

# Contact Mechanics and Elements of Tribology

## Lecture 1.

### *Motivation: Industrial Applications*

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@ Centre des Matériaux (virtually)  
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Vladislav A. Yastrebov

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

- Composite material: cords and elastomer
- Cords: fiber, steel
- Cords ensure strength (internal pressure  $\approx 2.1$  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)



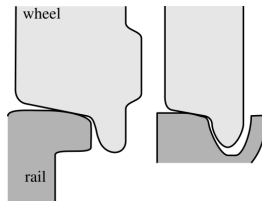
[www.motortrend.com](http://www.motortrend.com)

# 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](http://www.railway-wheel-axle.com)



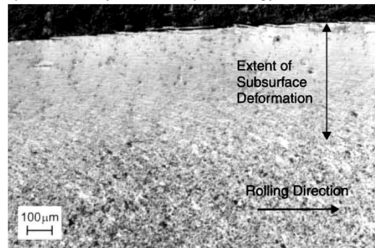
Railway                      Tram  
Wheel flange (*boudin*)  
adapted from Wikipedia

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*Slight hollow wear and some fatigue cracking  
from KTH Royal Institute of Technology [www.kth.se](http://www.kth.se)*

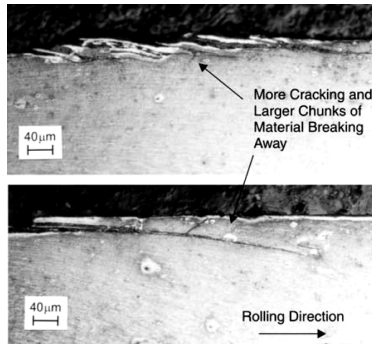


*Sections parallel to the rolling direction through the wheel disc run at 3% slip<sup>[1]</sup>*

[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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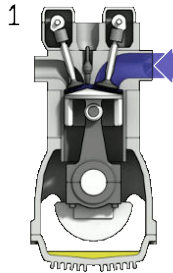


Sections parallel to the rolling direction through the wheel disc run at 5% slip<sup>[1]</sup>

[1] Lewisa R. and R. S. Dwyer-Joyce. Wear mechanisms and transitions in railway wheel steels. Proc Instt 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  $\approx 25\%$  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](#)



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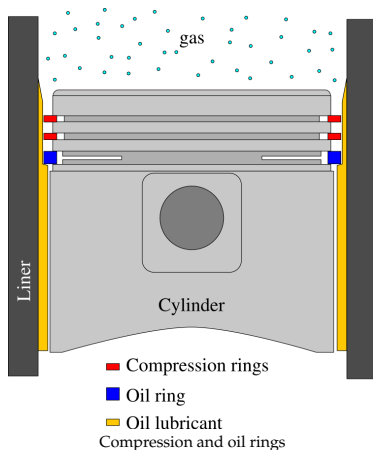
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Piston rings  
from Wikipedia

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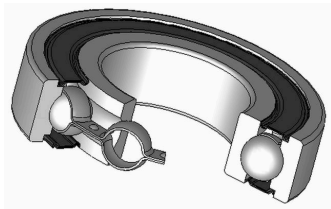
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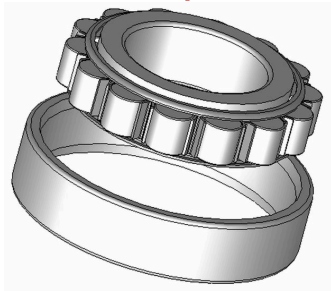
Zoom on grooves and the drain system for oil  
from [www.engine-labs.com](http://www.engine-labs.com)

# 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](#)

- From wrist watches to ship gear boxes
- Impact contact, vibration
- Friction, lubrication
- Material: non-ferrous alloys, cast iron, powder metallurgy, plastics
- Failure reasons<sup>[1]</sup>:
  - 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](http://www.linngear.com)

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Interior of Rolex watches  
[www.rolex.com](http://www.rolex.com)



