Chapter 1: Physics is Different[1]

The physicist who coined the term black hole – John Archibald Wheeler - wrote some time ago:

> *Recent decades have taught us that physics is a magic window. It shows us the illusion that lies behind reality - and the reality that lies behind illusion. Its scope is immensely greater than we once realized. We are no longer satisfied with insights only into particles, or fields of force, or geometry, or even space and time. Today we demand of physics some understanding of existence itself.*

If this quote seems too modest, here is another, from Charles Misner:

> *The organist chemist, in answer to the question,Why are there ninety-two elements, and when were they produced? may say The man in the next office knows that. But the physicist, being asked, Why is the universe built to follow certain physical laws and not others? may well reply,God knows that.*

And what about this from a well-known physicist who shall remain anonymous:

> *Fundamental physicists are titillated by the thought that perhaps only one more step separates them from the Ultimate Design. ... .. we are beginning to feel that we are on the threshold of really knowing His thoughts.*

In this chapter, we will take a brief tour of some rather elementary physics, as a beginning of our effort to find out what is the worldview that science represents and nurtures. Our goal will be to find out which - if any - of the above quotes reflect the true nature of modern physics.

We will begin by describing, in some detail, three cases where everyone - independent of their physics background - will be able to proceed from the simplest beginnings, through the simplest steps, to some of the most profound views of Nature modern

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[1] for Figures 1 and 2 please see www.phys.washington.edu/users/vladi/PhysicsFigures.pdf

physics provides. In fact, I humbly recommend even to physicists not to skip this part – they may find it interesting how one of their colleagues teaches Einstein, Feynman and Heisenberg to a very diverse enrollments of students (there is a whole chapter later in the book on this topic.)

If you are brave enough to deal with a few equations, I strongly encourage you at this point to switch to the Appendix - I assure you that gaining or reviewing and refreshing the most elementary math skills will be very much worth the effort. On the other hand, if the Appendix looks too dense, please feel free to come back and continue reading from here - there is just one equation we simply must introduce.

Why is there Something rather than Nothing?

Perhaps the most famous equation in whole of Physics is Einsteins $E = mc^2$. The mass of a body is a measure of its inertia, i.e. of the extent to which the body resists attempts to change its state of motion. It also happens to be the measure of the force which the body experiences in gravitational field (incidentally: the equivalence of the inertial and gravitational mass led Einstein to his General Theory of Relativity). And Einsteins equation tells us that the mass is also a measure of the energy content: any mass, even when at rest, has energy, and equivalently, rest energy corresponds to mass.

So far so good, I hope. Now consider a system consisting of two components bound by a mutual attraction: take for example the Moon orbiting around Earth. The question is how does the total mass of the (Earth-Moon) system relate to the sum of the mass of Earth plus the mass of the Moon. The first reaction is likely to be that they are equal: after all, if you load a 1 ton pickup with a half-ton lawn mower, the whole thing will have 1.5 tons, right?

And then you recall I just discussed energy: clearly, the Moon is attracted to Earth (and Earth is attracted to the Moon), there is gravitational field between them, this field has some energy, and this energy, according to Dr. Einstein corresponds to some mass. So now tell me: is the mass of the (Earth-Moon) system equal, smaller than or greater then the sum of the masses of Earth plus Moon?

The understanding of this question is so important that I suggest you spend at least five minutes pondering it before turning the page.

Well, I tested this on a bunch of Physics majors and graduate students. About three out of four majors and one out of four graduate students quickly reply that the mass of the system is larger than the sum of masses - *"because the binding energy corresponds to some mass, too."* They get it right when they think about it some more, but it shows you that even a simple question like this is far from being trivial.

To see what is the correct response, consider what you have to do if you wish to split the system into its constituents - for example you want to remove the Moon from its orbit and place it somewhere far from Earth (so that it is no longer an Earth-Moon system but an independent Earth here, and an independent Moon somewhere else). Clearly you have to deliver energy to the system to accomplish this - the Moon is bound to Earth by gravity, and you have to convince it - say by hitting it with a giant golf club.

So you have to it add some energy to the rest energy of the Earth-Moon combination to convince it to split into the Earth and the Moon separate from each other. Therefore, the rest energy of the system is smaller than the rest energy of the constituents, and by $E = mc^2$ (see Appendix) this implies that the mass of the system is in fact *smaller* than the sum of the masses of the constituents. In other words, the binding energy is, effectively, *negative*.

