Forces & Newton's Laws
(Chapters 2, 4, 5)

In our discussion with motion, objects accelerated for mysterious reasons. We will now explain why objects accelerate. Newton's law of motion is the physics of everyday and is the basis of your intuition. This chapter will put your intuition into the language of physics. Challenge: with motion it was difficult to not mix up velocity and acceleration; with Newton's laws it will be much more difficult, not to mix up acceleration and force. This difference will be much more subtle. One further note: since these "laws" (they really should be called rules not laws) describe the cause of motion, they define the states of motion: either (i) a = 0 or (ii) a ≠ 0 in terms of the net force, which will be shortly defined.

Newton's 1st Law

The 1st law appears to be "easy" and naïve, however, it is deep and in some sense, its probability the deepest concept we will cover. In some since, it is the basis for Einstein's general theory of relativity (the best theory we have that describes the large structure of the universe). Here are the key points:

- Defines what the **"natural" states of motion are, either at rest and constant velocity**. In essence, the first law sets up the basis to define what accelerated motion is, which we address with Newton's 2nd law.

- Defines the type of coordinate systems so that Newton's laws are valid. These coordinate systems are called inertial reference frames.

> **Newton's 1st Law**
>
> Things at rest tend to stay at rest. Things moving at a const velocity tend to continue moving at a const velocity UNLESS a force changes its state. That is, no force is required to be in these states of motion (**Force-free motion**)

INERTIA is the tendency of things to **resist changes in motion**

DEMO Air puck

Consider an "air hockey puck," it can have force free motion two ways:

i.   If an object is at rest, then

$$\text{rest} \rightarrow a = 0 \rightarrow \underbrace{\text{no net force is required to keep it al rest}}_{\text{force free motion}}$$

ii. If an object is moving at constant velocity, then

$$v = \text{const} \rightarrow a = 0 \rightarrow \underbrace{\text{no net force is required to keep it moving at } v = \text{const}}_{\text{force free motion}}$$

In fact, it would move at constant velocity forever, similarly to an asteroid moving through empty space.

DEMO Bowling ball and tennis ball

What state of motion is the tennis ball (or bowling ball) in? Do these two objects have the same state of motion? Yes. If I start to move these two objects, which object has a higher resistance in changing its rest state of motion, that is, which is harder to accelerate? Clearly the bowling ball, so we say that the bowling ball has a higher inertia than the tennis ball. A classic demonstration of inertia is as follows.

DEMO Penny and a wine bottle, Classic table cloth and dishes

Youtube Bed of nails & brick – http://www.youtube.com/watch?v=icXlTShblj0&feature=related

Analogy

In the physics sense of the word, inertia refers to laziness or the resistance to change to the state of the motion of an object. In the everyday sense of the word, inertia refers to a habit or a rut – resistance to change is difficult. For example,

- After eating a big meal (a large burrito at Vallarta's), it is hard to move. Therefore, your inertia has increased.
- Your mother asks you to take out the garbage. All of sudden, you've increased your inertia.

Mass & Weight

The amount of inertia depends on how much stuff (or matter) is inside an object. If I compare a lead and air filled tennis ball, the lead tennis ball has more stuff inside, and therefore, has a higher inertia. Mass is a measure of the inertia of a material object. For example, after eating a big burrito, it is hard to move because I've increased the amount of stuff inside of me and therefore, my inertia has increased. The tricky thing about mass is that we interpret mass as weight. It is easy to see why because **mass is directly proportional to weight**.

$$\text{mass} \equiv m \quad \text{vs.} \quad \text{weight} \equiv \text{force of gravity} \equiv mg$$

$$\boxed{\text{Mass} \propto \text{Weight}}$$

However, there is a difference between mass and weight, and here is why.

