

Contents

| | |
|--|----|
| INTRODUCTION: A Journey through Gravity | 1 |
| 1 A Universal Language | 11 |
| <i>The Universality of the Speed of Light</i> | 14 |
| <i>Michelson and Morley's Infamous Failed Experiment</i> | 18 |
| <i>Rotations in Space and Time</i> | 24 |
| <i>The Equivalence Principle and Universality of Gravity</i> | 27 |
| 2 The Gravity of Our Curved Reality | 34 |
| <i>The Thread in the Fabric of Spacetime</i> | 36 |
| <i>A Spacetime Geometry</i> | 41 |
| <i>A Straight Line in a Curved Spacetime</i> | 42 |
| 3 Gravity and the Force Within | 48 |
| <i>A Feeling of Gravity</i> | 51 |
| <i>Tidal Forces</i> | 56 |
| <i>A Messenger for Gravity</i> | 60 |
| <i>Catching a Glimpse of Glight</i> | 67 |
| <i>Einstein Was Right! Or Was He?</i> | 75 |

| | | |
|----------|---|-----|
| 4 | Predicting Our Own Fall | 80 |
| | <i>Gravity at Its Limit</i> | 87 |
| | <i>Singularities</i> | 89 |
| | <i>Embracing the Planck Scale</i> | 92 |
| | <i>Our Journey inside a Black Hole</i> | 96 |
| | <i>Our Journey to the Beginning of Time</i> | 102 |
| 5 | Expanding into Nothingness | 106 |
| | <i>A Mysterious Universe in Continuous Expansion</i> | 111 |
| | <i>An Accelerated Expansion</i> | 115 |
| | <i>Dark Energy</i> | 120 |
| | <i>Einstein's Cosmological Constant</i> | 124 |
| | <i>Diving into the Vacuum</i> | 126 |
| | <i>The Greatest Discrepancy in Scientific History</i> | 132 |
| 6 | The Graviton, What a Particle!? | 137 |
| | <i>So Far, So Good</i> | 138 |
| | <i>Gravity with a Sense of Humor?</i> | 140 |
| | <i>The Ghost of Massive Gravity</i> | 148 |
| | <i>From Extra Dimensions to Massive Gravitons</i> | 154 |
| | <i>Tickling an Elephant</i> | 162 |
| | <i>Graffiti in the Sky</i> | 167 |
| 7 | Our Lives in Pursuit of Gravity | 172 |
| | <i>Lightness of Gravity</i> | 178 |
| | <i>(Space)Time Will Tell</i> | 179 |
| | <i>Pi in the Sky</i> | 184 |

| | |
|--|-----|
| <i>The Irrevocable Quantum Nature of Gravity</i> | 188 |
| <i>From Waves to Particles</i> | 191 |
| <i>The Ultimate Journey</i> | 194 |
| CONCLUSION: Creatures of Gravity | 202 |
| <i>Bibliography</i> | 207 |
| <i>Index</i> | 209 |

INTRODUCTION

A Journey through Gravity

Gravity. Such a familiar concept, present in every language and culture, yet one that scientists have struggled to understand for millennia. It is the overarching miracle connecting everything, everywhere, forever in the Universe. Universal in every sense. As humans, we may think of it as the hidden force that keeps us firmly planted on Earth, the reason why the Earth orbits the Sun, or the interaction that allowed the Milky Way and its hundreds of billions of stars to form. But that barely hints at its true significance. Gravity is the reason why the Universe itself can even exist and evolve. It elevates space and time from mere pieces of scenery into central actors in the unfolding drama of reality. As we embrace gravity, we can't help but also pit ourselves against it: leaping, floating, or flying as we pursue brief moments of freedom from its command. I, for one, have been chasing gravity my entire life—seeking, like so many scientists who have come before me, to unravel its deepest mysteries.

Imagine yourself alone in the cockpit of a small, single-engine aircraft, patiently waiting on the taxiway for the signal from air

traffic control. Four simple words, “clear to take off,” resonate like a magical password, unlocking a precise series of events that will achieve what would have been impossible just over 120 years ago: lifting and floating a one-ton object into midair. As the craft zooms down the runway, you are pressed back into the foam of your seat, accelerating horizontally to a speed of 100 to 200 km/h. Ironically, it is this horizontal speed that will allow the pressure under your wings to overcome the vertical pull of gravity and lift you skyward. As you rise to cruise altitude, even the slightest amount of turbulence shakes the small plane. For a moment, you feel like you are trapped inside a snow globe, existing at the mercy of some titanic, mischievous shaker—until you remember that a little tweak of the rudder, a gentle push on the trims, or a subtle twist of your ailerons is all you need to take control and surf gracefully on the airflow, simultaneously pushed upward by the pressure and pulled downward by gravity.

If soaring above the clouds is not for you, perhaps you would prefer to picture yourself submerged in the deep blue, mingling with thousands of coral reef fish a few dozen meters below the surface. As you contemplate the serenity of this underwater world, you are plunged into a silence broken only by the popping sounds of the vibrant coral reef and that of your own breath as you slowly inhale from your air tank and exhale small bubbles that shoot to the surface. With each breath, your body gently bobs up and down a few centimeters as the pressure of the air in your lungs tries to compensate for the force of gravity and the mass of the column of water that is pressing against every cell in your body.

Flying high in the air and diving deep under the sea are two of the most thrilling ways to defy gravity, at least here on Earth. But to achieve the ultimate feeling of weightlessness, nothing compares to floating in space, seemingly escaping gravity’s

clutches altogether. The feeling of freedom is no longer an illusion—there are no strings to pull or pressures to counteract. Observing Earth from orbit, you can savor the absolute freedom of free fall, a concept deeply engrained in our understanding of gravity, even while it remains a luxury that few have had the opportunity to enjoy.

In my life, I have experienced the joy of flying and diving and came within a hair's breadth of making it to outer space. But we don't need a fancy plane, scuba gear, or space shuttle to experiment with gravity. In fact, whether we are doing something as simple as dropping a ball, swinging in a hammock, or skipping a stone, we're all scientists conducting our own personal experiments and drawing our own conclusions about this universal yet mysterious phenomenon.

