SAMPLE

General Relativity

Gravity as Curved Spacetime

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Chapter 1: The Falling Man and the Making of a Theory

Every account of general relativity begins in the same place, because Einstein himself put it there. In 1907, while working as a patent clerk in Bern and still refining the special theory of relativity he had published two years earlier, he sat at his desk and had what he would later describe as the happiest thought of his life: someone falling freely from a roof feels none of their own weight. While the fall lasts, gravity vanishes from the falling person's experience. Loose objects drift alongside them as though no force acted on anything.

The observation sounds trivial, but it contains a seed that took Einstein eight years to grow. The feeling of weight, it suggests, is not the direct perception of a gravitational force; it is what happens when something prevents you from following gravity's natural motion. A person standing on a floor feels weight because the floor pushes back. A person in free fall feels nothing at all because nothing intervenes. If the sensation of gravity can be abolished by falling, then perhaps gravity is not, at bottom, a force in the ordinary sense, and perhaps the natural, unforced motion of a body near the Earth is not stillness but the fall itself.

That idea had an experimental partner already in place. Astronomers and physicists had long known, with growing precision, that all bodies fall with the same acceleration regardless of what they are made of. Newton had been forced to assume this coincidence, giving inertial mass, the measure of a body's resistance to being pushed, and gravitational mass, the measure of its response to gravity, exactly the same value without any explanation for why the two should agree. The Hungarian physicist Loránd Eötvös spent decades verifying the agreement in delicate balance experiments, and found no discrepancy. Einstein took the equality not as an accident but as a clue: if the response to gravity is universal, then gravity must be a property of space and time rather than of the individual bodies moving through them.

The path from that clue to a finished theory was neither quick nor straight. Einstein tried and abandoned ideas for years, published false starts, and was repeatedly blocked by mathematics he did not yet command. What he needed, he slowly realized, was a geometry suited to curved spaces, and he found it ready-made: the non-Euclidean geometry developed by Bernhard Riemann in the nineteenth century, in which the familiar rules of flat space, parallel lines and straight lines and the angles of triangles, give way to curvature that varies from place to place. Mathematicians in Zurich, among them Einstein's classmate Marcel Grossmann, taught him the machinery. A version of Riemannian geometry, adapted to space and time together, became the language in which the theory was finally written.

The end came in November 1915, in four weekly lectures before the Prussian Academy in Berlin. In the first, Einstein offered field equations he did not yet trust; by

the eighteenth of November he had recalculated the orbit of Mercury and found his theory explaining, without adjustment, an anomaly that had troubled astronomers for half a century; and in the final lecture, on the twenty-fifth of November, he presented the equations in the form still used today. He later described the intense month as a time of exhaustion and fluctuating confidence, and the arrival at the correct equations as a moment of palpitation of the heart. The falling man of 1907 had, at last, reached the ground.

Chapter 2: The Equivalence Principle: Gravity Abolished and Restored

The hinge on which general relativity turns is called the equivalence principle, and it deserves a careful statement, because everything else in the theory follows from taking it seriously.

Begin with the observation that closed the previous chapter: free fall abolishes the sensation of gravity. Now take the complementary step, which is to ask what happens aboard a vehicle that accelerates. A passenger sealed in a rocket far from any planet, with the engines firing at precisely the right thrust, feels exactly what they would feel standing in a room on the Earth: a floor pressing upward, dropped objects falling toward it, a definite down and up. No experiment conducted entirely inside the rocket, without looking outside, can distinguish that artificial gravity from the real thing. The situation aboard an accelerating vehicle in gravity-free space is indistinguishable from the situation in a gravitational field.

Einstein illustrated the pairing with an elevator. An observer in a windowless elevator who floats weightlessly cannot know whether the elevator is falling freely toward the Earth or drifting in empty space far from everything. An observer who feels a steady pull toward the floor cannot know whether the elevator rests on the Earth or is being accelerated through space by a cable. The two situations are, in every physical respect, the same.

