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## Symmetry and Symmetry Breaking

How Symmetry Shapes Physics

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# Chapter 1: The Idea of Symmetry

The word entered English through the Greeks, who built it from two pieces: together, and measure. To the Greeks, symmetry meant proportion, the right relation of parts to each other and to the whole. A temple was symmetric when no part demanded more attention than the design allowed. A face was symmetric when the halves agreed. The word has since narrowed and deepened, and physics keeps both meanings alive at once: proportion in the classical sense, and changelessness in the modern one. The modern sense is the one this book follows, and it deserves a careful first statement, because everything later grows from it.

The modern definition is short enough to carry anywhere: a symmetry is an alteration that leaves its object itself. Not all change, and not unchanged in every respect, but a specific change, applied to a specific thing, with a specific survivor. A circle survives any turn about its center, so every one of those turns is a symmetry of the circle. A square survives only four of them: the identity turn that does nothing, then the three next turns, each a further quarter of the way round. Turn a square by an eighth of a revolution and the corners land where edges used to be; the square has visibly moved, so the eighth turn is not one of its symmetries. The face in the mirror is the same test with reflection instead of rotation: the mirror changes left for right, the face survives, and the change is a symmetry. The definition's quiet power is that it makes symmetry countable. A circle has infinitely many rotational symmetries; a square has four; a rectangle has two that matter; a scalene triangle has only the identity, the change that changes nothing. Symmetry admits of more and less, which means it can be compared, graded, and even ordered, and a physics that can be ordered can be reasoned about with unusual discipline.

The definition has two different targets. A thing can be symmetric: the circle, the snowflake, the honeycomb. A law can also be symmetric: the rule that generates the thing, the statement that survives a change with its meaning intact. The law of gravity does not care whether the two masses are in Shanghai or in Stockholm, today or in 1859, aligned with the room's walls or tilted against them. Move the whole experiment, and the law says the same thing. The law is symmetric under translations in space, translations in time, and rotations, and this trio of symmetries is so basic that most people never notice it as a fact at all. But it is a fact, it is a fact with consequences, and one of this book's later chapters will show that the conservation laws taught in every first physics course, the conservation of momentum, energy, and angular momentum, are not separate discoveries bolted onto the laws of motion. They are the laws' symmetries, worn as a different face. The connection is called Noether's theorem, and it is the single most important sentence in this neighborhood of physics. It is stated plainly, in words, in its own chapter.

Between the symmetric thing and the symmetric law lies the subject's whole drama. The laws of physics, as far as anyone has ever measured, are far more symmetric than the world they produce. The laws of electricity and magnetism are perfectly

happy with a universe of nothing but radiation, light in equilibrium with light, a featureless blaze with no matter in it at all. The actual universe is not like that. The laws treat left and right, on paper, with perfect even-handedness, and the actual world has spiral galaxies turning one way, amino acids all of one handedness, and a matter surplus over antimatter that has no business existing if the laws are as even-handed as they read. The laws know nothing of north, and every compass needle on Earth points, with eerie agreement, along the planet's field. The gap between the law's symmetry and the world's lopsidedness is not a scandal. It is, as the twentieth century learned, the engine of almost everything interesting. The mechanism that fills the gap is called symmetry breaking, and its study is the reason this book exists.

The distinction deserves its own careful sentence, because the two halves of the subject are often confused in casual talk. A symmetric law can produce a symmetric state, and then nothing much happens: the uniform blaze, the faceless equilibrium, the circle. Or a symmetric law can produce, from a symmetric starting point, a state that is not symmetric at all, one candidate among several equally legal ones, chosen by accident and then stuck to. That second outcome is symmetry breaking, and the word spontaneous is reserved for the case where nothing external made the choice: no hand tilted the bowl, no field favored the direction. The universe simply had to pick something, picked at random, and the pick became history. Spontaneity is the difference between a pushed thing and a settled thing, and the whole subject's most important examples, the magnet, the crystal, the vacuum, are settled things. Their laws are symmetric; their states are not; and the settling is the story.

The chapter's closing image is the smallest honest exhibit of the whole idea: a plain round dinner roll on a plain dinner table, with a knife laid beside it. The roll can be cut from any angle; the result is the same roll, and the uncut roll's symmetry is complete. But once the knife goes in from one side, that one cut is a broken symmetry in miniature: any angle was legal, one was chosen, and the choice is now visible to everyone at the table. Nobody supposes the roll's law, so to speak, preferred that side. The knife simply had to enter somewhere. The subject of this book is the physics of that necessity, from dinner rolls to the first second of the universe, and the reader who holds the image holds the subject's whole architecture in miniature.

