Chapter 13: Accelerated environments.

A. Consequences of Newton's 2nd Law for a human being

The forces acting on a human being are balanced in most situations, resulting in a net external force of zero. When standing, sitting or lying down the gravitational force on the body is balanced by the compression forces of the things on which we sit, stand or lie, acting on a localized part of our body. The objects we contact often have cushions that compress to generate the force needed to balance the gravitational force. The cushions, by conforming to the shape of our body, allow the compression forces to be applied more uniformly over the contacting surface, rather than at one point.

Placing your head on hard flat surface is uncomfortable because only a small portion of your curved head can contact the surface and it must compress a large amount to produce a force that balances the full weight of your head. The force can be applied more uniformly over the surface of the head by using a pillow. The many small forces produced over the surface of the pillow sum to the weight of the person’s head, and each small force produces only a small localized compression. In both cases, yhe gravitational force on the head is balanced by a compression force acting on the head, yet the human perception of in the two situations is very different.

Thus the perception of forces by the human body can be deceiving. The gravitational attraction between the earth and our various body parts compresses or stretches our body against another object. The body of a person in free fall, however, will have no other force but gravity acting on the body, and no compression forces will be generated within the body. The lack of compression is interpreted as “weightlessness” by the brain. Another consequence is that a liquid in tubes that are part of the inner ear is no longer pressing against the lower portion of the tubes. The brain interprets this in a way that can be nausiating. The gravitational force causes the acceleration of the person downward but this force is not perceived during the fall. Each part of the body is attracted by a gravitational force in proportion to its mass, thus creating a single acceleration with magnitude, g, for every body part.

There is no force, other than gravity, that can be applied in this democratic way over the body. Other forces can be applied to only one side (front, back, bottom, top, left or right) of the body. The net effect of these other applied forces cannot *uniformly* balance the gravitational force on the body and the resulting distortions of the body will always be felt by a human being. For most of us, the closest thing to this feeling occurs while swimming in water where the forces balancing gravity are distributed as evenly as possible over the body.

A person standing on the floor has a gravitational force applied over the entire body, but the compression of the floor applies the balancing force only to the bottom of the feet. applied only to the feet the balancing force causes an internal compression force that varies from the full weight of the body at the bottom of the feet to zero at the top of the head. This state of compression is what we call "normal" and any other state of compression or tension will be perceived as a different state.

B. Environments with a linear acceleration.

A car that accelerates from rest with an acceleration comparable to *g* has a startling affect within the human body. These effects and how they are perceived by human beings is at the heart of many misconceptions about forces. The material in this course provides tools to explain these feelings (and related ones) to another person without resorting to forces that have no apparent origin.

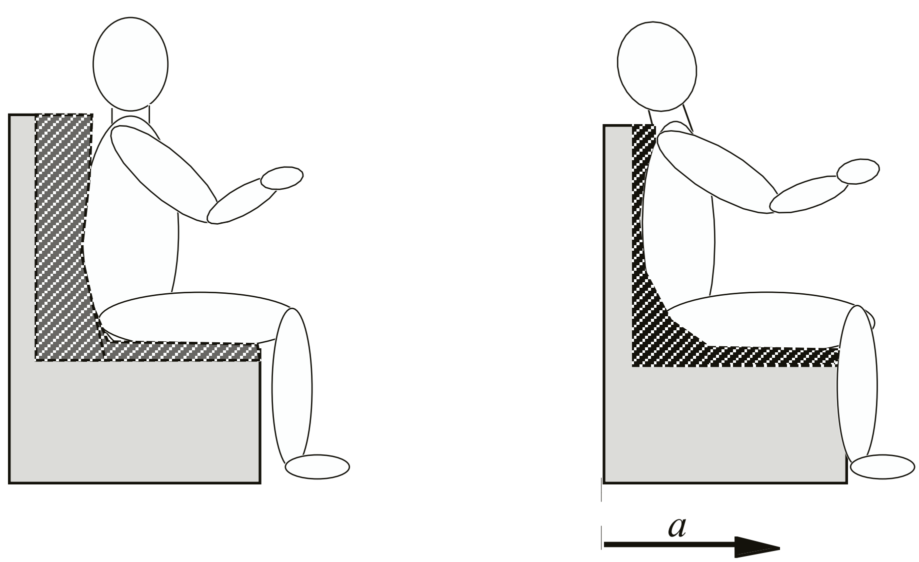

Figure 13.1 Person in a car at rest (left) and with a large acceleration (right)

The person in Figure 13.1 is shown on the left in a car at rest and on the right in the same car (with the gas pedal flat to the floor) with an acceleration comparable to *g*. We use the following words to describe a number of things that happen to the person in the accelerating car:

1. The head of the person is "pushed" backward.
2. The torso of the person is "pushed" into the back of the seat.
3. The chest of the person is "compressed" toward the persons back.