But what exactly is going on in those moments? What is gravity? It seems like such an innocent question, yet the answer always seems to be hidden behind abstruse laws of physics. Physical phenomena are often portrayed as a set of obscure fundamental rules—Archimedes' principle, Newton's inverse square law, Bernoulli's principle, and the like—that nature must unquestionably and rigidly obey. These laws are, of course, central to our understanding of the world and the structure of our reality. They have revealed how buoyancy allows boats to float, and how the difference in pressure caused by the motion of the air beneath their wings allows birds and planes to navigate the skies. They have enabled us to send a man, and hopefully soon a woman, to the Moon. Yet the presentation of these laws as being set in stone belies our scientific history. Far from being immutable and unchanging, our understanding and appreciation of these laws—what they mean, where they come from, and what lies behind them—is continuously unfolding before us.

Galileo Galilei, Johannes Kepler, Sir Isaac Newton, Albert Einstein, Stephen Hawking, Sir Roger Penrose, Andrea Ghez, and countless other brilliant scientists have each brought a new perspective to our understanding of gravity, but our journey is far from finished. Think of this book, then, as an invitation to join me in the quest to uncover the meaning of gravity, to grasp its connection with the structure of reality. Fortunately, for the most part we will not be undertaking this adventure alone. Instead, we will be guided by some of the greatest scientific minds of the past several centuries—that is, at least, until we reach the edge of the map, where we will take some exploratory steps into the unknown. Our journey will begin, however, in well-charted territory with a few trustworthy companions.

With their realization that gravity must be a universal force, acting on everything and accelerating everyone in the same way, regardless of their mass, Galileo, Kepler, and Newton provided the first crucial piece of the puzzle. This insight was made possible by a new perspective on what it means to *be free*, a perspective that discarded centuries of Aristotelian dogma and radically transformed the concept of *inertia*.

This new perspective was brought to light in 1632, with the publication of Italian astronomer and physicist Galileo Galilei's *Dialogue Concerning the Two Chief World Systems* (*Dialogo sopra i due massimi sistemi del mondo*). In the dialogue, Galileo championed a new Copernican revolution, one that went beyond merely denying that the Earth occupied a special place in the solar system, by further dismissing the idea that *any* person or object could ever hold a privileged position with respect to the laws of nature.

To make this argument, Galileo considered the world through the eyes of a sailor confined to the main cabin below the decks

of a moving ship. Unable to see the world outside, the sailor was entertained by watching the motion of “some flies and butterflies” with whom she shared the cabin. Galileo realized that the sailor would not be able to tell whether the ship was at rest or in motion at constant speed, at least not from observing these small flying animals. Why? Because if the ship moves at constant speed, so does everything on board, including the air in which the flies and butterflies flutter about. The sailor, trapped below deck, can only observe the motion of the flying creatures relative to the inside of the ship’s cabin. Galileo used this thought experiment, which highlighted the importance of *relative* motion, to explain how the Earth could rotate without us being able to feel it. Moreover, once we recognize that we cannot tell the difference between the lower deck of a ship at rest and that of one in uniform motion, we can infer that the laws of physics should be the same for any observer moving at constant velocity, no matter the speed.

It is precisely this notion of “Galilean relativity”—the realization that the laws of nature are the same regardless of who describes them—that is enshrined in Newton’s first law of motion, which holds that every object will remain at rest or in uniform motion in a straight line unless compelled to change its state by the action of an external force.¹ Newton realized that *being free* is the privilege to carry on undisturbed, pursuing our journey at the same velocity, uniformly. Building on the work

1. This idea replaced the Aristotelian notion of *inertia*—the desire to slow down and come to a state of absolute rest. In contrast to Aristotle, who thought that forces were necessary to maintain velocity, Newton realized that *forces* lead to *acceleration* (change in velocity). In our everyday lives, friction with the air and the ground acts as a force, naturally slowing us down (deceleration or negative acceleration). However, in outer space, where there is no air and no friction, objects can be free and maintain a uniform velocity.

of Kepler, who developed the laws of planetary motion, this insight would later lead to Newton's 1687 law of universal gravitation, also known as Newton's inverse square law. According to this law, the force of gravity exerted between any two massive particles (that is, particles having mass) is a *universal* and *instantaneous* force, whose intensity decays as the square of the distance between the two particles.

Newton's law, as many of us have been taught, describes how an object, when dropped, is inexorably attracted by the mass of the Earth. But the universal nature of gravity extends far beyond this simple phenomenon. It applies to everything and everyone, no matter the object, no matter the separation. In 1798, Henry Cavendish was among the first to test it formally in a laboratory, and more than three centuries after its discovery, Newton's inverse square law has been scrutinized with impeccable precision, from distances smaller than a tenth of the width of human hair to separations that extend billions of kilometers. In fact, Newton's law of universal gravitation is so fundamental that it can still be used to predict how gravity has governed most of the evolution of our Universe, from the gravitational collapse of dark matter to the formation of clusters of galaxies and the creation of the solar system.

Centuries passed before observational evidence began to cast a sliver of doubt on Newton's law of gravity. However, in retrospect, the idea that gravitational attraction between any two objects happens *instantaneously* should have raised a red flag. According to Newton's simple law, if two particles were to appear, they would be *immediately* attracted to one another without any delay. No matter what your views on attraction may be, we all know that this phenomenon cannot be immediate. Even when it comes to love at first sight, you first need to "see" the other person (that is, to "communicate," even if not

verbally) for attraction to take place. Newton himself, in a letter to Richard Bentley, expressed his discomfort with the concept of an instantaneous law: “Tis unconceivable that inanimate brute matter should (without the mediation of something else which is not material) operate upon & affect other matter without mutual contact; as it must if gravitation in the sense of Epicurus be essential & inherent in it. And this is the reason why I desired you would not ascribe {innate} gravity to me” [1].

