

INTRODUCTION TO TRIBOLOGY

1. The Term Tribology

- **Etymology:** Derived from the Greek word 'tribos', which means 'rubbing'.
- **Core Definition:** Includes all sciences and technologies of interacting surfaces in relative motion. The primary focus areas are:
 - **Friction**
 - **Wear**
 - **Lubrication**
- **The Jost Report (1966):** The term was first used in 1966 in the Jost Report, a study conducted in the United Kingdom investigating annual financial losses due to friction and wear.

- **Multidisciplinary Nature:** Tribology integrates multiple academic disciplines including:
 - **Mechanical Engineering:** Focusing on machine elements such as journal and roller bearings, and gears.
 - **Materials Science:** Researching wear resistance.
 - **Surface Technology:** Surface topography analysis and surface coatings.
 - **Chemistry:** Chemistry of lubricants and performance additives.
- **Younger Tribological Disciplines:** Recent research branches include:
 - **Bio-tribology:** Wear, friction, and lubrication of total joint replacements.
 - **Nanotribology:** Studying friction and wear on micro- and nanoscales.
- **Professional Bodies & Societies:** Numerous mechanical engineering institutions incorporate dedicated tribology divisions. For instance, Germany hosts the Gesellschaft für Tribologie (GfT) with 7 regional subcommittees. The international meetings at Technische Akademie Esslingen (TAE), organized by W. Bartz, are among the most heavily attended worldwide.

2. Importance of Tribology

- **Energy Waste Reduction:** Governments in industrialized nations have established strategies to minimize energy waste using tribological principles.
- **Economic Losses & Savings Potential:** Key studies demonstrate significant potential savings:
 - **United Kingdom (1966):** The Jost Report highlighted massive economic waste due to misrecognition of tribology.
 - **United States (1977):** A government report estimated potential savings of US\$ 16.25 billion through proper tribological applications.
 - **Germany (1979–1983):** W. Bartz conducted studies assessing savings specific to lubricated contacts.
 - **P. Jost Assessment (1990):** Potential savings were evaluated at 1.3% to 1.6% of Gross Domestic Product (GDP).

Table 1: Potential Savings (in US\$ Billion) by Correct Use of Tribological Knowledge (1.6% of GDP 2008)

Country / Region	Potential Savings (US\$ Billion)
European Union	303
United States	186
China	68
Japan	63
Germany	50
France	48
United Kingdom	36

- **Categories of Savings (W. Bartz Study):** Categorized into three distinct savings levels:
 - **Primary Savings:** Direct reductions in mechanical friction.
 - **Secondary Savings:** Lesser exchange of machine parts due to wear reduction.
 - **Tertiary Savings:** Use of new materials raising the energy content of materials in production.
- **Life Cycle Assessment (LCA):** Modern tribology aims at environmental and economic performance, extending machine service life alongside friction reduction.

3. History of Tribology

- **Primary Driving Force:** Facilitating daily human activities by reducing friction in weapons, tools, crafts, and construction.

A. Ancient Times & Early Civilizations

- **Mesolithic Period (11,000 – 5,500 years ago):** Identification of earliest man-made bearings: stone door sockets, bearings for wheeled vehicles, and bearings for stone potter's wheels.



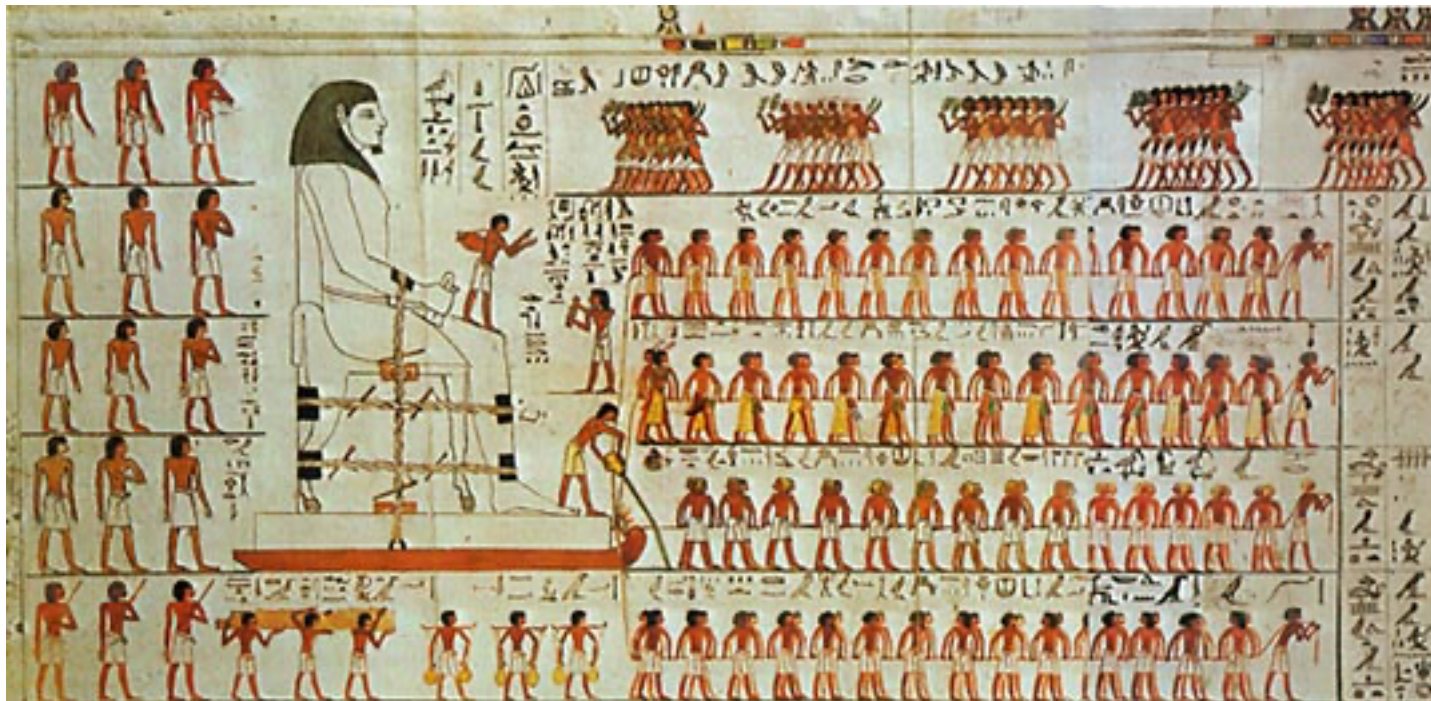
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- **Early Lubricants (5,000 years ago):** Bitumen used to lubricate potter's wheels. An Egyptian wall painting from the tomb of Tehuty-Hetep at El Bersheh (1800 BC) depicts a man pouring lubricant (likely water) in front of a sledge transporting a colossal statue.



