Today:
- Friction, Drag
- Rolling without slipping
- Examples of Newton’s Second Law

Microscopic bumps and holes crash into each other, causing a frictional force.

![Diagram of atomic-level view of friction](image)

**FIGURE 6.19** An atomic-level view of friction.
The box is in static equilibrium, so the static friction must exactly balance the pushing force:

\[ f_s = F_{\text{push}} \]

This is not a general, “all-purpose” equation. It is found from looking at the free body diagram and applying horizontal equilibrium, since \( a_x = 0 \).

There’s a limit to how big \( f_s \) can get. If you push hard enough, the object slips and starts to move. In other words, the static friction force has a maximum possible size \( f_{s_{\text{max}}} \):

- The two surfaces don’t slip against each other as long as \( f_s < f_{s_{\text{max}}} \).
- The surfaces slip when \( f_s = f_{s_{\text{max}}} \).
- A static friction force \( f_s > f_{s_{\text{max}}} \) is not physically possible. Many experiments have shown that:

\[ f_{s_{\text{max}}} = \mu_s n \]

where \( n \) is the magnitude of the normal force, and the proportionality constant \( \mu_s \) is called the “coefficient of static friction”.
A wooden block weighs 100 N, and is sitting stationary on a smooth horizontal concrete surface. The coefficient of static friction between wood and concrete is 0.2. A 5 N horizontal force is applied to the block, pushing toward the right, but the block does not move. What is the force of static friction of the concrete on the block?

A. 100 N, to the left  
B. 20 N, to the left  
C. 5 N, to the left  
D. 20 N, to the right  
E. 5 N, to the right

A wooden block weighs 100 N, and is sitting stationary on a smooth horizontal concrete surface. The coefficient of static friction between wood and concrete is 0.2. A horizontal force is applied to the block, pushing toward the right. What is the maximum pushing force you can apply and have the block remain stationary?

A. 200 N  
B. 100 N  
C. 20 N  
D. 10 N  
E. 5 N
Kinetic Friction

The kinetic friction force is proportional to the magnitude of the normal force. Many experiments show the following approximate relation:

\[ f_k = \mu_k n \]

where \( n \) is the magnitude of the normal force, and the proportionality constant \( \mu_k \) is called the “coefficient of kinetic friction”.

Forces with general, “all-purpose” equations:

1. The force of gravity on an object near the surface of the Earth is always: \( \vec{F}_G = mg \), down.

2. The force of kinetic friction on an object which is sliding along a surface is always: \( \vec{f}_k = \mu_k n \), opposite to the direction of velocity relative to the surface.
A wooden block weighs 100 N, and is sliding to the right on a smooth horizontal concrete surface at a speed of 5 m/s. The coefficient of kinetic friction between wood and concrete is 0.1. A 5 N horizontal force is applied to the block, pushing toward the right. What is the force of kinetic friction of the concrete on the block?

A. 100 N, to the left
B. 10 N, to the left
C. 5 N, to the left
D. 10 N, to the right
E. 5 N, to the right

Rolling without slipping

Each point on rim moving at speed = \( v \) relative to center of wheel.

velocities relative to \( O \)  
velocities relative to road

\( 0 \) velocity at contact 

2v
Rolling Friction

- Due to the fact that the wheel is soft, and so is the surface upon which it is rolling. Plowing effect produces a force which slows down the rolling.

\[ f_r = \mu_r n \]

<table>
<thead>
<tr>
<th>Materials</th>
<th>Static $\mu_s$</th>
<th>Kinetic $\mu_k$</th>
<th>Rolling $\mu_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber on concrete</td>
<td>1.00</td>
<td>0.80</td>
<td>0.02</td>
</tr>
<tr>
<td>Steel on steel (dry)</td>
<td>0.80</td>
<td>0.60</td>
<td>0.002</td>
</tr>
<tr>
<td>Steel on steel (lubricated)</td>
<td>0.10</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Wood on wood</td>
<td>0.50</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Wood on snow</td>
<td>0.12</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Ice on ice</td>
<td>0.10</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>
Drag force in a fluid, such as air

- Air resistance, or drag, is complex and involves fluid dynamics.
- For objects on Earth, with speeds between 1 and 100 m/s and size between 1 cm and 2 m, there is an approximate equation which predicts the magnitude of air resistance

\[ D = (0.25 \text{ kg/m}^3)A v^2 \]

where \( A \) is the cross-sectional area of the object, and \( v \) is the speed.
- The direction of air resistance, or Drag Force, is opposite to the direction of motion.
- It depends on size and shape, but not mass.

Cross Sectional Area depends on size, shape, and direction of motion.

\( A = \pi r^2 \)
\( A = 2rL \)

…Consider the forces on a falling piece of paper, crumpled and not crumpled.
### Ch.6 force summary

Specific information about three important forces:

<table>
<thead>
<tr>
<th>Force</th>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>$\vec{F}_G = (mg, \text{ downward})$</td>
<td></td>
</tr>
<tr>
<td>Friction</td>
<td>$\vec{f}_k = (0 \text{ to } \mu_k n, \text{ direction as necessary to prevent motion})$</td>
<td>$\vec{f}_k = (\mu_k n, \text{ direction opposite the motion})$</td>
</tr>
<tr>
<td>Drag</td>
<td>$\vec{D} \approx \left( \frac{1}{2} \rho Av^2 \right)$</td>
<td>direction opposite the motion</td>
</tr>
</tbody>
</table>

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### Analyzing problems in segments

- The equations of chapters 1-6 help us solve problems in which the acceleration is constant.
- Sometimes the acceleration changes abruptly.
- In this case, divide the motion into segments: 1, 2, 3, …
- The final position and velocity of segment 1 become the initial position and velocity of segment 2, etc…
- Solve using the equations of constant acceleration for each segment.
A cyclist is pushing on his pedals, and therefore accelerating to the left.

What is the direction of the force of static friction of the ground on the back wheel?

A. Left
B. Right
C. Up
D. Down
E. zero

A cyclist is pushing on his pedals, and therefore accelerating to the left.

What is the direction of the force of static friction of the ground on the front wheel?

A. Left
B. Right
C. Up
D. Down
E. zero
4 discussion questions in a set. [3 / 4]

- A cyclist is pushing on his pedals, and therefore accelerating to the left.
- What is the direction of the force of rolling friction of the ground on the back wheel?

A. Left  
B. Right  
C. Up  
D. Down  
E. zero

4 discussion questions in a set. [4 / 4]

- A cyclist is pushing on his pedals, and therefore accelerating to the left.
- What is the direction of the force of rolling friction of the ground on the front wheel?

A. Left  
B. Right  
C. Up  
D. Down  
E. zero