If you read or watch science fiction, you've probably heard of antimatter. The starships in Star Trek are powered by matter-antimatter reactors; Isaac Asimov's robots are based on antimatter electrons; Riff Raff in the Rocky Horror Picture Show boasts of "a laser capable of emitting a beam of pure antimatter." (In case you're keeping score. . . The Star Trek idea is scientifically plausible, including the magnetic containment fields that the engineers are constantly shoring up to keep the engines from exploding. Asimov offers no explanation of his "positronic brains"; he seems to have simply been exploiting a scientific term that was new in the 1930s. And Riff's boast is a contradiction in terms.)

Science fiction aside, antimatter is very real. It is used in scientific research, it's the basis of important medical technology, and it's at the heart of a great mystery in the study of the early universe.

We're going to begin this section with a basic description of what antimatter is and its basic properties. Then we'll present two historically interesting interpretations of why there is such a thing as antimatter. After that we will discuss the role (and the mystery) of antimatter in the early universe, and we will close with a brief look at antimatter in modern technology.

What is Antimatter?

Every type of "matter" particle has a corresponding "antimatter" particle. Here are the five basic things to know about a particle and its antiparticle.

- An antiparticle is generally named by prefixing "anti" to the original name: antiproton, antiquark, and so on. The main exception is that, for historical reasons, the antiparticle of an electron is called a positron.
- A particle and its antiparticle have *identical properties,* with one exception that we'll discuss in the next bullet. For instance, a positron has the exact same mass as an electron, its spin has magnitude $\left(\sqrt{3}/2\right)\hbar$ and z-component $\pm\hbar/2$, it obeys the Pauli exclusion principle and the Fermi-Dirac distribution, and so on.
- Here's the exception: a particle and its antiparticle have *opposite charges.* We are using the word "charge" broadly here: we often use the word to refer only to the property that governs the electric force, but the strong and weak force have their own charges, and those also reverse for antimatter. For instance, an up quark has charge $(2/3)e$, and might have the "color" (strong force charge) called blue. So an antiup quark has charge $-(2/3)e$, and might have color antiblue. (See Section 13.2 for more about the strong force and color.) A particle with no charge of any kind, such as a photon, is its own antiparticle.
- If a particle and its antiparticle meet, they can annihilate each other, releasing all their energy in the form of radiation. (This 100% conversion is why they would make a good power source for a starship, although it's not clear where you would get all that antimatter.)
- The reverse process can also happen: photons with the right amount of energy can spontaneously create a particle and its antiparticle.

If you got those five bullet points, you know the basics of antimatter.

Dirac's Prediction of Antimatter

Section 13.3 describes Carl Anderson's 1932 experimental detection of a positron in some detail.[1] Here we want to discuss the remarkable fact that Paul Dirac had already predicted the existence of positrons on purely theoretical grounds! Dirac painted a picture very different from the "particles with identical properties but opposite charges" model given above.

Dirac had previously developed a relativistic version of quantum mechanics, pairing Schrödinger's theory with the relativistic $E^2 = p^2c^2 + m^2c^4$ instead of the Newtonian $E = (1/2)mv^2$. He noticed that when you solve this equation for E, you should properly write $E = \pm\sqrt{p^2c^2 + m^2c^4}$. Another scientist might have ignored those negative energies, but Dirac decided to pursue their consequences.

He quickly saw that they posed a problem. A particle will tend over time to fall into its lowest possible energy state. For example, most of the atoms in the air around you are currently in their ground states. If there were an infinite set of negative energy states available, then all particles would fall into ever-lower negative energies and emit radiation indefinitely. No matter would be stable.

To avoid this crisis, Dirac postulated in a 1929 paper that these negative states are all full! He said that the universe is filled with an infinite sea of negative energy electrons, everywhere at all times, filling every available negative energy state.

If there are all these electrons and electron states around us, why haven't we noticed? Well, a positive-energy electron can't fall into one of these states, because the states are all full. And the electrons filling those states are uniformly spread throughout the universe, so their electric forces all cancel. In general, therefore, these electrons have almost no visible effect on the universe.

But Dirac noted one crucial exception. Remember that a photon can sometimes "kick" an electron into a higher-energy state. (Think of the absorption spectrum of hydrogen described in Section 4.1, or the photoelectric effect in Section 3.4.) So, a sufficiently high energy photon could kick one of these negative-energy electrons up into a positive energy state. Here's what we would see in the lab: a photon would disappear, a new electron would seem to appear from nowhere, and a "hole" would appear in the sea of negative energy electrons (Figure 1).

