



From Atoms to Higgs Boson

Voyages in Quasi-Spacetime

Chary Rangacharyulu
Christopher Polachic



The background of the slide is a complex, monochromatic collage of geometric and organic patterns. It features a large, dark, fan-like structure in the upper left, composed of many fine, radiating lines. To the right and in the lower half, there are various circular and spherical patterns, some resembling woven baskets or complex molecular structures, and others that look like stylized flowers or sunbursts. The overall effect is one of intricate, layered geometry.

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*This book is dedicated
to those men and women,
in all times, young in heart and soul,
who devote themselves to fathom
the submicroscopic world
and unravel its mysteries.*

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Preface

This book has taken a few years of careful thinking, from start to finish, although its roots go back much further than that. It has grown out of the reality of how we teach and learn physics in higher education.

Every physics professor, especially a young one, faces the challenges of being an active, productive researcher in knowledge creation and an educator in knowledge transmission to the next generation. They return each semester to the challenge of presenting their undergraduate students with the set of standard topics prescribed in their syllabi and chosen textbooks. The flow of topics must cleave to an orthodoxy and reach its conclusion within the strict deadlines of the academic calendar.

The students also face their own demands in terms of time management and finding space in their brains to accommodate a growing knowledge of physics alongside information from many other, different courses. They, too, have their deadlines as they struggle to complete labs and assignments on time and adequately prepare themselves for graduate work or a successful career.

For both parties, success in these time-sensitive obligations requires a commitment to pragmatism. Although many undergraduate students would probably embrace the opportunity to contemplate the deeper philosophical aspects of physics and the structure of nature with their professors, the latter do not have the luxury of time or preparation to guide students in confronting some of the most interesting questions of this kind. The exception to this would be, perhaps, a more rigorous examination of the mathematical formalism and empirical evidence pertaining to their standard curricular topics, but these discussions do not necessarily probe the implicit mathematical and physical assumptions and philosophical scaffolding in sufficient detail.

Textbooks offer little help in this regard. They present the subject material as well-established facts suggesting that students (and instructors) who fail to unhesitatingly accept the subject matter

should doubt their own intelligence. The textbook presentations thus encourage a perspective that physics has developed its orthodoxy along the lines of historical inevitability: If Einstein had not devised his special theory of relativity, including its metaphysical commitments, it was only a matter of time before someone else arrived at precisely the same conclusions and nuances. It must be so because all the content of our syllabus describes nature as it is, chapter and verse, takes note of it, and writes it down.

In this pedagogical tradition, it is not uncommon that a professor enthusiastically asserts, without reference to the awkward contextual background information, that in their state of special genius the founding fathers of modern physics (especially Einstein and Bohr) brought forth revolutionary ideas as mere postulates. The more counterintuitive the revolution, the better, because this enhances the mystery of the professional physicist as a gatekeeper and inheritor of a spark of this genius. This is quite frustrating to a student when a professor is pontificating on the self-evident truths of particle-wave duality, four-dimensional spacetime, or various other mathematical constructs inaccessible to direct experimental verification. Even if a professor has time for contemplation of these matters and how they might be best introduced and justified to students (which is very doubtful), years of devotion is required to weed through the vast amounts of not-so-easy-to-access literature of the nineteenth and early twentieth centuries (much of it in German) and assess all the false starts, varying views, doubts, or limits of usefulness of theoretical arguments expressed by the proponents of these “revolutionary concepts,” prior to their ultimate acceptance as dogma. Thus, despite the best intentions of any physics professor, it is difficult to teach a subject as profound as modern physics while also understanding—let alone communicating to students—the real, historical, contextual limitations of our supposed knowledge of physical reality.

The authors of this book have traveled this voyage, this quest for the knowledge of physical reality, together for some years: first as a professor–student collaboration and later as two researchers and educators (one old and one young professor), working together with the same common interest. Both of us believe that we are not here to hand the knowledge of true physics down as established facts to aspiring young minds, but to engage these minds, insofar as this is

possible within a tight university curriculum setting. This book is the product of an ongoing search comprising nearly 50 man-years between the two of us.