What is more: if the binding energy becomes larger, the resulting mass gets *smaller*. This is certainly counter-intuitive and perhaps interesting, but you are probably not really impressed by all this - not yet. But keep thinking along the same direction.

Could the binding be strong enough that the resulting mass of the system would be zero? And the answer is: in principle, yes. I hope you agree that this starts to get interesting: you take two particles, each with non-zero mass (and therefore each with non-zero energy) and - if you bind them strongly enough - you get the total of zero: zero mass, zero energy!

But you say: this is just two academic particles - who cares about them. So you think some more, and say: wait a minute: the Universe is full of particles (some of them quite large, such as planets, stars ,) and they are all bound to each other by gravity. As we mentioned, gravity is very weak, but could it be that the overall binding of everyone to everyone is just sufficient to cancel all the masses of all the stars and planets, to produce net mass equal to zero, and net energy equal to zero?

And the answer to this is: detailed calculations show that yes, it is possible. There are many additional factors to consider, but yes, it is possible that the total mass and the total energy of the Universe are zero. But if they are zero, then it is possible to create all the Universe, with all its galaxies, stars and planets, out of nothing - it does not violate the law of conservation of energy.

Every Physics Department – faculty, postdocs, graduate students and ambitious undergraduates – meet once per week for a secular Mass called "Physics Colloquium". The speakers are instructed to aim at a level where Professors are not bored and students are not lost (or is it the other way around?).

A few years back we had a Colloquium on the subject:

Why is there Something rather than Nothing?

The speaker went through one hour of calculations and reasoning, and at the end the answer was:

Maybe there is Nothing, cleverly disguised as Something.

So there you have it. Centuries-old philosophical question gets a new meaning, and just about all students in my Science and Society course - English majors and all - are able to follow the reasoning, and share the wonder.

The Central Mystery of Quantum Mechanics

We met Richard Feynman already in the Prelude, and we will come back to him quite often in this book. Many Nobel Prize winners are quite narrow, highly specialized, and downright ordinary or even boring and silly outside their discipline. Feynman was a true polymath, and more: in addition to his work on theoretical particle physics (which brought him the prize) he was - with a single article - at the origin of the field of Nanotechnology. With another article, he foresaw the field of Quantum Computing long before others came to realize that the mysteries of Quantum Physics could be exploited for computations. He was also a talented artist, musician and story teller. He was a show-off, but he was also, in his own way, a rather wise and profound philosopher (due to his rather strong accent, some called him philosopher from Brooklyn.)

Feynmans Lectures on Physics became an instant classic soon after they were published. They were originally written as a transcript of his freshman physics lectures at Caltech in 19xx. Soon after I started teaching at the University of Washington, I assigned them as an optional reading, to accompany the standard College textbook we were using. After a few days, a student came to see me, and complained bitterly: "Those Caltech kids are lucky to have such a fascinating book, while we have to suffer through our pedestrian textbook". And I had to tell him that in fact the Lectures are not really used at Caltech for the intended purpose - the level is too high even for the smart students there. But it is not the mathematical level being too advanced. The books represent a window into the mind of a genius. At CERN, I knew a retired physicist, rather well known, who would come every day to his office to read Feynmans Lectures on Physics. He would say: now I can start to really understand Physics.

Well, when Feynman comes to Quantum Mechanics he writes:

> *Things on a very small scale behave like nothing that you have any direct experience about. They don't behave like waves, they don't behave like particles, ... or like anything you have ever seen. ... Because atomic behavior is so unlike ordinary experience, it is very difficult to get used to and it appears peculiar and mysterious to everyone, both to the novice and to the experienced physicist. Even the experts do not understand it the way they would like to ... In this chapter we shall tackle immediately the basec element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery..*

So, let us follow Feynman, and imagine an electron gun spraying a wall with two holes (two "slits" in Physics jargon); one hole is presently closed (see Figure 1). Some distance after the wall there is an electron detector - imagine we have an old-fashioned counter which makes an audible click when it is hit. It is important to place the detector at the right place to experience the effect we will describe. It is not difficult to determine the proper location - more about this later.

The gun is not very good - the electrons fly, randomly, in every which direction. Obviously, many electrons hit the wall, and that is the end of that electron. But some electrons do make it through the open hole, ricochet up or down, and some will hit the detector: click .. click, .. click,click, .click.