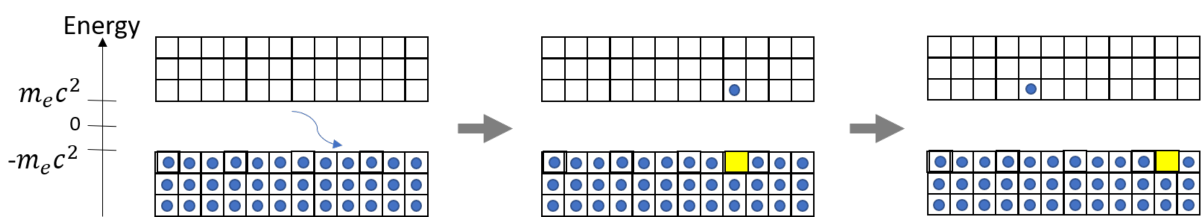

Figure 1: When electrons fill the sea of negative energy states uniformly (left image), those electrons are undetectable. But then the light beam in the left image knocks one of those electrons into a positive energy state (middle image), leaving behind an unfilled negative energy state. A moment later (right image), the positive energy electron and the hole have moved off in different directions. The former appears as a normal electron. The hole appears to be a positive energy, positively charged particle: a positron.

How much energy would that require? Every negative energy state is the mirror image of some positive energy state. From the equation $E = \pm\sqrt{p^2c^2 + m^2c^4}$ we see that the lowest possible positive energy for an electron is m_ec^2, and the highest possible negative energy is $-m_ec^2$. To kick a particle from a negative energy state to a positive energy state would require a single photon with at least $2m_ec^2$ of energy, so such events would be very rare.

[1] Several other people had seen positrons before this, but had dismissed the evidence and failed to follow through. Patrick Blackett and Giuseppe Occhialini also discovered antimatter in 1932, but Anderson published first and got the credit, and later the 1936 Nobel prize for it.

Now suppose the positive energy electron flies far away, and consider what the remaining hole would look like. All of space would be filled by a uniform sea of negative-energy electrons, *except at one spot.* This would cause the same electric field you would expect if there were a positive charge at that spot. In fact, Dirac showed that this hole would behave in every way like a particle with the same mass as an electron but with a positive charge.

Dirac thought that these positive-charge holes might be protons, although he acknowledged that the holes should have the same mass as electrons, which protons don't. Robert Oppenheimer pointed out a more serious problem: if a hole and an electron were near each other, the electron would spontaneously fall into that hole, emitting radiation and filling the negative energy state. This would cause both "particles" (the electron and the hole) to disappear. If protons were holes in the negative-energy electron sea, then hydrogen atoms would be unstable.

So in 1931 Dirac came out with another paper in which he argued that these holes would be an as-yet-unobserved particle with the mass of an electron, but with positive charge. He called the new particle an "anti-electron." High energy photons should be able to spontaneously create electron/anti-electron pairs, and those pairs should in turn be able to spontaneously annihilate and emit radiation.

While Dirac's model led him to correctly predict the existence of antimatter, we no longer view positrons as holes in a negative energy electron sea. Rather, our current view of antimatter comes from quantum field theory.

Antimatter in Quantum Field Theory

Section 13.5 offers a brief overview of "quantum field theory" (QFT). If you haven't read that section, what you need to know here is that quantum field theory updates Schrödinger mechanics—treating all fields quantum mechanically, and building particle decay into the model—to create our current most accurate description of the microscopic world.

Quantum field theory describes every particle as a local excitation of a field. For instance, a photon is a local excitation of electric and magnetic fields, and the Higgs boson is a local excitation of the ubiquitous Higgs field. The math of QFT predicts that every field corresponding to charged particles can be excited in two different ways, with opposite charges. So once again, the existence of antimatter particles emerges as a theoretical necessity—not just "they happen to exist," but "they *must* exist." But those particles are now viewed as oppositely-charged particles in their own right, rather than as holes in otherwise filled negative-energy states.

Or, there is alternative way to view the antimatter particles predicted by the theory. In the 1940s, Ernst Stueckelberg and Richard Feynman realized that the calculations of quantum field theory yield all the same predictions if, instead of thinking of a positron as an electron that has a positive charge, you think of it as an electron that *travels backward in time.*

As an example, consider the following sequence of events.