This is a stronger statement than Newton's theory can make. In Newtonian physics, gravity is a force that acts on all bodies alike, but acceleration is a different kind of thing, and the equivalence of the two is a coincidence. In Einstein's reading, the equivalence is a principle: a law about how nature is built. If the effects of gravity and the effects of acceleration are indistinguishable, then the natural motion of a body, the motion it exhibits when nothing acts on it, is free fall. Free fall is the analogue, in a gravitational field, of the straight-line, constant-speed motion that Newton's first law assigns to force-free bodies.

A second strand deepens the principle. From special relativity, Einstein had learned that the laws of physics look identical to every observer in uniform motion. The equivalence principle extends the ambition: the laws should take the same form for any observer in free fall, anywhere, including observers in accelerated vehicles, provided the comparison is made locally, in a small enough region and over a short

enough time. Gravity, in this picture, is not a force that changes the laws of physics for different observers; it is the deviation between one observer's local straightness and another's. What one person calls a gravitational field, another, falling freely, calls the coasting of an undisturbed body.

The principle also dictates how the theory must treat light. If light crosses an accelerating rocket, it appears, to anyone inside, to bend, because the floor rises to meet the beam as it travels. By the equivalence principle, light in a gravitational field must bend likewise, because an observer in a gravitational field is in the same situation as an observer in the accelerating rocket. Gravity must therefore act on light, which has no mass in the old sense at all. This was among the first quantitative predictions Einstein extracted from the principle, and although his first calculation, from 1911, gave half the correct value, the reasoning was sound; only the full theory of curved spacetime supplied the missing half.

The equivalence principle, in summary, abolishes gravity as a force and restores it as geometry. Free fall is not what gravity does to a body; free fall is what a body does when nothing is done to it. What remains, to be explained, is why freely falling bodies that start side by side converge, why the floor rises to meet the dropped cup, why the Earth's mass and the Moon's motion are bound together. Curvature is that explanation, and the next chapter builds it.

One more consequence of the principle deserves statement, because it fixes the theory's logical structure. Since no experiment inside a freely falling laboratory can detect the presence of a gravitational field, the effects of gravity are, in the precise sense, universal: they act on everything alike, including the laboratory, its clocks, its rulers, and the physicists inside. That universality is what licenses the leap from the falling elevator to the geometry of the universe. A theory whose effects were detectable in free fall would need a different mathematics; the theory that follows from the equivalence principle needs only the geometry of curved spacetime, because the field it describes, being nothing but the tilt and stretch of the stage itself, cannot be shielded, weakened, or separated from the physics that happens on it.

Chapter 3: The Geometry of Spacetime: Light Cones and World Lines

To speak of curved spacetime, one must first know what spacetime is when it is flat, and that was the achievement of special relativity, Einstein's 1905 theory of the electrodynamics of moving bodies.

Special relativity rests on two postulates: that every uniformly moving observer finds the same laws of physics, and that the speed of light in empty space is the same for all such observers, regardless of how fast the light source or the observer moves. The second postulate defies common sense, and it is nonetheless an experimental fact, established in 1887 by Albert Michelson and Edward Morley, who attempted to measure the Earth's motion through the supposed luminiferous aether, the medium in

which light was then believed to wave, and found no trace of it. Whatever the Earth's velocity, light traveled at the same speed in every direction.

From that stubborn constancy, strange consequences follow that experiments have confirmed in full. Clocks moving relative to an observer run slow, an effect called time dilation, and moving objects are measured shortened along their direction of travel. Events that are simultaneous for one observer occur in sequence for another. Energy and mass are knitted together, so that the energy of a body at rest is a measure of its mass. In 1938, Herbert Ives and G. R. Stilwell confirmed the transverse Doppler effect, the slowing of a moving clock, in light emitted by fast hydrogen ions, and decades of particle accelerators have shown unstable particles surviving far past their resting lifetimes simply by moving fast.

Einstein's former mathematics teacher Hermann Minkowski saw what the theory implied. Space by itself and time by itself, he declared, would sink into shadow, and only a fusion of the two would survive as an independent thing. That fusion is spacetime: a four-dimensional continuum in which an event, something happening at a particular place at a particular moment, is a single point, and a body's entire history is a curve, called a world line, threading through it.