Our own journey will begin two centuries later, when American scientists Albert Michelson and Edward Morley revealed the results of their infamous “failed experiment,” ushering in a new scientific revolution. Shortly thereafter, Einstein introduced new ideas of relativity into our understanding of gravity: first putting forward the notion of special relativity, which supplanted the kinematics of Galileo, and then unveiling gravity as we understand it today through the theory of general relativity. Guided by these theories, we will uncover an entirely new structure of physics and understanding of our Universe in which gravity is fundamentally identified with the very fabric of space and time, entwined and unified.

Today, more than a century has passed since Einstein’s breakthroughs, and general relativity stands stronger than ever. Gravity has been exhaustively tested, including in some of the most extreme environments, and the evidence unflinchingly accords with Einstein’s predictions. The very force within gravity has been detected thanks to gravitational waves. At the same time, we have also learned much more about the quantum nature of our world through atomic, nuclear, and particle physics, quantum chemistry, and the numerous technological advances of the electronic and computer age. With these advances, new ideas and theories constantly bubble up in our effort to make sense of

the world in which we live. And yet, to date, none has surpassed Einstein's theory of general relativity, despite the obvious need for new physics. For there is one thing that, from the very beginning, general relativity itself has been forthright about: there is a point where the theory must fail, where a brand-new layer of physics waits to be unveiled. From this failure comes the opportunity to probe and appreciate nature on an even deeper level.

As we continue on our journey, we shall see how gravity, viewed from a more modern perspective, can also be thought of as the manifestation of a fundamental particle—the graviton—much like electromagnetism is the manifestation of the photon, the fundamental particle of light. In the very same way that we can “see” *light* as electromagnetic waves propagate through space and time, we can now “hear” gravitational waves (or *glight*, as we shall call it here) as they disturb the very fabric of spacetime. We have now observed gravitational waves through many different instruments, and the reality of *glight* has become unquestionable. Their detection offers an unparalleled opportunity to decipher the many mysteries that our Universe is still hiding. What is the origin of the Universe? What are the dark components of the Universe that explain its structure and evolution but cannot be directly detected with our instruments? What is our fate? These profound questions are begging for answers. And who wouldn't want to follow that trail?

Eventually our journey will take us to the edge of the map. While Einstein's theory of general relativity has provided natural and elegant answers to some of the most perplexing questions about the nature of gravity, it also has raised several puzzles with which we continue to grapple. How is it that the contributions of known particles that we understand so well in our underground particle accelerators affect the Universe in ways we cannot even start to comprehend?

As we attempt to reconcile the evolution of our Universe with the fundamental quantum nature of the world, we will be forced to reconsider gravity on an even deeper level. What if, on large cosmological scales, gravity behaves differently than predicted by general relativity? What if gravity, long assumed to be massless, in fact has mass? This idea is almost as old as general relativity itself and has been explored by some of the greatest scientists of the past century. Until recently, all attempts to make sense of this idea have failed dramatically. Yet far from being the end, this is where the most exciting part of our journey will begin as I guide you through new pathways that my colleagues and I have recently uncovered in our quest to grapple with gravity.

These paths previously looked so unpromising that their exploration was considered not only impractical or dangerous but simply unthinkable. Today, however, it seems that they may lead us to an entirely new way to think about gravity. And while these new theories may not provide final answers to all of our questions, by exploring gravity as it might be, even if not in our own reality, we may come to appreciate nature for all that it has to offer.

Gravity is one of the first physical phenomena of which we are aware, and we possess a near universal desire to probe its limits. As babies, we repeatedly push toys off the table, watching them tumble to the ground (and watching our exasperated parents retrieve them). As children, we jump tirelessly on the trampoline, seeing how high we can soar before being pulled back down to our terrestrial home. As old friends, we skip stones at the beach, observing the beauty of the cascading ripples. In every instance, we both play with and try to counteract this tenacious phenomenon. Its constant pull is the source of so

much stress in our lives, but rather than hiding from it we all learn to embrace it.

As we fall through the curvature of spacetime as freely as we fall through our lives, we soon realize that, while being free and straight, our journey through space and time is far from straightforward. Certainly, our journey would not be complete without its share of obstacles and falls. Embracing them and appreciating the beauty of falling is essential if we are to make progress in our never-ending quest. All theories of gravity developed so far have experienced the virtue of failure. Daring to fail means appreciating each fall not as an embarrassing epilogue but rather as an opportunity for a more fundamental understanding of nature.

Think of this journey, then, as a celebration of gravity's mysteries and of science itself—complete with its doubts and failures, yes, but also with the incredible thrill of discovery. This is not just my quest, nor that of my colleagues. It is not the discovery of Einstein or Newton alone. It is our *shared* adventure, yours as much as that of the great scientists who paved the way. It is a journey that began thousands of years ago, and one that may never end. Along the way, however, we hope to gain knowledge that will enrich the lives of future generations and civilizations, allowing them to pursue their own destiny, to surf between new layers of reality, and to interact with the all-encompassing fabric of the Universe.

Index

Note: Page numbers in *italics* indicate figures.

- academia, 57–60, 59n, 106, 108, 110, 158.
 See also peer review; theoretical physics
- accelerated expansion. *See* cosmic acceleration
- Amazon (Peru), 13, 38
- amplitude, of gravitational waves or glight, 65, 68, 71–72, 74, 100, 150, 195, 196
- Andromeda, 111–112, 124
- angular momentum, 148–149. *See also* spin
- Antananarivo, Madagascar, 34, 35. *See also* Madagascar
- antigravity, 120–121, 121n
- antiparticle, 128, 133
- Apollo missions, 187; Apollo 15 mission, 28–29, 41, 187
- Archimedes’ principle, 3
- arXiv, 76, 158, 174, 174n. *See also* peer review
- astronauts, 2–3, 29, 35, 39, 41, 48–51, 80–86, 92, 106, 110, 137, 172–173, 205
- atoms, 60, 60n
- Ayacucho, Peru, 11, 12. *See also* Sendero Luminoso
- backreaction: gravitational, 143n;
 quantum, 190–191
- baryonic matter, 123
- being free, 5, 5n, 10. *See also* free fall; straight line
- Bentley, Richard, 7
- Bernoulli’s principle, 3
- Big Bang, 102–104, 114, 115, 119, 135, 138
- black holes, 89–92, 96–102, 101n
- “Blind Men and the Elephant, The” (Saxe), 162
- Boltzmann, Ludwig, 107
- Brandenberger, Robert, 157
- brane (membrane or surface), 157
- breathing mode polarization, 66–68, 67, 150, 150, 151, 185–186. *See also* glight polarizations; π field
- Brownian motion, 26, 107
- Burgess, Cliff, 157
- Burnell, Dame Susan Jocelyn Bell, 69n

