LAB 9b NONINERTIAL FRAMES

EXPERIMENTAL QUESTION

In this lab, you will explore the distinction between inertial and non-inertial reference frames. According to chapter N9, Newton’s second law *fails* to hold in a reference frame attached to an object that is accelerating relative to the ground. As a result, it *appears* as if strange forces act on objects moving in such frames.Your fundamental task in this lab is to observe how objects appear to behave in two different kinds of noninertial reference frames (a rotating frame and a frame that is linearly accelerating), observe how these objects look in the ground frame, and finally *explain* the objects’ strange behavior in the noninertial frame using your observations in the ground frame.

EDUCATIONAL PURPOSE

This lab will give you some concrete experience with the tricks that your mind plays on you when you are in a noninertial frame. This will make the discussion of accelerating reference frames in chapter N9 more meaningful.

EQUIPMENT

This experiment has two parts, a “cart part” and a “merry-go-round part”. The equipment for the **cart part** of the experiment is as follows:

- A cart, like you used for the Newton’s 3rd Law lab
- A bicycle helmet
- A spring-loaded gun for launching a ball vertically in the air
- A setup that uses a falling weight to accelerate the car through a certain distance

This equipment will be available in the hallway. The equipment for the **merry-go-round part** is:

- A horizontal wooden board mounted on a bearing so that the board rotates around a vertical axis going through the board’s center
- A circular table mounted on the board centered on the axis of rotation
- A pendulum suspended so that its bob swings just above the rotating table-top.

Those sitting on the board will view the motion of the pendulum above the circular table from the rotating frame of the table, while someone standing on the floor will view its motion from the ground frame (see Figures 1a and 1b).

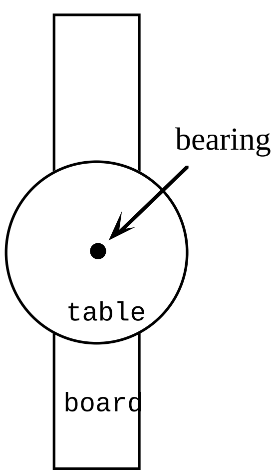

Figure 1a: Top view of the basic "merry-go-round" apparatus for this lab.

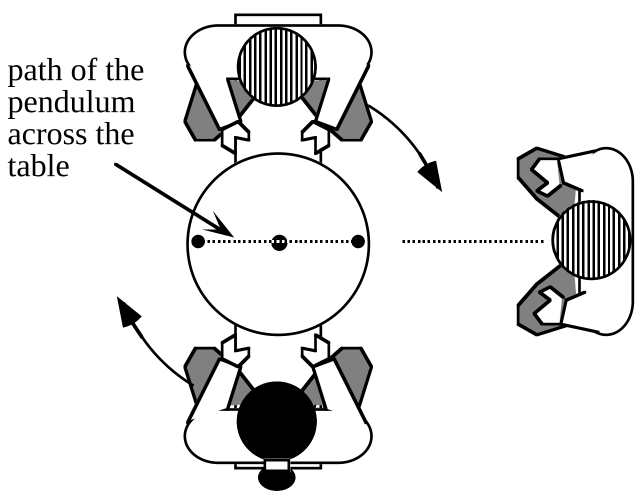

Figure 1b: This diagram shows the apparatus in use. The people sitting on the board are viewing the motion of the pendulum from the rotating frame of the circular table. The third person is viewing the situation from the frame of the ground.

