STUDY GUIDE

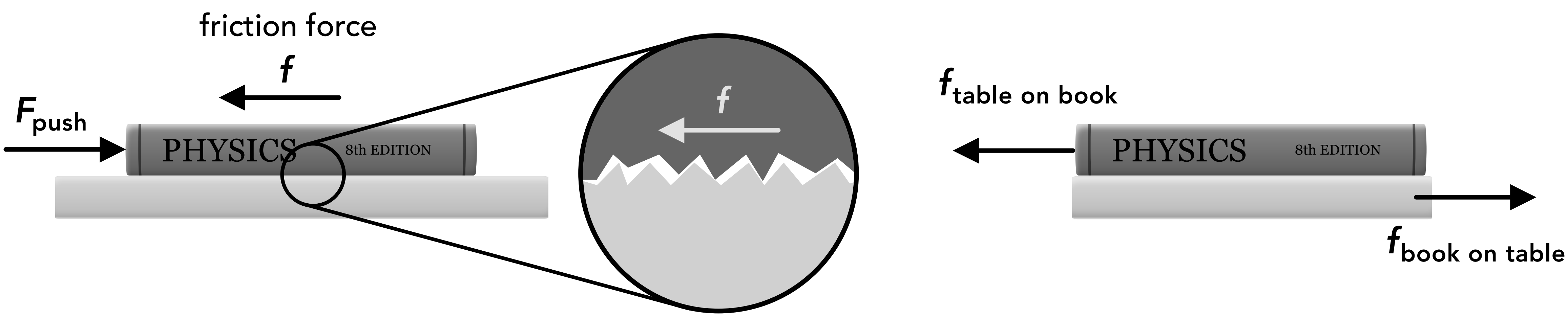
FRICTION

Friction

- **Friction** is a force that acts between two objects that are in contact with each other (or between an object and a surface) which acts to oppose or prevent motion.
- The friction force is the reason why moving objects appear to slow down and stop on their own, and why most objects remain at rest. Without the friction force between objects and the surface they're on, things would be sliding everywhere. You also wouldn't be able to walk forward, ride a bike or drive a car.
- The friction force arises between the surfaces of two objects which is rough at the microscopic level. In simple terms, the "mountains" from one surface get stuck in the "valleys" in the other surface, which results in sideways forces that prevent or oppose motion (the force acts parallel to the surface).

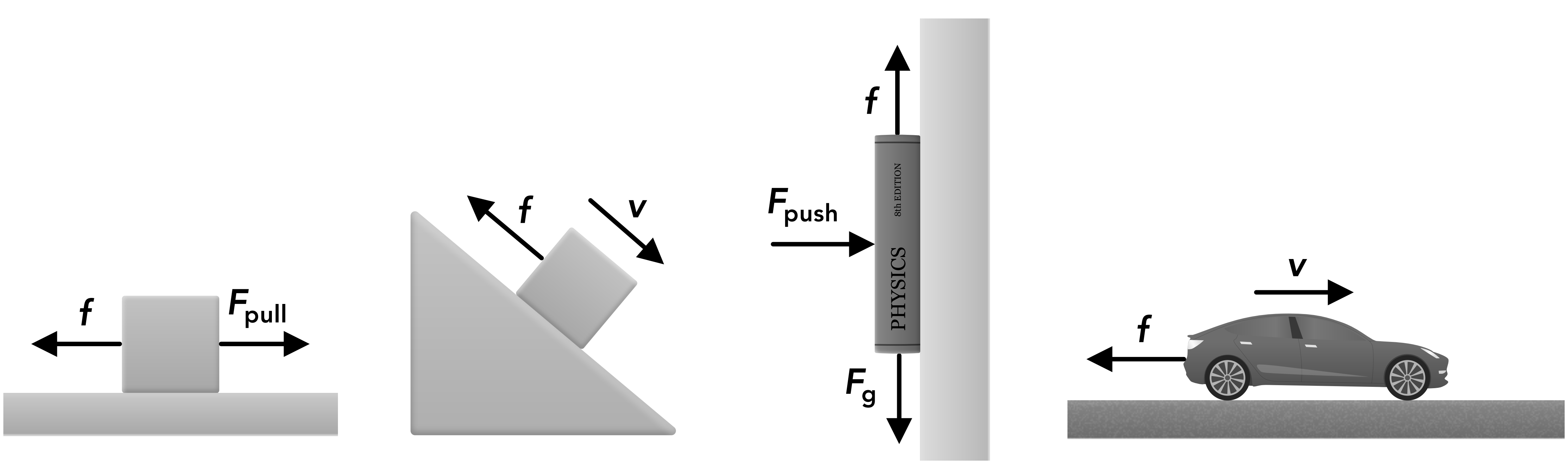
Variables		SI Unit
f_s	static friction force	N
f_k	kinetic friction force	N
f_r	rolling friction force	N
μ_s	coefficient of static friction	
μ_k	coefficient of kinetic friction	
μ_r	coefficient of rolling friction	
F_n	normal force	N

A pair of friction forces is caused by surface roughness at a microscopic level



- Friction forces come in pairs as described in Newton's 3rd law of motion. In the example above, a book is being pushed across a table. The table applies a friction force on the book and the book applies a friction force on the table with an equal magnitude in the opposite direction.
- There are several types of friction: static friction, kinetic friction, rolling friction and others. The drag force (air resistance) is also a type of friction between an object and the air around it.
- The friction force on an object always acts **parallel to the surface** and in the direction that **opposes its motion** or **prevents its motion** (if it's not moving).

