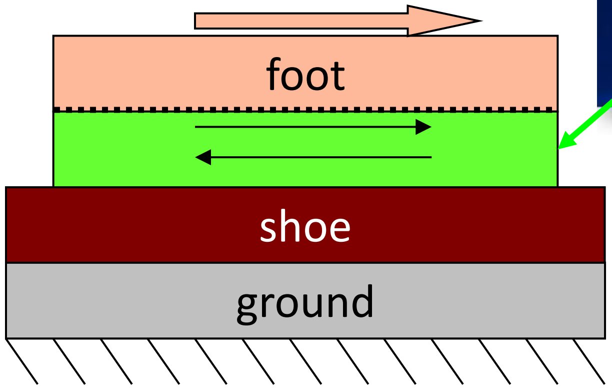


solution 1



↘ f (foot / sock) (talc)
→ accommodation foot / sock

solution 2



↗ f (foot / sock) (knitting)
→ accommodation in the volume of the sock

SCALES OF TRIBOLOGICAL PROBLEMS

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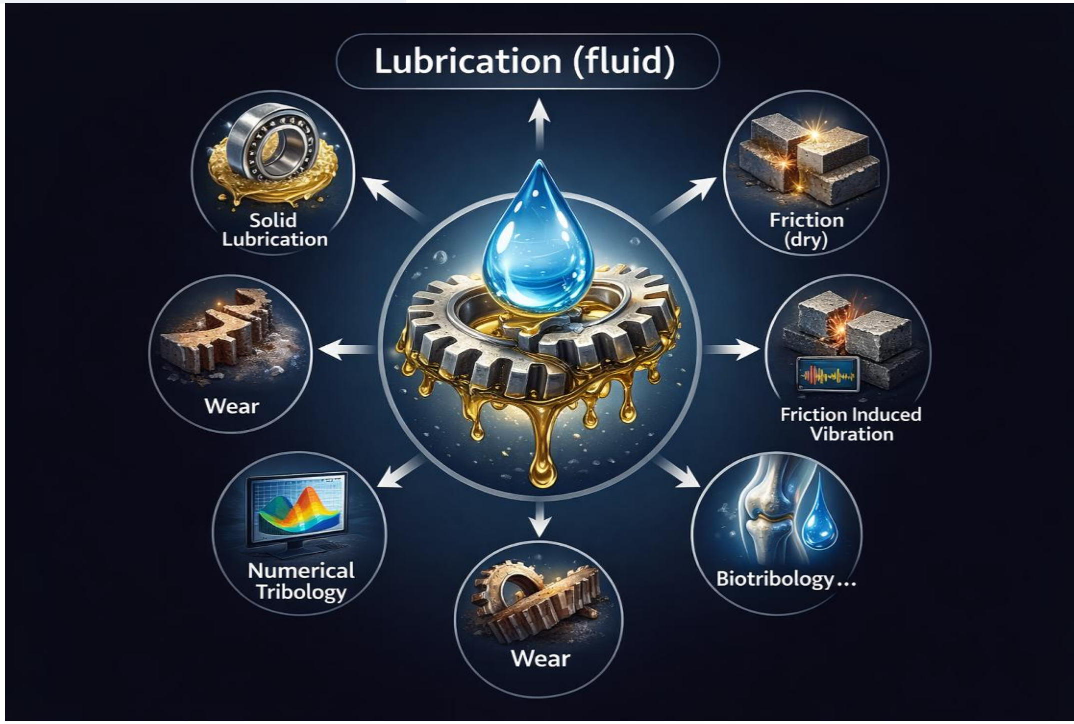
CONTENT OF TRIBOLOGYTODAY 2026

Tribology =

- Lubrication (fluid)
- Solid lubrication
- Friction (dry)
- Wear
- Numerical tribology
- Friction Induced Vibration
- Biotribology …



- **Lessons from examples: beware of apparent simplicity.**

Examples can generate **false certainties** and **important omissions**:

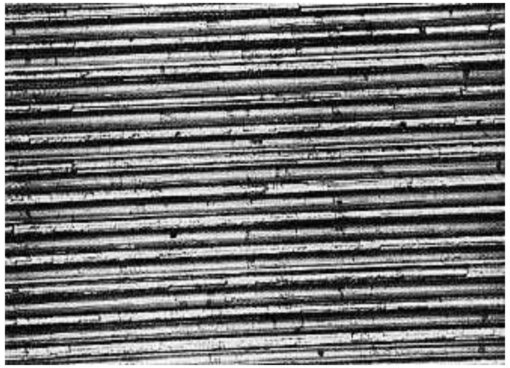
- *the harder the material, the less it wears*;
- *high friction means high wear*.
- Learn to connect **causes and consequences**, independently of scale

ROUGHNESS

Examples of surface topographies

Geometrical irregularities of industrial surfaces (Cartier 2000)

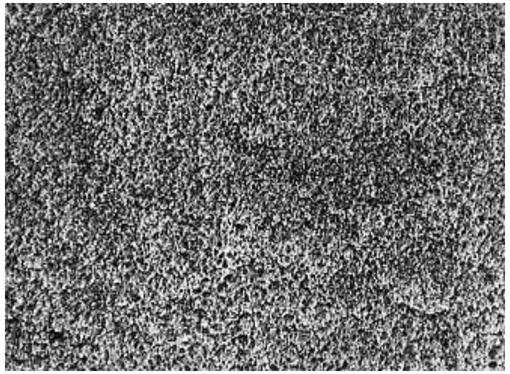
Milled surface (x55)



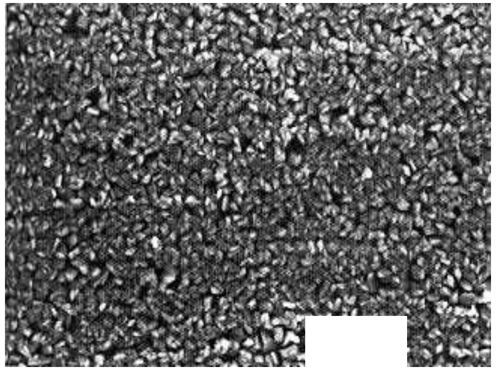
Turned surface (x55)

Grinded surface (x55)

Shot peened surface (x55)



Sand blasted surface (x55)



Phosphated surface (x1000)

The surface is the most irregular and perturbed zone of a mechanical component

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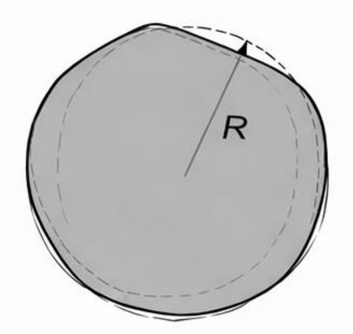
Classification of topographical defects of a surface

Macroscopic defects

Form deviation

with respect to a surface of reference.

("first order" defects)



Defects of planarity, circularity, etc…

Waviness

("second order" defects)

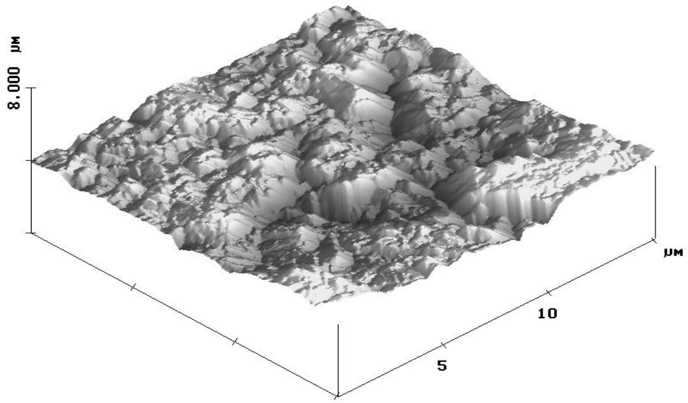
Periodical form defects (e.g. by vibrations during machining)

"Surface defects" are often the consequence of the machining process

Microscopic defects

Roughness

("third and forth order" defects)



*Need for several **criteria** (parameters) for distinguish and describe surface defects!*

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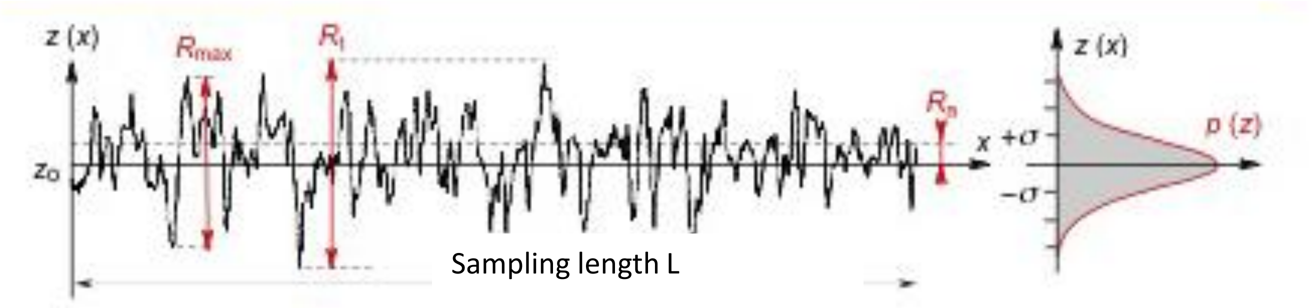
Main criteria for roughness characterization

(Europe ISO 13565, 1997)



R_t (µm) : It is the distance from the higher and lower point of the profile.

R_a (µm): It is the arithmetic mean of the absolute value of the profile.

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

R_q (µm): It is root mean square (RMS) of the value of the profile.

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

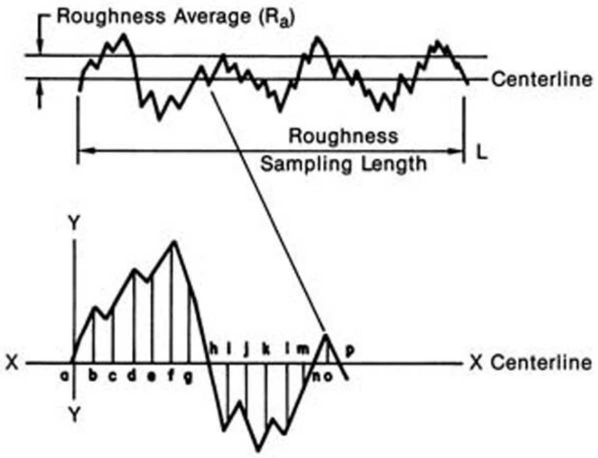
Calibrated roughness samples

Sand casting:	$R_a \approx 50$ µm
Milling, turning:	1 µm < R_a < 10 µm
Rectifying:	0,2 µm < R_a < 0,5 µm
Polishing:	0,02 µm < R_a < 0,2 µm

Main criteria for roughness characterization

Root-Means-Square roughness (R_a or RMS)

- Closely related to the roughness average (Ra)
- Square the distances, average them, and determine the square root of the result
- The resulting value is the index for surface texture comparison
- Usually 11% higher than the Ra value

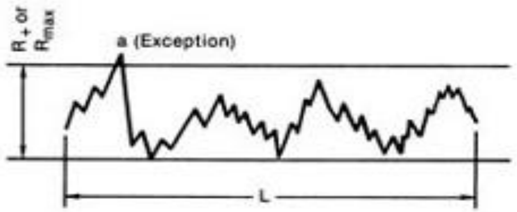


$$R_a = \frac{y_a + y_b + y_c \cdots + y_n}{n}$$

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

Maximum Peak-Valley Roughness (R_{max} or R_t)

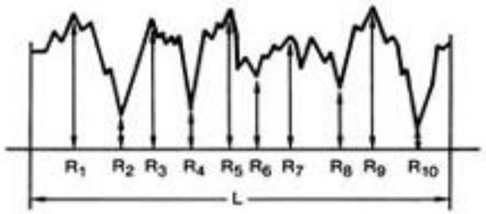
- Determine the distance between the lines that contact the extreme outer and inner point of the profile
- Second most popular method in industry



A. MAXIMUM PEAK-TO-VALLEY ROUGHNESS HEIGHT (R_t OR R_{max})

Ten-Point Height (R_z)

- Averages the distance between the five peaks and five deepest valleys within the sampling length

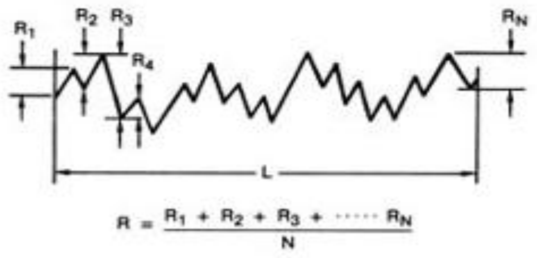


$$R_z = \frac{(R_1 + R_3 + R_5 + R_7 + R_9) - R_2 + R_4 + R_4 + R_6 + R_8 + R_{10})}{5}$$

Main criteria for roughness characterization

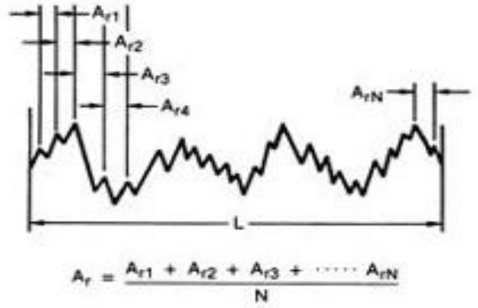
Average Peak-to-Valley Roughness (R or H or H_{pl})

- Average the individual peak-to-valley heights
- Use the height between adjacent peaks and valleys, not measure from a center line to peak valleys



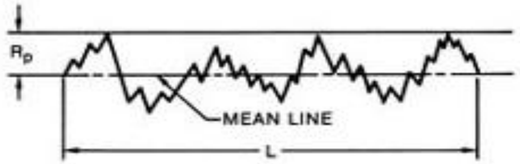
Average Spacing of Roughness Peaks (A_r or A_R)

- Average the distance between the peaks without regard to their height



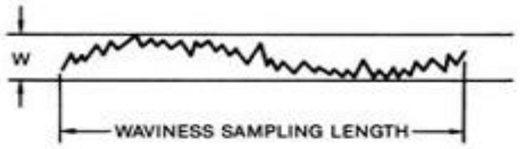
Leveling Depth (R_p and others)

- Measure the height between the highest peak and the mean line
- See figure G



Waviness Height (W)

- Assess the waviness without regard to roughness by determining the peak-to-valley distance of the total profile within the sampling length



Etc … (spacing of periods, wavelengths, ….)

Refer to ISO for more details!

What's "in" surface and what's "on" surface?!