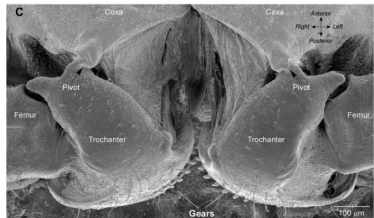
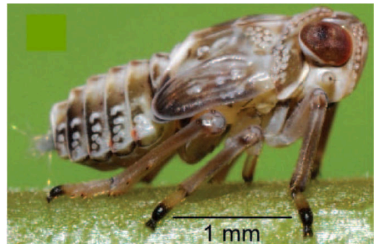
Ship reduction gearbox 14 MW  
(e.g. Renault Mégane 1.4  $\approx$  60 KW)  
[www.renk.eu](http://www.renk.eu)

# Gears

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

# Brake systems

- Renault Mégane at 130 km/h



Renault Mégane [Renault](#)

- Boeing 747 at landing



Boeing 747-400

[www.airplane-pictures.net](http://www.airplane-pictures.net)

- TGV Eurostar at 300 km/h



TGV Eurostar [www.lepoint.fr](http://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

[www.airplane-pictures.net](http://www.airplane-pictures.net)

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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](http://www.airplane-pictures.net)

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Renault Mégane [Renault](#)

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Boeing 747-400

[www.airplane-pictures.net](http://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](http://www.lepoint.fr)

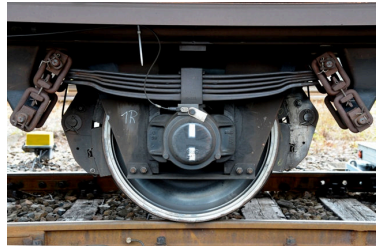
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# Brake systems

- 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](#)

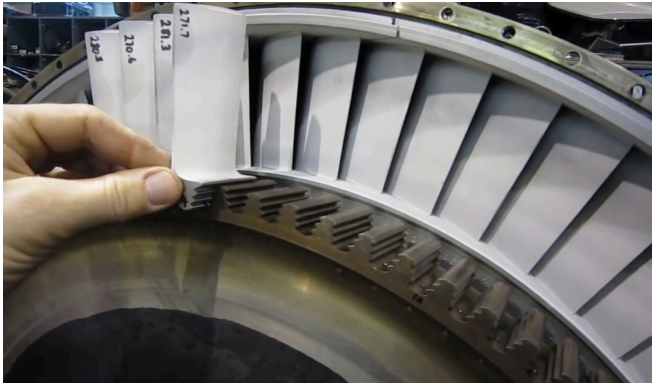
# Assembled pieces

- 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 (video)
- Stress relaxation



Modern steam turbine [Wikipedia](#)

# Assembled pieces



GE J47 turbojet

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

[www.news.cn](http://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
  - a part of Canyon Diablo meteorite is stored 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.*



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

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Mercedes crash test  
Insurance Institute for Highway Safety

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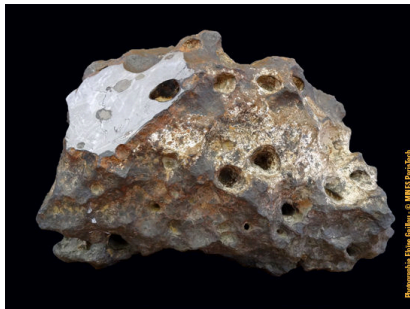
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Crater of the Canyon Diablo meteorite  
Barringer Crater, Arizona, USA [bp.blogspot.com](http://bp.blogspot.com)

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Part of the Canyon Diablo meteorite (226 kg)  
<http://www.musee.mines-paristech.fr>

Photographie Elise Gullier - © MINES ParisTech

# 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](http://www.luckygunner.com)



Sherman Firefly armor piercing shell on Tiger tank  
armor, Bovington Tank Museum  
Andy's photo [www.flickr.com](http://www.flickr.com)

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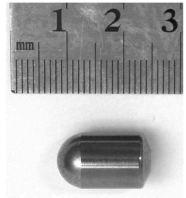


Fruit perforation  
[lunabeteluna.wordpress.com](http://lunabeteluna.wordpress.com)



