HOW EINSTEIN REINVENTED REALITY

HISTORY

Albert Einstein created his most famous theory amid personal strife, political tension and a scientific rivalry that almost cost him the glory of his discovery

By Walter Isaacson

The general theory of relativity began with a sudden thought. It was late 1907, two years after the "miracle year" in which Albert Einstein had produced his special theory of relativity and his theory of light quanta, but he was still an examiner in the Swiss patent office. The physics world had not yet caught up with his genius. While sitting in his office in Bern, a thought "startled" him, he recalled: "If a person falls freely, he will not feel his own weight." He would later call it "the happiest thought in my life."

The tale of the falling man has become an iconic one, and in some accounts it actually involves a painter who fell from the roof of an apartment building near the patent office. Like other great tales of gravitational discovery—Galileo dropping objects from the Leaning Tower of Pisa and the apple falling on Isaac Newton's head—it was embellished in popular lore. Despite Einstein's propensity to focus on science rather than the "merely personal," even he was not likely to watch a real human plunging off a roof and think of gravitational theory, much less call it the happiest thought in his life.

Einstein soon refined his thought experiment so that the falling man was in an enclosed chamber, such as an elevator, in free fall. In the chamber, he would feel weightless. Any objects he dropped would float alongside him. There would be no way for him to tell—no experiment he could do to determine—if the chamber was falling at an accelerated rate or was floating in a gravity-free region of outer space.

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Then Einstein imagined that the man was in the same chamber way out in space, where there was no perceptible gravity, and a constant force was pulling the chamber up at an accelerated rate. He would feel his feet pressed to the floor. If he dropped an object, it would fall to the floor at an accelerated rate—just as if he stood on Earth. There was no way to make a distinction between the effects of gravity and the effects of being accelerated.

Einstein dubbed this "the equivalence principle." The local effects of gravity and of acceleration are equivalent. Therefore, they must be manifestations of the same phenomenon, some cosmic field that accounts for both acceleration and gravity.

It would take another eight years for Einstein to turn his falling-man thought experiment into the most beautiful theory in the history of physics. He would go from his sedate life as a married father working at the Swiss patent office to living alone as a professor in Berlin, estranged from his family and increasingly alienated from his Prussian Academy of Sciences colleagues there by the rise of anti-Semitism. The decision last year by the California Institute of Technology and Princeton University to put an archive of Einstein's papers online for free permits a glimpse of him juggling the cosmic and the personal throughout this period. We can relish his excitement in late 1907 as he scribbled down what he called "a novel consideration, based on the principle of relativity, on acceleration and gravitation." Then we can sense his grumpy boredom, a week later, as he rejected an electric company's patent application for an alternating-current machine, calling the claim "incorrectly, imprecisely and unclearly prepared." The coming years would be full of human drama, as Einstein raced against a rival to give mathematical expression to relativity while struggling with his estranged wife over money and his right to visit his two young boys. But by 1915 his work climaxed in a completed theory that would change our understanding of the universe forever.

Einstein faced two ticking clocks: he could sense that Hilbert was closing in on the correct equations, and he had agreed to give a series of four formal Thursday lectures on his theory.

BENDING LIGHT

FOR ALMOST FOUR YEARS after positing that gravity and acceleration were equivalent, Einstein did little with the idea. Instead he focused on quantum theory. But in 1911, when he had finally breached the walls of academia and become a professor at the German Charles-Ferdinand University in Prague, he turned his attention back to coming up with a theory of gravity that would help him generalize special relativity—the relation between space and time that he defined in 1905.

As Einstein developed his equivalence principle, he realized that it had some surprising ramifications. For example, his chamber thought experiment indicated that gravity would bend light. Imagine that the chamber is being accelerated upward. A light beam comes in through a pinhole on one wall. By the time it reaches the opposite wall, the light is a little closer to the floor because the chamber has shot upward. And if you could plot the beam's trajectory across the chamber, it would be curved because of the upward acceleration. The equivalence principle says that this effect should be the same whether the chamber is accelerating upward or is resting still in a gravitational field. In other words, light should bend when passing through a gravitational field.

In 1912 Einstein asked an old classmate to help him with the complicated mathematics that might describe a curved and warped four-dimensional spacetime. Until then, his success had been based on his talent for sniffing out the underlying physical principles of nature. He had left to others the task of finding the best mathematical expressions of those principles. But now Einstein realized that math could be a tool for discovering—and not merely describing—nature's laws.