These effects are consistent with a "force" that operates in the opposite direction to the acceleration that "pushes" the head back, "pushes" the torso into the seat, and "compresses" the chest. This force is certainly not the gravitational force and couldn't be any electromagnetic force from an invisible object pressing against the person's chest. The origin of this "force" is mysterious to the driver. Looking at these effects from the point of view of someone standing stationary on the ground next to the car as it accelerates clears up the mystery. These effects can be explained in this non-accelerated "frame of reference" with the same rules that have applied in all other cases. An attempt to explain them in the accelerated frame will be confusing for many reasons, but primarily because the perception of forces by the human body cannot be trusted.

1. The head of a person at rest, shown on the left in Figure 13.2, is supported by a compression force, C , equal to the weight of the head. When the car accelerates the seat accelerates the body of the person forward along with the car.

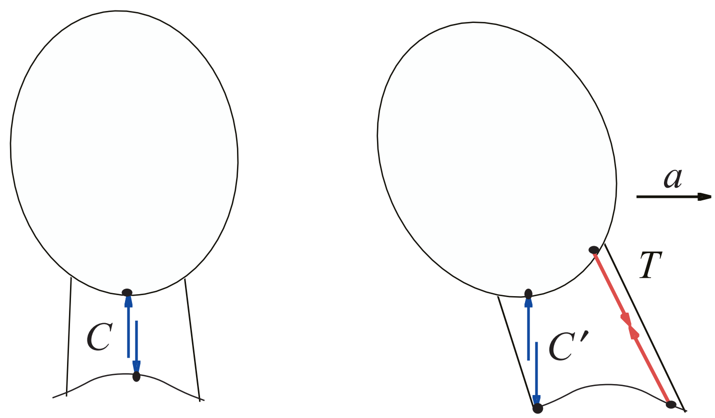

Figure 13.2 Elastic forces acting in the neck of a person at rest (left) and accelerating (right)

The seat does not contact the head and yet a net force is needed to accelerate the head forward with the car. The head would remain at rest if it were not for the stretch of the person's neck caused by the body accelerating forward, leaving the head behind, and generating a tension force, T, that pulls the head forward and down, as shown on the right in Figure 13.2. The downward part (component) of the tension is balanced by an increased compression force, C', at the back of the neck while the forward part of the tension force accelerates the head forward. *There is no force acting on the head in the backward direction.*

We experience this as a force "pushing" our head backward, when in truth, it is the body pulling forward, stretching the neck and pulling the head forward. When our necks are stretched in this way there is usually something pushing backward on the front of our head. Though we can't find the effects of someone's hand pressing on our face, we still interpret the motion of our head backward with respect to our body, incorrectly. If we take the time to correctly interpret the feelings we have in an accelerating car, there is no need to invoke any mysterious forces.

2. The torso is not "pushed" back into the seat. The seat of the car is accelerated forward toward the body of the person. As the seat moves forward the elastic materials or springs in the seat are compressed, as shown on the right in Figure 13.1. The more the

springs are compressed the harder they push on the torso. The front of the seat will continue to compress against our body until the compression force generated is large enough to accelerate the torso forward with same acceleration as the seat and the car.

3. The chest of the person is not "compressed" by any external force. The feeling of compression is caused by distortions of the inner organs of the body: the heart, lungs, stomach, intestines, etc. When the seat accelerates forward the only way the heart, located centrally in the torso, as shown in Figure 13.3, can be accelerated is if the person's back is moved toward the heart compressing the lung and other tissues between the back and the heart. The movement backward in the torso also stretches the tissues in front of the heart. These stretched tissues are attached to the ribs at the front of the torso and they pull the ribs inward and contribute to the acceleration of the heart by pulling it forward. In response to the stretched internal tissues, the ribs, considerably stronger than any of the internal organs, compress a small distance toward the back, generating a sufficient force to maintain the internal tension forces acting on the heart.