The chemical composition of the surfaces is extremely different from the one of the bulk

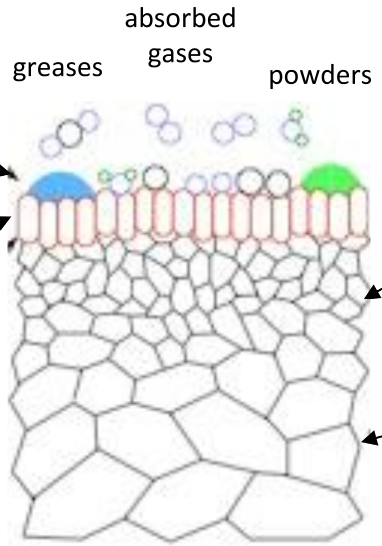
Surface

Contaminate film

(0,1 to 3 *nm*)
Absorbed molecules
Organic molecules
(can be eliminated by heating in vacuum)

Oxide film

(10 *nm* to 10 *µm*)
Reaction layer
(oxygen diffusion)
generally amorphous



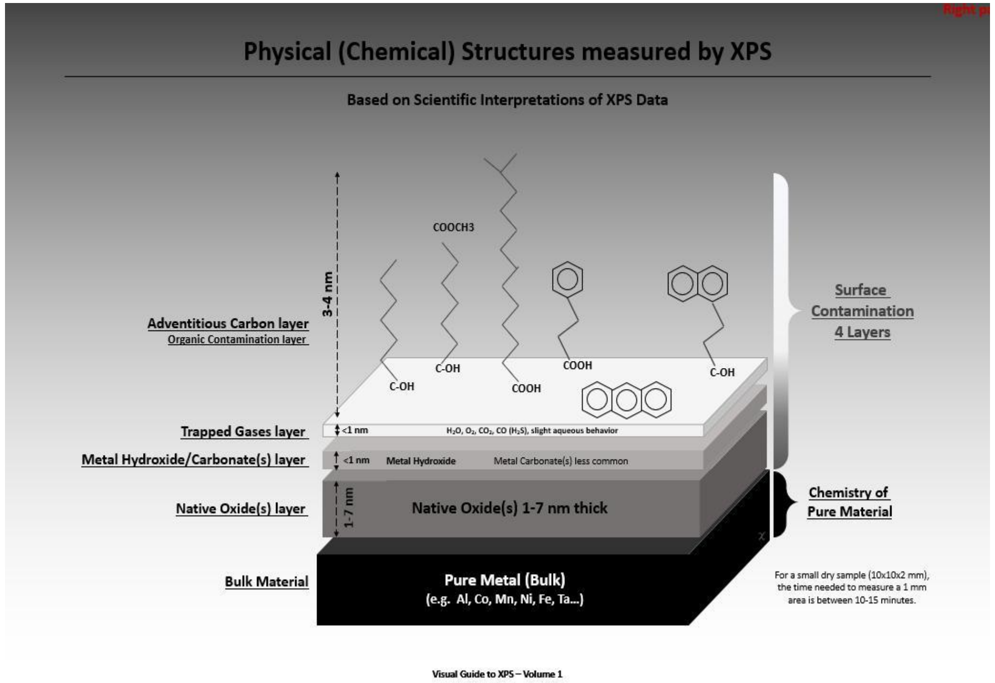
Bulk

Modified layer (TTS)

(1 to 100 *µm*)
Modified structure
Modified grains
May be phase changes
Possible diffusion of elements between volume and surface

Deep layer

(1 *µm* to some *mm*)
Crystal structure unchanged, but still under the effects of contact



100Cr6 steel

Superficial composition *(XPS)*

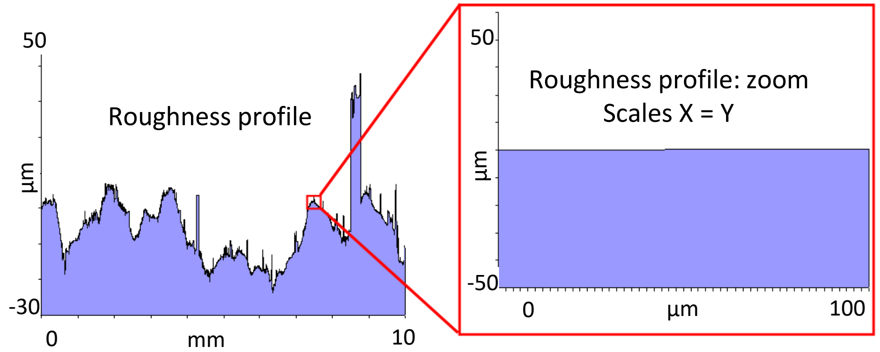
Element	Fe (2p3)	C (1s)	O (1s)	others
Mass %	3,1	49,9	37,9	9,1

Deeper composition *(SIMS)*

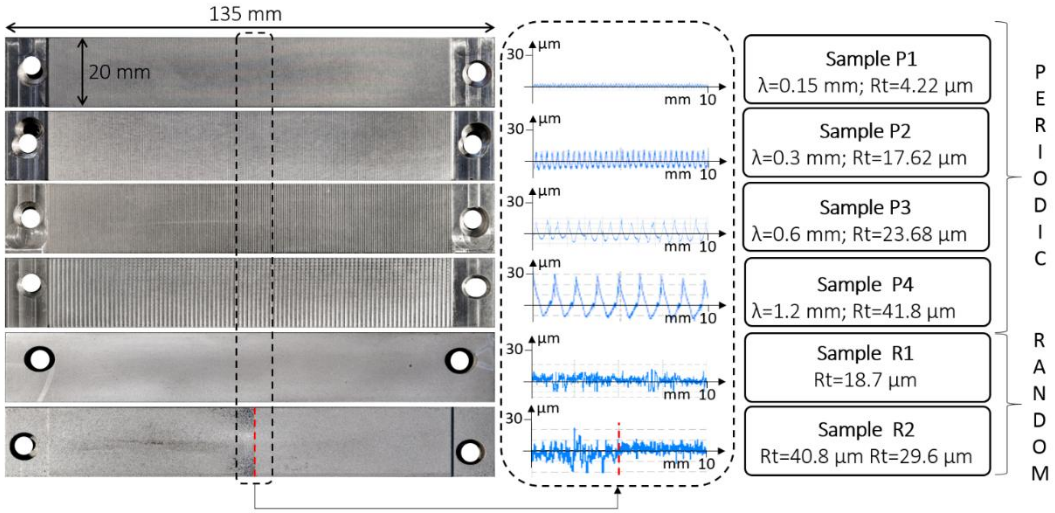
Element	Fe	C	Cr	others
Mass %	96,8	1,2	1,5	0,5

Think about what are you measuring and what are you measuring for!

Which is the scale of interest? The parameter of interest?



Always identify the relevant roughness scale—and understand how mechanisms across scales interact.



Which parameter truly represents the surface? It depends on the application and on the issue being addressed. For example, samples P2 and R1 have the same Rt, yet completely different profiles.

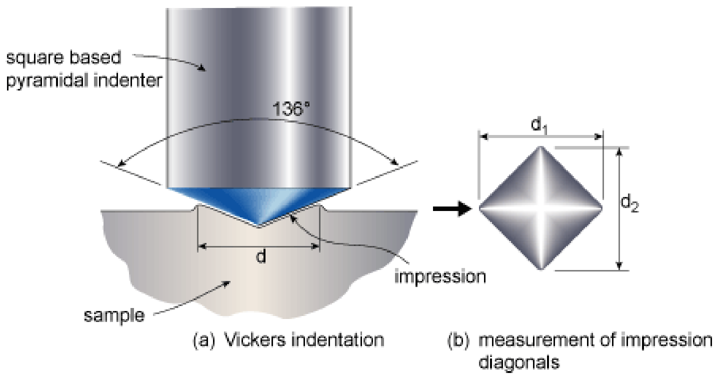
HARDNESS

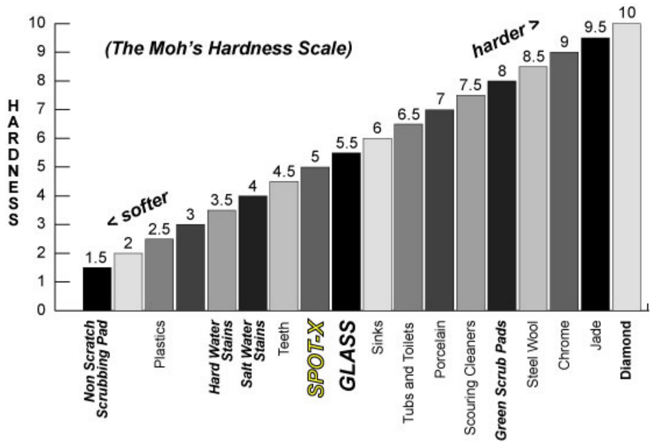
How measuring material hardness

Hardness is assessed by measuring a material’s resistance to indentation or scratching.

A hard body, called an **indenter**, is pressed against the material surface.
The applied force and the resulting indentation are measured: the softer the material, the deeper the indentation.

The three main hardness tests are:
- **Brinell**, using a ball indenter;
- **Vickers**, using a diamond square-based pyramid indenter;
- **Rockwell**, using a steel ball for soft materials and a diamond cone for hard materials.





Hardness of what?!

Hardness is not just a material property.

It is affected by many factors beyond the material itself, including:

- surface treatments;
- coatings;
- oxidation and environmental interactions;
- third-body layers and tribological surface transformations;
- indenter size.

Always be clear about what you are measuring—and what you are measuring it for.

Hardness of the "natural" coating, or hardness of the material?!

HERTZ

HERTZIAN THEORY

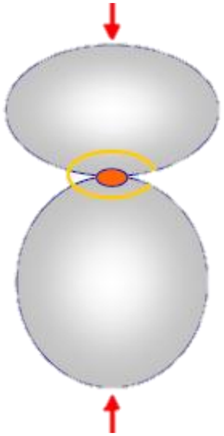
Contact problem between curved surfaces

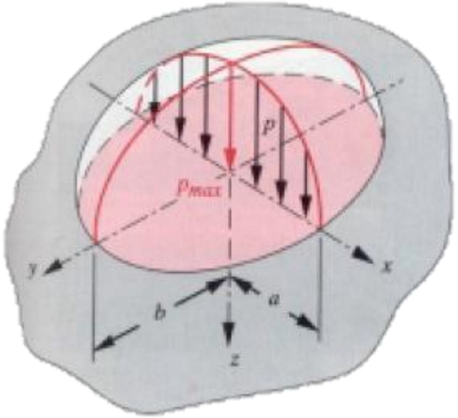
Hertz solved the contact problem of two elastic bodies with curved surfaces.

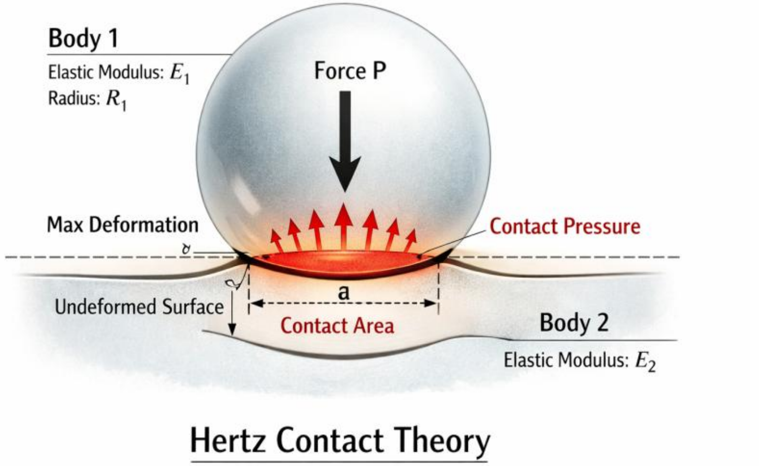
It provides the values of contact area, contact pressure and stresses distribution.

Maximum pressure : $$p_{max} = \sqrt[3]{\frac{6P(E^*)^2}{\pi^3 R^2}}$$

Contact dimension : $$a = \sqrt[3]{\frac{3PR^2}{4(E^*)^2}}$$







…see course of applied mechanics for details.

The theory is based on the following assumptions:
•deformation is small and entirely elastic;
•the contacting surfaces are continuous and non-conforming, implying a contact area much smaller than the characteristic dimensions of the bodies;
•each body can be modeled as an elastic half-space;
•friction at the interface is neglected.

Heinrich Rudolf Hertz (1857–1894)

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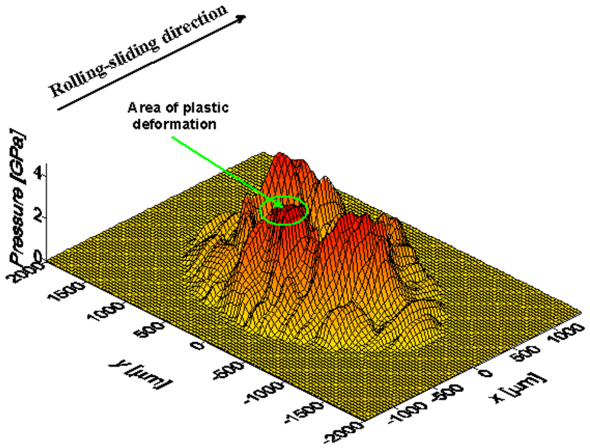
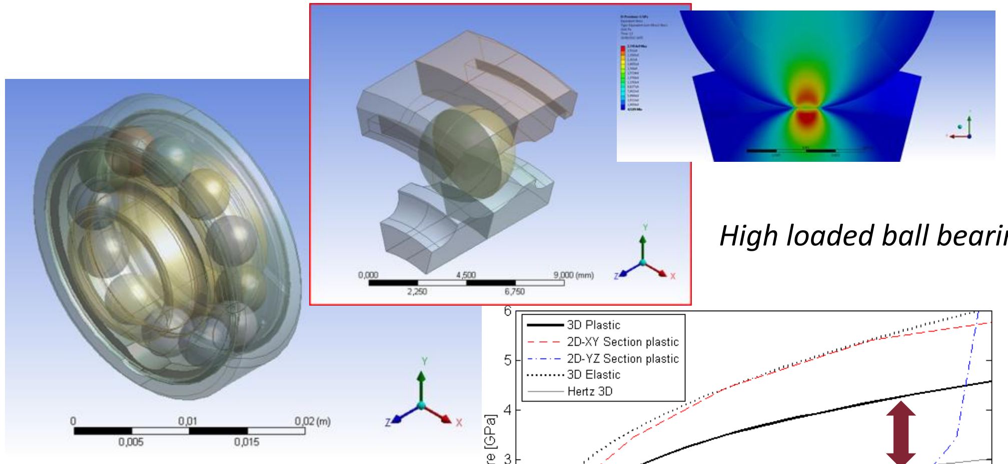
…and real contacts?

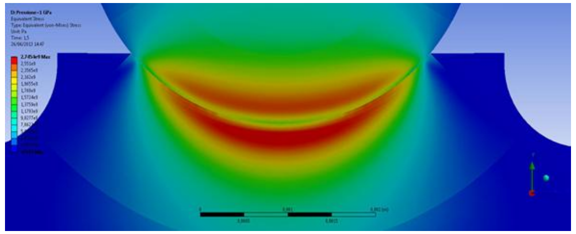
Effect of roughness

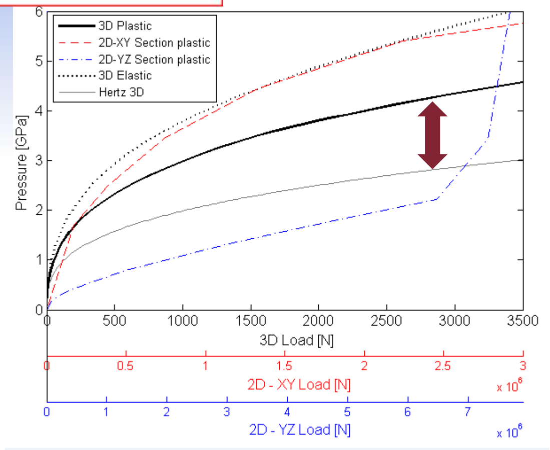




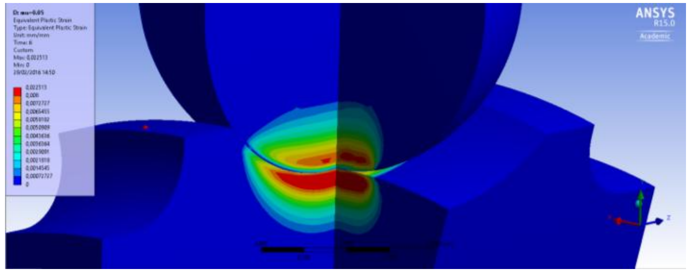
High loaded ball bearing

Effect of conformity





Effect of plasticization



Hertzian theory is elegantly well-behaved on paper; real contacts, unsurprisingly, are not always so polite. It predicts stress and pressure distributions effectively—but mainly within a limited subset of practical applications..

