Contact Mechanics and Elements of Tribology

Lecture 1.
Motivation: Industrial Applications

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Outline

1. A lot of relevant applications (really many ☺)
2. Short summary

Tire/road

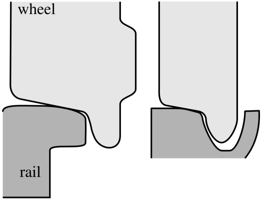
- Composite material : cords and elastomer
- Cords : fiber, steel
- Cords ensure strength (internal pressure ≈ 2.1 bar)
- Elastomer : Styrene-butadiene rubber (SBR) with glass transition $T_g \approx -60$ °C
- Rolling resistance VS wear resistance and grip
- Decrease rolling friction and increase sliding 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`



Wheel flange (boudin)
adapted from Wikipedia

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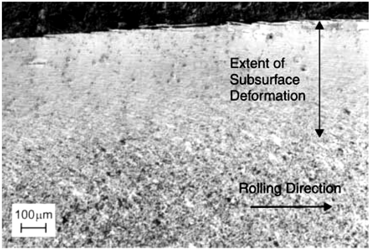
Slight hollow wear and some fatigue cracking from KTH Royal Institute of Technology `www.kth.se`



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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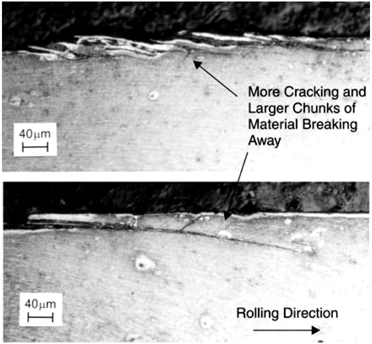
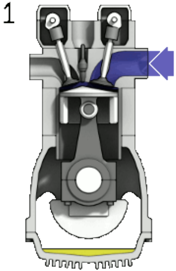


Sections parallel to the rolling direction through the wheel disc run at 5% slip[1]

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

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Piston rings
from Wikipedia

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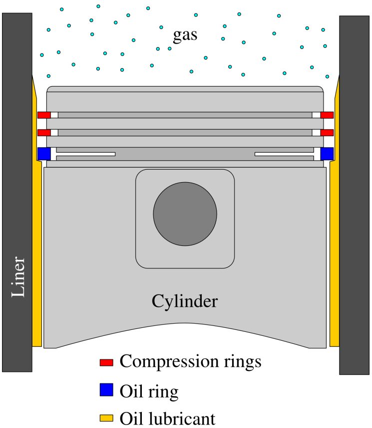

Compression and oil rings

Piston/cylinder

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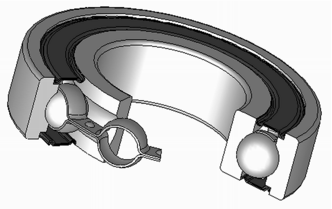
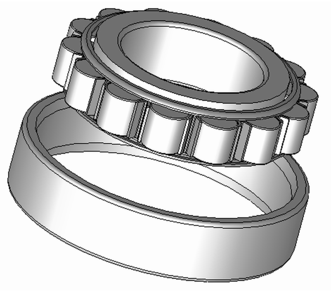
Zoom on grooves and the drain system for oil from www.enginelabs.com

Bearings

- Reduce friction between moving parts
- Constraint motion of machine elements
- **Rolling bearing**
- Fluid bearing (fluid of 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

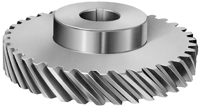
Gears

- 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 341 (2013)

Change gear



Helical gear

Bevel gear

www.linngear.com

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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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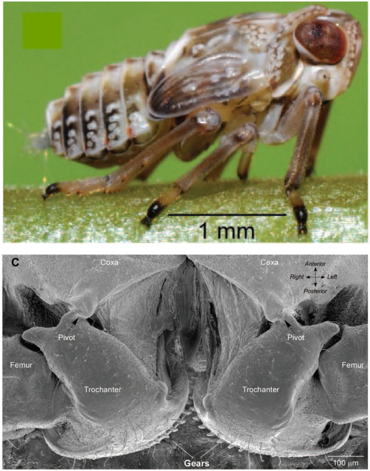

"Functional gears in the ballistic jumping of the flightless planthopper insect Issus"
(only in nymphs, nut not adults)[2]

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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

