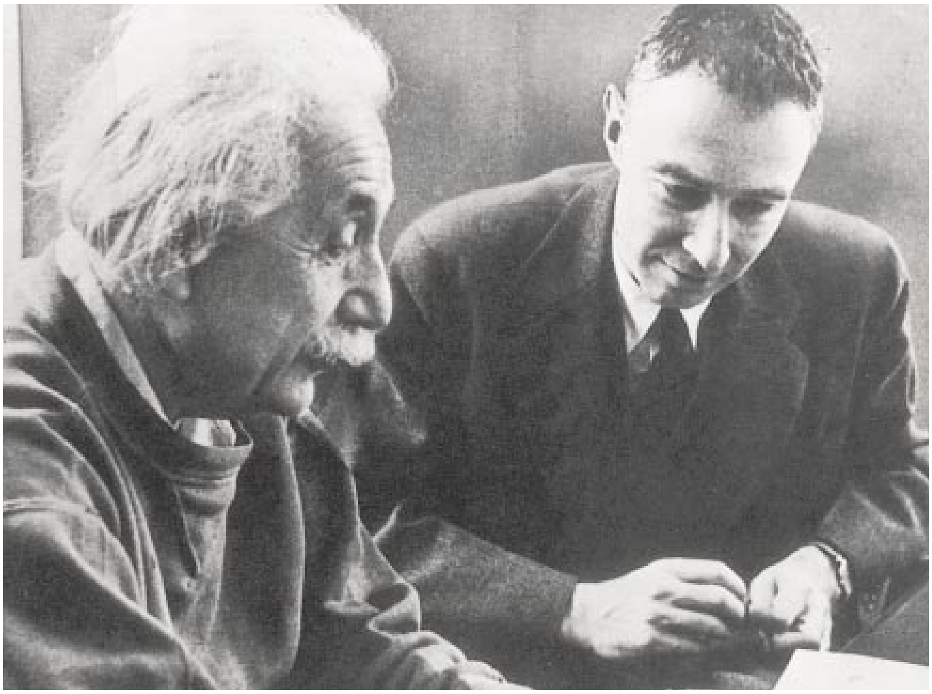

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The Reluctant Father of Black Holes

Albert Einstein's equations of gravity are the foundation of the modern view of black holes; ironically, he used the equations in trying to prove these objects cannot exist

by Jeremy Bernstein

Great science sometimes produces a legacy that outstrips not only the imagination of its practitioners but also their intentions. A case in point is the early development of the theory of black holes and, above all, the role played in it by Albert Einstein. In 1939 Einstein published a paper in the journal *Annals of Mathematics* with the daunting title "On a Stationary System with Spherical Symmetry Consisting of Many Gravitating Masses." With it, Einstein sought to prove that black holes—celestial objects so dense that their gravity prevents even light from escaping—were impossible.

The irony is that, to make his case, he used his own general theory of relativity and gravitation, published in 1916—the very theory that is now used to argue that black holes are not only possible but, for many astronomical objects, inevitable. Indeed, a few months after Einstein's rejection of black holes appeared—and with no reference to it—J. Robert Oppenheimer and his student Hartland S. Snyder published a paper entitled "On Continued Gravitational Contraction." That work used Einstein's general theory of relativity to show, for the first time in the context of modern physics, how black holes could form.

PRO AND CON: In 1939 J. Robert Oppenheimer (*right*) argued for the existence of black holes, at the same time Albert Einstein tried to disprove them. Their careers crossed paths at the Institute for Advanced Study in Princeton, N.J., in the late 1940s, when this photograph was taken, but it is unknown whether they ever discussed black holes.

Perhaps even more ironically, the modern study of black holes, and more generally that of collapsing stars, builds on a completely different aspect of Einstein's legacy—namely, his invention of quantum-statistical mechanics. Without the effects predicted by quantum statistics, every astronomical object would eventually collapse into a black hole, yielding a universe that would bear no resemblance to the one we actually live in.

Bose, Einstein and Statistics

Einstein's creation of quantum statistics was inspired by a letter he received in June 1924 from a then unknown young Indian physicist named Satyendra Nath Bose. Along with Bose's letter came a manuscript that had already been rejected by one British scientific publication. After reading the manuscript, Einstein translated it himself into German and arranged to have it published in the prestigious journal *Zeitschrift für Physik*.