PRE-LAB EXERCISE (for the merry-go-round part)

Before actually doing the lab, you should see if you can predict how the pendulum's motion will look when viewed in the frame of the rotating table. Figure 2 below shows how we can make a *qualitative* prediction of the motion. The left edge of the top row of the diagram shows the position of the pendulum at successive evenly spaced instants of time, and three top views of the rotating tabletop at the same successive evenly spaced instants of time appear immediately to the right. Imagine that when viewed from the frame of reference of the ground, the pendulum swings in a straight line (vertical on the diagram), starting at the bottom. The position of the pendulum bob at the first three instants of time can then be drawn successively on the three pictures of the board, as shown. Finally, by noticing where these positions fall relative to the coordinate axis on the table, one can reconstruct (on the diagram tabletop at the bottom) the path of the pendulum as viewed in the frame of the rotating table. (For example, the position of the bob at the second instant of time is seen to be a bit to the right and about 3/4 of the way down the vertical axis of the table, so that is where it is drawn on the diagram at the far right.) This process can be continued as far as necessary to get a good prediction of the pendulum's motion.

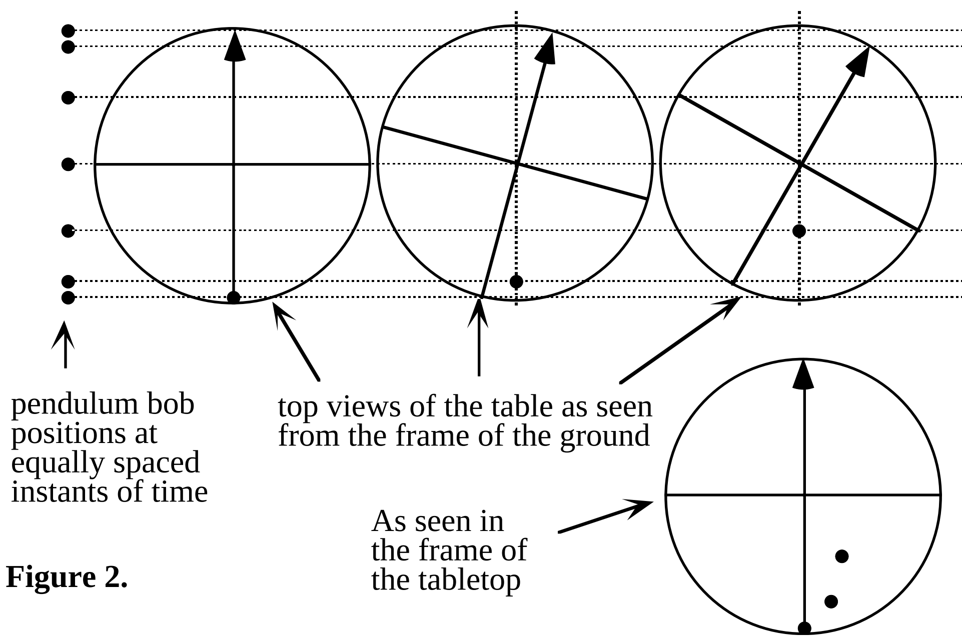

Figure 2.

On the facing page, you will find a worksheet with blank diagrams of the tabletop for two cases: one where the tabletop rotates one half turn for each complete cycle of the pendulum swing and one where the tabletop rotates a full turn for each such cycle. Using the technique shown in Figure 2, construct a sketch of the pendulum's motion (on the diagram labeled "as seen in the frame of the tabletop") for each of the two cases. **Do this before starting the lab**. Note that in making these predictions, you are using the entirely ordinary behavior of the pendulum in the ground frame to predict what the motion will look like in the rotating frame of the tabletop.

PROCEDURAL COMMENTS

You will do this short experiment during the ninth week of lab (the same week that you finish the *Simple Pendulum* lab). Your helper will let you know when it is your turn to do this lab.

The point of this lab is to gain experience with noninertial reference frames, not to take and analyze lots of data. Your notebook should provide a record of your *predictions* and *experiences*.