Flat Minkowski spacetime has a built-in structure that gives physics its causal skeleton. Through every event runs a pair of light rays, one outgoing into the future and one arriving from the past, and these define nested surfaces that geometers call light cones. The forward cone of an event contains every place a signal emitted at that event could reach; the backward cone contains every place from which a signal could have come to it. Nothing outside the two cones can influence the event or be influenced by it, because influence cannot outrun light. The light cones, in other words, encode the deepest fact about nature, that causes precede effects and information has a speed limit.

They also define what straight means. In flat spacetime, a body free of forces follows a straight world line, and light follows the cones themselves. Minkowski's geometry assigns every observer a natural measure of time along their own world line, the reading of the clock they carry, and the mathematics of the theory is organized around making that reading, the so-called proper time, come out the same for all observers.

Curved spacetime generalizes each piece of this picture. Through every event, the light cones still exist; light still travels on them and nothing still outruns it. But the cones are no longer all parallel to each other. The fabric of spacetime can be thought of as a field of little flat neighborhoods, each behaving locally like Minkowski's world, patched together so that their straight directions do not line up. A traveler who follows the straightest possible path through one patch after another, never turning locally, can nonetheless arrive somewhere far from where the naive picture predicts, exactly as a walker who follows a straight path on the Earth's curved surface crosses a triangle whose angles no longer add to two right angles. Curvature is the failure of local straightness to knit into global straightness, and it will turn out to be gravity.

The 1887 null result was refined rather than abandoned. In 1932, Roy Kennedy and Edward Thorndike varied the design so that the two arms of the interferometer differed in length, closing a loophole the original had left open; the result remained null. Modern descendants of the experiment use resonant optical cavities, two crystals whose atomic vibrations define the length scale, compared as the Earth rotates and orbits; any breeze of an aether or any preferred direction for light would show as a daily and seasonal wobble, and none has been seen to a few parts in a billion trillion. The constancy of light speed, the strange postulate on which everything else was built, is among the most thoroughly tested statements in physics.

Chapter 4: Curvature and the Field Equations: What Matter Does to Geometry

The central question of general relativity is how much curvature a given amount of matter produces, and where, and the answer is the field equations Einstein presented in Berlin in November 1915. To state them in words requires care, but no symbols.

Consider first what is being related. On one side stands geometry: the curvature of spacetime, which at each point and in each direction can be measured by watching how a small ring of freely falling particles changes shape and volume, or how a gyroscope carried along a path comes home pointing differently than it left. On the other side stands matter: not mass alone, but everything that carries energy and momentum, including mass, pressure, tension, radiation, and fields. Special relativity had already shown that mass is only one component of a richer quantity that physicists call the stress-energy, the complete inventory of what a region of matter and radiation contains and how it flows.

Einstein's equations say that the curvature of spacetime, in a form that captures the part of curvature most directly felt by matter, is proportional to the stress-energy present, position by position: where there is more matter and energy, there is more curvature, in a precisely quantified way. In empty regions, where the stress-energy vanishes, the equations do not say the geometry is flat; they say that the particular part of curvature tied to matter sources is zero, while the geometry is still free to curve, carrying gravitational waves or the imprint of distant masses. The vacuum, in general relativity, is not nothing.

Because the theory is built from geometric objects called tensors, it carries a remarkable property: its laws take the same form in every coordinate system whatsoever. This general covariance, as it is called, means there are no privileged observers and no privileged directions in the mathematics; nature's bookkeeping does not care how we choose to label events. Einstein fought through several wrong formulations before accepting, guided by the mathematician David Hilbert's simultaneous work and by his own earlier struggles with Grossmann, that full covariance was not an obstacle but the theory's essence.

The equations have a striking consequence: they are not merely constraints on a

given instant, but the complete history of a region. Each solution is an entire universe, or a piece of one, evolving in time. They also demand, for consistency, that matter behaves sensibly: the same equations that relate curvature to matter imply, automatically, that energy and momentum are conserved, that whatever flows out of a region is accounted for by what flows in.

