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### Sliding friction

*From microscopic contacts to Amontons' law*

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# Introduction

In the average car[1], only 6% of the fuel energy is converted into inertia (movement). A large fraction of the other 94% of the fuel energy is consumed by sliding and rolling friction in the engine, driveline and at the tires (Figure 1.1). Frictional losses do not just occur in cars, any application with moving components is subject to friction and it has been estimated that a third of the world energy consumption[2] is spent on overcoming frictional forces. Understanding and manipulating friction is therefore of great practical importance.

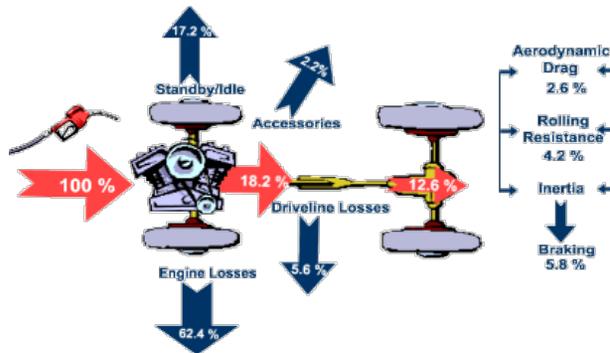


Figure 1.1: Energy losses in an internal combustion engine car (image taken from cealdoctor.com).

The study of friction, wear and lubrication, also known as tribology, has a long history. Arguably, the first recorded tribologist lived in ancient Egypt at around 2400 BC. A tomb drawing from the ancient Egyptian burial ground Saqqara shows this 'tribologist' pouring water in front of a sledge that is used to transport the statue of Ty, the 'director of the hairdressers of the great house' (Figure 1.2). The ancient Egyptians used sledges for transport over

land and while there are more tomb drawings (see for instance Figure 3.1) that show workers pour water in front of sledges, the tribological significance of this is debated. Cotterell and Kamminga[3] for instance write: 'A man pouring water is almost always shown in Egyptian scenes depicting the transport of life-sized statues of rulers or high officials, but significantly this activity is never shown when the load on the sledge is other than a statue. We believe that the pouring of water before sledges is part of a purification ritual.' Davison alternatively writes[4] that: 'If the ground were earthen it would become more slippery, but if it were soft, flat, and sandy, as it is in Egypt, the liquid would filter through the sandy soil with no effect at all.' In chapter 3 we present friction experiments that demonstrate that the addition of some -but not too much- water to sand can reduce the friction between a sledge and the sand with almost 50%. The ancient Egyptians were likely aware of this effect and may have applied it not just to the transport of statues but also to the transport of pyramid building blocks.



Figure 1.2: Transport of the statue of Ty (2400 BC). A worker pours water in front of the sledge to facilitate the sliding (image taken from leonardocentre.co.uk).

Almost 3000 years after the Egyptians and their sledges, Leonardo da Vinci conducted the first systematic friction experiments[5]. Da Vinci used weights and a pulley system to measure the friction between a block and a substrate (Figure 1.3). He measured that friction is independent of contact area; no matter what face of the block was in contact, the friction was the same (Figure 1.3). Da Vinci also concluded that by doubling the load on the block, the friction also doubles; friction is proportional to load. This was rediscovered by Guillaume Amontons in 1699[6] and later confirmed by Charles-Augustin de Coulomb. The proportionality between friction and load, now known as Amontons' first law of friction, is obeyed in most dry

frictional systems.

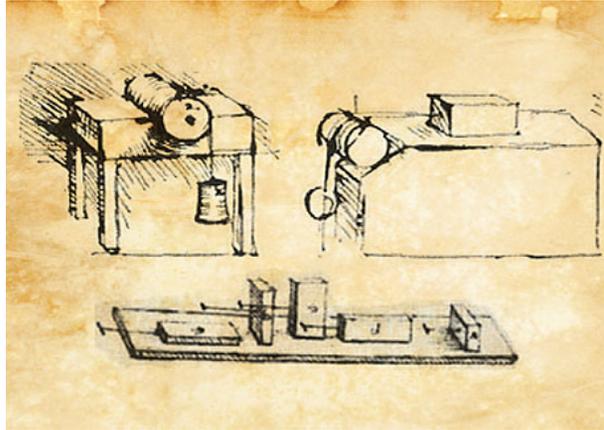


Figure 1.3: Sketches of Leonardo da Vinci's friction experiments. (image taken from newtonsapple.org.uk).