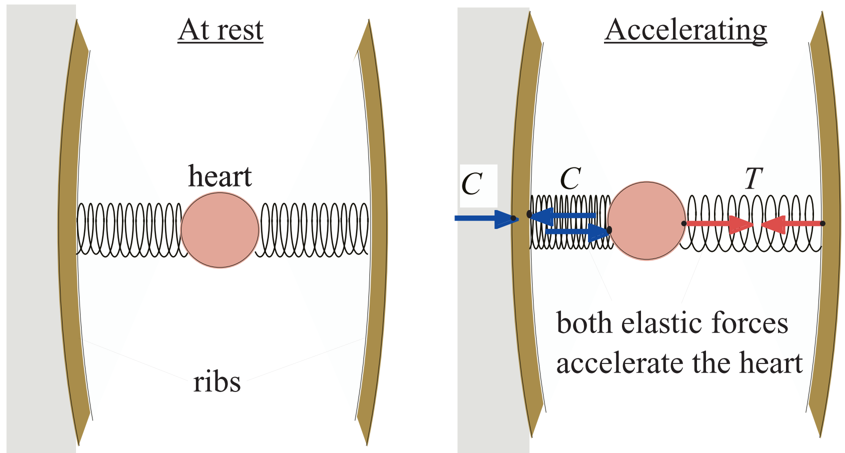

Figure 13.3 The ribs (brown) and heart (red) of a person as seen from the top in car at rest (left) and accelerating forward (right)

The ribs in the chest of a person are compressed if the person is lying down and a weight is placed on the chest. Human thought processes are so trained by these expectations that we cannot easily distinguish the compression of the ribs caused by a weight pushing inward and the compression caused by the internal tissues attached to the ribs pulling inward. Again we have been deceived by internal forces within our bodies that mimic those felt in other more common circumstances.

C. Circular motion and environments that are rotating

The changes that occur in our bodies in a rotating environment are so unusual that their interpretation can be easily mistaken without following the techniques developed in this chapter. Again the description of what occurs and what is felt is more easily explained in a "frame of reference" that is not rotating with respect things on the earth.

A classic rotating environment is the merry-go-round or rotating table. The interpretation of what is felt in this environment will require an introduction to rotations.

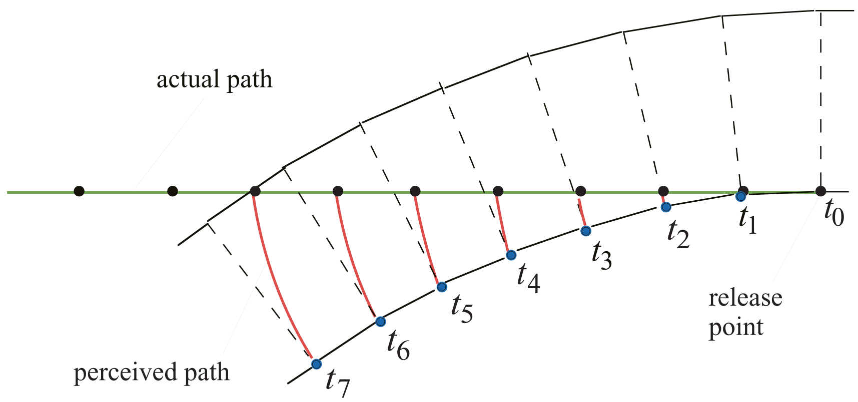

Figure 13.4 The observation of a released object on a rotating table.

A person at a fixed distance from the edge of a rotating table, as shown from above in Figure 13.4, moves along a circle starting at the point labeled, t_0, in seven equal intervals of time until t_7. The person releases an object at the starting time and it moves without friction on the surface of the table from the time it is released.

The actual path of the released object is a straight line: there is no force acting on it that can change its direction from the time it is released. *The object will move along the straight line with the speed and direction it had when it was released*; the same speed that the person moves around the circle. The actual path will be tangent to the circle at the point of release. The released object will move a fixed distance in each time interval that is the same distance that the person will move around the circle. A dashed line is shown that moves with the table and points toward the center of the circle.

The released object when viewed by the person on the table moves along a very strange path. The perceived path during the seven time intervals, shown in Figure 13.4 by the solid (red) lines curve slightly away from the dashed lines that point back to the center of the circle. The released object, from the perspective of the person on the rotating table, moves outward and slightly backward and this motion appears to be caused by a force acting outward from the center of the circle. This apparent force is also felt by the person and interpreted as a push outward on the table.