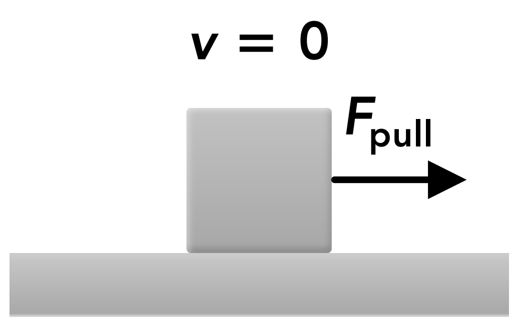
The friction force always acts parallel to the surface

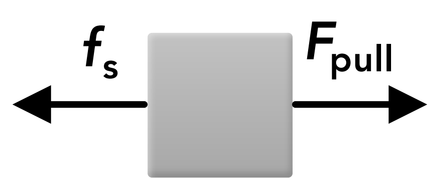


Static Friction

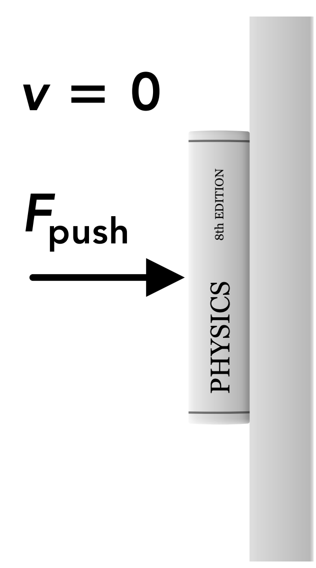
- **Static friction** is a type of friction force that acts on a static (not moving) object to prevent it from moving.
- If you push or pull an object and it doesn't move, there is a static friction force acting in the opposite direction as the force you're applying.
- Notice that the equation below can be used to find the **maximum** static friction force acting on an object. Unlike kinetic friction, the magnitude of a static friction force depends on other forces acting on the object along the same axis, like a normal force does. To find the static friction force on an object the other forces must be known.

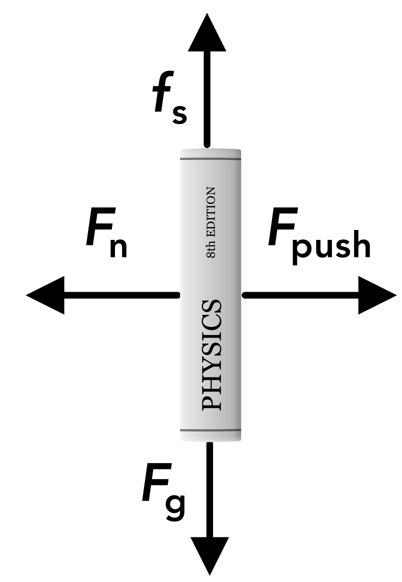
The static friction force depends on the other forces acting on the object along the same axis





$$\sum F_x = ma_x$$
$$F_{pull} - f_s = m(0\ m/s^2)$$
$$f_s = F_{pull}$$





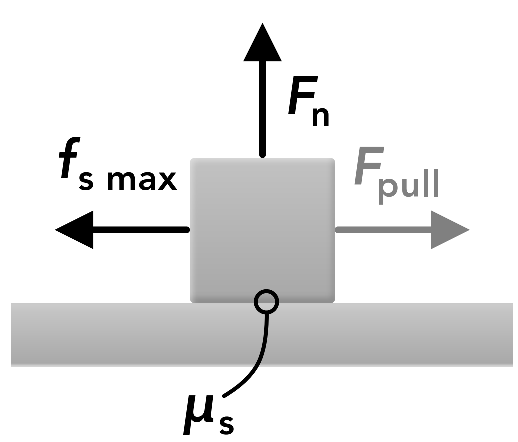
$$\sum F_y = ma_y$$
$$f_s - F_g = m(0\ m/s^2)$$
$$f_s = F_g$$

- The maximum static friction force that is possible between an object and a surface depends on the coefficient of static friction between the two surfaces and the normal force between the two surfaces.
- The **coefficient of friction** μ (the Greek letter "mu") is a value that depnds on the materials and the conditions of the two surfaces. The value is usually between 0 and 1 and it does not have a unit.

Maximum static friction force

$$f_{s\ max} = \mu_s F_n$$

μ_s : coefficient of static friction



coefficient of static friction between box and ground

Some static friction coefficients:

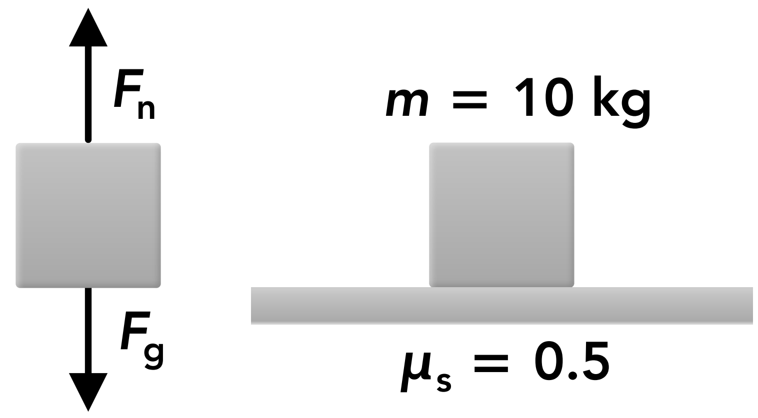
Materials	μ_s
Tire / road (dry)	1.0
Tire / road (wet)	0.2
Skin / metal	0.9
Steel / aluminum	0.6
Steel / ice	0.03

- Again, the equation above can be used to calculate the maximum possible static friction force.
- **The actual static friction force is some value between zero and that maximum value**, and depends on the other forces being applied along the same axis.