Over this time, we have seen that physics, as a subject of academic inquiry, has two faces. First, it is application oriented: The discipline has ever been, and continues to be, an enterprise that yields extraordinary results in utilitarian, technological innovation resulting in human flourishing. Second, physics sets itself to uncover and unravel the conceptual foundations of the dynamics of our physical universe, motivated by the innate curiosity of our species to simply understand what is true and real.

In the first aspect of our discipline, operational definitions, effectively expressed in mathematical symbols, are quite useful without necessarily being grounded in physical reality. Unfortunately, these operational definitions and their associated mathematical formalism are also indiscriminately applied to the second task, relating to conceptual foundations. At this point, an assumption can often be made, out of habit, to ascribe to every detail of our useful formalism a correspondence to some element of physical reality. This may be justified during an initial stage in creating our mathematical models. However, as the usefulness of the models increases for the purpose of “solving” complex problems and thus advancing our goal of application, so also do the mathematical elements of the model tend to drift far away from what we originally understood them to represent.

To this state of affairs, we have given the name *quasirealism*, based on the *quasiparticle* approach of solving otherwise intractable problems, which was first employed in the field of condensed matter physics and then extended to nuclear physics and, ultimately, to the realm of theoretical particle physics. The following pages are our attempt to ask some healthy questions about the quasirealist philosophy in modern physics, through various illustrations and perhaps not a few bold—even controversial—postulates of our own. We do not pretend, however, that they are the work of genius, just honest concern. And we will let the readers decide for themselves. If nothing else, may the reading of these questions and ideas provide as much stimulation and enjoyment as we have had working them out.

As co-authors we both share the desire to thank our families for their cheerfulness during the process of drafting this manuscript. They have patiently supported us in many ways and accompanied us both physically and emotionally through the long stages of writing.

During the course of our careers in physics, we have worked with and encountered various types of physicists. Some of them are dedicated to probing the depths of the physical mysteries they encounter in their work. Others are techno-savvy, motivated by the challenge of working with hardware, software, and analytical methods. Still others are tactful managers who get things done. We have also seen eager young minds come to our offices with hopes to become the next Einstein; and non-science majors, having heard rumors that reality is stranger than fiction, arrive with a willingness to trust any claims we make about the bizarre and spooky world of relativity, quantum theory, and the subatomic world. We have had many fruitful discussions on physics with all these kinds of colleagues. The SPIE San Diego series of conferences on “The Nature of Light: What Are Photons?” also kept us focused on this subject for more than 14 years. We thank Professor Chandrasekhar Roychoudhuri for engaging the first author in this series.

We are very thankful to Kaylyn Olshanoski who created several important figures for this book. Also her constructive feedback from the perspective of an engineering physics undergraduate student was quite helpful. Thank you to Kiyoko Kato, as well, for the exceptional image used in our cover design. It visually captures the intricacy and beauty of our subject matter and is worth glancing back at every-so-often as you peruse the book.

We are particularly grateful to our publisher, Stanford Chong, for suggesting that a book of this kind is desired and waiting patiently for it to be finally produced with extended deadlines. We also thank Jenny Rompas and Shivani Sharma of Jenny Stanford Publishing for their indispensable assistance in formatting and proofing our text and providing helpful guidance as we worked through the process of publication.

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Introduction

The French don't care what they do, actually, as long as they pronounce it properly.

—Professor Henry Higgins
My Fair Lady (1964)

Our task is to learn to use these words correctly—that is, unambiguously and consistently.