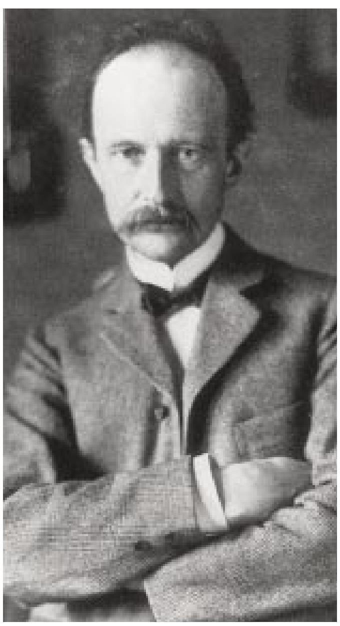
Why did Einstein think that this manuscript was so important? For two decades, he had been struggling with the nature of electromagnetic radiation—especially the radiation trapped inside a heated container that attains the same temperature as its walls. At the turn of the century the German physicist Max Planck had discovered the mathematical function that describes how the various wavelengths, or colors, of this "black body" radiation vary in intensity. It turns out that the form of this spectrum does not depend on the material of the container walls. Only the temperature of the radiation matters. (A striking example of black-body radiation is the photons left over from the big bang, in which case the entire universe is the "container." The temperature of these photons was recently measured at 2.726 ± 0.002 kelvins.)

Somewhat serendipitously, Bose had worked out the statistical mechanics of black-body radiation—that is, he derived the Planck law from a mathematical, quantum-mechanical perspective. That outcome caught Einstein's attention. But being Einstein, he took the matter a step further. He used the same methods to examine the statistical mechanics of a gas of massive molecules obeying the same kinds of rules that Bose had used for the photons. He derived the analogue of the Planck law for this case and noticed something absolutely remarkable. If one cools the gas of particles obeying so-called Bose-Einstein statistics, then at a certain critical temperature all the molecules suddenly collect themselves into a "degenerate," or single, state. That state is now known as Bose-Einstein condensation (although Bose had nothing to do with it).

An interesting example is a gas made up of the common isotope helium 4, whose nucleus consists of two protons and two neutrons. At a temperature of 2.18 kelvins, this gas turns into a liquid that has the most uncanny properties one can imagine, including frictionless flow (that is, superfluidity). U.S. researchers in the past year accomplished the difficult task of cooling other kinds of atoms to several billionths of a kelvin to achieve a Bose-Einstein condensate.

Not all the particles in nature, how-

An Early History of Black Holes



AMERICAN INSTITUTE OF PHYSICS EMILIO SEGRÈ VISUAL ARCHIVE

1900
Max Planck discovers black-body radiation.

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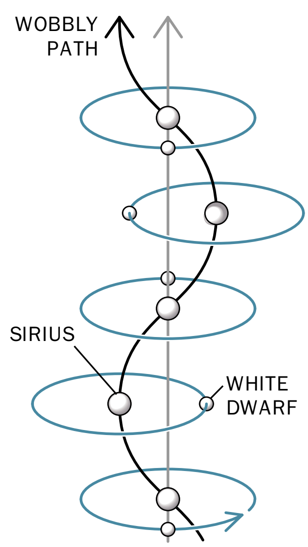
1905
In a paper on black-body radiation, **Albert Einstein** shows that light can be viewed as particles (photons).



JARED SCHNEIDMAN DESIGN

1915
Through spectroscopic studies, astronomer Walter S. Adams identifies Sirius's faint companion (which causes Sirius to wobble slightly as it moves) as a small, hot, dense star—a white dwarf.

UPI/BETTMANN

1916
Einstein publishes his general theory of relativity, producing equations that describe gravity.

ever, show this condensation. In 1925, just after Einstein published his papers on the condensation, the Austrian-born physicist Wolfgang Pauli identified a second class of particles, which includes the electron, proton and neutron, that obeyed different properties. He found that no two such identical particles—two electrons, for example—can ever be in exactly the same quantum-mechanical state, a property that has since become known as the Pauli exclusion principle. In 1926 Enrico Fermi and P.A.M. Dirac invented the quantum statistics of these particles, making them the analogue of the Bose-Einstein statistics.