Amontons' law is empirical, its physical origin continues to be subject of investigation by tribologists. In the 1930s, Bowden and Tabor[7] made an important contribution when they highlighted the importance of surface roughness. On small length scales almost all surfaces are rough and resemble a mountain landscape (Figure 1.4). When two such landscapes are brought into contact, only the mountain tops, usually called asperities, will touch. The real area of contact between these asperities can then be much smaller than the apparent area of contact, defined as the area that appears to be in contact when surface roughness is not considered. For a given contact force, the smaller the real contact area the larger the contact pressure. Bowden and Tabor hypothesized that the contact pressure may be high enough to make the contacting asperities flow such that the real contact area increases until the contact pressure drops below the material yield stress. In this description of rough on rough contacts, the real contact area is proportional to the load resting on this real contact area; the contact pressure is constant and equal to the material yield stress. Bowden and Tabor then continued to assume that the force of friction is proportional to the real contact area; what follows is Amontons' law, friction and load are both proportional to the same contact area and therefore to each other.

The work of Bowden and Tabor led to the development of rough surface contact mechanics. The contact mechanics of smooth surfaces had been developed by Heinrich Hertz in the late 19th century[8] and formed the

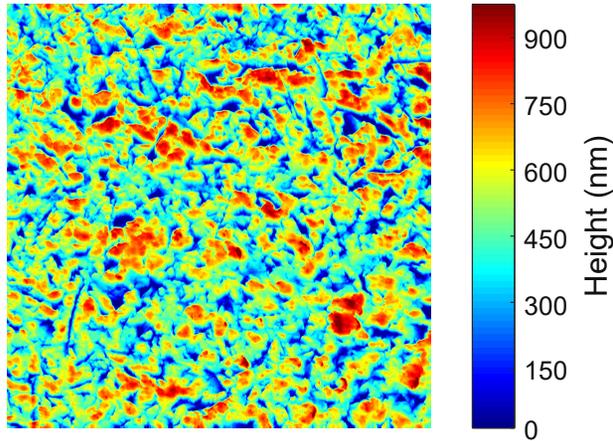


Figure 1.4: The height map of a plastic surface imaged with an atomic force microscope. Image size is  $65\ \mu\text{m} \times 65\ \mu\text{m}$ .

starting point: in 1966 Greenwood and Williamson[9] (GW) approximated a rough surface as a collection of asperities of varying height with spherical tips. They showed that if the spherical tips were smooth and followed the contact mechanics described by Hertz, a linear relation between real contact area and load can be obtained. Hertzian contact mechanics is elastic and does not involve irreversible flow of material like that proposed by Bowden and Tabor. GW theory therefore demonstrates that Amontons' law can be obtained regardless of the precise mechanism by which the asperities on a rough surface are deformed in contact, elastic or plastic. In the decades after Greenwood and Williamson's initial paper, asperity contact theory has been greatly refined[9, 10, 11, 12] and more recently an alternative rough-on-rough contact theory was developed by Persson[13]. Computer simulations of rough contacts have shown that the Persson theory actually works much better than multi-asperity theory because it does not assume that the roughness can be approximated by a discrete collection of asperities[14]. Instead, Persson takes into account that the surface of an 'asperity' can have roughness.

While the theory of rough contacts has advanced significantly since the first description by Bowden and Tabor, experiments that test the developed ideas and try to make the link between the contact mechanics and friction are rare[15, 16]. The main reason for this is that the real contact area is difficult to measure; it is buried between two bulk phases and can have nanometric details. In this thesis we introduce a new technique to measure the real contact area that makes use of molecules that light up when confined in a

contact. In chapter 4 we show how a monolayer of such molecules can be chemically attached to very smooth glass surfaces and used in actual contacts to visualize contact areas. The Hertzian solution to a sphere on flat contact is reproduced by the experiments.

In chapter 5 we add roughness to the problem and measure the contact area between a rough sphere and flat glass (Figure 1.5). By combining the experiments with contact simulations, we are able to show that the roughness is deformed elasto-plastically; multi-asperity theory fails to describe this deformation. Bowden and Tabor hypothesized that both friction and normal force are proportional to the real contact area. In our rough sphere on flat glass experiments, we find that the real contact area rises sublinearly with normal force, but that the friction force is proportional to the real contact area. The consequence is that Amontons' law is broken; we find that this deviation is caused by the specific type of plasticity by which the sphere surface deforms.