FRICTION COEFFICIENT

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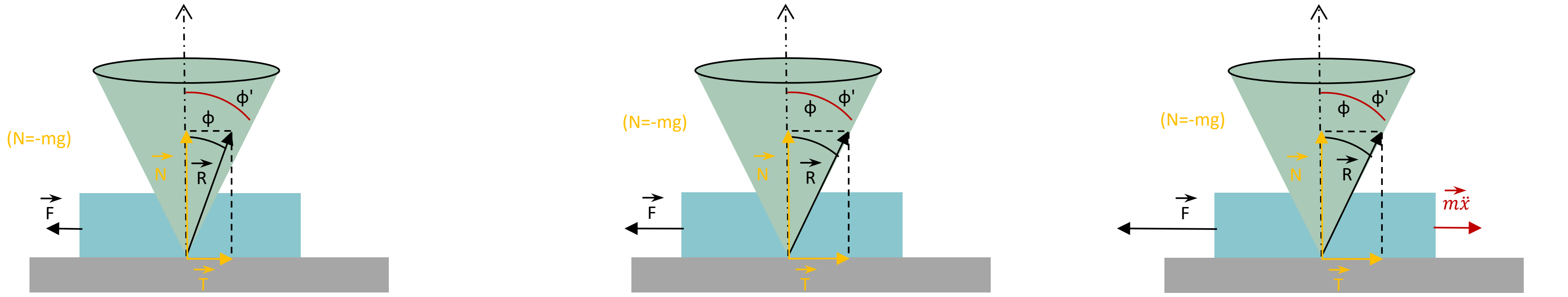
Basic concepts ? …or basic misconceptions?

Cone (angle) of Friction



Sticking ϕ < ϕ' Vr = 0

Friction limit ϕ = ϕ' Vr = 0

Sliding ϕ = ϕ' Vr ≠ 0

The contact force R acts always against the relative motion between the contacting surfaces.

Amontons – Coulomb law:

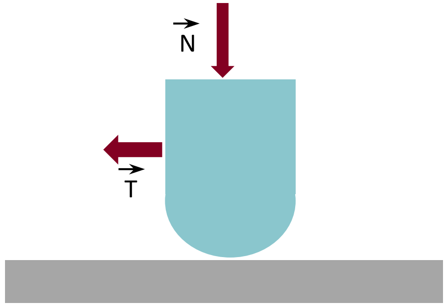
$\mu = T/N \qquad \mu = \tan \phi'$

Just a ratio of two force components? Not quite.
What does it really say about surfaces, operating conditions, and the physics behind the contact?

FRICTION COEFFICIENT(S)

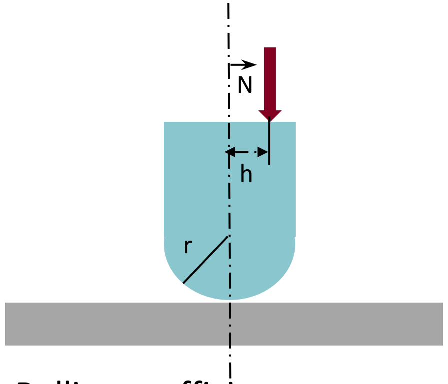
Basic concepts ? …or basic misconceptions?

Sliding, rolling, pivoting



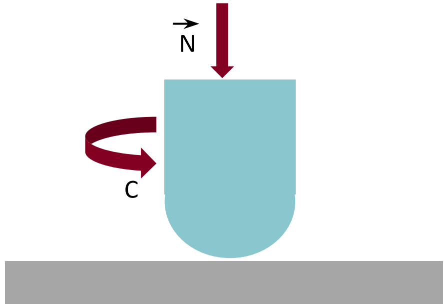
Friction coefficient:

$\mu = T/N$



Rolling coefficient:

$u = h/r$



Pivoting coefficient:

$\mu_p = C/N$ [m]

Real contact is always the result of three combined contributions, even if some of them can, in certain cases, be neglected.

*These coefficients have only **limited physical meaning**: they are often treated as universal, although they are in fact **highly dependent on the system and operating conditions**.*

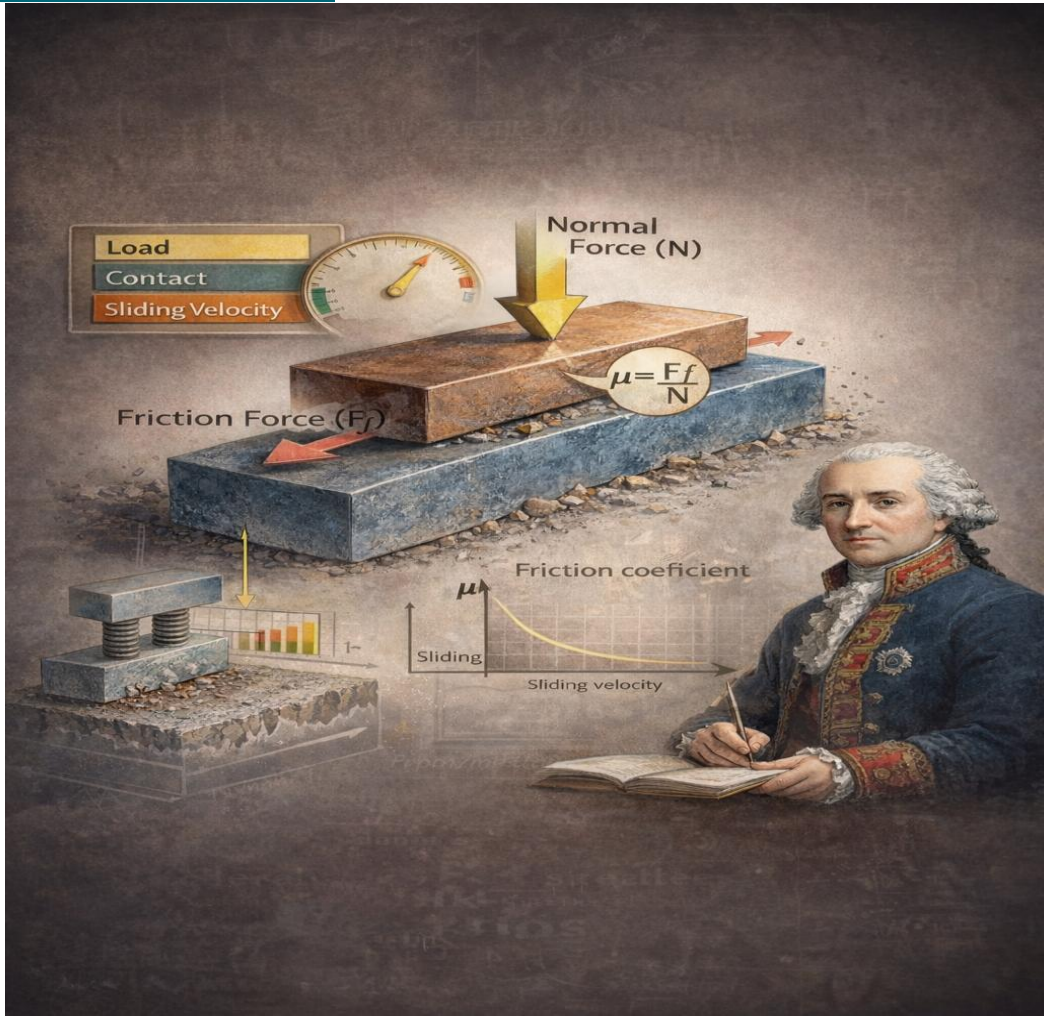
*From an energetic standpoint, friction should be understood as a **process of energy dissipation**.*

FRICTION COEFFICIENT(S)

Classical friction models are useful for preliminary mechanical design, but they are often inadequate for tribological analysis.

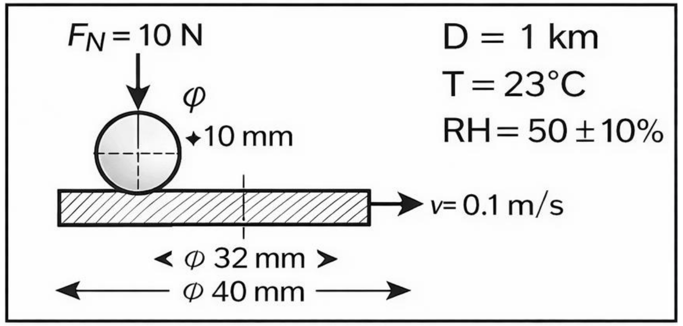
Even Coulomb questioned the universality of the law that bears his name. His experiments showed that friction is not a purely intrinsic constant, but a system-dependent response influenced by load, contact conditions, and sliding velocity.

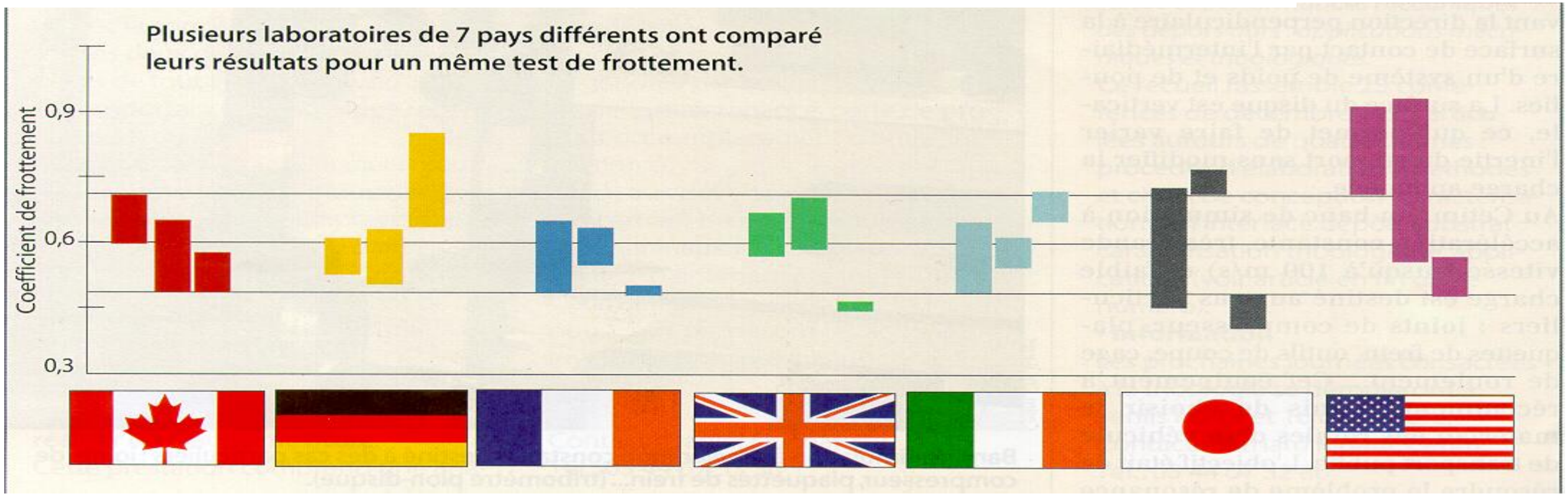
The friction coefficient is therefore best regarded as a macroscopic engineering parameter rather than a physically self-sufficient quantity.



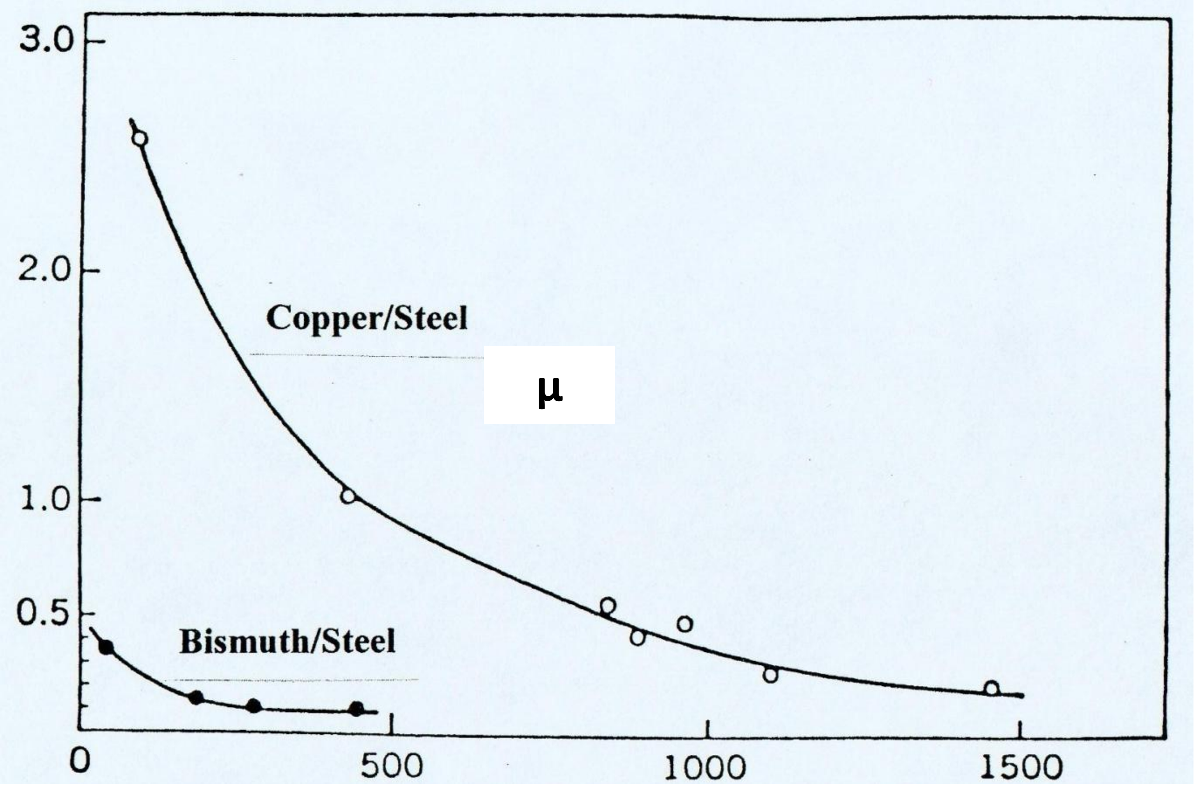
Friction coefficient(s)

31 laboratories, 7 countries, one steel–steel dry ball-on-disc test
(Czichos, 1987)
Boundary conditions were said to be well defined—
but the experimental set-up itself was not specified.
And yet the system matters:
rigidity, heating, machine architecture, and other mechanism-dependent effects all influence the result.
So the idea of compiling a universal database of friction coefficients? Highly problematic.