There is nothing pushing the person outward on the table. Imagine that the person's shoes are glued to the table and the person is not holding on to anything else on the table. The head of the person is like the released object and it will tend to move off the table along the same line unless some force moves it around the circle. The force that moves parts of the person's body around the circle is the stretch of the neck, torso and legs as the feet are pulled around the circle. The direction of the stretch is outward along the dashed lines to keep the head moving around the circle. The stretch of the body outward is interpreted as the head being "pulled" outward away from the body while in truth its the feet that are being pulled inward to keep them, the body and the head moving around the circle.

The frictionless circular motion of an object tethered with a string is shown in Figure 13.5 as viewed from above. The path of the object with speed, v, without the tether is a straight line tangent to the circle; only with the tension force, T, in the string does the object move in a circle.

The direction of the tension force vector is always inward along the string and is always perpendicular to the direction of the object's velocity around the circle. The tension force does not affect the speed of the object but acts to turn the velocity vector as the object moves around the circle. The inward tension force is an example of a "centripetal force" that is required to maintain circular motion at a constant speed. The centripetal force creates an inward acceleration that does not increase the speed of the object but does change the direction of the velocity. The frictionless motion of the object will allow it to move around the circle with a constant speed, v, without any means of propulsion.

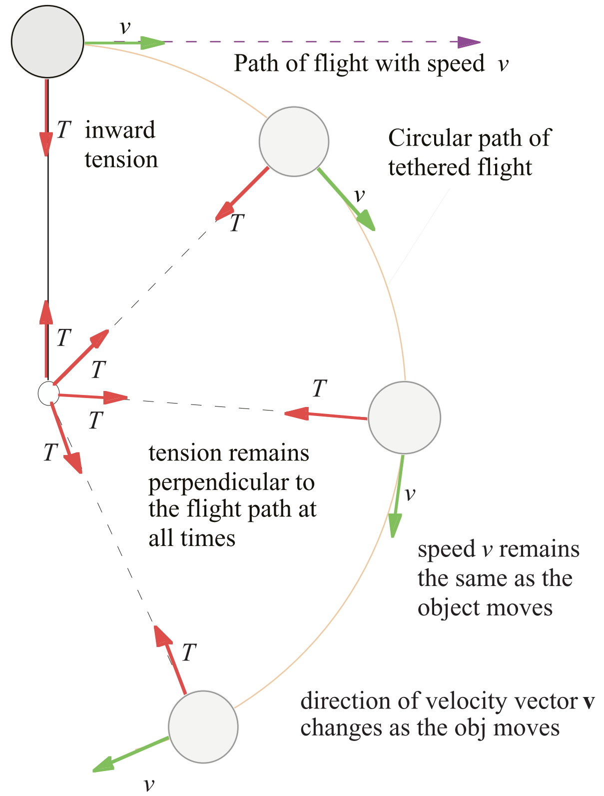

Figure 13.5 Forces required for circular motion without air friction.

The presence of air friction during the movement of an object around a circle will continuously remove energy from the motion and slow the speed of the object. An energy source is needed to replace the energy lost to friction and to maintain a constant speed around the circle.

A model airplane, attached to control lines back to the “pilot” at the center, is flown around a circle as shown in Figure 13.6. To keep the airplane moving in the circle the pilot must pull inward on the control lines generating a tension force in them. Without this inward force the model would follow the straight path at a friction limited speed, v. This inward force will cause an inward acceleration; a direction that is perpendicular to the motion around the circle.

The inward force and acceleration will not cause a change in the speed of the airplane but will continuously make the velocity vector of the airplane *point in the new direction* that will take it to the next point around the circle. The only force acting on the airplane to keep it moving in a circle is this inward "centripetal force" provided by the stretched control lines. The action of the motor of the airplane is required only to replace the energy lost to frictional forces.