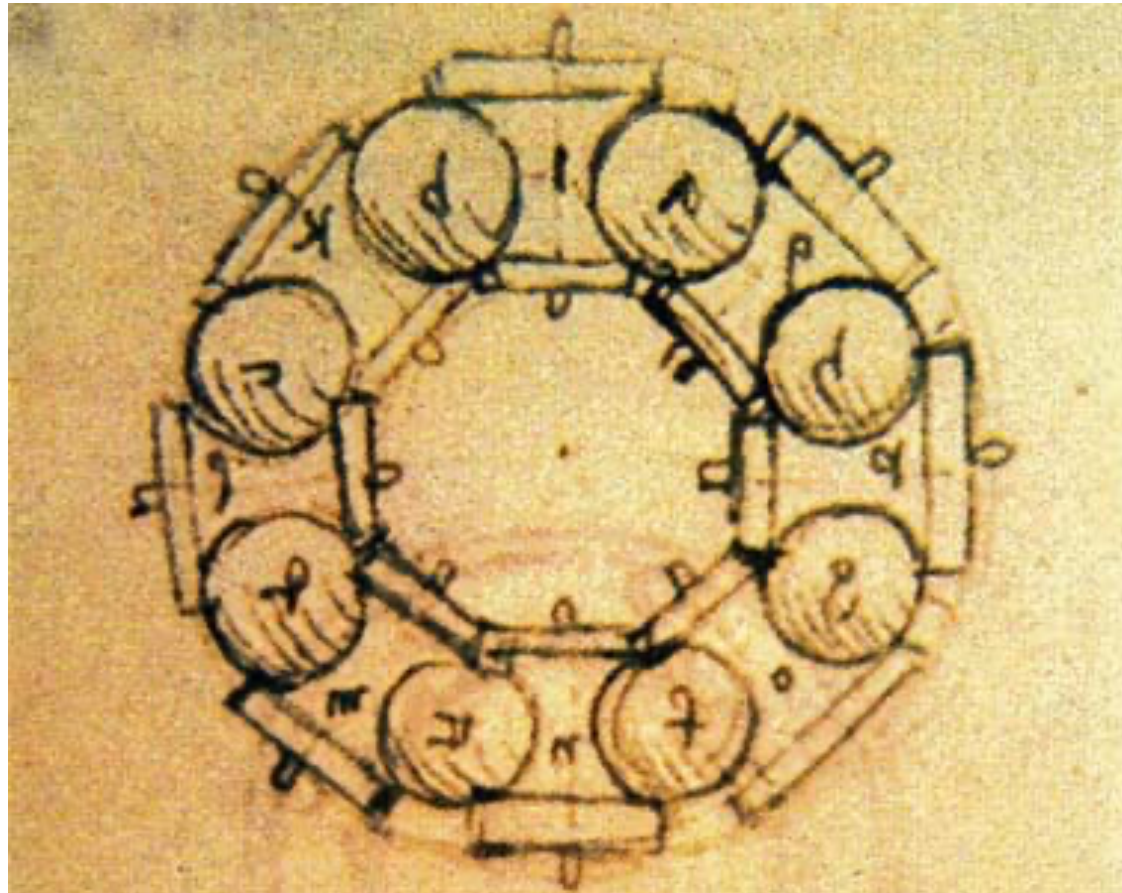
- **The “First Tribologist”:** Dowson noted an Egyptian tribologist 600 years older than the El Bersheh example, who applied lubricant similarly for heavy statue transport.
- **Early Roller Bearings:** Wooden rollers beneath sledges recorded during the first millennium BC.
- **The Wheel (c. 3500 BC):** Transition from sledges to wheeled vehicles represented a critical tribological innovation. Wheel remains from the 3rd millennium BC found across Europe and Asia.

- **Greek & Roman Period (900 BC – AD 400):**
 - Production of bitumen and petroleum oils.
 - Iron bearings used in olive mills (500 BC).
 - Bronze rolling bearings in China (200 BC).
 - Bronze journal bearings for wheels and axles (AD 300).
- **Middle Ages Decline:** Western technical knowledge lost; bronze/iron bearings reverted to wood and stone. Technical progress continued in the Islamic world (9th–12th centuries) and the Byzantine empire.

