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1
THE PHYSICAL WORLD IS COMPREHENSIBLE

> The most incomprehensible thing about the world is that it is comprehensible.[1]

Why is the world comprehensible?

Of Einstein's many insightful sayings, this is my favorite. Indeed, this apparent miracle, that the world is comprehensible, is what motivates physicists. In a lawless universe behaving with neither rhyme nor reason, physics would be impossible.

I should hasten to say what hardly needs to be said, but with silly nitpickers lurking about I have to say it. What Einstein meant by the world is the physical world, the world studied by physicists. Plenty of questions are beyond the comprehension and grasp of physics, of course. What is the meaning of life? Why are we here at all? Why does the universe exist? Is there another level of existence we know nothing about? You could make up your own list.

We have made stupendous progress since our days in the caves when nearly everything was incomprehensible. But even within almost living memory, the progress has been so vast that it almost beggars imagination. Two hundred years ago, physicists did not know what light was. One hundred and fifty years ago, physicists had no inkling that spacetime was curved. One hundred years ago, physicists struggled to grasp the laws governing the realm of the quantum underlying our world. It is true that progress in theoretical physics has slowed nowadays. Nevertheless, progress is being made.

Why should Nature be comprehensible by the mind of these creatures that evolved recently on a dust mite of a planet orbiting an insignificant star drifting in a far-from-prestigious neighborhood of a mediocre average-looking galaxy? Why should the laws of physics be simple and beautiful? We could have found ourselves living in an intrinsically ugly universe, a chaotic world in no way graspable through thinking, as Einstein, he again, put it.

A smashingly revolutionary idea

Some readers might be surprised by my choice of the idea that tops my list of top ideas. The world is comprehensible! We tend to take for granted that physics is possible, that the physical world is comprehensible. But as far as I know, no ancient civilization, East or West, harbored the idea that the world was comprehensible, except, arguably, for a handful of Greeks. Even in the West, this enormous and profound idea surfaced only in the last four or five centuries, and the first inkling that the world could be understood without invoking the divine was met with ferocious resistance. It was a slow, gradual awakening threatened with excommunication, torture, and death.

The sun god pulling his chariot daily across the sky from east to west, and then somehow teleporting himself and his entire conveyance back to the east at night—this was our "understanding" not all that long ago. Yet now, for the first time in human history, a reasonably advanced student of physics could open a book on astrophysics and learn how to calculate the temperature and pressure inside a star, a particularly simple homework exercise for a garden-variety star like the sun, neither a red giant nor a white dwarf, without too many peculiar features.

Why versus how

I cannot tell you why the world is comprehensible. It is important to understand that physics does not answer the why questions. Physicists strive to steadily turn the whys into hows. We cannot tell you why the apple falls, but we can tell you how it falls, and reduce a variety of phenomena into an ever smaller set of underlying phenomena. Along the way, many whys were replaced by fewer whys, and whys by hows. Indeed, a crucial step in making physics possible is to separate the how questions from the why questions.

We can tell you why the sky is blue. It has to do with how light scatters off the air molecules, and after a heroic struggle we have reduced that to how two quantum particles, the photon and the electron, interact with each other. We can tell you that every massive object in the universe attracts every other massive object. We can tell you a lot about this force called gravity, and how it is equivalent to curved spacetime. But we cannot tell you why our universe contains such a force. Of course, were this force absent, then our universe would look quite different from the one we know.

The preceding sentence gives a capsule summary of the anthropic principle. It has been abused to answer every why question with the existence of humans. You know the jingle; various physical constants must have the value they have, since otherwise humans would not exist. A fascinating subject perhaps, but I will stay away from it in this book. Only the tried and true foundational ideas, as I said.

We do not know why there are four fundamental interactions in the universe, instead of two or six, but physics can tell us how three of these four interactions could be unified into a grand unified theory, as we will see in chapter 7.