Example: A 10 kg box is sitting on the ground at rest. The normal force between the box and the ground is equal to the weight force, 98 N. The coefficient of static friction between the box and the ground is 0.5. The maximum static friction force between the box and the ground is 49 N. A rightwards pulling force is then applied to the box.

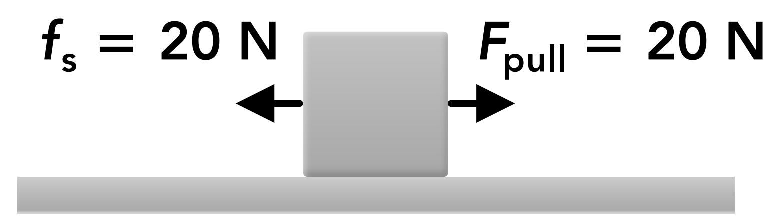
$$\sum F_y = ma_y$$
$$F_n - F_g = m(0\ \text{m/s}^2)$$
$$F_n = F_g = mg = (10\ \text{kg})(9.8\ \text{m/s}^2) = 98\ \text{N}$$

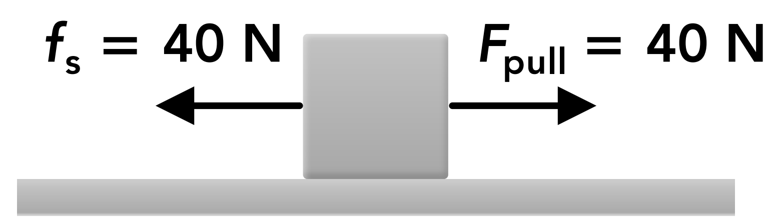
$$f_{s\ max} = \mu_s F_n = (0.5)(98\ \text{N}) = 49\ \text{N}$$



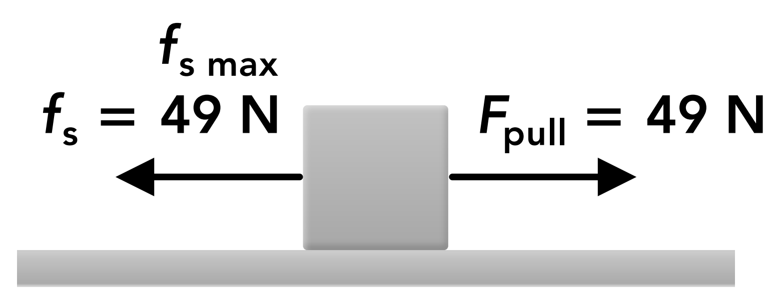
If the applied force is zero (there's no other forces acting parallel to the surface) there is no static friction force because there are no forces for friction to "react to" or any motion to prevent.

As the applied force increases, the static friction "reacts" and also increases so it has the same magnitude in the opposite direction.

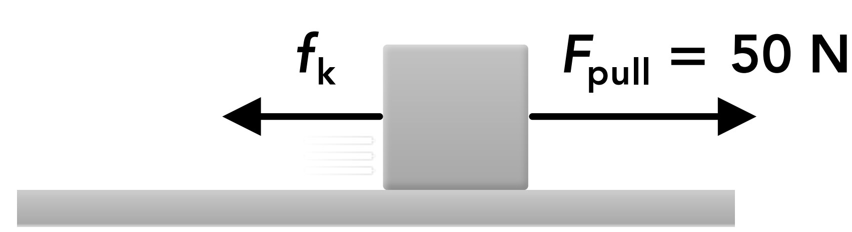




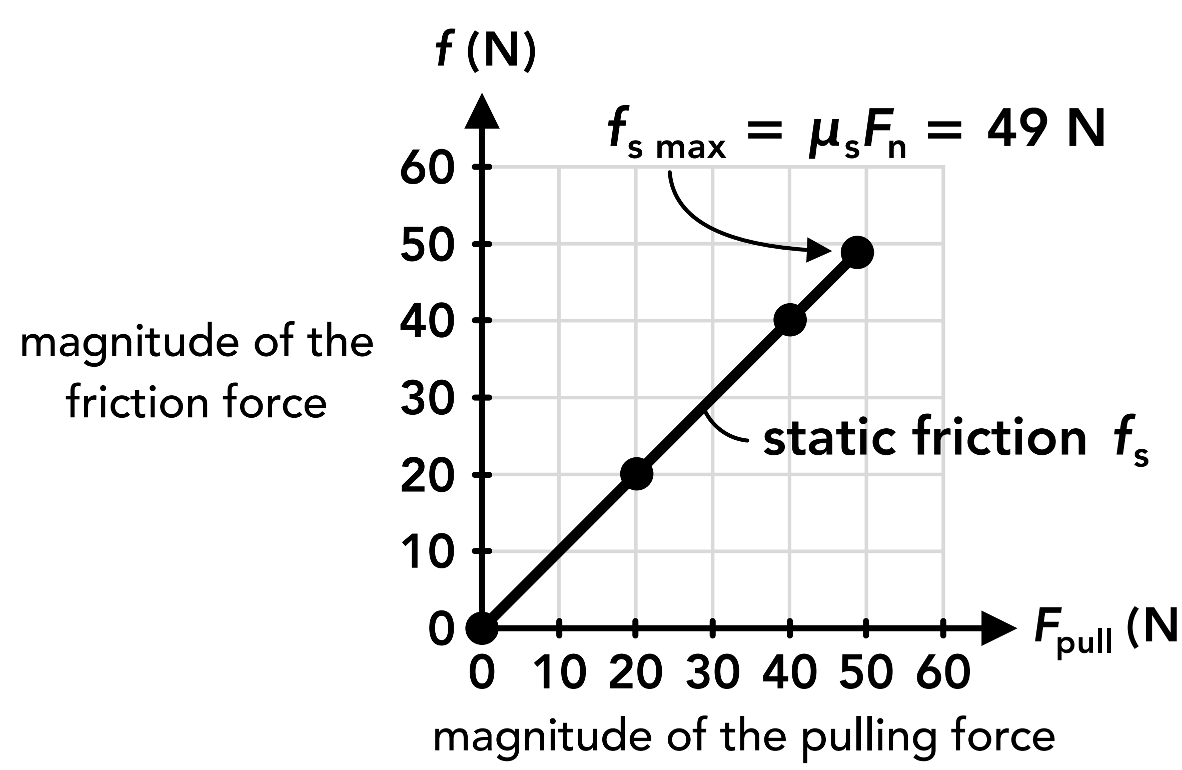
Eventually the applied force equals the maximum static friction force that's possible between the box and the ground.