Einstein's goal as he pursued his general theory of relativity was to find the mathematical equations describing two interwoven processes: how a gravitational field acts on matter, telling it how to move, and how matter generates gravitational fields in spacetime, telling spacetime how to curve.

For three more years Einstein wrestled with drafts and outlines that turned out to have flaws. Then, beginning in the summer of 1915, the math and the physics began to come together.

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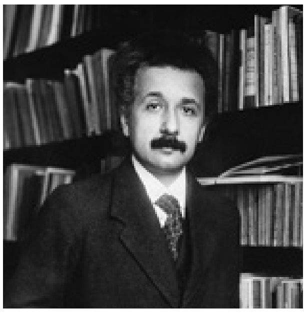
IN BRIEF

Einstein's realization that gravity and acceleration are equivalent put him on an eight-year path to generalize his special theory of relativity.

He raced to discover the correct mathematical formulas for his theory before a rival, mathematician David Hilbert, could do so first. Einstein simultaneously struggled on the home front, as he went through a divorce from his first wife and a separation from his sons while he courted a cousin whom he would later marry.

Despite these challenges, Einstein triumphed and delivered one of the world's supreme scientific works in his general theory of relativity.



Road to Relativity

Einstein faced difficulties, both scientific and personal, while formulating general relativity

1907
Einstein realizes that a person falling freely would not feel his weight—an insight that set him on the path to general relativity

1914
Einstein and his first wife, Mileva Marić, separate. She moves from Berlin, where they had been living, to Zurich with their two sons

1911
Now a professor at the German Charles-Ferdinand University in Prague, Einstein starts working to expand his special theory of relativity to include gravity

1912
The physicist begins an affair with his cousin, Elsa Löwenthal, whom he later marries

PERSONAL UNRAVELING

BY THEN, HE HAD MOVED TO BERLIN to become a professor and member of the Prussian Academy. But he found himself working pretty much without support. Anti-Semitism was rising, and he formed no coterie of colleagues around him. He split with his wife, Mileva Marić, a fellow physicist who had been his sounding board in formulating special relativity in 1905, and she moved back to Zurich with their two sons, ages 10 and four. He was having an affair with his cousin Elsa, whom he would later marry, but he lived by himself in a sparsely furnished apartment in central Berlin, where he ate intermittently, slept randomly, played his violin and waged his solitary struggle.

Throughout 1915 his personal life began to unravel. Some friends were pressing him to get a divorce and marry Elsa; others were warning that he should not be seen with her or let her come near his two boys. Marić repeatedly sent letters requesting money, and at one point Einstein replied with unbridled bitterness. "I find such a demand beyond discussion," he responded. "I find your constant attempts to lay hold of everything that is in my possession absolutely disgraceful." He tried hard to maintain a correspondence with his sons, but they rarely wrote back, and he accused Marić of not delivering his letters to them.

Yet amid this personal turmoil, Einstein was able to devise, by late June 1915, many elements of general relativity. He gave a weeklong series of lectures at the end of that month on his evolving ideas at the University of Göttingen in Germany, the world's preeminent center for mathematics. Foremost among the geniuses there was David Hilbert, and Einstein was particularly eager—perhaps too eager, it would turn out—to explain all the intricacies of relativity to him.

A RIVALRY

THE VISIT TO GÖTTINGEN WAS A TRIUMPH. A few weeks later Einstein reported to a scientist friend that he "was able to convince Hilbert of the general theory of relativity." In a letter to another colleague, he was even more effusive: "I am quite enchanted with Hilbert!"

Hilbert was likewise enchanted with Einstein and with his theory, so much so that he soon set out to see if he could do what Einstein had so far not accomplished: produce the mathematical equations that would complete the formulation of general relativity.

Einstein began hearing Hilbert's footsteps in early October 1915, just as he realized that his current version of the theory—which was based on an *Entwurf,* or outline, he had been refining for two years—had serious flaws. His equations did not account properly for rotating motion. In addition, he realized that his equations were not generally covariant, meaning that they did not really make all forms of accelerated and nonuniform motion relative, nor did they fully explain an anomaly that astronomers had observed in the orbit of the planet Mercury. Mercury's perihelion—its point of closest approach to the sun—had been gradually shifting in a way not accounted for by Newtonian physics or by Einstein's then current version of his own theory.