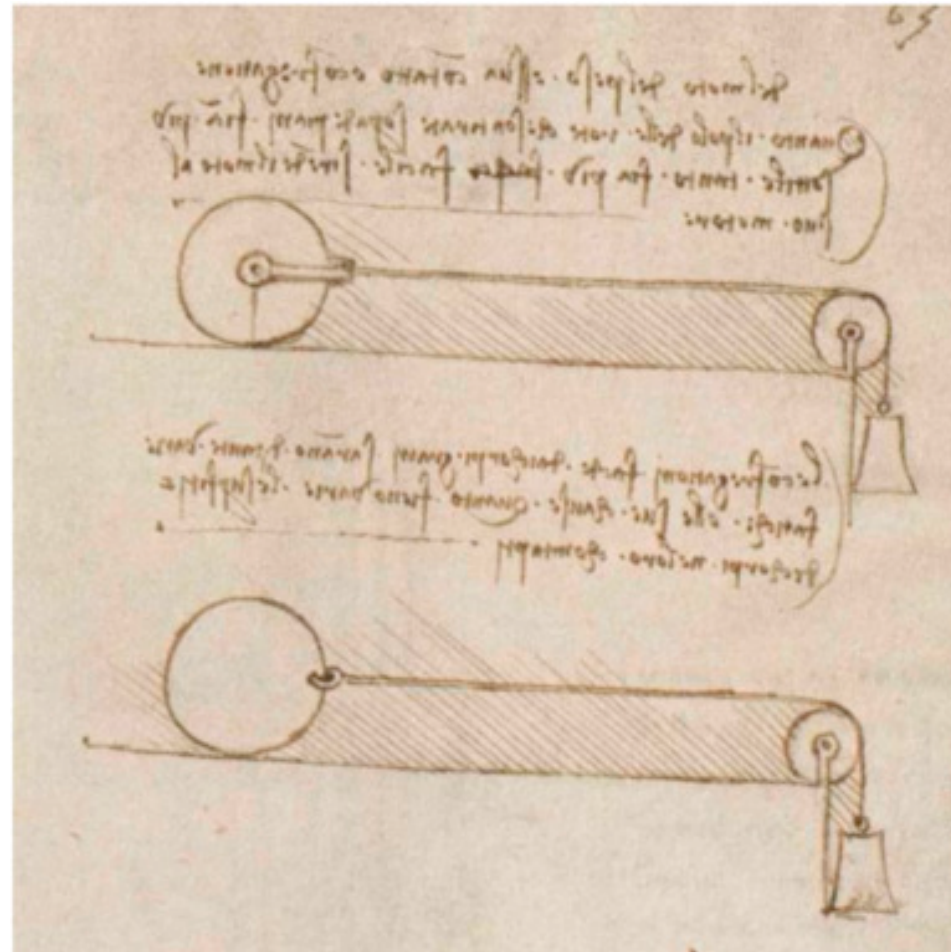
B. The Renaissance (1450 – 1600 AD)

- **Leonardo da Vinci (1452–1519):** First scientific investigator of tribology. His manuscripts (Codex Atlanticus, Codex Madrid I & II) comprised over 5,000 pages:
 - **Investigated friction forces on horizontal and inclined planes.**
 - **Analyzed the influence of apparent contact area on friction.**
 - **Described low-friction bearing alloys and early forms of ball-bearing cages / pivot bearings.**
 - **Leonardo's Laws of Friction:** Friction force is directly proportional to applied load and independent of apparent contact area.

[Leonardo da Vinci's studies of friction (2016). Wear, volumes 360–361, p.51-66]



A ball bearing invented by Leonardo da Vinci.



Leonardo da Vinci's studies of friction.

Leonardo da Vinci's Tribology Concept: Rolling Friction vs. Axle Friction.

Overview:

This page from Leonardo da Vinci's notebooks illustrates early experiments and observations in tribology—specifically comparing rolling resistance / axle friction (top) with pure rolling motion (bottom).

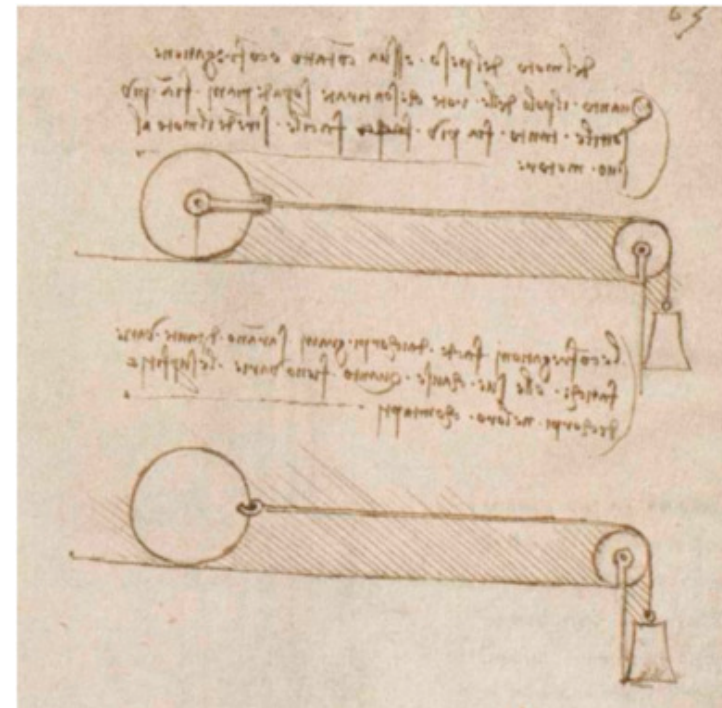
Key Descriptions & Interpretations:

Top Figure: Wheel with Fixed Axle (Sliding/Axle Friction)

Mechanism: A wheel mounted on a central axle, pulled horizontally by a cord connected to a suspended weight via a pulley.

Tribological Concept: When the wheel turns around a fixed central axle, it introduces journal/axle friction (sliding contact between the axle and its bearing).

Observation: The resistance to motion is higher because of the friction generated at the axle interface.



