INTRODUCTION

A revolution in science began in 1905 when Albert Einstein published two papers on relativity and one on quantum theory. For the latter, he built upon a paper published in 1900 by Max Planck suggesting that energy can be thought of as produced in discrete miniscule bundles. In *The Many Voices of Modern Physics*, we trace the key discoveries of physics and astrophysics from then to now. Unlike Newtonian physics, this new physics often departs wildly from common sense, a radical divorce that presents a unique communicative challenge to physicists when writing for other physicists or for the general public, and to journalists and popular science writers as well.

Our focus is not on the history of modern physics, but on its communication. We are not historians like Peter Galison, telling the story of the bubble chamber.[1] Nor are we sociologists like Andrew Pickering, delving deeply into the social construction of quarks,[2] or philosophers like Thomas Kuhn, revealing the structure of scientific revolutions.[3] In our two long careers, we have explored how scientists communicate with each other and with the general public. That is our main concern here.

Our book is a tribute to the written communication practices of the physicists who convinced their peers and the general public that the universe is a place far more complex, far more bizarre, and far more interesting than their nineteenth-century predecessors ever could have imagined. In our survey of the communicative practices concerning modern physics, we move from peak to peak of scientific achievement. By means of extensive and frequent quotation, our persistent focus is how physicists use the communicative tools available—words, equations, graphs, diagrams, photographs, and thought experiments—to convince others that what they say is not only true but significant, that it *must* be incorporated into the body of scientific and general knowledge. We especially favor the many celebrated physicists, including Einstein, who have devoted considerable time and ingenuity to communicating their discoveries and those of others not only to the physics community but also science enthusiasts in general. We also make use of extracts by others: science journalists in particular, but also philosophers, sociologists, historians, even an opera composer and a patent lawyer. Each chapter is thus a chorus of voices, including ours, of course.

While our polyphonic approach is distinctive, we are not breaking new ground. We have models we hope to imitate and improve upon. First, there is Rom Harré, whose *Great Experiments: Twenty Experiments That Changed Our View of the World* is still in print after four decades.[4] Its contents stretch from Aristotle on chick embryos to Albert Michelson and Edward Morley on the nature of light and Otto Stern on molecular beams. Strategically interspersed within his chapters are passages from relevant scientific texts and images published over the last millennium. Harré divides his twenty experiments into three unequal groupings: those illustrating different aspects of experiment, its importance in theory development, and its use in technique development. We find Harré's exposition exemplary; his choices, admirable; and his range, too broad for such short a book. Readers are left with no clear impression of change over time. Nevertheless, his is a feast for any science enthusiast.

There is also Alan Lightman's *The Discoveries: Great Breakthroughs in 20th-Century Science*, which covers such important twentieth-century milestones as Alexander Fleming's discovery of penicillin and Niels Bohr's theory of the atom.[5] For each milestone, after an introductory essay, Lightman reproduces the entire relevant scientific article when reasonably short and a large proportion when not. But Lightman jumps in chronological order from one discipline to another without any other connecting threads. As a result, Max Planck's 1900 paper on the quantum is jarringly followed by the 1902 paper by William Bayliss and Ernest Starling on hormones. Moreover, while his introductory essays are exemplary, they can be of marginal use in understanding the scientific papers that follow. These comments aside, the book should be on every science enthusiast's reading list.

Finally, there is Laura Garwin and Tim Lincoln's *A Century of Nature: Twenty-One Discoveries That Changed Science and the World*, which covers significant discoveries that appeared in *Nature* magazine, such as seafloor spreading and DNA sequencing.[6] For each, Garwin and Lincoln reproduce an article in its entirety. They also preface each article with an essay by a world-leading expert in the subject matter. Unfortunately, the *Nature* papers reproduced are for the most part impenetrable to all but those with specialized knowledge. Although T. H. Maimon's paper on his discovery of the laser is preceded by an informative introduction by Nobel Prize winner Charles H. Townes, for instance, Townes gives the reader little help in understanding the paper itself. This defect is general. Still, the introductions are illuminating and much can be learned from them about discoveries that changed science and the world.

