Before and after $e=mc^2$

One hundred years after Albert Einstein's "miracle year" of breakthrough physics papers, here's a look at the lingering effects of one of those papers on the world at large and on what became the nuclear sciences.

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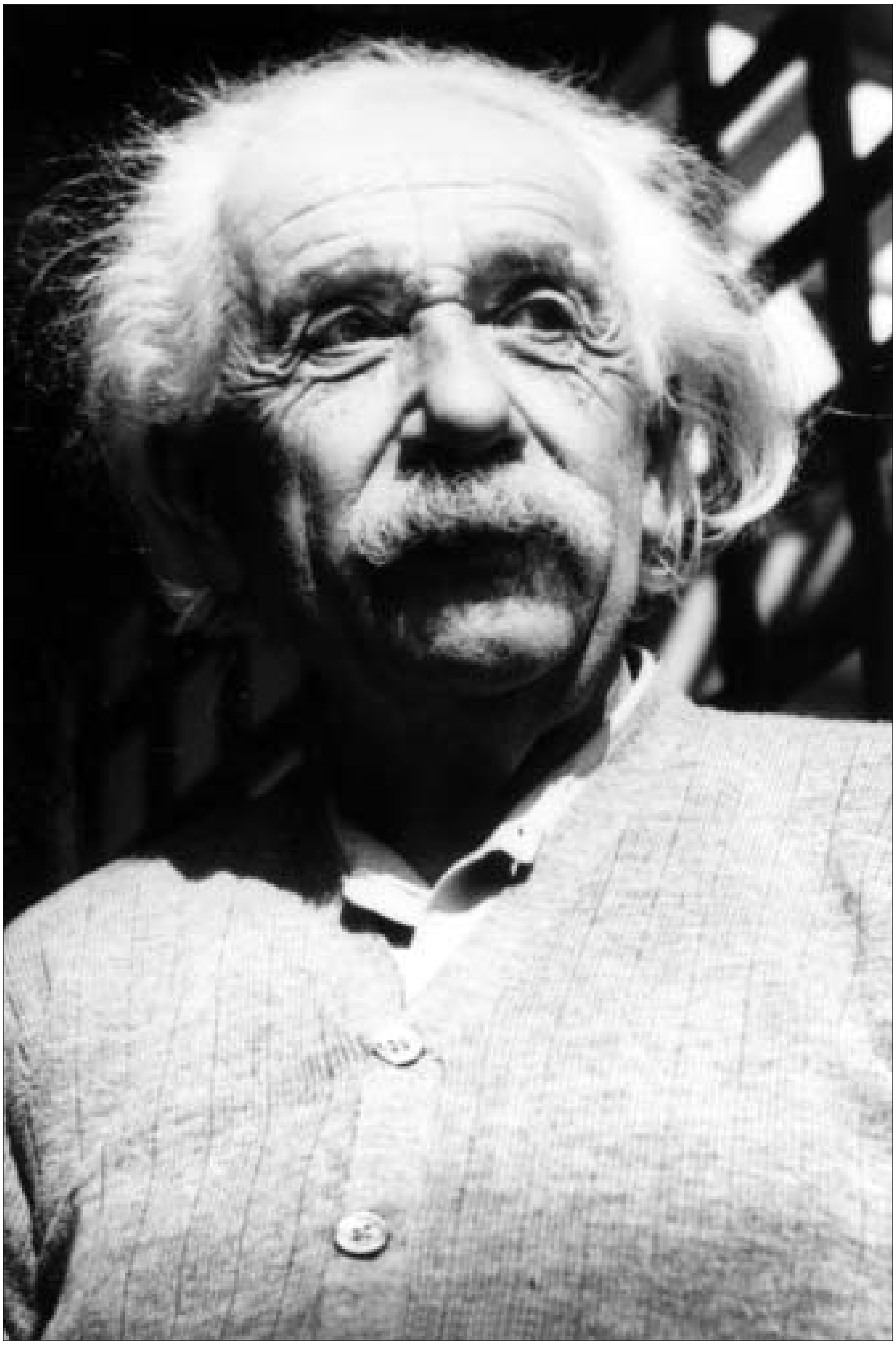

The actual equation $e=mc^2$ did not appear in Einstein's paper on mass-energy equivalence.