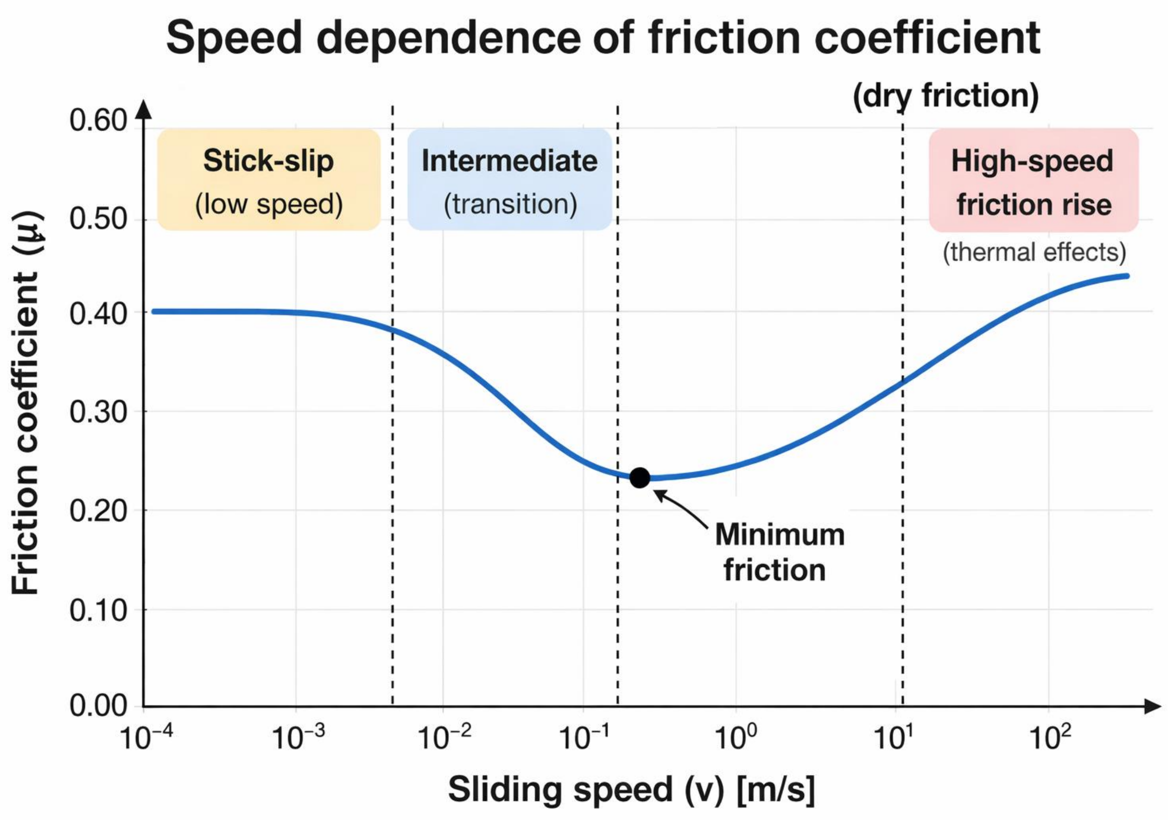




Speed Dependence of Friction



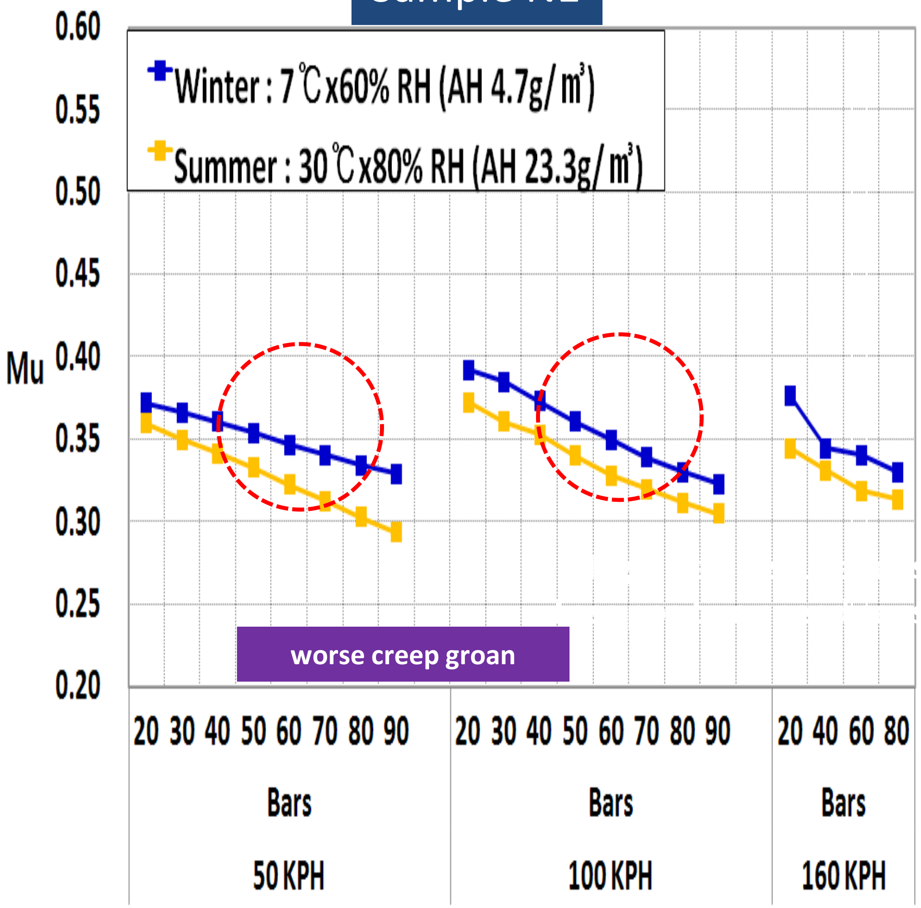
Sliding Speed (mph)



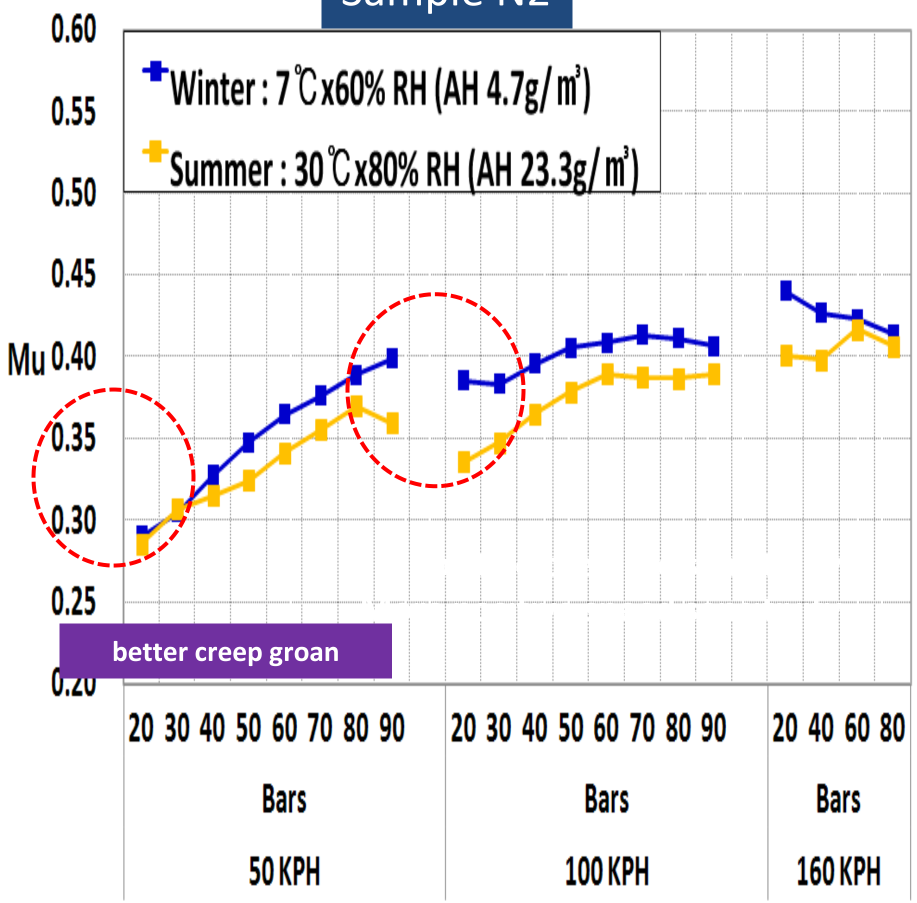
Friction coefficient of steel ball rubbing against copper and bismuth at high speeds; modest vacuum. (*Bowden and Tabor)*

Ex: Tests on brake pad materials under High and Low Humidity

Sample N1



Sample N2



Pad Control Temp. ; 90℃

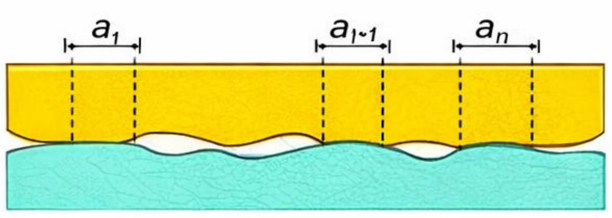
(SJ Lee et al., SAE Brake Coll. 2012)

FRICTION COEFFICIENT(S)

Fundamental concepts

REAL contact area

Mechanical aspect

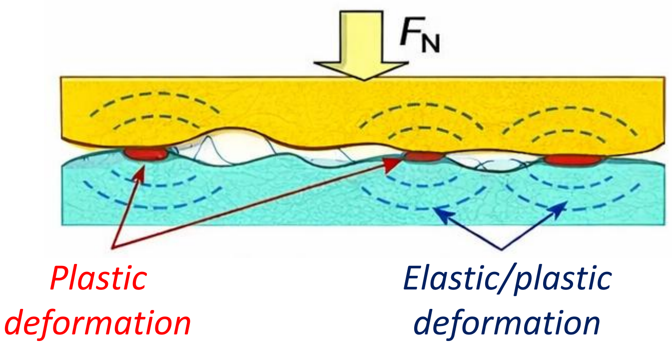


Real contact area = $\sum$ *local contacts*

Real contact area (Ar) << Apparent contact area (Ac)

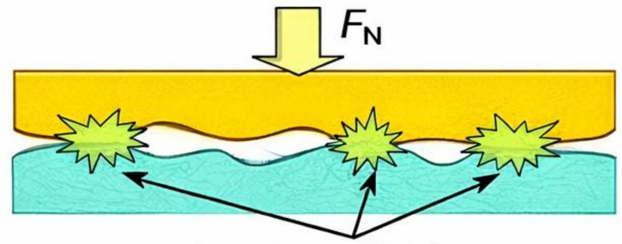
Often Ar < 1% Ac

The local contacts bring the whole load



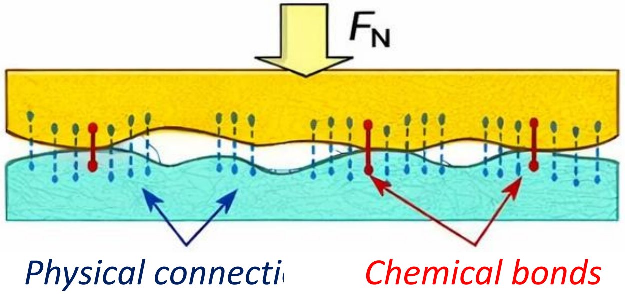
Microscopic defects

Physiochemical aspect



Adhesive connections

Development of molecular bonds by the contact due to the close approaching of atoms when pressing the surface



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Adhesive interactions

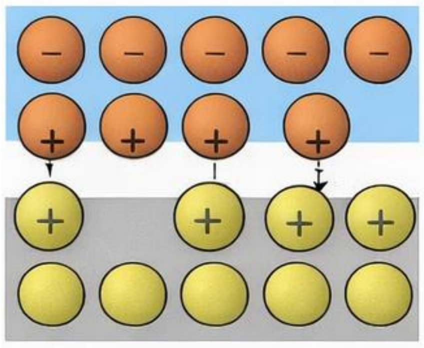
Physical interactions

INTERmolecular forces

low directionality
Van der Waals forces (weak)
large action distance (0,2 to 10 nm)

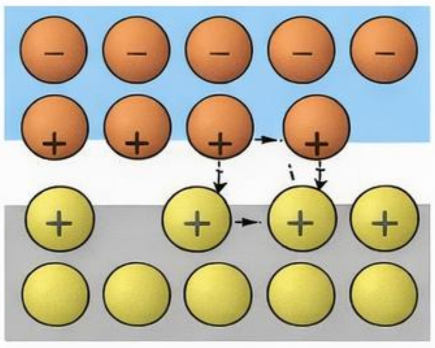
Maintaining the interface

Physical absorption



induced dipoles
All materials

Electrostatic adhesion



double eclecticized layer (charge accumulation)
Dielectric materials

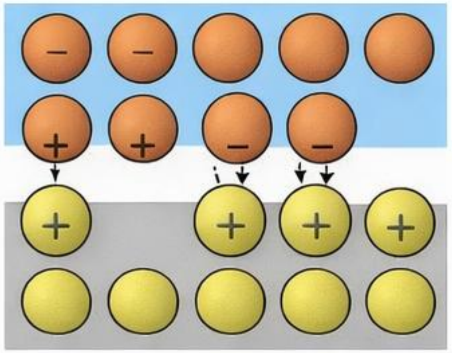
Chemical interactions

INTRAmolecular forces

High directionality
Chemical connections (strong)
Small action distance (< 0,1nm)

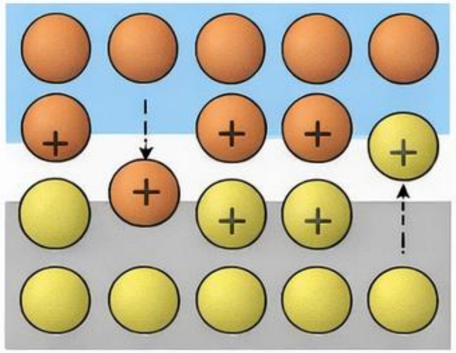
No more interface

Chemical absorption



Crystal filiation
Metallic or covalent materials

Atomic interdiffusion



Atom migration (if sufficient temperature)
Miscible materials

Source: - course of « Introduction à la tribologie», J. Denape, ENI of Tarbes.