# 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



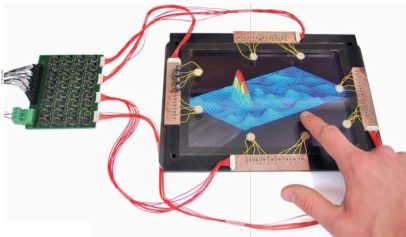
Drill crown and a single drill-bit button WC-Co



Varel's drill crowns [www.varelint.com](http://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](http://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

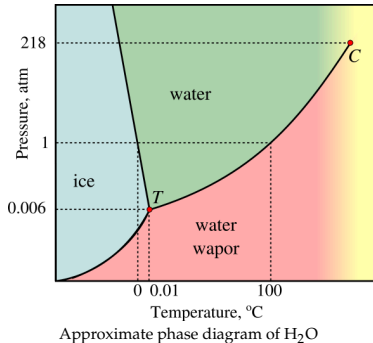
*Nontrivial physical question:  
why ice is slippery?*

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

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

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

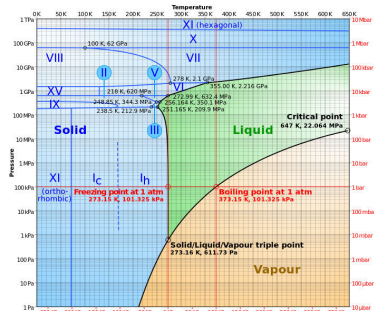
F.P. Bowden, T.P. Hughes (1939), S. Colbeck (1988-1997)



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- 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!<sup>[1]</sup>

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



Accurate phase diagram of H<sub>2</sub>O

# Ice Skating/ski

## ■ Ice skating

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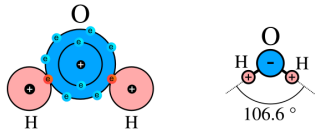
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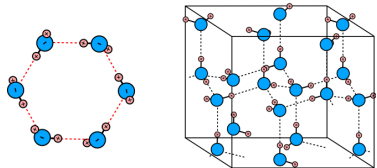
## ■ *Correct answer: Because the one-molecular surface layer cannot bond properly to the bulk forming a “water-like” film, which lubricates the contact!*<sup>[1]</sup>

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

### Covalent bond



### Hydrogen bond



Chemical bonds of H<sub>2</sub>O

# Ice Skating/ski

## ■ Ice skating

*Nontrivial physical question:  
why ice is slippery?*

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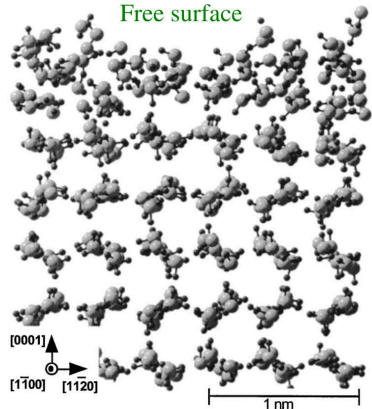
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Molecular-dynamics studies of surface of ice Ih,  
J Chem Phys 120 (2004)

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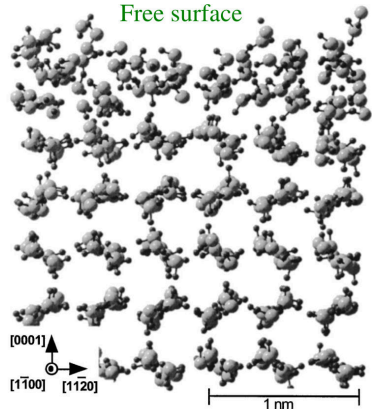
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# Footwear contact

- 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.



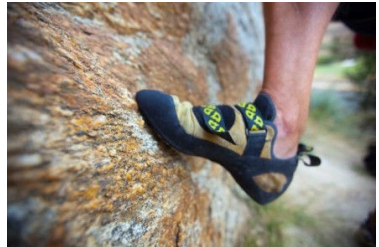
Holland wooden shoes  
[www.rubylane.com/](http://www.rubylane.com/)

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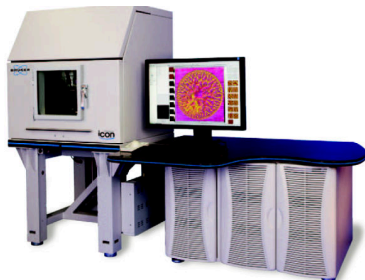
Sport shoes  
(Rafael Nadal VS Quentin Halys, RG 2015)  
[www.zimbio.com](http://www.zimbio.com)