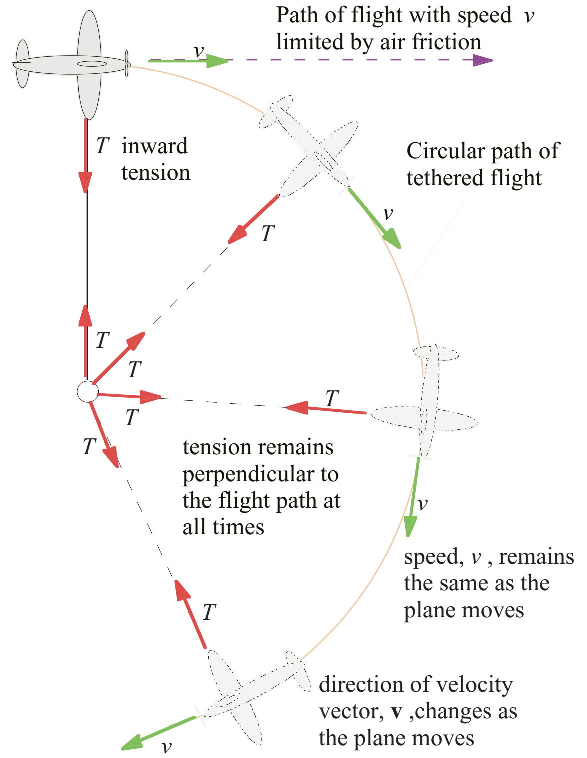

Figure 13.6 Motion of a tethered model airplane with a motorized propeller that continually replaces the energy lost to air friction.

The tension force in the control lines is maintained by the force of the pilot pulling inward and by tension forces in the wing of the airplane. These tension forces within the wing of the plane decrease with the position across the wing and reach zero and the far tip of the wing. The tension forces at any point (radius) within the wing are just large enough to accelerate the mass of the plane that is at a larger radius.

This motion is understandable from the point of view of someone standing on the ground. There are cases, however, where the motion is viewed from within a rotating object. Inside an earth satellite, phenomena can occur that are particularly difficult to understand and many misconceptions about forces originate in false explanations.

An astronaut aboard a satellite in a circular orbit around the earth is maintained in the orbit by the gravitational force, as shown in Figure 13.7. There is no air friction above the atmosphere of the earth and no further propulsion is needed to maintain the speed, v, in orbit. Without the gravitational force the astronaut would travel on a straight line path tangent to the circular orbit.

The gravitational forces in this situation hold the satellite and astronaut in orbit and perform the same function as the tension forces do for the model plane shown earlier, however, the similarity ends there.

The gravitational forces act over the entire mass of the astronaut and satellite. No internal forces of compression or tension are needed to maintain the orbit of the body or the satellite. The satellite does not have to act on the astronaut or vise-versa to maintain the orbit. The lack of internal forces in the astronaut creates a feeling of "weightlessness". The common orbiting behavior of all parts of the satellite and the objects within give the impression that there is no gravitational force acting on the objects. The gravitational force is still there, what is missing is the tension or compressions within the body of the astronaut, or in any of the other objects contained within the satellite.

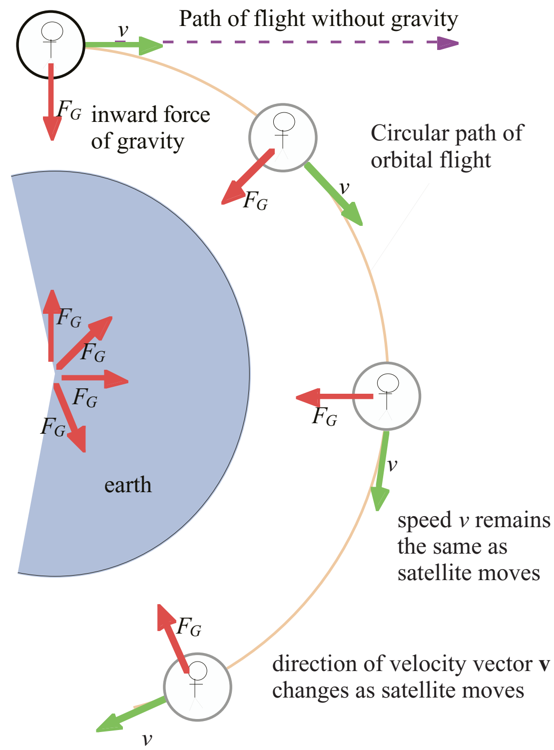

Figure 13.7 A person aboard a satellite in a circular orbit around the earth

A dramatic demonstration of this difference imagines the same astronaut far away from the earth, but made to travel in a circle with the same speed and radius of the orbit, by the tension of a rope wrapped around the waist and not by gravity. This astronaut feels very differently from the one in the orbiting satellite. The rope tension acts on the body of the astronaut only at the waist, but the remainder of the body must be accelerated inward by tension forces generated by the stretching of all other body parts.