Because of the Pauli principle, the last thing in the world these particles want to do at low temperatures is to condense. In fact, they exhibit just the opposite tendency. If you compress, say, a gas of electrons, cooling it to very low temperatures and shrinking its volume, the electrons are forced to begin invading one another's space. But Pauli's principle forbids this, so they dart away from one another at speeds that can approach that of light. For electrons and the other Pauli particles, the pressure created by these fleeing particles—the "degeneracy pressure"—persists even if the gas is cooled to absolute zero. It has nothing to do with the fact that the electrons repel one another electrically. Neutrons, which have no charge, do the same thing. It is pure quantum physics.

Quantum Statistics and White Dwarfs

But what has quantum statistics got to do with the stars? Before the turn of the century, astronomers had begun to identify a class of peculiar stars that are small and dim: white dwarfs. The one that accompanies Sirius, the brightest star in the heavens, has the mass of the sun but emits about 1/360 the light. Given their mass and size, white dwarfs must be humongously dense. Sirius's companion is some 61,000 times denser than water. What are these bizarre objects? Enter Sir Arthur Eddington.

When I began studying physics in the late 1940s, Eddington was a hero of mine but for the wrong reasons. I knew nothing about his great work in astronomy. I admired his popular books (which, since I have learned more about physics, now seem rather silly to me). Eddington, who died in 1944, was a neo-Kantian who believed that everything of significance about the universe could be learned by examining what went on inside one's head. But starting in the late 1910s, when Eddington led one of the two expeditions that confirmed Einstein's prediction that the sun bends starlight, until the late 1930s, when Eddington really started going off the deep end, he was truly one of the giants of 20th-century science. He practically created the discipline that led to the first understanding of the internal constitution of stars, the title of his classic 1926 book. To him, white dwarfs were an affront, at least from an aesthetic point of view. But he studied them nonetheless and came up with a liberating idea.

In 1924 Eddington proposed that the gravitational pressure that was squeezing the dwarf might strip some of the electrons off protons. The atoms would then lose their "boundaries" and might be squeezed together into a small, dense package. The dwarf would eventually stop collapsing because of the Fermi-Dirac degeneracy pressure—that is, when the Pauli exclusion principle forced the electrons to recoil from one another.

The understanding of white dwarfs took another step forward in July 1930, when Subrahmanyan Chandrasekhar, who was 19, was on board a ship sail-


ROBERT BEIN *AIP Emilio Segrè Visual Archive*

1916
Karl Schwarzschild shows that a radius of a collapsing object exists at which Einstein's gravity equations become "singular"—time vanishes, and space becomes infinite.


MAX PLANCK INSTITUTE *courtesy of AIP*

1924
Einstein publishes **Satyendra Nath Bose**'s work on black-body radiation, developing so-called quantum statistics for one class of particles (such as photons).


UPI/BETTMANN

1924
Sir Arthur Eddington proposes that gravity can strip away electrons from protons in a white dwarf.


AIP EMILIO SEGRÈ VISUAL ARCHIVE

1925
Wolfgang Pauli formulates the exclusion principle, which states that certain particles cannot be in exactly the same quantum-mechanical state.

ing from Madras to Southampton. He had been accepted by the British physicist R. H. Fowler to study with him at the University of Cambridge (where Eddington was, too). Having read Eddington's book on the stars and Fowler's book on quantum-statistical mechanics, Chandrasekhar had become fascinated by white dwarfs. To pass the time during the voyage, Chandrasekhar asked himself: Is there any upper limit to how massive a white dwarf can be before it collapses under the force of its own gravitation? His answer set off a revolution.

A white dwarf as a whole is electrically neutral, so all the electrons must have a corresponding proton, which is some 2,000 times more massive. Consequently, protons must supply the bulk of the gravitational compression. If the dwarf is not collapsing, the degeneracy pressure of the electrons and the gravitational collapse of the protons must just balance. This balance, it turns out, limits the number of protons and hence the mass of the dwarf. This maximum is known as the Chandrasekhar limit and equals about 1.4 times the mass of the sun. Any dwarf more massive than this number cannot be stable.