That the physical world is comprehensible is miraculous

Physics as a subject wouldn't exist were the world not comprehensible.

Yet, if you think about it, the very comprehensibility of the world is miraculous. Sad that we have grown blasé in this enlightened age and take so much for granted. But flash yourself back a few millennia when no one even presumed to imagine the possibility of comprehending the world, let alone to attempt the task of actually comprehending the world.

You need only look at ancient cultures around the world. In school, we learned about the realm of rationality that is ancient Greece. Even in Greek myths, we could discern the urge to understand. But the notion that we could comprehend the physical world was far from universal. For example, the philosophers of ancient China envisaged man in harmony with Nature and emphasized understanding human behavior rather than the physical world. The West emphasized the control of Nature. Perhaps controlling is but one small step from understanding. To some extent, the entire Greco-Roman Judeo-Christian conception of Nature to be conquered and ravaged was missing in ancient China.[2]

Noticing regularity alone is not enough. Certainly, Asians recorded regularity with as much diligence as the Greeks. But the notion that there might be laws governing these regularities was mostly absent. That the world was comprehensible was far from obvious to every thinker in every civilization.

Nor should we assume that the development of physics as it happened on our planet is typical. For example, a civilization could develop in a binary star system, on one of the nineteen planets orbiting the two stars, which in turn waltz around each other in a highly eccentric ellipse. The regularity of the heavens, as well as the usual law of gravitation, might remain hidden from this particular civilization for a long time, perhaps longer than the natural lifetime of the civilization.

Or imagine us in a civilization on a planet much like Terra, except that it is completely covered by a single deep ocean. Electricity might be known as an epiphenomenon associated with some peculiar fish regarded as far inferior to *Pisces sapiens*, which is what we call ourselves scientifically. Magnetism is however totally unknown and light is merely an exotic phenomenon near the edge of the habitable world. Physicists would have developed an extensive understanding of water waves.[3] Some of our dead sink to a nether region where none of us are able to roam due to the crushing pressure. Others among our dead would float upward, and from observing these lightweight dead, politicians, celebrities, and such, some bright youngster eventually proposed the existence of a force named buoyancy. Later, a fishy Einstein would have the brilliant insight that buoyancy is due to a more fundamental[4] force called gravity pulling the water around these lightweight objects down.

We alone could understand the universe?

I do not doubt for a second what my computer science friends tell me, that with massive data analysis, artificial intelligence would in the foreseeable future allow us to communicate with animals. At that point, perhaps we could ask them what they understand of the physical world. Yet I also have no doubt that no other lifeforms on earth can understand nonabelian gauge theories (which we will encounter in chapter 7), let alone invent them. But then why is the physical world comprehensible to humans (at least thus far)?

Einstein was absolutely right that it is a profound mystery. It could well be that this particular primate species, after eons of evolution, is no more capable of fully understanding the physical world than one of the gophers in my backyard. (The emphasis is on "fully"!) It is certainly possible, of course, that we will eventually hit a brick wall. The pessimists in the physics community would say that we have already hit that proverbial wall.

I want to be optimistic because I need that optimism to buoy me professionally. Einstein expressed his profound wonderment more than a hundred years ago. He and his contemporaries could also feel, when confronted with the mysteries of the quantum world, that the striking progress in understanding of the physical world gained in the 19th century may come to a grinding halt. But they didn't, and pressed on. And progress has been made for a century and more. Of course, in deciphering the quantum world, that generation of physicists was pushed along by an almost excessive wealth of experiments, which are now sorely lacking, no matter what the cheerleading boosters try to convince us otherwise. Needless to say, I am talking about landmark experiments that reveal some deep truths, not routine experiments measuring the decay rate of an absurdly named particle or the conductivity, super or not, of some newly minted alloy.

