

Contact Mechanics and Elements of Tribology

Lecture 1.

Motivation: Industrial Applications

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@ Centre des Matériaux
February 11, 2019

- 1 A lot of relevant applications (really many 😊)
- 2 Short summary

- Composite material: cords and elastomer
- Cords: fiber, steel
- Cords ensure strength (internal pressure ≈ 2.1 bar)
- Elastomer: Styrene-butadiene rubber (SBR) with glass transition $T_g \approx -60$ °C
- Rolling resistance VS wear resistance and grip
- Decrease rolling friction and increase sliding friction
- Tread role: avoid hydroplaning, reduce noise (play with eigen frequencies) and wear
- Bicycles, **vehicles**, aircrafts
- Wheel-surface contact: on the Moon and Mars (granular bed)



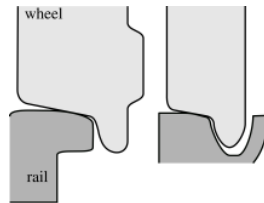
www.motortrend.com

Wheel/rail

- Metal-to-metal contact
- Wheel + rail tire (*bandage*)
- Special conical form
- Decrease rolling resistance
- Traction can be reduced by water, grease, oil
- Steel-steel friction $f \approx 0.75$, in service $f \approx 0.4$, it determines the maximal tractive torque
- To increase traction at starting a heavy train, sand is distributed in front of driving wheels
- Curved paths: use cant (*dévers*) to increase the speed
- On wheel: **wear, fatigue cracks, oxide delamination, noise, martensite formation**
- On rail: **corrugation, cracking**



Railway wheel www.railway-wheel-axle.com



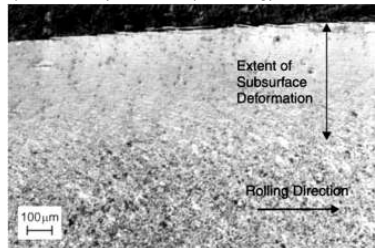
Railway Tram
Wheel flange (*boudin*)
adapted from Wikipedia

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*Slight hollow wear and some fatigue cracking
from KTH Royal Institute of Technology www.kth.se*

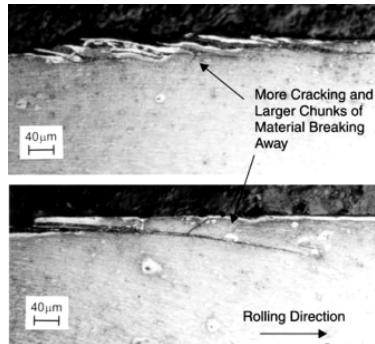


Sections parallel to the rolling direction through the wheel disc run at 3% slip^[1]

[1] Lewisa R. and R. S. Dwyer-Joyce. Wear mechanisms and transitions in railway wheel steels. Proc Instit Mech Engin J: J Engin Trib 218 (2004)

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Sections parallel to the rolling direction through the wheel disc run at 5% slip^[1]

[1] Lewisa R. and R. S. Dwyer-Joyce. Wear mechanisms and transitions in railway wheel steels. Proc Instn Mech Engrs J: J Engrn Trib 218 (2004)

Piston/cylinder

- Metal-to-metal sliding contact seal
- Piston ring (*segmentation*) mounted on the cylinder
- 3 rings for 4 stroke and 2 rings for 2 stroke engines
- Cast iron or steel + coating (chromium, or plasma sprayed (also PVD) ceramic)
- Objective: avoid gas from escaping to use entirely the gas work
- Good sealing VS high friction
- Responsible for $\approx 25\%$ of engine friction
- Lubricated contact: difficult conditions, permanent sliding direction reversion
- Relatively high temperature



Four-stroke cycle in cylinder
(*moteur à quatre temps*)
from Wikipedia

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Cylinder with grooves for piston rings
from [Wikipedia](#)

Piston/cylinder

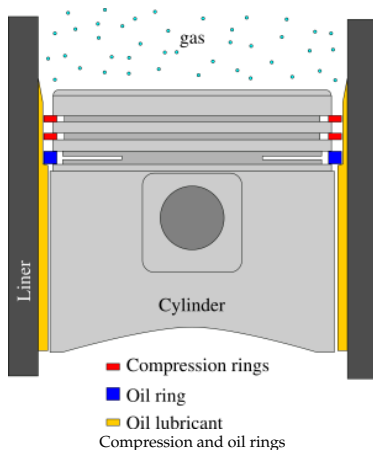
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Piston rings
from Wikipedia