1. An electron travels along a path through space, moving forward in time in the usual way.
2. At some point—let's call this moment $t = 0$—the electron emits some photons, causing it to recoil.
3. The recoil from that emission changes the electron's path in space, and also sends it moving backwards in time.

What would all that look like to us, viewing the whole thing as we move forward in time?

1. Before $t = 0$ we would appear to see two different particles, each with the mass of an electron, moving along different spatial paths. The one that is actually moving forward in time would appear to be exactly what it was: an electron. But using quantum field theory, Stueckelberg and Feynman showed that a backwards-in-time particle would appear to us to have a charge opposite its actual charge. In this case, the backward-traveling negative charge looks to us like a forward-traveling positive charge.
2. At $t = 0$ the two paths would converge on a single point.
3. After that moment, neither particle would exist, but there would be some new photons.

So what we originally described as an emission-and-recoil event would appear to us as an annihilation event. That is one specific example of the general result that Stueckelberg and Feynman found from the equations of quantum field theory, which is that a forward-moving positron and a backward-moving electron would lead to identical measurable results.

This strange model has certain advantages, which is why antimatter particles of all kinds are represented in Feynman diagrams with arrows that point backward in time.[2] John Wheeler took the idea further and suggested that perhaps all of the electrons and positrons in the universe are one single electron, traveling backwards and forwards in time along a complicated path! (Returning to our science fiction discussion, some readers may be reminded of the Robert Heinlein short story "—All You Zombies—.")

You can think of a positron as a perfectly ordinary particle that has the mass of an electron but a positive charge, and that happens to annihilate any time it encounters an electron. You can also think of a positron as a hole in Dirac's infinite sea of negative-energy electrons, or as a backward-in-time traveling electron. The three interpretations all predict the same experimental results, so most physicists today don't spend much time trying to tease them apart.

Matter and Antimatter in the Early Universe

Section 14.1 discusses the early universe. Antimatter plays a key role in that story, and it is a role that is still not entirely understood.

At some moment early in the post-Big-Bang universe's first second, the universe's energy decayed from a "scalar field" (Section 14.7) into forms that are more familiar today: matter, antimatter, and electromagnetic radiation, among others. For a while after that moment, particles and their antiparticles were continually colliding and annihilating, but the opposite process—pair production, in which energy spontaneously created particles and their antiparticles—was also happening.

Approximately one second after the Big Bang, the universe's temperature cooled to a point where there was rarely enough concentrated energy for pair production. You can guess what happened next. The matter and antimatter annihilated each other, and since there was no pair production to replace them, the universe was left with only electromagnetic radiation, right?

Not quite, and here's why: for every 1,000,000,000 particles of antimatter, the early universe had 1,000,000,001 particles of matter. So after all the mutual destruction, those one-in-a-billion particles were left over. All the stars, planets, and galaxies we see in the universe today come from those surviving particles of matter.

We said at the beginning of this section that antimatter is "at the heart of a great mystery in the study of the early universe." *Why was there more matter than antimatter?* A moment before the scalar field decayed, there were effectively no particles of either type. Some process during the next second created slightly more matter than antimatter. But as of this writing, physicists do not know any process that would lead to such an imbalance.

Antimatter Today

We opened this section with some science fiction applications (of varying plausibility) of antimatter. To conclude, we want to mention some of the things real people have done or are trying to do with antimatter.

In 1995 Walter Oelert first produced "antihydrogen," a positron bound to an antiproton. Because this requires huge particle accelerators and produces very few antiatoms, in 1999 NASA estimated that antihydrogen was the most expensive material ever produced, at a cost of roughly $62.5 trillion per gram.

Positrons, however, are produced much more routinely. For example, "Positron Electron Tomography," or "PET scans," are widely used in medical research. In this procedure a radioactive tracer is injected into a patient. It binds to certain chemicals that trigger a decay process that includes positron emission. Those positrons then annihilate with electrons and emit gamma rays. By detecting the gamma rays it's possible to see where those chemicals are most active. PET scans are used for applications ranging from studies of the brain to cancer detection.

[2] "Feynman diagrams," described in Section 13.5, can be roughly thought of as pictures showing the world lines of interacting particles.

Less immediately, antimatter could theoretically be used as a power source for rockets. There are enormous challenges to such research, not the least of which are how to produce and how to store sufficient quantities of antimatter, but a number of groups are actively researching those problems. The real world may be inching closer to the fictional world of Star Trek even as you read this.