The Cart Part

In the cart part of this experiment (which you should do first), a person riding the cart will use a spring-gun to launch a ball vertically into the air. Both the person in the cart and the people

standing around the cart should observe the motion of the ball (1) while the cart is at rest, (2) while the cart is in uniform motion, and (3) while the cart is being accelerated forward by a constant force. Before you do the experiment, your team should discuss what you predict that (a) the person riding in the cart would see and (b) what people standing in the hall would see for each case. Be sure to describe your *predictions* to your helper. Then do the experiment to see what happens. Take turns so that everyone has a chance to see all three experiments from the point of view of the cart as well as from the point of view of the hallway. Does what you see agree with your predictions? What is special about the ball's motion when viewed from the frame of an accelerating cart?

The Merry-Go-Round Part

In the merry-go-round part of the experiment, two of you will ride the merry-go-round and the other will watch the pendulum swing back and forth from the ground. The ground-based observer should verify (by sighting along the pendulum's path) that the pendulum swings in a nice straight line back and forth. What do you see the pendulum doing in the rotating frame of the merry-go-round? Do you observe something like the patterns that you found in the pre-lab exercises? Make sure that everyone gets a chance to observe the pendulum's motion in both the ground frame and the rotating frame.

You should also try to set the pendulum in motion so that it travels in a circle around the rim of the circular table in the middle of the merry-go-round. Then set the merry-go-round rotating at the same angular speed. What does the pendulum look like in the merry-go-round frame? Would this kind of behavior be possible in a ground frame?

QUESTIONS TO PONDER

Instead of handing in an analysis summary for this lab, you will go through a mandatory checkout interview and take a short quiz after the interview. As you prepare for the checkout interview, think about answers to the following questions. You should also read the "Parting Comments" section below *before* you do your checkout interview.

Cart part:

1. How did the launched ball appear to move in both the ground and cart frames when the latter was moving at a constant velocity? Was there any difference in the motion? Are observations in both frames consistent with the idea that the only significant force acting on the ball is a downward force of gravity?
2. How did the launched ball appear to move in both the ground and cart frames when the latter was accelerating? Was there any difference in the motion? Are observations in both frames consistent with the idea that the only significant force acting on the ball is a downward force of gravity?
3. Does Newton's second law appear to hold in the accelerating cart frame? Why or why not?

Merry-go-round part:

1. What is some evidence that Newton's second law *does* adequately describe the motion of the pendulum in the ground frame?
2. What is the evidence that if Newton's second law were to be true in the rotating frame, there must be some very strange forces acting on the pendulum bob in this frame?
3. What is the evidence that these forces are not real forces arising from real interactions with external objects?
4. Imagine yourself on a playground merry-go-round that is turning rapidly. You can *feel* the centrifugal force pulling you outward! How can this force not be real? How might you explain what you feel *without* invoking the fictitious "centrifugal force"?

SOME PARTING COMMENTS
(Read this *after* doing the lab but before your Checkout Interview)

The point of merry-go-round part of the lab is that the pendulum bob *appears* to move along either a complicated curved path in the rotating reference frame (when it is really simply swinging back and forth in a straight line in the ground frame) or it is impossibly at rest (when its is moving in a circle in the ground frame). When you are riding the merry-go-round, it is hard to convince yourself that the pendulum is actually moving in a straight line, and you are tempted to explain the motion of the pendulum by imagining that it is acted on by some complicated forces.

Because the earth itself rotates, the ground frame (that we have been *assuming* to a good reference frame) is actually not exactly well-behaved either! Because the earth rotates very slowly, one doesn't usually need to worry about this when doing physics experiments, but the effects of the earth's rotation *can* be observed in certain circumstances.

For example, one can observe the motion of a pendulum in the rotating frame of the earth, just like we have viewed it in the frame of the rotating table. The effect is easiest to understand if we imagine that we set up a pendulum at the north pole of the earth so that the earth rotates under it in exactly the same manner as the table rotates under the pendulum in this lab. As the pendulum swings back and forth in a straight line with respect to the frame defined by the distant stars, its path as viewed on the earth will appear to be a many-lobed version of your first answer to the pre-lab exercise (many lobes because the pendulum will probably swing tens of thousands of times during the time that the earth rotates once). You may have seen a large **Foucault pendulum** in a science museum. (This pendulum is named after the French physicist who first described in detail the effect of the earth's rotation on the motion of a pendulum.) The line along which such a pendulum swings appears to rotate slowly with respect to the earth because of the earth's rotation (actually the earth is rotating under the constant swing direction of the pendulum!). Historically, this was one of the first experiments to show that the earth really does rotate (contrary to the ancient understanding that the stars and planets revolve around a motionless earth).