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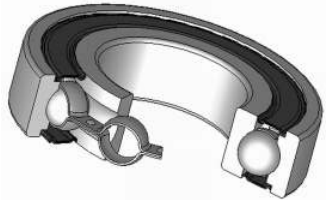
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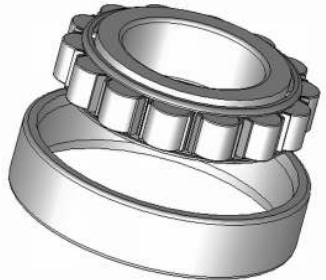
Zoom on grooves and the drain system for oil
from www.engine-labs.com

Bearings

- Reduce friction between moving parts
- Constraint motion of machine elements
- **Rolling bearing**
- Fluid bearing (liquid or gas)
- Magnetic bearing (no contact)
- To reduce friction and wear: use balls or rollers and lubricant (liquid or solid)
- Loads: radial, axial, bending
- Speed: rolling < fluid < magnetic
- Failure analysis: pressure-induced welding, fatigue, abrasion



A sealed deep groove ball bearing
from [Wikipedia](#)



A cylindrical roller bearing
from [Wikipedia](#)

Gears

- From wrist watches to ship gear boxes
- Impact contact, vibration
- Friction, lubrication
- Material: non-ferrous alloys, cast iron, powder metallurgy, plastics
- Failure reasons^[1]:
 - Lubrication:
 - rubbing wear (slow),
 - fatigue cracking (pitting),
 - scoring (thermally triggered rapidly evolving wear)
 - Strength:
 - plastic flow,
 - breakage

[1] Ku P.M. Gear failure modes - importance of lubrication and mechanics. ASLe Trans. 19 (1976)

[2] Burrows M., Sutton G. Interacting gears synchronize propulsive leg movements in a jumping insect. Science V.A. Yastrebov

Lecture 1



Change gear



Helical gear



Bevel gear

www.linngear.com

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Lecture 1



Interior of Rolex watches
www.rolex.com



Ship reduction gearbox 14 MW
(e.g. Renault Mégane 1.4 \approx 60 KW)
www.renk.eu

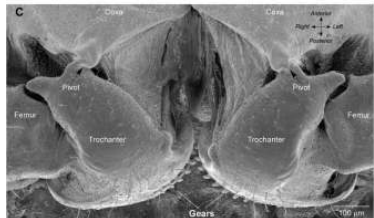
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"Functional gears in the ballistic jumping of the flightless planthopper insect Issus" (only in nymphs, not adults)^[2]

Brake systems

- Renault Mégane at 130 km/h



Renault Mégane [Renault](#)

- Boeing 747 at landing



Boeing 747-400

www.airplane-pictures.net

- TGV Eurostar at 300 km/h



TGV Eurostar www.lepoint.fr

Brake systems

- Renault Mégane at 130 km/h

$$E_{\text{kin}} \approx \frac{1}{2} 960 \text{ kg } 36^2 \frac{\text{m}^2}{\text{s}^2} = 622 \text{ kJ}$$

Would melt 0.7 kg of steel*

To stop in 5 seconds $P \approx 124 \text{ kW}$

- Boeing 747 at landing



Renault Mégane [Renault](#)



Boeing 747-400

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*Steel $C_p = 0.49 \text{ kJ}/(\text{kg} \cdot \text{T})$, $T_m \approx 1300 \text{ }^\circ\text{C}$, $\Delta H_f = 270 \text{ kJ/kg}$

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Renault Mégane [Renault](#)

- Boeing 747 at landing

$$E_{\text{kin}} \approx \frac{1}{2} 3 \cdot 10^5 \text{ kg } 72^2 \frac{\text{m}^2}{\text{s}^2} = 777 \text{ MJ}$$

Would melt 857 kg of steel

To stop in 1 minute $P \approx 13 \text{ MW}$



Boeing 747-400

www.airplane-pictures.net

- TGV Eurostar at 300 km/h



TGV Eurostar www.lepoint.fr

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Boeing 747-400

www.airplane-pictures.net

- TGV Eurostar at 300 km/h

$$E_{\text{kin}} \approx \frac{1}{2} 713 \cdot 10^3 \text{ kg } 83^2 \frac{\text{m}^2}{\text{s}^2} = 2.5 \text{ GJ}$$

Would melt 2 756 kg of steel

To stop in 2 minutes $P \approx 21 \text{ MW}$



TGV Eurostar www.lepoint.fr

*Steel $C_p = 0.49 \text{ kJ}/(\text{kg} \cdot \text{T})$, $T_m \approx 1300 \text{ }^\circ\text{C}$, $\Delta H_f = 270 \text{ kJ/kg}$