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

  Would melt 0.7 kg of steel*

  To stop in 5 seconds $P \approx 124$ kW

- Boeing 747 at landing

- TGV Eurostar at 300 km/h

Renault Mégane Renault

Boeing 747-400
www.airplane-pictures.net

TGV Eurostar www.lepoint.fr

*Steel $C_p = 0.49$ KJ/(kg· T), $T_m \approx 1300$ °C, $\Delta H_f = 270$ kJ/kg

Brake systems

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- Boeing 747 at landing

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

Would melt 857 kg of steel

To stop in 1 minute $P \approx 13$ MW

- TGV Eurostar at 300 km/h

Renault Mégane Renault

Boeing 747-400
www.airplane-pictures.net

TGV Eurostar www.lepoint.fr

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  Would melt 857 kg of steel

  To stop in 1 minute $P \approx 13$ MW

- TGV Eurostar at 300 km/h

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

  Would melt 2 756 kg of steel

  To stop in 2 minutes $P \approx 21$ MW

*Steel $C_p = 0.49$ KJ/(kg· T), $T_m \approx 1300$ °C, $\Delta H_f = 270$ kJ/kg

Renault Mégane Renault

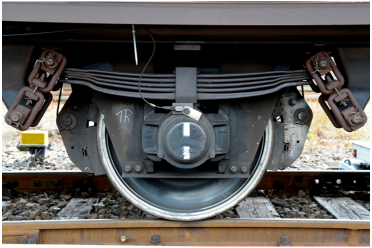
Boeing 747-400
www.airplane-pictures.net

TGV Eurostar www.lepoint.fr

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

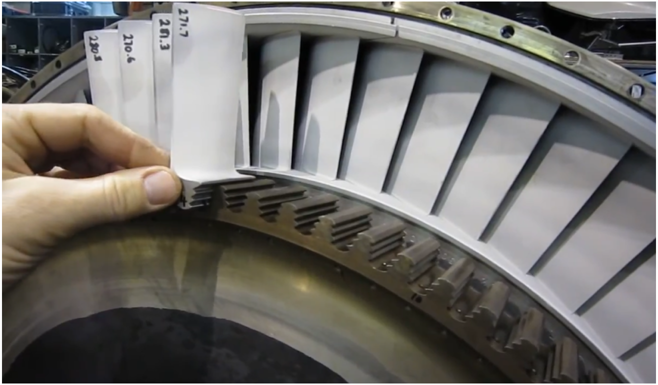
- Disk-blade assembly in turbines
  wear, friction, fretting, crack initiation

- 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 ≈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

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

- 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
  $E_{\text{kin}} = \frac{1}{2} 3 \cdot 10^5 \text{ kg} \cdot 13.9^2 \cdot 10^6 \text{m}^2/\text{s}^2 \approx 29 \text{ TJ}$
  it would melt 32 000 tonnes of steel.

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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

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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

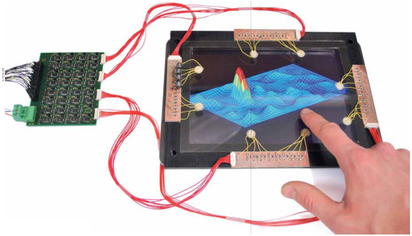
Varel's drill crowns www.varelint.com

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

Braille page www.todayifoundout.com

Touch screen from "Minority Report"



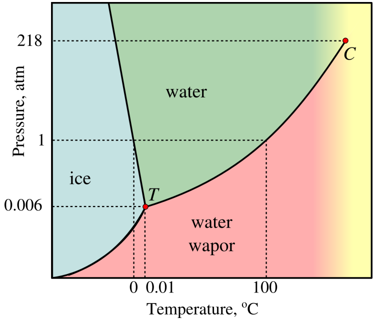
Sensory interacting system
V. Hayward, ISIR UPMC, CNRS International Magazine 34 (2014)

Ice Skating/ski

- Ice skating
  Nontrivial physical question :
  why ice is slippery ?