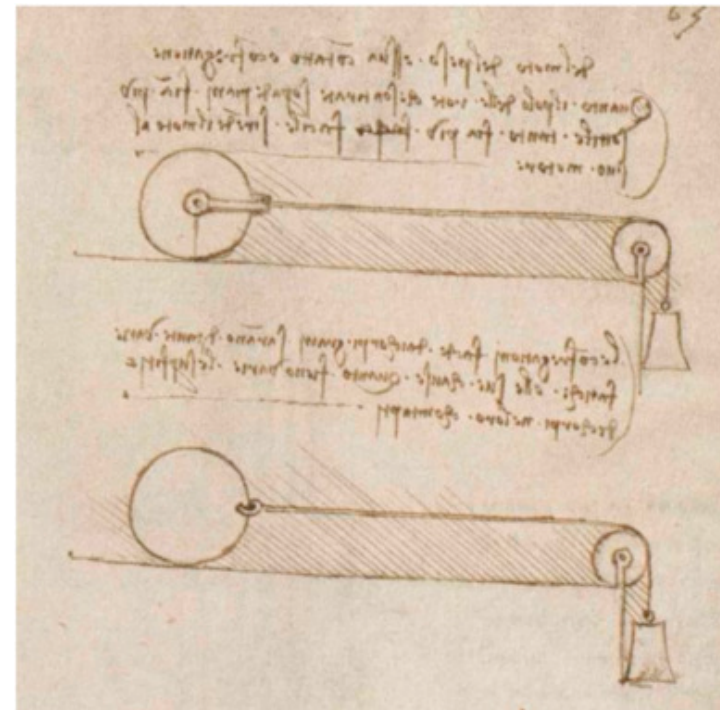
Key Descriptions & Interpretations:

Bottom Figure: Wheel Pulled directly from the Perimeter/Rim (Pure Rolling)

Mechanism: The pulling force (cord connected to the weight) is attached directly to the edge/rim of the cylinder or roller rather than an axle.

Tribological Concept: This setup isolates pure rolling friction by eliminating axle bearing friction.

Observation: The required force to move the cylinder is significantly lower because rolling resistance is much smaller than sliding/axle friction.

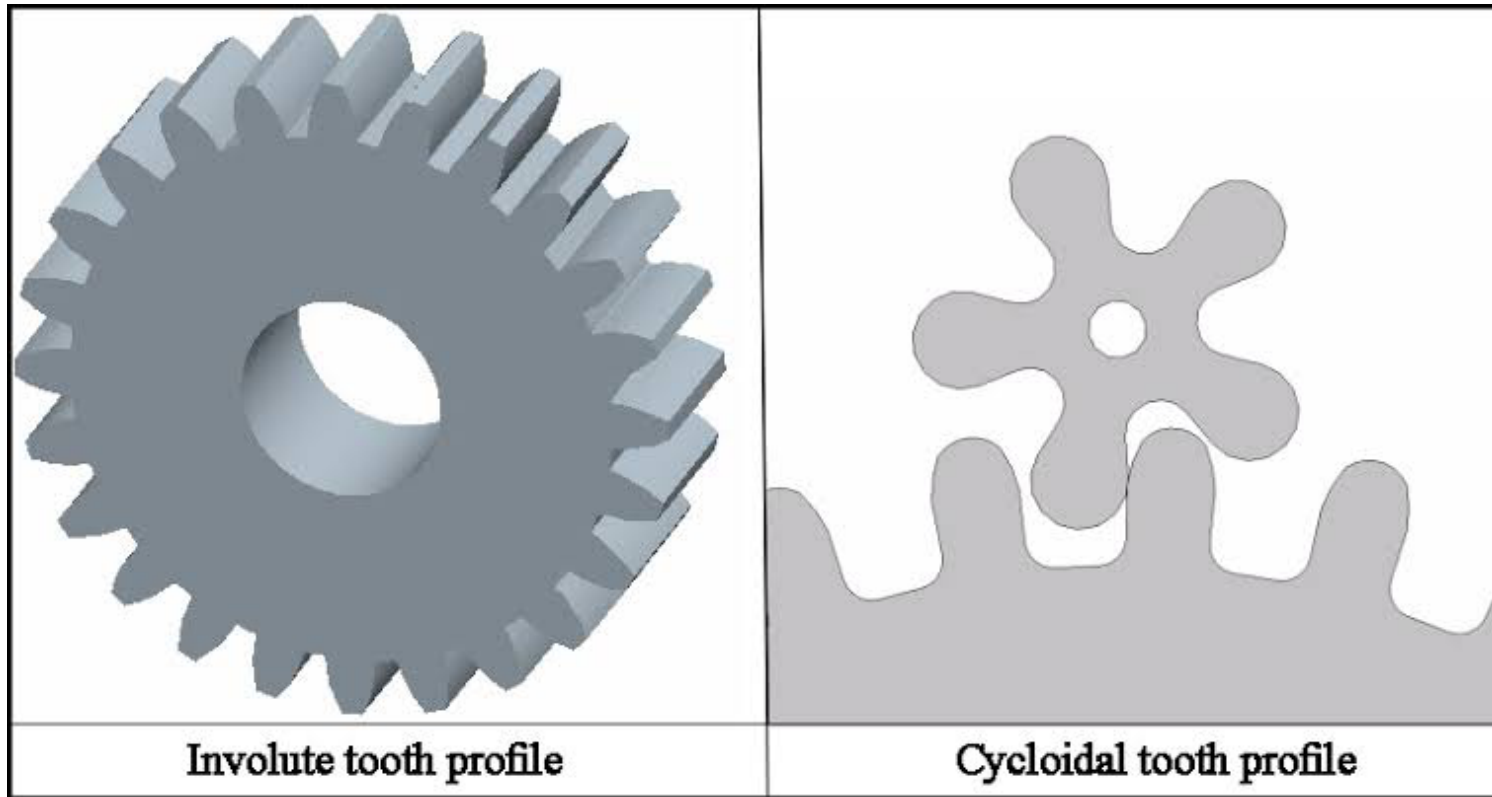


Core Tribological Insights:

Friction Proportionality: Demonstrates how applied load (hanging weight) overcomes frictional force.