In writing *The Many Voices of Modern Physics*, we set out to exploit to our own ends what we learned from these three books' experiments in exposition. For ease of comprehension, we quote passages of varying lengths from technical and popular accounts that are either self-explanatory, or that we are careful to try to explain. We readers are blessed in that many celebrated physicists have devoted considerable time and ingenuity to communicating their discoveries to science enthusiasts in general. In each chapter, we quote from popular accounts by these physicists liberally, and sometimes at length. But also quoted are scientific papers, journalistic accounts, history of physics books and articles, press releases, letters, memoirs, declassified technical documents, a patent application, and even Senate committee testimonies. For thematic consistency, we employ these texts as exemplary illustrations of the use of words and pictures in communicating physics to diverse audiences. For narrative consistency, we place our choices in a limited historical framework: highlights in physics and astrophysics from 1900 to the present, with a few detours into earlier centuries. Our emphasis throughout is the verbal and visual communications related to not only the theories of modern physics—a dominant topic in popular science books in general—but also the discovery machines and novel materials with strange and remarkable properties.

In the course of the time span covered in this book, written communications in physics have radically transformed the picture of the world around us. Those on relativity theory revised the definitions of time, space, mass, energy, and gravity. Those on quantum mechanics revealed an incommensurability between the nature of the hidden microworld and the visible macroworld. Those on grand unification theories and modern cosmology radically reshaped and are still reshaping our understanding of the origin of matter and the picture of the universe we inhabit. Those on materials of science like semiconductors and superconductors changed the meaning of what a thing is and can do.

Key Written Communication Practices

In communicating this new science-based picture of the world, physicists and science writers frequently rely upon analogy. Classical rhetoric defines *analogy* as a linguistic structure constructed from pairs, where meaning emerges from the interactions between their similarities and contrasts. As one example, Aristotle offers "the cup is related to Dionysus as the shield to Ares," where a cup used for alcohol consumption is linked with the Greek god of unrestrained consumption, and a shield used in battle is linked with the Greek god of war and valor.[7] This analogy hinges on the similarity of two common man-made implements, the similarity of two Greek gods, and the contrast between the lack of impulse control of one god and the military discipline of the other god. Aristotle's second example is "old age is to life as evening is to day," where the similar pairs are old age/evening and life/day and the contrasting pairs are old age/life and evening/day. For this example, Aristotle shows how one can combine the third and second elements to give "the evening of life," a metaphor for the first element, "old age." These analogical elements can also be combined into a simile, "old age is like the evening of life." In *The New Rhetoric* Chaïm Perelman and Lucie Olbrechts-Tyteca define analogy in a mathematical way consistent with Aristotle: "As a resemblance of structures, the most general formulation of which is: A is to B as C is to D. This conception of analogy is in line with a very ancient tradition."[8]

Perelman and Olbrechts-Tyteca give analogy a lofty place as a rhetorical device: "No one will deny the importance of analogy in the workings of the intellect."[9] Moreover, they add that "analogies are important in invention and argumentation fundamentally because they facilitate the development and extension of thought."[10] In a book on Perelman commenting on *The New Rhetoric*, Alan Gross and Ray Dearin offer a precise explanation of a possible argumentative function of analogy: "To create, strengthen, or intensify the adherence of minds to a persuasive thesis."[11]

The importance of analogy to scientific discourse and argument has long been recognized.[12] Such analogies are often expressed as a comparison between the abstract world of science and the world the reader is assumed to know through experience or common knowledge. As Marcello Pera notes in *The Discourses of Science*,[13] for example, running throughout Charles Darwin's *Origin of Species* are analogies in support of an argument for natural selection as the ruling mechanism behind biological evolution. One such potent example is natural selection is to all organic beings in the wild as artificial selection is to domesticated animals and plants. And when Lise Meitner and Otto Frisch discovered nuclear fission and reported it in *Nature* magazine, they analogized uranium bombarded with neutrons as comparable to an unstable liquid drop that divides into two.[14]

Analogy has tremendous communicative utility because it can transform the abstractions of science into more easily comprehended language. Even certain equations of physics can be thought of as having an analogy-like flavor on occasion, comparing mathematical operations with physical processes. To give a fairly simple example, the equation $E = mc^2$ is analogous to the statement that energy is interchangeable with mass.