## Chapter 2: The People and the Discovery

Every idea has a biography, and symmetry's biography is unusually long, because the idea was noticed by artisans, geometers, and decorators long before anyone could state it. The Greeks knew the five regular solids and treated them as a kind of civic achievement. The astronomers used symmetry as a working tool: Ptolemy's models, and later Copernicus's, were judged partly by how evenly they distributed the heavens' business, and Kepler's first attempt at the planets was an almost touching attempt to force the solar system into the symmetric nesting of those same five solids. The crystallographers of the eighteenth and nineteenth centuries, counting the angles of rock faces, were doing symmetry science without the word, and by 1848 the French physicist Auguste Bravais could classify the ways atoms could repeat in space:

fourteen lattices, every crystal in the world a resident of one of them. The idea was working long before it was named, which is the usual order in physics.

The naming, in its modern sense, arrives with the mathematics of the nineteenth century, and the crucial figure is not usually counted a physicist at all. Évariste Galois, a French republican radical killed in a duel in 1832 at the age of twenty, had asked which algebraic equations could be solved by formulas and which could not, and in answering had invented the study of the changes that leave a structure intact. His word for such a family of changes was group, and the group would become to symmetry what the number is to counting. The idea traveled from equations to geometry to physics over the rest of the century, and by 1905 Einstein had used it without ceremony, and by the 1920s the physicists spoke it fluently. Galois died without seeing any of this. The story is one of the subject's standing tragedies, and the reader is allowed to be annoyed by it; the mathematics that runs the Standard Model of particle physics is, at bottom, Galois's idea with a century of polish.

The physicist who first made symmetry breaking itself a principle, rather than an embarrassment, was Pierre Curie, and his sentence deserves quotation in spirit: it is dissymmetry that creates the phenomenon. Curie, writing in the 1890s, was studying magnetism and crystal optics, and he noticed that a completely symmetric medium, left completely alone, does completely nothing interesting. Effects require a mismatch, a tilt, a lopsidedness somewhere in the arrangement. A symmetric cause in a symmetric environment produces a symmetric, uninformative result; to get a deflection, a current, a polarization, something in the setup must already have less symmetry than the laws. Curie's principle is the first honest statement of the subject's economy: the effect cannot be less symmetric than its causes, taken together. It sounds modest, and it organizes a surprising amount of laboratory practice. It also sets up, for later chapters, the twentieth century's central puzzle: the effects in nature are spectacularly asymmetric, the laws are spectacularly symmetric, and if the effect cannot be less symmetric than the cause, then the cause must be hiding something asymmetric. The hunt for the hidden asymmetry, in magnets, in crystals, and finally in the vacuum, is the plot of the rest of this book.

The next name is the subject's greatest, and the theorem is the one promised earlier. Emmy Noether, a German mathematician, published in 1918 the result now called Noether's theorem: every continuous symmetry of the laws carries a conserved quantity with it, like a shadow that cannot be lost. Symmetry under shifts in time yields the conservation of energy; symmetry under shifts in place yields the conservation of momentum; symmetry under turns yields the conservation of angular momentum. Noether herself was doing the work in Göttingen at the invitation of David Hilbert, in the middle of the First World War, while being refused a paid professorship on the grounds of her sex; she lectured for years under other men's names. The theorem's biography is told in its own chapter. For this chapter's purpose, the point is that by 1918 symmetry had stopped being an aesthetic preference and had become the spine of physical law. Conservation, which every schoolchild is taught as a list of separate miracles, was revealed as a wardrobe of symmetry's coats.

The discovery that symmetry breaks, and that the breaking is law-abiding, is the twentieth century's contribution, and it arrived from several directions at once. Lev Landau in the Soviet Union built a general theory of phase transitions around the idea that an ordered state is a broken symmetry, with a quantity he called the order parameter to measure the lopsidedness; that was 1937, and it still organizes the subject. Hideki Yukawa's meson, the nuclear forces, and the puzzle of particle masses all pressed in the same direction. Yoichiro Nambu in Japan, studying superconductivity, recognized in 1960 that its physics was symmetry breaking in disguise, carried the insight over to the particles, and showed that the proton's mass is mostly a broken symmetry's doing; the Nobel committee caught up with him in 2008, half a century later. Jeffrey Goldstone named the waves that a breaking is required to produce, and Peter Higgs, with Robert Brout and François Englert beside him, showed in 1964 how the universe could break a symmetry without paying Goldstone's toll. Philip Anderson, solid-state physicist, had seen the same mechanism in superconductors in 1962 and said so in print. The final act, the discovery of the Higgs boson in 2012, and the 2013 Nobel Prize to Higgs and Englert, closed a loop that runs from crystals to the Large Hadron Collider in one unbroken thread. The thread is the subject; the rest of the book follows it.

