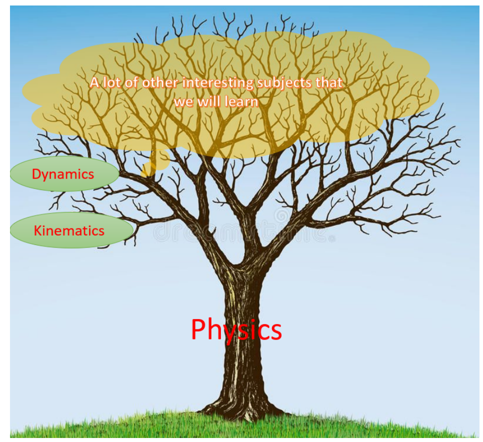
INERTIA AND NEWTON'S LAWS
NOVEMBER 6, 2023

Theory recap



Our last class was concluding our exploration of kinematics. Kinematics is a branch of physics that tells us how to describe the motion geometrically: in space and time. We have learned about distance, displacement, speed, velocity, acceleration and reference frames. But we did not ask the question: what caused the motion? In kinematics it was enough to know that motion occurs, and then we were able to relate some physical quantities to other physical quantities (like we related acceleration and time to change in velocity).

Today we start considering dynamics. Dynamics is another branch of physics and, as opposed to kinematics, it is concerned with reasons causing motion. These reasons are interactions with other objects.

Newton's first law. Why should there be any interactions for motion to occur? Cannot an object be in motion just by itself? It can, but only if it is already in motion. If the object does not interact with anything else, it will continue moving with the same velocity. In particular, if it was moving with zero velocity (which means it stayed at rest), it will continue to stay at rest in the absence of interactions with other objects. This is called **the law of inertia or Newton's first law** after Sir Isaac Newton, who has laid the foundation of classical mechanics more than 350 years ago.

It makes perfect sense that if a body at rest does not interact with anything, it will stay at rest. It takes a little bit more effort to understand that the same principle applies to motion with constant velocity. Imagine a puck on very smooth ice. After being hit, it will go at almost constant velocity (almost because there is still a tiny leftover friction). If the ice is even smoother, the velocity will change even less. We conclude that if there was no friction at all, the velocity would just stay constant indefinitely.

In slightly different words, Newton's first law tells us that in order to change its velocity, an object should interact with something else. In other words, some **force** should act upon it.

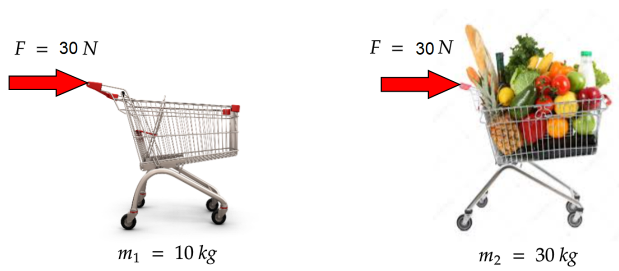
Newton's second law. Newton's first law does not tell us how will velocity change if there is some force acting on the object. To address this question we need **Newton's second law**: force F causes an object of mass m to move with acceleration a which depends on force and on object's mass. The connection between the three quantities is expressed by the formula:

$$F = ma$$

As we can see, for heavier objects acceleration produced by the same force is smaller. In this formula we encounter one familiar physical quantity - acceleration, and two new quantities - force and mass. Recall that acceleration tells us how velocity is changing with time and let us discuss force and mass now.

First, let's talk about mass. Although sometimes confused in everyday life, mass is not the same thing as weight. Weight is how much an object presses on the surface supporting it (and weight is actually a force, as we will discuss later). Weight of an object would be different in an accelerating elevator or on other planets (we will come back to that in further classes). Mass, on the other hand, is a measure of inertia and is always the same. For any object mass could be calculated from Newton's second law by acting on it with a known force F and measuring acceleration a. Then $m = \dfrac{F}{a}$. In physics mass is measured in kilograms (kg) or in grams (g): 1 kg = 1000 g.

Now we move on to discuss force. A big part of our course will deal with different kinds of forces, some examples being: gravity force, normal force, friction force, elasticity force. What is common to all of them is that they describe how different bodies act upon each other. We will talk about them in detail in several next classes. Unit of force is called Newton and denoted by N. The force of 1 N acting on a body with mass 1 kg creates an acceleration 1 m/s^2, or $1\ \text{N} = 1\ \dfrac{\text{kg}\cdot\text{m}}{\text{s}^2}$.



For example, consider a shopping cart. Suppose an empty shopping cart has a mass $m_1 = 10$ kg. After you load it with groceries you need for the next week total mass of the cart becomes $m_2 = 30$ kg. If you push the cart with the same effort (same force), say 30 N, the heavier cart will have a smaller acceleration than the lighter cart. How many times smaller? Denote accelerations of the carts by a_1 and a_2 respectively. Let us use Newton's second law:

$$F = m_1 a_1 \Rightarrow a_1 = \frac{F}{m_1} = \frac{30\ \text{N}}{10\ \text{kg}} = 3\ \frac{\text{N}}{\text{kg}} = 3\ \frac{\text{m}}{\text{s}^2}$$
$$F = m_2 a_2 \Rightarrow a_2 = \frac{F}{m_2} = \frac{30\ \text{N}}{30\ \text{kg}} = 1\ \frac{\text{N}}{\text{kg}} = 1\ \frac{\text{m}}{\text{s}^2}$$

So a shopping cart three times heavier gets acceleration that is three times smaller.

Homework

1. Why do we need seatbelts in a car?
2. Many automobile passengers have suffered neck injuries when struck by cars from behind. How does the law of inertia apply here? How do headrests help to guard against this type of injury?

3. Two closed containers look the same, but one is packed with lead and the other with few feathers. How could you determine which had more mass if you and the containers are orbiting in a weightless condition in outer space?

4. An accelerating airplane takes 30 seconds to reach the takeoff speed of 100 m/s. Mass of the airplane is 60 tons (1 ton is 1000 kilograms). Find the force acting on the airplane during the acceleration process. Express it in N; use scientific notation.