Axle Friction vs. Rolling Motion: Highlights the advantage of rolling contact over journal/sliding contact, laying early foundations for modern bearing designs and rotational tribology.

- **Nikolaus von Kues (1401–1464):** Described the cycloids of gears.



A cycloid gear (also known as a cycloidal gear) is a type of gear whose tooth profile (the curved shape of its teeth) is formed using a cycloid curve, rather than the involute profile commonly used in modern gears today.

How is a Cycloid Tooth Shape Formed?

A cycloid curve is generated by the path of a point on a circle as it rolls along a straight line or another circle without slipping (rolling without slipping):

Epicycloid: Forms the upper part / tip of the tooth (tooth tip / addendum).

Hypocycloid: Forms the lower part / root of the tooth (tooth root / dedendum).

Key Features & Advantages

Very Low Friction & Wear: The contact surfaces between two cycloid teeth move in pure rolling motion (pure rolling). This significantly reduces friction and wear.

Better Load Distribution: The design allows a larger surface area of the teeth to make contact, thereby reducing contact stress.

Low Backlash: Ideal for applications that require high precision movement (precision motion).

Disadvantages

Highly Sensitive to Center Distance: Cycloid gears require an extremely precise center distance between the two shafts. Even a slight deviation in shaft alignment will cause uneven motion and potential damage.

Difficult to Manufacture: Requires complex cutting processes and high design precision compared to involute gears.

Where are Cycloid Gears Used?

Mechanical Watches & Wall Clocks: Due to their exceptionally low friction, these gears minimize energy consumption from the mainspring.

Cycloidal Speed Reducers (Cyclo Drives): Widely used in industrial robotics, robotic arms, and CNC machinery that demand high precision, near-zero backlash, and resistance to heavy shock loads.

- **Georg Agricola (1494–1555):** Published 'De re metallica' (Book VI) on mining technology, indicating little progress since Roman times (e.g., wheelbarrow bearings remained simple holes in wooden planks).



Wheelbarrow bearing.

C. 17th & 18th Centuries (Development of Physical Laws)

- **Robert Hooke (1635–1703):** Investigated rolling friction, wheel hardness, surface deformation, and adhesion between wheel and ground. Introduced bearing designs, seals, materials, and lubrication concepts.

Rolling friction is the resistive force that opposes the motion when a spherical or cylindrical object (such as a wheel, ball, or roller) rolls over a surface.

Magnitude: Rolling friction is significantly lower than sliding friction.

Contact Mechanism: In rolling, contact points continually lift off and land on the surface rather than continuously rubbing/scraping across it.

Key Factors Affecting Rolling Friction

- **Material Hardness:** Harder materials (e.g., steel wheels on steel rails) suffer less deformation and yield lower rolling friction than softer materials (e.g., rubber tires on asphalt).
- **Radius/Diameter:** Larger wheels experience lower rolling resistance compared to smaller wheels.
- **Surface Roughness:** Rougher or softer surfaces increase deformation and resistance.

Practical Applications

- **Bearings:** Ball bearings and roller bearings replace sliding contact with rolling contact to minimize energy loss in machinery.
- **Vehicles:** Proper tire inflation reduces deformation, lowering rolling friction to improve fuel efficiency.

- **Guillaume Amontons (1699):** Presented experimental friction results and defined Amontons' Laws:

- **First Law: Friction force is directly proportional to applied load.**

Increasing the weight or force pressing two surfaces together increases the frictional force proportionally ($F \propto N$).

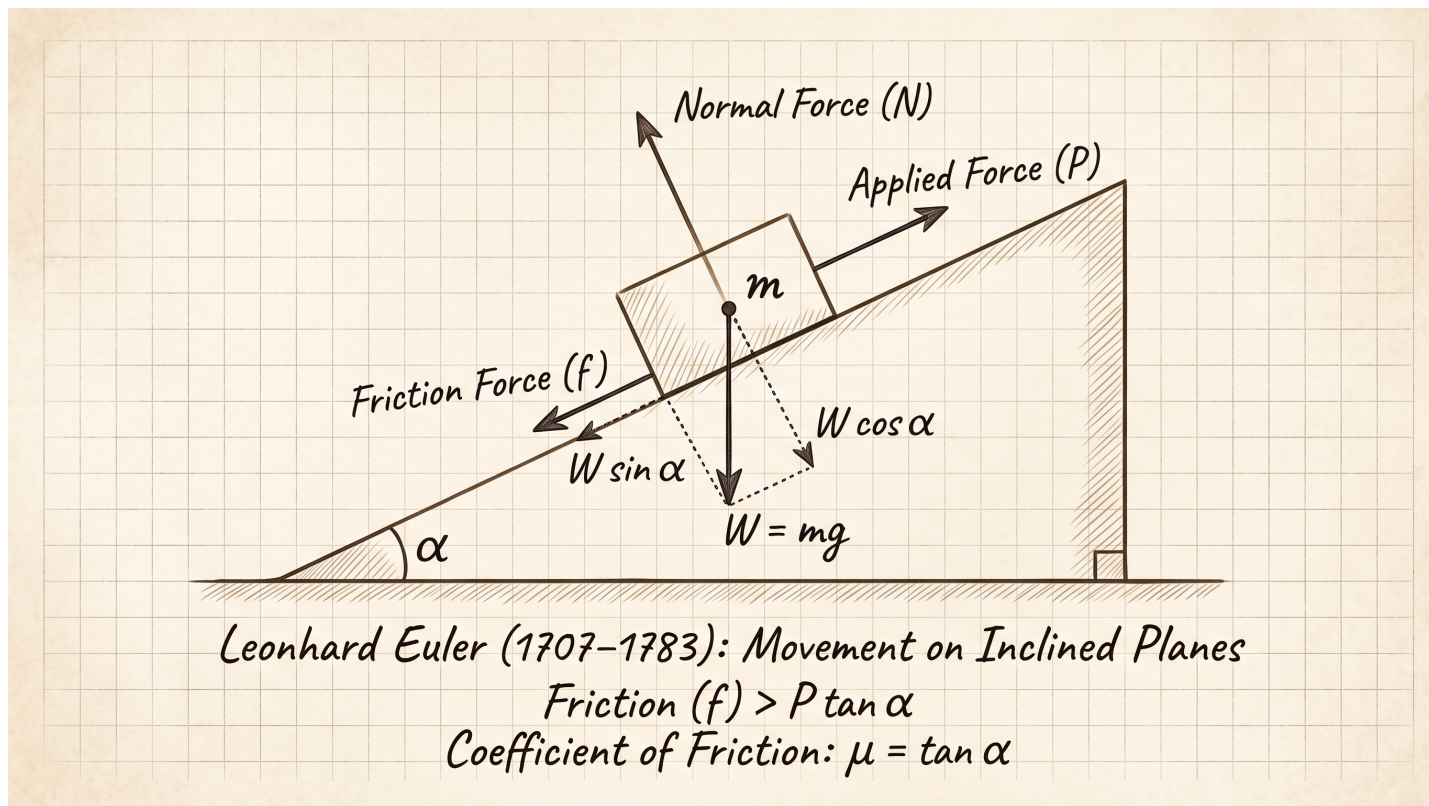
Formula: $F = \mu N$, where F is frictional force, μ is the coefficient of friction, and N is the normal load.

