Gravity slows time

In this section: from the redshift of light it follows that time itself slows down when gravity is strong. The GPS navigational satellite system, which relies on highly accurate clocks, must take this effect into account in order to maintain its accuracy.

The gravitational redshift leads us to a very profound conclusion about time itself: gravity makes it run slower. Suppose we build two identical clocks, in such a way that the clocks tick once in every period of the oscillation of the electromagnetic wave that we use in the redshift experiment. We place clock one on top of the tower in the experiment and leave the other on the ground. By design, the one on the ground ticks at the same rate as the frequency of the light signal that we emit there. Suppose we keep it there for, say, 10^{20} ticks. (Since visible light oscillates at about 10^{15} times a second, this would be about one day.) Now, the clock at the top of the tower receives the light redshifted, so the light frequency at the top of the tower is less by one part in 10^{14} (see Equation 2.5). The clock at the top is therefore ticking faster than the arriving light by that same factor.

Now, the light going up the tower is just a wave; one oscillation corresponds to the arrival of one "crest" of the wave. Crests don't disappear on the way up, so exactly as many oscillations of light arrive at the top during the experiment as were emitted at the bottom: 10^{20} in this case. But during the experiment, the clock at the top has ticked more times, by one part in 10^{14}. That means it has ticked 10^6 times more than the one on the ground. When the experiment finishes, we immediately bring the clock from the top of the tower down to the ground and compare it to the one on the ground. The one that has been sitting on the tower is ahead of the one on the ground, by these 10^6 ticks. This is only one nanosecond (1 ns = 10^{-9} s), but it is measurable.

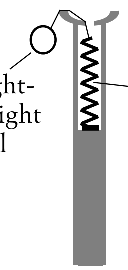

Figure 2.5. *Einstein's equivalence-principle toy. This "toy" was a gift to Einstein from E M Rogers. It consists of a light ball tied to a spring too weak to pull the ball into the cup. The secret of getting the ball into the cup is to make it weightless. Then the spring will be able to pull it in. Your challenge is, how do you make the ball weightless? Einstein delighted in demonstrating the equivalence principle with this toy. The toy and Einstein's reaction are described in* Einstein: A Centenary Volume, *ed. A P French (Heinemann 1979), pp 131–132.*

Let us take stock of what we have learned. Given two identical clocks, if we place one for a while higher up in a gravitational field and then bring it down to the other one, we will find it has gone faster. This conclusion applies to any clock, biological or physical, regardless of how it is made: the workings of the clock did not come into the argument above.

> Since all clocks run faster higher up, we conclude that time itself runs faster higher up in the gravitational field: after all, time is only what we measure using clocks.

This is not just an abstract point. Today there are in orbit around the Earth a number of satellites that form the Global Positioning System (GPS). Launched by the US Air Force, they constantly send radio signals down to Earth that can be used in navigation: with a GPS receiver one can pinpoint one's location to within 10m, an extraordinary accuracy. The satellites carry precise atomic clocks, the most accurate clocks that can be made. Because of the effect of gravity on time, these tick faster than do clocks on the ground; the difference is about three microseconds per day. (A microsecond or μs is 10^{-6} s.) Yet to give a position that is accurate to 10m requires clocks that are accurate to the time it takes the radio waves from the satellites to travel 10 m, which is 0.03 μs. Therefore, this redshift correction *must* be taken into account in order for the system to function. (Actually, there is also a velocity correction that we will go into in Chapter 15, and this has to be taken into account as well.)

The routine use of the GPS by airplanes, ships, long-distance trucks, and even private cars confirms the gravitational redshift and the effect of gravity on time to a much higher accuracy than the original Pound–Rebka–Snider experiment.