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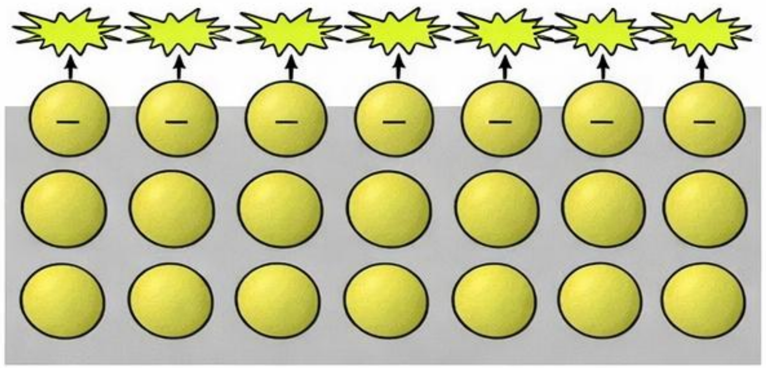
Adhesive interactions

Origin of surface energy of solids

Chemical dangling bonds along the free surfaces



Exceeding (available) energy ➡ Surface energy

The higher the surface energy of a solid is, the more it is reactive at the contact

➡ *Absorption of organic molecules, oxidation of materials, oxide hydration, stability of the surfaces of polymers*

Surface energy contributions

$$\gamma_S = \gamma_S^{LW} + \gamma_S^{AB}$$

- γ_S^{LW}: Dispersive contribution (nonpolar) → Lifschitz–van der Waals forces…
- γ_S^{AB}: Non dispersive contribution (polar) → Acid – Base interactions (electron exchanges)

Formation of a junction between two solids = reduction of the surface energy

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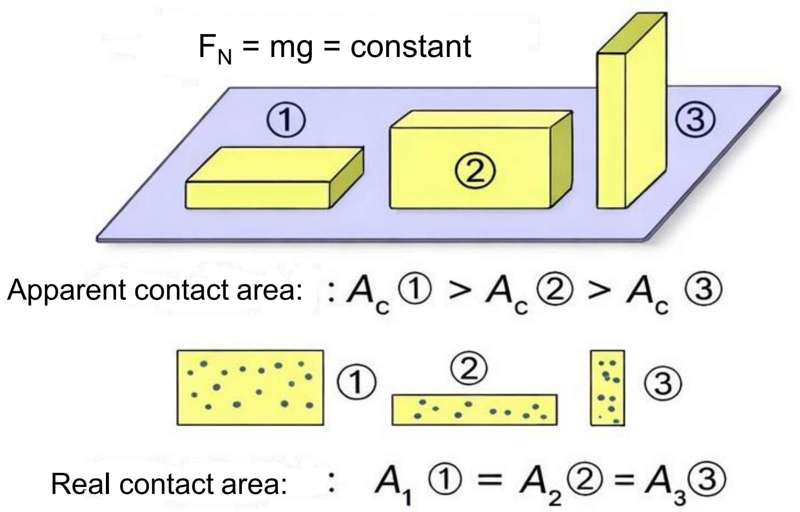
A look back to the Coulomb friction law

Independence from contact area

Frictional contact of the same object on different contact areas

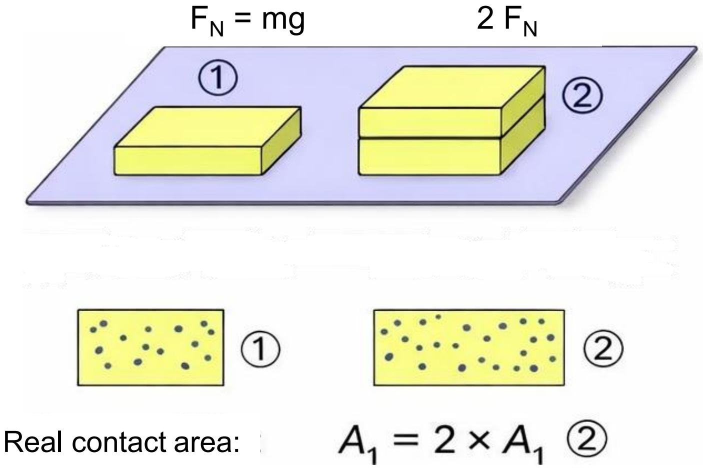


Increasing of the density of microcontacts, without increasing of the real local contact pressure at the asperities

Interpretation: it is the real contact area which is proportional to the load!

Independence from the load

Frictional contact of the same surface with different loads



$$\mu = \frac{F_T}{F_N}$$

Same local contact pressure -> same friction coefficient

Non generalizable empirical laws… several physical parameters act and interact each other!

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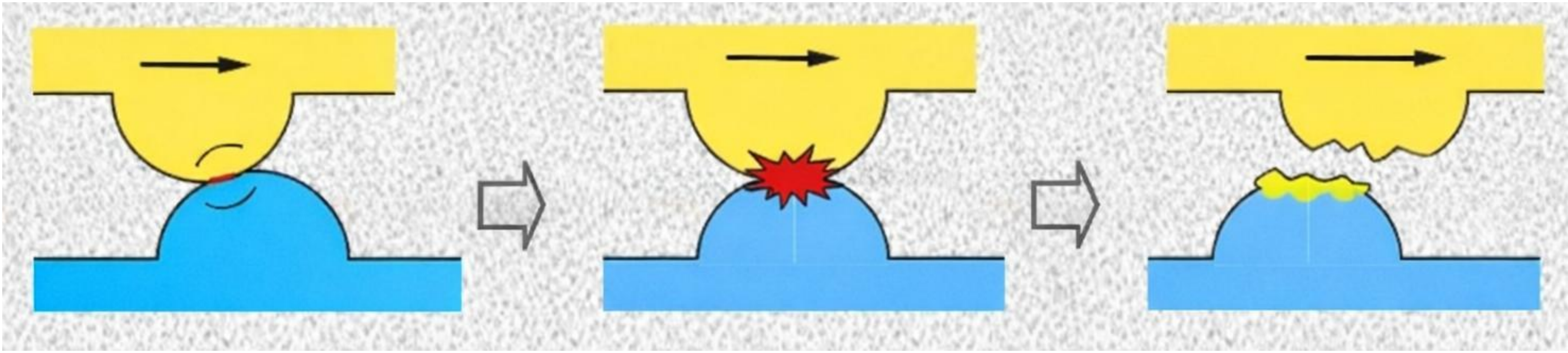
Classical approach to friction

(Bowden & Tabor 1950)

Contact engagement → Physiochemical connection → Contact detachment



Mechanical interaction between asperities on the real contact area

Physiochemical reactions between atoms under the contact load

Detachment of the asperities by shear stresses at the connections

DOUBLE CONTRIBUTION TO FRITION:

$$F_T = F_{deformation} \text{ (mechanical) } + F_{adhesive} \text{ (physicochemical)}$$

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Third body approach…

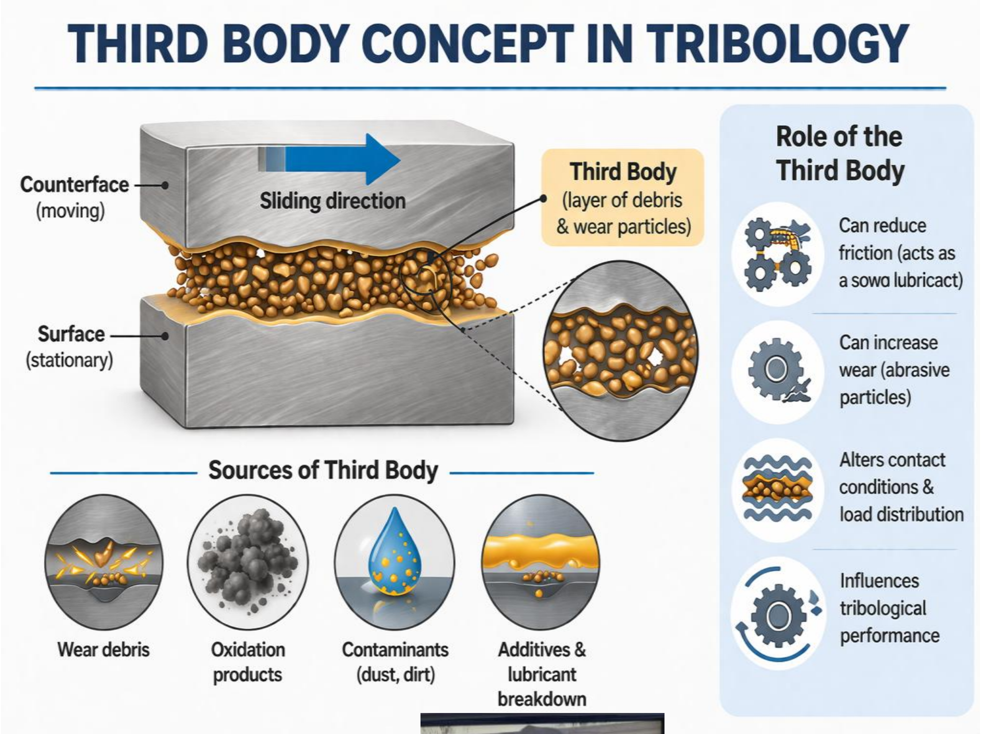
The term “**third body”** is addressed to all the “elements” between the two contacting surfaces of the two “first bodies” in contact:

1st body:

: 3rd body

1st body:

…oxides, contaminants, detached ~~“wear”~~ particles, lubricants, …



The direct contact between only two bodies doesn’t exist (Godet 1984)

Artificial 3rd body → Intentional introduction of a lubricant (solid, liquid, grease, gas)

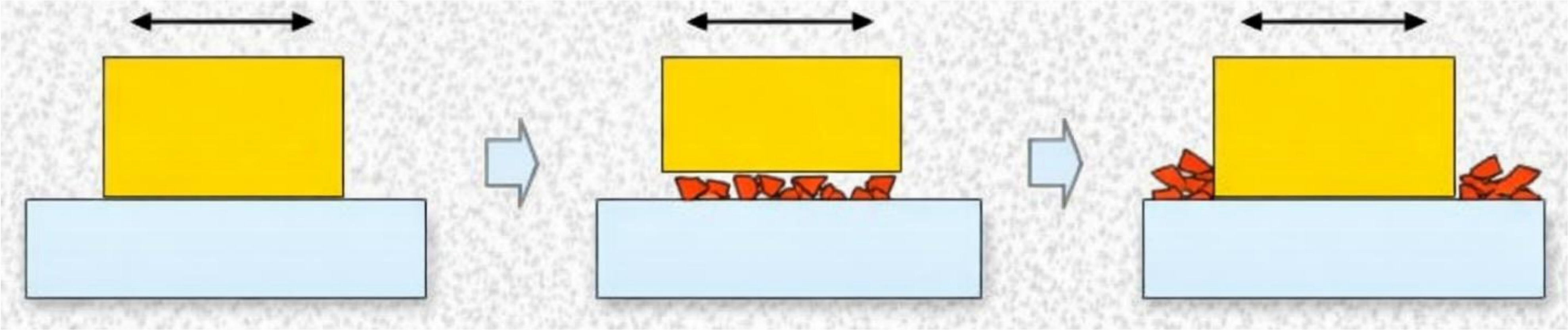
Natural 3rd body → Induced by the surface reactivity (oxides, superficial films), the degradation phenomena (particle detachment, surface transformations) and external contaminations

WEAR

Wear or wears?!

The three main phases of the wear process (a simplification of wear process)

First phase: 3rd body production	Second phase: 3rd body circulation	Third phase: 3rd body ejection
Detachment of particles from the degradation of the surfaces of the 1st bodies	Trapping and recirculation of 3rd body particles WITHIN the contact	Ejection of the 3rd body particles OUT of the contact



Definition of **wear** = quantity of material definitively lost at the contact

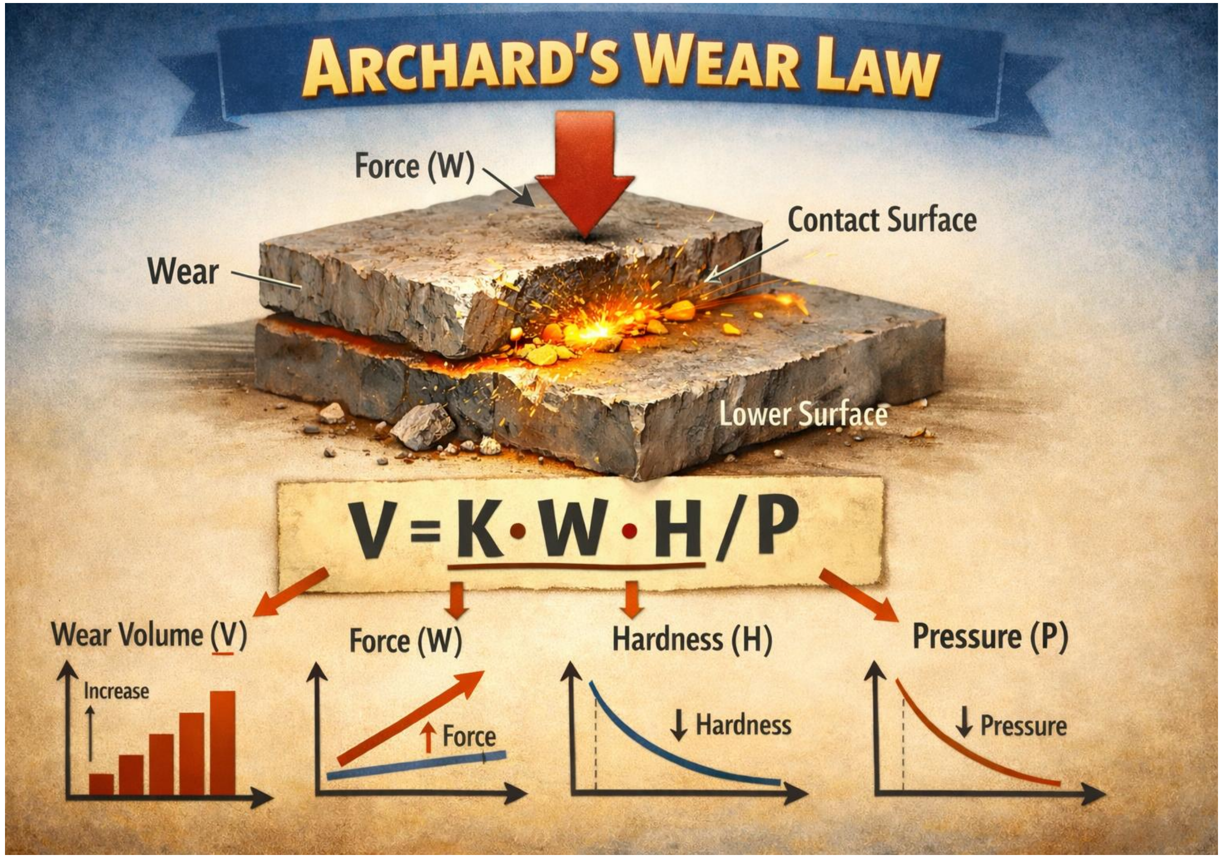
but

How does wear occur? Which physical mechanisms are involved?Abrasive wear, erosive wear, cavitation wear, adhesive wear, corrosive and oxidative wear, fatigue wear, fretting, and more.

Reye’s hypothesis: used for pre-dimensioning a mechanical system (Applied Mechanics)

Reye’s hypothesis states that the volume of material removed by wear per unit time is proportional to the power dissipated by friction.

$$dV = h\,dA = k\,\mu\,p\,v_r\,dA \quad \Rightarrow \quad h = k\,\mu\,p\,v_r \qquad p = \frac{h}{k\,\mu\,v_r}$$



$dV = h\,dA$: volume of worn material during $\Delta t = 1$

k = constant

dA = contact area

h = wear deep

p = contact pressure

v_r = sliding velocity

μ = friction coefficient

pdA = normal force

μpdA = frictional force

$\mu pdAv_r$ = dissipated power

Once the distributions of μ and vr are known, it is possible to determine either: h from p , for drum brakes or multi-DOF brake systems;p from h for clutches or disc brakes.

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The Archard law, the "law of wear"... i.e. the "umbrella" of all works about wear!

1952, Archard law *(1952 PhD, 1953 publication.)*

Vu: worn volume, m3
Fn: applied normal load N
L: contact distance, m
k: wear rate, Pa-1

$$Vu = k\ Fn\ L$$

k is an adjustment coefficient ranging from 10^{-4} and 10^{12} !

sometimes Vu, the worn volume, is confused with wear rate … k then takes the necessary dimensions!

… what about materials?

S : contact surface
s_y : yield stress of the « softer » material

$$Vu = K\ Fn\ S / s_y$$

Note: *The **Archard wear equation** is a simple model used to describe sliding wear and is based around the theory of asperity contact. The Archard equation was developed later than the Reye's hypothesis, though both came to the same physical conclusions, that the volume of the removed debris due to wear is proportional to the work done by friction forces. Reye's model became very popular in Europe and it is still taught in university courses of applied mechanics. This theory has, however, been totally ignored in English and American literature where subsequent works by Ragnar Holm and John F. Archard are usually cited.*

WEAR

The Archard law, the “law of wear”… i.e. the “umbrella” of all works about wear!