Suppose now that we decided to play catch with the tennis ball and I get to throw it and you have to catch it. When I throw the tennis ball with good speed, are will likely not be hurt when catching it. Why? The tennis ball has a small inertia and it is easy to change its state of motion. Suppose now that instead of the tennis ball, I throw the bowling ball. If I throw it with good speed, the bowling ball is more likely to hurt you. Why? The bowling ball has a large inertia and it is much harder to change its state of motion and consequently, the work that your body has to do to decelerate the bowling ball is what is hurtful. Now suppose we move up to empty outer space (Magic School Bus). The reason for the difference is that weight is the force of gravity, which is due to the earth acting on you. If you where in outer space very far away from all objects, there is no gravity and you would be "weightless." Caution: this is NOT the same as the commonly used expression of "weightless." If I now threw the bowling ball at you, would it still hurt you? Yes – why? It would be exactly the same as throwing it on earth because even though the bowling ball is weightless, it is NOT massless. And it is the massive property that is harmful because of its great tendency to remain in motion.

Here is a second example on inertia. "Top gun" pilots have long worried about taking a turn too tightly. As a pilot's body undergoes centripetal acceleration, the blood has inertia and wants to continue in a straight line, even though the plane is being forced to go in a circle. As a result, the blood pressure in the brain decreases and eventually leads to loss of brain function. There are several warning signs to signal a pilot to ease up: when the centripetal acceleration is 2g or 3g, the pilot feels heavy.

Centripetal Acceleration	Pilot Effect
1g	normal
2g or 3g	feels heavy
4g	vision switches to black & while, "tunnel vision"
4g or higher	g-LOC

If that acceleration is sustained or increased, vision ceases and, soon after, the pilot is unconscious—a condition known as **g-LOC** for "g-induced loss of consciousness." If an

unwary pilot caught in a dogfight puts the aircraft into a tight turn that exceeds 4g, the pilot goes into g-LOC almost immediately, with no warning signs to signal the danger.

Examples

- In terms of Newton's first law, how does a car headrest help to guard against whiplash in a rear-end collision while you are at a stop light?
- Push a cart and it moves. When you stop pushing, it comes to rest. Does this violate Newton's 1st law? Defend your answer.

Newton's 2nd Law

Any object that is not in force free motion (rest or moving at constant velocity) there must be an applied force acting on it; therefore, the object is accelerating. Newton's 2nd describes and gives the details of how these objects undergo acceleration. That is, since acceleration is a vector, it describes the magnitude and direction of the acceleration.

$$\text{Magnitude:} \quad \text{acceleration} = \frac{\text{Net Force}}{\text{mass}} \longrightarrow a = \frac{F_{net}}{m} \text{ or } F_{net} = ma$$

$$\underbrace{\qquad\qquad}_{F_{net} \text{ causes acceleration}}$$

Direction: The acceleration is always in the direction of the net force

Units of measurement for mass and force

$[F] = [ma] = kg \cdot m/s^2 = 1 \text{ Newton} = 1N$

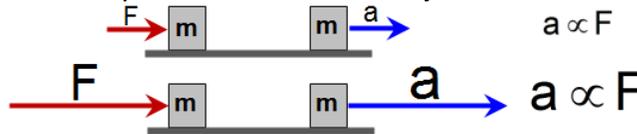| System	Force	Mass
Metric	Newton = N	kilogram = kg
English	Pounds = lbs	slug

$$\underbrace{200 \text{ lbs} \approx 850 \text{ N}}_{force} \longrightarrow \underbrace{85 \text{ kg}}_{mass}$$
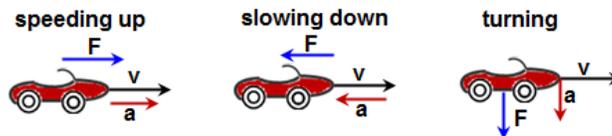
1 Newton = 0.225 lb ≈ cell phone