Of special import to the physics literature is another analogy-like linguistic construction, the thought experiment, a fiction that has the unusual property of telling us something significant about the real world. Philosophers continue to make a living disagreeing about what one is. Typically, thought experiments involve the author setting up some imaginary scenario with an analogy to the real world, letting it run its course before the readers' eyes—consistent with laws of science—and drawing some conclusions about it.[15] These have been a way of science at least since the days of Galileo.[16] In a break with the past, an escape from Aristotle's long shadow, for example, Galileo created a thought experiment. Aristotle believed heavy bodies fall faster than lighter ones; that they must do so is a clear dictate of common sense. So let's think—just think—about a cannon ball tied to a musket ball and dropped from the Leaning Tower of Pisa. This combination must fall faster than the cannon ball alone because it is heavier, right? On the other hand, it must also fall slower because the attached musket ball must impede its downward movement, right? Aristotle's view cannot be correct if it leads to a contradiction. QED: regardless of weight, all objects must fall at the same speed. This "experiment" is notable because Galileo could not have performed it with any precision using real cannon and musket balls dropped from a real leaning tower. Just try.

Thought experiments are a notable exception to the rule that scientific theories must be tested against the world. At the start of the twentieth century, faced with understanding and explaining the bizarre behavior of moving objects in a relativistic world, Einstein repeatedly turned to thought experiments. The same was true for the quantum physicists confronted with the even more bizarre behavior of motion in the microworld.

Another central communicative device in popular science books, just as in scientific articles, is visual representation, which also can have an analogy-like foundation, comparing a diagram or schematic with some aspect of the real or a theoretical world. Actual scientific visuals have not been much discussed in the literature on rhetoric. The ancient Greek rhetorician Longinus did write that "weight, grandeur, and urgency in writing are very largely produced . . . by the use of 'visualizations' (phantasiai). That at least is what I call them; others call

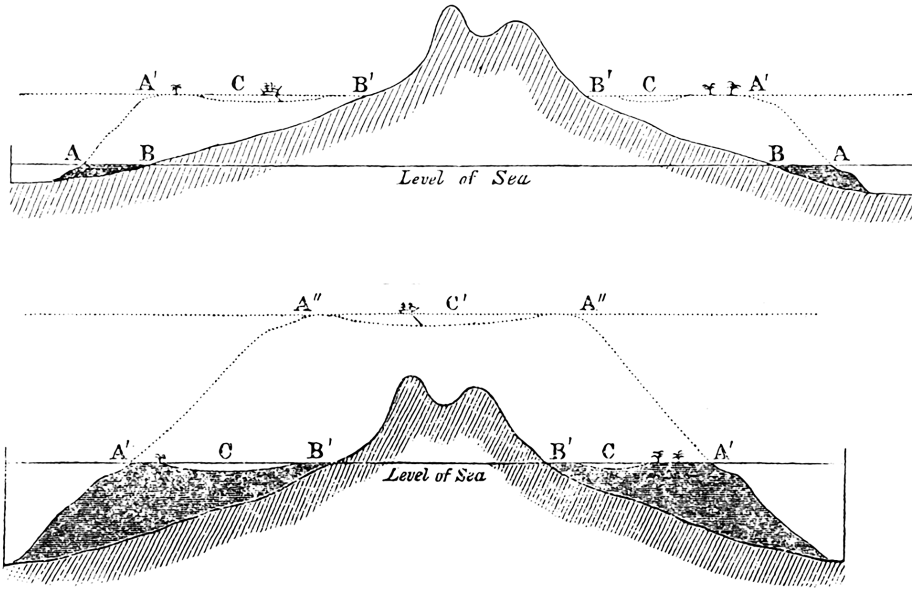

Figure I.1. Illustration of Darwin's theory of the evolution of an atoll from volcanic island with fringing coral reef. From Charles Darwin, *Structure and Distribution of Coral Reefs* (1842). Images on separate pages (98 and 100) combined into one here.

them 'image productions.'"[17] But of course, Longinus was referring to verbal "image productions" that vividly evoke some scene before the eyes of an audience.