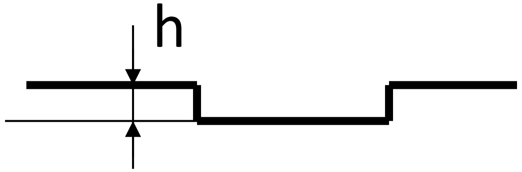
$$Vu = k\ Fn\ L$$

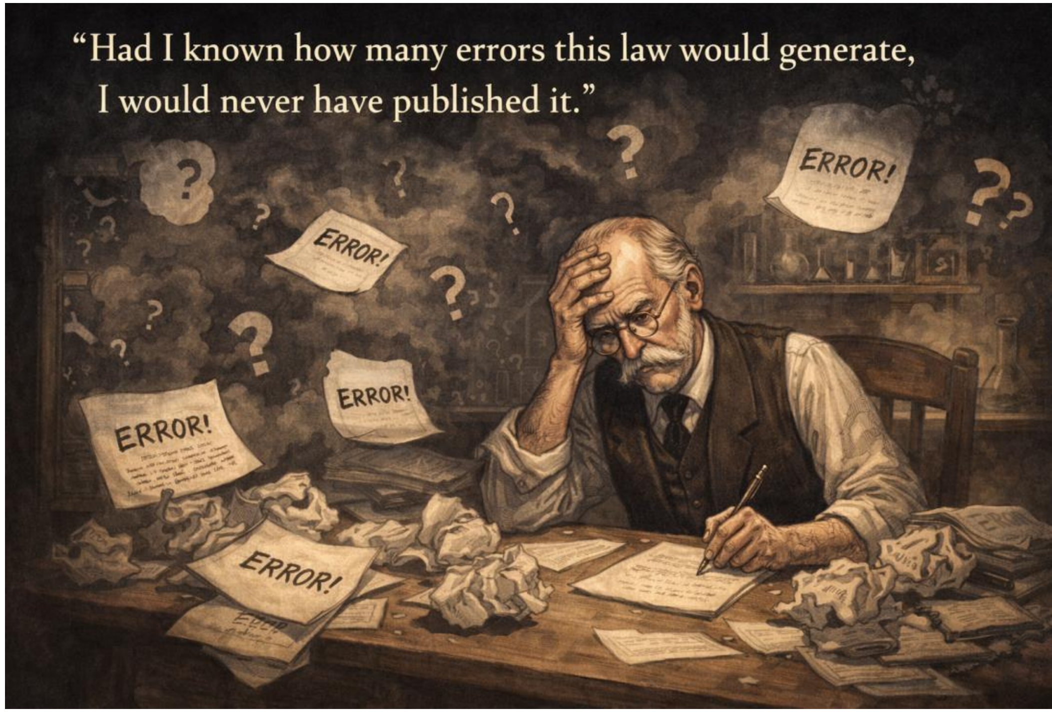
Vu = h x S *L = V x t*

$$h = k\ Fn/S\ V\ t$$

$$dh/dt = k\ p\ V$$

p: Apparent contact pressure, dh / dt: wear rate





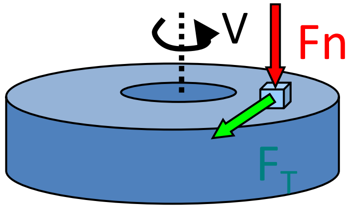
These three forms of Archard’s law constitute the historical foundation of wear-law development, prior to the widespread use of polynomial approximations and numerical tools.

They provided one of the earliest theoretical frameworks for interpreting experimental observations of wear.

As Archard himself reportedly remarked, quoted by Y. Berthier:“ ***Had I known how many errors this law would generate, I would never have published it.****”*

The Archard law, or the Archard laws?!

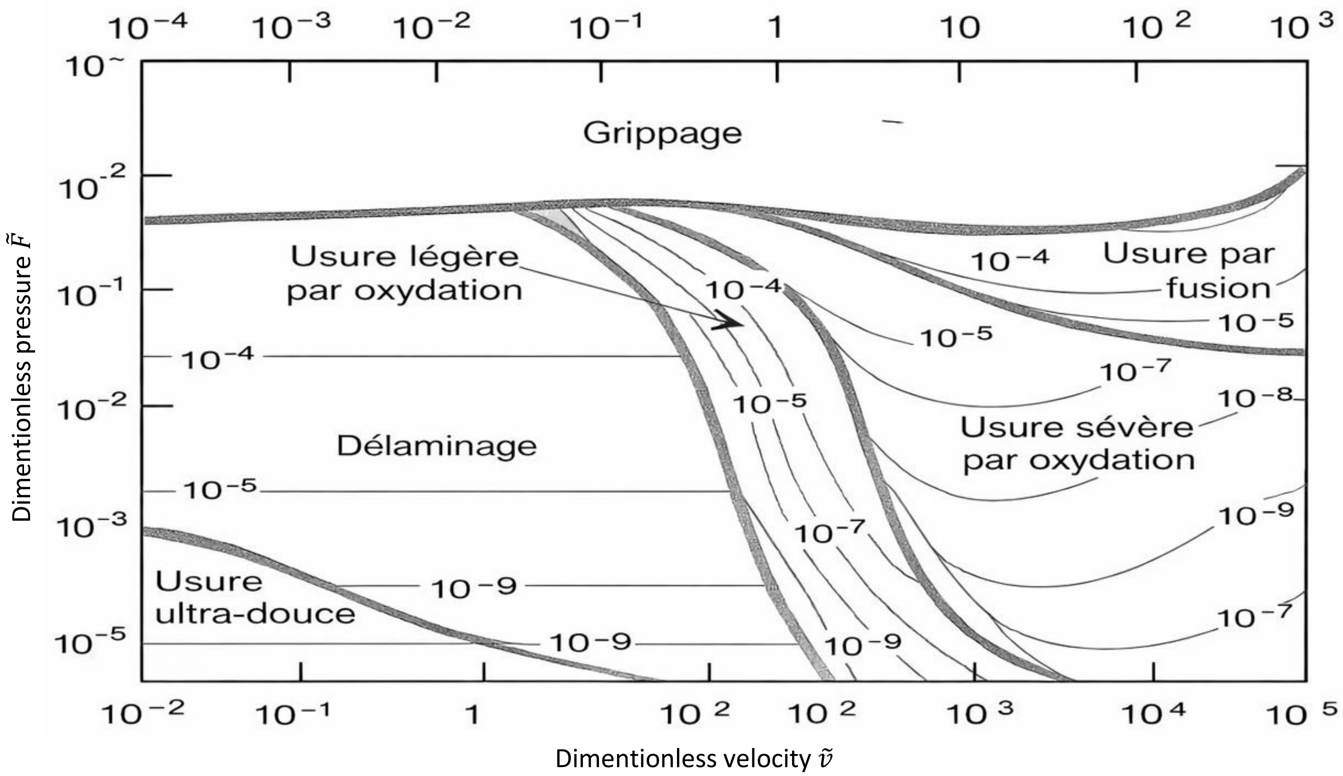
Wear maps from pion-disc tests



Dimensionless pressure = Fn / SH

Dimensionless velocity= vr_0 /a

S, contact area; H, hardness of the softer material; r_0, radius of the apparent contact area; a, thermal diffusivity.



Steel-steel dry contact on pion-disc configuration

(S.C. Lim and M.F. Ashby, 1987)

Under which conditions? which law? which parameters?... difficult to generalize!

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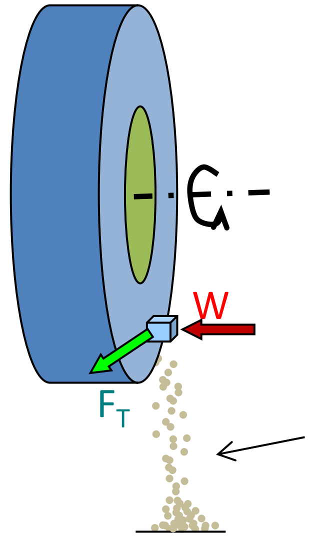
Wear and boundary conditions

Same load, material velocity, …, but different disc orientation:

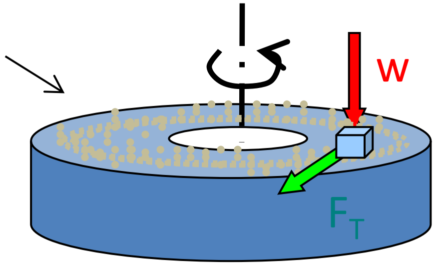
Configuration A



3rd body ejection flow (wear)

Configuration B

3rd body recirculation flow



… different wear rate!

- If the 3rd body is “protective” wear rate in configuration A will be higher;
- If the 3rd body is abrasive, wear rate in configuration B will be higher.

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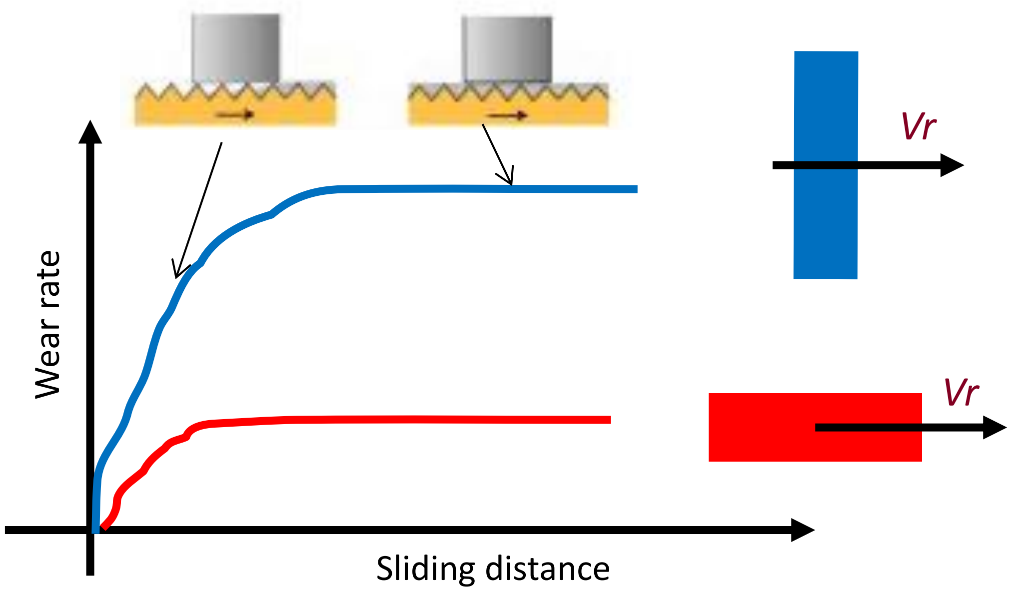
Wear and boundary conditions

Same load, material velocity, …, but different sample orientation:



If the 3rd body « protects» the surface, if not opposite trend

The tribological performance of a pair of materials depends on its ability to form and sustain a third-body layer within the contact, thereby preventing direct interaction between the two surfaces.

As Godet (1985) emphasized, "A good friction system is one that sacrifices the surface to preserve the bulk."

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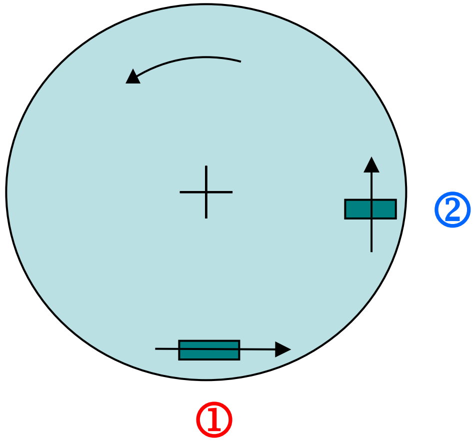
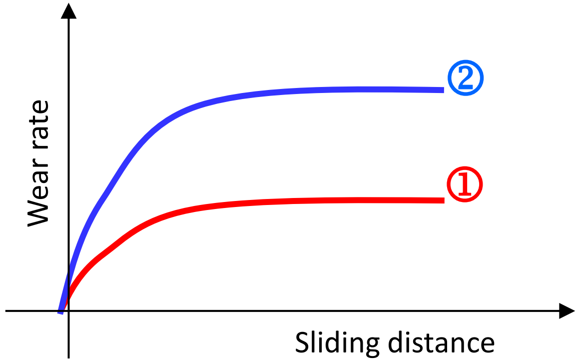
Wear and boundary conditions

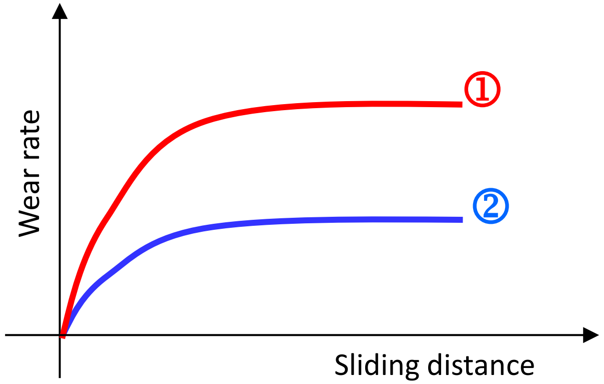
Same load, material velocity, ..., but different sample orientation:



Protective 3rd body

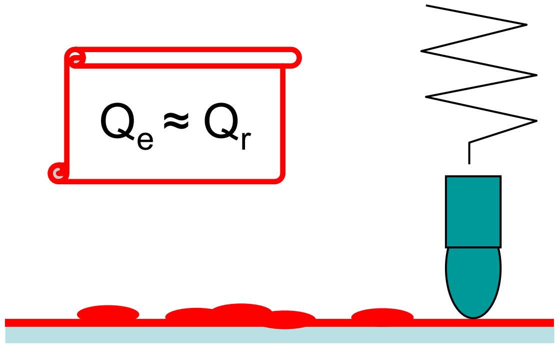


«Degrading» 3rd body

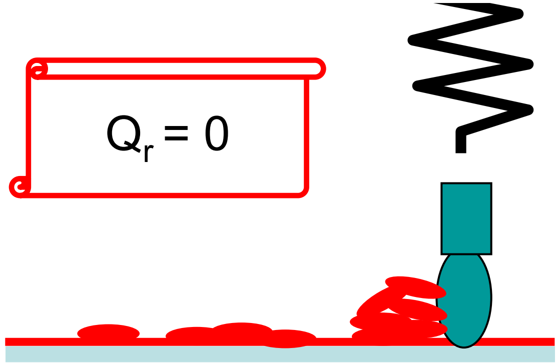


Wear and boundary conditions

Influence of the stiffness of the system (mechanism):



Low stiffness :
all the 3rd body passes by



High stiffness:
few of the 3rd body passes by

Extrapolating from one contact configuration to another is only meaningful if the actual contact stresses are known.

Wear maps must therefore be constructed for a given mechanism.