If the applied force is greater than the maximum static friction force, the box will begin to slide and the friction transitions from static friction to kinetic friction.

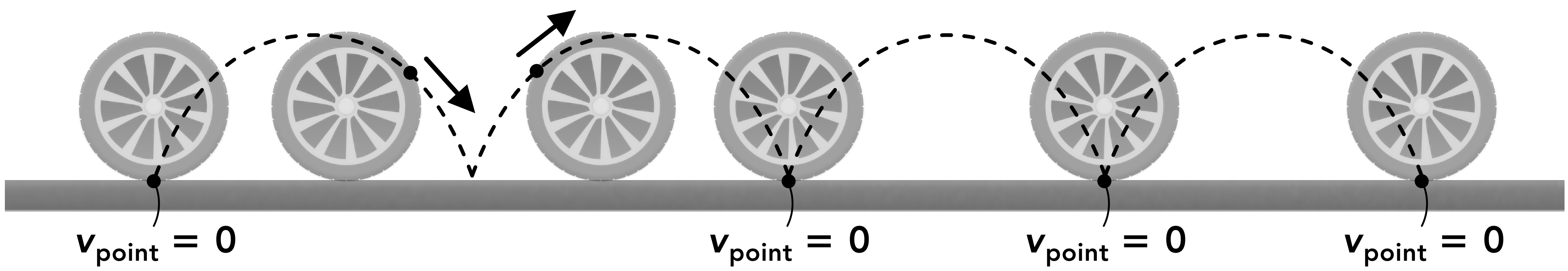


A graph of the static friction force vs the applied force is a straight line with a slope of 1. The static friction force is equal to the applied force until it reaches the maximum static friction force (which is found using the equation above). The points represent the above diagrams.

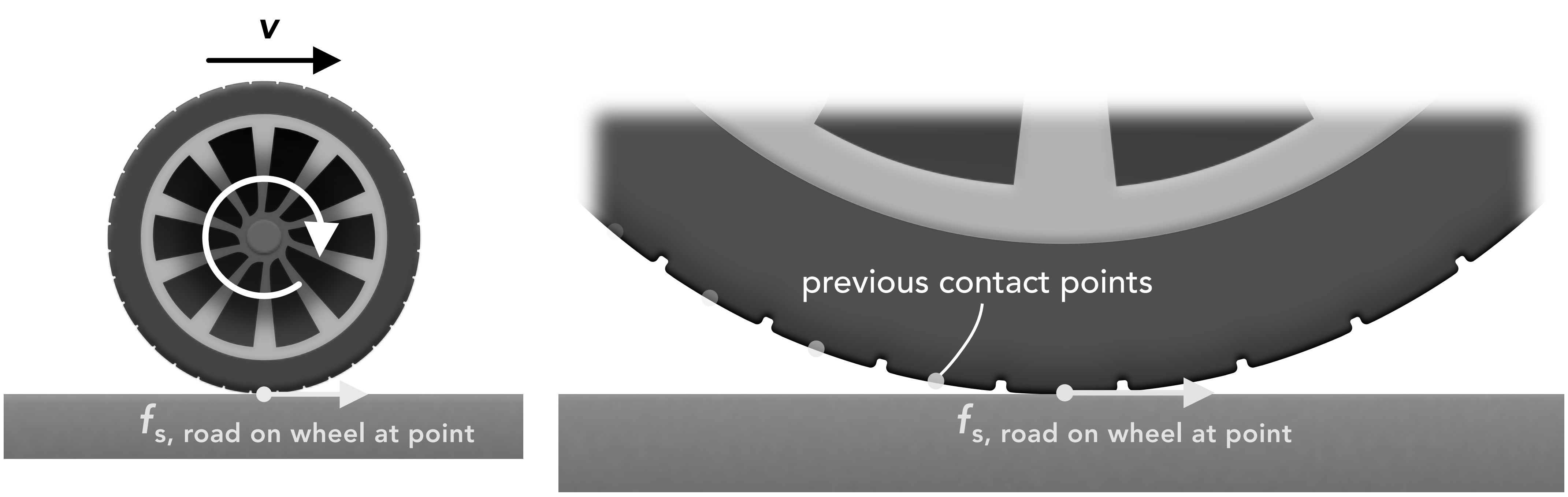


- When an object like a wheel is rolling, there is only a single point of contact between the object and the surface (this is a simplification, there is a small surface area instead of a point if the object deforms).
- As the object rotates, the point on the edge of the object which is in contact with the surface changes.
- At any one moment, the contact point on the rolling object is **not moving relative to the surface**.
- This means that there is a momentary **static friction force** between that point on the edge of the object and the surface that it's rolling on. If this static friction didn't exist for a car tire, the tire would slip and the car would not be able to drive forwards.
- Torque and rotational dynamics are responsible for a car driving forwards as its wheels rotate without slipping, but it's worth noting here that static friction is responsible for the concept of "rolling without slipping".