Remarks

1. Acceleration ∝ force: if I pusher harder on an object, it accelerates faster.

$a \propto F$

2. Acceleration ∝ 1/mass: if I apply the same force to two different masses, the heavier one is "harder to accelerate."

$a \propto \frac{1}{m}$
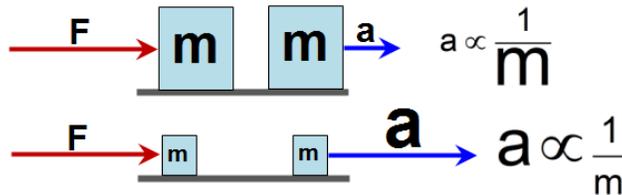
3. The acceleration is in the direction of net force:

Physical Interpretation

I will interpret Newton's 2nd law by breaking it up into two categories: (1) Force free motion ($F_{net} = 0$ or equilibrium or force-free motion) and accelerated motion ($F_{net} \neq 0$ or nonequilibrium).

Case 1: Equilibrium or Force-free states

From Newton's 2nd law, there are two ways to be in force-free state:

$$\vec{a} = 0 \longrightarrow \text{rest or constant velocity} \longrightarrow \vec{F}_{net} = 0$$

Physically, this means that ALL the forces acting on an object must **sum to zero** or **balance out**:

$$F_{net} = 0 \longrightarrow \begin{cases} F_{net}(\text{horizontal}) = 0 \longrightarrow F_{right} = F_{left} \\ F_{net}(\text{vertical}) = 0 \longrightarrow F_{up} = F_{down} \end{cases}$$

That is, to be in force free motion implies **at least two forces are acting in opposite directions**. Language-wise we say that if an object is at rest then it is in **static equilibrium;** if an object is moving at constant velocity then it is in **dynamic equilibrium**. In order words, in order to understand what causes an object to be in force free or accelerated motion, we will need to at the forces acting on the object. If the forces balance, we know it is in equilibrium; however, if unbalanced then it must be accelerating. We use force diagrams (FBD) to help understand the cause of the motion.

DEMO mass in your hand

For an object to be in static equilibrium, the net force must be zero. To see this consider a mass held up by your arm.

$$a = 0 \longrightarrow F_{net} = 0 \quad (\text{Forces balance})$$

$$\longrightarrow F_{up} = F_{down} \longrightarrow F_{hand} = mg$$
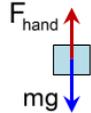
Key point: if the net force is zero, it doesn't mean that no forces are acting on the object at all. It means that at least two forces must be acting on the object that balances each other out.
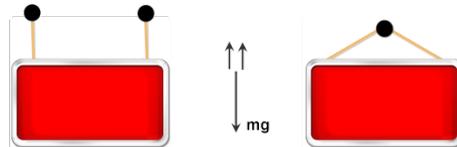
Example

Using the other form of Newton's 2nd law (F_{net} = ma), the weight of an object is determined by the force of gravity:

$$F_{net} = ma = mg = 1 \text{ kg} \cdot 10 \text{ m/s}^2 = 10N$$

DEMO Spring scale with 1 kg mass attached
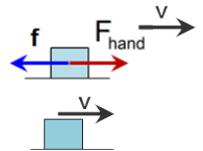
How is weight distributed with hanging picture frames?

DEMO push mass at constant velocity

Suppose I push this object across a table at a constant velocity. This means that

$$a = 0 \longrightarrow F_{net} = 0 \quad (\text{Forces balance})$$

$$\longrightarrow F_{left} = F_{right} \longrightarrow F_{hand} = F_{friction} = f$$

Friction **always** opposes the direction of motion. **Key point**: in the "real world" objects moving at constant velocity will 99% encounter friction, therefore, there must be at least two forces at work. However, if there is a frictionless environment, then no force will be required for the object to stay in dynamic equilibrium.

Example

When you fly in an airplane at night in smooth air, there is no sensation of motion, even though the plane may be moving at 800 km/h (500 mi/h). Why is this?