I am among those who believe that the universe, with its zillions of galaxies each with zillions of stars, is teeming with intelligent life. I have even thought seriously about communicating with extraterrestrial intelligence.[5] When we finally come into contact with extraterrestrial intelligent beings, what can we talk about? Not terrestrial biology, which may or may not be similar to their biology.[6] And definitely not Tang dynasty poetry, nor Shakespearean plays, which so many scholars spent, are spending, and will spend entire lifetimes on. But surely, if the extraterrestrials have mastered enough technology to communicate with us, they could discuss the classification of Lie algebras* and gauge theories with us, perhaps teaching us a thing or two. Whatever, but I could hardly doubt that they have also come to realize that the universe is comprehensible.

Could have been an impenetrable mess

A priori, the laws of physics governing our universe could have been an impenetrable morass. Or they could be evolving in a horribly complicated way. Or consider the amusing science fiction scenario that our universe

*From a branch of mathematics called group theory and used in advanced physics. More in chapters 4, 7, and 8.

is a school-assigned experiment carried out by a high school student in a metauniverse. Perhaps he or she or it has even started a whole bunch of universes, like ant farms, and stashed them away somewhere in the basement, out of his or her parents' way. Perhaps he (that's a lowercase H) has lost interest and forgotten about his universes, leaving some to expand, others to collapse, in utter futility and silence.

In our computer age, we are perhaps more inclined to think that we may be living inside somebody's giant computer. (Whatever that means! I for one have not the foggiest idea, in spite of various popular movies.) If so, then what an elegant program this computer is running!

To the contrary, we could certainly imagine a monster of a nasty program with ten trillion lines of code governing the motion of particles we display on a 3-dimensional screen, with the motion specified by some ghastly mess of an algorithm, but consistent with Newton's laws almost all of the time. For instance, line 4,878,923,767,863 could state that when the time in an internal clock expressed in some unit and truncated to an integer is given by a prime number, the laws of motion would be altered for a brief time equal to the eleventh smallest factor of the number one higher than that prime number. Line 4,878,923,867,863, on the other hand, could state that whenever a country whose English name starts with the letter R, such as Romania, has a national holiday the laws would be reversed for 93 nanoseconds, if we were so provincial as to refer to human coined units and alphabets. The poor physicists living inside this computer would be bitterly frustrated trying to figure out what is going on.

But no! Instead, theoretical physicists have discovered that the laws governing our universe are so simple that they could be written down on the back of a small envelope, as will be described in chapters 7 and 10, and that they are described by established (and elementary) branches of mathematics such as group theory and differential geometry. Furthermore, only the introductory portion of these subjects is needed for physics: the relevant mathematics is simple enough to be mastered by bright undergraduates, as will be discussed in chapter 8. So far, there is absolutely no evidence that physics requires any theory so complicated that it will take bright graduate students several decades, rather than a mere several years, to learn. To me, both a miracle and a mystery!

Physicists from Einstein on have been awed, and mystified, by this truly profound fact that as we examine Nature on deeper and deeper levels, She appears ever more beautiful. This beauty is not just a matter of vague feel-good talk, but a beauty that could be mathematically quantified by the notion of symmetry, as I will explain in chapter 5.

To me, the comprehensibility of the universe that so boggled Einstein's mind testifies that the universe is ordered at a deep level and not thrown together with random abandon.

Nature's kindness to physicists

During my study of physics I was repeatedly struck by Nature's kindness to physicists. It often seems that Nature is taking physicists by the hand and guiding them step by step through a predetermined curriculum.