—Niels Bohr¹

Physics had its beginnings in the work of ancient natural philosophers. These experts esteemed the power of human reason, alone, as the chief means to discern truths about the fundamental structure and operations of nature—in a sense, through careful attention to the pronunciation of ideas and the correct and consistent use of words referring to features of the physical world, whether visible or invisible. In modern times, physics has assumed a role that is somewhat different from these beginnings. It is hailed as the most fundamental, rigorous, and hardcore of the sciences. Its practitioners are ultimately recognized for excellence in technological innovation and unrelenting progress in taming the secrets of the physical universe through objective experimental methods. At the heart of every technological innovation—whether computers, health instrumentation, agricultural technology, energy production, communications, or any of the myriad other possible categories—physics models are operational. It is inarguably impressive that physicists, using mathematical modeling based on a few basic conservation laws and associated symmetries, have been able to probe the interiors of the minutest of minute entities and to

¹As quoted by Jørgen Kalckar, “Niels Bohr and his youngest disciples,” Ed. S. Rozental, *Niels Bohr—His Life and Work as Seen by His Friends and Colleagues* (John Wiley: New York, 1967), 227–238.

realize applications that were hardly imaginable just a few decades ago. Seen in this light, the most obvious success of the discipline of physics cannot be measured by words pronounced and used correctly (as Professors Higgins and Bohr suggest), but by tangible achievements in the form of new technology.

The practice of physics involves an extensive study of complex systems composed of denumerably infinite degrees of freedom. Physicists reduce these unwieldy systems to computationally tractable equivalents. Inevitably, over the long history of this activity, physicists have taken the liberty to develop their own vocabulary, often derived from our day-to-day language rooted in common-sense perceptions, and from that of cognate disciplines. Physicists tend to communicate among themselves using familiar words and phrases endowed with novel meanings and significance, referring to abstract elements of the effective² theories they use to describe these complex systems. There are even differences in how the same term is used from one sub-discipline of physics to another. For example, in condensed matter physics, which focuses on the science of solid and liquid materials, an “electron” is not necessarily the same entity whose nominal mass we find in the data tables used by particle physicists, nor the one we refer to when we teach undergraduate physics courses. For plasma physicists, a “photon” is not always something that has zero mass, traveling at the constant speed of light, as it does for other physicists.

These discrepancies in vocabulary arise because of a tendency to retain the original labels when physicists develop and employ effective models of physical reality. These models are powerful and

²The word *effective* is an example of this very point. Common usage of this term implies the notion of “appropriateness” and “accomplishing the intended result.” Thus, an *effective theory* might be understood outside of physical science circles to mean a scientific theory that appropriately captures the real physical attributes of a natural system: It is *effective* in doing what it is supposed to do. To the physicist, however, *effective* most often denotes a technical simplification that replaces real parameters of a tremendously complicated system with statistical averages or abstract substitutions. These retain important similarities to the physical system of interest but no longer provide direct information about the physical world. To a physicist, then, an *effective theory* allows progress to be made in finding *some* solution to a problem, if not the one we really desire. The theory must be carefully interpreted to discern what information this progress yields about the original physical system of interest. Effective theories and models are, of course, common in other disciplines as well, such as economics.

useful in large part because they can retain a logical connection back to the original physical concepts, but the connection must be carefully followed, like a trail of breadcrumbs leading one back through a tangled forest. It is thus natural to re-use familiar words for the new, effective entities or concepts. However, taken too literally, this re-use of common labels may lead to surprising results. In the leading effective model of superconductivity, two interacting “electron” partners, called a *Cooper pair*, are not located at any particular position in a superconducting medium but are present throughout the material at any given time. Physicists can mathematically define lasers as negative temperature devices (below zero Kelvin). They can define entities in their experiments that behave like material *particles* having negative mass, which accelerate in a direction opposite to an applied force.

Properly understood, none of these is a deliberate equivocation or misuse of terminology, so long as we recall the essential deviation we have taken from reality when we devise a solvable effective theory. Without that care, however, the conceptual consequences that arise may be the source of endless astonishment among non-specialists, providing fodder for exciting headlines in popular science news reporting. Negative mass! Faster-than-light speeds! Curved spacetime! Rather than viewing these novelties with consternation, the public trusts that the details they glean, leaking out of physicists’ effective models, must be referring to something fundamentally real in our physical world: a revelation that would be otherwise inaccessible to humanity, if not for the inspired proclamations of the scientific magisterium. This trust should not be dismissed as naïve: The greatest *apologia* for modern physics is technological application. Technology talks.