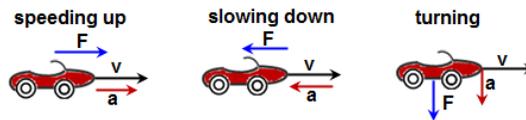**CASE 2: Nonequilibrium or accelerated states**

When objects accelerate then two things occur: (i) there are **unbalanced** forces and (ii) the object accelerates in the direction of the unbalanced force (F_{net}). That is,

$$a \neq 0 \longrightarrow F_{net} = F_{hand} - f \neq 0 \text{ (unbalanced)}$$

$$\longrightarrow F_{hand} > f$$

Newton's Laws - 4

DEMO Use a dynamics cart with a spring

Forces in acceleration and deceleration situations

$$F_{net} = ma = m\frac{\Delta v}{\Delta t} \longrightarrow \begin{cases} m\dfrac{\Delta v}{\Delta t} = ma = F_{net} \quad \text{(small force)} \\[2ex] m\dfrac{\Delta v}{\Delta t} = ma = F_{net} \quad \text{(large force)} \end{cases}$$

Examples
- Truck hitting a hay stack vs. a brick wall
- airbags
- Boxing glove vs. bare-fisted punch
- Catching a baseball bare handed
- Race car drivers

Youtube High dive (Stan Lee's) http://www.youtube.com/watch?v=WYkU21xBgpU

DEMO Throw an egg into a sheet

Example: During free fall motion of a ball, when the ball reaches its maximum height is the ball in equilibrium or nonequilibrium motion? Nonequilibrium! Why - there is an unbalanced force (F_{net}) acting on the ball:

$$a = g \neq 0 \longrightarrow F_{net} = mg \neq 0 \text{ (unbalanced)}$$

Weird and Interesting
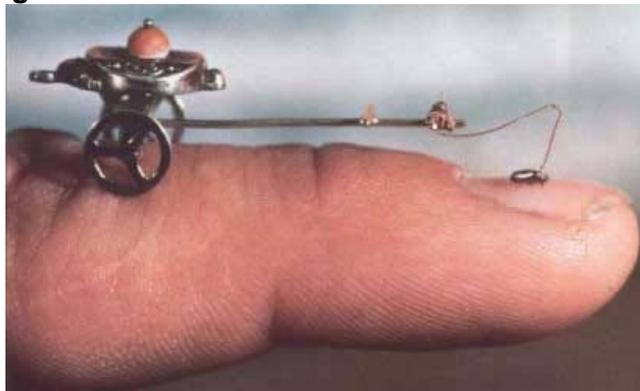
This photo shows a flea pulling a toy cart. Maria Fernanda Cardoso has created a circus of trained fleas and toured with them. Cardoso used a thin wire to attach Brutus, "the strongest flea on Earth," to a toy train car. She then used sound and carbon dioxide to induce Brutus to hop. Videos show that when Brutus hops, the train car jerks through a distance of about one centimeter. This is an amazing feat because **the mass of the toy train car is 160,000 times greater than that of a flea**.

Forces & Free Fall Motion

By definition, free fall motion is defined when the only force acting on a projectile is the force of gravity. In chapter 2 and 4 we saw that two objects in free fall (a heavy and a lighter object) hit the ground at the same time when dropped simultaneously. Do they hit the ground simultaneously because the same force of gravity acts on both objects? NO! The force of gravity does not act the same for both masses because $F_g = mg$ is mass dependent, and both of these objects have different masses. Newton's 2nd law shows that
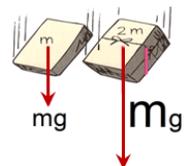
$$a = \frac{F_{net}}{m} \longrightarrow \frac{mg}{m} = \frac{\mathbf{m}g}{\mathbf{m}} = g$$

Because it does not depend on the mass, we say that it is **mass independent**.