Another example of a rotating environment is the amusement park ride, shown in Figure 13.8. The walls and floor spin, causing the rider to be “pushed” against the wall with a large force perpendicular to the walls.

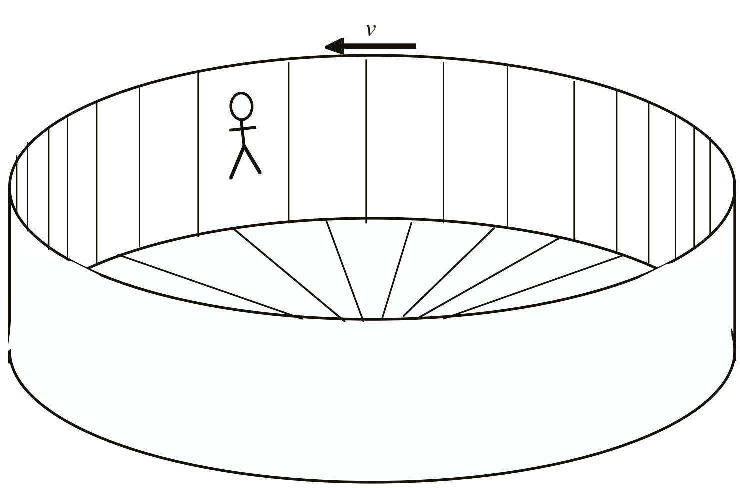

Figure 13.8 Amusement park ride spins, floor drops away, but you are stuck to the wall

When the floor of the ride drops down, the riders “stick” to the wall though a static frictional force. Each rider is fairly sure there is no real force pushing on the chest, pressing the body up against the wall. That feeling must be due to compression of our body that mimics the way we feel when a weight is put on our chest. This force is large enough that the frictional force of the wall against the back is sufficient to balance the gravitational force and prevent the rider from sliding down the wall.

The origin of the compression of your body is similar to the first example of the accelerating car. Here, the acceleration is always inward to keep the riders moving around the circle. The inward force comes from the stretch of the walls of the drum. This can be more easily seen if the walls of the drum are a thin rubber sheet making them more elastic. The natural motion of a rider would be to move along a straight line tangent to the drum. The walls of the drum stretch as they turn. The stretch causes tension in the walls that, acting on the riders, provides the inward force necessary to move them around the circle. The remainder of the arguments are the same as in the accelerating car.

The inner organs of your body, such as your heart, must also be accelerated inward toward the center to move around the circle. The inward force is created by the compression of your lungs and other tissues between your heart and your back and by the stretch of the tissues that are in front of your heart that are attached to your ribs. It is the internal forces pulling your ribs toward your back that compresses them and cause you to perceive that a force is acting on your chest. The force that is causing this feeling is, in fact, the tension force applied to your ribs from your internal organs that have moved backward in your torso.

D. Vertical accelerations in the presence of gravity.

An elevator is another classic example of accelerated environment. The five stages of motion for an UP-elevator car are shown in Figure 13.9. The car is assumed to be massless in comparison to the mass of the person.

The initial state of the car is stationary ($\mathbf{a}_0 = 0$), then in stage-1 the car accelerates upward ($\mathbf{a}_1 = +a$) for a short time, obtaining a maximum velocity ($\mathbf{v} = +v$). The car then moves up with a constant speed v ($\mathbf{a}_2 = 0$) in stage-2 until near the desired floor where the car must slow in stage–3 ($\mathbf{a}_3 = -a$) and stop when reaching it ($\mathbf{a}_4 = 0$) in stage-4.

There are two external forces acting on the person: the gravitational force acting downward and the compression force of the car's floor, acting upward on the person, caused by the tension in the elevator cables. The periods of time where the speed of the elevator car is not changing (stage-0, 2 and 4) the acceleration is zero and therefore no *net* force acts on the person. The weight of the person is balanced by the compression of the elevator floor. The car is moving in stage-2 but with a constant speed also indicating balanced forces.

The tension in the cables must be larger than the gravitational force on the person in stage-1 to create the positive acceleration while the tension in the cables must be less than the weight of the person in stage-3 to create the negative acceleration that slows the elevator car. The person in the elevator car feels quite normal in stage-0, -2, and -4 where the acceleration is zero. The tension in the cables and the weight of the person cause the floor of the car to compress and generate a compression force to match the weight of the person.

The car accelerates upward in stage-1 due to the tension in the cables being larger than the weight of the person. The compression force of the car floor increases to the value of the cable tension and acts upward on the person to give a net force that accelerates the person upward.