Einstein faced two ticking clocks: he could sense that Hilbert was closing in on the correct equations, and he had agreed to give a series of four formal Thursday lectures on his theory in November to the members of the Prussian Academy. The result was an exhausting monthlong whirlwind during which Einstein wrestled with a succession of equations, corrections and updates that he rushed to complete.

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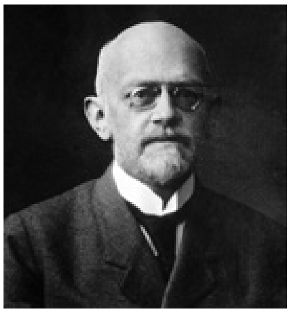
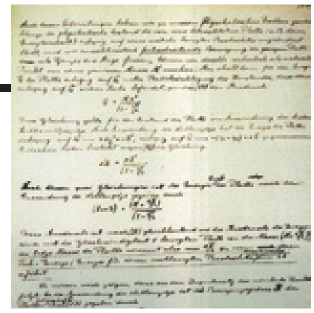
JUNE 1915

Mathematician David Hilbert attends a lecture where Einstein describes his ideas about general relativity. Hilbert begins to race Einstein to devise the mathematics of the theory





NOVEMBER 1915

During his fourth lecture that month at the Prussian State Library, Einstein finally delivers a paper reporting his field equations for general relativity

SUMMER AND FALL OF 1915

Einstein lives alone, eats and sleeps intermittently, and consoles himself with his violin while he struggles to produce equations to formalize general relativity

Even as he arrived at the grand hall of the Prussian State Library on November 4 to deliver the first of his lectures, Einstein was still wrestling with his theory. “For the last four years,” he began, “I have tried to establish a general theory of relativity.” With great candor, he detailed the problems he had encountered and admitted that he still had not come up with equations that fully worked.

Einstein was in the throes of the one of the most concentrated frenzies of scientific creativity in history. At the same time, he was dealing with personal crises within his family. Letters continued to arrive from his estranged wife that pressed him for money and discussed the guidelines for his contact with their two sons. Through a mutual friend, she demanded that he not ask that his children come visit him in Berlin where they might discover his affair. Einstein assured the friend that in Berlin he was living alone and that his “desolate” apartment had “an almost churchlike atmosphere.” The friend replied, referring to Einstein’s work on general relativity, “Justifiably so, for unusual divine powers are at work in there.”

On the very day that he presented his first paper, he wrote a painfully poignant letter to his elder son, Hans Albert, who was living in Switzerland:

> *Yesterday I received your dear little letter and was delighted with it. I was already afraid you didn’t want to write me at all anymore.... I shall press for our being together for a month every year so that you see that you have a father who is attached to you and loves you. You can learn a lot of fine and good things from me as well that no one else can offer you so easily.... In the last few days I completed one of the finest papers of my life; when you are older, I will tell you about it.*

He ended with a small apology for seeming so distracted. “I am often so engrossed in my work that I forget to eat lunch,” he wrote.

Einstein also engaged in an awkward interaction with Hilbert. He had been informed that the Göttingen mathematician had spotted the flaws in the *Entwurf* equations. Worried about being scooped, he wrote Hilbert a letter saying that he himself had discovered the flaws, and he sent along a copy of his November 4 lecture.

In his second lecture, delivered on November 11, Einstein imposed new coordinate conditions that allowed his equations to be generally covariant. As it turned out, the change did not greatly improve matters. He was close to the final answer but making little headway. Once again, he sent his paper off to Hilbert and asked him how his own quest was going. “My own curiosity is interfering with my work!” he wrote.

Hilbert sent him a reply that must have unnerved Einstein.

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He said he had a "solution to your great problem," and he invited Einstein to come to Göttingen on November 16 and have the dubious pleasure of hearing it. "Since you are so interested, I would like to lay out my theory in very complete detail this coming Tuesday," Hilbert wrote. "My wife and I would be very pleased if you stayed with us." Then, after signing his name, Hilbert felt compelled to add a tantalizing and disconcerting postscript. "As far as I understand your new paper, the solution given by you is entirely different from mine."

