Friction

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Friction is the force resisting the relative motion of solid surfaces, fluid layers, and/or material elements sliding against each other. It may be thought of as the opposite of "slipperiness".

There are several types of friction:

- **Dry friction** resists relative lateral motion of two solid surfaces in contact. Dry friction is subdivided into *static friction* between non-moving surfaces, and *kinetic friction* between moving surfaces.
- **Fluid friction** describes the friction between layers within a viscous fluid that are moving relative to each other.[1][2]
- **Lubricated friction** is a case of fluid friction where a fluid separates two solid surfaces.[3][4][5]
- **Skin friction** is a component of drag, the force resisting the motion of a solid body through a fluid.
- **Internal friction** is the force resisting motion between the elements making up a solid material while it undergoes deformation.[2]

When surfaces in contact move relative to each other, the friction between the two surfaces converts kinetic energy into heat. This property can have dramatic consequences, as illustrated by the use of friction between pieces of wood to start a fire.

Another important consequence of many types of friction can be wear, which may lead to performance degradation and/or damage to components. Friction is a component of the science of tribology.

Friction is not a fundamental force but occurs because of the electromagnetic forces between charged particles which constitute the surfaces in contact. Because of the complexity of these interactions friction cannot be calculated from first principles, but instead must be found empirically.

Contents

Classical mechanics

$$\mathbf{F} = \frac{\mathrm{d}}{\mathrm{d}t}(m\mathbf{v})$$

Newton's Second Law

History of classical mechanics · Timeline of classical mechanics

Branches

Statics · Dynamics / Kinetics · Kinematics · Applied mechanics · Celestial mechanics · Continuum mechanics · Statistical mechanics

Formulations

- Newtonian mechanics (Vectorial mechanics)
- Analytical mechanics:
  - Lagrangian mechanics
  - Hamiltonian mechanics

Fundamental concepts

Space · Time · Velocity · Speed · Mass · Acceleration · Gravity · Force · Impulse · Torque / Moment / Couple · Momentum · Angular momentum · Inertia · Moment of inertia · Reference frame · Energy · Kinetic energy · Potential energy · Mechanical work · Virtual work · D'Alembert's principle

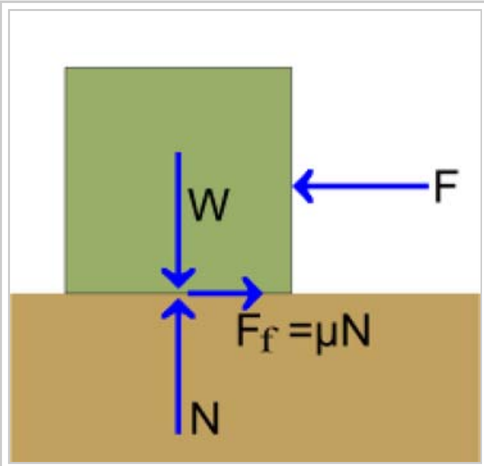
Core topics

Rigid body · Rigid body dynamics · Euler's equations (rigid body dynamics) · Motion · Newton's laws of motion · Newton's law of universal gravitation · Equations of motion · Inertial frame of reference · Non-inertial reference frame · Rotating reference frame · Fictitious force · Linear motion ·

Mechanics of planar particle motion · Displacement (vector) · Relative velocity · **Friction** · Simple harmonic motion · Harmonic oscillator · Vibration · Damping · Damping ratio · Rotational motion · Circular motion · Uniform circular motion · Non-uniform circular motion · Centripetal force · Centrifugal force · Centrifugal force (rotating reference frame) · Reactive centrifugal force · Coriolis force · Pendulum · Rotational speed · Angular acceleration · Angular velocity · Angular frequency · Angular displacement

Scientists

Isaac Newton · Jeremiah Horrocks · Leonhard Euler · Jean le Rond d'Alembert · Alexis Clairaut · Joseph Louis Lagrange · Pierre-Simon Laplace · William Rowan Hamilton · Siméon-Denis Poisson



Force diagram for block on ground. Arrows are vectors indicating directions and magnitudes of forces. W is the force of weight, N is the normal force, F is an applied force, and F_f is the force of kinetic friction which is equal to the coefficient of kinetic friction times the normal force. Since the magnitude of the applied force is greater than the magnitude of the force of kinetic friction opposing it, the block is

History

Several famous scientists and engineers contributed to our understanding of dry friction.[6] They include Leonardo da Vinci, Guillaume Amontons, John Theophilus Desaguliers, Leonard Euler, and Charles-Augustin de Coulomb. Nikolai Pavlovich Petrov and Osborne Reynolds later supplemented this understanding with theories of lubrication.