A point on the edge of a rolling object has no velocity during the moment it's in contact with the ground



There is a momentary static friction force acting on the contact point, causing the object to move forward
***This is not rolling friction, this is just how rolling without slipping occurs**



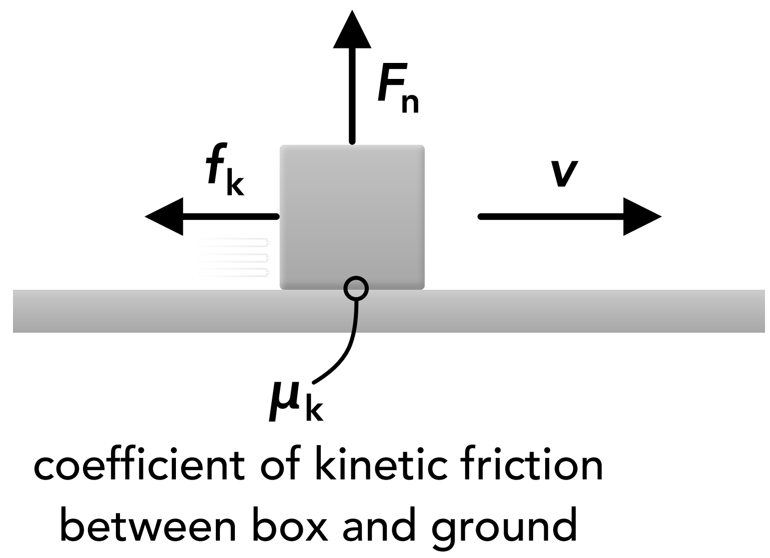
Kinetic Friction

- **Kinetic friction**, also referred to as **sliding friction** is a type of friction force that acts on a moving object in the opposite direction as its motion.
- More specifically, kinetic friction occurs between two surfaces that moving **relative to each other**. For example, the contact point on a tire does not move relative to the road as seen in the static friction section. Even though the car is "moving" that doesn't mean every friction force involved with the motion is kinetic friction.
- Unlike static friction, **kinetic friction does not depend on other forces along the same axis or the velocity**. It only depends on the normal force acting perpendicular to the surface and the coefficient of kinetic friction.
- For the same object, surface and normal force, **the kinetic friction will be less than the maximum static friction**.

Kinetic friction force

$$f_k = \mu_k F_n$$

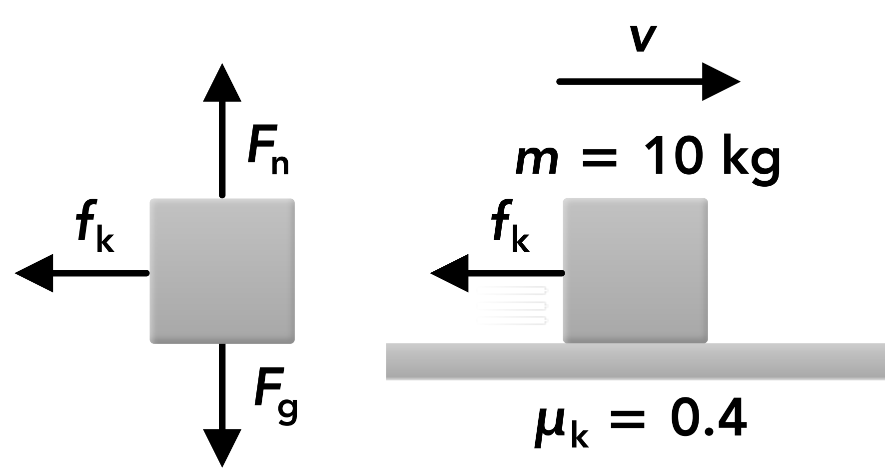
μ_k : coefficient of kinetic friction



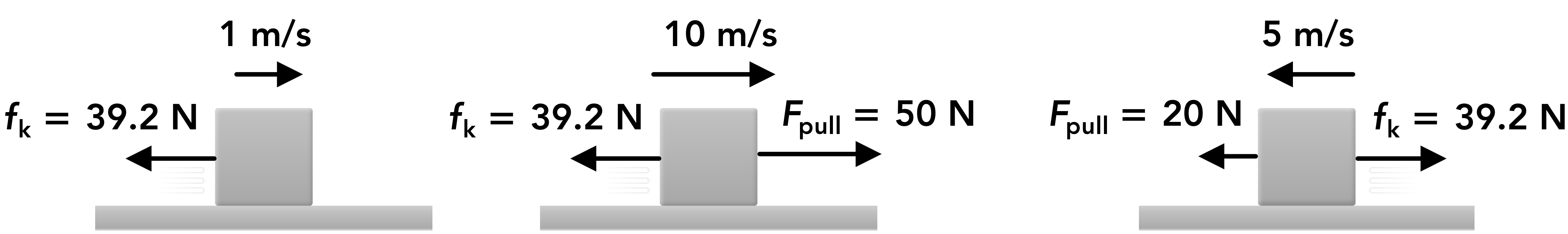
Example: A 10 kg box is sliding along the ground. The normal force between the box and the ground is equal to the weight force, 98 N. The coefficient of kinetic friction between the box and the ground is 0.4. The kinetic friction force is 39.2 N regardless of the velocity and any other horizontal forces.

$$\sum F_y = ma_y$$
$$F_n - F_g = m(0\text{ m/s}^2)$$
$$F_n = F_g = mg = (10\text{ kg})(9.8\text{ m/s}^2) = 98\text{ N}$$

$$f_k = \mu_k F_n = (0.4)(98\text{ N}) = 39.2\text{ N}$$



The kinetic friction force always acts in the opposite direction as the velocity and is always equal to $\mu_k F_n$