Starting around the end of the 19th century and up till the 1920s or so, theoretical physicists understood, after much confusion and controversy, that electromagnetism is described by an abelian gauge theory. (For our purposes here, it is not important to even know what this technical term means.) During the same period, spearheaded by experimental discoveries, physicists came to realize that, in addition to gravity and electromagnetism, the world contains two other fundamental interactions, the strong and the weak interactions, which manifest themselves only in the subatomic world. In the 1970s, two of these four interactions, namely electromagnetism and the weak interaction, were unified into a single interaction, now enshrined in textbooks as the electroweak interaction, described by a nonabelian gauge theory, which contains the abelian gauge theory governing electromagnetism as an almost trivial piece. Again, it is not important to know what this gobbledygook term means, besides the fact that nonabelian gauge theories are orders of magnitude more intricate and difficult to master than abelian gauge theories, as you might have guessed.[7]

We will come back to this drive toward unification in chapter 7, but here I want to impress upon you Nature's kindness to physicists. Without first having been exposed to the easy case of electromagnetism, a practice problem as it were, theoretical physicists would have been in no position to tackle the weak interaction. So it is almost as if Nature taught physicists the baby stuff first, and then gently showed them how to move on from the abelian to the nonabelian case. Why not hit them with the nonabelian stuff first and blow them back to the cave of dark ignorance?

Allow me to repeat what I said in the prologue. Readers who have gotten this far must have realized that this book is most useful to those who have had some prior exposure to theoretical physics through popular books and the media. In contrast, those who have never heard of atoms, say, might find this book tough going. In short, this book is meant for those who appreciate an overview of theoretical physics and who are not particularly interested in what Einstein called "this and that."

As easy as possible, but not any easier

As another gesture of kindness, Nature couples the electromagnetic field to the charged fields, such as the electron field, rather feebly, as measured by the fabled fine structure coupling α with the approximate value of 0.007. This teeny number enabled a bright young post–World War II generation of theoretical physicists including Feynman and Schwinger to master quantum electrodynamics. Their perturbative approach involves successive approximation in powers of α, treating the first correction and the next correction as small and even smaller,[8] proportional respectively to $\alpha \simeq 0.007$ and $\alpha^2 \simeq 0.00005$. (Some readers might have heard of Feynman diagrams, which are merely pictorial devices quantum field theorists use to keep track of successive terms in this approximation scheme.[9]) If we were so unfortunate as to live in a universe with $\alpha \simeq 7.1$ say (just to write down an arbitrary number), subsequent terms would be explosively larger, and this glorious thrust forward of physics after World War II would have been impossible.

As an older example, the orbit of the moon around the earth and the orbits of the planets around the sun, while not perfectly circular, are fairly close to being circular. Thus, physicists could master the much simpler case of a circular orbit first, and then go on to tackle elliptical orbits.[10] Students are certainly taught this way: first the circle, and then the more complicated ellipse. The eccentricity of the ellipse may be treated as a small perturbation. Why should Nature care? Physicists could have been faced with highly elliptical orbits from the very start.

Nature's kindness pops up again and again. Understanding surface water waves gave physicists the mathematical tools to understand electromagnetic waves, and from that later to quantum waves. As a 20th century example, during their forays into the atomic and nuclear world physicists realized that they had to learn a branch of mathematics known as group theory, as will be discussed in chapter 5. Nature showed them the simplest groups first. Just to give you a flavor, let me mention a few of the groups that popped up in physics in chronological order: $SO(2)$, $SO(3)$, $U(1)$, $SU(2)$, $SU(3)$, $SU(5)$, $SO(10)$. You don't have to know anything about group theory to suspect that the integers represent a progression[11] in baby steps from quasi-triviality to graduate school level stuff. I teach this stuff[12] to undergraduates every year, and even the less endowed students are capable of progressing from $SO(2)$ to $SU(3)$, while the more talented sail on easily to $SU(5)$ and $SO(10)$. In some alternative universe, Nature could easily have been unkind and blasted physicists with $SO(10)$ the moment they set foot in the quantum world.

I feel that Nature takes great care to make physics as easy as possible, but not any easier, to paraphrase Einstein.