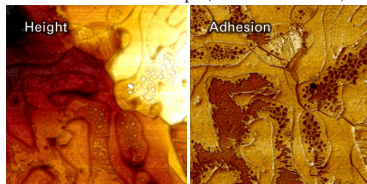
Climbing shoes  
[www.alp.org.ua](http://www.alp.org.ua)

# 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



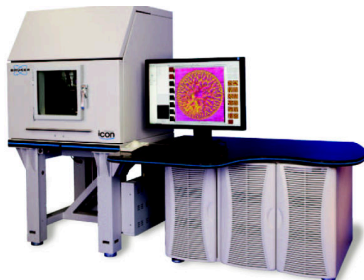
Atomic force microscope ([www.bruker.com](http://www.bruker.com))



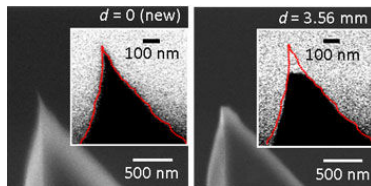
Height and adhesion measurements of Sn-Pb alloy surface (AFM)  
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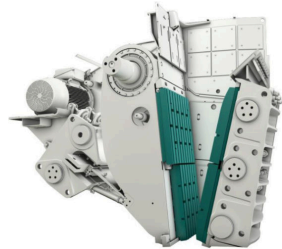
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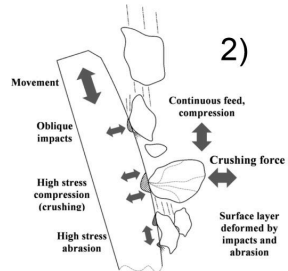
Virgin and worn AFM tip  
National Institute of Standards and Technology  
[www.nist.gov](http://www.nist.gov)

# 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



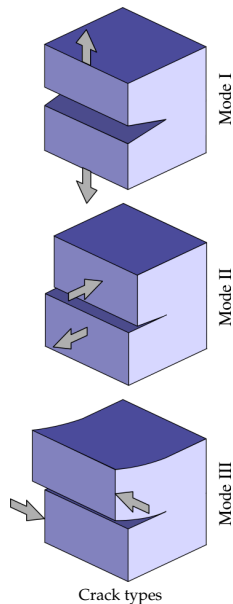
Mineral crusher  
[www.metso.com](http://www.metso.com)



Stone-crusher interaction  
from M. Lindroos

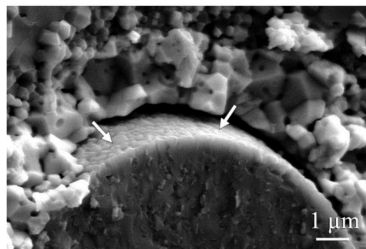
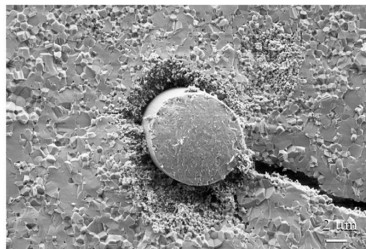
# Crack interfaces

- 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<sup>[1]</sup>

[1] D. Blaese et al.  $\text{ZrO}_2$  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](http://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)

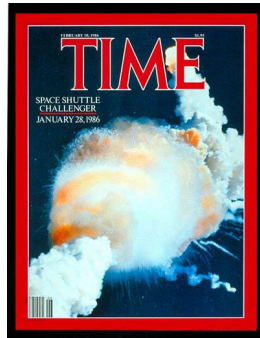
Space shuttle Challenger disaster January 28, 1986:

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



O-rings

[www.powersportsnetwork.com](http://www.powersportsnetwork.com)