Basic properties

Basic properties of friction have been described as laws: [6]

- **Amontons' 1st Law**: The force of friction is directly proportional to the applied load.

accelerating to the left.

- **Amontons' 2nd Law**: The force of friction is independent of the apparent area of contact.
- **Coulomb's Law of Friction**: Kinetic friction is independent of the sliding velocity.

Amontons' 2nd Law is an idealization assuming perfectly rigid and inelastic materials. For example, wider tires on cars provide more traction than narrow tires for a given vehicle mass because of surface deformation of the tire.[citation needed]

Dry friction

Dry friction resists relative lateral motion of two solid surfaces in contact. The two regimes of dry friction are *static friction* between non-moving surfaces, and *kinetic friction* (sometimes called sliding friction or dynamic friction) between moving surfaces.

Coulomb friction, named after Charles-Augustin de Coulomb, is an approximate model used to calculate the force of dry friction. It is governed by the equation:

$$F_\mathrm{f} \leq \mu F_\mathrm{n}$$

where

- F_f is the force exerted by friction (in the case of equality, the maximum possible magnitude of this force).
- μ is the coefficient of friction, which is an empirical property of the contacting materials,
- F_n is the normal force exerted between the surfaces.

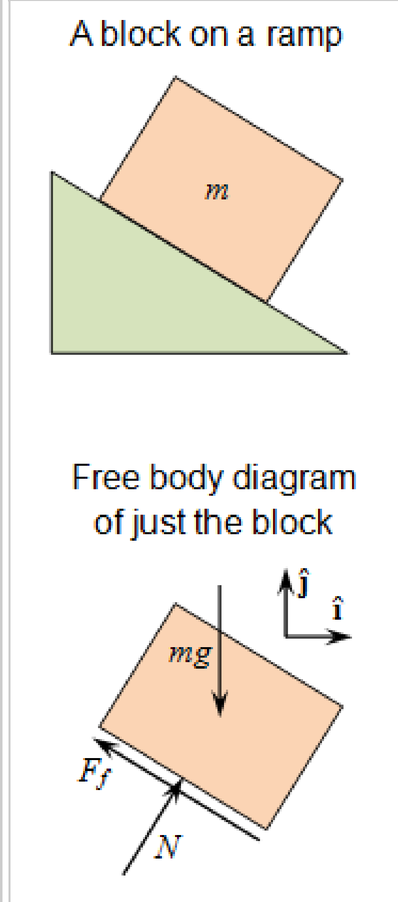
The Coulomb friction F_f may take any value from zero up to μF_n, and the direction of the frictional force against a surface is opposite to the motion that surface would experience in the absence of friction. Thus, in the static case, the frictional force is exactly what it must be in order to prevent motion between the surfaces; it balances the net force tending to cause such motion. In this case, rather than providing an estimate of the actual frictional force, the Coulomb approximation provides a threshold value for this force, above which motion would commence. This maximum force is known as traction.

The force of friction is always exerted in a direction that opposes movement (for kinetic friction) or potential movement (for static friction) between the two surfaces. For example, a curling stone sliding along the ice experiences a kinetic force slowing it down. For an example of potential movement, the drive wheels of an accelerating car experience a frictional force pointing forward; if they did not, the wheels would spin, and the rubber would slide backwards along the pavement. Note that it is not the direction of movement of the vehicle they oppose, it is the direction of (potential) sliding between tire and road.

In the case of kinetic friction, the direction of the friction force may or may not match the direction of motion: a block sliding atop a table with rectilinear motion is subject to friction directed along the line of motion; an automobile making a turn is subject to friction acting perpendicular to the line of motion (in which case it is said to be 'normal' to it). The direction of the static friction force can be visualized as directly opposed to the force that would otherwise cause motion, were it not for the static friction preventing motion. In this case, the friction force exactly cancels the applied force, so the net force given by the vector sum, equals zero. It is important to note that in all cases, Newton's first law of motion holds.