Chandrasekhar's result deeply disturbed Eddington. What happens if the mass is more than 1.4 times that of the sun? He was not pleased with the answer. Unless some mechanism could be found for limiting the mass of any star that was eventually going to compress itself into a dwarf, or unless Chandrasekhar's result was wrong, massive stars were fated to collapse gravitationally into oblivion.

To Eddington, white dwarfs were an affront.

Eddington found this intolerable and proceeded to attack Chandrasekhar's use of quantum statistics—both publicly and privately. The criticism devastated Chandrasekhar. But he held his ground, bolstered by people such as the Danish physicist Niels Bohr, who assured him that Eddington was simply wrong and should be ignored.

A Singular Sensation

As researchers explored quantum statistics and white dwarfs, others tackled Einstein's work on gravitation, his general theory of relativity. As far as I know, Einstein never spent a great deal of time looking for exact solutions to his gravitational equations. The part that described gravity around matter was extremely complicated, because gravity distorts the geometry of space and time, causing a particle to move from point to point along a curved path. More important to Einstein, the source of gravity—matter—could not be described by the gravitational equations alone. It had to be put in by hand, leaving Einstein to feel the equations were incomplete. Still, approximate solutions could describe with sufficient accuracy phenomena such as the bending of starlight. Nevertheless, he was impressed when, in 1916, the German astronomer Karl Schwarzschild came up with an exact solution for a realistic situation—in particular, the case of a planet orbiting a star.

In the process, Schwarzschild found something disturbing. There is a distance from the center of the star at which the mathematics goes berserk. At this distance, now known as the Schwarzschild radius, time vanishes, and space becomes infinite. The equation becomes what mathematicians call singular. The Schwarzschild radius is usually much smaller than the radius of the object. For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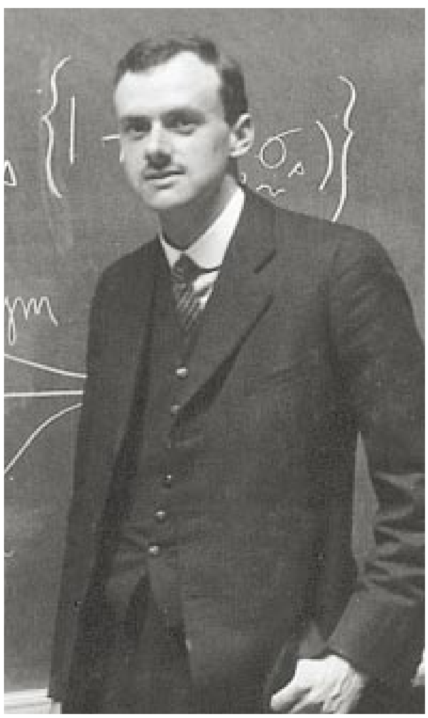

AIP EMILIO SEGRÈ VISUAL ARCHIVE


UPI/BETTMANN

1926
Enrico Fermi and **P.A.M. Dirac** develop quantum statistics for particles that obey Pauli's exclusion principle (such as electrons and protons). When compressed, such particles fly away from one another, creating a so-called degeneracy pressure.

1930
Using quantum statistics and Eddington's work on stars, **Subrahmanyan Chandrasekhar** finds that the upper mass limit for white dwarfs is 1.4 times the mass of the sun, suggesting that more massive stars collapse into oblivion. Eddington makes fun of him.

the sun, for example, it is three kilometers, whereas for a one-gram marble it is 10^{-28} centimeter.

Schwarzschild was, of course, aware that his formula went crazy at this radius, but he decided that it did not matter. He constructed a simplified model of a star and showed that it would take an infinite gradient of pressure to compress it to his radius. The finding, he argued, served no practical interest.

But his analysis did not appease everybody. It bothered Einstein, because Schwarzschild's model star did not satisfy certain technical requirements of relativity theory. Various people, however, showed that one could rewrite Schwarzschild's solutions so that they avoided the singularity. But was the result really nonsingular? It would be incorrect to say that a debate raged, because most physicists had rather little regard for these matters—at least until 1939.

