# 10.1: Einstein’s Equivalence Principle

**What Do You Think: Floating in Space**


The thought experiment outlined above, with the windowless room on a rocket ship (or maybe not on a rocket ship!) is one of the examples Einstein used when thinking about extending his special theory of relativity. Recall that special relativity deals with unaccelerated motion. Its natural extension, therefore, is to try to describe what happens when motion (or frames of reference) are accelerated. Such a theory would be more general than one limited to uniform motion. It might therefore be called the general theory of relativity — and so it is.

Think about the room on the rocket ship a little more. If the rocket ship is not accelerating, and if it is in space far away from any sources of gravity, then we know that it will be in one of the so-called inertial frames, the kind described by special relativity. In inertial frames, objects set in motion obey Newton’s first law; they move in a constant direction at a constant speed. So we could imagine floating in the room, with objects like pens, notebooks, and cups of tea floating alongside us. We could also push off of the floor of the ship and travel all the way to the ceiling at a constant speed, only stopping when we ran into the confining surface. We could then push off the ceiling to propel ourselves back to the floor— in such a situation does it even make sense to have a “floor” and “ceiling?” It would be more appropriate to talk about six walls. There would be no basis on which we could distinguish between any of them. Without an acceleration, any direction is as good as any other, so we could also bounce back and forth between any of the walls that we wished, as in Figure $10.1.1$.

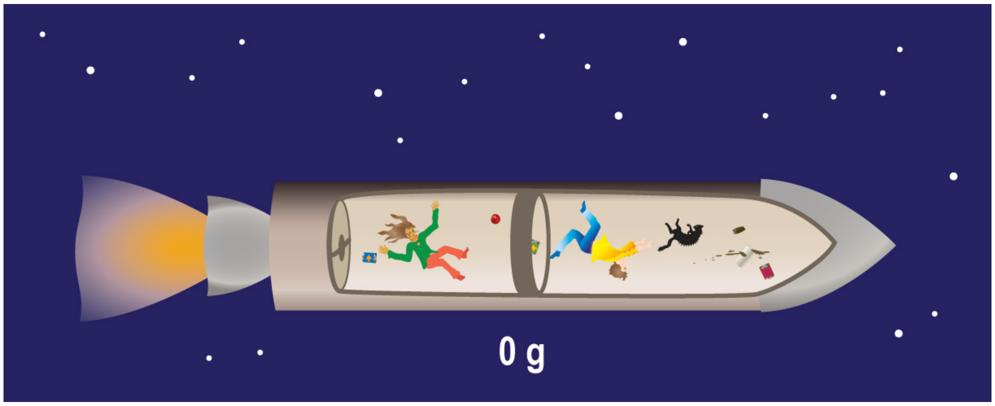


Figure 10.1.1: If we were in a region far from any massive objects, where gravity was essentially zero, we would be in a frame of reference described by special relativity. Credit: NASA/SSU/Aurore Simonnet

Now imagine the rocket engines are turned on and the rocket begins to accelerate forward. Since we and our fellow floating objects are not connected to the rocket ship, we do not move. However, we do see the walls of the room begin to move. In particular, we see the wall of the room toward the back of the rocket begin to accelerate toward us, while the opposite wall toward the front accelerates away. It makes sense to talk about a floor and a ceiling under these circumstances. In order to avoid a painful collision, we will imagine that the acceleration starts off very slowly, perhaps only 0.1g. Then, only after we (and the other objects on the ship) are on the floor does the rocket attain its full acceleration of 1g.

At this point we find ourselves pinned to the floor. If we jump up toward the ceiling, the rocket quickly accelerates to catch us, and we are stuck on the floor again. Furthermore, if we momentarily let go of something, such as a pen, it will hurtle down to the floor as well. Or does the floor race up to meet the object? Can we tell? That is the question that Einstein pondered. His answer was simple: no. We cannot tell if we are falling toward the floor of a windowless room on Earth, or if the floor is racing up to meet us as on an accelerating rocket. From our vantage point, within a small windowless room, both situations look exactly the same. There is no way for us to differentiate between them.

We can turn this situation around. Imagine that we are located in an elevator suspended by a cable inside a building. Just as we did not before realize that we were on a rocket, now we do not realize we are in an elevator. We only know that we are in a small room, and that we are pinned to the floor by gravity (or something we call gravity). Of course, if we let go of a cup of tea it drops to the floor, making a mess. This is all very familiar stuff.

But what if at the same instant that we drop our cup, some mischievous person cuts the cable supporting the elevator? Now we do not see the cup drop to the floor. Why? Because as the cup falls, the elevator itself falls at the same rate. Both accelerate toward the ground at 1g. In addition, we no longer feel ourselves pinned to the floor. We can push off the floor and go floating up to the ceiling if we like. In fact, we will find ourselves in a situation indistinguishable from that of the room on the rocket ship before the engines were turned on. This situation is called **free fall**.