Solving the equations, however, is ferociously difficult. They are among the most complicated equations in all of physics, ten interlinked relations among the components of the metric, the object that encodes distances and times in the curved spacetime, and there is no general method for writing down the geometry produced by an arbitrary arrangement of matter. Most of the theory's subsequent history is a catalog of ingenious schemes for finding exact solutions where symmetry makes the problem tractable, approximations where it does not, and, since the late twentieth century, computers powerful enough to evolve the equations numerically, a field called numerical relativity. The first exact solution arrived almost immediately after the theory itself, and its consequences were so strange that physics needed half a century to digest them. It is the subject of Chapter 6.

Chapter 5: Geodesics: The Straightest Lines in a Curved World

If gravity is geometry, then the motion of bodies under gravity needs a new description: they do not follow paths dictated by a force, they follow the straightest possible paths the geometry allows. Such paths are called geodesics.

In flat spacetime, geodesics are ordinary straight lines: a body left alone moves at constant velocity forever. On the curved surface of the Earth, the geodesics are the great circles, the paths that airplanes follow on long routes because they are the straightest tracks available on a sphere. In curved spacetime, the definition is local: at every point of its journey, a geodesic is as straight as the local geometry permits, never turning relative to the small patch of nearly flat space around it. Sewn together across the whole curved region, these locally straight segments produce a path that, viewed globally, curves. The curvature is in the space, not in the motion.

This is why freely falling bodies, which are following geodesics, can converge without any force acting between them. Two objects dropped from opposite sides of a room fall toward the Earth's center, and so approach each other slightly as they fall. The old Newtonian explanation says the Earth's force pulls them inward. The Einsteinian explanation says that the Earth's mass has curved the spacetime in the room, and the geodesics that pass through it, the straightest lines available, converge toward the Earth's center; the falling bodies are simply going straight in a curved neighborhood. Their convergence, measured from a small cloud of falling particles, is in fact one of the standard ways to define the curvature at a point: watch what a little ball of freely floating dust does, and its shrinking or shearing reveals the geometry.

The description extends to light. Light rays follow geodesics too, the ones that stay on

the light cones, and because those cones themselves tilt and bend in a curved spacetime, light bends around massive bodies. A star's light passing near the Sun is deflected by an amount the theory specifies precisely. A whole galaxy, bending the light of galaxies far behind it, can produce multiple images, arcs, and rings. Nothing is pulling the light; the light is following the straightest available path, and the mass has made straight no longer what straight was.

The geodesic picture also explains, in one stroke, the ancient equality of falling bodies. A feather and a cannonball, released together in vacuum, follow the same geodesic, because the geodesic is a property of the spacetime region, not of the object. The old theory needed inertial and gravitational mass to coincide for this to work; the new theory needs nothing of the kind, because the falling body's own mass never enters the description of its free motion. What a body's mass does, through the field equations, is help shape the geometry for everything else. A falling pebble curves spacetime too, by an amount that is real but immeasurably small beside the Earth's.

The same framework organizes motion around the Earth and Sun. A satellite in orbit is not circling because a force bends it away from straightness; it is traveling the straightest path available in the geometry shaped by the Earth, a path that, in the tilted and stretched time of the region, closes on itself as an ellipse. The planets, the Moon, and the dropped cup are all doing the same thing, each following its geodesic through the geometry that the masses of the Sun and the Earth have laid down. Where Newton described one body pulling on another, Einstein describes one geometry, and bodies going straight through it.

The geodesic picture also supplies the honest description of what a gravitational field does to an extended body. Because the geometry curves, neighboring geodesics converge or diverge, and the parts of a body, each following its own slightly different path, are pulled together in some directions and stretched in others. These tidal forces are the only locally felt aspect of gravity: a freely falling laboratory can abolish the pull of gravity throughout itself, but it cannot abolish the variation, and an astronaut falling feet first toward a mass feels their body stretched along the fall and squeezed around the middle. Far from a body the tides are gentle, and the ocean tides of the Earth are their familiar face; near a black hole they become lethal, stretching any object into a filament long before the horizon is reached. The tidal pattern, mapped through a cloud of falling dust, is one of the theory's definitions of curvature, and it is the physical content of the statement that geometry, not force, is gravity.