The normal force

Main article: Normal force



Block on a ramp (top) and corresponding **free body diagram** of just the block (bottom).

The normal force is defined as the net force compressing two parallel surfaces together; and its direction is perpendicular to the surfaces. In the simple case of a mass resting on a horizontal surface, the only component of the normal force is the force due to gravity, where $N = mg$. In this case, the magnitude of the friction force is the product of the mass of the object, the acceleration due to gravity, and the coefficient of friction. However, the coefficient of friction is not a function of mass or volume; it depends only on the material. For instance, a large aluminum block has the same coefficient of friction as a small aluminum block. However, the magnitude of the friction force itself depends on the normal force, and hence the mass of the block.

If an object is on a level surface and the force tending to cause it to slide is horizontal, the normal force N between the object and the surface is just its weight, which is equal to its mass multiplied by the acceleration due to earth's gravity, g. If the object is on a tilted surface such as an inclined plane, the normal force is less, because less of the force of gravity is perpendicular to the face of the plane. Therefore, the normal force, and ultimately the frictional force, is determined using vector analysis, usually via a free body diagram. Depending on the situation, the calculation of the normal force may include forces other than gravity.

Coefficient of friction

The 'coefficient of friction' (COF), also known as a 'frictional coefficient' or 'friction coefficient' and symbolized by the Greek letter μ, is a dimensionless scalar value which describes the ratio of the force of friction between two bodies and the force pressing them together. The coefficient of friction depends on the materials used; for example, ice on steel has a low coefficient of friction, while rubber on pavement has a high coefficient of friction. Coefficients of friction range from near zero to greater than one – under good conditions, a tire on concrete may have a coefficient of friction of 1.7.[*citation needed*]

For surfaces at rest relative to each other $\mu = \mu_{\mathrm{s}}$, where μ_{s} is the *coefficient of static friction*. This is usually larger than its kinetic counterpart.

For surfaces in relative motion $\mu = \mu_{\mathrm{k}}$, where μ_{k} is the *coefficient of kinetic friction*. The Coulomb friction is equal to F_{f}, and the frictional force on each surface is exerted in the direction opposite to its motion relative to the other surface.

The coefficient of friction is an empirical measurement – it has to be measured experimentally, and cannot be found through calculations. Rougher surfaces tend to have higher effective values. Both static and kinetic coefficients of friction depend on the pair of surfaces in contact; for a given pair of surfaces, the coefficient of static friction is *usually* larger than that of kinetic friction; in some sets the two coefficients are equal, such as teflon-on-teflon.

Most dry materials in combination have friction coefficient values between 0.3 and 0.6. Values outside this range are rarer, but teflon, for example, can have a coefficient as low as 0.04. A value of zero would mean no friction at all, an elusive property – even magnetic levitation vehicles have drag. Rubber in contact with other surfaces can yield friction coefficients from 1 to 2. Occasionally it is maintained that μ is always < 1, but this is not true. While in most relevant applications μ < 1, a value above 1 merely implies that the force required to slide an object along the surface is greater than the normal force of the surface on the object. For example, silicone rubber or acrylic rubber-coated surfaces have a coefficient of friction that can be substantially larger than 1.

While it is often stated that the COF is a "material property," it is better categorized as a "system property." Unlike true material properties (such as conductivity, dielectric constant, yield strength), the COF for any two materials depends on system variables like temperature, velocity, atmosphere and also what are now popularly described as aging and deaging times; as well as on geometric properties of the interface between the materials. For example, a copper pin sliding against a thick copper plate can have a COF that varies from 0.6 at low speeds (metal sliding against metal) to below 0.2 at high speeds when the copper surface begins to melt due to frictional heating. The latter speed, of course, does not determine the COF uniquely; if the pin diameter is increased so that the frictional heating is removed rapidly, the temperature drops, the pin remains solid and the COF rises to that of a 'low speed' test.[*citation needed*]

