2.1: The Law of Inertia

There is something funny about motion with constant velocity: it is *indistinguishable from rest*. Of course, you can usually tell whether you are moving *relative to something else*. But if you are enjoying a smooth airplane ride, without looking out the window, you have no idea how fast you are moving, or even, indeed (if the flight is exceptionally smooth) whether you are moving at all. I am actually writing this on an airplane. The flight screen informs me that I am moving at 480 mph relative to the ground, but I do not feel anything like that: just a gentle rocking up and down and sideways that gives me no clue as to what my forward velocity is.

If I were to drop something, I know from experience that it would fall on a straight line—relative to me, that is. If it falls from my hand it will land at my feet, just as if we were all at rest. But we are *not* at rest. In the half second or so it takes for the object to fall, the airplane has moved forward 111 meters relative to the ground. Yet the (hypothetical) object I drop does not land 300 feet behind me! It moves forward with me as it falls, even though I am not touching it. *It keeps its initial forward velocity*, even though it is no longer in contact with me or anything connected to the airplane.

(At this point you might think that the object is still in contact with the air inside the plane, which is moving with the plane, and conjecture that maybe it is the air inside the plane that "pushes forward" on the object as it falls and keeps it from moving backwards. This is not necessarily a dumb idea, but a moment's reflection will convince you that it is impossible. We are all familiar with the way air pushes on things moving through it, and we know that the force an object experiences depends on its mass and its shape, so if that was what was happening, dropping objects of different masses and shapes I would see them falling in all kind of different ways—as I would, in fact, if I were dropping things from rest outdoors in a strong wind. But that is not what we experience on an airplane at all. The air, in fact, has no effect on the forward motion of the falling object. It does not push it in any way, because it is moving at the same velocity. This, in fact, reinforces our previous conclusion: the object keeps its forward velocity while it is falling, in the absence of any external influence.)

This remarkable observation is one of the most fundamental principles of physics (yes, we have started to learn physics now!), which we call the **law of inertia**. It can be stated as follows: in the absence of any external influence (or *force*) acting on it, an object at rest will stay at rest, while an object that is already moving with some velocity will keep that same velocity (speed and direction of motion)—at least until it is, in fact, acted upon by some force.

Please let that sink in for a moment, before we start backtracking, which we have to do now on several accounts. First, I have used repeatedly the term "force," but I have not defined it properly. Or have I? What if I just said that forces are precisely any "external influences" that may cause a change in the velocity of an object? That will work, I think, until it is time to explore the concept in more detail, a few chapters from now.

Next, I need to draw your attention to the fact that the object I (hypothetically) dropped did not actually keep its *total* initial velocity: it only kept its initial *forward* velocity. In the downward direction, it was speeding up from the moment it left my hand, as would any other falling object (and as we shall see later in this chapter). But this actually makes sense in a certain way: there was no forward force, so the forward velocity remained constant; there was, however, a vertical force acting all along (the force of gravity), and so the object did speed up in that direction. This observation is, in fact, telling us something profound about the world's geometry: namely, that forces and velocities are *vectors*, and laws such as the law of inertia will typically apply to the vector as a whole, as well as to each component separately (that is to say, each dimension of space). This anticipates, in fact, the way we will deal, later on, with motion in two or more dimensions; but we do not need to worry about that for a few chapters still.

Finally, it is worth spending a moment reflecting on how radically the law of inertia seems to contradict our intuition about the way the world works. What it seems to be telling us is that, if we throw or push an object, it should continue to move forever with the same speed and in the same direction with which it set out—something that we know is certainly not true. But what's happening in "real life" is that, just because we have left something alone, it doesn't mean the world has left it alone. After we lose contact with the object, all sorts of other forces will continue to act on it. A ball we throw, for instance, will experience air resistance or drag (the same effect I was worrying about in that paragraph in parenthesis in the previous page), and that will slow it down. An object sliding on a surface will experience friction, and that will slow it down too. Perhaps the closest thing to the law of inertia in action that you may get to see is a hockey puck sliding on the ice: it is remarkable (perhaps even a bit frightening) to see how little it slows down, but even so the ice does a exert a (very small) frictional force that would bring the puck to a stop eventually.

This is why, historically, the law of inertia was not discovered until people started developing an appreciation for frictional forces, and the way they are constantly acting all around us to oppose the relative motion of any objects trying to slide past each other.

