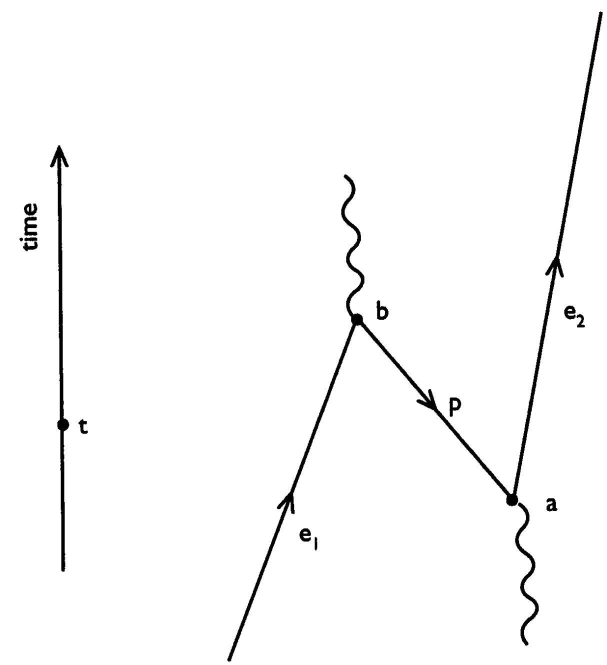
A MATTER OF TIME REVERSAL

Shortly after Wheeler and Feynman worked out their entertaining theory, Wheeler put Feynman on to another bizarre idea involving backward-in-time action. This time it had to do with antimatter. The concept of antimatter dates back to about 1930 and a famous prediction by Paul Dirac, who had been struggling to merge the new quantum mechanics with Einstein's special theory of relativity. Dirac wanted to know how a quantum particle such as an electron would behave when moving close to the speed of light. He discovered an equation that seemed to fit the bill, but he was baffled to find that every solution of the equation that described an electron came paired with a sort of mirror solution that did not seem to correspond to any known particle. After a certain amount of head-scratching, Dirac came up with a bold hypothesis. The "mirror" solutions, he claimed, correspond to particles that are identical to electrons, except their properties are reversed. For example, instead of hav-

ing a negative charge, the mirror particles should be positively charged. Within a year or two, Dirac's "positrons" had been found in cosmic-ray showers. They really do exist.

Physicists eventually came to realize that every sort of subatomic particle in nature has a corresponding antiparticle. In addition to antielectrons (still called positrons) there are antiprotons, antineutrons and so on. Today these antiparticles are routinely produced in the laboratory and are well understood, but in the 1940s they were still a bit mysterious. Only the positron was familiar. Positrons are created twinned with electrons in violent encounters between gamma rays and matter. Typically, a gamma-ray photon colliding with an atom produces an electron-positron pair. The newborn electron flies off to enjoy a more or less permanent existence, but the poor positron faces hazards from the outset. If a positron runs into an electron (and the universe is packed with them), the pair will instantly annihilate, reversing the pair-creation process and giving back photons. This generally makes for a short career for the positron.

Now let me turn to Wheeler's proposal, as developed by Feynman. Fig. 9.1 is a spacetime diagram showing the creation and subsequent



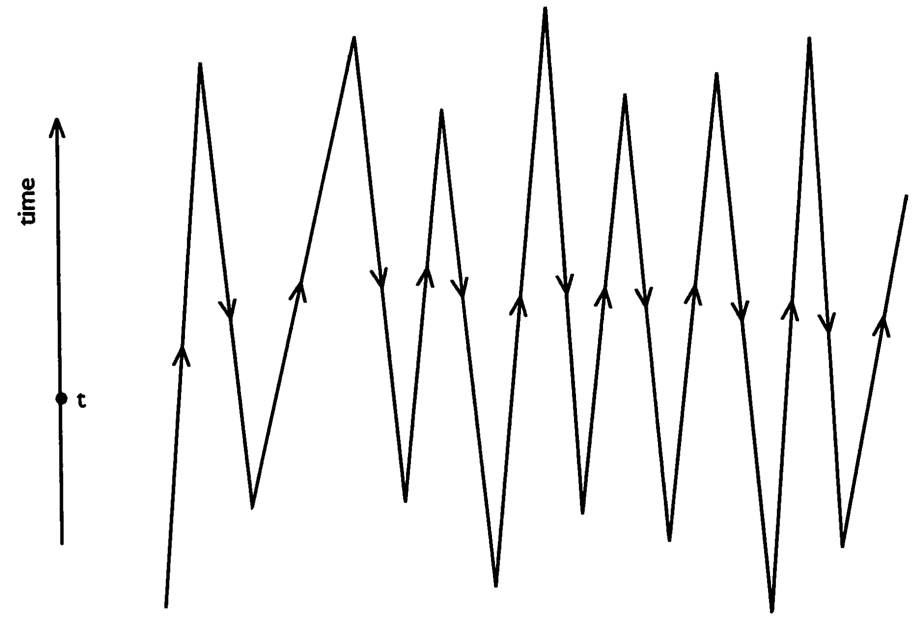
9.1 The spacetime diagram depicts a photon creating an electron-positron pair (e_2, p) at a, with the positron subsequently being annihilated by electron e_1 at b. At time t, *an observer would see three particles in existence: p, e_1 and e_2. According to Feynman, the zigzag track can be viewed as the world line of just one particle, an electron that travels back in time between b and a (see arrow).*

