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That Famous Equation and You

By BRIAN GREENE

DURING the summer of 1905, while fulfilling his duties in the patent office in Bern, Switzerland, Albert Einstein was fiddling with a tantalizing outcome of the special theory of relativity he'd published in June. His new insight, at once simple and startling, led him to wonder whether "the Lord might be laughing ... and leading me around by the nose."

But by September, confident in the result, Einstein wrote a three-page supplement to the June paper, publishing perhaps the most profound afterthought in the history of science. A hundred years ago this month, the final equation of his short article gave the world $E = mc^2$.

In the century since, $E = mc^2$ has become the most recognized icon of the modern scientific era. Yet for all its symbolic worth, the equation's intimate presence in everyday life goes largely unnoticed. There is nothing you can do, not a move you can make, not a thought you can have, that doesn't tap directly into $E = mc^2$. Einstein's equation is constantly at work, providing an unseen hand that shapes the world into its familiar form. It's an equation that tells of matter, energy and a remarkable bridge between them.

Before $E = mc^2$, scientists described matter using two distinct attributes: how much the matter weighed (its mass) and how much change the matter could exert on its environment (its energy). A 19th century physicist would say that a baseball resting on the ground has the same mass as a baseball speeding along at 100 miles per hour. The key difference between the two balls, the physicist would emphasize, is that the fast-moving baseball has more energy: if sent ricocheting through a china shop, for example, it would surely break more dishes than the ball at rest. And once the moving ball has done its damage and stopped, the 19th-century physicist would say that it has exhausted its capacity for exerting change and hence contains no energy.

After $E = mc^2$, scientists realized that this reasoning, however sensible it once seemed, was deeply flawed. Mass and energy are not distinct. They are the same basic stuff packaged in forms that make them appear different. Just as solid ice can melt into liquid water, Einstein showed, mass is a frozen form of energy that can be converted into the more familiar energy of motion. The amount of energy (E) produced by the conversion is given by his formula: multiply the amount of mass converted (m) by the speed of light squared (c^2). Since the speed of light is a few hundred million meters per second (fast enough to travel around the earth seven times in a single second), c^2, in these familiar units, is a huge number, about 100,000,000,000,000,000.

A little bit of mass can thus yield enormous energy. The destruction of Hiroshima and Nagasaki was fueled by converting less than an ounce of matter into energy; the energy consumed by New York City in a month is less than that contained in the newspaper you're holding. Far from having no energy, the baseball that has come to rest on the china shop's floor contains enough energy to keep an average car running continuously at 65 m.p.h. for about 5,000 years.

Before 1905, the common view of energy and matter thus resembled a man carrying around his money in a box of solid gold. After the man spends his last dollar, he thinks he's broke. But then someone alerts him to his miscalculation; a substantial part of his wealth is not what's in the box, but the box itself. Similarly, until Einstein's insight, everyone was aware that matter, by virtue of its motion or position, could possess energy. What everyone missed is the enormous energetic wealth contained in mass itself.

The standard illustrations of Einstein's equation - bombs and power stations - have perpetuated a belief that $E = mc^2$ has a special association with nuclear reactions and is thus removed from ordinary activity.

This isn't true. When you drive your car, $E = mc^2$ is at work. As the engine burns gasoline to produce energy in the form of motion, it does so by converting some of the gasoline's mass into energy, in accord with Einstein's formula. When you use your MP3 player, $E = mc^2$ is at work. As the player drains the battery to produce energy in the form of sound waves, it does so by converting some of the battery's mass into energy, as dictated by Einstein's formula. As you read this text, $E = mc^2$ is at work. The processes in the eye and brain, underlying perception and thought, rely on chemical reactions that interchange mass and energy, once again in accord with Einstein's formula.

The point is that although $E=mc^2$ expresses the interchangeability of mass and energy, it doesn't single out any particular reaction for executing the conversion. The distinguishing feature of nuclear reactions, compared with the chemical reactions involved in burning gasoline or running a battery, is that they generate less waste and thus produce more energy - by a factor of roughly a million. And when it comes to energy, a factor of a million justifiably commands attention. But don't let the spectacle of $E=mc^2$ in nuclear reactions inure you to its calmer but thoroughly pervasive incarnations in everyday life.

That's the content of Einstein's discovery. Why is it true?

Einstein's derivation of $E = mc^2$ was wholly mathematical. I know his derivation, as does just about anyone who has taken a course in modern physics. Nevertheless, I consider my understanding of a result incomplete if I rely solely on the math. Instead, I've found that thorough understanding requires a mental image - an analogy or a story - that may sacrifice some precision but captures the essence of the result.

Here's a story for $E = mc^2$. Two equally strong and skilled jousters, riding identical horses and gripping identical (blunt) lances, head toward each other at an identical speed. As they pass, each thrusts his lance across his breastplate toward his opponent, slamming blunt end into blunt end. Because they're equally matched, neither lance pushes farther than the other, and so the referee calls it a draw.

This story contains the essence of Einstein's discovery. Let me explain.

Einstein's first relativity paper, the one in June 1905, shattered the idea that time elapses identically for everyone. Instead, Einstein showed that if from your perspective someone is moving, you will see time elapsing slower for him than it does for you. Everything he does - sipping his coffee, turning his head, blinking his eyes - will appear in slow motion.