Brake systems

- Vehicle, aircraft, locomotive
- Disk-pad vehicle/aircraft
- Clasp brake for trains
they wear the wheel tire and thus increase the noise or rolling
- Disk: steel/ceramic/carbon
- Pad (*plaquette*): ceramics/Kevlar
- Strong thermo-mechanical coupling
- Thermal instabilities
- Brake squeal
- Particle emission
- Performance VS longevity
- Wear, friction, water lubrication



Reinforced carbon brake disc on a Ferrari F430
[Wikipedia](#)



New LL brake blocks aimed to reduce noise from rail sector [photo: UIC/EuropeTrain](#)

Assembled pieces

- Disk-blade assembly in turbines
wear, friction, fretting, crack initiation
- Rivets
- Bolts
- Screws (*vis*)
- Nails (*clou*)
- Nontrivial mechanical problems involving fracture and frictional contact
- Vibrational nut removal
- Stress relaxation



Modern steam turbine [Wikipedia](#)

Assembled pieces



GE J47 turbojet

Assembled pieces

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Fuselage of modern aircraft contains $\approx 100\,000$ rivets

www.news.cn

Impact and crash-tests

- Aircraft impact
 - Nuclear reactor containment building has to be designed to sustain it*
- Bird on aircraft impact
 - Bird/engine, bird/fuselage*
- Vehicle crash tests
 - Plasticity, contact, self-contact, friction*
- Plasma deposition of powder
- Drop tests
- Traumatic injury (brain, organs)
- Meteorite impact
 - see a piece of Canyon Diablo meteorite in Musée de Minéralogie de l'Ecole des Mines*
 - $$E_{\text{kin}} = \frac{1}{2} \cdot 3 \cdot 10^5 \text{ kg} \cdot 13.9^2 \cdot 10^6 \text{ m}^2/\text{s}^2 \approx 29 \text{ TJ}$$
 - it would melt 32 000 tonnes of steel.*



Crash test of supersonic jet fighter McDonnell Douglas F-4 against a reinforced concrete target
Sandia National Lab

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Bird impact traces on aircraft's nose/wing

Impact and crash-tests

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Mercedes crash test
Insurance Institute for Highway Safety

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Crater of the Canyon Diablo meteorite in Arizona, USA
bp.blogspot.com

Penetration and perforation

- Military applications
- High velocity impact
- Energy dissipating materials
- Problematics:
 - **attack:** increase penetration
 - VS
 - **defense:** decrease penetration



Handgun Self-Defense Ammunition Ballistics Test
(bullet penetration in synthetic silicon)

www.luckygunner.com



Sherman Firefly armor piercing shell on Tiger tank
armor, Bovington Tank Museum
Andy's photo www.flickr.com

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Fruit perforation
lunabeteluna.wordpress.com

Drilling

- Home/industrial/geological
- Percussive, rotary, etc.
- Ductile/brittle materials
- Rocks: hard/soft
- High temperature, high pressure
- Wear vs rate of penetration (RoP)
- Stability of the column in the borehole
- Diamond coatings/hardmetals (WC)
- Industry: oil/gas, thermal energy



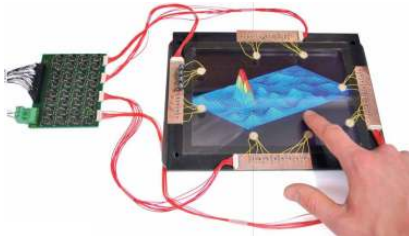
Drill crown and a single drill-bit button WC-Co



Varel's drill crowns www.varelint.com

Haptic perception

- Shape and roughness
- Temperature and heat capacity
- Braille is a tactile writing system
- Touch user interfaces (TUI)
- Touchscreens
 - capacitive (performance)
 - resistive (robustness)
 - surface acoustic waves
- + Haptic response



Sensory interacting system

V. Hayward, ISIR UPMC, CNRS *International Magazine* 34 (2014)



Braille page www.todayifoundout.com



Touch screen from "Minority Report"

Ice Skating/ski

- Ice skating

*Nontrivial physical question:
why ice is slippery?*



The skating minister
by Henry Raeburn, National Gallery of Scotland in
Edinburgh

Ice Skating/ski

- Ice skating

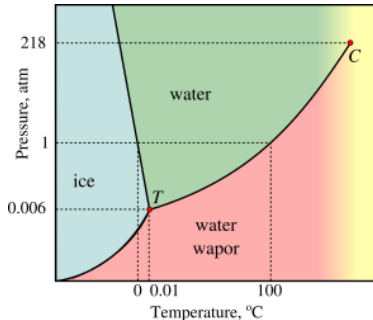
*Nontrivial physical question:
why ice is slippery?*