DEMO (i) airless tube, (ii) incline plane with two different masses

VIDEO feather and hammer on the moon: http://www.youtube.com/watch?v=-4_rceVPVSY

WEIGHTLESSNESS – an example of free fall motion

Suppose you are in an elevator standing on a weight scale. What does the scale read for each of the following cases?
- Stationary - normal
- Accelerating upward – feel heavier
- Accelerating downward – fell lighter
- Free fall – the scale would read zero.

Because the scale reads zero one states that you are weightless.

Questions: Is a force acting on you? YES - gravity

Applet Newton's Cannon

Newton's Cannon and orbiting round the planet Earth

Suppose you are a passenger in the space shuttle Atlantis. As you orbit Earth, you float through your cabin. What is going on?

Both you and the shuttle are in uniform circular motion and have accelerations directed toward the center of the circle. Again by Newton's second law, centripetal forces must cause these accelerations. This time the centripetal forces are gravitational pulls (the pull on you and the pull on the shuttle) by Earth, radially inward, toward the center of Earth. In the shuttle, the centripetal force is Earth's gravitational pull on every atom of your body. Thus, there is no compression (or pull) on any one part of your body and no sensation of a force acting on you. (The sensation is said to be one of "**weightlessness**," but that description is tricky. The pull on you by Earth has certainly not disappeared and, in fact, is only a little less than it would be with you on the ground.)

CASE 3: Falling with air resistance – nonequilibrium and equilibrium motion

Air Resistant force F_{air}

Air resistance is a force that is produced by all the air molecules "**blocking**" the path of a moving object. It depends on two things:
- Size of the object: smaller (larger) area, less (more) interaction of the air and therefore, smaller (larger) air resistant force. Example – drop a crumble vs. flat sheet of paper.
- Speed of the object: faster (slower) moving object encounters more (less) air, and therefore will experience a larger (smaller) air resistant force. Example: when walking one does not notice the air resistance of the air, however, when riding a bike we immediately feel the air resistant force F_{air}.

Let's drop a feather (or coffee filter) in air. We will not be able to ignore air resistance, so it acts as a frictional force. So what happens when I drop it?

1. At first the feather starts from rest; if it is not moving then there is no air resistive force. The only force acting on the feather is gravity, which is an unbalanced force.
2. So the feather accelerates from rest and speeds up. If the feather is speeding up, it is encountering more air and the air resistive force F_{air} will increase. The faster it

moves, the larger the resistive force grows. The result is that the net force acting on the feather is getting smaller and therefore, accelerates at a slower rate.

$$\underbrace{F_g > F_{air}}_{F_g \text{ is greater than } F_{air}} \longrightarrow F_{net} > 0 \text{ (accelerates)}$$

3. As the feather goes faster and faster, the air resistant force gets larger and larger until the air resistant force balances out the force of gravity. That is,

$$\underbrace{F_g = F_{air}}_{F_{air} \text{ balances out } F_g} \longrightarrow F_{net} = 0 \text{ (constant velocity)}$$

At this point, the feather slowly floats downward at constant velocity to the ground.
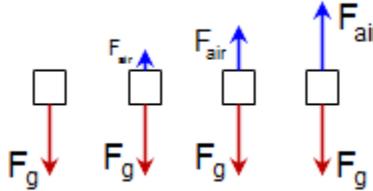
4. When the speed of a falling object reaches this constant velocity, we call this **terminal velocity** $\equiv v_{term}$.

> The **terminal velocity** (**speed**) is the speed of an object when dynamic equilibrium is established between F_{air} and F_g.

Properties of terminal velocity
DEMO
- Drop a flat sheet of paper vs. a textbook simultaneously. Compare areas & weights. Which one hits the ground first?
- Place the flat sheet of paper on top of the book and drop them again. How is the time of fall related to each other? Why did the sheet fall at the same rate as the book?

These demonstrations show that area and weight plays a major role in the fall speeds (and in turn terminal velocity) of objects.