Approximate coefficients of friction

Materials		Static friction, μ_s	
		Dry & clean	**Lubricated**
Aluminum	**Steel**	0.61	
Copper	**Steel**	0.53	
Brass	**Steel**	0.51	
Cast iron	**Copper**	1.05	
Cast iron	**Zinc**	0.85	
Concrete (wet)	**Rubber**	0.30	
Concrete (dry)	**Rubber**	1.0	
Concrete	**Wood**	0.62[7]	
Copper	**Glass**	0.68	
Glass	**Glass**	0.94	
Metal	**Wood**	0.2–0.6[7]	0.2 (wet)[7]
Polythene	**Steel**	0.2[8]	0.2[8]
Steel	**Steel**	0.80[8]	0.16[8]
Steel	**Teflon**	0.04[8]	0.04[8]
Teflon	**Teflon**	0.04[8]	0.04[8]
Wood	**Wood**	0.25–0.5[7]	0.2 (wet)[7]

The slipperiest solid known, discovered in 1999, dubbed BAM (for the elements boron, aluminum, and magnesium), has an approximate coefficient of friction of 0.02, about half that of Teflon.[9]

Static friction

Static friction is friction between two solid objects that are not moving relative to each other. For example, static friction can prevent an object from sliding down a sloped surface. The coefficient of static friction, typically denoted as μ_s, is usually higher than the coefficient of kinetic friction.

The static friction force must be overcome by an applied force before an object can move. The maximum possible friction force between two surfaces before sliding begins is the product of the coefficient of static friction and the normal force: $f = \mu_s F_n$. When there is no sliding occurring, the friction force can have any value from zero up to F_{max}. Any force smaller than F_{max} attempting to slide one surface over the other is opposed by a frictional force of equal magnitude and opposite direction. Any force larger than F_{max} overcomes the force of static friction and causes sliding to occur. The instant sliding occurs, static friction is no longer applicable—the friction between the two surfaces is then called kinetic friction.

An example of static friction is the force that prevents a car wheel from slipping as it rolls on the ground. Even though the wheel is in motion, the patch of the tire in contact with the ground is stationary relative to the ground, so it is static rather than kinetic friction.

The maximum value of static friction, when motion is impending, is sometimes referred to as **limiting friction**,[10] although this term is not used universally.[1] It is also known as traction.

Kinetic friction

Kinetic (or dynamic) friction occurs when two objects are moving relative to each other and rub together (like a sled on the ground). The coefficient of kinetic friction is typically denoted as μ_k, and is usually less than the coefficient of static friction for the same materials.[11][12] In fact, Richard Feynman reports that "with dry metals it is very hard to show any difference."[13]

New models are beginning to show how kinetic friction can be greater than static friction.[14] Contrary to earlier explanations, kinetic friction is now understood not to be caused by surface roughness but by chemical bonding between the surfaces.[15] Surface roughness and contact area, however, do affect kinetic friction for micro- and nano-scale objects where surface area forces dominate inertial forces.[16]

Angle of friction

For certain applications it is more useful to define static friction in terms of the maximum angle before which one of the items will begin sliding. This is called the *angle of friction* or *friction angle*. It is defined as:

$$\tan\theta = \mu$$

where θ is the angle from horizontal and μ is the static coefficient of friction between the objects.[17] This formula can also be used to calculate μ from empirical measurements of the friction angle.

Friction at the atomic level

Determining the forces required to move atoms past each other is a challenge in designing nanomachines. In 2008 scientists for the first time were able to move a single atom across a surface, and measure the forces required. Using ultrahigh vacuum and nearly-zero temperature (5 K), a modified atomic force microscope was used to drag a cobalt atom, and a carbon monoxide molecule, across surfaces of copper and platinum.[18]

Limitations of the Coulomb model

The Coulomb approximation mathematically follows from the assumptions that surfaces are in atomically close contact only over a small fraction of their overall area, that this contact area is proportional to the normal force (until saturation, which takes place when all area is in atomic contact), and that frictional force is proportional to the applied normal force, independently of the contact area (you can see the experiments on friction from Leonardo Da Vinci). Such reasoning aside, however, the approximation is fundamentally an empirical construction. It is a rule of thumb describing the approximate outcome of an extremely complicated physical interaction. The strength of the approximation is its simplicity and versatility – though in general the relationship between normal force and frictional force is not exactly linear (and so the frictional force is not entirely independent of the contact area of the surfaces), the Coulomb approximation is an adequate representation of friction for the analysis of many physical systems.

When the surfaces are conjoined, Coulomb friction becomes a very poor approximation (for example, adhesive tape resists sliding even when there is no normal force, or a negative normal force). In this case, the frictional force may depend strongly on the area of contact. Some drag racing tires are adhesive in this way. However, despite the complexity of the fundamental physics behind friction, the relationships are accurate enough to be useful in many applications.

