SAMPLE

Conservation Laws

The Rules Physics Follows

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Contents

Introduction

Chapter 1: How to Find a Rule That Cannot Break

Chapter 2: Momentum: The Law of the Collision

Chapter 3: Angular Momentum: The Law of the Spin

Chapter 4: Energy: The Law of Forms

Chapter 5: The Discoverers' Decades: How the Balances Were Built

Chapter 6: Mass and Energy: The Merged Ledger

Chapter 7: Charge: The Ledger of the Circuit

Chapter 8: Noether's Theorem: Symmetry Writes the Rules

Chapter 9: Local Bookkeeping: Flows, Currents, and Continuity

Chapter 10: The Quantum Ledgers: Baryon, Lepton, and the Strangeness Family

Chapter 11: The Approximate Rules: Particle Numbers and Broken Ledgers

Chapter 12: The Cosmic Auditors: Conservation in Astronomy

Chapter 13: The Practical Power: What the Laws Forbid

Chapter 14: Testing the Ledgers: Open Questions

Chapter 15: Conclusion: The Book of the Universe

This free sample contains the Introduction and Chapter 1. The complete book contains the full contents above.

Introduction

Every game has rules, and the deepest game of all, the universe at large, has the shortest rulebook ever found. Nothing here is about forbidding motion or commanding it; the rules of physics run on a stranger logic, a list of quantities that simply cannot change. The total energy of an isolated system never goes anywhere else. Its total momentum never appears or vanishes. Its total angular momentum, its electric charge, a handful of particle numbers, each holds steady through every collision, every explosion, every chemical reaction and every stellar cataclysm, and the whole spectacle of the physical world is what happens while those ledgers stay balanced. This book is about the ledgers: what the conserved quantities are, who built the balances and when, why the rules exist at all, and what they let scientists do, from judging the impossibility of a perpetual motion machine to predicting an invisible particle before anyone had seen it.

The subject deserves a general audience's attention more than almost any other in physics, because conservation laws are the field's most democratic tool. An equation of motion takes training to read; a conservation law takes bookkeeping. When a skater pulls in her arms and spins faster, when a rocket throws mass backward and slides forward, when a cannon recoils as its ball flies out, the same three-line argument settles each: whatever the total was before, it must be the total after. The professional physicist and the curious reader can play the same game, on the same terms, and the game turns out to be the most reliable one in science, because it has never once caught the universe cheating.

The tour follows a natural arc. The opening chapters tell the history: how the idea of an unchanging something behind the changes arose, how chemistry's mass balance and the century-long hunt for mechanical energy gave the conservation laws their modern form, how the balances were built by their discoverers in one crowded decade, and how the unification of mass and energy folded the two oldest ledgers into one. The middle chapters take the great conserved quantities one at a time: momentum, the law of collisions and rockets; angular momentum, the law of spins and orbits; energy, the law of forms and transformations; charge, the law that underlies every circuit; and the deep result behind them all, the theorem that connects every symmetry of nature to a conserved quantity and explains why the rules exist rather than merely that they do.

The later chapters go further afield: the quantum ledgers of baryon and lepton number, whose bookkeeping explains why the proton is forever and why anything material exists at all; the approximate and broken rules of the

particle world, where some quantities are conserved only by some forces; the conservation bookkeeping of astronomy, from spinning neutron stars to colliding black holes; and the practical power of the laws, which lets a physicist sign off on a proposed experiment, a machine, or a fraud without touching a single instrument. The final chapters face the fine print honestly: the open questions at the edges of physics where the ledgers themselves are being tested, and the standing lesson that even the most trusted rules must survive being checked.

A note on neighbors, since this book lives on a crowded shelf. The companion volume on energy carries the full story of that quantity's forms, machines, and thermodynamics; the volumes on relativity and spacetime carry the geometry that reconciles the ledgers for fast-moving observers; the volumes on atoms and particles carry the menagerie in full. Here the laws themselves are the subject, and each famous quantity gets a chapter's justice rather than a book's, with the deeper treatments living in their own volumes. No equations follow, the arithmetic stays honest, and the reader is asked only for the willingness to believe that the universe keeps books, keeps them exactly, and can be caught doing it.