- **Second Law: Friction force is independent of apparent contact area.**

Changing the orientation of an object (e.g., placing a block flat vs. on its edge) does not change the friction force, because the actual microscopic contact area remains determined solely by the applied load.

- **(Note: Since Da Vinci discovered these 200 years prior, they are often referred to as Da Vinci's Laws of Friction).**

- **Leonhard Euler (1707–1783):** Defined movement on inclined planes mathematically ($f > P \tan \alpha$), introduced coefficient of friction μ ($\mu = \tan \alpha$), and differentiated static from kinetic friction.



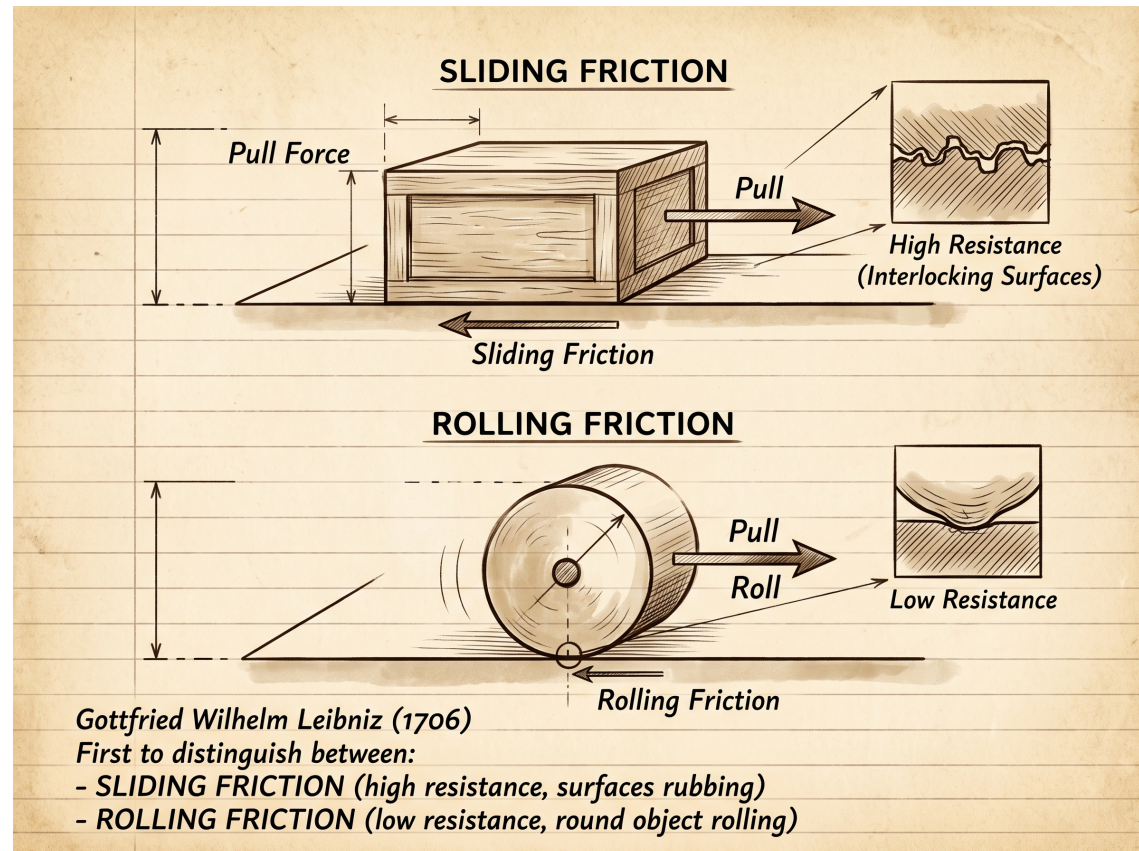
$$f = \mu N$$

f is friction force and equal to $W \sin \alpha$

N is normal force and equal to $W \cos \alpha$

$$\mu = \frac{W \sin \alpha}{W \cos \alpha} = \tan \alpha$$

- **Gottfried Wilhelm Leibniz (1706):** First to distinguish between rolling friction and sliding friction.



- **Sir Isaac Newton (1642–1727):** Formulated 'defectus lubricitatis' in his law of viscous flow, now known as internal fluid friction or viscosity.

Concept: In his masterpiece *Philosophiae Naturalis Principia Mathematica* (1687), Sir Isaac Newton defined the resistance arising from the lack of slipperiness (defectus lubricitatis) between fluid layers.