In his 1939 paper Einstein credits his renewed concern about the Schwarzschild radius to discussions with the Princeton cosmologist Harold P. Robertson and with his assistant Peter G. Bergmann, who is now professor emeritus at Syracuse University. It was certainly Einstein's intention in this paper to kill off the Schwarzschild singularity once and for all. At the end of it he writes, "The essential result of this investigation is a clear understanding as to why 'Schwarzschild singularities' do not exist in physical reality." In other words, black holes cannot exist.

To make his point, Einstein focused on a collection of small particles moving in circular orbits under the influence of one another's gravitation—in effect, a system resembling a spherical star cluster. He then asked whether such a configuration could collapse under its own gravity into a stable star with a radius equal to its Schwarzschild radius. He concluded that it could not, because at a somewhat larger radius the stars in the cluster would have to move faster than light in order to keep the configuration stable. Although Einstein's reasoning is correct, his point is irrelevant: it does not matter that a collapsing star at the Schwarzschild radius is unstable, because the star collapses past that radius anyway. I was much taken by the fact that the then 60-year-old Einstein presents in this paper tables of numerical results, which he must have gotten by using a slide rule. But the paper, like the slide rule, is now a historical artifact.

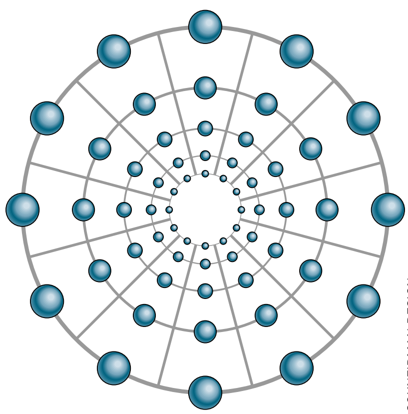
From Neutrons to Black Holes

While Einstein was doing this research, an entirely different enterprise was unfolding in California. Oppenheimer and his students were creating the modern theory of black holes [see "J. Robert Oppenheimer: Before the War," by John S. Rigden; Scientific American, July 1995]. The curious thing about the black-hole research is that it was inspired by an idea that turned out to be entirely wrong. In 1932 the British experimental physicist James Chadwick found the neutron, the neutral component of the atomic nucleus. Soon thereafter speculation began—most notably by Fritz Zwicky of the California Institute of Technology and independently by the brilliant Soviet theoretical physicist Lev D. Landau—that neutrons could lead to an alternative to white dwarfs.

BETTMANN ARCHIVE

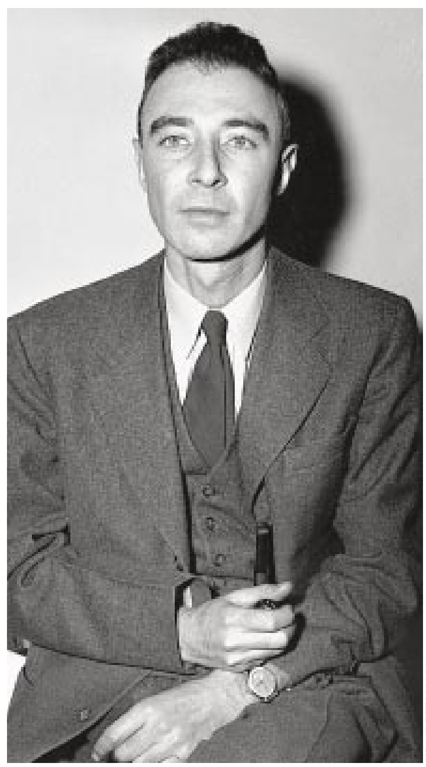
1932
James Chadwick discovers the neutron. Its existence leads researchers to wonder if "neutron stars" could be an alternative to white dwarfs.

"On a Stationary System with Spherical Symmetry Consisting of Many Gravitating Masses"
– Albert Einstein in *Annals of Mathematics*, 1939



JARED SCHNEIDMAN DESIGN

1939
Sparked by conversations with colleagues, Einstein tries to kill off the Schwarzschild radius once and for all: he concludes that black holes are impossible in a paper published in *Annals of Mathematics.*



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1939
Using ideas of collapsing neutron stars and white dwarfs, **J. Robert Oppenheimer** and his student Hartland S. Snyder show how a black hole can form.