- *Because skate exerts locally a high pressure which melts the ice?*

J Joly (1886), O. Reynolds (1899)

- *Because friction-generated heat melts the ice?*

F.P. Bowden, T.P. Hughes (1939), S. Colbeck (1988-1997)

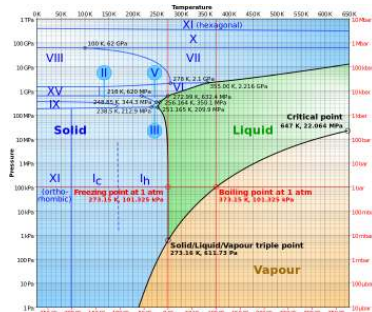


Approximate phase diagram of H₂O

Ice Skating/ski

- Ice skating
*Nontrivial physical question:
why ice is slippery?*
- Because skate exerts locally a high pressure which melts the ice? **No!**
J Joly (1886), O. Reynolds (1899)
- Because friction-generated heat melts the ice? **No!**
F.P. Bowden, T.P. Hughes (1939), S. Colbeck (1988-1997)
- Correct answer: Because the one-molecular surface layer cannot bond properly to the bulk forming a “water-like” film, which lubricates the contact!^[1]

[1] R. Rosenberg. Why is ice slippery? Physics Today (Dec'2005)



Accurate phase diagram of H₂O

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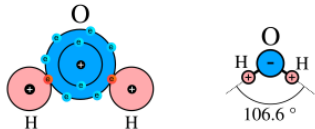
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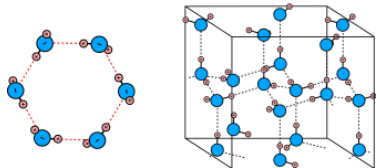
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Covalent bond



Hydrogen bond



Chemical bonds of H₂O

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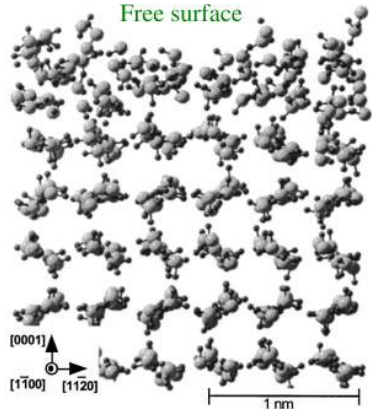
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Molecular dynamics simulation of ice surface^[2]

[2] T. Ikeda-Fukazawa, K. Kawamura.
Molecular-dynamics studies of surface of ice Ih,
J Chem Phys 120 (2004)

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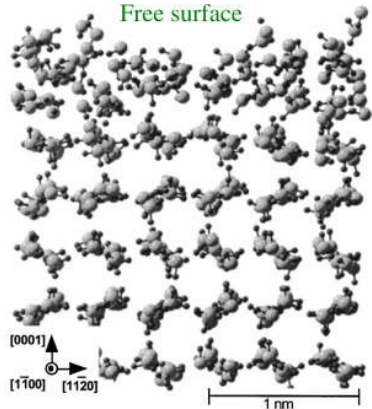
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Footwear contact

- Footwear
Wooden boots vs modern shoes
- Adhesion and wear-resistance properties
- Water resistance vs air circulation
- Rock climbing:
adhesion \gg wear-resistance
- Other sports:
football, tennis, basketball, etc.



Holland wooden shoes
www.rubylane.com/

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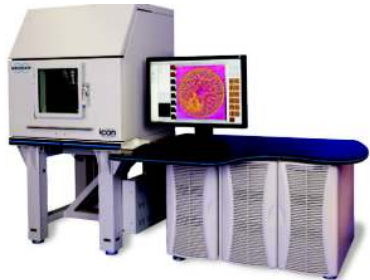
Sport shoes
(Rafael Nadal VS Quentin Halys, RG 2015)
www.zimbio.com



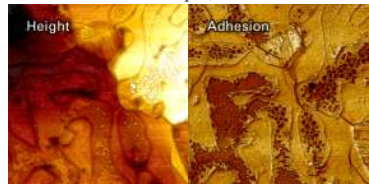
Climbing shoes
www.alp.org.ua

Atomic force microscopy (AFM)

- Oscillating cantilever beam
- Atomically sharp tip
- Measures:
 - topography at atomic scale
 - rigidity
 - adhesion
 - electric resistance
- Wear of the tip affects the precision
- Studies in nano-tribology: friction, indentation, wear



Atomic force microscope (www.bruker.com)