# Chapter 3: The Grammar of Symmetry: Group Theory in Plain Words

The mathematics behind symmetry has a name that frightens people, and the name is group theory. This chapter states plainly what the name hides, using no equations, and argues that the reader already knows most of it. A group, in the mathematician's sense, is a family of changes with three honest properties: the changes compose, doing one then another leaves you doing a third member of the same family; every change can be undone, and the undoing is itself a member of the family; and there is always a do-nothing member, the identity, so that the family has a floor. That is all. The turns of a square, the shufflings of a deck, the rotations of a sphere, the permutations of four books on a shelf: wherever those three properties hold, there is a group, and the group is the complete account of the thing's symmetry.

The square's group deserves one careful walk, because it shows everything on a thing small enough to hold. The square has, as rotations, the identity, the quarter turn, the half turn, and the three-quarter turn. It also has reflections: the flip about the vertical axis, the flip about the horizontal, and the two diagonal flips. Eight changes in all, four turns and four flips, and together they are the symmetry group of the square. The reader can verify the properties by hand: turn then flip, and the result is always one of the eight; every member has a partner that undoes it; the identity does nothing, as required. The group's table, the ledger of which pair composes into which, was drawn up by schoolchildren before anyone called it mathematics; the musician's hand on the piano transposing a melody into every key runs the same kind of ledger. The square's group has eight members. The pentagon's has ten. The circle's has infinitely many. The triangle's has six. This counting is the grammar's first lesson: symmetry is a

number before it is anything else, and comparing the numbers is comparing the shapes.

The second lesson is subtler and more important for the physics to come: groups can be ranked, and smaller groups sit inside larger ones like a sentence inside a paragraph. The circle's group of all rotations contains the square's group of four rotations as a small corner of itself. The sphere's group of all turns contains the hexagon's, the pentagon's, and the square's, all at once. This nesting is what physicists mean when they say that a symmetry is broken: the full, symmetric group is still there in the laws, but the state of the world only respects some subgroup of it, some corner. The magnet's iron obeys laws that are symmetric under any rotation whatsoever, but the magnetized state picks one axis and respects only the turns about that axis. The full group did not vanish; it stopped being respected by the state. The subgroup is the fossil of the choice, and reading these subgroups off the wreckage of broken choices is a large part of how modern physics actually proceeds. The Standard Model's celebrated structure is one of these subgroup chains, read backwards from the particles that exist.

The third lesson is that some groups are continuous and some are discrete, and the difference matters physically. Continuous groups contain smooth families of changes, like the rotations of a circle, where a quarter turn can be approached through an infinity of neighboring angles. Discrete groups contain separated changes, like the square's eight, with nothing in between a quarter turn and a half turn. The continuous symmetries are the ones Noether's theorem binds to conservation laws, and every one of them corresponds to something that can be shifted gradually: time, place, angle. The discrete symmetries, like the mirror's left-right flip or the crystal's lattice translations, have their own physics, and some of the subject's strangest episodes, including the overthrow of the mirror's honesty in 1957, belong to them. The two baskets must be kept separate, because the vocabulary depends on the distinction: continuous symmetries carry conserved quantities; discrete symmetries carry, at most, rules and bookkeeping.

The fourth lesson is that the grammar composes across chapters of physics without translation. The crystallographers' space groups, worked out in full by 1890, are families of moves that tile space; the particles' internal groups are families of changes among kinds, a neutron into a proton in the right bookkeeping; the gauge symmetries, which the subject treats later, are families of changes of description whose failure to be mere description is the plot of the modern theory. The same three properties compose, undo, and identity run underneath all of them. The reader who has held the square's eight changes in mind has already understood, in miniature, the grammar in which the deepest theories of physics are written. The grammar's own motto, stated as fact and not mysticism: nature counts its possibilities, and the counting is what a symmetry group is. Every exhibit in the rest of this book is one of those counts, doing something.

