CHAPTER 4:   NEWTON'S LAWS OF MOTION

Objectives: This chapter will present Newton's laws of motion.   By the end of the chapter you will be able to use Newton s laws to calculate forces and accelerations in everyday, practical situations.

4.1 Newton's Laws

Newton's three laws of motion are as follows.

Law 1. Bodies move at constant, unchanging speed unless acted on by a force.
Law 2. The mass times the acceleration of a body equals the sum of all forces acting on that body.
Law 3. Whenever you exert a force, an equal counterforce is exerted back on you.

First Law: This is common sense. Things don't usually speed up or slow down by themselves. Something must act, a force must cause the change.

Second law: This is probably the most important and useful equation in all of physics.   Mass is an amount of stuff, and, unlike weight, is the same everywhere, even in space. If g is the acceleration of gravity, then weight can be written in the following equation:

The difference between mass and weight can be easily seen, here. The mass is the same everywhere, but the weight is less or more, depending on how strong gravity is wherever you re at.   Weight is a force, and is measured in pounds in the English system, or Newtons in the MKS system. Mass is not a force, and is measured in slugs in the English system, kilograms in the MKS system. The gravitational acceleration on Earth, g, is 9.8 meters per second squared, or 32 feet per second squared.

Example 1. Slugs. Find your mass in slugs, given that you weigh 150 pounds on Earth.

Solution: Start with the equation for weight, and divide both sides by g

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Dump in the numbers, getting:

Example 2. Moonweight. Find your weight on the moon if you weigh 150 pounds on Earth.
Solution: On the moon, the acceleration of gravity, g_{moon}, is about 1/6 that on your weight is about 1/6 your weight on Earth, but your mass is the same. So your weight is given by

Now that we have a better feeling for what mass is, as opposed to weight, we can write down Newton s second law in mathematical form:

F=force in Newtons (or pounds, British system)
m= mass in Kilograms (or slugs, British system)
a= acceleration in meters per second per second (feet per second per second in British units)

If there are more forces, just add them together on the left-hand side. Three forces, for example, would be:

Force is a vector, as is acceleration, though if there is only one direction of motion in the problem, vectors aren t needed. Newton s law originally wrote his law in terms of the change of the momentum, mv, but that will be taken up later.

Example 3. A rocket pack on the back of an astronaut exerts a thrusting force of 100 Newtons. If the astronaut has a mass of 70 kilograms, what is his acceleration, assuming he doesn t spin?

Solution: Here, F=100 N. and m=70 kg. Plug into the second law:

Example 4. A paratrooper jumps out of an airplane. Ignoring air friction, how fast is he going after 5 seconds?

Solution: This is a ballistics problem, but in fact it comes from the second law. The force of gravity is F=-mg. Newton s second law then says

In gravity problems, the mass cancels. This is actually very interesting and special why the mass associated with acceleration should be the same as the mass used to get the gravity force. At any rate, cancel the m s and get

Now we use ballistics. The acceleration times the time, plus any original velocity, , is the velocity of the body.

So we see that the ballistics problems are just special cases of Newton s laws.

Example 5. A car having a mass of 1000 kilograms accelerates at 5 meters per second per second. What force is the engine exerting?

Solution: Here, we have m=1000 kilograms and a=5 m/s^2. Stick them in Newton s second law:

The last equation defines the MKS units of force in terms of kilograms, meters, and seconds.

Third Law: This at first may seem strange: when you push on something, it pushes back! We usually don't notice this because we unconsciously brace ourselves. Stand flat-footed next to a wall and push, and of course you fall backwards. If you're out in space and push on something, it goes one way and you go the opposite way. You may have also noticed that when you throw something hard, you unconsciously brace yourself. These are all third-law situations.

Example 6. Jack and Jill are astronauts on a space walk. Jack has total mass, including suit, of 110 kilogram, while Jill has total mass of 95 kilograms. Jill, annoyed with Jack, gives him a push, exerting a force of 10 Newtons for two seconds. (A) What is Jack's acceleration? (B) What is the counterforce on Jill? (C) What is Jill's acceleration? (D) At what speed is each astronaut going after two seconds?

Solution: (A) We can get Jack's acceleration from F=ma. F=10 N., m=110 kg. Divide through by Jack's mass.

(B) The counterforce on Jill is just -10 meters per second per second, the negative of the force she exerted on Jack.

(C) Jill's acceleration can now be obtained by F=ma, where F=-10 m/s^2 and m=95 kg.

Jill's acceleration is a little greater, because she doesn't mass as much.

(D) To get the velocities after 2 seconds, just multiply the accelerations by time, . For Jack,

The minus sign just means they're moving in opposite directions.

Notice that the first law is a consequence of the second law. Acceleration is the change of velocity with time, and will be zero, by Newton s second law, if the force is zero. This last sentence is a restatement of the first law in different words. The third law is also closely related to the second law, but that s much harder to see.