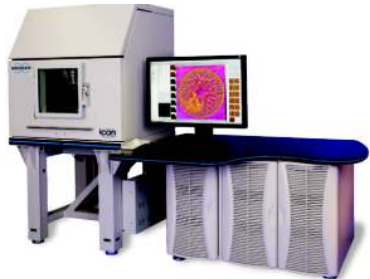


Height and adhesion measurements of Sn-Pb alloy surface (AFM)

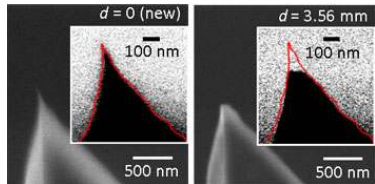
www.bruker.com

Atomic force microscopy (AFM)

- Oscillating cantilever beam
- Atomically sharp tip
- Measures:
 - topography at atomic scale
 - rigidity
 - adhesion
 - electric resistance
- Wear of the tip affects the precision
- Studies in nano-tribology: friction, indentation, wear



Atomic force microscope (www.brucker.com)



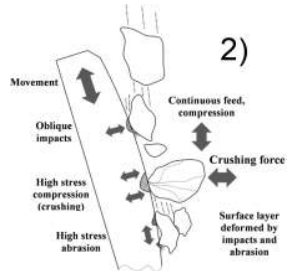
Virgin and worn AFM tip
National Institute of Standards and Technology
www.nist.gov

Mining industry

- Mines digging
- Producing of gravel
concrete and roadways
- Mineral crushers
- Excavator/bulldozer
bucket/blade
- Transportation of gravel
- Charge and discharge results in
impact and abrasive wear
- Thermo-mechano-metallurgical
coupling



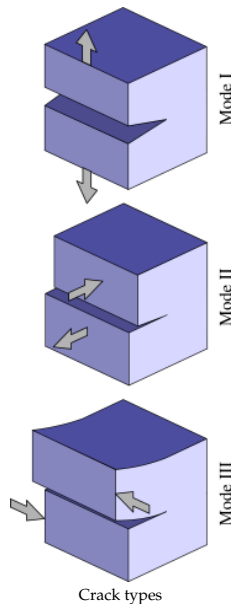
Mineral crusher
www.metso.com



Stone-crusher interaction
from M. Lindroos

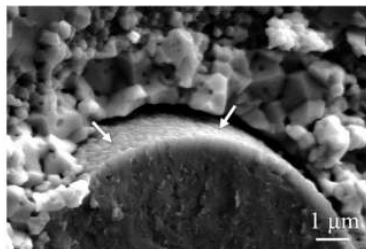
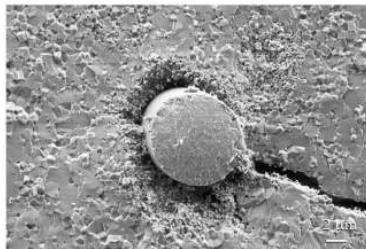
Crack interfaces

- Mode II and III cracks in monotonic loading
- All cracks in cycling loading
- Fatigue crack propagation
- Cracks in contact interfaces (pitting, fretting cracks)
- Plasticity in rocks
- Rapid cracks in composites (elastodynamic frictional phenomenon)
- Analogy between fracture mechanics and friction phenomenon



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Fiber-matrix interface^[1]

[1] D. Blaese et al. ZrO_2 fiber-matrix interfaces in alumina fiber-reinforced model composites, J Eur Ceramic Soc 35 (2015)

Electrical contact

- Switches
- Micro-Electro Mechanical Systems (MEMS)
- Electric brushes
- Electrical contactors
- Electrical brushing
trains, trams, metro
- Coupled thermo-mechano-electro-magneto-metallurgical problem
- Complex interplay of involved phenomena:
mechanical contact →
current intensity →
Joule heating →
temperature rise →
material properties →
mechanical contact → *etc.*



Siemens Switch www.siemens.com



Rouen's tram brush
[Wikipedia](#)

Sealing engineering

- Contact/non-contact seals
- Static/dynamic seals
- Liquid/gas sealing
- Topic:
 - cylinder/liner, bearings
 - gaskets, o-rings
 - rock permeability
 - shale gas/oil extraction
 - water circuits (civil, nuclear power plants)
- Polymers/metals
- Pressure/capillary action driven
- Interface geometry/roughness
- Permeability (e.g., tennis balls)
VS transmissivity (seals)

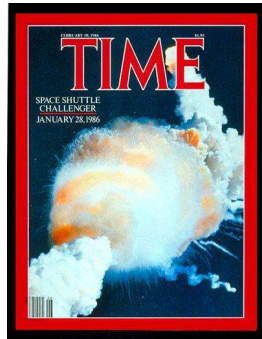
Space shuttle Challenger disaster January 28, 1986:

A rubber o-ring failed because of usage “well below its glass transition on an unusually cold Florida morning”



O-rings

www.powersportsnetwork.com



Space shuttle Challenger disaster

www.time.com

Granular matter

- Contact and friction determines their mechanical behavior
- Coupling with liquid (beach sand)
- Granulometry
- Carrier engineering
critical slope
- Earth-slides
- Gauge (granular layer) in geological faults
- Third body (wear particles and contaminants in contact)
- Brazil nut effect (granular convection)

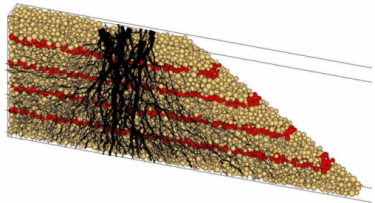


Dunes

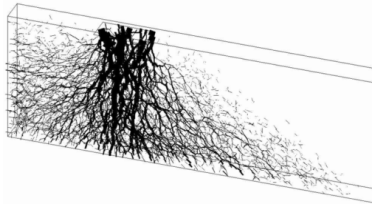
by Declan McCullagh www.mccullagh.org/

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DEM simulation of a soil slope (particles)



DEM simulation of a soil slope (chain forces)

Fabio Gabrieli (University of Padova)

geotechlab.wordpress.com

Granular matter

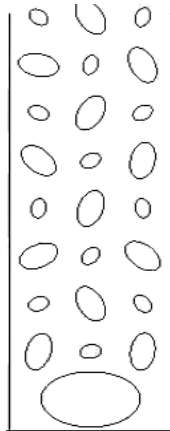
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Video: soil liquefaction:
ANIM/Liquefaction

Granular matter

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Animation: Granular convection simulation
Dynaflow Research Group www.dynaflow.com

Human joints and implants

- Lubrication/lack of lubrication
- Vertebral column (≈ 24 joints)
- Knees/shoulders/elbows
- Artificial joints
- Bio compatible materials
- Wear particle contamination
- Teeth/bone implants
- Stents



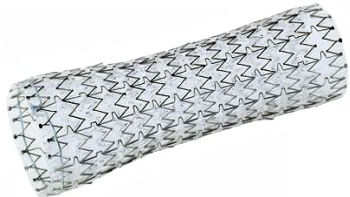
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Teeth implant
www.michaelsinkindds.com



Self-expanding Nitinol stent
endotek.merit.com

Bowed string instruments & sound

- Specific friction
- Material: natural fibers
catgut string vs horse hair in bow
- Stick-slip phenomenon
- Brake squeal
- Grasshoppers
- Crickets
- In general, sound producing is related to mechanical contact



Violin and bow
www.walmart.com



Grasshopper's leg
by Nico Angleys on www.flickr.com

Metal forming and machining

- Deep drawing
- Huge pressure
- Severe plastic deformations
- Specific friction laws
friction is no longer proportional to contact pressure
- Dies should be properly lubricated to avoid braking
- Machining (*usinage*)
- Wear of the cutting tool
- Friction between the tool and swarf (*copeaux*)



Metal forming
www.thomasnet.com



Metal cutting (machining)
www.hurco.com

Hard disk drive

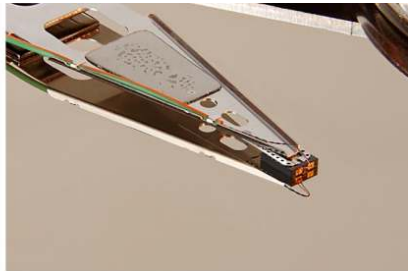
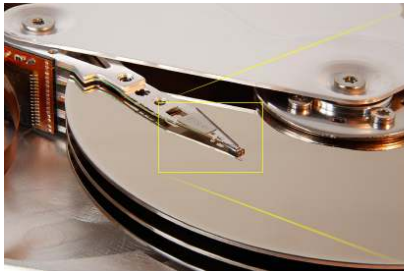
- Hard disk drive
- Air lubrication is used to avoid direct contact between the disk and the head
linear velocity 35 m/s
- Soon ($\approx 2020-2025$) will be replaced by SSD



Hard disk drive (HDD)
www.ssd-hdd.info

Hard disk drive

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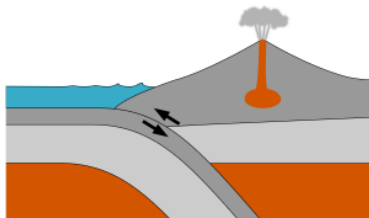
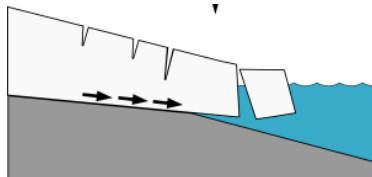