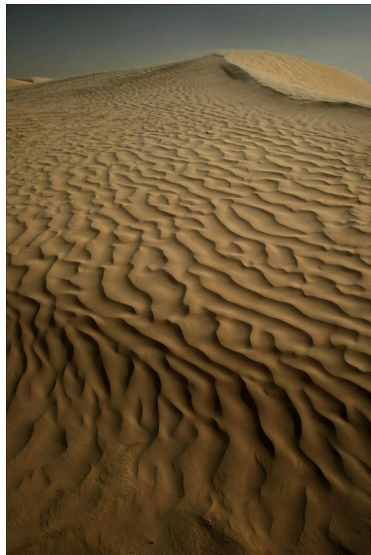


Space shuttle Challenger disaster

[www.time.com](http://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)

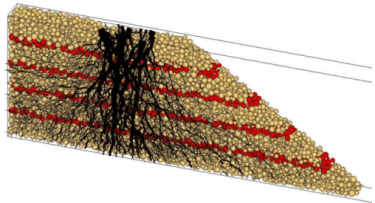


Dunes

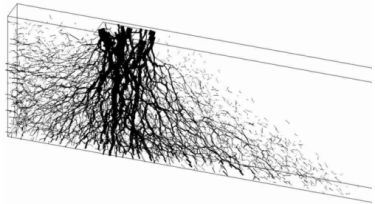
by Declan McCullagh [www.mccullagh.org/](http://www.mccullagh.org/)

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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](http://geotechlab.wordpress.com)

# Granular matter

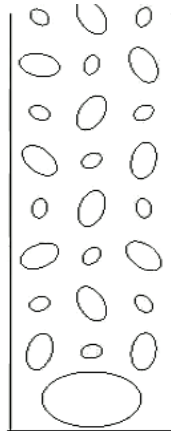
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Video: soil liquefaction:  
ANIM/Liquefaction

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Animation: Granular convection simulation  
Dynaflow Research Group [www.dynaflow.com](http://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

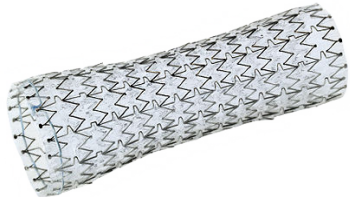
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Teeth implant

[www.michaelsinkindds.com](http://www.michaelsinkindds.com)



Self-expanding Nitinol stent

[endotek.merit.com](http://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](http://www.walmart.com)



Grasshopper's leg  
by Nico Angleys on [www.flickr.com](http://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](http://www.thomasnet.com)



Metal cutting (machining)  
[www.hurco.com](http://www.hurco.com)

# Hard disk drive

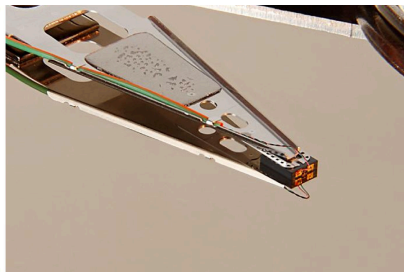
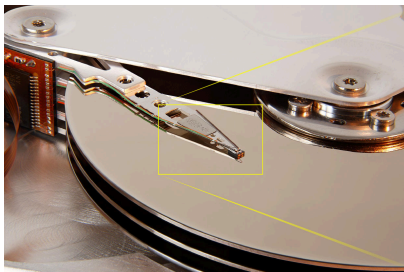
- Hard disk drive
- Air lubrication is used to avoid direct contact between the disk and the head  
*linear velocity 35 m/s*
- Soon ( $\approx 2020-2025$ ) will be replaced by SSD



Hard disk drive (HDD)  
[www.ssd-hdd.info](http://www.ssd-hdd.info)

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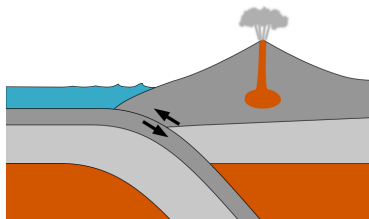
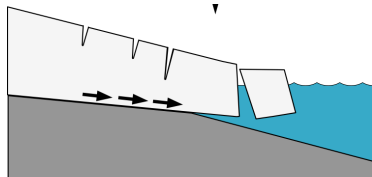