Fluid friction

Main article: Viscosity

Fluid friction occurs between layers within a fluid that are moving relative to each other. This internal resistance to flow is described by *viscosity*. In everyday terms viscosity is "thickness". Thus, water is "thin", having a lower viscosity, while honey is "thick", having a higher viscosity. Put simply, the less viscous the fluid is, the greater its ease of movement.

All real fluids (except superfluids) have some resistance to stress and therefore are viscous, but a fluid which has no resistance to shear stress is known as an ideal fluid or inviscid fluid.

Lubricated friction

Main article: Lubrication

Lubricated friction is a case of fluid friction where a fluid separates two solid surfaces. Lubrication is a technique employed to reduce wear of one or both surfaces in close proximity moving relative to each another by interposing a substance called a lubricant between the surfaces.

In most cases the applied load is carried by pressure generated within the fluid due to the frictional viscous resistance to motion of the lubricating fluid between the surfaces. Adequate lubrication allows smooth continuous operation of equipment, with only mild wear, and without excessive stresses or seizures at bearings. When lubrication breaks down, metal or other components can rub destructively over each other, causing destructive damage, heat, and failure.

Skin friction

Main article: Parasitic drag

Skin friction arises from the friction of the fluid against the "skin" of the object that is moving through it. Skin friction arises from the interaction between the fluid and the skin of the body, and is directly related to the area of the surface of the body that is in contact with the fluid. Skin friction follows the drag equation and rises with the square of the velocity.

Skin friction is caused by viscous drag in the boundary layer around the object. There are two ways to decrease skin friction: the first is to shape the moving body so that smooth flow is possible, like an airfoil. The second method is to decrease the length and cross-section of the moving object as much as is practicable.

Internal friction

Main article: Plastic deformation of solids

See also: Deformation (engineering)

Internal friction is the force resisting motion between the elements making up a solid material while it undergoes plastic deformation.

Plastic deformation in solids is an irreversible change in the internal molecular structure of an object. This change may be due to either (or both) an applied force or a change in temperature. The change of an object's shape is called strain. The force causing it is called stress. Stress does not necessarily cause permanent change. As deformation occurs, internal forces oppose the applied force. If the applied stress is not too large these opposing forces may completely resist the applied force, allowing the object to assume a new equilibrium state and to return to its original shape when the force is removed. This is what is known in the literature as elastic deformation (or elasticity). Larger forces in excess of the elastic limit may cause a permanent (irreversible) deformation of the object. This is what is known as plastic deformation.

Other types of friction

Rolling resistance

Main article: Rolling resistance

Rolling resistance is the force that resists the rolling of a wheel or other circular object along a surface caused by deformations in the object and/or surface. Generally the force of rolling resistance is less than that associated with kinetic friction.[19] Typical values for the coefficient of rolling resistance are 0.001.[20] One of the most common examples of rolling resistance is the movement of motor vehicle tires on a road, a process which generates heat and sound as by-products.[21]

Triboelectric effect

Main article: Triboelectric effect

Rubbing dissimilar materials against one another can cause a build-up of electrostatic charge, which can be hazardous if flammable gases or vapours are present. When the static build-up discharges, explosions can be caused by ignition of the flammable mixture.

Belt friction

Main article: Belt friction

Belt friction is a physical property observed from the forces acting on a belt wrapped around a pulley, when one end is being pulled. The resulting tension, which acts on both ends of the belt, can be modeled by the belt friction equation.

In practice, the theoretical tension acting on the belt or rope calculated by the belt friction equation can be compared to the maximum tension the belt can support. This helps a designer of such a rig to know how many times the belt or rope must be wrapped around the pulley to prevent it from slipping. Mountain climbers and sailing crews demonstrate a standard knowledge of belt friction when accomplishing basic tasks.

Reducing friction

Devices

Devices such as wheels, ball bearings, roller bearings, and air cushion or other types of fluid bearings can change sliding friction into a much smaller type of rolling friction.

Many thermoplastic materials such as nylon, HDPE and PTFE are commonly used in low friction bearings. They are especially useful because the coefficient of friction falls with increasing imposed load.[*citation needed*] For improved wear resistance, very high molecular weight grades are usually specified for heavy duty or critical bearings.