Zoom on the head of Seagate HDD

[Wikipedia](#)

Geological faults

- Slip in faults (*faille*)
- Dominant mechanism of earthquakes
- Elastic energy stored in the crust can be liberated by local slip
- Stick-slip phenomenon
- Partly dissipated in friction
- Partly removed by elastic-waves
- Huge pressure
intermediate-depth earthquake
70-300 km
- Presence of fluid pressure
- Non-trivial friction law
slip and velocity dependent
- Thermo-mechanical coupling

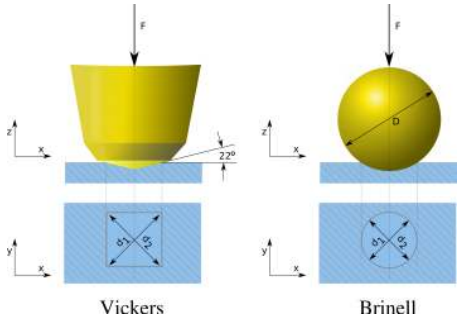


0.1-100 km

Geophysical scale slip
- basal glacial slip on the bedrock
- rock-rock slip in faults

Hardness testing

- Non-destructive material test
- Can be tested with portable equipment
- Material parameters at small scales: specific phase, thin film, etc.
- Various macroscopic tests:
 - Vickers (HV)
 - Brinell (HB)
 - Rockwell (HR)
 - etc
- Elastic/plastic properties

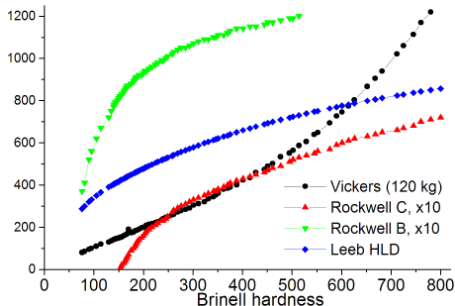


Vickers hardness $HV = \frac{F}{A}$

Brinell hardness $BHN = \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})}$

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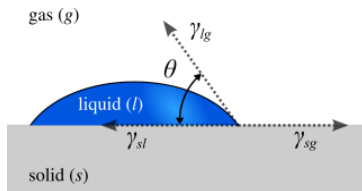


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Fluid-solid “contact” and adhesion

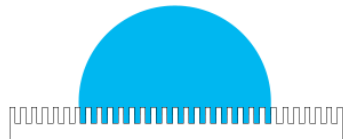
- Wetting (*mouillage*)
- Surface energy and surface tension
- Contact angle θ : balance of forces
 $\gamma_{sg} = \gamma_{lg} + \gamma_{sl} \cos(\theta)$
- Roughness of solids VS surface tension
- Apparent contact angle:
Wenzel VS Cassie-Baxter models
- Self-cleaning surfaces (lotus)
- Super-hydrophobic surfaces
- Wet adhesion (meniscus)
Sand castles



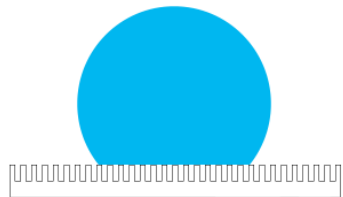
Equilibrium of interface forces
(adapted from Wikipedia)

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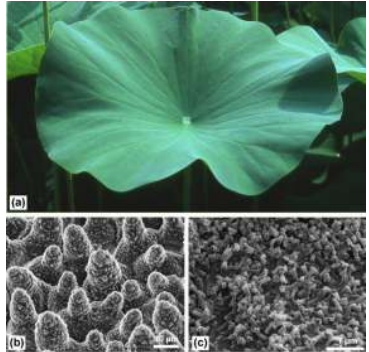
Wenzel model (Wikipedia)



Cassie-Baxter model (Wikipedia)

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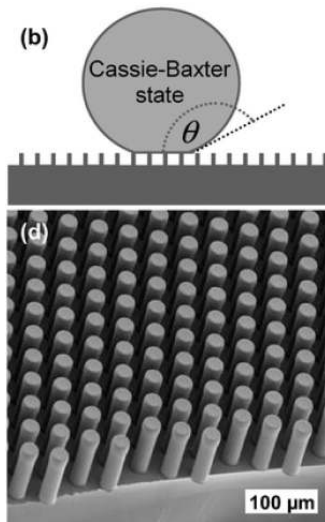
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H.J. Ensikat et al. Superhydrophobicity in perfection: the outstanding properties of the lotus leaf. *Beilstein J Nanotech* (2011)