Physics has a broad scope. This is, in fact, an outrageous understatement. Over the centuries, the discipline has addressed questions about the physical universe at astronomical scales as well the tiniest entities comprising the heart of matter and has offered descriptions of how nature operates in the present as well as what its properties and rules were at the beginning of the universe. Physicists have even weighed in as eschatologists, employing current models to speculate on the future evolution and ultimate end of the cosmos. The inclination to apply physical theories to a description of the universe as a whole was, in an earlier time in the Christian and

Muslim West, a useful “handmaiden” to theological studies, confined to the investigations of *natural theology* in which sensory data from the Book of Nature could provide insight into interpretations of revealed knowledge from the Book of Scripture.

Over time, the study of the cosmos took on a life of its own in physics, disengaging from its theological context. It has now become an overarching narrative that motivates the entire industry of fundamental research. The unifying theme of this secular cosmology is no longer supernatural metaphysics, but the vision of physical reductionism. That is to say, if we can uncover the ultimate, basic building blocks of the universe (however tiny and practically inaccessible they may be) and determine how they interact with one another at all energies and at all distances (however close or far apart they are), then we can tame the universe within the mathematical prescription of some ultimate, all-encompassing model of physical reality in its entirety.

Fortunately for physicists, at least as a first approximation, energies and distances are not uncorrelated. It is understood that any useful probe of the most miniscule interior structures of matter will require experiments involving higher energies. In the first half of the twentieth century, physicists hurled electrons, protons, or neutrons onto protons in an attempt to study the interactions that occur between bits of matter at short distances. Surprisingly, as energies increased, hitherto unknown new entities made their appearance as transient bodies borne out of the explosive energies in these collisions. What was expected to be a simple measurement of two small bodies scattering off one another became a complex analysis of many bodies possessing new information about physical reality.

Undeterred by this development—indeed, emboldened by the opportunity to investigate “new physics”—physicists have marched on. The post-Second World War era saw the rise of particle physics as a distinct area of investigation, equipped with a generous kit of theoretical and experimental tools developed over many decades to probe the mysteries of the subatomic world. Particle physics now makes its own reductionist contribution to our knowledge of matter, and thus to a grand theory of the structure and history of the entire universe. Today, this toolkit takes the form of complicated, effective mathematical models and immense technological devices designed

to access the behavior of bits of matter at enormous energy scales. Through familiarity with these effective models, the language of particle physics has taken on a life of its own. The word “particle,” for example, and the concept of “mass” have subtly but profoundly diverged from the way these terms were understood only a century ago, and the way most people outside of the discipline—including other scientists—still think of them today.

This book is an effort to understand and humbly critique the accomplishments, logical rigor, and faithfulness to basic notions about physical reality that have accompanied the modern quest to unravel the physics of the universe. Of particular importance to our analysis—indeed, the central formal point behind this work—is the influence of effective models and theories on the way physicists think and talk about physical reality. This book is not meant to call into question any of the elegance, technical competence, or ingenious problem-solving that continues to define the outstanding work done by the international community of physicists who are investigating the world in which we live. We only hope to raise a serious concern about interpretation of results. It is a concern of metaphysics, really, and of ensuring that what the community of physicists says about our results to the listening world (and to ourselves and our students) is *true*, and not just *useful*. Mathematical models can be extraordinarily useful, without directly providing true knowledge about physical reality. This distinction is what we want our colleagues and those who are non-professionally interested in physics to consider more carefully.

The initial two chapters, together, define our larger concern with the metaphysical confusion just explained. The first chapter sets the stage with a discussion of reductionism as the driving motive of modern physics. In the second chapter, we devise and illustrate a new term: *quasirealism*. Quasirealism involves a failure to distinguish effective theoretical concepts from real, physical entities and properties. It is a term we use throughout the book. Any reader more comfortable with physics apart from philosophy may prefer to skim these chapters on first reading, becoming familiar with the main ideas, and return later on to fill in the details.

One can think of each subsequent chapter as offering a variation on the central theme that quasirealist assumptions dramatically affect the conclusions that physicists draw about the fundamental

nature of the world in which we live. Each of these chapters focuses on a different concept in the current of modern physics, and while they are ordered to build conceptually upon one another, they may be read in isolation and out of order without too much detriment to our overall point (we hope). The flow, however, begins with big ideas and moves toward specificity by the end of the book.