Zoom on the head of Seagate HDD

[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

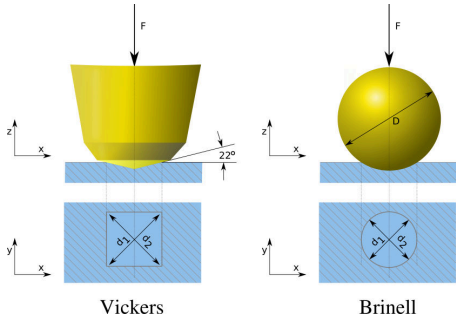


0.1-100 km

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

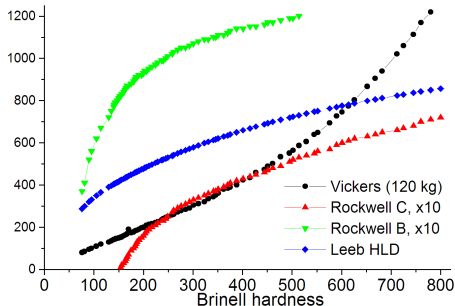


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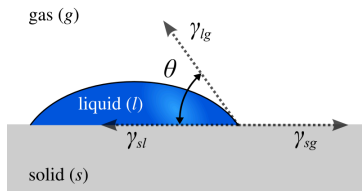


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# Fluid-solid “contact” and adhesion

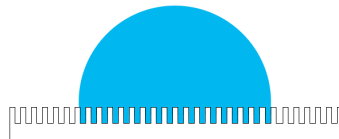
- Wetting (*mouillage*)
- Surface energy and surface tension
- Contact angle  $\theta$ : balance of forces  
 $\gamma_{sg} = \gamma_{lg} + \gamma_{sl} \cos(\theta)$
- Roughness of solids VS surface tension
- Apparent contact angle:  
*Wenzel VS Cassie-Baxter models*
- Self-cleaning surfaces (lotus)
-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



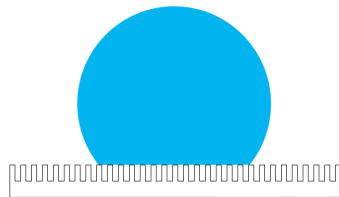
Equilibrium of interface forces  
(adapted from Wikipedia)

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Wenzel model (Wikipedia)

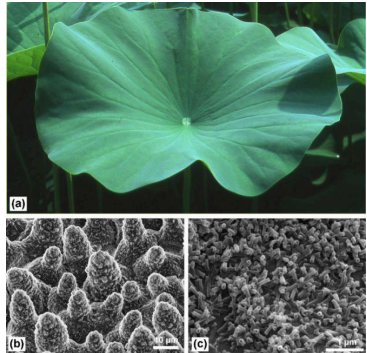


Cassie-Baxter model (Wikipedia)



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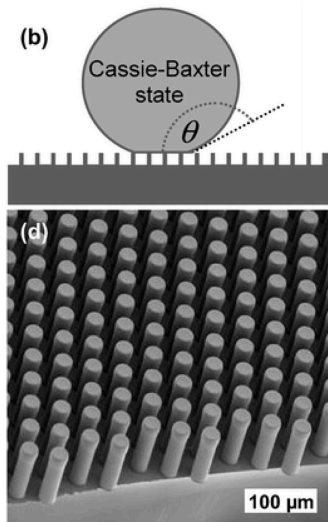
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H.J. Ensikat et al. Superhydrophobicity in perfection: the outstanding properties of the lotus leaf. *Beilstein J Nanotech* (2011)

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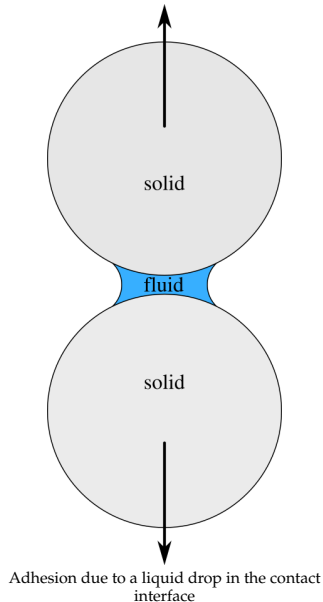
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G. McHale, M.I. Newton, N.J. Shirtcliffe. Immersed superhydrophobic surfaces: Gas exchange, slip and drag reduction properties. *Soft Matter* (2010)