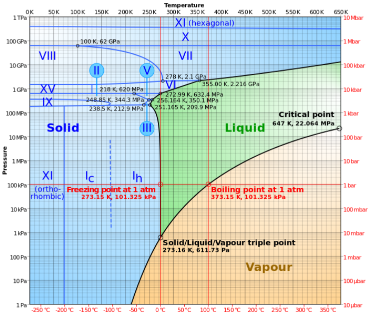
The skating minister
by Henry Raeburn, National Gallery of Scotland in Edinburgh

- Ice skating
  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 H_2O

- 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 H_2O

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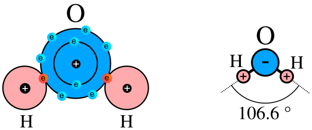
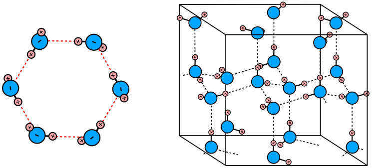
Covalent bond



Hydrogen bond



Chemical bonds of H_2O

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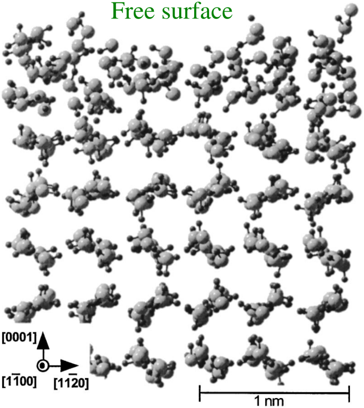
Free surface



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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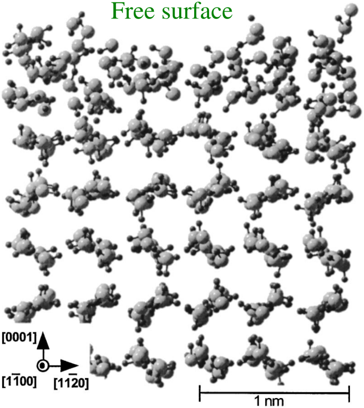
- Correct answer : *Because the one-molecular surface layer cannot bond properly to the bulk forming a "water-like" film, which lubricates the contact !*[1]
  [1] R. Rosenberg. Why is ice slippery ? Physics Today (Dec'2005)
- Ski

Free surface



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)

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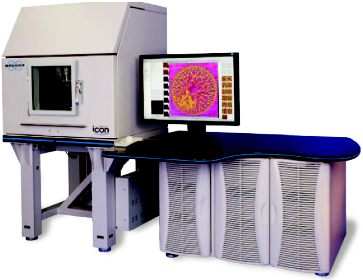
Sport shoes
(Rafael Nadal VS Quentin Halys, RG 2015)
www.zimbio.com

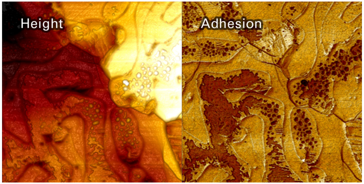
Climbing shoes
www.alp.org.ua

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.brucker.com)



Height and adhesion measurements of Sn-Pb alloy surface (AFM)
www.brucker.com

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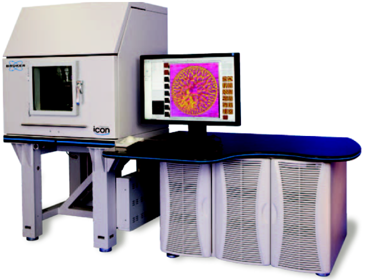

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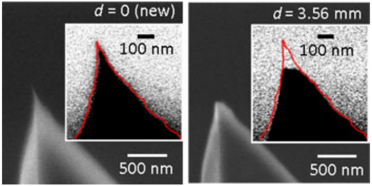
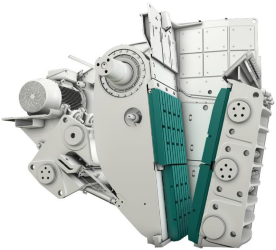
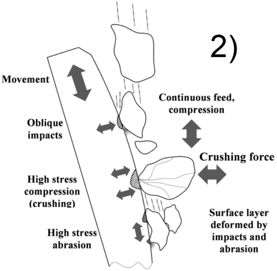


Virgin and worn AFM tip
National Institute of Standards and Technology
www.nist.gov

- 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



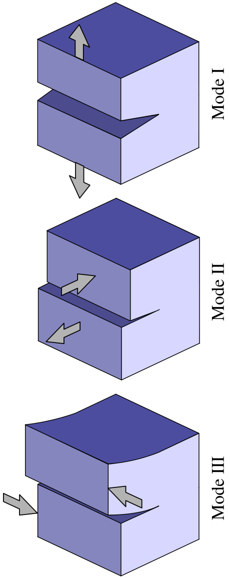
Mineral crusher
www.metso.com



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



Crack types

Crack interfaces

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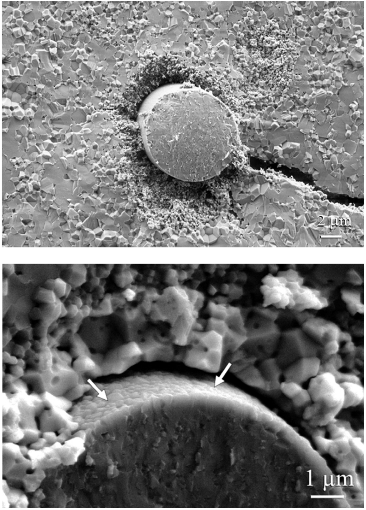