The earlier chapters of this book involve a discussion of mass, space, and time, concepts that form the background of all discussions in physics. For physicists, the meaning of these two words has changed dramatically in the past 200 years, and this is scarcely acknowledged except among the most careful treatments by philosophers and interested scientists. Already in the late nineteenth century it was realized that a thorough understanding of space and time, in which entities exist and interactions occur, is essential for a proper description of physical dynamics. In a formal sense, the study of material objects in space requires a background assumption of geometrical relations that were provided with great clarity and objective physical consistency by the Greek mathematician Euclid. Over nearly two millennia the quest to improve upon and advance beyond Euclidean geometrical postulates led to non-Euclidean geometries. Although not obviously related to the properties of our own spatial reality, these new geometries yielded important mathematical developments.³ It was only a matter of time before they were adopted into a serious physical framework: Einstein's theories of relativity.

This leads quickly and naturally to a discussion of mathematical spaces, such as Hilbert space and complex spaces, and we argue that physicists should take special care to avoid the confusion (both of themselves as well as their aspiring students and the general public) that may arise if conceptual, metaphysical rigor is lost in favor of mathematical gain. The influence of quasirealism cannot be discounted in all these conceptual maneuvers, and we attempt to raise important questions about this influence and how it leaves us impoverished.

We continue our discussion with a move to the smallest scales, examining the development of quantum theory and its connection to quasirealist interpretation. In that light, we explore the meaning of

³We hasten to add that the terms "geometry" and "space" are often erroneously used as synonyms.

elementary quanta, considered to be fundamental pieces of physical reality. This involves us with the classical concept of *atomicity*, which until recently⁴ centered on the notion of physical indivisibility. Our discussion explores how the modern concept of atomicity and the word *particle* have evolved with reference to the building blocks of ordinary matter and energy, identified by particle physicists as electrons, quarks, and photons. In the case of quarks, the question of interest is how much ontological reality to allow these apparent entities. To what extent can we consider them physically real when they are defined in our leading theories primarily as composite mathematical structures, built on deeper mathematical forms, only loosely related to anything tangible that one might observe in a well-designed experiment?

We separately discuss electrons and photons, raising the concern that quasirealist interpretations have confused our picture of these particles in the modern physics framework, taking us further away from the reductionist aims of physics. In the case of the electron, it was the first fundamental part of subatomic matter to be observed directly as a simple corpuscle, confirming Dalton's (and Democritus') atomic hypothesis. In that discussion we return to the topic of quantum theory to show, in the specific example of the electron, how quasirealist quantum mechanical interpretations served to confound physicists' thinking about the physical properties of this otherwise uncontroversial species of the subatomic world.

All of this necessitates some discussion of the quantum theory of fields, wherein photons have friends among the other gauge bosons, namely the W, Z, and gluons (besides the gravitons). We examine the role of these bosons in particle physics models, and the assignment of their properties as suggested by theory and constrained by experiment. The thinking behind this book was inspired by the announcement of the Higgs boson's discovery at CERN—a momentous event in the history of physics—and so it is natural that we devote an entire concluding chapter to this entity and the determination of its unique properties. After all, it has been delegated the angelic assignment of providing mass to all other bodies in the universe.

As already said, the reader should find that the central theme remains basically the same throughout the parts of this book,

⁴"Recently" with respect to the grand sweep of history, at least.

restated with different emphases: Quasirealist perspectives have clouded the noble reductionist vision of modern physics, and the conclusions we think we are reaching about physical reality—especially those derived from particle physics—may be moving us in the wrong direction from where we think we are going. Even if this concern is found to be misguided, we hope that the analysis we provide in the following pages will serve to generate conversation among the most important audience this book can reach: the next generation of aspiring physicists, studying in their discipline as undergraduate and graduate students, dreaming the same dreams as their illustrious predecessors that they might someday, soon, help to expand our shared knowledge of the underlying, real stuff that makes the world we live in what it is.