COMING TO A HEAD

EINSTEIN WROTE FOUR LETTERS on November 15, a Monday, that give a glimpse into his intertwined personal and professional dramas. To Hans Albert, he suggested that he would like to travel to Switzerland at Christmas to visit him. "Maybe it would be better if we were alone somewhere," such as at a secluded inn, he said to his son. "What do you think?"

He then wrote his estranged wife a conciliatory letter that thanked her for her willingness not "to undermine my relations with the boys." And he reported to a friend, "I have modified the theory of gravity, having realized that my earlier proofs had a gap.... I shall be glad to come to Switzerland at the turn of the year to see my dear boy."

He also replied to Hilbert and declined his invitation to visit Göttingen the next day. His letter did not hide his anxiety: "The hints you gave in your messages awaken the greatest of expectations. Nevertheless, I must refrain from traveling to Göttingen.... I am tired out and plagued by stomach pains.... If possible, please send me a correction proof of your study to mitigate my impatience."

As he hurriedly rushed to come up with the precise formulation of his theory, Einstein made a breakthrough that turned his anxiety into elation. He tested a set of revised equations to see if they would yield the correct results for the anomalous shift in Mercury's orbit. The answer came out right: his equations predicted the perihelion should drift by about 43 arc seconds per century. He was so thrilled that he had heart palpitations. "I was beside myself with joy and excitement for days," he told a colleague. To another physicist, he exulted, "The results of Mercury's perihelion movement fill me with great satisfaction. How helpful to us is astronomy's pedantic accuracy, which I used to secretly ridicule!"

The morning of his third lecture, November 18, Einstein received Hilbert's new paper and was dismayed by how similar it was to his own work. His response to Hilbert was terse and clearly designed to assert priority. "The system you furnish agrees—as far as I can see—exactly with what I found in the last few weeks and have presented to the Academy," he wrote. "Today I am presenting to the Academy a paper in which I derive quantitatively out of general relativity, without any guiding hypothesis, the perihelion motion of Mercury. No gravitational theory has achieved this until now."

Hilbert responded kindly and generously the following day, claiming no priority for himself. "Cordial congratulations on conquering perihelion motion," he wrote. "If I could calculate as rapidly as you, in my equations the electron would have to capitulate, and the hydrogen atom would have to produce its note of apology about why it does not radiate." The next day, however, Hilbert sent a paper to a Göttingen science journal describing his own version of the equations for general relativity. The title he picked for his piece was not a modest one: "The Foundations of Physics," he called it.

It is not clear how carefully Einstein read Hilbert's paper or if it affected his thinking as he prepared his climactic fourth lecture at the Prussian Academy. Regardless, he produced in time for his final lecture on November 25—entitled "The Field Equations of Gravitation"—a set of covariant equations that described a general theory of relativity.

It was not nearly as vivid to the layperson as, say, $E = mc^2$. Yet using the condensed notations of tensors, in which sprawling mathematical complexities can be compressed into little subscripts, the crux of the final Einstein field equation is compact enough to be emblazoned on T-shirts worn by physics geeks. In one of its many variations, it can be written as:

$$R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R = -8 \pi G T_{\mu\nu}$$

The left side of the equation—which is now known as the Einstein tensor and can be written simply as $G_{\mu\nu}$—describes how the geometry of spacetime is warped and curved by massive objects. The right side describes the movement of matter in the gravitational field. The interplay between the two sides shows how objects curve spacetime and how, in turn, this curvature affects the motion of objects.

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Both at the time and to this day, there has been a priority dispute over which elements of the mathematical equations of general relativity were discovered first by Hilbert rather than by Einstein. Whatever the case, it was Einstein's theory that was being formalized by these equations, one that he had explained to Hilbert during their time together in Göttingen that summer of 1915. Hilbert graciously noted this in the final version of his paper: "The differential equations of gravitation that result are, as it seems to me, in agreement with the magnificent theory of general relativity established by Einstein." As he later summed it up, "Einstein did the work and not the mathematicians."

Within a few weeks Einstein and Hilbert were repairing their relationship. Hilbert proposed Einstein for membership in the Royal Society of Sciences in Göttingen, and Einstein wrote back with an amiable letter saying how two men who had glimpsed transcendent theories should not be diminished by earthly emotions. "There has been a certain ill-feeling between us, the cause of which I do not want to analyze," Einstein wrote. "I have struggled against the feeling of bitterness attached to it, and this with complete success. I think of you again with unmixed geniality and ask you to try to do the same with me. Objectively it is a shame when two real fellows who have extricated themselves from this shabby world do not afford each other mutual pleasure."