Chapter 6: Schwarzschild: The First Solution and the Dark Star Within

Within weeks of Einstein's November lectures, while serving in the German army at the eastern front, the astronomer and physicist Karl Schwarzschild produced the first exact solution of the fresh field equations: the geometry of empty space surrounding a single perfectly spherical, non-rotating mass. He sent the solution to Einstein, who presented it to the Prussian Academy in January 1916 and praised it as a beautiful

piece of work; Schwarzschild died a few months later of an illness contracted at the front, and the solution that bears his name became the foundation stone of relativistic astrophysics.

The Schwarzschild geometry reproduces Newtonian gravity far from the central mass, but it departs from it in detail. Orbits are not exactly closed: the point of closest approach slowly rotates, which is the theory's explanation of Mercury's anomalous perihelion, treated in the next chapter. Light leaving the region is reddened as it climbs out of the gravity well, an effect soon sought in the light of compact stars. And clocks near the mass run slow relative to clocks farther away, an effect now measured routinely with instruments from laboratory clocks to satellites.

The solution's strangest feature lay deeper. At a certain critical distance from the central mass, a distance proportional to the mass itself, the coordinates in which Schwarzschild wrote his solution behave pathologically, and the geometry there hides something from which nothing returns. If a mass is compressed within its critical radius, the equations say that no path, however powered, leads back out: the region within is causally sealed, a black hole, and the boundary is called the event horizon. Light generated just outside skims the surface and circles; light within cannot reach the outside at all. To a distant observer, a falling object appears to slow and redden as it approaches the horizon, its image fading; in the falling object's own experience, the horizon is crossed uneventfully in a finite time.

Physicists were slow to accept that such objects were anything more than a coordinate curiosity. Einstein himself doubted nature would permit the compression; Arthur Eddington, decades later, dismissed the notion that a body could be screened by its own gravity. But the mathematics held, and the 1960s brought both the tools of global geometry, with which Roger Penrose and others proved rigorously that collapse to trapped surfaces, not merely strange coordinates, is a generic outcome, and the observational discovery of quasars, enormously bright and compact objects whose power output found a natural explanation in matter falling into deep gravitational wells.

The Schwarzschild solution was generalized almost as soon as it appeared. Later workers added electric charge, and Roy Kerr, in 1963, solved the equations for a rotating mass, the case that actually applies to real astronomical bodies. The Kerr geometry has its own horizon and, outside it, a region where the geometry itself is dragged around by the rotation, so that any body, however hard it tries to stand still relative to the distant stars, is swept along; this frame dragging is a genuine, measurable prediction, discussed in Chapter 9. Between the solutions and the singularity theorems, black holes moved, over half a century, from scandal to staple, and they now anchor the theory's most striking chapters, including the one in which they turn out to have a temperature.

Seen from inside, the Schwarzschild geometry has a further lesson about what a horizon means. The tipping of the light cones toward the central mass, steeper and steeper as the horizon nears, is the geometry's way of saying that the future of every world line within the horizon points inward: for the infalling traveler, the direction of

the center has become the direction of time, and the singularity is not a place ahead but a moment ahead, an unavoidable tomorrow rather than a distant site. This exchange of roles, in which a location becomes a time, is among the strangest and most durable images the theory has produced, and it carries the essential warning about the interior: no experience of the falling object spans the crossing in a way the outside can share, and the classical theory's account of the endpoint stops at the singularity, where its story ends mid-sentence.

Chapter 7: The Three Classical Tests: Mercury, Starlight, and Reddened Clocks

Einstein proposed three tests of general relativity in 1916, calling them the classical tests, and he was candid about what hung on them. The chief attraction of the theory, he wrote, lay in its logical consistency: if a single conclusion drawn from it proved wrong, the theory must be given up. The theory survived all three.