Lubricants

A common way to reduce friction is by using a lubricant, such as oil, water, or grease, which is placed between the two surfaces, often dramatically lessening the coefficient of friction. The science of friction and lubrication is called tribology. Lubricant technology is when lubricants are mixed with the application of science, especially to industrial or commercial objectives.

Superlubricity, a recently-discovered effect, has been observed in graphite: it is the substantial decrease of friction between two sliding objects, approaching zero levels. A very small amount of frictional energy would still be dissipated.

Lubricants to overcome friction need not always be thin, turbulent fluids or powdery solids such as graphite and talc; acoustic lubrication actually uses sound as a lubricant.

Another way to reduce friction between two parts is to superimpose micro-scale vibration to one of the parts. This can be sinusoidal vibration as used in ultrasound-assisted cutting or vibration noise, known as dither.

Energy of friction

According to the law of conservation of energy, no energy is destroyed due to friction, though it may be lost to the system of concern. Energy is transformed from other forms into heat. A sliding hockey puck comes to rest because friction converts its kinetic energy into heat. Since heat quickly dissipates, many early philosophers, including Aristotle, wrongly concluded that moving objects lose energy without a driving force.

When an object is pushed along a surface, the energy converted to heat is given by:

$$E_{th} = \mu_\mathrm{k} \int F_\mathrm{n}(x) dx$$

where

F_n is the normal force,
μ_k is the coefficient of kinetic friction,
x is the coordinate along which the object transverses.

Energy lost to a system as a result of friction is a classic example of thermodynamic irreversibility.

Work of friction

In the reference frame of the interface between two surfaces, static friction does *no* work, because there is never displacement between the surfaces. In the same reference frame, kinetic friction is always in the direction opposite the motion, and does *negative* work.[22] However, friction can do *positive* work in certain frames of reference. One can see this by placing a heavy box on a rug, then pulling on the rug quickly. In this case, the box slides backwards relative to the rug, but moves forward relative to the frame of reference in which the floor is stationary. Thus, the kinetic friction between the box and rug accelerates the box in the same direction that the box moves, doing *positive* work.[23]

The work done by friction can translate into deformation, wear, and heat that can affect the contact surface properties (even the coefficient of friction between the surfaces). This can be beneficial as in polishing. The work of friction is used to mix and join materials such as in the process of friction welding. Excessive erosion or wear of mating surfaces occur when work due frictional forces rise to unacceptable levels. Harder corrosion particles caught between mating surfaces (fretting) exacerbates wear of frictional forces. Bearing seizure or failure may result from excessive wear due to work of friction. As surfaces are worn by work due to friction, fit and surface finish of an object may degrade until it no longer functions properly.[24]

Applications

Friction is an important factor in many engineering disciplines.

Transportation

- Rail adhesion refers to the grip wheels of a train have on the rails.
- Road slipperiness is an important design and safety factor for automobiles
  - Split friction is a particularly dangerous condition arising due to varying friction on either side of a car.
  - Road texture affects the interaction of tires and the driving surface.

Measurement

- A tribometer is an instrument that measures friction on a surface.
- A profilograph is a device used to measure pavement surface roughness.

See also

- Angle of repose
- Drag (physics)
- Factor of adhesion
- Friction welding
- Frictionless plane
- Stick-slip phenomenon
- Tire
- Traction (engineering)
- Triboelectric effect
- Tribology
- Tribometer
- Wear
- Galling

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External links

- Coefficients of Friction (http://www.roymech.co.uk/Useful_Tables/Tribology/co_of_frict.htm) – tables of coefficients, plus many links
- Physclips: Mechanics with animations and video clips (http://www.physclips.unsw.edu.au/) from the University of New South Wales
- CRC Handbook of Chemistry & Physics – Values for Coefficient of Friction (http://books.google.com/books?id=WDll8hA006AC&pg=PT2503&lpg=PT2503)
- Characteristic Phenomena in Conveyor Chain (http://chain-guide.com/basics/2-3-1-coefficient-of-friction.html)
- Atomic-scale Friction Research and Education Synergy Hub (AFRESH) (http://nsfafresh.org) an Engineering Virtual Organization for the atomic-scale friction community to share, archive, link, and discuss data,

knowledge and tools related to atomic-scale friction.

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