"THE BOLDEST DREAMS"

EINSTEIN'S PRIDE WAS UNDERSTANDABLE. At age 36, he had produced a dramatic revision of our concept of the universe. His general theory of relativity was not merely the interpretation of some experimental data or the discovery of a more accurate set of laws. It was a whole new way of regarding reality.

With his special theory of relativity, Einstein had shown that space and time did not have independent existences but instead formed a fabric of spacetime. Now, with his general version of the theory, this fabric of spacetime became not merely a container for objects and events. Instead it had its own dynamics that were determined by, and in turn helped to determine, the motion of objects within it—like the way that the fabric of a trampoline will curve as a bowling ball and some billiard balls roll across it and in turn that the dynamic curving of the trampoline fabric will determine the path of the rolling balls and cause the billiard balls to move toward the bowling ball.

The curving and rippling fabric of spacetime explained gravity, its equivalence to acceleration and the general relativity of all forms of motion. In the opinion of Paul Dirac, the Nobel laureate pioneer of quantum mechanics, it was "probably the greatest scientific discovery ever made." And Max Born, another giant of 20th-century physics, called it "the greatest feat of human thinking about nature, the most amazing combination of philosophical penetration, physical intuition and mathematical skill."

The entire process had exhausted Einstein. His marriage had collapsed, and war was ravaging Europe. But he was as happy as he would ever be. "The boldest dreams have now been fulfilled," he exulted to his best friend, engineer Michele Besso. "*General* covariance. Mercury's perihelion motion wonderfully precise." He signed himself "contented but quite worn-out."

Years later, when his younger son, Eduard, asked why he was so famous, Einstein replied by using a simple image to describe his fundamental insight that gravity was the curving of the fabric of spacetime. "When a blind beetle crawls over the surface of a curved branch, it doesn't notice that the track it has covered is indeed curved," he said. "I was lucky enough to notice what the beetle didn't notice." SA

MORE TO EXPLORE

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On the Generalized Theory of Gravitation. Albert Einstein; April 1950.

An Interview with Einstein. I. Bernard Cohen; July 1955.

scientificamerican.com/magazine/sa

THE BASICS

Relativity Primer

General relativity redefined the concept of gravity—rather than a force pulling masses together, the theory exposed it as a simple consequence of the geometry of space and time. The notion grew out of a revelation from the more limited special theory of relativity, which Albert Einstein conceived 10 years earlier. This theory established space and time as a single entity, spacetime (*below*). In his general theory of relativity, Einstein described what happens when mass is present in spacetime (*top right*), causing it to curve and forcing objects traveling through it to follow a bent path. If enough mass is packed into a very small region, spacetime becomes infinitely curved, creating a black hole (*bottom right*).

Spacetime without Mass

The special theory of relativity first established that the universe as we know it has four dimensions—three of space and one of time. In the absence of mass, spacetime is essentially a grid, and the shortest path for an object to travel through it is a straight line. Because we cannot portray four dimensions on this two-dimensional page, we show a simplified diagram of the three spatial dimensions with the position of an object at various times standing in for the missing fourth dimension.