1. An object that has a larger area has more air molecules hitting the surface of the object.

|	
larger area $\longrightarrow$ larger F_{air} $\longrightarrow$ smaller v_{term}
smaller area $\longrightarrow$ smaller F_{air} $\longrightarrow$ larger v_{term}
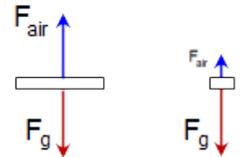
DEMO use a crumble vs. flat sheet of paper

As a consequence, an object with a larger (smaller) area reaches terminal velocity quicker (longer).

2. An object with less weight will need to encounter less air molecules to build up its air resistive force to balance out the force of gravity, and reach terminal velocity.

less weight $\longrightarrow$ smaller F_{air} to balance F_g $\longrightarrow$ lower v_{term}
more weight $\longrightarrow$ larger F_{air} to balance F_g $\longrightarrow$ higher v_{term}
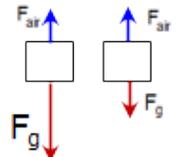
DEMO book and flat sheet of paper

As a consequence, a heavier (lighter) object will take longer (shorter) to reach terminal velocity.

Terminal Speeds in Air			
Object	Terminal Speed (m/s)	(mph)	Distance (m)
Baseball	42	95	210
Tennis Ball	31	70	115
Basketball	20	45	47
Shot Put	145	325	2500
Sky Driver (head down position)	60	135 200	430
Parachutist	5	11	3

An interesting application of objects that do not reach terminal velocity and one that does, is of cats' falling out of buildings.

Cats Falling Out of Apartment Buildings

Cats, which enjoy sleeping on window sills, are often kept in apartment buildings. When a cat "accidentally" falls out of a window and onto a sidewalk, the extent of injury (such as the number of fractured bones or the certainty of death) **decreases** with the height if the fall is more than7 or 8 floors. There is even a record of a cat that fell 32 floors and suffered only slight damage to its thorax and one tooth. How can this be?

A cat must fall about 6 floors (about 60 ft) to reach v_{term}. A good way to look at this is what happens to the cat that falls from a height of less than 6 floors verses a cat fall from more than 6 floors. Either way, one has to analyze the force diagram to understand each of the two situations.

Falling from less than 6 Floors

When a cat falls from less than 6 floors, the cat **does not** reach v_{term}. The reason for this is that the air resistance has not had enough time to build up to counteract the weight of the cat. Physics wise, this means

$$v_{cat} \neq v_{term} \longrightarrow a \neq 0 \text{ (cat is accelerating)} \longrightarrow F_{net} \neq 0 \ (F_g > F_{air})$$

Side note

Imagine yourself on a city bus with no railing to hold on while standing up. How would you feel if the driver made a sudden turn or a sudden stop? Very uneasy!

So what does the cat feel? Since the cat senses that it is accelerating, it feels a F_{net} similar to you on an accelerating bus. Consequently, the cat gets frightened, which means

- tucks its feet and head in (smaller cat area)
- F_{air} decreases and v_{term} increases
- faster moving cat increase the possibility of serious injury when it hits the ground

Falling from more than 6 floors

When a cat falls from more than 6 floors, the cat **does** reach v_{term}. The reason for this is that the air resistance has had enough time to build up to counteract the weight force of the cat (i.e., the force of gravity). Physics wise, this means

$$v_{cat} = v_{term} \longrightarrow a = 0 \text{ (cat is not accelerating)} \longrightarrow F_{net} = 0 \ (F_g = F_{air})$$

Side note

Imagine yourself on a city bus again. If the bus driver is nice and drives at constant velocity, you cannot tell the difference between standing in the bus or standing on the ground.