Anticipating the mind-boggling and headache-inducing development to come in a minute, you spend quite some time verifying that everything makes sense. You make sure that each click signals an arrival of a whole electron - that the particle does not split into two. An electron either arrives, whole, at the detector, or it does not. And you measure the timing, and indeed - every click arrives at the right time delay after being emitted by the gun, convincing you that it was indeed emitted by the gun, and went in a straight line to the hole, and from there in a straight line to the detector (see Figure).

When you are done with all the checks and cross-checks you can think of, you open the second hole, *and the clicks cease.* Silence – no clicks - the electrons stopped coming. Previously, they were coming through the top hole, and you did not do anything to that possibility: you just opened up an additional possibility for an electron to go from the gun to the detector, and as a result the electrons stopped arriving.

You cannot believe what happened. You cover the bottom hole - click, clikclick, click. Open it again: silence. Cover the top hole: click click click. Open it: silence.

That is the Central Mystery of Quantum Mechanics. In fact, it is more. As the Intelligent Design people like to say about evolution, Quantum mechanics is just a theory - more about this later. But what we have described is not result of any theory - it is an experimental fact (and a simple one to describe, if not to understand). So perhaps it should be called Central Mystery of Nature

I always start a course in Quantum Physics with an exposition like this, and students are always fascinated. “Professor”, they say, “this is so interesting. We should not proceed with all those equations we saw ahead in the textbook. Instead we should discuss this until we really understand this.” But I know better, and I reply: “Yes, yes, this is very interesting indeed, and if there is time at the end of the course, we will come back to this.”

Two things invariably happen. First, there is never time at the end of the course. More importantly, by the end of the course students have learned many useful things. They now know how to calculate all kinds of quantum magic, and most of them rarely if ever recall that the original mystery was never resolved.

Now, readers with some previous physics knowledge will point out that in fact there *are* things we do understand about all this. I mentioned the importance of placing the detector in the right position. What happens if we move it a little up or down? It turns out that as soon as we move it, clicks start to happen even when both holes are open. As we keep moving the detector, the frequency of the clicks keeps increasing, and at some position the number of clicks per second for both holes open is twice the number when only one is open. Thats what you would have expected to start with. But if you keep moving the detector, more and more clicks keep coming, until they come four-times faster than when a single hole is open. That is the maximum. Additional detector shift results in a gradual decrease in click frequency, until you reach a new position where clicks cease when both holes are open.

So it seems we are dealing here with some kind of a wave phenomenon, with an interference of waves coming through the individual holes. And indeed: in the rest of the course students learn about the psi wave-function, about the Schroedinger equation which governs it and how the solution leads to all kinds of extremely precise and useful calculations.

But the quantum wave is something very strange: we know how to use it, but we don't know what it really means. Since the celebrated Einstein-Bohr discussions in the 1920s, thousands of scholarly (as well as not-so-scholarly) articles and hundreds of books were written about its interpretation. We know that the value of the wave function at some position can be used to determine the probability of finding the particle at that particular position. But as soon as we find it there, the probability of finding the particle anywhere else must instantly become zero this is the infamous collapse of the wave function which is the first of the many non-local aspects of the Quantum Theory.

Many solutions and "interpretations of Quantum Mechanics" were proposed; some decidedly worse that the disease they were trying to cure. And recently, something exciting happened: the decades old, interminable debates (starting with Einstein vs. Bohr in the 1930s) were replaced by a pragmatic attitude: the paradoxes and mysteries were transformed into a technological resource, and the brand new fields of Quantum Computing and Quantum Information were born. We will have many opportunities to discuss the significance and implications of this development.

The Heisenberg Uncertainty, and the nature of Vacuum

In the last of the three specific mini-investigation we will start with one of my favorite subfields of physics - acoustics - and we will try to estimate the frequency of a signal depicted on Figure 2. It is a simple tone, starting from silence, and after some finite duration ending in silence again. The most precise way to determine the frequency is to choose some "reasonable" duration, count the number of periods during that time interval, and then to determine the length of one period by a simple division.

Again: it is not difficult to show that the margin of error in the determination of frequency (uncertainty of frequency) and the duration of time (uncertainty of time) are related:

(uncertainty of frequency) times (uncertainty of time) = universal constant (equal to $\frac{1}{4\pi}$

So far, all this is "only" acoustics, but it has all the aspects of the "real thing": the product of the two uncertainties cannot be arbitrarily small, i.e. if e.g. uncertainty of time is small, then the uncertainty of frequency must be large, and vice versa. When you think about it, it explains why you can trill with a flute but not with a tuba - and there are other, more significant applications, too.

