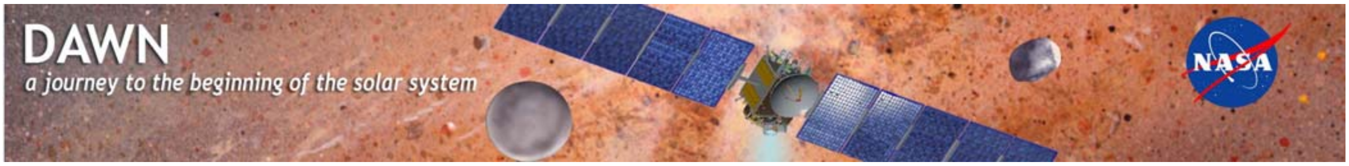


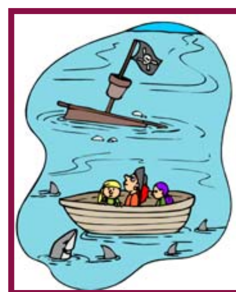
Ion Propulsion

Frames of Reference

STUDENT READING

Our goal is to develop an understanding of how an ion propulsion engine propels a spacecraft through outer space to a distant target such as an asteroid. In order to reach this goal we must have a firm understanding of the subtle nature of motion. So follow along as we journey from some basic experiences involving motion to the application of Newton's third law to motion within the ion propulsion engine of the Dawn spacecraft.

Have you ever experienced the sensation of not knowing whether or you are moving or stationary while seated in a vehicle such as a train or airplane? Almost everyone has had this kind of an experience when the view to the outside world is restricted in such a way that visual background clues are minimized. This phenomenon is particularly noticeable while looking through small "porthole" style airplane windows that provide a very restricted view of the outside world. If one observes an adjacent plane "moving" it sometimes is difficult to determine whether that plane is actually moving or whether the plane you are seated in is moving. In this case, you need a stationary object (such as the terminal building) against which to make a visual assessment of movement.



The point is that <u>motion is relative</u> and the entire concept of motion is very subtle because it depends on the chosen **frame of reference**. It is useful to pursue this a bit more with some additional examples. Let's assume you are in a lifeboat with no oars and no engine in the middle of an ocean (a terrible predicament for sure) and another boat comes into view. Without any navigation aids, how do you determine your motion relative to the other boat? Is your boat stationary? Is the other boat is moving? Or is the other boat stationary and your boat moving? Or are both boats moving simultaneously? If you define yourself as the observer, you might decide that you are motionless and the other boat is moving as it comes into view. On the other hand, if the people on the other boat are the observers, they might decide that they are motionless and your boat is moving toward them. Motion is relative and it is necessary to define "relative to what." Let's consider one more example. Assume you are in the batter's box and a pitcher throws a 90 mph fastball in your direction. As the batter, you decide that the ball is clearly in motion relative to your position at the plate. But what would happen if the baseball were the "observer"? Wouldn't the baseball regard itself as stationary and decide that you and the bat were hurtling toward it at 90 mph? It all depends on the frame of reference.

This brings us to Newton's laws, which describe and predict the way in which an object moves – but moves with reference to what? Let's say we want to analyze the motion of a ball dropped inside an airplane traveling at 300 miles per hour. Should we carry out the analysis with respect to the interior of the airplane or with respect to the surface of the Earth? Does it make a difference which choice we make? Surely you would think it might be easier to do the calculations with respect to the airplane. If you make this choice, your frame of reference would be the interior of the airplane. Now let's put this in a celestial context. On Earth we generally have a fixed background against which we assess movement. A car passes us by and we define the car as moving because we view it with respect to the fixed background of trees and so on. We conclude that we are stationary, but the car is moving. But are we really stationary? What would an observer on the Sun conclude about our motion? That observer would see us as moving (as well as the car) because of the motion of the Earth relative to the Sun. Well, what about the Sun? Is it stationary? Not really, because the solar system is moving within our galaxy. Is our galaxy stationary? Of course it is not.

Now consider analyzing the motion of a ball dropped within the interior of an orbiting spacecraft. Should the motion of the ball be calculated with respect to the spacecraft interior, or relative to the Earth, or relative to the Sun, or relative to the galaxy? Each choice would be regarded as a frame of reference. It should be clear that the concept of motion must be handled with care.