ALBERT EINSTEIN'S REVELATION that energy can be transformed into matter, and vice versa, eventually led to another transformation: It changed the way people perceived and understood the world around them. Before 1905, and the publication of Einstein's paper on the subject, it was taken as a first principle that whatever changes matter might undergo, it was still matter, which conservation laws reasonably dictated to be something that could neither be created nor destroyed. Even forms of matter that were used to release energy (chiefly through combustion) were seen as substances that merely contained a potential that could be released under the proper circumstances. This view was a significant intellectual advance over the old alchemical notion that fuels contained a substance called phlogiston, which was manifested in fire.

It is now accepted as routine that not only can a great deal of matter be transformed completely into pure energy, but that energy can also be transformed back into matter. This requires a worldview in which the solidity we perceive is a special case that can generally be counted on to stay as it is under nearly all real-world conditions but that has the potential to be anything but firm. This is a far more fantastic model than even the alchemists' phlogiston, but we live our lives in roughly the same relationship to the world around us as people did before 1905. Even so, it may be nearly as difficult for people now to understand the old paradigm as it would surely be for people then to grasp the new one.

In 1905, Albert Einstein, who had completed his student work in physics but had been unable to gain approval for his thesis, was working as a clerk in the Swiss patent office in Bern. Thus it was that someone who was neither employed as a scientist nor accepted to the faculty of a university had what is widely regarded as the most brilliant single year of scientific publications in history, with numerous papers published in the leading physics journal in the world at the time, *Annalen der Physik (AdP)*, in Germany. This year is the centennial of what is being called Einstein's *annus mirabilus* (miracle year, more or less), and virtually all periodicals in the physical sciences (plus several more for general audiences) have already weighed in on his profusion of landmark developments, so many of them within a single year (and three within a single issue of the journal).

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Not a complete outsider

There is a tendency to romanticize Einstein's outsider status somewhat. He had, in fact, been publishing papers in *AdP* since 1901 (although with neither the frequency nor the impact that he would four years later), and he was not the only author accepted for publication by that journal who did not have a university position. As the 20th century began, the physics community was small, even by the standards of academia at the time, and there is no indication that Einstein had difficulty gaining the attention of the establishment just because he had a day job at the patent office. Academia may not have had any better offers for Einstein at the time. He finally received his doctorate from the University of Zurich in 1906, but he continued to work at the patent office for another two and a half years. Perhaps old tales about the genteel poverty of professors were real enough to influence career choices.

There is also some dispute over the extent to which Einstein can be credited for $e=mc^2$ and the attendant mass-energy interchangeability. Physicist Max Born, for one, criticized Einstein for not appropriately crediting earlier work by such luminaries as Henri Poincaré. There have been even more reckless statements made, including charges of plagiarism, perhaps because the centennial may provide an audience for them. Whether Einstein was meticulous enough in his citations may be open to question, but it is plainly untrue that he ever claimed sole credit for work clearly done by others (such as the Lorentz-FitzGerald contraction, a formula that formed a basis of special relativity and was developed, obviously, by Lorentz and FitzGerald—and derived in response to even earlier experiments by Michelson and Morley). Einstein's work surely would not have survived *AdP* peer review had it been completely derivative.

While $e=mc^2$ may be the most famous scientific formula ever, it does not appear in the paper titled *Does the Inertia of a Body Depend upon its Energy Content?*, which was dated September 27, 1905. This was a fairly short paper pointing out an apparent consequence of Einstein's theory of special relativity, which was submitted to *AdP* in July. A 1922 English translation, available online at <www.fourmilab.ch/etexts/einstein/E_mc2/www/>, includes the following passage:

> If a body gives off the energy L in the form of radiation, its mass diminishes by L/c^2. The fact that the energy withdrawn from the body

> becomes energy of radiation evidently makes no difference, so that we are led to the more general conclusion that:
>
> The mass of a body is a measure of its energy-content; if the energy changes by L, the mass changes in the same sense by $L/9 \times 10^{20}$, the energy being measured in ergs, and the mass in grammes.
>
> It is not impossible that with bodies whose energy-content is variable to a high degree (e.g. with radium salts) the theory may be successfully put to the test.
>
> If the theory corresponds to the facts, radiation conveys inertia between the emitting and absorbing bodies.

And so, in the formula's first publication, Einstein chose to express it in terms of a change in inertia (or mass) as equivalent to a change in energy divided by the square of the speed of light, or (using "e" for energy instead of "L") $m=e/c^2$. This was more in keeping with the topic of the earlier paper in which he proposed special relativity as an explanation for the electrodynamics of moving bodies, and the key point appeared to be the change in mass from the emission of electromagnetic radiation. The excerpt above is the paper's only statement of the relationship, and "$m=e/c^2$" is not even stated separately as a formula, but the text shows that mass (or inertia) is the focal point of the conclusion, to be placed alone on the left side of the equation, while the right side includes all other terms.