This mention of relative motion, in a way, brings us full circle. Yes, relative motion is certainly detectable, and for objects in contact it actually results in the occurrence of forces of the frictional, or drag, variety. But *absolute* (that is, without reference to anything external) motion with constant velocity is fundamentally undetectable. And in view of the law of inertia, it makes sense: if no force is required to keep me moving with constant velocity, it follows that as long as I am moving with constant velocity I should not be feeling any net force acting on me; nor would any other detection apparatus I might be carrying with me.

What we do feel in our bodies, and what we can detect with our inertial navigation systems (now you may start to guess why they are called "inertial"), is a *change* in our velocity, which is to say, our *acceleration* (to be defined properly in a moment). We rely, ultimately, on the law of inertia to detect accelerations: if my plane is shaking up and down, because of turbulence (as, in fact, it is right now!), the water in my cup may not stay put. Or, rather, the water may try to stay put (really, to keep moving, at any moment, with whatever velocity it has at that moment), but if the cup, which is connected to my hand which is connected, ultimately, to this bouncy plane, moves suddenly out from under it, not all of the water's parts will be able to adjust their velocities to the new velocity of the cup in time to prevent a spill.

This is the next very interesting fact about the physical world that we are about to discover: forces cause accelerations, or changes in velocity, but they do so in different degrees for different objects; and, moreover, the ultimate change in velocity *takes time*. The first part of this statement has to do with the concept of *inertial mass*, to be introduced in the next chapter; the second part we are going to explore right now, after a brief detour to define *inertial reference frames*.

Inertial Reference Frames

The example I just gave you of what happens when a plane in flight experiences turbulence points to an important phenomenon, namely, that there may be times where the law of inertia may not *seem* to apply in a certain reference frame. By this I mean that an object that I left at rest, like the water in my cup, may suddenly start to move—relative to the reference frame coordinates—even though nothing and nobody is acting on it. More dramatically still, if a car comes to a sudden stop, the passengers may be "projected forward"—they were initially at rest relative to the car frame, but now they find themselves moving forward (always in the car reference frame), to the point that, if they are not wearing seat belts, they may end up hitting the dashboard, or the seat in front of them.

Again, nobody has pushed on them, and in fact what we can see in this case, from outside the car, is nothing but the law of inertia at work: the passengers were just keeping their initial velocity, when the car suddenly slowed down under and around them. So there is nothing wrong with the law of inertia, but *there is a problem with the reference frame*: if I want to describe the motion of objects in a reference frame like a plane being shaken up or a car that is speeding up or slowing down, I need to allow for the fact that objects may move—always relative to that frame—in an *apparent* violation of the law of inertia.

The way we deal with this in physics is by introducing the very important concept of an *inertial reference frame*, by which we mean a reference frame in which all objects will, at all times, be observed to move (or not move) in a way fully consistent with the law of inertia. In other words, the law of inertia has to hold *when we use that frame's own coordinates to calculate the objects' velocities*. This, of course, is what we always do instinctively: when I am on a plane I locate the various objects around me relative to the plane frame itself, not relative to the distant ground.

To ascertain whether a frame is inertial or not, we start by checking to see if the description of motion using that frame's coordinates obeys the law of inertia: does an object left at rest on the counter in the laboratory stay at rest? If set in motion, does it move with constant velocity on a straight line? The Earth's surface, as it turns out, is *not* quite a perfect inertial reference frame, but it *is* good enough that it made it possible for us to discover the law of inertia in the first place!

What spoils the inertial-ness of an Earth-bound reference frame is the Earth's rotation, which, as we shall see later, is an example of *accelerated motion*. In fact, if you think about the grossly non-inertial frames I have introduced above—the bouncy plane, the braking car—they all have this in common: that their velocities are changing; they are *not* moving with constant speed on a straight line.

So, once you have found an inertial reference frame, to decide whether another one is inertial or not is simple: if it is moving with constant velocity (relative to the first, inertial frame), then it is itself inertial; if not, it is not. I will show you how this works, formally, in a little bit (section 2.2), after I (finally!) get around to properly introducing the concept of acceleration.

It is a fundamental principle of physics that *the laws of physics take the same form in all inertial reference frames*. The law of inertia is, of course, an example of such a law. Since all inertial frames are moving with constant velocity relative to each other, this is another way to say that absolute motion is undetectable, and all motion is ultimately relative. Accordingly, this principle is known as the **principle of relativity**.