The first was already, before Einstein, a fifty-year-old embarrassment. Astronomers had long known that Mercury's orbit is not a perfect closed ellipse: its perihelion, the point closest to the Sun, slowly advances, drifting around the sky relative to the fixed stars. Newtonian physics accounts for most of the drift by the pulls of the other planets, but a stubborn remainder survived every correction, close to forty-three arcseconds each century, a small but unambiguous excess that the nineteenth century tried to explain with an extra undiscovered planet, a flattening of the Sun, and other inventions, none of which worked. Einstein, having struggled for years with equations he feared might not yield the answer, recalculated the orbit in November 1915 and found the theory produced the missing angle without any adjustable element. He wrote to his friend Michele Besso that his heart had palpitated with the result: perihelion motions explained quantitatively. All the other planets shift too, and the Earth's perihelion advances by an amount the theory also fixes, but Mercury, closest to the Sun, shows the effect a hundred times more strongly than any planet easily measured.

The second test concerned light. Einstein's first, incomplete version of the theory had already predicted, in 1911, that starlight passing near the Sun would bend; the complete theory doubled the value to 1.75 seconds of arc for a grazing ray, and the measurement became a question of waiting for a total solar eclipse, when stars near the Sun's disk become visible against a darkened sky. The 1919 eclipse expeditions, organized by Arthur Eddington, photographed star fields from Sobral in Brazil and the island of Príncipe off West Africa, and found the deflection matching the full relativistic value, not the half value and not zero. The result made Einstein world-famous overnight. The measurement, on a small number of stars with instruments strained by the conditions, was later criticized as too uncertain to have been decisive, but repeat eclipse expeditions through the following decades, notably one from the Lick Observatory at Wallal, Australia, in 1922, confirmed the deflection to improving accuracy. Modern techniques no longer wait for eclipses: radio telescopes observe

quasars passing near the Sun year-round, and the deflection of their radio waves now agrees with general relativity to about one part in ten thousand. In 2017, astronomers even measured the deflection of starlight by a white dwarf star, Stein 2051 B, as it passed in front of a more distant star, bending its light by a few hundred milliarcseconds.

The third test concerned time rather than space. Light climbing out of a gravitational well should lose energy, arriving reddened, so that a clock deep in a gravitational field runs slow relative to a clock higher up. The effect was first sought in the light of Sirius B, a white dwarf whose light left a strong gravitational field, but the measurements were confused by the star's unknown radius; the definitive measurement came in the 1950s from the spectrum of the same star, and, far more cleanly, from laboratory experiments. In 1959, Robert Pound and Glen Rebka used the gamma rays emitted and absorbed by atomic nuclei in a tower at Harvard, comparing the frequency of rays climbing and falling seventy-four feet, and detected the tiny shift the theory required, later refined by Pound and Joseph Snider to one percent accuracy. Half a century later, the gravitational slowing of clocks has become an ordinary engineering fact: optical clocks can resolve the difference in height of centimeters, and satellite navigation systems correct for it continuously.

A fourth test, proposed by Irwin Shapiro in 1964, rounds out the classical set. Light passing a massive body is not only bent but delayed, its travel time lengthened by the geometry it crosses, and radar signals bounced off Mercury or Venus, timed as they graze the Sun, would arrive measurably late. The Shapiro delay, as it is called, was detected within a few years by bouncing radar off the planets, agreeing with the predicted value, and it is now measured to exquisite accuracy by tracking spacecraft, including the Cassini probe, whose radio signals grazing the Sun confirmed the delay to about one part in a hundred thousand. It is sometimes called the fourth classical test.

Radio brought the light-deflection test indoors, in effect. A radio source passing near the Sun cannot be photographed at an eclipse, but it can be timed year-round with interferometry, and the solar corona, the Sun's own atmosphere, refracts radio waves enough to matter; experimenters learned to combine observations at two frequencies, exploiting the refraction's wavelength dependence, and to correct for the plasma the signals cross. The result is that the deflection is now checked continuously rather than once an eclipse at a time, with the agreement between the measured deflection and the theoretical value standing at about one part in ten thousand, an accuracy the eclipse expeditions could not have imagined. Each refinement of the test has measured not whether Einstein was right but by how little room he left to be wrong.

Chapter 8: The Renaissance Around 1960 and the Search for Alternatives

General relativity's early triumphs were followed by decades in which the theory, in the words of later historians, lay relatively dormant: its mathematics seemed difficult,

ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

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