In time, it became more conventional for people (including Einstein) to use the form $e=mc^2$, perhaps because the energy of emitted radiation became the point of greater interest. Given work that had been done in recent years by Röntgen, Becquerel, and the Curies, Einstein was probably not alone in supposing that "bodies whose energy-content is variable to a high degree (e.g. with radium salts)" would be a promising medium for testing his hypothesis.

Forty years later, with the conversion of the binding energy of actinide nuclei into a runaway chain reaction of neutrons colliding with more actinide nuclei, the interchangeability of mass and energy became a stunning reality, and apparently no one has thought since then that the left side of the equation should include anything other than energy.

The study of radioactive materials, as noted above, existed before Einstein's paper, but it was a very new field. The techniques for detecting nuclear radiation were still rudimentary, and those for learning the chemistry of the large, newly identified elements that emitted these radiations were not much more advanced. All of the eventual developments that led to the fields covered by this magazine might have happened in about the same time, with or without Einstein's paper, but his calling attention to the mass-energy interchange suggested by special relativity may have spurred interest among physicists in the possibility that radioactivity was a process of mass being converted to energy.

In the world at large, however, $e=mc^2$ would remain largely unknown until sometime around August of 1945, after which it became ubiquitous. Suddenly, there existed nuclear weapons, which in less than one week ended a war that previously appeared headed toward an invasion of Japan that might have lasted months or years. Even as the weapons brought peace, they gave the victorious allies the unsettling awareness that the world had become a much different place. And as the multitudes who were not privy to the Manhattan Project struggled to understand how such weapons were possible, they encountered images of Einstein (now at the Institute for Advanced Study in Princeton, N.J.) and the formula $e=mc^2$.

The "too-simple math"

The late science fiction author Cyril M. Kornbluth had a term for this: "too-simple math." A blackboard full of Greek letters and square-root signs looks so complex to the uninitiated that it seems more comical than threatening. The too-simple math of $e=mc^2$ is different. It seems to have broken through the complexity to something basic and pure, revealing one of the fragile strands that hold existence together. And suddenly, it seemed, the equation was out in the open, perhaps available to be used by anyone—maybe Josef Stalin. And so the Cold War began.

Of course, it took a monumental espionage effort and an economically ruinous diversion of resources for the Soviet Union to develop its own nuclear capability. It's not as though a Moscow academician happened to see an American newsreel showing Einstein writing $e=mc^2$ on a blackboard and shouted, "Of course! That's what we've been looking for!" But to people in general, the fact that the too-simple math was loose in the world was enough to haunt them, regardless of who could make use of it.

And yet, the undeniable virtue of the Cold War was that it remained cold. To this day, Harry S. Truman remains the only person ever to have ordered the detonation of atomic weapons on an inhabited target. And as decades passed, even before the Soviet Union imploded, people learned to accept their new awareness of the world and move on. Those of us who grew up during such events as the Cuban missile crisis may have inadvertently gained some perspective on matters that a single individual (even a citizen of the richest, most powerful nation in history) can, and can't, control.

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It also didn't escape the public's notice that so many of the Manhattan Project scientists, as well as Einstein himself, were quick to declare the importance of controlling the technology they had launched. What they pointed out most effectively was what would be left after the tremendous explosion: a scatter of radioactive material whose effects were clearly lethal in large amounts and, at that time, unknown in lesser amounts.

Meanwhile, the aftermath of their work was the transformation of a fairly obscure field of science into a lavishly funded colossus of research and development. In time, the field outgrew the "born classified" imperative, which had been limited to the building of bigger warheads, and through Atoms for Peace the nuclear disciplines created dozens of ways to support the betterment of life worldwide.

Life in 1905 might already have seemed excessively frantic. A farmer traveling to a familiar city after an absence of a few years might be staggered by the encroachment of motorized transportation, telegraphy and telephony, railroads, electricity, radio—and, if the city were Dayton, Ohio, perhaps the overhead passage of a Wright flyer. Still, the farmer might return home thinking that his part of the world hadn't changed, and wouldn't have to, because in the end the world was firm and solid.

And today? Maybe our view is more sophisticated, with even the nontechnical populace somewhat aware that much more is possible than what we see and feel. This perception might evolve further if, a hundred years hence, everyday experience includes routine encounters with superstrings, quantum wormholes, and entangled electrons. If someone from that era should chance to read, or cerebrally download, this article, he or she might derive great amusement from its quaint fascination with that painfully obvious cliche, $e=mc^2$.