An object that is moving in a simple way relative to the distant stars *appears* in a rotating or accelerating reference frame to be acted on by a mysterious force that *seems* to cause it to accelerate away from its expected motion. This acceleration (and thus the force) is only *apparent* because what is really happening is that the frame is rotating or otherwise accelerating out from under the object as it moves in its simple path, making its motion appear to be more complicated than it really is. The forces that appear to act on an object in a rotating or otherwise accelerating reference frame are usually called *fictitious* (or sometimes *inertial*) *forces*.

When viewed from the rotating surface of the earth, large-scale wind and ocean currents seem to be bent by such fictitious forces. For example, imagine that you view the rotating earth from above the north pole, and imagine that you watch a hunk of air initially moving directly southward from the pole toward a low pressure zone somewhere in the middle latitudes. As the earth rotates eastward under this moving hunk of wind, the wind appears to veer to the west when viewed from the surface of the earth, even though the wind is moving straight south when viewed from outer space (see Figures 3). This tendency of winds to curve away from the very low-pressure zones that cause them to blow in the first place is what creates hurricanes, where the winds circulate endlessly *around* a severe low-pressure zone. If the earth did not rotate, air would simply flow in straight lines directly into any low pressure zone that might be created, filling it before it could develop into anything very severe.

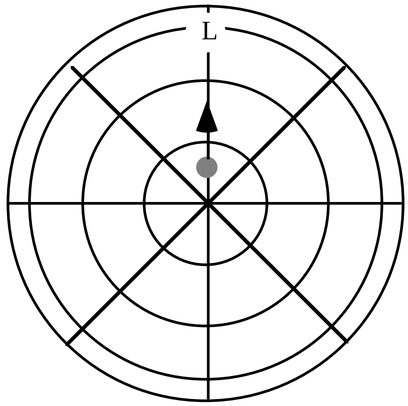

Figure 3a: This diagram shows the Earth viewed from an inertial frame directly above the North Pole. A hunk of wind (shown in grey) starts traveling southward toward a low-pressure zone near the Equator.

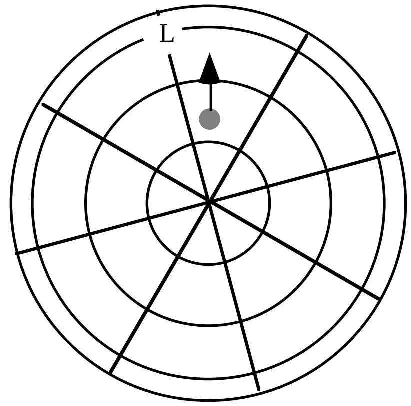

Figure 3b: The same scene a few hours later. The rotation of the Earth toward the east causes the hunk of wind to seem to deflect westward when viewed from the Earth's surface, even though the wind is traveling in a straight line when viewed from space.

The fictitious force that seems to hold the pendulum bob at rest at an angle in the rotating frame of the table is the well-known (or more accurately, frequently *imagined*!) **centrifugal** force, the same force that seems to pull you away from the center of a playground merry-go-round, pull you outward when you go around a corner in an automobile, or press you against the tracks at the bottom of a valley or the top of a loop-de-loop in a roller-coaster ride. Of course, there is no need to even think about this force if you use a proper reference frame to describe the situation.

Chapter N10 of the class text discusses fictitious forces and noninertial reference frames in more mathematical depth. This lab is meant to provide you with the background and experience to make the issues discussed in this chapter more real and comprehensible.