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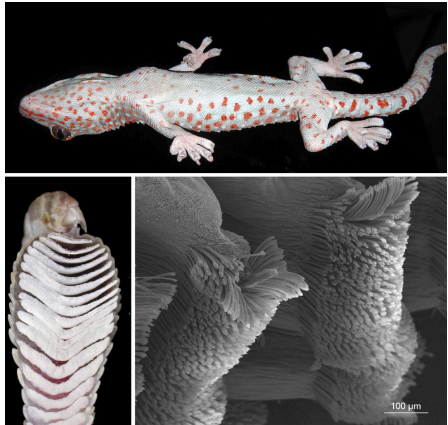
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# Adhesion

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

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

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- Quasi-statics
- Dynamics
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## **In terms of fields**

- Solid mechanics
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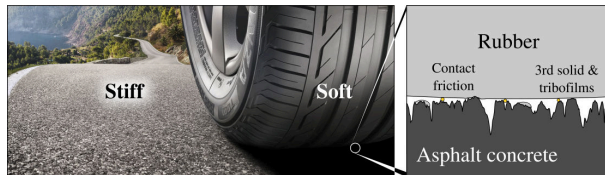
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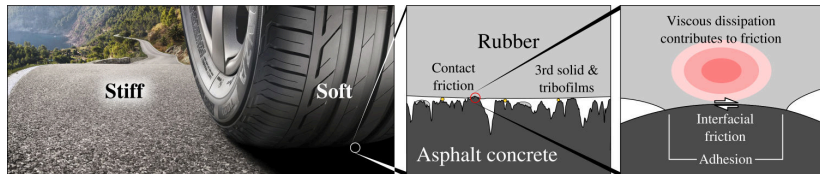
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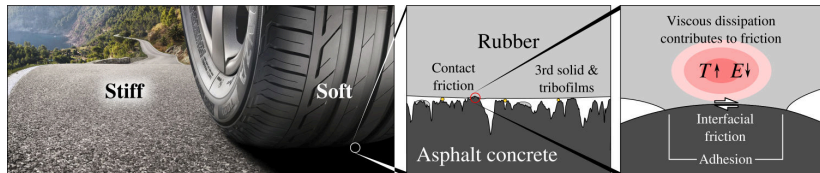
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- Soft/soft

## In terms of interface properties

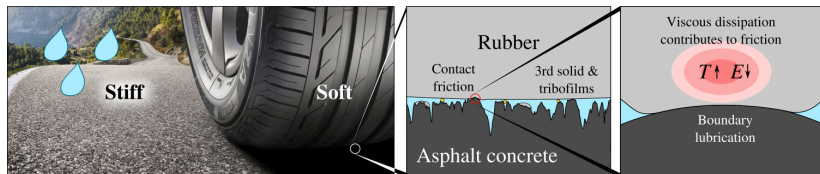
- Frictionless
- Dry friction
- $\pm$ Adhesive
- **Lubricated**

## In terms of inertia

- Quasi-statics
- Dynamics
- Vibration

## In terms of fields

- Solid mechanics
- **Thermomechanics**
- Solid+fluid
- Thermo-electro-mechanics



# Classification

## In terms of material stiffness

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

## In terms of interface properties

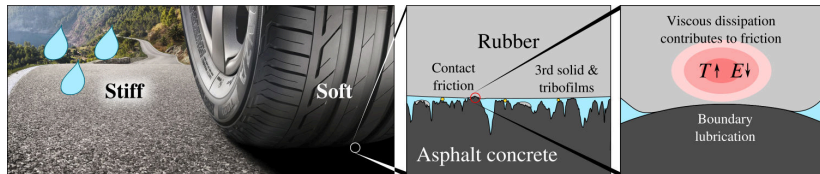
- Frictionless
- Dry friction
- $\pm$ Adhesive
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## In terms of inertia

- **Quasi-statics**
- **Dynamics**
- **Vibration**

## In terms of fields

- Solid mechanics
- **Thermomechanics**
- Solid+fluid
- Thermo-electro-mechanics



# 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!

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