We get to the "real thing" by adding another, simple but ground-breaking equation to the mix. About 100 years ago, Max Planck (reluctantly) came to the conclusion that the energy of the electromagnetic radiation is "quantized" in integer multiples of a "quantum of energy" which needs to be proportional to frequency. Einstein subsequently obtained his Nobel Prize for applying the same equation on the photoelectric effect, and finally a young French doctoral student Louis de Broglie proposed that the same equation applies to everything, not just light: there is a "wave function" ψ associated with everything.

Unlike Einstein, Dr.deBroglie never achieved anything much after getting his degree, but this alone was sufficient for him to get to meet the king of Sweden. And his Nobel Prize was well deserved - the wave function was found to obey a particular equation (Dr. Schrodinger → trip to Stockholm) and - a few years later - its meaning (at least for the purposes of calculations) was understood (Dr. Born → trip to Stockholm).

With this added ingredient, the "acoustical" Heisenberg relation yields the "quantum Heisenberg":

(uncertainty of time)times (uncertainty of energy) = universal constant (equal to "Planck constant/4π)

with an interpretation that it is impossible to assign to a particle both a value of its velocity as well as a value of its position - if the velocity is known, the position is not, and vice versa. This means that the concept of a "trajectory" loses its meaning, to emerge only as an illusion for particles large enough (such as bowling balls, or people, ...) However, in the atomic and subatomic world, with tiny particles, the trajectories are replaced by a “quantum fuzziness” with which we have no direct experience, as explained by Richard Feynman.

But there is more, much more. The time-energy relation can be interpreted not only as “prohibitive” (“there shall not be a product less than ...) but also as a “permissive”: violation of energy by an amount may be possible if the duration of the violation is short enough. This leads to the current view of vacuum as constantly “boiling” with emission and reabsorption of particle-antiparticle pairs - of all kinds: electron/positron, proton/antiproton/ ... - with the duration of each occurance subject to the Heisenberg time-energy relation. Thus in modern physics, the vacuum, rather than being the simplest of all phenomena, is in fact the most complicated one.

Physics is indeed different

The reader must have noticed that so far I have been only dealing with rather old concepts - no mention has been yet made of the Big Bang, the Superstring theory in n+1 dimensions, or the possibility of creating a baby Universe in laboratory. We will have a chance to talk about some of these topics later on, but quite remarkably, the points I am trying to make in this chapter can be made using concepts known since the late 1930s.

What are we to make of all this? Physics indeed is different. With what Wigner called “the unreasonable effectiveness of mathematics”, we seem able to overcome what Weinberg calls an “equally puzzling phenomenon: the unreasonable ineffectiveness of philosophy”. In spite of our limitations (starting with our size, utterly negligible in comparison witth the cosmic scale, and grotesquely large and awkward compared to subatomic scale) we seem able to “understand” more and more of Nature, from quarks to clusters of Gallaxies, and from the Big Bang 15 billions years ago to the fate of our Sun 5 billions years from now.

We do it in a strange way, though: we don’t really know what we are doing. The late, great John Bell (about whom more later) and the late, great Arthur Koestler (about whom more later, too) both compared the procedure to sleepwalking. As mentioned above, Max Planck discovered the quantum in 1900. But he did not do it by any lofty and profound reasoning. By purely mathematical manipulation, he managed to get two different formulas to merge into a third one, which happened to agree with the experimental data so well, that he set out to investigate: ”What would I had to assume to obtain the third formula directly from my physics assumption?”. And he found the assumption - $E = hf$ - two months after he found the formula.

Similarly, Schrodinger did not know the meaning of the wave function ψ when he wrote down his famous equation for it. As mentioned above, again, it was another physicist, Max Born, several years later, who came up with the right interpretation.

And so it goes. As always, there are exceptions, most famous being Einstein's Special and General Relativity. But by and large, the process is not rational nor logical. It has been said that in physics, we often can formulate the question only when we almost know the answer, not before!