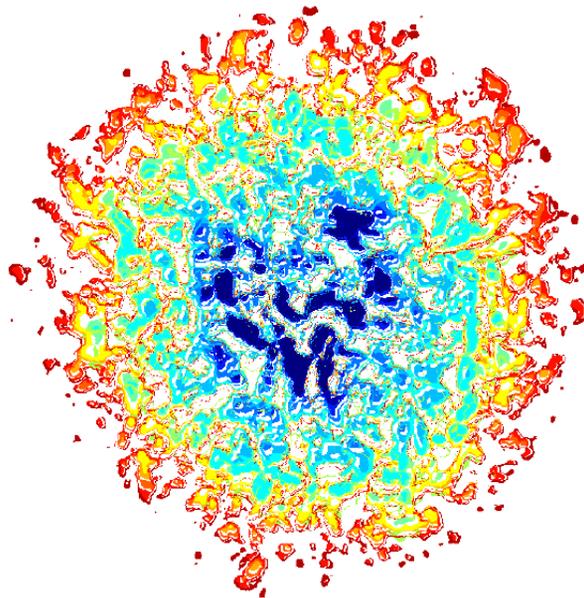


Figure 1.5: Contact between a rough sphere and a flat glass surface covered with a monolayer of rigidochromic molecules. The molecules light up when confined and reveal the real contact area. Different colors indicate the growth of contact area with the addition of normal force. The image is  $70\ \mu\text{m} \times 70\ \mu\text{m}$ .

We continue, in chapter 6, to show how friction evolves in time. The same

rough sphere on flat contact that was used in chapter 5 is now left at rest as we track the gradual changes in contact area. We show that the contact area grows because the sphere is slowly squeezed flatter and flatter by the contact force. The growth in contact area can be related to the increase of friction with contact time. The static friction force, that needs to be overcome to initiate sliding, gradually relaxes towards the dynamic friction force, that is required to continue the sliding. We show that this relaxation is caused by the shear induced softening of the sphere surface.

In the final chapter of this thesis, we combine concepts experimentally tested in the other chapters such as Hertzian contact and proportionality between contact area and friction, and apply them to ice friction. The question of why ice is slippery has attracted the attention of tribologists for more than a century. The consensus is that a liquid water film lubricates the ice surface during sliding. We show however, that diffusion of water molecules over the ice surface is sufficient to lower the friction without the existence of a film of liquid water.

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# Bibliography

- [1] K. Holmberg, P. Andersson, and A. Erdemir. Global energy consumption due to friction in passenger cars. *Tribol. Int.*, 47:221 – 234, 2012.
- [2] A. Szeri. *Tribology: Friction, Lubrication and Wear*. Hemisphere Publication, 1980.
- [3] B. Cotterell and J. Kamminga. *Mechanics of pre-industrial technology*. Cambridge University Press, 1990.
- [4] C. St. C. Davison. Transporting sixty-ton statues in early Assyria and Egypt. *Technol. Cult.*, 2:11–16, 1961.
- [5] I. M. Hutchings. Leonardo da vinci’s studies of friction. *Wear*, 360–361:51 – 66, 2016.
- [6] G. Amontons. *De la résistance causée dans les machines*. Imprimerie royale (Paris), 1699.
- [7] F. P. Bowden and D. Tabor. The area of contact between stationary and between moving surfaces. *P. Roy. Soc. Lond. A Mat.*, 169:391–413, 1939.
- [8] H. Hertz. Über die Berührung fester elastischer Körper. *J. Reine Angew. Math.*, 1882:156–171, 1882.
- [9] J. A. Greenwood and J. B. P. Williamson. Contact of nominally flat surfaces. *P. Roy. Soc. Lond. A Mat.*, 295:300–319, 1966.
- [10] D. J. Whitehouse and J. F. Archard. The properties of random surfaces of significance in their contact. *P. Roy. Soc. Lond. A Mat.*, 316:97–121, 1970.
- [11] A.W. Bush, R.D. Gibson, and T.R. Thomas. The elastic contact of a rough surface. *Wear*, 35:87 – 111, 1975.
- [12] J. A. Greenwood and J. H. Tripp. The Elastic Contact of Rough Spheres. *J. Appl. Mech.*, 34:153–159, 1967.

- [13] B. N. J. Persson. Theory of rubber friction and contact mechanics. *J. Chem. Phys.*, 115(8):3840–3861, 2001.
- [14] G. Carbone and F. Bottiglione. Asperity contact theories: Do they predict linearity between contact area and load? *J. Mech. Phys. Solids*, 56:2555 – 2572, 2008.
- [15] J. H. Dieterich and B. D. Kilgore. Direct observation of frictional contacts: New insights for state-dependent properties. *Pure Appl. Geophys.*, 143:283–302, 1994.
- [16] S. M. Rubinstein, M. Shay, G. Cohen, and J. Fineberg. Crack-like processes governing the onset of frictional slip. *Int. J. Fracture*, 140:201–212, 2006.