This is a book about big questions. What is time? What is light? How did quantum mechanics change our vision of the world? What are black holes and gravitational waves? How will our understanding of the physical laws change in the future? How will the universe itself end?

Vitor Cardoso (the author of this book) and I have known each other and worked together for about twenty years.[1] We are both first-generation college students from small, rural towns. How did we end up studying black holes for a living? For the same reason why any kid becomes a scientist: *curiosity*.

The 1970s are sometimes called the "Golden Age" of black hole physics. In those days Kip Thorne (a co-recipient of the 2017 Nobel Prize for the discovery of gravitational waves) was the youngest professor at the California Institute of Technology and he mentored a fantastic group of students. William Press, who would later became a scientific advisor for President Obama, was one of these students. During the Covid pandemic, Press wrote a memoir with a title that says it all: *"More than curious."* An insatiable curiosity is really all you need to get into science. As I often say to my friends, I consider myself lucky to actually *get paid* to think about these things.

There is usually one event that scientists recall as their "ha-ha" moment, the one that convinced them to take *that* particular fork in the road[2] and spend the rest of their life doing science. As it turns out, two popular books from the 1980s inspired both Vitor and me to become physicists. The first was Steven Weinberg's *"The first three minutes"*, a book on early Universe cosmology: how did everything begin? The second was Stephen Hawking's *"A brief history of time"*, a book about black holes: how does everything, including possibly even the laws of physics, come to an end? We both read these books in high school, and our path was set. Hopefully *this* book will do the same for you.

Adolescence is usually the age when you ask hard questions about yourself and your role in the world. Why am I here? Why did life develop at all? Why here on Earth and not elsewhere? What is the meaning of life? (If you don't find useful answers to this question in Vitor's book, I would recommend the Monty Python movie.) Why is the Earth, of all planets, so special? Why can we understand at least part of the universe and of its physical laws? How and why did it all begin? How will it all end? I remember spending many days reading popular science books (and lots of Stephen King horror stories, but I won't digress) at my family's apartment by the beach in Italy during our summer vacations.

Now, here is the catch. To get answers, you'd better be ready to study a lot of mathematics. So here is a warning: in this book you will find some equations (Vitor could not resist, despite his fear that he could end up making less money from the sales). As Galileo said in his book "Il Saggiatore",

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[1] We also lived together for a while, so I know all sorts of things about Vitor - from his prodigious ability at calculations to his love of baby food. Don't ask.

[2] One of the members of Vitor's thesis committee, Stanley Deser, called his adventurous autobiography *"Forks in the road"*. The title comes from one of the many illogical and funny mottos by baseball player Yogi Berra: *"When you come to a fork in the road, take it!"* In fact, Berra-isms became so popular that many of those attributed to Berra are apocryphal. As Berra himself put it: *"I never said most of the things I said."*

published 400 years ago: *"Philosophy is written in this great book that's continuously open right in front of our eyes (I mean the Universe), but it can't be understood unless you first learn the language and the characters in which it's written. It is written in the language of mathematics."*[3]

Why a logical construct of our human brains should be able to work so well at describing the Universe is a great mystery that fascinated Einstein himself: "*How can it be that mathematics, being after all a product of human thought which is independent of experience, is so admirably appropriate to the objects of reality? Is human reason, then, without experience, merely by taking thought, able to fathom the properties of real things?"*

Every time we have come across a new problem in physics, the answer turned out to be written in mathematical language. Sometimes we have to make up new branches of mathematics as we go, but the trick seems to work every single time. Why is that? We don't know. Eugene Wigner wrote a beautiful essay called *"The unreasonable effectiveness of mathematics"*[4] in which he makes this point very clear: *"The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve. [...] We are in a position similar to that of a man who was provided with a bunch of keys and who, having to open several doors in succession, always hit on the right key on the first or second trial. He became skeptical concerning the uniqueness of the coordination between keys and doors."*

The usefulness of mathematics in physics and in all of the natural sciences has no rational explanation. This mysterious power of mathematical concepts developed by the brains of our lowly species raises the question: why do our physical theories work at all? Would different civilizations evolved at different points in the universe, with different biological "brains", discover the same laws? In other words, are these physical theories unique? Is there a final theory?

It is not at all natural that "laws of nature" should exist in the first place, and much less that man is able to discover them. Furthermore, as every physicist knows, there are layers of "laws of nature." For example, as Vitor explains in this book, Newton's law of gravitation is perfectly adequate for most gravitating objects, but it turns out to be wrong at high velocities and for strong gravitational fields; Newton's classical mechanics becomes inaccurate for energies comparable to the Planck scale; and so on.