- California Institute of Technology, 84
Cape Town, South Africa, 35
Cambridge University. *See* University of Cambridge
Case Institute of Technology, 18. *See also* Case Western Reserve University
Case Western Reserve University, 18, 59n2
Cavendish, Henry, 6
Cepheid variables, 115
CERN (Conseil Européen pour la Recherche Nucléaire or European Council for Nuclear Research), 95, 158. *See also* Large Hadron Collider
Cleveland, Ohio, 35
color: of glight, 72–73, 75, 181; of light, 15, 26, 193. *See also* glight; wavelengths
conformal mode. *See* breathing mode polarization
cosmic acceleration, 115–120, 132–134, 141–142
cosmic expansion, 111–115
cosmic inflation, 103, 119, 119n, 198
cosmic voids, 124, 126–127, 131. *See also* vacuum
cosmological constant (Λ), 124–126
cosmological constant problem, 135, 139, 141–143, 178
cosmological paradigm, 138–140
cosmology, 8–9, 35, 78; challenges, 138–140; early Universe, 102–105; expansion, 111–126; massive gravity, 170–171, 180–181
curvature, 41, 53–55, 57, 60, 76, 90–92, 134; extrinsic, 167; from glight, 143n
curvature fluctuations, 198–199, 198–199n
curved space, 40, 44–45, 46. *See also* Earth, curvature of
curved spacetime, straight line in, 42–47, 46
dark energy, 110–111, 120–124, 127, 132–136, 147. *See also* cosmological constant; cosmological constant problem
dark matter, 47, 111–112, 118–119, 123, 178
Davis, Anne, 157
Davisson, Clinton, 191
de Broglie, 7th Duc of (Louis Victor Pierre Raymond), 192
de Broglie relation, 94
Deffayet, Cedric, 186
degravitation, 157, 158
de Rham, Claudia: Andrew Tolley, 51, 58–59, 108, 164–165; astronaut training, 48–51; Case Western Reserve University, 18, 59n; ESA third selection round, 82–86; extra-dimensional model, 158–161; Imperial College London, theoretical physics group, 59n, 145, 191–192; massive gravity, theory of, 169, 169–171; moving around, 34–36, 43–44, 108; new beginning, 106–110, 137–138; Perimeter Institute for Theoretical Physics, 59, 59n, 157; Sendero Luminoso, 11–12; universal language, 11. *See also* dRGT; two-body problem; women in physics
Deser, Stanley, 143
determination, 48, 124, 137, 179
diffraction, 192
dipole, 59n3
diversity: gender diversity, 108; in science, 177
diving: free fall, 37, 79, 100, 126, 203, 205; scuba diving, 2–3, 49, 85, 87; skydiving, 36
Doppler effect, 116
dRGT (de Rham Gabadadze Tolley theory of massive gravity), 164–171, 168, 169, 173–175, 178–179

- Dvali, Gia, 186
- Dyson, Freeman, 198; 2012 Poincaré Prize Lecture, 196
- $E = mc^2$, 93, 117, 117n, 133, 133nn6–7, 167
- Earth, curvature of, 44–45, 44n, 46, 53–55, 55
- Earth-Moon system, 71, 72, 187–188, 187n4
- École Polytechnique (Paris), 35
- École Polytechnique Fédérale de Lausanne (EPFL), 35, 194
- Einstein, Albert: cosmological constant, 124–126; “Einstein was right,” 75–79; “greatest blunder,” 125; “miraculous year,” 107; Nobel Prize, 107. *See also* $E = mc^2$; general relativity; special relativity
- Einstein-Hilbert action for gravity, 56–57
- Einstein-Podolsky-Rosen paradox, 77
- Einstein-Rosen bridge, 77
- Einstein’s theory of general relativity. *See* general relativity
- electric charge, 30, 32, 130, 193
- electromagnetic waves, 8, 14–15, 52, 61, 64, 142, 194. *See also* light; Maxwell’s theory; speed of light, universality of
- electromagnetism, 28–29, 60n, 61–62, 194. *See also* “Maxwell’s equations”; Maxwell’s theory
- electrons: discovery of, 191; electric charge, 30; electron-positron pair, 128n; eV, 129n; Planck scale, 95; in Sun’s core, 68; wave-particle duality, 191–192
- electronvolt (eV), 129n
- electroweak scale, 195
- empty space, 15–16. *See also* cosmic voids; vacuum
- energy conservation, 121–122
- energy density: 117; accelerated expansion, 118, 132, 133; cosmological constant, 125; of dark energy, 117, 121–124, 121n; of massive particles, 117; of massless particles, 117, 117n; of matter, 117–119; of radiation, 117n, 118–119; of the Universe’s, 117, 123, 135; of the vacuum, 127–128, 128n, 132–135
- equivalence principle: cosmological constant and, 125; between inertial and gravitational masses, 32–33, 32n; lightness of gravity, 178–179; overview, 141; polarizations, 66, 66n; testing, 32, 186–188, 187n3; vacuum energy, 131–132
- Eratosthenes, 44, 44n
- European Astronaut Centre, 84
- European Space Agency (ESA), 48, 50, 80–82, 84, 85, 137
- Event Horizon Telescope (EHT), 99–100
- exclusion principle, 53
- expansion: accelerated expansion, 115–120, 126, 198–199; breathing mode, 66; cosmic expansion, 111–115; dark energy, 120, 122–123; effect of graviton mass on, 147, 171
- extra dimensions, 154–158, 161, 186
- extrinsic curvature, 166–167
- Faraday, Michael, 14
- Fermi, Enrico, 195
- Fermi scale, 195
- Feynman, Richard, 143
- Fierz, Markus, 148
- fifth force, 185–186, 187n3
- flat: space, 44, 47, 54, 166, 176; spacetime, 26n, 37, 39, 47, 122. *See also* Minkowski spacetime

