MICROSCOPIC DESCRIPTION
OF FRICTION

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ABSTRACT: In this seminar I will first show some of the earlier concepts of friction. I will present the basic pedagogical mistakes and problems when explaining friction phenomena. I will describe a microscopic view of friction and the effect of the different types of motion on the microscopic bonds between the surface and the moving object.
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INTRODUCTION
Friction is a process we encounter on a daily basis – when we walk, drive a car, even when we shake hands. We learn about the physical properties of friction early in high school. Despite that we aren’t aware of the physical depth and complexity of the phenomena. A detailed study of friction (the branch of physics researching it is called tribology [1]) reveals that the most common description is far from precise.

I will show the classical approach to teaching friction, and some of the problems we encounter when we try to apply it on a smaller scale.

HISTORY
The first descriptions of friction go back to 15th century. It was Leonardo da Vinci in his Atlantic codex notes. [2] He discovered several properties of the force of friction:

- The force of friction is proportional to roughness of the surface.
- The force of friction is doubled if the load is doubled.
- If the surface inclination will allow the body to shift one quarter of its weight toward motion, the body will try to move downwards.
- On a smooth inclined surface every body exerts friction proportional to one quarter of its weight.
- Friction that is caused by a body stays the same, even if the body is placed on a different plane.

Da Vinci was describing friction as the drag of friction. [2]

The first to mathematically describe the Friction process and put it into equations was Charles Augustin de Coulomb in 1764. His model of friction was presented as interlocking and deformation of rough surfaces in contact. [3] The wooden surface on the picture (Fig. 1) is interlocked with its fibers. If the block is moved, the interlocked fibers bend and deform, thus obstructing movement. When the block is moving the fibers separate and are sliding on top of each other.

![Figure 1: Coulombs representation of friction – several types of interlocking “fibers” of the two surfaces.][3]
He started a series of experiments in which measured the force of friction with a torque scale. He came to several conclusions: [2]

- There are two different types of friction: static and dynamic
- In both cases the force depends on the material and its coating.
- The force of static friction depends on the time of contact.
- The force of dynamic friction is independent on speed.
- Dynamic friction is at least in some part the result of molecular attraction.

From his observation he derived this equation: which was named after him (Coulomb's friction).

\[ F_{fr} = k_{fr}N, \]  

where \( k_{fr} \) is the coefficient of friction and \( N \) is the normal force. This equation is also called Coulomb's friction equation. Coulomb noted several different types of friction such as: kinetic, static and rolling friction. He first suggested that friction is caused by molecular attraction, but later dismissed the idea because he found out that the friction force is not dependant on the contact surface. [4]

He claimed that the magnitude of friction is proportional to the normal force, and independent of the contact surface and relative speed of the objects. We now know that the force of friction and coefficient of friction are in general dependant of the relative speed at which the objects are moving. [5] Friction is strongly dependant on the material we are observing. Some materials such as plasticine and putty, which are adhesive, present friction even without a load or with negative load. One of such examples is the rolling of a rigid cylinder on the underside of an inclined smooth surfaced sheath of rubber (Fig. 2).[6] The rubber sheet can easily be charged. The cylinder is held to the surface by electrostatic adhesion. At the joint the weight of the cylinder and the electrostatic force are in equilibrium.

![Figure 2: Cylinder rolling on the underside of an inclined rubber sheath.](image)

Another historical model was presented by Bernard Forest de Bélidor in 1737. Bélidor was a professor of artillery, and was the first to use integral calculus for solving technical problems. [3] He suggested a model of spherical asperities. His model predicted that the microscopic surface image consists of geometrical - spherical elements. When the surfaces are moving,
relative to each other, the spherical asperities are interlocking, thus creating friction (figure 3). All of his equations were derived from geometrical properties of spheres. This model has nowadays only a historical value.

![Figure 3: A graphical representation of Bélidor’s model of spherical asperities. [3]](image)

**WHAT IS FRICTION**

The most basic description of physic is given in high school – a block sliding on a rough surface (Fig. 1). The force of friction, in this simple case, is described by Coulomb’s friction.