As we mention in *Science from Sight to Insight*,[18] pictures are an integral part of scientific communications, where meaning typically emerges from the interactions between the words in the text and the pictures integrated therein. As an example from evolutionary theory, in *Science from Sight to Insight*, we chose to analyze a pair of visuals from Charles Darwin's 1842 *The Structure and Distribution of Coral Reefs* (figure I.1), a monograph meant to be understandable by any reasonably well-informed amateur naturalist. These two diagrams visually represent Darwin's theory that volcanic islands subside into the sea over many millions of years until all that remains is an atoll, a circular reef with lagoon inside. In the top image, we see the geology of a volcanic island in the distant past as the sea level rises from the solid horizontal line (A-A) to the dotted one (A′- A′). Important to note is that a barrier reef spreads out from the volcano (below A′- B′). In the bottom image, fast forward many millions of years later, we see the volcano having subsided completely, and the barrier reef having swollen to become an atoll enclosing a lagoon with ship anchored in the middle where the island once stood (see C′ near the dotted line at the top of the image).

In *Science from Sight to Insight*, one of our visual examples from physics comes from Galileo's *Two World Systems*, as part of his argument that the apparent retrograde motion of Jupiter (forward, then backward, then forward again) in the night sky is an illusion that can be explained geometrically if the planet circles the sun.[19] This masterful diagram can be viewed as Galileo's visual analogy for the illusion of planetary retrograde motion. It shows a complicated arrangement of lines and circles bearing little physical resemblance at all to Jupiter in its orbit. Yet, if we scan the lines from right to left in the way Galileo guides us in his verbal text, we can mentally reconstruct the orbit of Jupiter as it deceptively appears from Earth to reverse directions twice, even though it is doing nothing of the kind. According to Galileo, along with the other evidence he presents, that "ought to be enough to gain ascent for the . . . [Copernican] doctrine from anyone who is neither stubborn not unteachable."[20]

It is important to caution that while thought experiments, analogies, and visuals have many positive attributes, there are limitations as well. As pointed out by John Norton, thought experiments can dupe readers into drawing flawed "conclusions about fundamental matters from bizarre imaginings."[21] And as mentioned by Gross and Dearin, analogies "are important but precarious techniques of argument."[22] Those questioning an analogy can simply claim that it is either wrong-headed or too vague, while the author may claim that it is no more than a metaphor. The result is that the analogy is caught between the "disavowal by its opponents and disavowal by its supporters."[23]

Analogies also have their limits in another sense. There is never a one-to-one correspondence between things of the everyday and some physics abstraction. There are always differences, and those differences can outweigh the similarities to the point of distortion. The commonplace analogy between the workings of our solar system and the atom is one of the more obvious examples. This meme-like analogy is certainly poetic and seductive and still very much alive today in popular science writing and on the internet. The spoiler is that quantum mechanics tells us electrons definitely do not orbit the nucleus like planets, but in accord with probabilistic instead of deterministic laws. Visual representations of the atom as a miniscule solar system (figure I.2) further spreads the false impression for the unwary.