Internal Fluid Friction: Newton recognized that when a fluid flows, adjacent layers slide against each other. The resistance between these sliding fluid layers is known as internal fluid friction or viscosity. Newton's Law of Viscous Flow:

$$\tau = \mu \left(\frac{du}{dy} \right)$$

Shear Stress (τ): The internal frictional force per unit area.

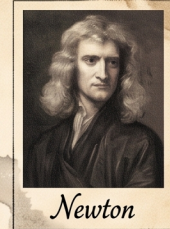
Dynamic Viscosity (μ): The measure of fluid resistance ("fluid thickness").

Velocity Gradient ($\frac{du}{dy}$): The rate at which fluid velocity changes across adjacent layers.

Significance in Tribology: Forms the foundational theoretical framework for hydrodynamic lubrication, explaining how liquid lubricants (like oil) separate solid moving parts to eliminate wear and reduce sliding friction.



Sir Isaac Newton (1687): Viscosity & Fluid Friction



Linear Velocity Profile

Velocity Gradient

Shear Force (F)

'Defectus Lubricitatis'
(Lack of Slipperiness /
Dynamic Viscosity μ)

- This constant property
represents the internal resistance
of a fluid to flow and the
source of viscous friction.

Velocity
Gradient $\frac{du}{dy}$

Top Moving Plate
(Velocity V)

Fluid Layer
(Dynamic Viscosity μ)

Shear Stress
 $\tau = \mu \left(\frac{du}{dy} \right)$

Stationary
Bottom Plate

Linear Velocity Profile

Shear Force (F)

Plate Area (A)

Foundation of Hydrodynamic Lubrication in Tribology

D. The Industrial Revolution (1750 – 1850)

- **Key Driving Force:** Mechanization of textile spinning/weaving, steam engines, and railways demanded effective bearings and lubricants.
- **Charles Augustin Coulomb:** Formulated friction equations based on experiments with rolling friction apparatus, inclined planes, and sliding resistance.

Coulomb's Law of Friction:

Kinetic Friction vs. Velocity: Kinetic friction force is virtually independent of sliding velocity once motion has started.

Static Friction vs. Kinetic Friction: Static friction (f_s) is always greater than kinetic friction (f_k), requiring more force to initiate motion than to maintain it.

- **Fluid Mechanics Foundations:** Devised by Euler, Bernoulli, Poiseuille (unit of dynamic viscosity “Poise” named after him), Claude Louis Navier, and George Gabriel Stokes (Navier-Stokes equations).

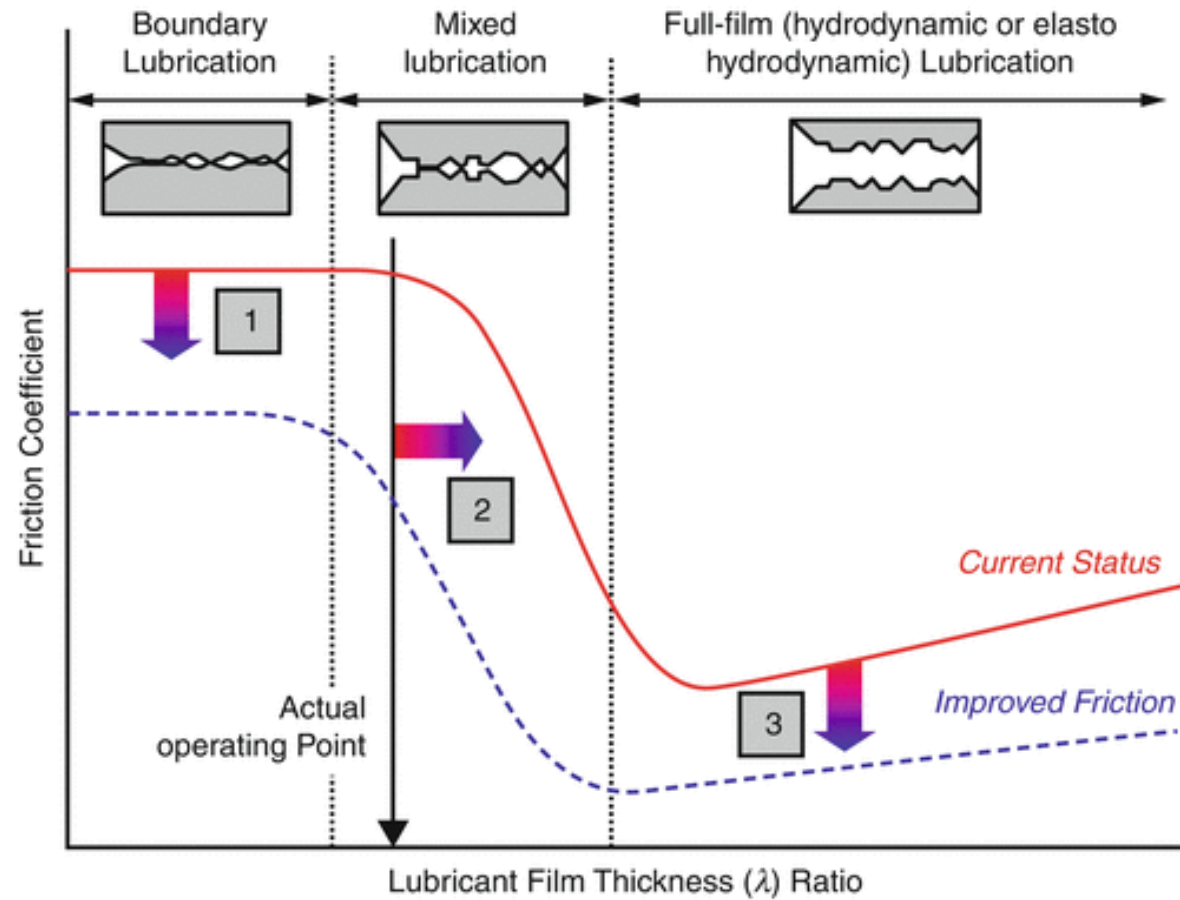
The greatness of the Navier-Stokes Equations lies in their ability to describe and model virtually all fluid and gas motions in the universe.