Intertwining ideas

The top ten ideas I talk about in this book naturally intertwine with each other to form an organic whole that is fundamental physics. That the world is comprehensible could only be made possible by the existence of immutable and universal laws, to be discussed in chapter 2. We could discover the underlying laws only if physics becomes simpler and simpler as we delve deeper and deeper. This will be discussed in chapters 5 and 7. Imagine, to the contrary, a world in which physics becomes more and more complicated, messier and messier. Many physicists, I for one, would simply give up. At least thus far, there is no sign of that disastrous scenario.

Kelvin versus Newton

> There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.[13]
>
> —Lord Kelvin, in 1897

> I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.
>
> —Isaac Newton, ca. 1726

Newton is partly right and partly wrong. Wrong if we take his metaphor too literally. He might not have known it, but Newtonian mechanics was a huge step toward making the universe comprehensible. Many later developments, such as fluid dynamics, amount to applying Newtonian dynamics to fluids, instead of particles and rigid bodies. But of course, he was also mostly right about the vast ocean of physics that he could not possibly know anything about, such as quantum mechanics and quantum field theory.

Kelvin, on the other hand, was entirely wrong, and has ever since been mocked as the paragon of the overly optimistic physicist. His sin consists of not asking too many questions, such as what constituted matter and how did the sun keep on burning for so long. So, let us desist in deriding an otherwise great physicist. Leave Kelvin in peace and pull up another optimist, albeit lesser known than that British Lord, speaking a generation or two later.

> It is difficult for those who did not witness it to imagine the enthusiasm, nay presumptuouness, which filled our hearts in those days. I shall never forget the terse way a friend of mine (now a very eminent figure in the world of physics) expressed his view of our future prospects: "In a couple of years," he said, "we shall have cleared up electrodynamics, another couple of years for the nuclei, and physics will be finished. We shall then turn to biology." Léon Rosenfeld (1904–1974), an early quantum physicist

Consider that Rosenfeld was twenty-one when Heisenberg (less than three years his senior) first wrote down, in 1925, quantum mechanics in the form we now know it. I do not know who Rosenfeld's friend was, but almost surely he was also a youngster in his twenties. So we could chalk this up to youthful enthusiasm.[14] At least Rosenfeld suspected that he and his friend were presumptuous.

The question I like to raise is whether our situation is closer to that described by Newton or that described by Rosenfeld's friend. The correct answer is of course nobody knows, least of all I. I am a theoretical physicist, not a fortuneteller. But still, as an exercise in futility, let me try to quantify the question. Does what we know amount to 5%, or 20%, or 80%, or 95% of all the physics there is to know? (Of course, in itself, without the kind of exhausting definitions philosophers are so fond of, this question is meaningless. But I think most working physicists know what I have in mind.) Physics may well never possess a full knowledge of turbulence, but I and many others feel that we have a reasonable understanding of the physics involved. As another example, a few decades ago, a detailed theory of how coffee stains formed was published. Does that mean the physics involved was beyond the ken of Einstein? Or even that of Kelvin? Of course not. They simply did not address the details of this particular phenomenon, and physicists never finish analyzing every possible physical phenomenon we would encounter. Rather, I am talking about broad understanding of how the universe is put together—what I call fundamental physics without bothering to define that term precisely.

It would be a fool's errand to attach some meaning to the percentages I just threw out glibly, but I will take the risk just so that the reader would have at least a rough idea of what I have in mind. Consider an insect sensitive to light crawling across a computer screen showing a movie being streamed. That insect would have not the faintest glimmer of the meaning behind the patches of changing color, let alone the electronics used to produce them. It has no way of distinguishing one patch from another, of understanding that one represents the Bad, the other the Ugly. In contrast, while I do not know how a computer works, I know about electrons, the emission of light, streaming, the wild American West and all that. I have even heard computer savvy types talking about strings of 0s and 1s. Let what that insect knows and what I know represent what I mean by 5% and 80% respectively. I believe that many of my colleagues in theoretical physics, I included, tend to believe that our understanding of the universe is more like the latter rather than the former. We know quite a lot about the universe already. I find it impossible to believe that the "patches of color" we observe "merely" represent some story enacted for the amusement of the gods.