Physicists know that among all options, the “frame of the stars” is the proper choice for the application of Newton’s equations. Clearly, this is not the most convenient frame for someone sitting on the surface of the Earth or, for that matter, in an orbiting spacecraft. It is much easier to analyze motion and apply Newton’s laws relative to immediate surroundings.

To handle the application of Newton’s laws physicists often (but not necessarily) choose a local frame that, relative to the rest of the universe, moves in a straight line with a constant velocity (note that standing still is moving with a constant velocity of zero meters per second). Such a frame is said to be an **Inertial Frame of Reference.** An inertial frame of reference can then be defined as a coordinate system that is not accelerating.

This leads to the Dawn spacecraft. Can its overall motion be analyzed with an inertial frame of reference? Strictly speaking, the answer is “no,” because it is accelerating and it is not traveling in a straight line. Its motion must be analyzed in an accelerated frame of reference and this is far beyond what we want to consider here.

Having said all of this, we are left with the proposition of understanding how the Dawn spacecraft is propelled on its journey to Ceres and Vesta. To gain this understanding we will define a local frame of reference that is very much like defining the interior of an airplane as a frame of reference for analyzing the motion of a falling ball. We will choose the interior of the spacecraft as a frame of reference and assume that at any moment it is traveling at constant velocity and in a straight line. These are not bad assumptions since the acceleration is very small and the curvilinear distances involved are very large. Within the frame of reference so defined, we can apply Newton’s laws and understand how an accelerated plasma can be used to propel the spacecraft toward its destination. (If you have not done so by now, read the handout called “Pushing with Plasma” before proceeding)

Let’s remind ourselves specifically of Newton’s third law—for every action there is an equal and opposite reaction. Within the spacecraft, plasma is created inside of a chamber. Situated at one end of the spacecraft are charged screens through which xenon ions can pass. Now let’s imagine applying a potential to the screens such that the xenon ions in the plasma are accelerated through the screens and are directed away from the spacecraft. We see that we would have a mass of xenon ions accelerated in one direction. Within the frame of reference defined as the interior of the spacecraft, Newton’s law requires that there be an equal and opposite reaction. That is to say, the spacecraft itself accelerates in a direction opposite to the acceleration of the xenon ions. This action/reaction couple is the mechanism—an ion propulsion engine– by which Dawn will be accelerated toward its destination. Note that in principle even one xenon ion would provide acceleration of the spacecraft (albeit vanishingly small!). The more xenon ions that are accelerated the higher the acceleration of the spacecraft. Now this leads to the beauty of an ion propulsion system. Even a small amount of "fuel" (xenon) provides acceleration. If the spacecraft is in deep space and is not in the grip of a strong gravitational force, very little acceleration is required to keep it moving toward its destination. In fact, the force by which the spacecraft is propelled is about the same as the force you feel when a sheet of paper rests on your hand. It is not much, but it is enough. And very little xenon fuel is required, especially when compared to the fuel required by a chemical rocket. For very long space flights, ion engines are an ideal means of propulsion.

Dawn Spacecraft Assembly
NASA/JPL

Questions:
Write complete sentences on a separate sheet to explain your answer.

1. Consider the following situation. You are riding on a school bus and are juggling three oranges. Ultimately, you wish to analyze the motion of the oranges by applying Newton's laws.
    a. Give two conditions that must be met for the interior of the bus to be used as an inertial frame of reference.
    b. If the windows of the bus were covered and the road was perfectly smooth, would you be able to determine whether or not the bus was moving?
    c. If you analyzed the motion of the oranges while the bus is traveling at 60 miles per hour and again while it is standing still, would you arrive at the same answers?
    d. Could you get any clues from the motion of the oranges as to whether or not the bus was moving?
    e. If the bus driver suddenly slammed on the brakes, slowing the bus from 60 miles per hour to a stop in a few seconds, would you be able to continue to juggle the oranges during the deceleration of the bus?
    f. During the deceleration of the bus, would it still qualify as an inertial frame of reference?

2. Consider juggling a set of three oranges while seated on a merry-go-round. Would it be possible to analyze the motion of the oranges within the context of an inertial frame of reference?

3. Consider standing on the surface of the Earth and juggling three oranges. Since the Earth is rotating and orbiting the Sun, is it possible to analyze the motion of the oranges within the context of an inertial frame of reference?