- **Lubricants:** Widespread use of animal/vegetable oils (olive, rapeseed, palm, coconut, lard, tallow). First mineral oil distillation in Prague (1812); first graphite lubricant patent in the UK (1835).

E. Period Between 1850 and 1945

- **1875:** Reynolds studied rolling friction.
- **1881:** Heinrich Hertz analyzed contact between elastic materials (Hertzian contact).
- **1883:** N.P. Petrov investigated unloaded journal bearings.
- **1884–1886:** Development of viscometers by Engler, Saybolt, and Redwood.
- **1885:** Hydrodynamic theory established by Tower and Reynolds.

- **1902:** Richard Stribeck measured journal bearing friction (Stribeck Curve).



Boundary Lubrication (High Friction, $\mu \approx 0.1 - 0.4$)

Condition: Very low speed, low viscosity, or high load.

Mechanism: Fluid film is thinner than surface roughness (asperities). Direct solid-to-solid contact occurs.

Protection: Relies entirely on chemical boundary additives (anti-wear/EP additives) attached to the surface.

Mixed Lubrication (Transition Zone)

Condition: Moderate speed and load.

Mechanism: The fluid film partially supports the load, but some surface asperities still touch.

Friction: Friction drops rapidly as speed/viscosity increases and solid contact decreases.

Hydrodynamic / Full-Film Lubrication (Low Friction, $\mu \approx 0.001 - 0.01$)

Condition: High speed, high viscosity, or low load.

Mechanism: A continuous, thick fluid film completely separates the two surfaces (zero solid contact).

Friction Behavior: Friction reaches its absolute minimum, then slightly increases at very high speeds due to internal fluid shear resistance (viscous drag).

Key Takeaway

Minimum Point: The lowest point on the curve represents the most energy-efficient operating point with zero solid wear.

Practical Application: Essential for designing journal bearings, engine pistons, gearboxes, and selecting proper lubricants to prevent wear and minimize energy loss.

- **1904:** Sommerfeld provided analytical solution to Reynolds' equation.
- **1914–1925:** Ludwig Gümbel identified primary sources of dry friction.
- **1917:** Langmuir studied thin surface films.
- **1922:** Hardy discovered polar compound mechanisms.
- **1927:** Introduction of Extreme Pressure (EP) and antiwear additives.
- **1930s:** Development of synthetic lubricants in Germany, VI improvers, antioxidants, and corrosion inhibitors.
- **1945:** Arthur Ertel formulated basic equations for Elastohydrodynamic Lubrication (EHL).

F. From 1950 to Present Day

- **EHL Theory Establishment:** Dowson and Higginson (1959) established foundational procedures for EHL contacts considering elastic distortion and viscosity-pressure characteristics.
- **The Jost Report (1966):** Coined the term 'Tribology' and triggered global recognition of friction, wear, and lubrication.
- **1970s Energy Crisis:** Accelerated government-sponsored tribological energy-saving research projects in Germany.
- **Ecological Tribology (1980s – Present):** Development of biodegradable lubricants from harvestable fats. RWTH Aachen University established a 12-year ecological tribo-systems research project in 1997.

The Jost Report (1966)



Professor Sir Peter Frederick Jost.

1. Why It Was Needed (Background & Motivation)

- **The Problem:** In the early 1960s, the UK industrial sector was experiencing frequent machine breakdowns, excessive wear and tear, and high energy losses due to poor lubrication practices.
- **Economic Strain:** The British Department of Education and Science noticed that industrial inefficiency due to friction and wear was costing the UK economy millions of pounds annually.
- **Lack of Interdisciplinary Approach:** Friction, wear, and lubrication were treated as separate engineering problems rather than an interconnected scientific field.

2. History & Development

- 1964 Committee: The UK Minister for State formed a committee headed by Peter Jost (a prominent British mechanical engineer) to investigate the status of lubrication education, research, and industrial needs.
- The Investigation: Over two years, Jost's committee consulted leading engineers, industrialists, and academics to assess friction and wear management in UK industry.
- Publication (1966): In March 1966, the report titled "Lubrication (Tribology) - Education and Research" (commonly known as the Jost Report) was published.

3. Coining of the Term "Tribology"

- Origin: During the drafting of the report, the committee recognized the need for a single, comprehensive term to describe the science of interacting surfaces in relative motion.
- Etymology: Derived from the Greek word tribos (τρίβος), meaning "rubbing" or "sliding."
- Official Definition (1966):

"Tribology is the science and technology of interacting surfaces in relative motion and of the practices related thereto."

- Scope: It unified friction, wear, lubrication, and bearing design into one recognized interdisciplinary science.

4. Key Findings & Impact of the Report

Economic Findings

- **Massive Savings:** The report estimated that the UK could save £515 million annually (approx. 1.1% of GDP at the time) through better application of tribological knowledge.
- **Sources of Savings:**
 - Lower maintenance and replacement costs.
 - Reduction in energy losses caused by friction.
 - Longer machinery service life and fewer catastrophic failures.

Global & Industrial Impact

- Establishment of Centers: Led to the creation of national tribology centers in the UK (e.g., Leeds, Swansea, Risley) and subsequently worldwide.
- Academic Integration: Catalyzed dedicated university curricula, research grants, and specialized engineering degrees in tribology.
- Global Benchmark: Prompted similar economic studies in the US, Germany, and Japan, establishing tribology as a critical discipline for global manufacturing and energy efficiency.
- Modern Relevance: Paved the way for modern applications including micro/nanotribology, bio-tribology (e.g., joint prosthetics), and green tribology (energy conservation).



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