- flying, 1–3, 18–20, 19, 31–32, 34–35, 36, 43, 45, 46, 49–50, 58, 86, 87, 154, 190, 205
- force-carrying particles, 8, 145–146, 193–194. *See also* gravitons; photons; W and Z bosons
- free fall, 2, 3, 10, 28, 36–39, 37n, 53, 65, 137, 138, 202. *See also* geodesic; straight line
- Gabadadze, Gregory, 158, 159, 173–174, 186. *See also* dRGT
- Gagarin, Yuri, 80
- Galileo Galilei, 4, 7, 17, 18, 25, 28, 53; *Dialogue Concerning the Two Chief World Systems (Dialogo sopra i due massimi sistemi del mondo)*, 4–5; free-fall experiment, 28; Galilean relativity, 5
- general relativity, 7–8, 167–169, 168; infinite range gravitational theory, 153
- Geneva, 35, 59, 128, 158, 160, 166. *See also* CERN; Large Hadron Collider; University of Geneva
- Genzel, Reinhard, 99
- geodesic, 60. *See also* free fall; straight line
- Ghez, Andrea, 4, 99
- ghost, 151–154, 152n, 161, 166; ghost particle, 152–154, 184–185
- giga-electronvolt (GeV), 129n. *See also* electronvolt
- Glashow, Sheldon, 145
- glight (gravitational waves), 7, 8; amplitude of, 65, 71–72; detection of, 67–76, 74, 180–184; generation of, 193; GW150914, 75; independent polarizations, 65–67, 65n, 66n; massive, 143, 143n; massless, 149–150; as messenger for gravity, 62–67; primordial, 200–201; from star or black hole mergers, 72–73; symphony of notes, 181. *See also* gravitational waves
- glight polarizations (polarization of gravitational wave), 65, 65–67, 67, 149, 150
- glight radiation (radiation of gravitational waves), 68n, 123, 197
- glight signal (gravitational wave signal), 75, 181–183, 182
- Global Positioning System (GPS) satellites, 42, 42n
- grand unified theory, 155
- gravitational attraction: black hole solutions, 90; dark energy, 120, 121n; Earth and Moon, 68; Einstein's cosmological constant, 124–125; mediation, 6–7, 62–67; Newton's inverse square law, 89; Newton's law of gravity, 6–7; non-instantaneous, 6–7, 62; Planck scale, 92–93. *See also* Einstein's theory of general relativity; Newton's theory of gravity
- gravitational coupling constant, 94
- gravitational mass, 29, 31–32, 32n, 37, 111
- gravitational waves (glight): amplitude of, 65, 71–72; detection of, 180–184; introduction, 7, 8; as messenger for gravity, 62–67; polarizations of, 65, 65; stars or black holes, 72–73; stochastic, 70–71, 184, 200. *See also* glight
- gravitational wave signal, 75, 181–183, 182. *See also* glight; glight signal; GW150914
- gravitino, 155
- graviton mass, 166, 170–171, 178–179, 180, 183, 186–188. *See also* dRGT; massive gravity; massive spin-2 particle

- gravitons: detecting, 195–201; general relativity, 138–140, 167–171, 168, 169; gravity with a sense of humor, 140–147; introduction, 8; massive gravity, 148–158, 150; massive spin-2 particles, 149–153; massless spin-2 particles, 149–150; polarizations, 149–151; wave–particle duality, 193–194
- gravity, 1–10, 33, 38–39, 53–56; feeling of, 51–56, 54n, 55; high-energy completion of, 95, 155, 189, 198; irrevocable quantum nature of, 188–191; lightness of, 178–179; our lives in pursuit of, 172–178; messengers for, 60–67; particles, from waves to, 191–194; sense of humor, 140–147
- Green, Michael, 155
- Gregory–Leibniz series rule, 176
- GW150914 (glight signal), 75
- Haigneré, Claudie, 82
- Hamiltonian constraint, 177
- Hassan, Fawad, 175
- Hawking, Stephen, 4, 91, 98, 104
- Heisenberg, Lavinia, 179–180
- Heisenberg, Werner, uncertainty principle, 128, 128n, 133, 196
- helicity, 149n, 177
- Hertz, Heinrich, 107
- Hewish, Antony, 69n
- hierarchy problem, 156–157
- Higgs, Peter, 129
- Higgs boson, 129–131, 129n, 134–135, 145–146, 149
- Higgs mechanism, 129–131, 145–146
- High-Z Supernova Search Team, 116, 119
- Hinterbichler, Kurt, 175
- holography, 156
- Hubble, Edwin, 115
- Hubble Space Telescope, 81–82
- Hulse, Russell, 68
- Hulse–Taylor binary system, 68–70, 186
- Imperial College London, 59n2, 145, 191; theoretical physics group, 145. *See also* Kibble, Sir Tom; Salam, Abdus; Thomson, Sir George Paget; Tolley, Andrew
- inertia, Aristotelian notion of, 5n
- inertial mass: definition, 30; $E = mc^2$, 93, 167; equivalence principle, 32–33, 32n, 187n3; glight, 143; graviton, 144, 149–150, 169; gravity, 143–144; gravity, universality of, 30–31, 31n; light, 63; particles, 31n; W and Z bosons, 129
- infinite range gravitational theory, 141, 143, 153. *See also* general relativity; universality of gravity
- infinity, 89. *See also* singularity
- inflation, 103, 119, 198; alternatives to, 114, 119n, 198–199n. *See also* cosmic inflation; cosmology, early Universe
- instantaneous force, inconsistency of, 5–6
- interferometers, 18–24, 21, 73, 74–75, 196–197. *See also* Kamioka Gravitational Wave Detector; Laser Interferometer Gravitational-Wave Observatory; Laser Interferometer Space Antenna; Michelson’s interferometer; Virgo European Gravitational Wave Observatory
- International Conference on Particle Physics and Cosmology (COSMO), 158
- invariance, under time translations, 121–122