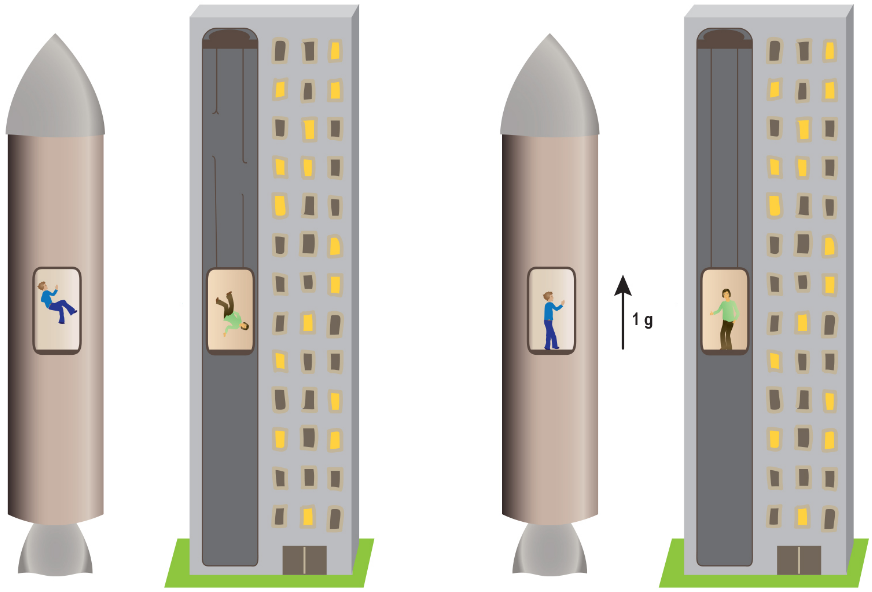


Figure 10.1.2: Accelerating in a rocket ship at 1g feels the same as being in Earth's gravitational acceleration. Credit: NASA/SSU/Aurore Simonnet

Because the case of an accelerated frame is indistinguishable, at least on small size scales, from that of the presence of a gravitational field, Einstein elevated the equivalence of the two to a principle, called the weak equivalence principle. It states, basically, that:

> *For small enough size scales, it is not possible to distinguish between the presence of a gravitational acceleration and an accelerated reference frame.*

In the statement of the weak equivalence principle we limit ourselves to small size scales— or "small enough." What does this mean? What happens when this condition is not met? To understand why we limit ourselves to small sizes, consider how gravity changes as we move through space. From Newtonian physics we know that the strength of the gravitational acceleration varies in proportion to the square of the distance to the source of the gravity. So in principle, the strength of Earth's gravity is a little bit larger at your feet than at your head because your head is a little bit farther from Earth's center than your feet are. Given that Earth has a radius of about 6400 km, the extra meter or two between your feet and head do not create a big change in the gravitational acceleration. It's so small that we can pretty much always ignore it. But in principle, if you jump off a high dive feet first, your feet should fall toward the ground slightly faster than your head does. (This has dramatic consequences when the gravitational acceleration is strong.)

The variation of the gravitational acceleration with distance is called the tidal effect. It causes the ocean tides on Earth, for example, because the variation in the gravity caused by the Moon (and Sun to a lesser extent) is noticeable across the distance of Earth's diameter. The Moon's gravity is a bit stronger on the side of Earth facing the Moon than it is on the opposite side, and this causes bulges in the oceans (and to a lesser extent on the ground as well) as Earth rotates. The tidal effect is always present when there is a gravitational acceleration, because the strength of the acceleration depends on how far we are from the source of the gravity. Given high enough precision, it can be measured.

Contrast this with an accelerating rocket ship. The floor of the room on the accelerating rocket will accelerate toward your feet and head no matter how tall you are; there is no tidal effect in an accelerating reference frame, not on any size scale. (There would be a time delay imposed by special relativity. It takes a little bit of time for the front of the ship to know that the back of the ship is being accelerated forward by the rocket engines, but that is not the same as the tidal effect of gravity.) The lack of a tidal effect can distinguish an accelerating reference frame from one in a gravitational acceleration. As a result, the weak equivalence principle holds whenever the precision of your measuring techniques is too low to discern a tidal effect. An equivalent statement of the weak equivalence principle is that:

> *For small enough size scales, the laws of physics for freely falling observers reduce to those of special relativity.*

This means that, for very small size scales, the effects of gravity (tides) become too small to notice, and the physics of unaccelerated frames becomes completely adequate for describing how things move on these small, local scales. How small this size is depends only on the precision of the measurements you can make.

You might be thinking that the existence of a weak equivalence principle implies the existence of a strong equivalence principle. If so, you are correct. The weak equivalence principle has to do with motions of objects under the influence of gravity alone, whereas the strong equivalence principle includes the other forces of nature, like electromagnetism and the nuclear forces. We will not worry about the strong equivalence principle, as it merely says that all the laws of physics must be the same for all observers, accelerated or not. This is a reasonable assumption to make for any description of the Universe, at least until such time as it is ever shown to be false.

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