Along with the image of a sliding block comes the statement that friction is a force that always resists movement. [7] This is the most basic and crude explanation of friction. It will be shown later that the statement: "friction is the force that opposes movement," is not always true. Friction can play a motive role - it is not even so uncommon.

![Figure 4: The most common representation of the force of friction – the force is opposing movement.](image)
Imagine two blocks one atop another (Fig. 5), placed on ice. If we apply a horizontal external force $F$ to the upper block, the whole system will start to move. For this specific case we have two places where friction occurs: between the blocks themselves and between the lower block and the ice. It is the friction (static friction) between the blocks that is causing the lower block to move. This force ($F_{fr(sta)2}$) plays the “motive role”, and the friction between the lower block and the ice ($F_{fr}$) is the force that opposes movement – “resistive role.”

For the upper block $F$ is the force causing movement and is equilibrated by $F_{fr(sta)1}$. For the lower block the force that causes motion is $F_{fr(sta)1}$, and is equilibrated by $F_{fr(sta)2}$ and is then equilibrated by $F_{fr}$.

A better definition of friction would perhaps be: “It is the force that equilibrates the force causing movement.”

Figure 5: Two wooden blocks sliding on an icy surface.

**COEFFICIENT OF FRICTION**

Coefficient of friction is a numerical representation of the interaction of two surfaces. It is specific for each case (fig. 6). In most cases for the coefficient of friction only measured values are known, as the results cannot be theoretically predicted.

<table>
<thead>
<tr>
<th>Contact surfaces</th>
<th>Coefficient of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>steel – steel</td>
<td>0,16</td>
</tr>
<tr>
<td>steel – steel (lubricated)</td>
<td>0,05</td>
</tr>
<tr>
<td>wood – wood</td>
<td>0,3</td>
</tr>
<tr>
<td>Surface Combination</td>
<td>Coefficient of Friction</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>wood – wood (lubricated)</td>
<td>0.1</td>
</tr>
<tr>
<td>steel- ice</td>
<td>0.02</td>
</tr>
<tr>
<td>ice – ice</td>
<td>0.028</td>
</tr>
<tr>
<td>rubber tire – asphalt (wet)</td>
<td>0.1</td>
</tr>
<tr>
<td>rubber tire – asphalt (dry)</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**Figure 6:** Some examples of the coefficient of friction. [7] [8] [9]

Coefficient of friction is not a fixed value for two given surfaces. It is strongly dependant of the relative speed between the object and surface and even temperature. Figure 7 shows velocity dependence of coefficient of friction. The friction coefficient decreases, as the speed increases. After reaching the low point it starts to increase with increasing speed. Such dependence is common for materials like steel, copper and lead. For other materials, such as Teflon, the coefficient of friction only increases as the speed increases. For most materials though, only complicated empirical graphs are known. [7]

**Figure 7:** Dependency of the coefficient of friction on speed for a steel block sliding on a steel surface. [5]

**CONTACT AREA**
One of the problems at smaller scales is the contact area between two surfaces. The apparent contact surface differs greatly from the real contact surface. Microscopic view of a surface reveals that it consists of many irregular asperities. Figure 8 shows an example of a real surface.
If the surfaces are moving relative to each other the contact surface is constantly changing. In light of this knowledge several models of contact surfaces were developed.

The block sliding on any surface may be supported by as few as three asperities. The friction force is divided between these asperities. The size of these asperities can go down to the size of a small group of molecules. When the surfaces are moving, relative to each other, the asperities are constantly deforming (even breaking – abrasion). Figure 9 shows a spring model of asperities. As the surfaces slide relative to each other the atomic groups (asperities) interlock, and deform elastically (they can also break). Work done by the pulling force is transferred to these bonds, and then further to heat, deformation and even sound waves. The sound we hear when two bodies are rubbing at each other is nothing else but the vibrating asperities transmitting energy. The molecular bonds between surfaces are constantly forming and breaking.