CONCEPTUAL TOOLS FOR TRIBOLOGICAL ISSUES

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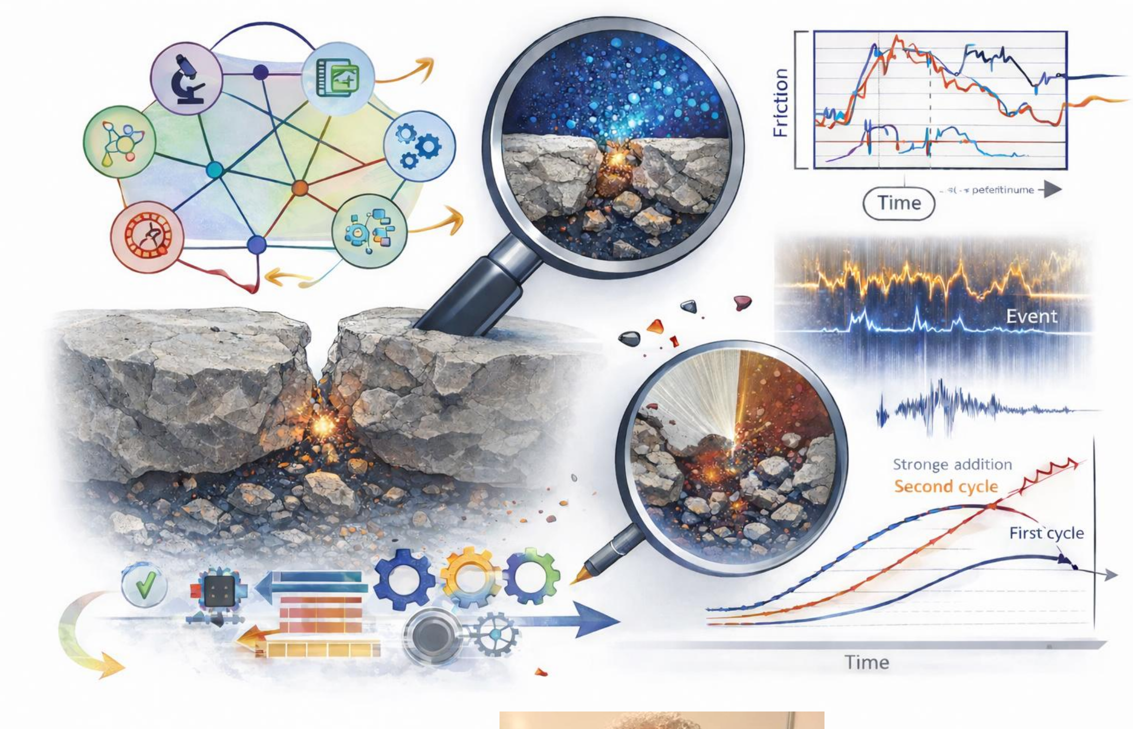
Tribology of dry friction

No generalized model currently exists.
There is still no truly predictive theory of friction and wear.



- A highly multidisciplinary and multiscale field
- Operational properties, with no simple correlation between friction and wear
- Strongly discontinuous, transient, and nonlinear behavior
- Coupled evolution of multiple interacting parameters
- trong history-dependent effects
- The impossibility of directly observing and measuring the contact while it is active

Friction and wear demand a pragmatic, efficient methodology

Main **conceptual tools** nowadays available for describing a dry contact (Berthier 1988):

The tribological triplet	The accommodation mechanisms	The tribological circuit

LUBRICATION

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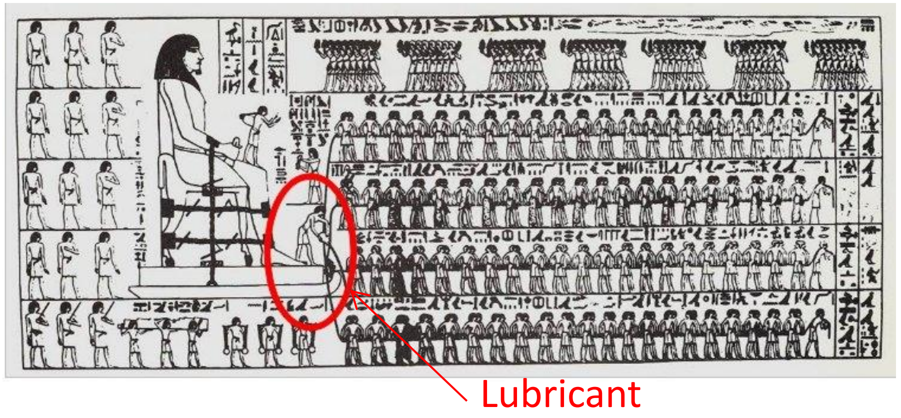
Lubrication or lubrications

One of the main solution to reduce friction and power lost in a contact is the introduction of an external 3rd body, which can be:

- liquid (oils, water, …)
- gas (air, azote,…)
- solid (MoS_2, PTFE, graphite, …)



Liquid lubrication is the more common and mastered form of lubrication, and different "behaviours" and tools can be distinguished,

As a function of the source of the lubricant pressure:

Hydrodynamic lubrication | Hydrostatic lubrication

Of the type of contact:

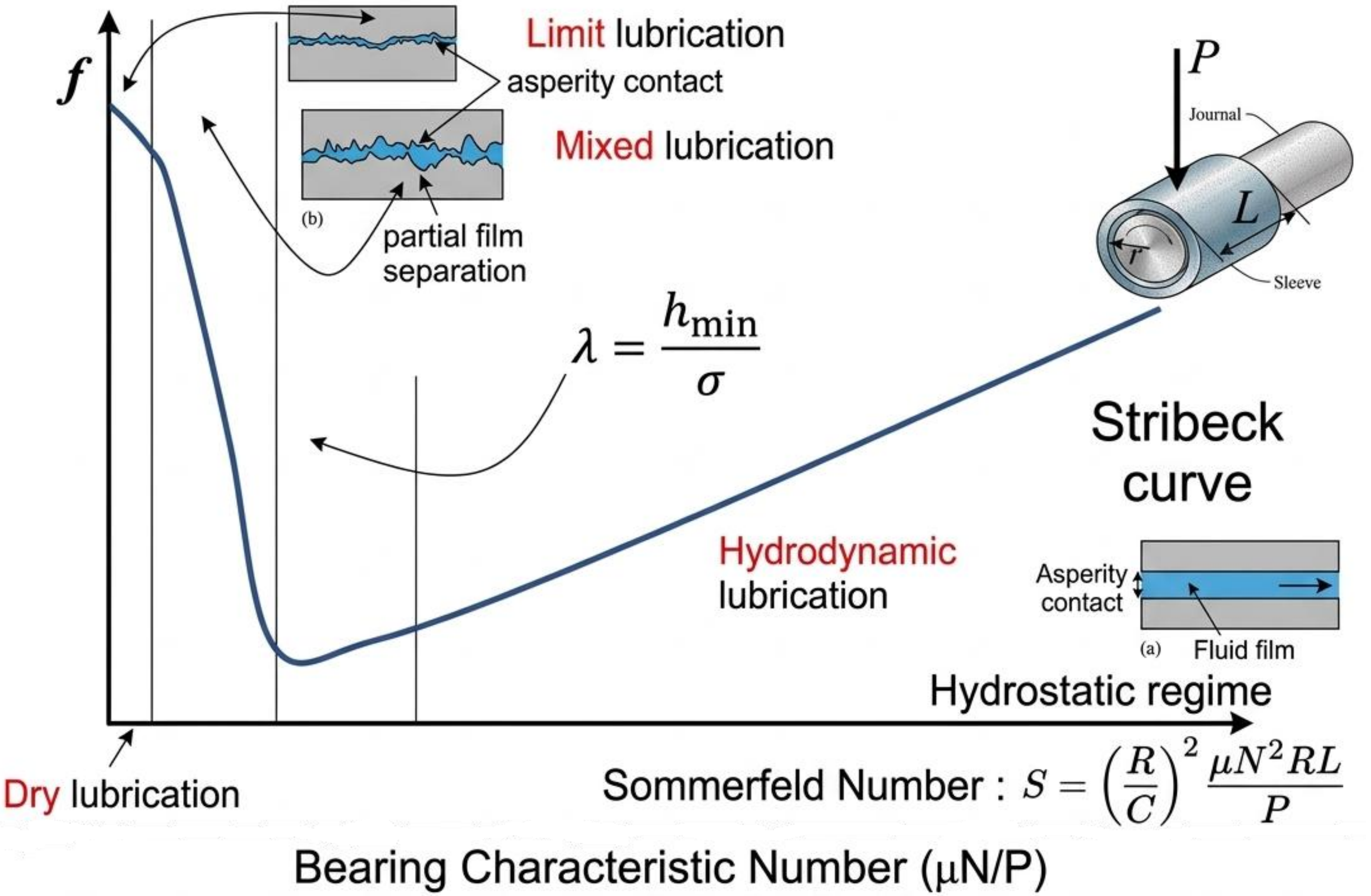
Hertzian contacts (0.5 GPa < p < 5 GPa)
Elastohydrodynamic regime

Surface contacts (0.1 MPa < p < 0.1 GPa)
Hydrodynamic regime

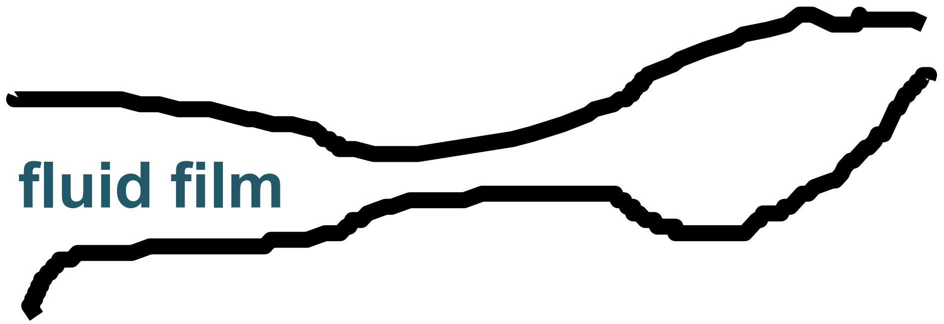
Of the functioning regimes:

Boundary lubrication or extreme pressure lubrication | Mixed lubrication | Hydrodynamic lubrication

Different lubrication regimes



Lubrication is the study of mechanisms where a lubricating film, generally fluid, is sandwiched between two massive solid.



Lubrication involves several complementary disciplines:

- fluid mechanics: study of the lubricant film.
- solid mechanics: study of solids in contact.
- rheology: study of the behavior of lubricants and solids.
- heat: assessment of temperature increasing and heating flows in the contact.
- chemistry: study of the composition of oils and their reactivity with surfaces.

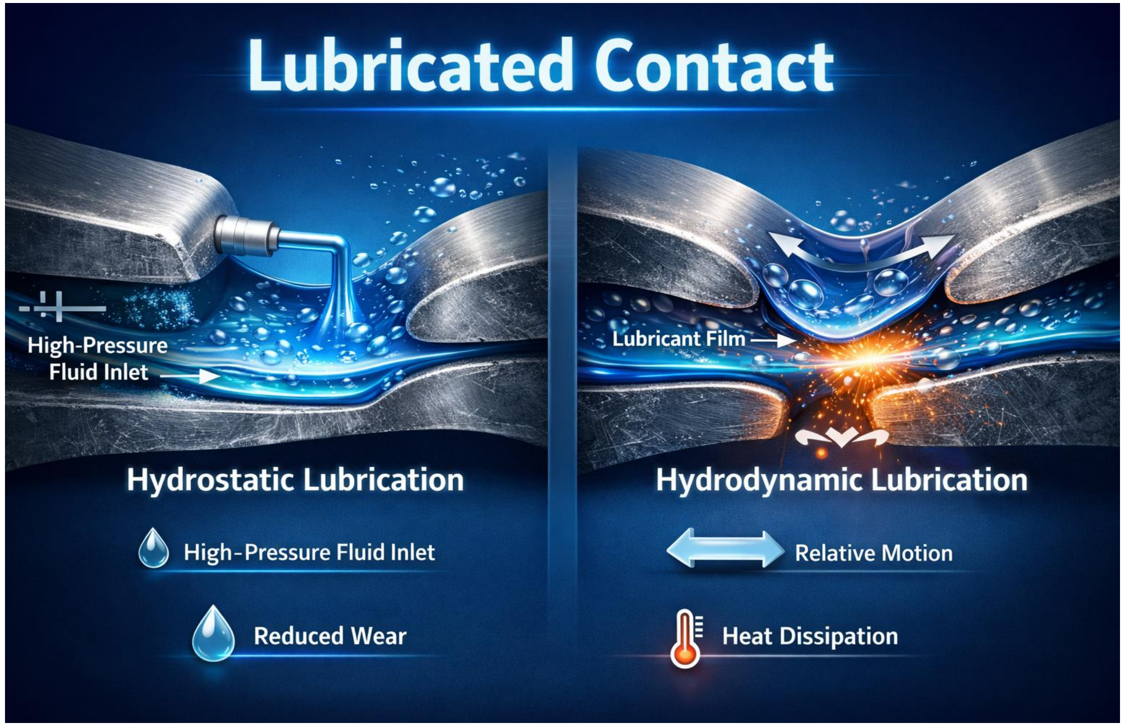
Lubrication has the essential functions of:

- reducing friction (power losses).
- reducing wear and preventing seizing.

Lubrication

As a function of the source of the film pressure, lubricated contacts can be classified as:

Hydrostatic lubrication	Hydrodynamic lubrication
The pressure within the lubrication film is generated by an external system.	The pressure within the lubrication film is generated by the relative movement between the surfaces.
(telescopes, machine-tools, turbopumps, …)	(journal bearings, thrust bearing, sliders, …)

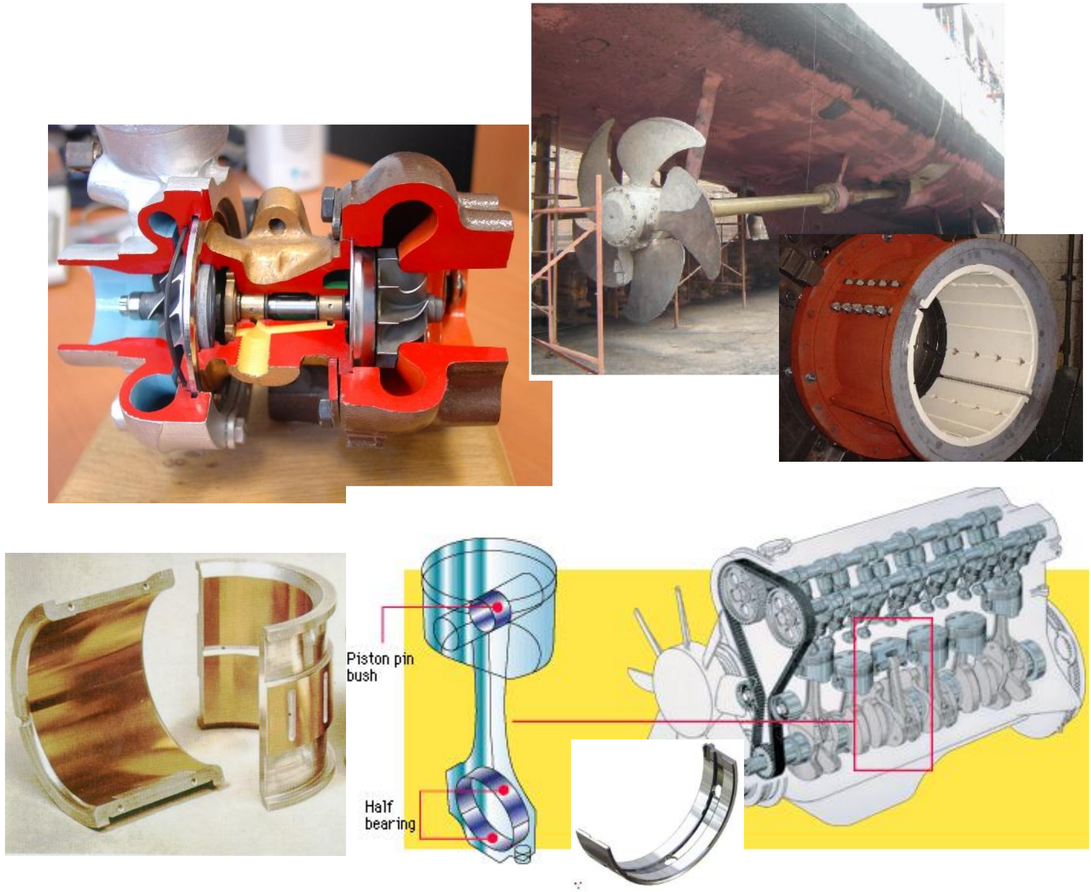


Lubrication

Hydrostatic and Hydrodynamic lubrication

As a fonction of the source of the film pressure, lubricated contacts can be identified:

Hydrostatic lubrication	Hydrodynamic lubrication



Lubrication

Hydrostatic and Hydrodynamic lubrication

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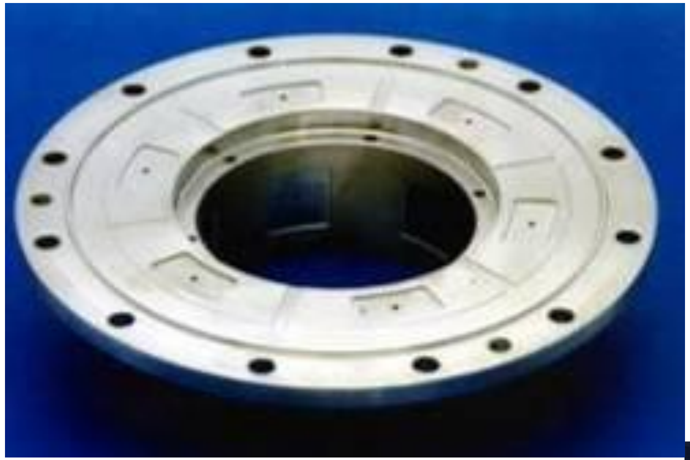
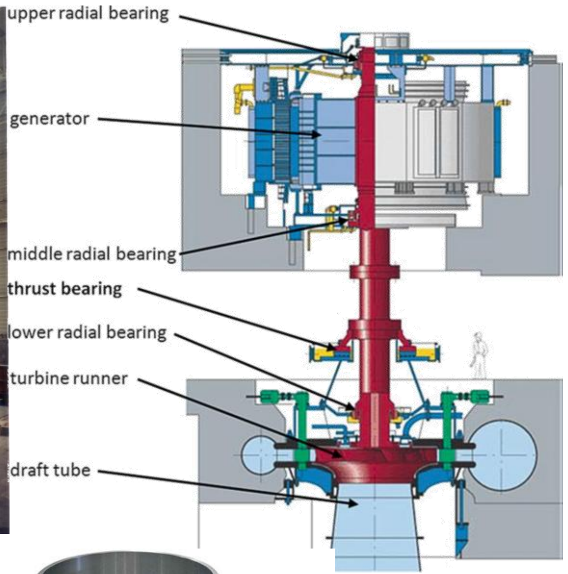
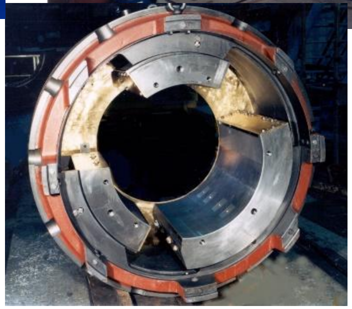
Hydrostatic lubrication	Hydrodynamic lubrication







Encyclopedia of Tribology, Springer, 2013.

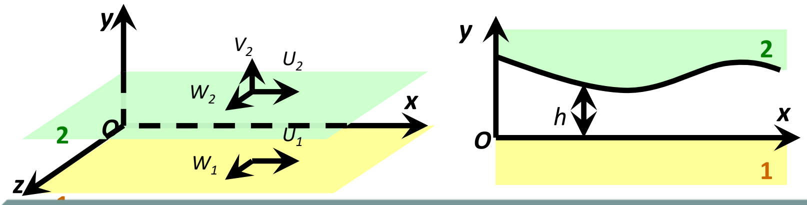
Kinds of contact

Two main cathegories of fluid lubricated contacts can be identified:

Hertzian contacts	Surface contacts
Reduced contact area Deformation of the solids in contact « Behaviours » of the lubricant Ex. grears, cams, ball bearings, rollers, …	Large contact area Low deformation of the solids in contact Newtonian behaviour of the lubricant Ex. journal bearings, thrust bearing, sliders, …
Elastohydrodynamic regime (EHD) *accounting for elastic deformations of the solids in contact and the changes of viscosity with pressure*	Hydrodynamic regime (HD) *Pressure field generated within a full fluid film between the sliding surfaces*

Predictive tools and advanced mathematical formalism

REYNOLDS equation

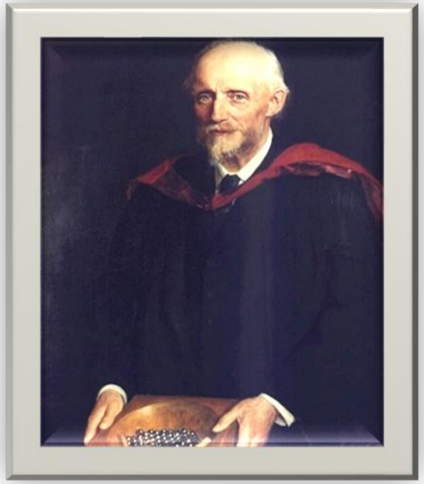


$$\frac{\partial}{\partial x}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial z}\left(\frac{h^3}{\mu}\frac{\partial p}{\partial z}\right) = 6(U_1 - U_2)\frac{\partial h}{\partial x} + 6(W_1 - W_2)\frac{\partial h}{\partial z} + 6h\frac{\partial}{\partial x}(U_1 + U_2) + 6h\frac{\partial}{\partial z}(W_1 + W_2) + 12V_2$$

Fluid lubrication can be described and investigated using relatively formalized mathematical tools, models, and numerical methods.

These models can often be generalized, since they are mainly governed by measurable and intrinsic parameters.

However, they tend to lose validity under extreme conditions, such as non-negligible roughness, fluid contamination, temperature effects, or the use of more complex modern lubricants containing additives or grease thickeners.



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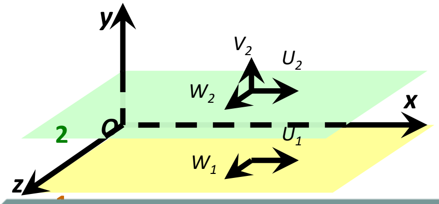
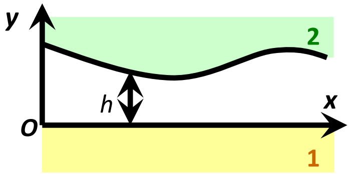
Predictive tools and advanced mathematical formalism

REYNOLDS equation





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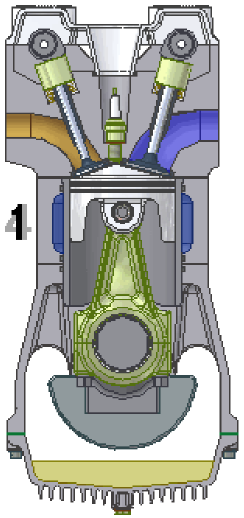

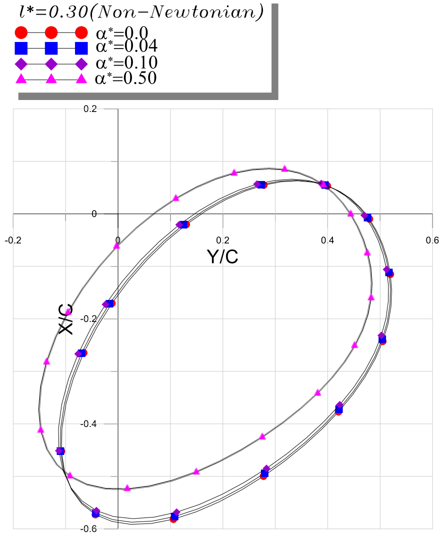

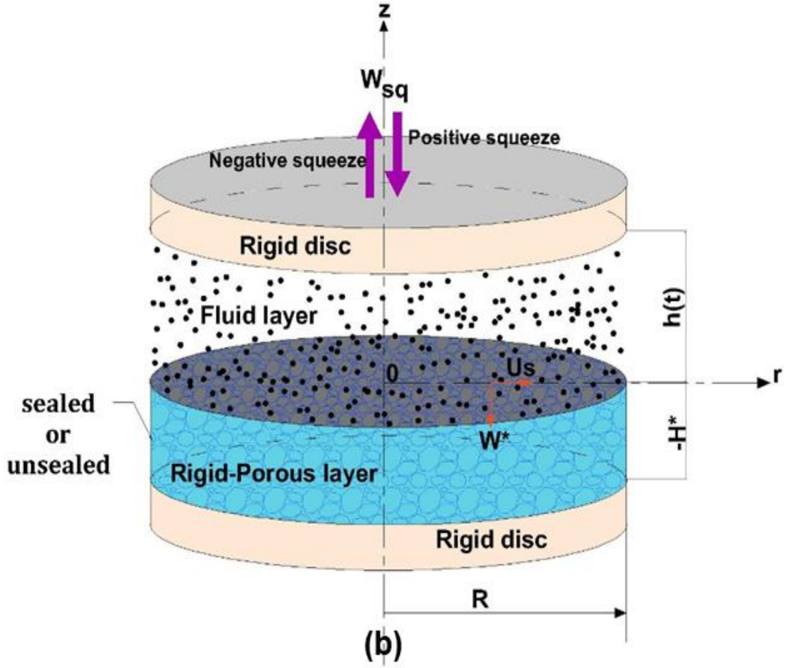

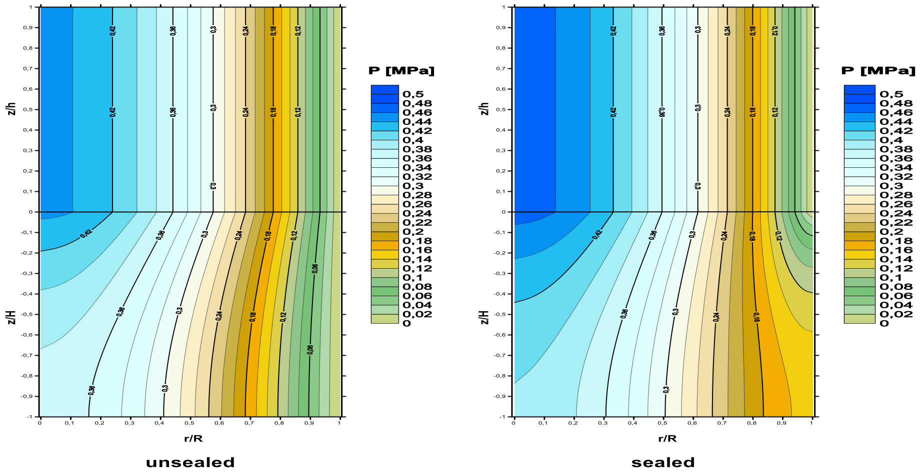

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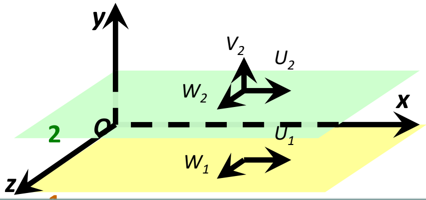
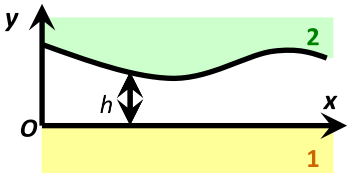
Predictive tools and advanced mathematical formalism

REYNOLDS equation





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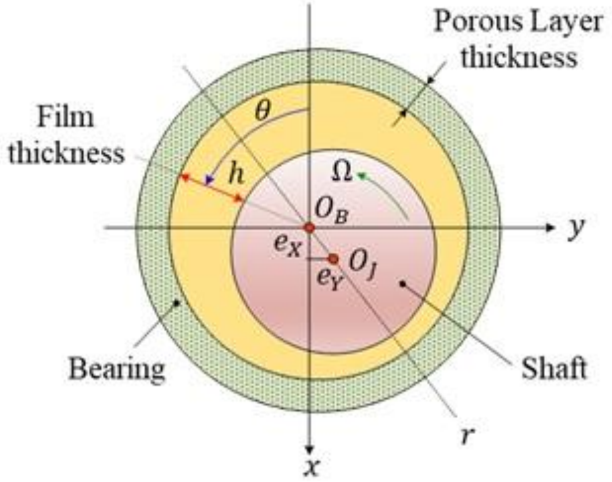

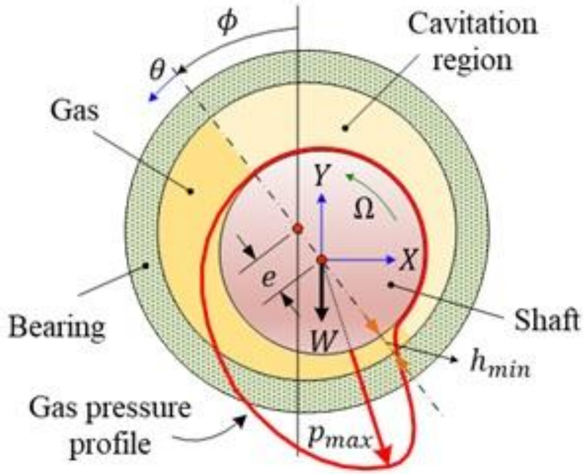

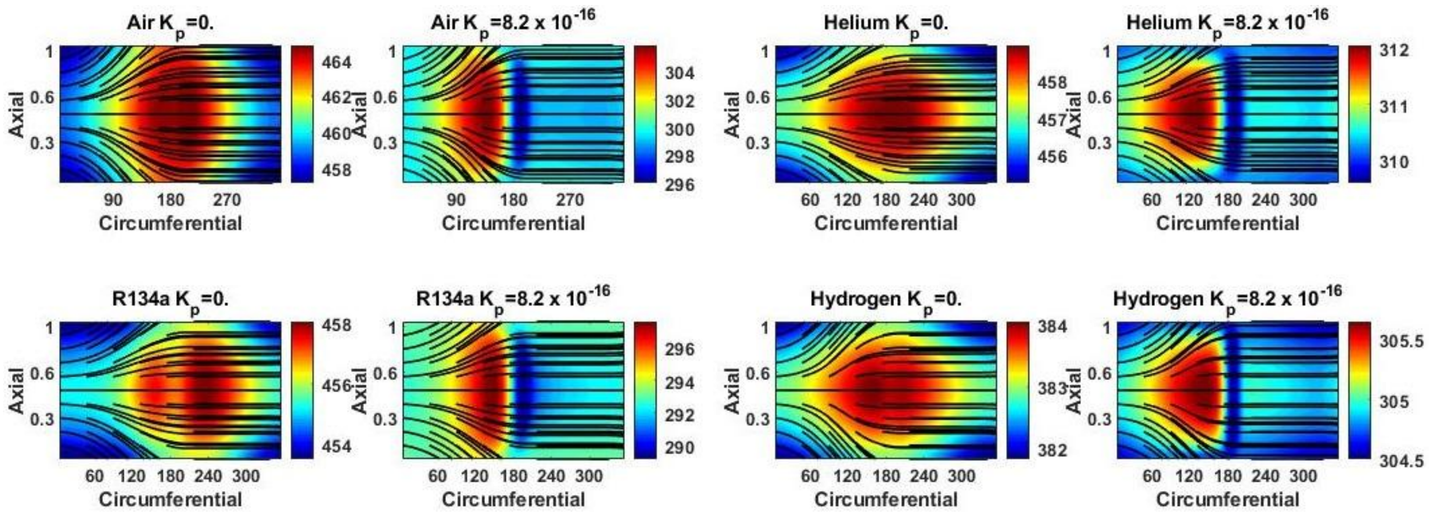

Benyebka Bou-Saïd
Laboratoire de Mécanique des Contact et des Structures (LaMCoS)

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