4.2 More Examples

Easy problems require only a cursory examination of Newton's three laws. Most involve simple applications of ***F=ma***. Typical steps are:

1. **Write down the F=ma equation.**
2. **Plug in and solve for the unknown quantity**

Example 7. The Box and the Rhino. A box with mass 40 kilograms rests on a frictionless surface. A rhinoceros pushes it with a horizontal force of 200 Newtons. (A) What's the acceleration? (B) Same problem, with friction a friction force of 100 Newtons acting in the opposite direction.

Solution: (A) This can be solved with Newton's second law. Let be the mass of the box, the acceleration.

(B) More on friction will be given in the next chapter. Here, it's easy. We just subtract the friction force from the rhino force, and set equal to ***ma***:

Example 8. Flying Leap. To test Newton s laws, you leap out of an airplane, skydiving towards the ground below, reaching a terminal velocity of 120 miles per hour. If your mass is 70 kg, what is the magnitude of the air drag force?

Solution: This is, in fact, very similar to part (B) of the previous problem. Let F_{drag} be the drag force. 'Terminal velocity' is a constant velocity that results when the upward force of air friction, at sufficiently high speed, exactly cancels the downward force of gravity. Then the net acceleration is zero:

Example 9. Braking Car. A 2,000 kg car traveling 100 m/s manages to brake uniformly (that is, steadily, at a constant rate) to 50 m/s in four seconds. What is the magnitude of the force slowing it down , assuming it is constant? Note: Physicists rarely use the word deceleration acceleration can be positive or negative, depending on direction, and that covers it.

Solution: Use Newton's second law. Let ***m*** be the mass of the car, ***a*** is acceleration, ***F*** the braking force. First, find the acceleration.

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Next, plug into the second law:

Example 10. Speedboat Drag. A speedboat's engine is capable of applying a force of 3,500 Newtons. If the 1,000 kg boat accelerates through the water at 2 meters per second squared, what is the drag force?

Solution: This is actually very similar to the previous problem, which involved a friction force. Let ***m*** be the mass of the boat, ***a*** the acceleration, $\boldsymbol{F_E}$ the force of the engines, $\boldsymbol{F_D}$ the drag force,. Then:

Solve this for the drag force:

Example 11. Hippo vs. Rhino. A hippo and rhinocerous have a tug of war, battling over a 2 metric ton box of delectable vegetables. If the hippo pulls with a force of 1,000 N. in one direction and the rhino pulls with a force of 800 N. in the other direction, what is the net acceleration of the box?

Solution: Another easy problem. $\boldsymbol{m}$=mass of box, $\boldsymbol{F_r}$ = rhino force, $\boldsymbol{F_h}$ = hippo force. Let the hippo force be in the positive x-direction.

Example 12: Space Shuttle. What is the acceleration of the space shuttle after liftoff? DATA. Masses: orbiter: 75,000 kg; payload: 29,500 kg ; tank: 35,400 kg empty; fuel: 616,500 kg oxygen and 102,000 kg hydrogen; boosters: 590,000 kg each. Thrust: boosters 11,800,000 Newtons each at launch; space shuttle main engine: 1,700,000 Newtons each (there are 3 of them).

Solution: The two forces are the thrust of the rocket engines and the force of gravity. The total mass of the rocket at launch is 858,400 kg. We have

Add up all the thrusts, getting

Next, plug in the numbers.

Example 13. Skydiving. Suppose a 70 kg skydiver, at 10,000 meters and falling at 30 m/s, experiences a constant drag force of 750 N. (A) What is the net force? (B) What is theacceleration?

Solution: (A) There are two forces: the drag force and gravity force (and a negligible buoyancy force).

Notice that the drag force is positive, acting upwards.

(B) Newton's second law gives the acceleration:

Even though the skydiver is falling down, with negative velocity, the acceleration is upwards--because the skydiver is slowing down.

Example 14. Elevator. (A) What force must the cable of an elevator massing 2000 kg, including load, exert if the elevator is to rise at a steady speed? (B) Same question, except the elevator is accelerating upwards at 2 m/s ^{2}.

Solution: There are two forces, the cable force, called T for the tension in the cable, and the gravity force, mg. Newton's law reads

(A)At steady speed, there is no acceleration, so **$a=0$**. Plug this in and solve for **T**:

(B) Now the elevator is accelerating upwards, so set **$a=2\ m/s^2$**:

Example 15. Mud-Trucking. A truck going 20 meters per second hits a stream. The engine dies immediately, and the jeep slows to a stop in three seconds. If the mass of the truck is 1500 kg, what average force was applied to the truck by the mud and water of the river?

Solution: First find the average acceleration.

Next, plug into the second law:

There are other forces on the right-hand side, of course--the normal force and gravity force, for example--but here, only the horizontal forces count, in this case the mud and water drag on the truck.

Example 16. Stacking Elephants. One elephant stands on top of another elephant. Each elephant weighs 8,000 Newtons. In each case, each of their four legs takes an equal amount of weight. (A) What is the reaction force of the ground on the bottom elephant? (B) What is the reaction force of the back of the bottom elephant on the top elephant?

Solution: The total weight, w_{tot}, acting down on the earth is

So the reaction force is exactly this same number but acting up instead of down. (B) The top elephant exerts a downwards force of 8,000 Newtons on the back of the bottom elephant, so the reaction force is also 8,000 Newtons, acting up instead of down.