**Figure 8**: Exaggerated rugged contact surface of two materials. [3]

**Figure 9**: Graphical representation of the interlocking asperities (spring model).
FRICTION ON A MICROSCOPIC SCALE [10]

One way to understand friction is to understand its microscopic picture. On small scales effects such as cold welding\(^1\), material mixing and other, become relevant. One way to explain these processes is by proposing a model with microscopic bonds. Figure 10 is a graphical representation of such a model. It consists of two rigid objects, sliding relative to each other. Both objects are connected by bonds that spontaneously break and reform upon contact. The dynamic of this bonds determines the force of friction. These bonds represent the van der Waals (intermolecular) force.

At this point I would like to stress that will be talking about friction process without the presence of any lubricant. If lubricant of any type is applied to either surface, the whole picture changes due to the effects of viscous friction.

![Figure 10: Schematic of the “bond” model](image)

Bonds are represented by a finite number (N) of elastic springs with a force constant \( \kappa \), and rest length \( l(0) \). The upper object with mass \( M \), and center-of-mass coordinate \( X \) is pulled with a linear spring of spring constant \( K \). The spring is pulled with a constant velocity \( V \). Its motion can be described by the following equation:

\[
M\ddot{X} + \mu\dot{X} + F_b + K(X - Vt) = 0
\]  

(2)

where

\[
F_b = \sum_{i=1}^{N} q_i f_i^{(x)}
\]

(3)

is the force due to interaction of bonds and the driven plate, and \( \mu \) is the damping coefficient. The parameter \( q_i \) characterizes the state of the individual bond: \( q_i = 1 \) corresponds to an intact bond that connects the two plates and \( q_i = 0 \) represents a bond connected to only one plate. The interaction between the intact bond \( i \) and the plate is given by the elastic force \( f_i = \kappa[l_i - l(0)] \), whose projection in the direction of motion equals \( f_i^{(x)} = f_i \frac{x_i}{l_i} \). Here \( l_i \) and \( x_i \)

\(^1\) Cold welding is a solid-state welding process in which joining takes place without fusion at the interface of the two parts to be welded. Unlike in the fusion-welding processes, no liquid or molten phase is present in the joint. [8]
are the length of the bond and its expansion in the X direction: \( l_i = \sqrt{x_i^2 + h^2} \), and \( h \) is the distance between the plates.

The friction process is governed by two processes: bond formation, and bond rupture. **Bond formation:** creation of a junction that tends to inhibit sliding. **Bond rupture:** detachment of a spring from one of the plates, a process that helps sliding.

For as long as the bond is intact it is stretched in the lateral direction with the velocity that equals the velocity of the top plate. A ruptured bond shrinks and relaxes to its equilibrium state. We can calculate the velocity of a given spring if we know the speed of the upper plate \((v)\), and the relaxation constant that describes the approach of the string to its equilibrium length \((\lambda)\). The dynamics of stretching and shrinking bonds can be described as:

\[
\dot{x}_i = q_i \dot{X} - \lambda (1 - q_i) x_i, \tag{4}
\]

This equation has two cases – the bond is intact \((q_i = 1)\), or the bond is ruptured and is shrinking \((q_i = 0)\). In the first case the velocity of the bond is equal to the speed of the upper plate: \(\dot{x}_i = q_i \dot{X}\). Otherwise the bond is approaching its equilibrium state as \(\dot{x}_i = \lambda x_i\).

To describe the governing dynamics of bond formation / rupture let us introduce a time step \(\Delta t\) in which we look at a bond. The state of the bond is described by the parameter \(q_i\). The equation can be written as:

\[
q_i(t + \Delta t) = q_i(t) - q_i(t)\theta(\xi_i - \Delta t k_{off}) + [1 - q_i(t)]\theta(\xi_i - \Delta t k_{on}), \tag{5}
\]

where \(\xi_i\) is a random variable chosen from the interval \((0,1)\), \(\theta(z)\) is a Heaviside step function that accounts for a stochastic formation/rupture of a bond that occurs for \(\xi_i < \Delta t k_{off} (on)\). The rates of these processes are given by \(k_{off}\) and \(k_{on}\) correspondingly.