We shall postpone answering the question posed at the beginning - how justified are the claims of "reading His mind" - until later in the book. However, I hope it is already quite clear that Wheeler was right. Physics indeed is a magic window, our everyday reality is an illusion, and the quantum mechanical "illusion" is a reality. It is all marvellous and probably undeserved. As it often happens, the last words goes to Albert Einstein:

> *The most incomprehensible thing about the world is that it is comprehensible.*

Appendix A: Physics is Different - and *easier* with a few equations[2]

Most books on science for general audience attempt to get by with no equations at all, and I think that is a mistake - you will see on the next few pages how far you can get with a few simple equations. If an equation of any kind looks frightening, or if a symbol with an index is intimidating, you may want to warm up a little by reading the Appendix B on Scientific Notation first (in order to bribe you, I promise to give you a glimpse at Infinity at the end of that Appendix ...). I assure you that gaining the most elementary math skills will be very much worth the effort.

Why is there Something rather than Nothing?

There will be very little of real science in this book, but there will be some, and we may as well begin with a spectacular example. We will start with some very simple considerations, and we will see how quickly we get to rather esoteric heights - I promise that even readers with not even high school physics will progress, by next page, from what looks like a dreaded, boring physics lecture to something quite remarkable.

Perhaps the most famous equation in whole of Physics is Einsteins $E = mc^2$. The mass of a body is a measure of its inertia, i.e. of the extent to which the body resists attempts to change its state of motion. It also happens to be the measure of the force which the body experiences in gravitational field (incidentally: the equivalence of the inertial and gravitational mass led Einstein to his General Theory of Relativity). And Einsteins equation $E = mc^2$ tells us that the mass is also a measure of the energy content: mass m, when at rest, has energy mc^2, and equivalently, rest energy $E = mc^2$ corresponds to mass $m = E/c^2$.

In various physical, chemical or biological processes, energy is always conserved:

$$total\ energy\ of\ the\ initial\ state = total\ energy\ of\ the\ final\ state$$

A specific example: consider a simple reaction: one atom of carbon joins with a molecule consisting of two atoms of oxygen, and the result is a molecule of carbon

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[2] for Figures 1 and 2 please see www.phys.washington.edu/users/vladi/PhysicsFigures.pdf

dioxide, and energy. In this case, the energy is produced in the form of heat, and the process is the ordinary burning of coal.

$$C + O_2 \Rightarrow CO_2 + energy$$

Numerically, the conservation of energy is, as always:

energy of the initial carbon and oxygen is equal the energy of the resulting product plus the energy released

The law of conservation of energy is very fundamental: in the past, whenever we thought it might be violated, it always turns out we forgot to include a particular form of energy (chemical, nuclear, energy in a spring,).

So far so good, I hope. Now consider a system consisting of two components bound by a mutual attraction: take for example the Moon orbiting around Earth. The question is how does the total mass of the (Earth-Moon) system relate to the sum of the mass of Earth plus the mass of the Moon. The first reaction is likely to be that they are equal: after all, if you load a 1 ton pickup with a half-ton lawn mower, the whole thing will have 1.5 tons, right?

And then you recall I just discussed energy: clearly, the Moon is attracted to Earth (and Earth is attracted to the Moon), there is gravitational field between them, this field has some energy, and this energy, according to $E = mc^2$ corresponds to some mass. So now tell me: is the mass of the (Earth-Moon) system equal, smaller than or greater then the sum of the masses of Earth plus Moon:

$$m_{EM} = m_E + m_M \ ?$$

$$m_{EM} < m_E + m_M \ ?$$

$$m_{EM} > m_E + m_M \ ?$$

The understanding of this question is so important that I suggest you spend at least five minutes pondering it before turning the page.

Well, I tested this on a bunch of Physics majors and graduate students. About three out of four majors and one out of four graduate students quickly reply that the mass of the system is larger than the sum of masses - *"because the binding energy corresponds to some mass, too."* They get it right when they think about it some more, but it shows you that even a simple question like this is far from being trivial.

To see what is the correct response, consider what you have to do if you wish to split the system into its constituents - for example you want to remove the Moon from its orbit and place it somewhere far from Earth (so that it is no longer an Earth-Moon system but an independent Earth here, and an independent Moon somewhere else). Clearly you have to deliver energy to the system to accomplish this - the Moon is bound to Earth by gravity, and you have to convince it - say by hitting it with a giant golf club. So for this process, the law of conservation of energy says

$$E_{EM} + \ extra\ (binding)\ energy\ needed\ to\ break\ the\ system = E_E + E_M$$

where E_E is "rest energy of the Earth, R_M is the "rest energy of the Moon, and E_{EM} is the "rest energy of the Earth-Moon system. But since the rest energy is $E = mc^2$ in general, this means

$$m_{EM}.c^2 + binding\ energy = m_E.c^2 + m_M.c^2$$

which is the same as

$$m_{EM} = m_E + m_M - binding\ energy/c^2$$

In plain English, the mass of the system (m_{EM}) is *smaller* that the sum of the masses of the constituents ($m_E + m_M$)).