An often overlooked but enormously important communicative device in combatting false impressions in science is use of qualifications and hedging language—that is, words like *maybe*, *probably*, *perhaps*, and so on.[24] By this means, scientists and science writers can separate already established science ("this is so") from the frontier of science ("this may be so, but only time will tell"). When writers leave out or misuse qualifications and hedges, they can confer far

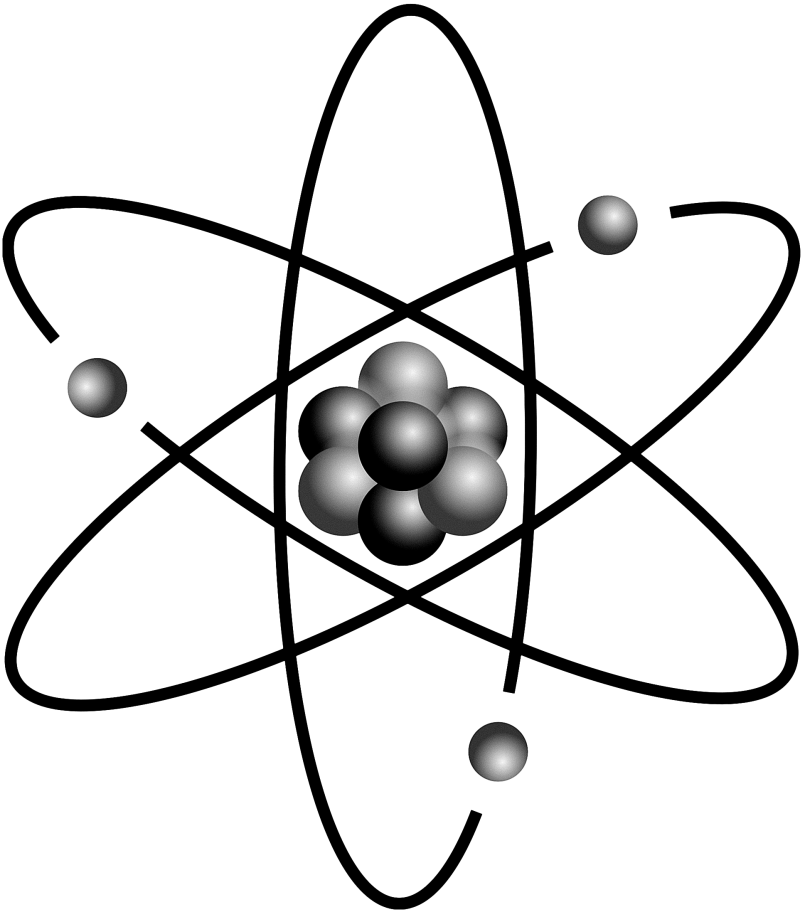

Figure I.2. Visual representing an atom as similar to miniature solar system.

greater certainty than the situation warrants. Studies have found, for example, that journalistic writing tends to shape the narrative as a race with clear winners and losers, redacting qualifications and hedges.[25] Even when hedges are handled with care, some readers can easily be persuaded by the authority of the voices of distinguished scientists. After all, who are we readers to doubt them on matters of science, whatever the hedging? But as we will address in several chapters, the spectacularly successful strange theories of the past like relativity and quantum mechanics do not by any means guarantee current ones will hold water, no matter how seductive or convincing the analogies, visuals, or thought experiments.

Communicating science also requires the act of definition, carefully tuned to a particular audience. A term like *Standard Model* requires no definition in a physics journal, but for any popular exposition, it does demand some level of definition, even though it is one of the monumental achievements of twentieth-century physics. One might describe it for readers with firm knowledge of elementary physics as "a field theory of all matter in which the nongravitational forces arise by exchange of a force particle with substance particles." But others less well versed would understandably want to know: What is a field theory? What are the nongravitational forces? What are force and substance particles? Luckily for those interested in the Standard Model, popular science writers have employed various inventive communicative strategies to more fully explicate what the Standard Model is. For example, in *Knocking on Heaven's Door*, physicist Lisa Randall gives much greater insight into the meaning of Standard Model by systematically arranging all the force and substance particles along with the nongravitational forces in a periodic-table-like table.[26] (We have more to say about that table in chapter 4.)