## Chapter 4: Noether's Gift

Emmy Noether was born in 1882 in Erlangen, the daughter of a mathematician, and the profession's first instinct was to keep her out. She passed her teaching examination in 1900 and chose instead to study, taking her doctorate in 1907 under Paul Gordan, a man of the old formula-multiplying school, and then found herself barred from the habilitation that would have made her a professor. For years she taught at Erlangen under her father's name, receiving no salary. In 1915, David Hilbert and Felix Klein, wrestling with Einstein's brand-new general relativity and its tangled questions about energy conservation, invited her to Göttingen, the world's mathematical capital, because they knew she was the one person who could sort out what the new theory's energy was. She sorted it out. Her 1918 paper, modestly titled about invariant variational problems, contains the theorem that now carries her name, and Göttingen's faculty nevertheless voted, more than once, against letting her habilitate. Hilbert's response, that a university senate is not a bathhouse, is one of the subject's favorite sentences,

The theorem itself deserves the plainest possible statement, because it is often buried under formalism. Wherever the laws of physics do not change under a continuous shift, something is conserved. Not approximately, not usually: exactly, necessarily, as a matter of identity. If the laws are the same today as tomorrow, energy is conserved. If the laws are the same here as in the next room, momentum is too. If the laws are the same after the whole laboratory is turned, angular momentum is conserved. Each conservation law, worn as a separate jewel in every schoolbook, is the same theorem wearing a different coat, and the coats are the symmetries of time, space, and rotation. The theorem also runs in reverse, in the cases that matter: a conserved quantity advertises a symmetry underneath. When a particle physicist finds a number that will not change, the instinct is to hunt for the symmetry it is protecting, and the hunt usually succeeds.

The theorem's connection to this book's subject, symmetry breaking, comes in the moment a symmetry wobbles. If the laws are almost but not quite the same today as tomorrow, energy is almost but not exactly conserved. The real world supplies such wobbles: the laboratory is in a gravitational field that points down, so the laws upstairs are not quite the laws downstairs, and momentum in the vertical direction is only conserved once the Earth is included in the account. On larger stages the wobbles become the whole story. The early universe, expanding, is not quite the same from one moment to the next, and the energy books of that era need careful keeping. The vacuum's hidden symmetry, the one the Higgs field breaks, is a bookkeeping symmetry rather than a motion of anything, and the theorem's descendants handle those too. The reader is promised no equations, and the promise holds; the honest summary is that Noether's theorem is the exchange rate between a law's indifference and the world's bookkeeping, and every later chapter makes withdrawals at that rate.

Her biography's second half is the profession's shame and the subject's gain. In 1919 Noether finally obtained her habilitation, in 1922 she was granted the title of an unofficial professor with the corresponding low pay, and through the 1920s Göttingen's mathematical world, including the young students who later ran American mathematics, passed through her lectures and her famous walks in the woods. Her

algebra, more than her physics, built her legend among mathematicians. In April 1933 the new Nazi government dismissed all Jewish faculty, and Noether, a Jew and a pacifist and a left-wing sympathizer of the most incorrigible kind, was out. She continued lecturing in her living room, the students arriving as if nothing had happened, until a position at Bryn Mawr College in Pennsylvania extracted her that autumn. She died there in April 1935, after an operation on a cyst, at fifty-three. Einstein wrote to the New York Times that she was the most significant creative mathematical genius since women's higher education began. The sentence is quoted here because it is true and because she never heard it.

The chapter closes with the theorem's standing place in the subject's architecture, stated as an inventory. Time shift: energy. Space shift: momentum. Rotation: angular momentum. The three conservation laws of the schoolroom, revealed as three symmetries of the laws. And beyond the inventory, the deeper lesson this book keeps returning to: conservation is not a set of lucky accidents but the laws' own self-consistency, worn as arithmetic. When, in later chapters, a symmetry breaks and something in the books changes character, the reader should remember whose exchange rate is being bent. Noether gave the subject its hardest currency, and the breaking of symmetries is, more than any other single subject in physics, the study of what happens when that currency is spent.

## Chapter 5: The Everyday Evidence

Physics books are fond of telling readers that their subject is everywhere, and this chapter earns the fondness with exhibits, all of which can be checked at home. The first exhibit is the snowflake, and its fact is famous but its reason is not: every snowflake is hexagonal, and the reason is that water molecules in ice settle into a hexagonal lattice, so the growing flake repeats the lattice's own counting, six of everything, at every scale. The subtler fact, and the one that belongs to this book's plot, is that no two snowflakes are identical. The hexagon is the law's symmetry; the particular branchy shape is the accident of the fall, the humidity, the wind, a record of one flake's particular history written in ice. A snowflake is a symmetric law producing an asymmetric object, and its six-foldness is the law's signature, not the flake's achievement. The reader who wants the subject in a single image may keep the snowflake and be done: symmetry of rule, broken symmetry of fact, the whole book in a crystal the size of an eyelash.