Yes, the nattering nabobs of negativity can easily sit back and compile a long list of things physicists do not know, such as what constitutes dark matter.[15] And yes, there could also be surprises over the horizon. Indeed, dark matter was unsuspected until Fritz Zwicky[16] inferred its existence in 1933 from observing the rotations of galaxies. Since then, experimentalists have spent decades of their lives searching for the particle responsible, and thus far, they have not detected any terrestrial evidence of its existence. The search goes on, and I sure hope that one of my experimentalist friends find it soon.

I could go on and on. There are lots of questions physicists have yet to answer definitively. While there are plausible theories about dark energy, it has not been pinned down.

Ironically, it is our understanding of quantum physics that bolsters our confidence in what we have yet to detect. Perhaps ironically, thanks to quantum connectedness, we could be more confident than we would be otherwise. To be concrete, when we calculate something apparently innocuous such as the magnetic moment of the electron (which measures how the electron responds to a magnetic field), the existence of a hitherto unknown particle would contribute to the theoretical value of the magnetic moment so that we can say something about its mass for instance.

To use a phrase made famous by a former secretary of defense[17] of the United States, in physics we are confronted with the known knowns, the unknown knowns, the known unknowns, and the unknown unknowns. It is of course the flaming promise of the final category that draws generations of bright young people to a lifetime of physics.

Incomprehensible comprehensibility

> Man is only a reed, the most feeble in nature, but he is a thinking reed.
>
> —Blaise Pascal

To conclude, what do we make of Einstein's "incomprehensible comprehensibility"? As I have already declared, we poor physicists cannot tell you why the physical world is comprehensible. For why, we have to defer to the philosophy professors. Meanwhile, you and I could also speculate over afternoon tea and cookies such as those provided at the institute for theoretical physics where I work. Whether or not you share Einstein's incomprehension of the comprehensibility of the physical world is of course completely up to you, and depends on your outlook.

There are those who believe that out of the vastness of the universe we humans are the chosen ones. They point to the fact that, also, out of the vastness of our planet we are the only ones who comprehend. We are somehow uniquely blessed and chosen by some divine creator to grasp and to admire its handiwork.

I refuse to believe our uniqueness, given the sheer number of galaxies, each containing an almost uncountably many stars. And I know of no physicists who would seriously believe this. (But that may be due to my limited circle of acquaintances. No doubt somewhere live religious zealots who also call themselves physicists.)

One possible view is that we comprehend only what we are able to comprehend, and that represents only a fraction of what there is to comprehend.[18] No idea how big or how small that fraction is! The British physicist Arthur Eddington concocted a parable[19] that left an impression on me when I first heard it as a student. Imagine a village of fishermen, among whom one with a particularly scintillating mind formulated the fundamental law of the sea stating that all fish are longer than 1 cm, not realizing that their fishing nets all have a mesh larger than 1 cm. Is it possible that the human mind filter out of that part of physical reality that we have no way of comprehending, leaving us with what we can comprehend? Notice that I was careful to qualify reality with the word "physical." Personally, I am quite willing to concede that there may be matters beyond the grasp and reach of physics.[20]

I no longer believe Eddington's parable now that I have understood more physics. Quantum connectedness would appear to make the story less plausible. To extend the parable, perhaps a weak analogy of connectedness would be big fish devouring smaller fish. What we do understand of the four interactions hangs together so seamlessly and wondrously that it is hard to believe that there is a lot more about physical reality that we have missed. I do not mean, of course, to dismiss the possibility that there may be a deeper layer in which quantities that we now treat as mere parameters, such as the masses of the quarks, could be calculated. Indeed, string theory is a possible candidate example for this deeper layer, independently of whether or not you believe it.