- James Webb Space Telescope, 14, 82
Jet Propulsion Laboratory (JPL), 35,
84. *See also* NASA
Journal of the Franklin Institute, 78
Julius, David, 52
- Kaluza, Theodor, 155–156. *See also*
Kaluza-Klein extra dimensions
Kaluza-Klein extra dimensions, 155–156
Kamioka Gravitational Wave Detector
(KAGRA), 24, 73, 74, 100, 196
Kepler, Johannes, 4, 6
Khoury, Justin, 157
Kibble, Sir Tom, 145. *See also* Imperial
College London, theoretical physics
group
Klein, Oskar, 156. *See also* Kaluza-Klein
extra dimensions
Kyoto, 35
- Lausanne, Switzerland, 35, 129
Large Hadron Collider (LHC), 95, 129,
130, 131, 195n. *See also* CERN
Laser Interferometer Gravitational-
Wave Observatory (LIGO): black
holes, evidence of, 100; glight,
detection of, 75–76, 180–181; gravi-
tational waves, first direct detection
of, 100; gravitational waves, sym-
phony of notes, 181; gravitational
waves, typical amplitude, 196;
graviton mass, upper bound on, 183;
interferometer, 24, 74; overview, 24,
73–75, 76; single graviton, detecting,
196–197; spacetime fluctuations,
detection of, 73–75
Laser Interferometer Space Antenna
(LISA), 183–184, 200
laws of planetary motion, 6
Leavitt, Henrietta Swan, 115
Lenz, Wilhelm, 134
Lescarbault, Edmond Modeste, 88
Le Verrier, Urbain, 88
light, 15, 16, 16n, 61–64. *See also* elec-
tromagnetic waves; luminiferous
æther; speed of light, universality of
light quanta, 192. *See also* quanta
light wind or luminiferous æther, 20.
See also luminiferous æther
Lima, 45, 46
Lodge, Sir Oliver, 134
Lombok, Indonesia, 35
London, 35, 58, 97. *See also* Imperial
College London
longitudinal mode (ghost of massive
gravity), 151–153, 152n. *See also* ghost
longitudinal mode polarization, 150, 150
loops, in quantum field theory, 130
Lorentz, Hendrik, 24, 107
Lorentz contractions, 24–27, 26n, 42n,
187n4
Lorentz transformations, 24–27, 26n
luminiferous æther, 16–23, 19, 21, 73
luminosity (absolute luminosity and
luminosity distance), 115
Lunar Laser Ranging (LLR), 187, 188.
See also equivalence principle
- Madagascar, 34, 45, 46, 47, 48, 54n,
86, 108. *See also* Antananarivo,
Madagascar
Maldacena, Juan, 156
manifold, 39, 39n. *See also* space;
spacetime
mass, 29–30. *See also* gravitational
mass; graviton mass; Higgs mecha-
nism; inertial mass; massive particles;
Planck mass; W and Z bosons, mass of
massive gravitational waves, 150. *See also*
massive gravity; massive spin-2 waves

- massive gravity: absence of ghost, 161, 164; backreaction, 143n; curvature, 153; equivalence principle, 178–179; ghost of, 148–154, 150; gravity, lightness of, 178; gravity, quantum nature of, 189–191; irrevocable ghost, 163–164; main motivation behind, 179; massive gravitons, extra dimensions to, 161; mathematical representation, 167–171, 168; model, scrutiny of, 173–178, 174n; modern incarnation, emergence of, 147; polarizations in, 162–167, 185; spacetime, 166; testing, 180–184, 182; theory of, 169, 169–171, 173–177. *See also* dRGT; graviton mass; massive spin-2 particle; massive spin-2 waves
- massive particles, 6, 31n, 117, 118, 178–179
- massive spin-0 particle, 149. *See also* Higgs boson; π field; pions
- massive spin-1 particle, 149. *See also* W and Z bosons
- massive spin-2 particle, 149. *See also* dRGT; graviton mass; massive gravity
- massive spin-2 waves, 149, 150, 181–183, 182. *See also* massive gravity
- massive waves, 181
- massless particles, 118, 123
- massless spin-1 particle, 149. *See also* photons
- massless spin-2 particle (graviton), 149, 178
- massless spin-2 waves (glight), 149–150, 150, 178
- Matas, Andrew, 180
- mathematical proof, 175–177
- matter, definition of, 118
- matter era, cosmological, 118–119, 119n
- Maxwell, James Clerk, 14, 107, 193
“Maxwell’s equations,” 14
- Maxwell’s theory, 15–16, 63, 122. *See also* electromagnetism; “Maxwell’s equations”; speed of light, universality of McGill University, 157. *See also* Montreal McMaster University, 59, 59n2, 157
- megaparsecs, 72
- Merbold, Ulf, 81
- Merchez, Marianne, 82
- Mercury, 87–88
- mergers, stars or black holes, 72–73, 100, 180–181, 182, 197
- messengers for gravity, 60, 62, 65
- Messier 87 galaxy, 99
- metric, 165–166. *See also* spacetime
- Michelson, Albert A., 7, 18–24, 19, 21.
See also Case Institute of Technology; Cleveland, Ohio; Michelson and Morley’s failed experiment; Michelson’s interferometer; Nobel Prize winners
- Michelson and Morley’s failed experiment, 18–21, 19, 21, 21–24
- Michelson’s interferometer, 18–24, 19, 21, 73–75, 74, 196–197
- Microscope Space Mission, 187n3.
See also equivalence principle
- Milky Way, 1, 111, 113, 124
- Miller, Dayton, 23. *See also* Case Western Reserve University; Cleveland, Ohio
- Minkowski, Hermann, 24, 26, 26n
- Minkowski spacetime, 26n
- Moon, 28, 29–30, 185; companion, 34–35; “observable radius of Universe would not even reach to the moon,” 134; test of equivalence principle, 41. *See also* Earth-Moon system; Lunar Laser Ranging
- Montreal, 35