Equation 5 tells us about the time dependence of the state parameter \((q_i)\). For a successful description of the state of the bond at \(t + \Delta t\), we must first know the state of the bond before the time step \((q_i(t))\). If the bond is intact we use the first part of the equation \((-q_i(t)\theta(\xi_i - \Delta t k_{off}))\), otherwise we use the second \([(1 - q_i(t))\theta(\xi_i - \Delta t k_{on})\]). Basically what we do is: if the bond is intact we wait and look at it at every time interval, until it breaks. If it is already ruptured we wait until it forms again.

The rupturing of a bond can be considered as a thermally assisted escape from a bound state, over an activation barrier, which is dependent on the spring length and diminishes as the elastic force \((f_i)\) increases. We differ strong bonds from weak bonds. In strong bonds the bond energy is much larger than \(k_b T\), and in weak bonds the bond energy is only slightly larger than \(k_b T\). \(T\) is the temperature of the bond, and \(k_b\) is the Boltzmann constant\(^2\).

\(^2\)\(k_b = 1.38 \times 10^{-23} \frac{L}{K}\)
For the presented simulation the next parameter values were taken into account: $N=300$, $M \alpha N$, $\kappa=10$, $K=10^{-2}\kappa N$, $l^2=h=0.25$, $\lambda=0.4\eta/M$ and $k_{on}=0.1$.

This model exhibits two different types of motion: two sliding (SI) types and a slick-slip (SS) motion between them. They are dependent on the velocity of the moving surface. Figure 11 shows velocity dependence of friction for all three cases of motion. Thick line represents the net kinetic friction which generally increases with velocity. The dashed line represents the rupture component of energy dissipation, which decreases with increasing velocity. With increasing velocity bond formation decreases rapidly, and eventually becomes impossible due to low contact time. The thin line represents the viscous components of energy dissipation $(F = \mu V)$, which determinates the force of friction at higher velocities.

**Figure 11:** Velocity dependence of time averaged frictional forces. Full line represents the net kinetic friction, dashed line represents the rupture component of energy dissipation and the thin line represents the viscous component of energy dissipation. SI and SS denote the sliding regime that occurs at a given velocity (SI – sliding and SS - slick/slip)

*Low velocity sliding* is the state in which bond rupture is determined by thermal (spontaneous) bond rupture rather than by the effects of stress and compression. This state actually corresponds to the stick/slip motion on the microscopic scale. Two types of energy dissipation are included in this motion: rupture and relaxation of the bonds, and viscous dissipation.

*Stick/slip motion* describes the motion of the plate has low velocity. At lower velocities this type of motion is quite irregular, but as the velocity increases, the motion becomes regular. At this regime we observe some kind of a stacking motion: the body starts to move, but then abruptly stops, and starts moving again etc. The transition to stick/slip motion is accompanied by a decrease of the rupture contribution to energy dissipation. This effect is compensated by a growing viscous component of dissipation. As a result the kinetic friction depends only slightly on the velocity in this type of motion.

*High velocity sliding* is the last type of motion we differentiate. In this region bond formation becomes impossible, due to short contact time, and friction is completely determined by viscous dissipation. Low and high velocity sliding differ by the rate of energy dissipation.
CONCLUSION
We have seen that it is the microscopic bonds between the object and the surface that
determines friction as we know it. We have seen that the complexity of the phenomena
increases greatly as we descend on a microscopic scale. Bond formation and rupture govern
the process of friction, and even determine the way an object is moving. Energy dissipation
causes the rise of temperature and it is even responsible for the sound we hear when objects
are rubbing at each other.

Thus friction is a process we essentially need, on one side, and a process we desperately want
to avoid on the other. Either way friction is an important basic process we need to understand
if we want to truly understand the nature around us.

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