Do not be confused by artificial intelligence, at least as it is now known. At present, the advantages of an inanimate computer over a human are its lightning speed and its complete ignorance of mental fatigue. But what was needed to master atomic physics was not massive amount of calculation in classical physics done blindingly fast, but deep insights and synthesis of observational data leading to a new kind of physics, namely quantum physics. Similarly, realizing that gravity is a manifestation of curved spacetime is not a matter of being able to perform a mountain of calculations using Newtonian gravity.

Eventually we could imagine artificial intelligence reaching a stage in which it could consider all possible theories (whatever that may mean in practice) and investigate the consequences and implications of each of them. When we reach that stage, then perhaps we could say that artificial intelligence has developed a measure of insight. But we appear to be far from that vision, and I am not sure that the notion of "all possible theories" could even be formulated.

In the meantime, there are still, and hopefully there will be, physicists to chew over the universe.

Notes

[1] Albert Einstein "Physics and Reality," *Franklin Institute Journal* (March 1936).

[2] Sadly, China is coming late to this highly useful idea, and now a common attitude goes "You ravaged the world, now it is our turn, so don't act holier than thou and preach to us."

[3] But not the surface water waves we commonly observe and teach to some undergraduates. See *FbN*, chapters VIII.1 and 2, in particular page 282.

[4] An early example of unification that I will talk about in chapter 7.

[5] See my SETI talk and the published papers mentioned therein. https://www.youtube.com/watch?v=MHuXlJzqKqs.

[6] See, for example, A. Kershenbaum, *The Zoologist's Guide to the Galaxy: What Animals on Earth Reveal about Aliens–and Ourselves*, and A. Weir, *Project Hail Mary*.

[7] Sadly, in physics, the name of Niels Henrik Abel (1802–1829), the brilliant Norwegian mathematical prodigy who died of tuberculosis young and poor, carries the connotation of being "simple minded."

[8] See Schwinger's tombstone shown in chapter 4.

[9] See *QFT ASAP*, chapter IV.3, and *QFT Nut*, chapter I.7.

[10] Such as that of Halley's comet. Newton in his genius appeared to have done both at the same time in his published treatise, but presumably in his actual work, he mastered the circular case first.

[11] The group $SO(2)$ describes rotations in the plane, as demonstrated all the time by hands in clocks and watches.

[12] Using my textbook *Group Nut*, which is based in turn on my course.

[13] Lord Kelvin, in 1897, speech addressing the British Association for the Advancement of Science.

[14] We could hear echoes of that sentiment in the early days of string theory when it was triumphantly called the theory of everything.

[15] The mainstream view is that dark matter consists of one or more particles. I, and I dare say most theoretical physicists, find the alternative of modifying Newtonian gravity just to accommodate the observed galactic rotation speeds ad hoc and distasteful. Part of the problem in the search for dark matter is that it is too easy to cook up a theory of the dark matter. You could simply make up a particle, which interacts only with gravity and hardly with anything else, and thus could affect the rotation of galaxies yet be virtually undetectable in any terrestrial laboratory. Such a theory is possible, but rather uninteresting. In this sense, theoretical physics could be laughably easy. Don't be impressed by someone who tells you that he or she has a theory of dark matter. Incidentally, I myself published one of the early particle theories, in which the dark matter is a particle that interacts only with the Higgs sector (never mind what that means for the moment). Hopefully, actual detection and subsequent experiments will help to sort out the theoretical morass.

[16] He of the "spherical bastard" fame in physics, a prickly legend even by the combative standards of theoretical physics.

[17] Donald Rumsfeld.

[18] For an alternative view based on the decoherent histories interpretation of quantum physics, see J. B. Hartle, arXiv:1612.01952 [gr-qc] 2016.

[19] See also *Fearful*, page 280.

[20] Here I could perhaps quote E. F. Sanders from her book *Eating the Sun*: "A sense of wonder can find you in many forms, sometimes loudly, sometimes as a whispering, sometimes even hiding inside other feelings, being in love, or unbalanced, or blue."

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