Fiber-matrix interface[1]

[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

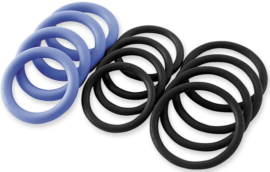
- Coupled thermo-mechano-electro-magneto-metallurgical problem
- Complex interplay of involved phenomena :
  mechanical contact $\rightarrow$
  current intensity $\rightarrow$
  Joule heating $\rightarrow$
  temperature rise $\rightarrow$
  material properties $\rightarrow$
  mechanical contact $\rightarrow$ *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)



O-rings
www.powersportsnetwork.com

Space shuttle Challenger disaster
www.time.com

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"

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 contaminates in contact)
- Brazil nut effect (granular convection)

Dunes
by Declan McCullagh www.mccullagh.org/

Granular matter

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- Carrier engineering *critical slope*
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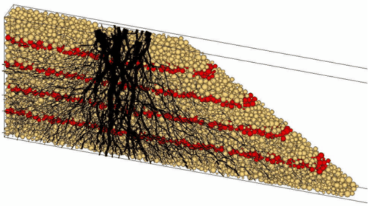
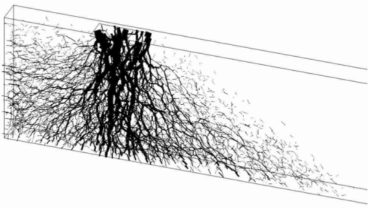


DEM simulation of a soil slope (particles)



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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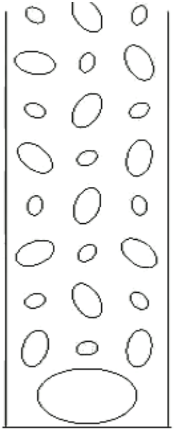

Animation : Granular convection simulation
Dynaflow Research Group www.dynaflow.com

Human joints and implants

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

Human joints

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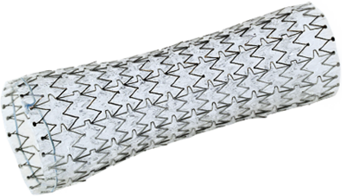
Teeth implant
www.michaelsinkindds.com



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
  e.g., Russian r-r-r-r

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 (≈2020-2025) will be replaced by SSD

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

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  linear velocity 35 m/s
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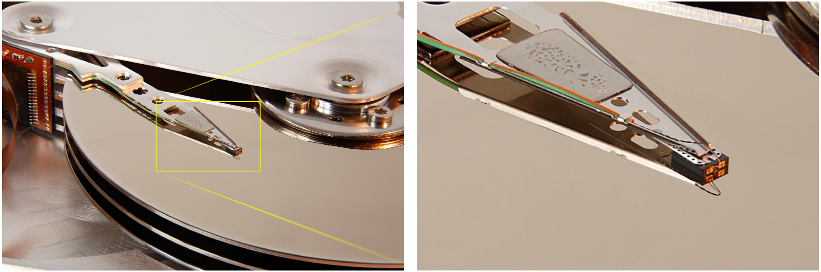
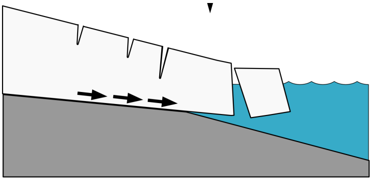
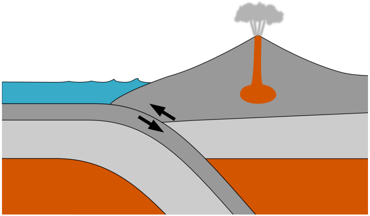