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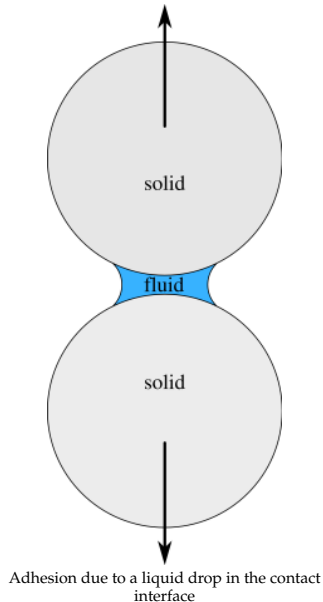
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G. McHale, M.I. Newton, N.J. Shirtcliffe. Immersed superhydrophobic surfaces: Gas exchange, slip and drag reduction properties. *Soft Matter* (2010)

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Adhesion

- Biology
- Bio-inspired devices
- Inspiring gecko's ability to climb on flat surface
- Van der Waals forces based adhesion^[1]

K. Autumn et al. Evidence for van der Waals adhesion in gecko setae. Proc Nat Acad Sci (2002)



Gecko's feet

(adapted from photos of Central Michigan university, Biology department)

Classification

In terms of material stiffness

- Stiff/stiff
- Soft/stiff
- Soft/soft

In terms of interface properties

- Frictionless
- Dry friction
- Adhesive
- Lubricated

In terms of inertia

- Quasi-statics
- Dynamics
- Vibration

In terms of fields

- Solid mechanics
- Thermomechanics
- Solid+fluid
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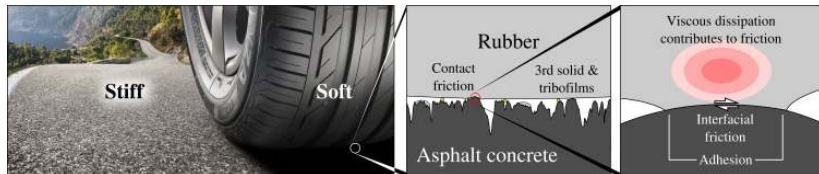
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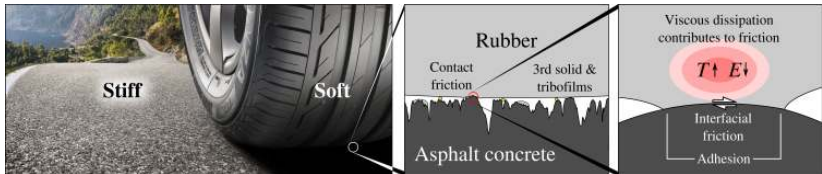
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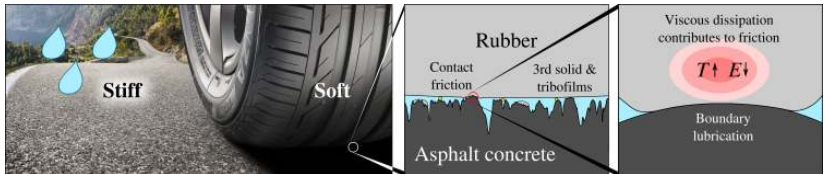
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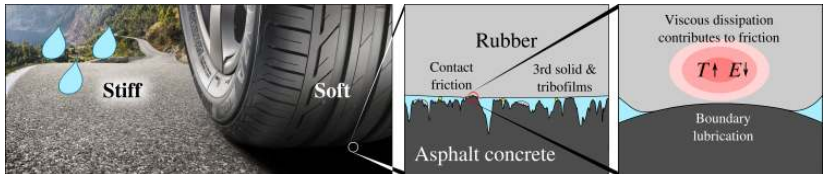
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Summary

- Application-wise objective: increase/reduce friction
rolling bearing vs tyre grip
- Application-wise objective: increase/reduce wear
polishing VS cylinder-liner
- Type of contact: normal/partial-sliding/sliding/rolling contact
touch interface VS rock shoes
- Interface type: dry/lubricated contact
brake system VS cylinder-liner
- Lubrication type: boundary, hydro-static/dynamic, elasto-hydrodynamic, mixed
cylinder-liner at middle path VS at extreme points
- Range of applied pressure matters
touch interface VS metal forming
- Involved temperatures (melting point of contactors)
- Phase changes (metalurgical aspects, glass transition)
- Other involved phenomena (electricity, material inter-diffusion, etc.)



Thank you for your attention!