- Morley, Edward W., 7, 18–24, 19, 21.
See also Cleveland, Ohio; Michelson and Morley’s failed experiment; University of Western Reserve
- motion: angular momentum, 148; brane’s, 157; Brownian, 76; equivalence principle, 33; GPS satellites, 42; gravity, relationship to, 33; introduction, 5–6; light in, 63–64, 64n; light traveling within a luminiferous aether, 19, 20; of Mercury, 88; Newton’s second law of, 31; pulsars, 69; rotations in space and time, 25; spacetime, 37; of stars (Keck telescopes), 99; Sun’s core, 68n; two-body system, 59. See also free fall
- M-theory, 156
- NASA (National Aeronautics and Space Administration), 35, 74, 80–84. See also Jet Propulsion Laboratory
- Nernst, Walther, 134
- Neutral Buoyancy Facility, 84–85
- neutrinos, 111, 130–131, 178, 197
- Newton, Sir Isaac, 4, 5–6, 5n, 25; first law of motion, 5, 5n; inverse square law, 3, 6–7, 89–90; law of universal gravitation, 6, 28, 30, 92; laws of gravitation, 87–88
- Newtonian mechanics, 96
- Newton’s theory of gravity, 61, 88, 89–90, 120, 121n
- New York University (NYU), 158.
See also Gabadadze, Gregory
- Nicollier, Claude, 81
- Nobel Prize winners: Abdus Salam, 145; Adam G. Riess, 119; Albert A. Michelson, 22; Albert Einstein, 107; Andrea Ghez, 99; Ardem Patapoutian, 52; Brian P. Schmidt, 119; Clinton Davisson, 191; David Julius, 52; François Englert, 129; George Paget Thomson, 191; Louis Victor Pierre Raymond, 192; Max Planck, 192; Peter Higgs, 129; Reinhard Genzel, 99; Robert Brout, 129; Roger Penrose, 98; Saul Perlmutter, 119; Sheldon Glashow, 145; Sir Joseph John Thomson, 191; Steven Weinberg, 145
- no-go theorems, 154, 161, 164
- nonrelativistic matter, 185, 185n. See also baryonic matter
- North American Nanohertz Observatory for Gravitational Waves (NANOGrav), 70. See also gravitational waves, stochastic; Pulsar Timing Array
- nothingness, expanding into: accelerated expansion, 115–120; cosmic expansion, 111–115; dark energy, 120–124; Einstein’s cosmological constant, 124–126; introduction, 106–111; Universe, 114; vacuum, diving into, 126–132
- observable Universe, 15, 114–115, 135, 168, 178, 205
- Ockels, Wubbo, 81
- ordinary matter, 135. See also baryonic matter; nonrelativistic matter
- Orion, 97
- particle–antiparticle pair, 133, 133n6
- particle density, 117, 118
- particle physics, 7, 120, 195n; eV, usage of, 129n; energy units, 195, 195n; expectations from quantum, 135, 136, 144; quantum, 131, 188; standard model of, 145; vacuum energy, 131, 132,

171. *See also* symmetry breaking; theoretical physics
- particles: of arbitrary spin, 149–150, 150; ghosts, 151–154, 152n, 184–185; introduction, 6, 8; massive gravity, ghost of, 148; nonrelativistic matter, 185, 185n; quantum theory, 93; relativistic particles, 185, 185n; vacuum energy, 128; from waves to, 191–194. *See also* gravitons; Higgs boson; particle physics; photons; pions; quarks; W and Z bosons; *individual particles*
- Patapoutian, Ardem, 52
- Pauli, Wolfgang Ernst, 53, 134, 148
- peer review, 77–78, 174, 174n. *See also* arXiv
- Penrose, Sir Roger, 4, 91, 98, 104
- Perimeter Institute for Theoretical Physics, 59, 157, 164. *See also* Waterloo, Canada
- Perlmutter, Saul, 119
- Peru, 11, 13, 45, 46, 47, 54n. *See also* Ayacucho; Lima; Peruvian Andes
- Peruvian Andes, 11
- photoelectric effect, 192–193, 197
- photons: capturing, 194; definition of, 193; $E=mc^2$, 93n; Higgs bosons decay into, 130–131, 145, 149; mass of, 183; Planck's formula, 117n; vacuum, diving into, 129. *See also* massless spin-1 particle
- physical phenomena, 3, 9
- Physical Review*, 77–78
- π field (pi-field), 185. *See also* breathing mode polarization; equivalence principle, testing; fifth force; massive gravity, testing; pions; π wave
- pions, 185
- Pirtskhalava, David, 179–180
- π wave (pi-wave), 186–187
- Planck, Max, 94, 107, 192
- Planck energy scale, 92–96, 95n, 97, 155, 169, 195
- Planck length, 15, 95n
- Planck mass, 94–96, 169
- Poincaré, Henri, 24
- Poincaré symmetries, 26n. *See also* Minkowski spacetime
- polarimeters, 199
- polarizations, 63–67, 64, 65, 149, 185
- polarizations of glight (or gravitational waves), 65, 65–67, 67, 149, 150
- polarizations of light, 63–64, 64
- polarized sunglasses, 63, 64
- positron, 128, 128n
- positron emission tomography (PET) scanning, 144
- primordial glight (primordial gravitational waves), 200–201. *See also* gravitational waves, stochastic
- Princeton, New Jersey, 35
- principle of conservation, 121. *See also* energy conservation
- pulsars, 68–70, 186–187
- Pulsar Timing Array (PTA), 70, 71, 184, 200
- quadrupole, 59n3
- quanta, 192, 197
- QuantiFERON TB test, 86
- quantum corrections, 92, 94–95. *See also* loops
- quantum field theory, 93–94
- quantum nature of light, proving, 194
- quantum particles, 131–132, 194
- quantum vacuum energy, 134, 136, 136n, 139, 168, 170
- quarks, 60n, 152
- Quechuan provinces, 11