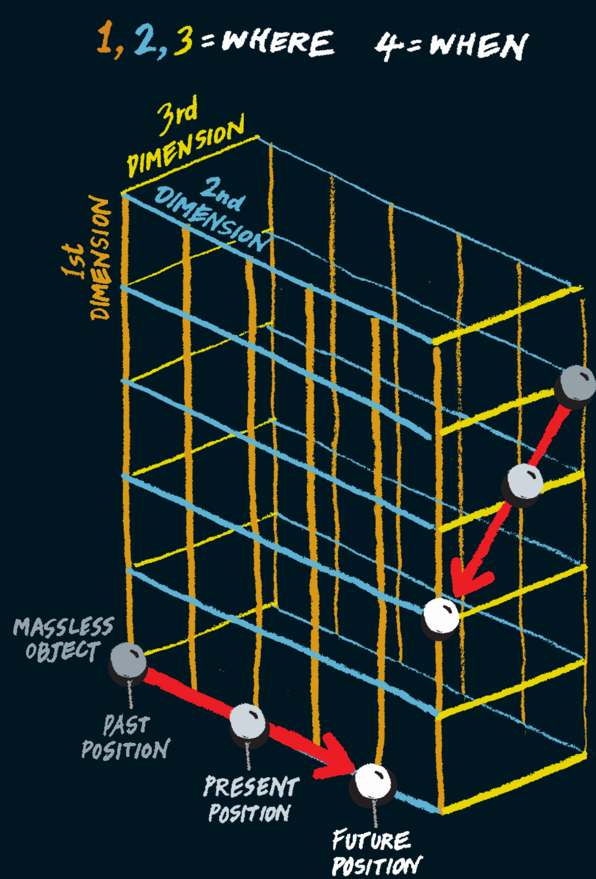
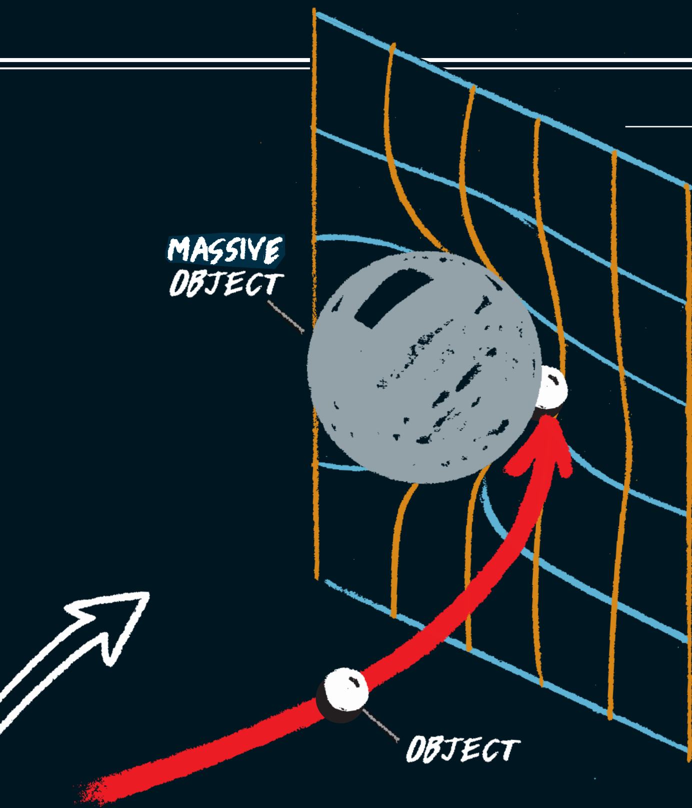
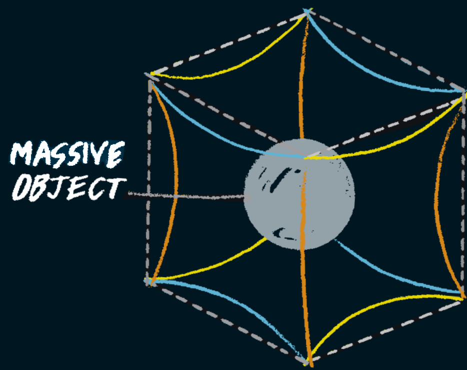


Illustration by Nigel Holmes



Spacetime with Mass

When mass—be it a star, a planet or a human being—is present, spacetime bends around it so that an object traveling nearby must follow a rounded trajectory that takes it closer to the mass. Just as it is impossible to move in a straight line on the surface of a sphere, it is likewise impossible to move in a straight line through curved spacetime. This effect produces gravity, which we observe as an attraction between two masses. On the left is a simplified two-dimensional diagram of spacetime curvature, and below is an approximation of the same situation in three dimensions.



Spacetime with Extreme Mass

One of the most startling consequences of general relativity is the idea of black holes. These occur when mass is dense enough to form a so-called singularity—a point where spacetime is infinitely curved. The black hole defines the region around the singularity where gravity is so strong that nothing that enters can exit again. Physicists now think that black holes are ubiquitous in the universe, often resulting from the death of stars. The drawing at the right shows a simplified picture of a black hole in a two-dimensional slice of space with an object's trajectory as it falls in; an approximation of the same situation in three dimensions of space appears below.