As rhetoricians Perelman and Olbrechts-Tyteca maintain,[27] definition can also be an element in argumentation of all kinds. For example, Einstein's argument for the validity of his new definition of *simultaneity* is central to his classic 1905 paper on special relativity.[28] And in his popular science book *A Brief History of Time*, Stephen Hawking first defines *black holes*, then pictures them, then expounds upon the strong evidence for their existence at that time, despite no one having yet observed one directly.[29]

We find it convenient to lump the majority of written scientific communications into two broad genres: (1) specialized scientific articles and books and (2) popular science ones. The purpose of the former is the communication of claims to new knowledge aimed at an audience of experts for their evaluation and possible use. Stylistically, authors of such communications heavily rely on a vast specialized terminology, which improves communicative efficacy at the expense of intelligibility. In fact, it is not hard to find passages in which everyday English words are banished, with the exception of verbs and connecting words like *prior to* and *because*. In such passages, most of the nouns and their modifiers are of a highly technical nature; even everyday words are enlisted in the service of science, words such as *force* and *particle*. Three other prominent contributors to cognitive and semantic complexity here are quantifications, abbreviations, and noun strings. The first confronts the reader with a sea of numbers; the other two make an already information-rich text even more compact.[30]

The language of physics in journal articles and technical books is not just words—it also is the language of mathematics. The common symbolism physicists now employ was invented in the seventeenth century. Gottfried Leibniz was the chief architect: "Among Leibniz' symbols which at the present time enjoy universal, or well-nigh universal, recognition and wide adoption are [in the calculus] his *dx*, *dy* [for differentials], his sign of integration, his colon for division, his dot for multiplication, his geometric signs for similar and congruence, his use of the Recordian sign of equality when writing proportions, his double-suffix notation for determinants."[31] Today, specialized communications on physics theory are typically a steady mathematical stream, equation after equation with connecting text moving toward a climax, a solution to a problem established in the introduction. They typically conclude with an argument for the theory's validity by comparison, a deceptively simple analogy-like communicative strategy. This comparison typically involves comparing predictions from the theory with experimental measurements or calculations by a different theory.[32]

The focus of most of our book, popular science books and articles in physics, constitutes a different genre for a different audience, with few if any equations and far more limited number of technical terms. We use the word *popular* as a catchall to encompass almost any communication on physics aimed at an audience beyond the very narrow one for specialized journal articles. The purpose of popular expositions is to spread the word to this audience about the most newsworthy discoveries of science, whether or not they have reached the stage of accepted knowledge. Here, the prominent communicative tools include analogy, thought experiment, visual representation of theory, hedging, and definition of technical terms. Also, unlike scientific articles, popular physics expositions are not striving for approval of new discoveries from a jury of peers, who would expect mathematics and data and a heavy dose of technical language. Nevertheless, they do seek to convince the science-interested public that the seemingly implausible physics described therein is not pie in the sky. The default position is that at least some popular science readers are highly skeptical about the claims being made, even ones long accepted ones by the scientific community, like the warping of space and relativity of time in physics, and that those doubts need to be assuaged by means more than just quantitative comparison of theory and experiment. That is where persuasive communicative devices like analogy, thought experiment, and visual representation come to the fore.

We organized the first part of this book around communications related to the main theoretical achievements in modern physics, with separate chapters on relativity theory, quantum mechanics, unification theories on the road to a "theory of everything," and various cosmological theories for the origin and evolution of the universe. Then, turning away from bold theories that repeatedly defy our perceptions of the world around us—the topic dominating most popular physics books—the later chapters treat communications on physics-based technologies and materials that have significantly affected nearly everyone's life or may do so in the future. Throughout, our emphasis is not the theories or technologies and materials per se or their historical context, but their communication with the tools outlined above, plus others that we will introduce later. In the end, we do not tell *the* story of physics starting in the early twentieth century, but *a* story—one told partly through the words and pictures of the discoverers as well as other physicists and science writers.

Our hope is that our story will be read by physicists, who do not usually think of themselves as the master communicators they can be, by communications scholars interested professionally in the doings of these master communicators, and by scholars in science studies. Our book might also be of interest to anyone curious about a developing science-based view of the universe that persistently defies common sense. While we will not pretend that our book is beach reading, our intent is that readers with little or no education in physics will not find this a handicap so long as they are willing to expend some effort in return for understanding some of the greatest intellectual achievements in science.