Zoom on the head of Seagate HDD
Wikipedia

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



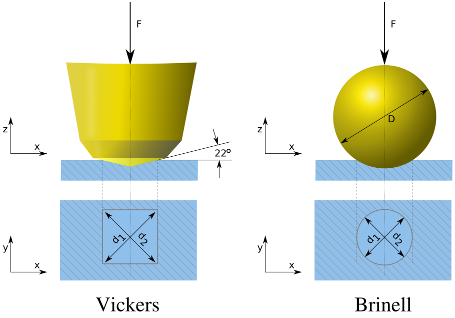


0.1-100 km

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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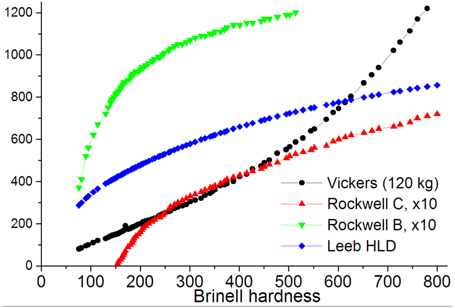


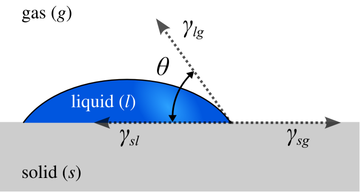
Comparison of hardness tests

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

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

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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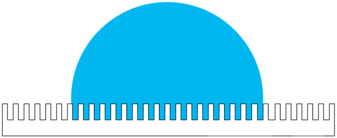
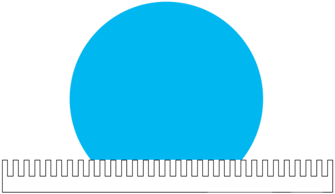


Wenzel model (Wikipedia)



Cassie-Baxter model (Wikipedia)

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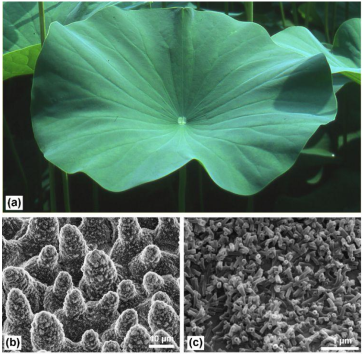

H.J. Ensikat et al. Superhydrophobicity in perfection : the outstanding properties of the lotus leaf. Beilstein J Nanotech (2011)

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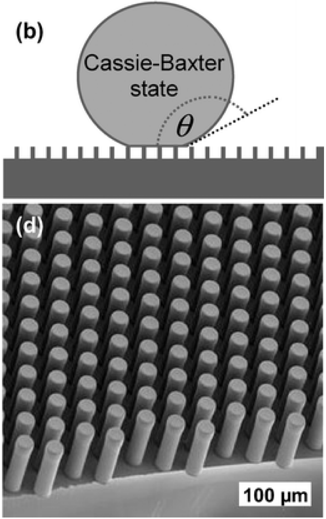

G. McHale, M.I. Newton, N.J. Shirtcliffe. Immersed superhydrophobic surfaces : Gas exchange, slip and drag reduction properties. Soft Matter (2010)

Fluid-solid “contact” and adhesion

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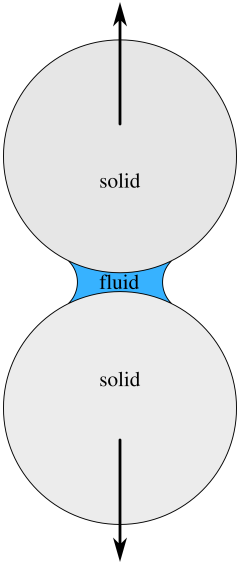
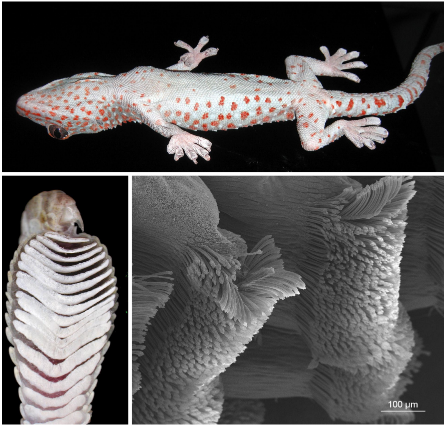


Adhesion due to a liquid drop in the contact interface

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)

Summary

- Increase/decrease friction
- Normal/sliding/rolling contact
- Dry/lubricated contact
- Interval of pressure
- Involved temperatures
- Phase changes
- Other involved phenomena (electricity, material inter-diffusion, etc.)

Thank you for your attention !