When the gravitational pressure got large enough, they argued, an electron in a star could react with a proton to produce a neutron. (Zwicky even conjectured that this process would happen in supernova explosions; he was right, and these "neutron stars" we now identify as pulsars.) At the time of this work, the actual mechanism for generating the energy in ordinary stars was not known. One solution placed a neutron star at the center of ordinary stars, in somewhat the same spirit that many astrophysicists now conjecture that black holes power quasars.

Although Einstein's reasoning was correct, his point is irrelevant.

The question then arose: What was the equivalent of the Chandrasekhar mass limit for these stars? Determining this answer is much harder than finding the limit for the white dwarfs. The reason is that the neutrons interact with one another with a strong force whose specifics we still do not fully understand. Gravity will eventually overcome this force, but the precise limiting mass is sensitive to the details. Oppenheimer published two papers on this subject with his students Robert Serber and George M. Volkoff and concluded that the mass limit here is comparable to the Chandrasekhar limit for white dwarfs. The first of these papers was published in 1938, and the second in 1939. (The real source of stellar energy—fusion—was discovered in 1938 by Hans Bethe and Carl Friedrich von Weizsäcker, but it took a few years to be accepted, and so astrophysicists continued to pursue alternative theories.)

Oppenheimer went on to ask exactly what Eddington had wondered about white dwarfs: What would happen if one had a collapsing star whose mass exceeded any of the limits? Einstein's 1939 rejection of black holes—to which Oppenheimer and his students were certainly oblivious, for they were working concurrently, 3,000 miles away—was of no relevance. But Oppenheimer did not want to construct a stable star with a radius equal to its Schwarzschild radius. He wanted to see what would happen if one let the star collapse through its Schwarzschild radius. He suggested that Snyder work out this problem in detail.

To simplify matters, Oppenheimer told Snyder to make certain assumptions and to neglect technical considerations such as the degeneracy pressure or the possible rotation of the star. Oppenheimer's intuition told him that these factors would not change anything essential. (These assumptions were challenged many years later by a new generation of researchers using sophisticated high-speed computers—poor Snyder had an old-fashioned mechanical desk calculator—but Oppenheimer was right. Nothing essential changes.) With the simplified assumptions, Snyder found out that what happens to a collapsing star depends dramatically on the vantage point of the observer.

Two Views of a Collapse

Let us start with an observer at rest a safe distance from the star. Let us also suppose that there is another observer attached to the surface of the star—"co-moving" with its collapse—who can send light signals back to his stationary colleague. The stationary observer will see the signals from his moving counterpart gradually shift to the red end of the electromagnetic spectrum. If the frequency of the signals is thought of as a clock, the stationary observer will say that the moving observer's clock is gradually slowing down.

Indeed, at the Schwarzschild radius the clock will slow down to zero. The stationary observer will argue that it took an infinite amount of time for the star to collapse to its Schwarzschild radius. What happens after that we cannot say, because, according to the stationary observer, there is no "after." As far as this observer is concerned, the star is frozen at its Schwarzschild radius.

Indeed, until December 1967, when the physicist John A. Wheeler, now at Princeton University, coined the name "black hole" in a lecture he presented, these objects were often referred to in the literature as frozen stars. This frozen state is the real significance of the singularity in the Schwarzschild geometry. As Oppenheimer and Snyder observed in their paper, the collapsing star "tends to close itself off from any communication with a distant observer; only its gravitational field persists." In other words, a black hole has been formed.

But what about observers riding with collapsing stars? These observers, Oppenheimer and Snyder pointed out, have a completely different sense of things. To them, the Schwarzschild radius has no special significance. They pass right through it and on to the center in a matter of hours, as measured by their watches. They would, however, be subject to monstrous tidal gravitational forces that would tear them to pieces.

The year was 1939, and the world itself was about to be torn to pieces. Oppenheimer was soon to go off to war to build the most destructive weapon ever devised by humans. He never worked on the subject of black holes again. As far as I know, Einstein never did, either. In peacetime, in 1947, Oppenheimer became the director of the Institute for Advanced Study in Princeton, N.J., where Einstein was still a professor. From time to time they talked. There is no record of their ever having discussed black holes. Further progress would have to wait until the 1960s, when discoveries of quasars, pulsars and compact x-ray sources reinvigorated thinking about the mysterious fate of stars. SA

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