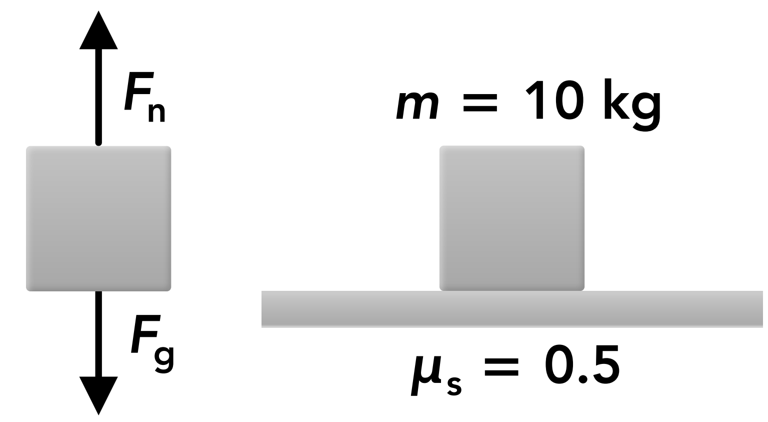
Transition From Static Friction to Kinetic Friction

- If an object begins at rest and a force is applied parallel to the surface, a static friction force acts on the object to prevent it from moving. If the applied force exceeds the maximum possible static friction force, the object begins to slide and the friction force transitions from a static friction force to a kinetic friction force.
- The magnitude of the static friction force changes based on the applied force, but the kinetic friction force is constant while the object is moving.
- The kinetic friction force is always **less than** the maximum static friction force.

Example: A 10 kg box is sitting on the ground at rest. The normal force between the box and the ground is equal to the weight force, 98 N. The coefficient of static friction between the box and the ground is 0.5. The maximum static friction force between the box and the ground is 49 N. A rightwards pulling force is then applied to the box.

$$\sum F_y = ma_y$$
$$F_n - F_g = m(0\ \text{m/s}^2)$$
$$F_n = F_g = mg = (10\ \text{kg})(9.8\ \text{m/s}^2) = 98\ \text{N}$$

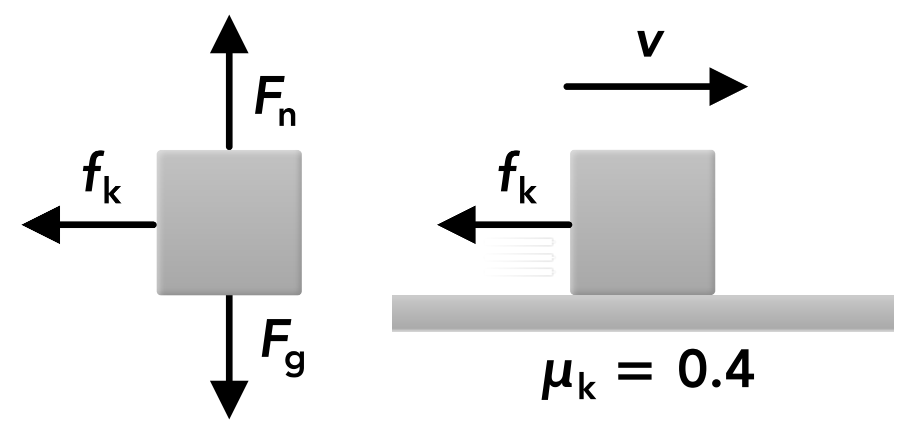
$$f_{s\ max} = \mu_s F_n = (0.5)(98\ \text{N}) = 49\ \text{N}$$



When the box is moving a kinetic friction force replaces the static friction force. The coefficient of kinetic friction between the box and the ground is 0.4. The kinetic friction force is always 39.2 N when the box is moving.

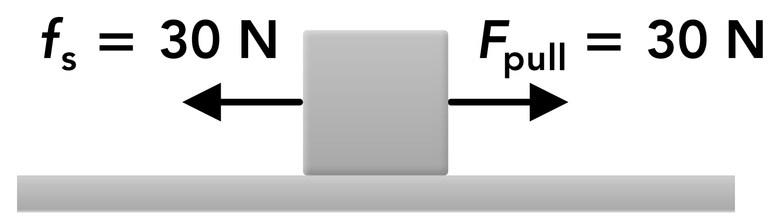
$$\sum F_y = ma_y$$
$$F_n - F_g = m(0\ \text{m/s}^2)$$
$$F_n = F_g = mg = (10\ \text{kg})(9.8\ \text{m/s}^2) = 98\ \text{N}$$

$$f_k = \mu_k F_n = (0.4)(98\ \text{N}) = 39.2\ \text{N}$$

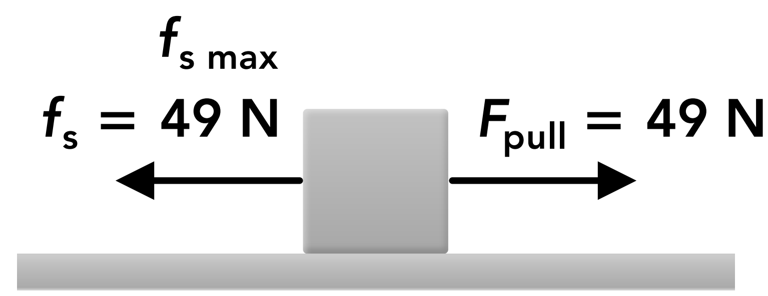


If the applied force is zero (there's no other forces acting parallel to the surface) there is no static friction force because there are no forces for friction to "react to" or any motion to prevent.