- radiation, 67, 68n, 118, 119, 123
radiation era, cosmological, 118, 119,
119n
radio waves, 15
receptors, 52
redshift, 116
relative motion, 4, 25. *See also* Lorentz
transformations
relativistic particles, 185, 185n. *See also*
radiation
Riess, Adam G., 119
Rigel, 97–98, 100–101
Robertson, Howard Percy, 78
Rosen, Nathan, 77
Rosen, Rachel, 175
rotations in space and time, 24–27, 26n.
See also Lorentz transformations
Sagittarius A*, 89, 99
Salam, Abdus, 145. *See also* Imperial
College London, theoretical physics
group; Nobel Prize winners
satellites, 41, 42. *See also* Moon
Saxe, John Godfrey, “The Blind Men
and the Elephant,” 162
Schmidt, Brian P., 119
Schwarz, John, 155
Schwarzschild, Karl, 102
Schwarzschild singularities, 91
Science, 116
Scott, David, gravity demonstration
on the moon, 28, 41
Sendero Luminoso (Shining Path), 12
Sharman, Helen, 82
Shepard, Alan, 80
singularities, 89–92
singularity, definition of, 89, 89n
singularity theorems, 91, 98, 100, 104.
See also Hawking, Stephen; Penrose,
Sir Roger
sky, 26–27, 137, 184, 198–201, 202; as
companion, 35, 49, 70, 198
space, 1–3, 23, 24–25, 27, 39n; rotations
in space, 26–27. *See also* empty
space; manifold; space exploration;
spacetime
space and time, rotations in, 24–27. *See
also* Lorentz transformations
space exploration, 3, 5n, 80–82
Spacelab-1, 81
spacetime: beginning of time, 102–104;
black holes, 96, 97–98, 100; curva-
ture of, 39–40, 60, 62, 63; dark
energy, 121–122; definition of, 26;
Earth-Moon system, 187n3; electrons,
effect of, 190; geometry, 41–42;
ghosts, 152, 153; glight, 65, 65n, 66n,
71, 73–74, 76, 143n; graviton, 141,
142; gravitons, detecting, 198–199,
201; gravity, feeling of, 52, 53–54,
55; metric, 165–166; M-theory, 156;
Planck scale, embracing, 93, 94–95;
polarizations, massive gravitational
waves, 150; quantum corrections,
92; rotations, 26, 26n; singularities,
89n, 90–91; straight line in a curved
spacetime, 46; superstring theory,
156; tidal forces, 57; vacuum, diving
into, 127. *See also* rotations in space
and time
spacetime curvature, 40, 41–42, 47,
170–171
spacetime geometry, 40, 41–42, 42n
special relativity: effect on Earth-
Moon system, 187n4; glight polar-
ization, 66n; introduction, 7; rotations
in space and time, 24, 25, 27; spacetime
geometry, 42n. *See also* Lorentz
transformations; Minkowski
spacetime

- speed of light, universality of, 14–18;
 precision of, 16n
sphere, 95n
spin, 148–151
square root structure of massive
 gravity, 166–167
standard candles, 115
straight line, 45–47, 46, 53–54, 54n, 55;
 in a curved spacetime, 42–47, 44–45n,
 46. *See also* free fall; geodesic
string theory, 155
STS-61 mission, 81
Stückelberg, 177
Sun, 47, 51, 68, 68n, 96–97
supergravity, 155
supernova, 82, 96, 115, 116, 119
Supernova Cosmology Project, 116, 119
supernova luminosity, 115
superstring theory, 156, 189
supersymmetric large extra dimensions
 (SLED), 157, 158
Syene, 44, 44–45n
symmetry breaking, 145–146

tachyonic instability, 152n
Taylor, Joseph, 68. *See also* Hulse–
 Taylor binary system
technical naturalness, 178
theoretical physics, 42, 50, 56, 58, 88, 101,
 104, 107, 109, 145, 157, 165, 174–178, 204.
 See also Imperial College London,
 theoretical physics group
Thiele, Gerhard, 84
Thomson, Sir George Paget, 191–192
Thomson, Sir Joseph John, 133, 191
tidal forces, 56–60. *See also* quadrupole
time, 1, 7; perception of, 25, 41–42
time-translation invariance, 121–122
Tolley, Andrew, 158, 159, 166–167. *See
 also* de Rham, Claudia; dRGT

Turok, Neil, 157
two-body problem, 57–60, 59n2
two-body system, 57–58, 59–60, 59n2
type IA supernovae, 115

unitarity, breaking of, 191
universality of gravity, 13, 27–32
universal language: equivalence
 principle, 31n, 32–33, 32n; gravity,
 universality of, 27–32; introduction,
 11–14; Michelson and Morley’s
 failed experiment, 18–28, 19, 21;
 rotations in space and time, 24–27,
 26n; speed of light, universality of,
 14–18, 16n
universal speed limit, 27
Universe, 102–105, 111–115, 141, 156–157;
 accelerated expansion of, 115–120;
 age of, 102; companion, 13, 35, 205;
 in continuous expansion of, 111–115;
 energy density of, 117
University of Cambridge, 35, 58
University of Geneva, 164
University of Western Reserve, 18.
 See also Case Western Reserve
 University

vacuum: definition of, 16
vacuum energy, 133; graviton, 139,
 141–143; effect of vacuum energy,
 179; effect of vacuum energy in
 massive gravity, 142, 144, 147
Vainshtein, Arkady, 186
vielbein, 177
Virgo European Gravitational Wave
 Observatory, 23–24, 73–75, 100,
 180–184, 182, 196–197
Virgo Supercluster, 113
virtual particles, 128–131, 135
Vulcan, 88

- W and Z bosons, 130, 144–145, 146, 149; mass of, 146. *See also* Higgs mechanism; symmetry breaking; weak nuclear force
- Waterloo, Canada, 35. *See also* Perimeter Institute for Theoretical Physics
- wavelengths: gravitational waves, 70–71; gravitational wave signal, 182; interferometers, 196; light, 14–15; particle with no mass, 117–118; thermal black-body spectrum of radiation, 67; waves and particles, duality between, 94
- wave–particle duality, 192, 193–194
- weak nuclear force, 144–145, 149
- weightlessness, 2–3, 13, 36–37, 49, 53, 84–85
- Weinberg, Steven, 143, 145, 157
- Witten, Edward, 156
- W. M. Keck Observatory, 99, 99n
- Women in physics, 59n, 99, 108–110, 154
- wormholes, 77
- Zel'dovich, Yakov, 134