This is hard to grasp because at everyday speeds the slowing is less than one part in a trillion and is thus imperceptibly small. Even so, using extraordinarily precise atomic clocks, scientists have repeatedly confirmed that it happens just as Einstein predicted. If we lived in a world where things routinely traveled near the speed of light, the slowing of time would be obvious.

Let's see what the slowing of time means for the joust. To do so, think about the story not from the perspective of the referee, but instead imagine you are one of the jousters. From your perspective, it is your opponent - getting ever closer - who is moving. Imagine that he is approaching at nearly the speed of light so the slowing of all his movements - readying his joust, tightening his face - is obvious. When he shoves his lance toward you in slow motion, you naturally think he's no match for your swifter thrust; you expect to win. Yet we already know the outcome. The referee calls it a draw and no matter how strange relativity is, it can't change a draw into a win.

After the match, you naturally wonder how your opponent's slowly thrusted lance hit with the same force as your own. There's only one answer. The force with which something hits depends not only on its speed but also on its mass. That's why you don't fear getting hit by a fast-moving Ping-Pong ball (tiny mass) but you do fear getting hit by a fast-moving Mack truck (big mass). Thus, the only explanation for how the slowly thrust lance hit with the same force as your own is that it's more massive.

This is astonishing. The lances are identically constructed. Yet you conclude that one of them - the one that from your point of view is in motion, being carried toward you by your opponent on his galloping horse - is more massive than the other. That's the essence of Einstein's discovery. Energy of motion contributes to an object's mass.

AS with the slowing of time, this is unfamiliar because at everyday speeds the effect is imperceptibly tiny. But if, from your viewpoint, your opponent were to approach at 99.99999999 percent of the speed of light, his lance would be about 70,000 times more massive than yours. Luckily, his thrusting speed would be 70,000 times slower than yours, and so the resulting force would equal your own.

Once Einstein realized that mass and energy were convertible, getting the exact formula relating them - $E = mc^2$ - was a fairly basic exercise, requiring nothing more than high school algebra. His genius was not in the math; it was in his ability to see beyond centuries of misunderstanding and recognize that there was a connection between mass and energy at all.

A little known fact about Einstein's September 1905 paper is that he didn't actually write $E = mc^2$; he wrote the mathematically equivalent (though less euphonious) $m = E/c^2$, placing greater emphasis on creating mass from energy (as in the joust) than on creating energy from mass (as in nuclear weapons and power stations).

Over the last couple of decades, this less familiar reading of Einstein's equation has helped physicists explain why everything ever encountered has the mass that it does. Experiments have shown that the subatomic particles making up matter have almost no mass of their own. But because of their motions and interactions inside of atoms, these particles contain substantial energy - and it's this energy that gives matter its heft. Take away Einstein's equation, and matter loses its mass. You can't get much more pervasive than that.

Its singular fame notwithstanding, $E = mc^2$ fits into the pattern of work and discovery that Einstein pursued with relentless passion throughout his entire life. Einstein believed that deep truths about the workings of the universe would always be "as simple as possible, but no simpler." And in his view, simplicity was epitomized by unifying concepts - like matter and energy - previously deemed separate. In 1916, Einstein simplified our understanding even further by combining gravity with space, time, matter and energy in his General Theory of Relativity. For my money, this is the most beautiful scientific synthesis ever achieved.

With these successes, Einstein's belief in unification grew ever stronger. But the sword of his success was double-edged. It allowed him to dream of a single theory encompassing all of nature's laws, but led him to expect that the methods that had worked so well for him in the past would continue to work for him in the f uture.

It wasn't to be. For the better part of his last 30 years, Einstein pursued the "unified theory," but it stubbornly remained beyond his grasp. As the years passed, he became increasingly isolated; mainstream physics was concerned with prying apart the atom and paid little attention to Einstein's grandiose quest. In a 1942 letter, Einstein described himself as having become "a lonely old man who is displayed now and then as a curiosity because he doesn't wear socks."

Today, Einstein's quest for unification is no curiosity - it is the driving force for many physicists of my generation. No one knows how close we've gotten. Maybe the unified theory will elude us just as it dodged Einstein last century. Or maybe the new approaches being developed by contemporary physics will finally prevail, giving us the ultimate explanation of the cosmos. Without a unified theory it's hard to imagine we will ever resolve the deepest of all mysteries - how the universe began- so the stakes are high and the motivation strong.

But even if our science proves unable to determine the origin of the universe, recent progress has already established beyond any doubt that a fraction of a second after creation (however that happened), the universe was filled with tremendous energy in the form of wildly moving exotic particles and radiation. Within a few minutes, this energy employed $E = mc^2$ to transform itself into more familiar matter - the simplest atoms - which, in the course of about a billion years, clumped into planets and stars.

During the 13 billion years that have followed, stars have used E = mc? to transform their mass back into energy in the form of heat and light; about five billion years ago, our closest star - the sun - began to shine, and the heat and light generated was essential to the formation of life on our planet. If prevailing theory and observations are correct, the conversion of matter to energy throughout the cosmos, mediated by stars, black holes and various forms of radioactive decay, will continue unabated.

In the far, far future, essentially all matter will have returned to energy. But because of the enormous expansion of space, this energy will be spread so thinly that it will hardly ever convert back to even the lightest particles of matter. Instead, a faint mist of light will fall for eternity through an ever colder and quieter cosmos.

The guiding hand of Einstein's $E = mc^2$ will have finally come to rest.

Brian Greene, a professor of physics and mathematics at Columbia, is the author of "The Elegant Universe" and "The Fabric of the Cosmos."