But the speed of light is a very large number, and - for the Earth-Moon system - the binding energy is small, because gravity is so weak. Therefore the effect is very small.

However, you can see that if the binding energy becomes larger, the resulting mass gets smaller. This is certainly counter-intuitive and perhaps interesting, but you are probably not impressed by all this - not yet. But keep thinking along the same direction. We see that the more strongly are two particles bound to each other, the *smaller* is the resulting mass.

What if you had binding so strong that the term

$$binding\ energy/c^2$$

became equal to the term

$$m_E + m_M$$

Wow: the two terms cancel, and the result is zero: $m_{EM} = 0$! Not only that, but the total energy is zero, too:

$$E_{EM} = m_{EM}c^2 = 0$$

I hope you agree that this starts to get interesting: you take two particles, each with non-zero mass (and therefore each with non-zero energy) and - if you bind them strongly enough - you get the total of zero: zero mass, zero energy!

But you say: this is just two academic particles - who cares about them. So you think some more, and say: wait a minute: the Universe is full of particles (some of them quite large, such as planets, stars ,) and they are all bound to each other by gravity. As we mentioned, gravity is very weak, but could it be that the overall binding of everyone to everyone is just sufficient to cancel all the masses of all the stars and planet, to produce net mass equal zero and net energy equal zero?

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That is the Central Mystery of Quantum Mechanics. In fact, it is more. As the Intelligent Design people like to say about evolution, Quantum mechanics is just a theory - more about this later. But what we have described is not result of any theory - it is an experimental fact (and a simple one to describe, if not to understand). So perhaps it should be called Central Mystery of Nature

I always start a course in Quantum Physics with an exposition like this, and students are always fascinated. “Professor”, they say, “this is so interesting. We should not proceed with all those equations we saw ahead in the textbook. Instead we should discuss this until we really understand this.” But I know better, and I reply: “Yes, yes, this is very interesting indeed, and if there is time at the end of the course, we will come back to this.”

Two things invariably happen. First, there is never time at the end of the course. More importantly, by the end of the course students have learned many useful things. They now know how to calculate all kinds of quantum magic, and most of them rarely if ever recall that the original mystery was never resolved.

Now, readers with some previous physics knowledge will point out that in fact there *are* things we do understand about all this. I mentioned the importance of placing the detector in the right position. What happens if we move it a little up or down? It turns out that as soon as we move it, clicks start to happen even when both holes are open. As we keep moving the detector, the frequency of the clicks keeps increasing, and at some position the number of clicks per second for both holes open is twice the number when only one is open. Thats what you would have expected to start with. But if you keep moving the detector, more and more clicks keep coming, until they come four-times faster than when a single hole is open. That is the maximum. Additional detector shift results in a gradual decrease in click frequency, until you reach a new position where clicks cease when both holes are open.

So it seems we are dealing here with some kind of a wave phenomenon, with an interference of waves coming through the individual holes. And indeed: in the rest of the course students learn about the psi wave-function, about the Schroedinger equation which governs it and how the solution leads to all kinds of extremely precise and useful calculations.

But the quantum wave is something very strange: we know how to use it, but we don't know what it really means. Since the celebrated Einstein-Bohr discussions in the 1920s, thousands of scholarly (as well as not-so-scholarly) articles and hundreds of books were written about its interpretation. We know that the value of the wave function at some position can be used to determine the probability of finding the particle at that particular position. But as soon as we find it there, the probability of finding the particle anywhere else must instantly become zero this is the infamous collapse of the wave function which is the first of the many non-local aspects of the Quantum Theory.

Many solutions and "interpretations of Quantum Mechanics" were proposed; some decidedly worse that the disease they were trying to cure. And recently, something exciting happened: the decades old, interminable debates (starting with Einstein vs. Bohr in the 1930s) were replaced by a pragmatic attitude: the paradoxes and mysteries were transformed into a technological resource, and the brand new fields of Quantum Computing and Quantum Information were born. We will have many opportunities to discuss the significance and implications of this development.