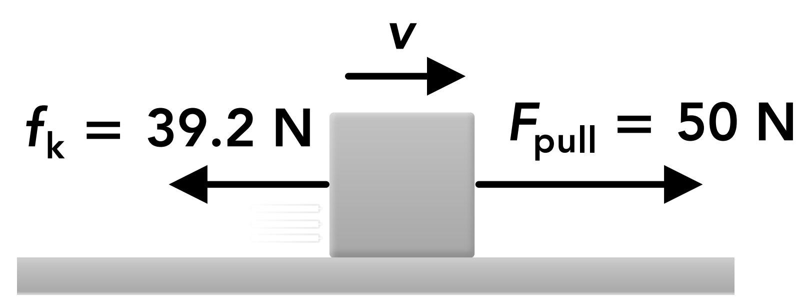
As the applied force increases, the static friction "reacts" and also increases so it has the same magnitude in the opposite direction.



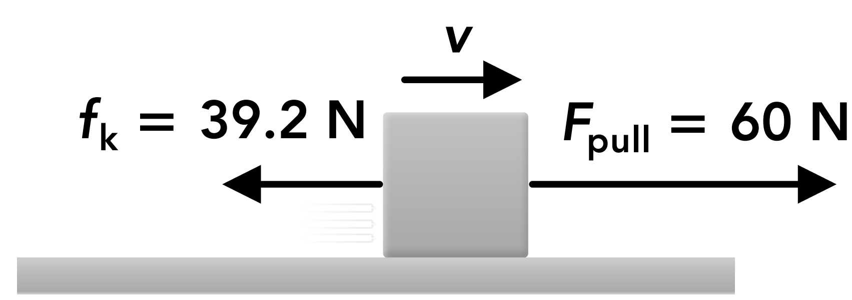
Eventually the applied force equals the maximum static friction force that's possible between the box and the ground.

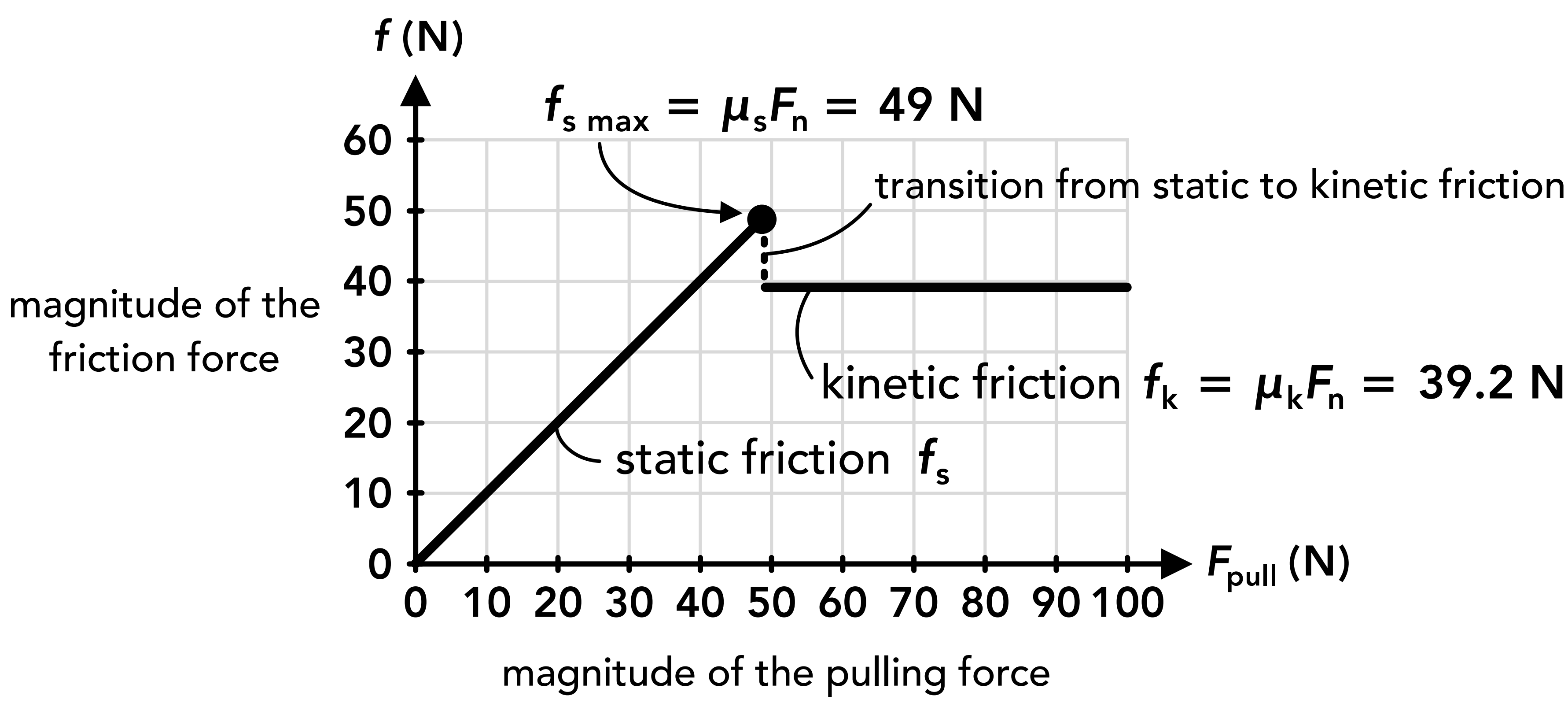


If the applied force is greater than the maximum static friction force, the box will begin to slide and the friction transitions from static friction to kinetic friction.



The kinetic friction force is constant regardless of the applied force or the velocity of the box.