The second exhibit is the honeycomb, and its history shows science taking sides with geometry. That bees build hexagons has been known as long as bees have been watched, and the guesses about why had two families: bees are clever, or hexagons are cheap. The cheapness case was made precisely by a honeycomb conjecture, stated in vague form for centuries and proved only in 1999 by Thomas Hales: of all ways to divide a plane into equal cells with least total wall, the hexagon wins. The bees, or rather the pressure of wax economics on bee behavior, found the optimum the hard way. The exhibit's detail for this book is the accident that the hexagon has six symmetries and the wall-length contest only needed one winner; the sixness is the

lattice's law again, and the hexagon's economy is a settled fact with a proof date attached. Physics books rarely get to cite a theorem proved in the reader's own lifetime; this chapter does, and

The third exhibit is the flower, the starfish, and the virus, a basket of living and half-living things that keep to odd counts. Flowers run to five petals in a large fraction of species, starfish to five arms, and many viruses to an icosahedral shell with, counted honestly, six five-fold axes of symmetry. The five-foldness is a puzzle with a real answer: five is awkward to tile, viruses cannot easily build it from repeated identical parts, and evolution discovered the workaround, building the shell from many identical protein units arranged so that the overall count comes out five-fold at the corners. The viruses' shell is a triumph of bookkeeping under an awkward symmetry, and the subject's later chapters, on quasicrystals and Penrose tilings, show the same awkward five returning in dead matter. The living world's preferences are not mystical; they are the same counting the mineral world does, done with softer bricks.

The fourth exhibit is the crystal, the subject's home ground. Table salt builds cubes; the garnet grows in a sphere's worth of faces but always the same few orientations; quartz, in all its varieties, keeps a triangle's worth of counting, one three-fold axis along its length. The law the crystals obey is the law of the lattice: identical units, repeated, at the smallest scale the solid has, and every larger symmetry the crystal shows is the lattice's symmetry writ large. The broken part is just as visible: the crystal sits in one place, oriented one way, though its material laws would have been just as happy anywhere and any way. A crystal is a broken translation symmetry you can hold, and Pierre Curie, studying exactly such lopsidedness in the 1890s, drew from it the principle that opens this book's second chapter. The salt in a shaker is modern physics's oldest exhibit, and it was on duty before anyone knew what it was exhibiting.

The fifth exhibit is the bathroom mirror, included because it sets up the book's eleventh chapter and because most readers believe something about it that is not true. The mirror, it is said, reverses left and right. It does not; it reverses front and back, along the axis perpendicular to its surface, and the reader can check this by lying down or by pointing at the mirror and watching the reflection point back. Left and right are the observer's own bookkeeping, invented when the observer names the sides of their own body, and the mirror has no part in it. It sounds like pedantry until 1957, when the mirror-image test was run on nature itself and nature failed it, in the deepest surprise of the century's physics. That story belongs to its own chapter. The exhibit here is the honest warm-up: a mirror in a bathroom, an ambiguity about which way it reverses, and the standing lesson that what a symmetry does and what an observer says it does are two different questions, one for the glass and one for the bookkeeping. The everyday world is symmetric to an almost embarrassing degree; the interesting physics begins at the exact places where it stops.

## Chapter 6: Spontaneous Breaking: The Ball in the

# Bowl

The subject's central mechanism can be drawn on the back of an envelope, and this chapter draws it. Take a bowl, the ordinary kind, and imagine its floor stretched upward in the middle into a rounded bump, so the bowl's profile is a Mexican hat seen edge-on: a rim, a valley all around it, and a central peak. Place a ball at the exact center of the peak. The situation is perfectly symmetric: the bowl looks the same from every side, the ball sits at the one point that belongs to no direction in particular, and an artist drawing the scene from above could rotate the paper at will. This symmetric arrangement is also unstable, which is the first half of the mechanism. The ball does not want to stay at the center. The center is the highest point of the valley's ring, and every direction away from it is downhill. The law of the bowl is symmetric, the state of the ball at the center is symmetric, and the two facts together are a recipe for nothing staying put.

