10.1: An Old and a New Axiom

The theory of special relativity is built on two postulates (our axioms for this chapter). The first one also applies to classical mechanics, and simply states that:

Axiom 1 (Principle of relativity). *The laws of physics are identical in every inertial reference frame.*

You probably haven't heard of 'inertial reference frames' before. Quite likely, you've not given this principle much thought either, but nonetheless, you are (almost certainly) intimately familiar with it on an intuitive level. Consider an example we'll use a lot in this chapter. Suppose you're in a train car with no windows. Is there any experiment you can devise within the confines of the car that will tell you whether the train is standing still or moving at constant velocity (both direction and magnitude)? The answer is no, of course - that's a direct consequence of Newton's first law. A pendulum will hang straight down in a stationary train and in one moving at constant velocity, and a ball you roll will trace out a straight line in both cases. Things change of course when the train accelerates (that's where Newton's second law comes in), but as long as you keep your speed (zero or not) and direction fixed, you might as well be stationary as far as physics is concerned.

Now what's an inertial reference frame? A reference frame is simply the set of measures you use to describe the world: your coordinate system. For the person on the platform, the system will be fixed to the platform, with the origin (for example) at the point they're standing. For someone on the train, it'd be convenient to have the origin at the corner of the car, and of course the frame co-moving with the car. An inertial reference frame could be defined either as any reference frame that moves at constant velocity with respect to another inertial reference frame, or (as is most often done), by inverting the principle of relativity, stating that an inertial reference frame is one in which the laws of physics (i.e., Newton's laws in classical mechanics, or more specifically Newton's first law) hold without modifications. To illustrate that this is not a trivial point, consider a rotating reference frame: there the laws of physics actually change (you experience additional forces like the centrifugal and Coriolis force), and you could figure out you're rotating from a simple experiment (a pendulum at rest will no longer point down, but slightly outward).

Returning to inertial reference frames, there is one more point to be made, which you also already know. Both position and velocity are relative concepts, in the sense that they depend on the observer. In the train example this is obvious. From the point of view of a person sitting on the train, other objects on the train are stationary in their comoving reference frame, so at a fixed position and zero velocity; the observer on the platform however will tell you that the same object has a changing position and a velocity equal to that of the moving train. In classical mechanics, what is not relative is acceleration. As Newton's second law holds in both inertial reference frames, the same force gives the same acceleration according to both observers. What Einstein discovered is that although this observation still holds at relatively low velocities, it is not true at higher speeds. Instead, both observers will agree on the value of a different observable quantity: the speed of light c.

Axiom 2 (Light postulate). *The speed of light in vacuum is the same in all inertial reference frames.*

The light postulate has an important consequence: it sets the speed of light as the ultimate speed limit in the universe. Worse, you (or any other object with mass), cannot even travel at the speed of light. We'll show this mathematically further on, but a simple thought experiment suffices to show that this point is true. Assume the opposite: suppose you can (and do) travel at light speed with respect to a stationary observer. Next, suppose you emit a light pulse, for instance by switching a flashlight on and off. From your point of view, the pulse travels at light speed, so it speeds ahead of you quickly. However, from the stationary observer's point of view, the pulse also travels at light speed - which is the same speed you travel at, so the photon would never leave you. As the photon needs to either leave you or stay with you (but cannot do both), we arrive at a logical contradiction, and conclude that you cannot travel at the speed of light.

> Albert Einstein (1879-1955) was a German physicist, and quite likely the most widely known scientist in the world today. Einstein studied physics in Zürich, but could not find a research position after he graduated, so he combined his research work with a position at the Swiss patent office in Bern. In 1905, his 'miracle year', Einstein published four papers, all with enormous impact on physics: one explaining Brownian motion of small particles in water, one on the (quantum-mechanical) photo-electric effect, one on special relativity, and one on the energy-matter relation (the famous $E=mc^2$). This work led to Einstein becoming a professor in 1909, and receiving the Nobel prize (for the photo-electric effect) in 1921. Einstein extended the theory of relativity to include gravity, resulting in the prediction of the bending of light by gravity (1911, confirmed 1919) and the existence of gravitational waves (1915, confirmed 2015). Einstein became a public figure in the 1920s, visiting many places around the world. When the Nazi's seized power in Germany in 1933, Einstein, who was Jewish and living in Berlin, became one of the first targets. He left Germany and gave up his citizenship, eventually moving to Princeton in the US, and

advocating for the active extraction of fellow Jewish German scientists. Having been a pacifist all his life, Einstein vehemently opposed war, but also realized that Nazi Germany would not hesitate to build and use an atomic bomb, so he argued that the US should develop one also (though he was horrified when it was used against Japan). In his years in Princeton, Einstein tried to find a theory unifying gravity and quantum mechanics, but failed to do so (we still haven't succeeded); he did not like the random nature inherent in quantum mechanics and tried to prove it was incomplete (formulating the Einstein-Podolsky-Rosen paradox), which, though later proven incorrect, led to the study of quantum entanglement that is the foundation of a future quantum internet.

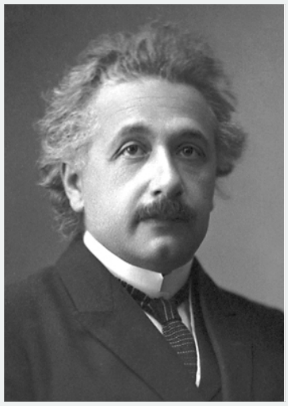

Figure 10.1: Official 1921 Nobel prize portrait of Albert Einstein [27].