annihilation of a positron. The commonsense way to interpret this diagram is that the gamma-ray photon, depicted by the wavy line coming up from the bottom, creates an electron-positron pair at event A, the electron (labeled "e_2") goes off to the right, while the positron, labeled "p," heads left, hits a second electron (labeled "e_1") at event B and annihilates, creating a photon once more. The net effect is that electron e_1 has disappeared in one place to be replaced by electron e_2 in another. Feynman's audacious conjecture was that electrons e_1 and e_2 are really the *same* particle, even though in the interval between events A and B both electrons are present together!

Feynman's idea is that the continuous zigzag track in Fig. 9.1 should be seen not as a concatenation of three distinct particle world lines, but as a continuous spacetime path of a *single* electron. The backward-sloping segment of the track—the bit corresponding to the positron—then depicts the electron *going backwards in time*. This time-flip is denoted by the arrows on the world line. In its normal, electron phase, the arrow points forwards in time, but during the positron phase it points backwards. Viewed this way, the original undisturbed electron (e_1) emits a photon (at B) and bounces back in time, then absorbs a photon (at A) and rebounds back to the future again. An observer located in time between A and B would see two electrons and a positron, but Feynman says this is really only one particle seen three times: first (as e_1) in its original undisturbed form, then (as the positron) coming back from the future, and finally (as e_2) going forwards in time once more.

The essential idea can be extended to include many more electrons and positrons by allowing the world line to zigzag repeatedly (Fig. 9.2). In fact, Wheeler proposed that all the electrons in the universe are really one and the same particle, simply bouncing back and forth in time! In other words, you and I, the Earth, the sun, the Milky Way and all the other galaxies are composed of just *one* electron (and one proton and one neutron too) seen squillions of times over. This offers a neat explanation for why all electrons appear to be identical. Of course, it also predicts that the universe will have exactly the same number of positrons as electrons, because every zig has a corresponding zag. In other words, the universe would be composed of one-half matter and one-half antimatter.

The link between time-reversal symmetry and matter-antimatter symmetry is in fact a very deep one. Whether or not we take seriously the idea of positrons as electrons traveling backwards in time, it can be shown on quite general grounds that if the laws of the universe are strictly symmetric in time then the universe should have equal shares of matter and antimatter. Some cosmologists have suggested just that. Antimatter *looks* the same as matter, so you can't tell from casual inspection whether or not, say, the Andromeda galaxy is made of matter or



9.2 Multiple zigzags could explain why all electrons are identical: they are all the same particle, bouncing repeatedly back and forth in time. An observer at time t *would erroneously interpret the single world line as a multiplicity of disconnected segments.*

antimatter. Perhaps half the galaxies are in one form and half in the other? To test this fascinating possibility, astronomers have looked for ways that antimatter might betray its presence. Whenever antimatter encounters matter, prodigious quantities of gamma radiation are produced, with distinctive energies. There are many known examples of galaxies in collision with each other, so if half the galaxies are made of antimatter we might expect the universe to be replete with distinctive gamma rays. However, almost no gamma rays of the right energy have been found. This suggests a major predominance of electrons over positrons, and generally of matter over antimatter.

The conclusion we can draw from these observations—and it is a very profound one—is that nature is *not* symmetric between matter and antimatter, so the laws of the universe are *not* exactly symmetric in time. Whatever physical processes brought about the creation of the cosmic material, presumably in the extreme conditions of the big bang, they must have been lopsided in their relation to time, even if only slightly. In other words, there must be at least one basic physical process that is not exactly symmetric under time reversal.