The Heisenberg Uncertainty, and the nature of Vacuum

In the last of the three specific mini-investigation we will start with one of my favorite subfields of physics - acoustics - and we will try to estimate the frequency of a signal depicted on Figure 2. It is a simple tone, starting from silence, and after some finite duration ending in silence again. The most precise way to determine the frequency is to choose some "reasonable" duration, count the number of periods during that time interval, and then to determine the length of one period by a simple division. For several reasons, physicists are very fond of Greek alphabet, and of indexing symbols. I know that this is disconcerting to many, but it is how all Uncertainty Relations are always printed, so you may as well get a glimpse of this notation. Here it is:

the duration of the signal (the "uncertainty in time") will be denoted by δ_t

the uncertainty in the frequency determination will be denoted by δ_f

the uncertainty in the number of periods will be denoted by δ_N

Apart from this "difficulty", everything else is a succession of several easy steps. However, the outcome will be quite non-trivial.

First: if the number of "wiggles" (i.e. number of periods) occuring during δ_t is estimated to be equal N, then the length of one period is simply

$$T = \frac{\delta_t}{N}$$

For the signal on the Figure, I have chosen $\delta_t = 13.7$ milliseconds, and estimated there to be $N = 6.3$ periods in that duration of time. Therefore my measurement of the period is $T = \frac{\delta_t}{N} = \frac{13.7}{6.3} = 2.2$ milliseconds $= 0.0022$ seconds.

Now, "frequency" expresses how many times the period occured per second, so if the duration of one period is T, then frequency is

$$f = \frac{1}{T} = \frac{N}{\delta_t}$$

In our case, our estimate for the frequency is $f = \frac{1}{T} = \frac{1}{0.0022} = 455$ Hz.

What is the *uncertainty* on the estimate of frequency that we have obtained? Well, the value of δ_t was my choice, and I can choose it as precisely as I wish (i.e. I can declare it to be $\delta_t = 13.700000000...$ milliseconds in our case.) However, the estimate of the number of periods N is subject to an unavoidable uncertainty ("margin of error") δ_N, i.e. the answer is $N \pm \delta_N$. The value of δ_N cannot possibly be as large as $\delta_N = 1$ – that would mean missing a whole wiggle, or adding one. On the other hand, it is surely impossible to do as well as $\delta_N = 0.01$. So let us settle on a "reasonable guess" of the "best possible determination" with $\delta_N = 0.1$. In our case, that means that the number of wiggles is known to be equal to 6.3 ± 0.1.

The implication of all this is that the final estimate of frequency has an uncertainty δ_f:

$$f = \frac{N}{\delta_t} \qquad \Rightarrow \qquad \delta_f = \frac{\delta_N}{\delta_t} = \frac{0.1}{\delta_t} = \frac{1}{10\delta_t}$$

In our example, we get $\delta_f = \frac{1}{10\delta_t} = \frac{1}{10\times 0.0137} = 7.3$ Hz, so that the frequency estimate is $f = 455 \pm 7$ Hz.

Multiplying both sides of the above general equation by δ_t yields the celebrated Heisenberg Uncertainty Relation:

$$\delta_f \delta_t = \frac{1}{10}$$

Had we applied the cosiderably more powerful apparatus of calculus, we would have obtained the relation in its correct form

$$\delta_f \delta_t = \frac{1}{4\pi}$$

Since $4\pi \sim 12 \sim 10$, our simple considerations produced an essentially correct result!

So far, all this is "only" acoustics, but it has all the aspects of the "real thing": the product of the two uncertainties cannot be arbitrarily small, i.e. if e.g. δ_t is small, then δ_f must be large, and vice versa. When you think about it, it explains why you can trill with a flute but not with a tuba - and there are other, more significant applications, too.

We get to the "real thing" by adding another, simple but ground-breaking equation to the mix. About 100 years ago, Max Planck (reluctantly) came to the conclusion that the electromagnetic radiation in a cavity is quantized in integer multiples of a "quantum of energy" which needs to be $E = hf$, where $h = 6.6 \times 10^{-34}$ (in metric units) is an exceedingly small constant - now obviously called "the Planck constant". Einstein subsequently obtained his Nobel Prize for applying the same equation on the photoelectric effect, and finally a young French doctoral student Louis de Broglie proposed that the same equation applies to everything, not just light: there is a "wave function" ψ associated with everything, and the relationship between the frequency of that wave function and the energy of that "anything" is

$$E = hf$$

Unlike Einstein, Dr.deBroglie never achieved anything much after getting his degree, but this alone was sufficient for him to get to meet the king of Sweden. And his Nobel Prize was well deserved - the wave function was found to obey a particular equation (Dr. Schrodinger → trip to Stockholm) and - a few years later - its meaning (at least for the purposes of calculations) was understood (Dr. Born → trip to Stockholm).