The modern viewpoint on these questions is beautifully illustrated in a book by Edwin Thompson Jaynes (who was a professor in Saint Louis, in the same physics department where Vitor and I spent one year together) called *"Probability theory: The logic of science."* Jaynes' viewpoint relies on a famous theorem in probability theory, called Bayes' theorem: all the laws of nature are *conditional statements* which allow us to predict some future events on the basis of the

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[3] *"La filosofia è scritta in questo grandissimo libro che continuamente ci sta aperto innanzi agli occhi (io dico l'universo), ma non si può intendere se prima non s'impara a intendere la lingua, e a conoscere i caratteri nei quali è scritto. Egli è scritto in lingua matematica."* (Galileo Galilei, "Il Saggiatore")
[4] https://www.maths.ed.ac.uk/~v1ranick/papers/wigner.pdf

knowledge of the present. However, most aspects of the present state of the world are irrelevant from the point of view of the prediction.

In practice, this works (more or less) as follows: we have some limited understanding of a physical phenomenon that we call our "prior" knowledge; we make an experiment; and based on the results of the experiment, we determine a "posterior" and update the state of our knowledge. As Jaynes noted, this process is intrinsically probabilistic even if we only consider the classical, deterministic laws of physics. However, in nature, things are even worse: *at the most fundamental level* the laws of nature are described by quantum mechanics, which tells us that the state of any system is only known in terms of probabilities! This inherent uncertainty is so disturbing that Einstein himself could not accept it (as he famously said, *"God does not play dice"*).

So, why should we trust that mathematics can be used to understand the universe? As Wigner put it in his essay: *"A possible explanation of the physicist's use of mathematics to formulate his laws of nature is that he is a somewhat irresponsible person."* (I lived with Vitor when we were young and reckless; I can't talk about all of our adventures in the bars of Saint Louis, but trust me, I know that Wigner was right).

If irresponsibility is not a good explanation, there is another commonly used criterion to "trust" physical theories which is, at heart, very unscientific. As Einstein stated, the only physical theories which we are willing to accept are the beautiful ones: there is a deep link between *truth* and *beauty*.[5] Einstein's observation can at best explain the properties of theories which we are willing to believe. It certainly has nothing to say about whether a theory is a valid description of nature. Chandrasekhar himself was perhaps too much in love with the idea that beautiful theories must be true: for example, he used to say (only half-jokingly?) that we should not waste our time testing general relativity, because we know that the theory is right. Some weeks ago I learned that when someone replied that Einstein himself was eager to test the theory, Chandrasekhar said: "That's because Einstein did not understand his own theory very well!"

In practice, and fortunately, science does not make progress in this way. Experiment is the guide of all of science. The first book we were recommended as undergraduate students in Rome - a department with a very strong tradition in experimental physics, going back to Marconi and Fermi - was Percy Bridgman's *"The logic of modern physics"*. Bridgman was an experimentalist with a (rather extreme) *operational* viewpoint on this subject: all concepts in physics are defined by the operations we use to measure them. For example, "length" is what you measure with a ruler. If you can't tell me how a quantity is measured, the concept corresponding to that quantity should not even be discussed in a physics department!

Ultimately (and fortunately), the arbiter of whether a theory is true or not has nothing to do with aesthetics. To quote Richard Feynman: *"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong."* Even worse: there are

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[5] Chandrasekhar, who appears at various places in this book, wrote a beautiful collections of essays on this topic. https://www.amazon.com/Truth-Beauty-Aesthetics-Motivations-Science/dp/0226100871/

many theories that are clearly false, but give alarmingly accurate descriptions of certain groups of phenomena. In fact, there are uncountable "beautiful" theories that are just wrong.

The recent difficulties in comparing the string theory landscape with observations means that many of us, physicists practitioners, have somewhat lost interest in the existence of a single "ultimate theory" that could consistently bring together the two incomplete building blocks of all physical theories we have today: general relativity and quantum mechanics. But I'm sure we will not stop looking. We are curious.

This book points out many fascinating connections between science and art. It also has a strong emphasis on history, and for a good reason. Both Weinberg and Chandrasekhar, in their old age, became fascinated with the history of physics. Weinberg wrote a book (*"To Explain the World: The Discovery of Modern Science"*) in which he reproduced in modern language many of the essential scientific ideas of antiquity. Similarly, Chandrasekhar spent the last years of his life rewriting Newton's *Principia* (probably the most important science treatise every written) in modern language. I believe that they did so, at least in part, because there is no better way to learn about the limits of science than exploring the flaws and virtues of physical theories that were once considered true, but turned out to be ultimately wrong. If we want to learn how the "science toy" works, there is no better place to look than the mistakes of the past.

I will close this introduction using the same quote that Eugene Wigner used at the opening of his essay:

"Mathematics, rightly viewed, possesses not only truth, but supreme beauty cold and austere, like that of sculpture, without appeal to any part of our weaker nature, without the gorgeous trappings of painting or music, yet sublimely pure, and capable of a stern perfection such as only the greatest art can show. The true spirit of delight, the exaltation, the sense of being more than Man, which is the touchstone of the highest excellence, is to be found in mathematics as surely as in poetry." (Bertrand Russell)

This book will take you on a thrilling journey through some of the key mysteries of modern physics (such as the idea of time, black holes, and gravitational waves), their connections with art, and the history of their development. Bon voyage.

Emanuele Berti
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