So what does the cat feel?
Since it senses that it is **not accelerating**, it feels **no net force** acting on it and the cat relaxes similar to your relaxing on the bus moving at constant velocity:

- stretches out like a flying squirrel (larger cat area)
- F_{air} increases and v_{term} decreases
- slower moving cat reduces the probability of a serious injury

For example, if a call falls from below 6 floors it reaches a terminal velocity of 60 mph while its feet are tucked in. On the other hand, a cat falling from above 6 floors that stretch out during terminal velocity reduces its terminal velocity to 40 mph. Apparently this difference in speed is the difference between serious injury or survivable injury.

Newton's 3rd Law

Begin with I can't touch you, without you touching me in return. I can't nudge this hair without the chair in turn nudging me back. That is, I can't exert a force on a body without that body in turn exerting a force on me.

Whenever there are two interacting objects,
1. Any **contact** between two objects has a **single interaction** between two things.
2. This single interaction requires **two forces**.

It is Newton's 3rd law that describes these details.

Newton's 3rd law (the Action-Reaction law)
Whenever one object exerts a force on a second object (i.e., some kind of contact), the second object exerts and **equal and opposite force** on the first.

Conceptual Examples
1. Pushing on a wall.

3. Identify the action-reaction pair of forces.
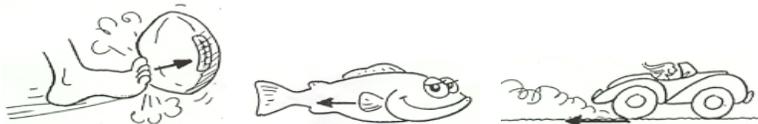
4. Mike Tyson in the ring with the instructor. When Mike punches me in the face who will feel a bigger impact force: my face or Mike Tyson's fist? Either according to the 3rd law.
5. I am driving my car at night and a bug smashes into my wind shield leaving a big gob. Who received the great impact force: the car or the smashed bug? Either.

DEMO Dynamics carts collision
According to Newton's 3rd law, any kind of crash or collision of any sort will have the same impact force. However, the impact force will result in different accelerations. For example, consider the case with bug collide with a car wind shield. According to Newton's 3rd and 2nd law,
- 3rd law tells us that the impact forces are the same: $F_{wind\ shield} = F_{bug}$.
- 2nd law tells us that the acceleration will depend only on the mass:

$$\Rightarrow \frac{F}{m} = a \Rightarrow \begin{cases} \dfrac{F}{m} = a & \rightarrow \text{ a large mass has a very small acceleration} \\ \dfrac{F}{m} = a & \rightarrow \text{ a small mass has a very large acceleration} \end{cases}$$

- The car's acceleration is so small that a person will not detect. However, a small bug will experience a very large acceleration which is what kills it.

It is the acceleration (or deceleration) that causes all of the damage (if not death) in certain situations. Once again, **it is the acceleration that kills a person in fatal car accidents according to Newton's 2nd law:**

$$F = ma \Rightarrow \begin{cases} F = ma & \rightarrow \text{ a small acceleration results in a small force} \\ \mathbf{F} = m\mathbf{a} & \rightarrow \text{ a large acceleration results in a large force} \end{cases}$$

Accelerating cars and friction

Examples: (i) Why can it hurt your foot more to kick a big rock than a small pebble? (ii)

Accelerating cars and friction

Interesting Point

On earth, whenever one turns a door knob there will always be a force applied by the door knob on your hand in the opposite direction that you turn it (Newton's 3rd law). The reason why you do not feel the reaction force is that your feet are anchored by the force of gravity and friction opposes the motion. It literally stops you from rotating.

Astronauts on the very first trip into space had major problems in turning a screw outside the space craft. Let me explain. When one of the astronauts tried to turn a knob on the outside of the space craft, because there was no way to anchor his feet and there is friction in space, when he tried to turn the knob, the knob applied an equal and opposite force that made him rotate. In fact, the astronaut took about an hour to finally turn the knob and in the process lost 10 lbs of water due to sweating. So how did they solve this problem for future flights – add foot petals so their feet locked in place.