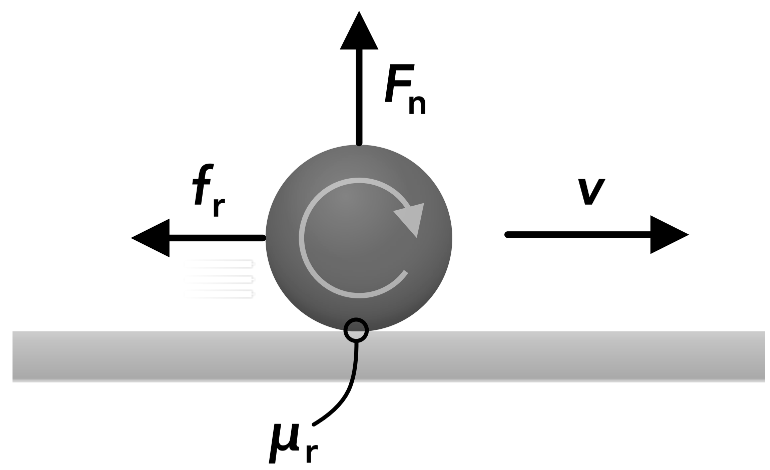
Rolling Friction

- **Rolling friction** is a type of friction force that acts on an object that is rolling on a surface, also sometimes referred to as **rolling resistance** or **rolling drag**.
- Rolling friction refers to the force acting on the object **while the object is rolling**, not a force that prevents a static object from beginning to roll (unless otherwise stated in a given scenario).
- When an object is rolling along the ground, the surface of the object deforms and interacts with the surface of the ground. This is a complex interaction with many factors, but the overall effect on the rolling object can be treated as a single rolling friction force.

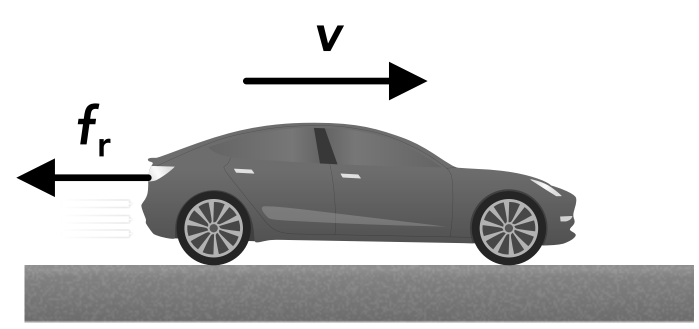
Rolling friction force

$$f_r = \mu_r F_n$$

μ_r : coefficient of kinetic friction

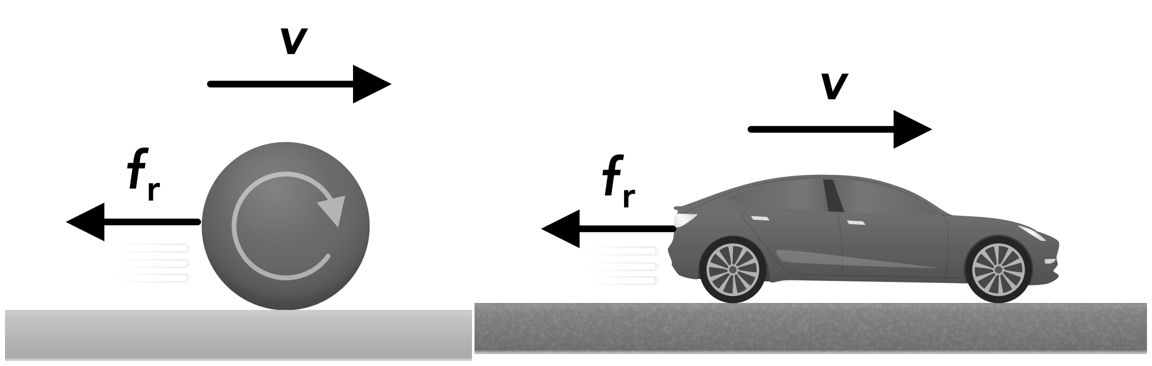


coefficient of rolling friction
between box and ground

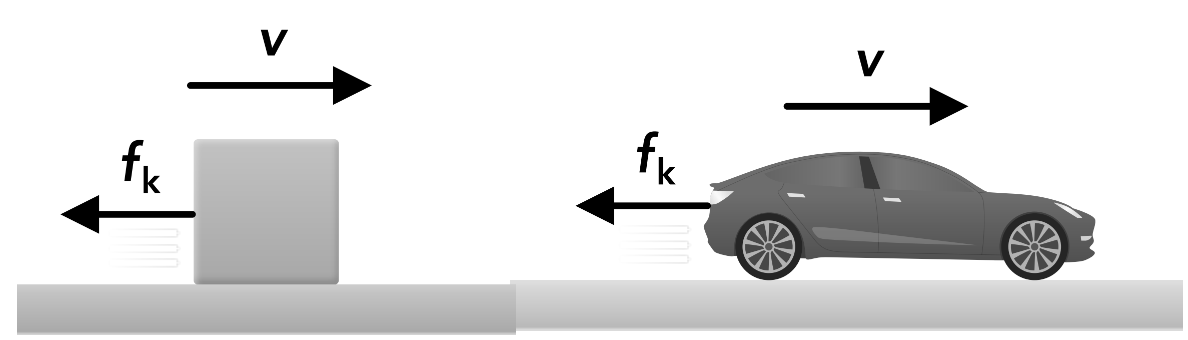


- Rolling friction should be thought of as an "overall friction force" acting a rolling object. This is in contrast to kinetic friction which acts on a sliding object. In most scenarios, only one of these two types of friction should be be used for a moving object.

Object or wheels are rolling without slipping,
rolling friction is used



Object or wheels are sliding,
kinetic friction (sliding friction) is used



car is sliding on ice, wheels are
slipping and not turning