Chapter 1: How to Find a Rule That Cannot Break

The first conserved quantity was more an act of faith than a finding. In the Greece of antiquity, a handful of natural philosophers argued, against the everyday evidence of things visibly appearing and vanishing, that nothing truly comes into being or passes away, that the changes of the world are rearrangements of some permanent underlying stuff. The argument was metaphysical, unsupported by any balance scale, and it set a pattern worth noticing: conservation laws tend to be believed before they are proved, trusted as articles of intellectual economy, and confirmed by instruments only centuries later. Faith in the idea arrived first; the ledger arrived when chemistry built one.

Chemistry built it in the eighteenth century, at the hands of a French tax collector and meticulous experimenter whose name is attached to the law of mass conservation. Before his work, the prevailing theory of combustion described burning as the release of an invisible fluid from materials, a theory that excused the fact that the ash of a burned log weighs less than the log. The reformer turned the balance sheet on chemistry: seal the burning in a vessel and weigh vessel, log, and all the smoke and gases together, and the total is unchanged. Rust a metal in a closed flask and the flask gains exactly the weight the metal gains. The physical transformations of matter are rearrangements; the mass of the closed system neither grows nor shrinks, and the sealed-vessel experiments of the era, with their balances reading the same before and after, converted the ancient metaphysical hunch into a working scientific instrument. Every quantitative chemistry course since has begun with the balance.

The nineteenth century ran the same discovery for motion. Water wheels, steam engines, and the industrial economy of energy conversion raised the practical question of where the power comes from and where it goes, and a sequence of experimenters, a French engineer observing military cannon barrels boring out heat, an English brewer measuring the warming of water by paddles driven by falling weights, a German physician finding the body's heat traceable to food intake, converged on one conclusion: the capacity to do work can change its form, mechanical to thermal to chemical and back, but the total, in a closed accounting, is invariant.

The concept was named energy, and its conservation, argued through the 1840s and standing ever since, became the first law of thermodynamics, the pivot of the physical sciences. It is worth pausing on how strange the

achievement was: no one has ever seen energy, only the pushes and movements it manifests in, and the law's content is precisely that the concept's various disguises, when properly booked, sum to a constant. Physics invented an invisible currency and then demonstrated, to extraordinary precision, that the books balance.

Momentum and angular momentum had their own history, older and quieter. The study of collisions in the seventeenth century, by founders whose names every physics student learns, showed that a certain measure of motion, mass times velocity, survives every impact: whatever one ball loses, the other gains, exactly. That ledger became the law of momentum conservation, the backbone of mechanics. Its rotational cousin, the law that a spinning system's total turn is conserved unless twisted from outside, matured alongside it, and the two completed the classical set: mass, energy, linear momentum, angular momentum, and, with electricity's arrival, charge, the ledger that closes every circuit and every chemical reaction.

One more thread belongs in the founding history, because it explains the book's later chapters. The conservation laws were found as empirical regularities, and for two centuries their deeper reason was unknown: they worked, like the laws of a well-run bank, but no one knew why the bank never made an error. The answer arrived in 1915, in the middle of the Great War, in the work of a mathematician in Gottingen, Emmy Noether, whose theorem, described properly in its own chapter, shows that each conserved quantity is a symmetry's shadow: energy is conserved because the laws of physics do not change with time; momentum because they do not change from place to place; angular momentum because they do not depend on direction.

The rulebook of the universe, it turned out, had a single author behind its entries, and the discovery transformed the laws from a list of coincidences into a consequence of the character of space and time themselves, which is the most elegant plot twist the history of physics contains.

The law of mass conservation also carries one of science's sobering footnotes about the discoverer. The chemist who balanced the books was also a nobleman of the old regime and a farmer-general, a collector of the taxes that his countrymen came to loathe, and in the revolution that followed his era's discoveries, he was arrested, tried, and sent to the guillotine in 1794, a colleague pleading in vain that the republic needed his kind of genius. The judge's recorded answer, that the revolution had no need of scientists, has been quoted for two centuries as the classic statement of a regime's blindness. The ledger he built survived him, though, and the balance scale he put at the center of chemistry has outlasted every government that has come

and gone since, a quiet standing argument that the books of nature, unlike the affairs of states, are beyond the reach of the scaffold.

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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.