The ball rolls. It rolls for no reason at all, or rather for the reason that molecules of air and the tremor of the table and the last person's footsteps supplied a nudge too small to mention, from a direction that has no privilege in the bowl's geometry. It comes to rest somewhere in the valley, at one particular angle, and at that moment the scene has changed character completely: the bowl is the same, the law is the same, but the resting ball has chosen an angle, and the paper can no longer be rotated without moving the ball relative to the bowl. The symmetric state has been replaced by an asymmetric one, every angle in the valley is exactly as legal as every other, and the choice, once made, is frozen into the scene. This is spontaneous symmetry breaking, and the reader now holds the whole mechanism: a symmetric law, a symmetric but unstable starting state, a family of equal choices, one choice taken, and the choice thereafter visible to every observer.

The physicist's vocabulary for the scene is worth learning now, because the rest of the book uses it without apology. The set of equal resting places, the whole ring of the valley, is called the vacuum manifold: the collection of states the system could have settled into and cannot tell apart. The choice of one point on the ring is called the order parameter, a name invented by Landau: a number or a direction that measures the lopsidedness, zero at the symmetric center, nonzero once the choice is made. The valley's lowest ring, where every choice costs the same and nothing, is called the flat direction, and physics that happens along it is physics for free, a phrase the next chapters make exact. With the three terms, manifold, order parameter, and flat direction, the reader can follow the subject into magnets, superconductors, and the early universe without equations ever being missed.

The first real system to run the mechanism is the everyday magnet, and its history makes the story honest. A bar of iron, hot enough, has no magnetization: its atomic little magnets point every which way, the directions cancel in every region, and the bar's laws are symmetric under any rotation. Iron's atoms interact in a way that wants neighboring magnets aligned, so as the bar cools, the local agreement spreads, and below a sharply defined temperature, about 770 degrees Celsius for pure iron, the

pointing wins: the bar settles into a state with a magnetization, a direction, an order parameter with a value. The direction itself is chosen by accident, by the residual field of the Earth, by the details of the bar's cooling, by the faint influence of the neighboring chairs in the room; the laws of iron are symmetric under all rotations and could not care less. The symmetric laws of a symmetric hot bar have produced a thing that points. The temperature at which the choice becomes compulsory is called the critical temperature, and the transition is called a phase transition; the next chapter and the one on phase transitions develop both.

The magnet's example clarifies a distinction the casual reader often misses, so the chapter states it as a boxed sentence would: breaking is not destruction. The laws of iron have not lost their rotational symmetry; they have it in full, and the hot bar above the critical temperature displays it. What has changed is the state. The subject's honest name is state selection, or in the older literature, hidden symmetry: the symmetry is not gone but hidden, respected by the laws, ignored by the state, and visible in the state's bookkeeping, as this book's later chapters show when the hidden six-foldness of a snowflake's law peeks through the flake's accident. The reader who internalizes the distinction now is spared the most common misreading of the subject's later episodes, in which the vacuum itself is said to lose a symmetry it never had any obligation to display.

The chapter closes with the mechanism's universality, stated as a roll call. A magnet cooling: one axis chosen from a sphere's worth. A liquid freezing into any crystal: one lattice orientation chosen from a continuum of orientations, one position chosen from a continuum of places. A superconductor below its critical temperature: a phase chosen from a circle's worth. The universe at a trillionth of a second old: a value chosen for a field that fills space, from a valley shaped, with almost no poetic license required, like the bowl this chapter began with. The Mexican hat is drawn in every textbook on the subject, and the reader who first met it on the back of an envelope has met it in its only honest form: a drawing, a ball, a choice, and the whole of the subject's mechanism waiting in the descent.

## Chapter 7: Explicit Breaking and the Difference

The subject's second kind of breaking is the easier one, and the honest way to teach it is to set it beside the first. Explicit symmetry breaking is what happens when something outside the system, with no obligation to respect the system's symmetry, tilts the scales. Take the same bowl from the last chapter and this time build the table's leg wrong: one side of the valley's ring is a hair lower than the rest. The ball still rolls, but the choice is no longer a choice; the lopsided bowl has told it where to go. Nothing about the ball's law changed, and nothing about the bowl's material changed, but the geometry now has a favorite, and the favorite decides. The breaking is explicit because it is written, plainly, into the conditions: the asymmetric cause is on public display, and the effect's asymmetry, by the principle of chapter two, is fully explained by the causes on the table. Nothing has been hidden; nothing has been chosen by accident.

# 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.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.