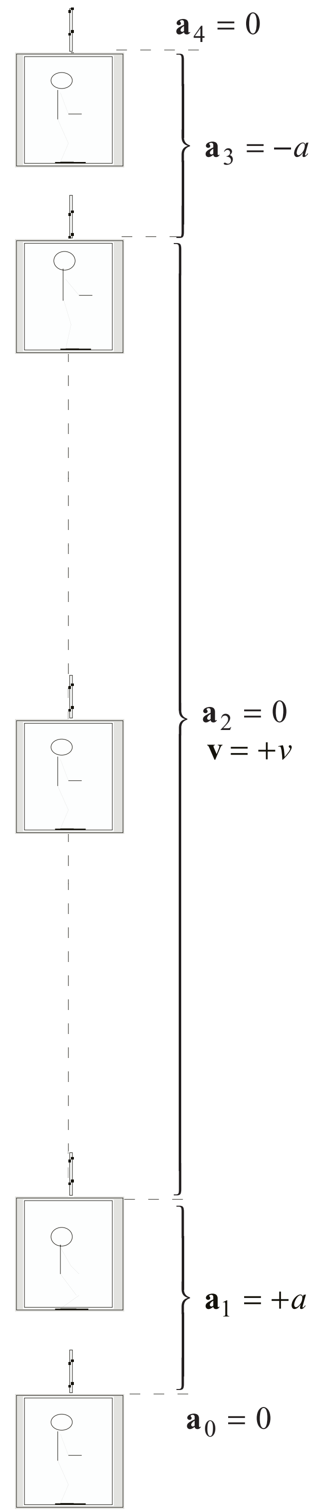

Figure 13.9 Up elevator

The compression force within the person's feet must also increase to match the compression of the car floor as required by Newton's 3rd law, and a general increase in the compression throughout the body occurs. It is this increase in the compression of the body that the person perceives as a "heavy" feeling. The person might easily mistake the feeling for an increase in the gravitational force on the body (the weight). The gravitational force acting on the person has not changed, only the compression forces acting on and within the body have changed.

Once the elevator reaches its maximum speed and continues upward at that speed the compression force of the floor on the person returns to the weight of the person and the forces become balanced so that the net force on the person is zero and the acceleration is also zero. The upward speed of the person will be constant and that will occur without the need for a net force. The person in the elevator during the constant speed portion of the motion will feel only the normal compression of the body and will hardly notice anything abnormal, except, perhaps for some vibrations.

It may still be uncomfortable for you to visualize something moving upward without a net force acting on it. A mass thrown up in the air has only the downward gravitational force acting on it thus slowing the speed mass. If there is an upward force acting on the mass with the same magnitude so that the net force on the mass is zero it will continue upward with the same speed it had initially and will not slow down. This is the state of the person in stage-2.

In stage-3 the tension in the cables is reduced so that it is less than the weight of the person. The compression force of the car floor decreases to value of the cable tension and is also smaller than the weight of the person. The net force on the person is, therefore, downward producing a downward acceleration that reduces the upward velocity ($+v$) of the person.

The compression force within the person's feet must also decrease to match the compression of the car floor as required by Newton's 3rd law, and is matched by a general decrease in the compression throughout the body. It is this decrease in the compression of the body that the person perceives as a "light" or "floating" feeling. It would be easy for the person to incorrectly attribute the feeling to a decrease in the gravitational force on the body (the weight). The gravitational force acting on the person has not changed and nor has the weight of the person. Only the compression forces acting on and within the body have changed.

The discussion of the DOWN elevator is left as an exercise. It should not surprise you to find that the "light" feeling occurs as the elevator starts its downward movement and the "heavy" feeling occurs when the elevator slows for the lower floor. The "light" feelings occur at the upper floor and the "heavy" feeling occurs at the lower floor in the motion of both an UP and a DOWN elevator.

Chapter Summary

- The lack of compression of a human body in free fall (without air friction) is a consequence of the fact that all body parts are affected by the gravitational force in proportion to its mass and accelerates each portion of the body mass at the same rate. There is no reason (forces) for the body to compress.
- A force applied by contact at one point on your body will accelerate that point. Elastic forces within your body will cause the rest of the body to also accelerate. The elastic forces generated within your body can be misinterpreted as changes in weight. The elastic forces within your body can also cause damage to your body.