When you now recall the "acoustical" Heisenberg relation

$$\delta_f \delta_t = \frac{1}{4\pi}$$

you should feel an urge to multiply both sides of the equation by the Planck constant h. Using $hf = E$ and therefore $h\delta_f = \delta_E$, you get instantly the real quantum mechanical Heisenberg:

$$\delta_E \delta_t = \frac{h}{4\pi}$$

What is more, by a completely similar reasoning you get, for a particle of mass m (restricting ourselves, for simplicity, to particles moving with velocity v much smaller than the speed of light) a relation

$$\delta_v \delta_x = \frac{h}{4\pi m}$$

with an interpretation that it is impossible to assign to a particle both a value of its velocity as well as a value of its position - if the velocity is known, the position is not, and vice versa. This means that the concept of a "trajectory" loses its meaning, to emerge only as an illusion for particles (such as bowling balls, or people, ...) with mass m so large in comparison with the value of the Planck constant h that the right hand side of the last equation is, for all practical purposes, negligible. However, in the atomic and subatomic world, with tiny particles, the trajectories are replaced by a "quantum fuzziness" with which we have no direct experience, as explained by Richard Feynman.

But there is more, much more. The time-energy relation can be interpreted not only as "prohibitive" ("there shall not be a product less that $h/4\pi$") but also as a "permissive": violation of energy by an amount δ_E may be possible if the duration δ_t is short enough so that $\delta_E \delta_t = h/4\pi$. This leads to the current view of vacuum as constantly "boiling" with emission and reabsorption of particle-antiparticle pairs - of all kinds: electron/positron, proton/antiproton/ ... - with the duration of each occurance subject to the Heisenberg time-energy relation. Thus in modern physics, the vacuum, rather than being the simplest of all phenomena, is in fact the most complicated one.

The list of books for "general audience" on this fascinating subject is very large, and most of them contains no equations whatsoever. If you made the effort to understand the simple equations used here, you will be able to actually *understand* the books which would otherwise just grace your coffee table.

Physics is indeed different

The reader must have noticed that so far I have been only dealing with rather old concepts - no mention has been yet made of the Big Bang, the Superstring theory in n+1 dimensions, or the possibility of creating a baby Universe in laboratory. We will have a chance to talk about some of these topics later on, but quite remarkably, the points I am trying to make in this chapter can be made using concepts known since the late 1930s.

What are we to make of all this? Physics indeed is different. With what Wigner called "the unreasonable effectiveness of mathematics", we seem able to overcome what Weinberg calls an "equally puzzling phenomenon: the unreasonable ineffectiveness of philosophy". In spite of our limitations (starting with our size, utterly negligible in comparison witth the cosmic scale, and grotesquely large and awkward compared to subatomic scale) we seem able to "understand" more and more of Nature, from quarks to clusters of Gallaxies, and from the Big Bang 15 billions years ago to the fate of our Sun 5 billions years from now.

We do it in a strange way, though: we don't really know what we are doing. The late, great John Bell (about whom more later) and the late, great Arthur Koestler (about whom more later, too) both compared the procedure to sleepwalking. As mentioned above, Max Planck discovered the quantum in 1900. But he did not do it by any lofty and profound reasoning. By purely mathematical manipulation, he managed to get two different formulas to merge into a third one, which happened to agree with the experimental data so well, that he set out to investigate: "What would I had to assume to obtain the third formula directly from my physics assumption?". And he found the assumption - $E = hf$ - two months after he found the formula.

Similarly, Schrodinger did not know the meaning of the wave function ψ when he wrote down his famous equation for it. As mentioned above, again, it was another physicist, Max Born, several years later, who came up with the right interpretation.

And so it goes. As always, there are exceptions, most famous being Einstein's Special and General Relativity. But by and large, the process is not rational nor logical. It has been said that in physics, we often can formulate the question only when we almost know the answer, not before!

We shall postpone answering the question posed at the beginning - how justified are the claims of "reading His mind" - until later in the book. However, I hope it is already quite clear that Wheeler was right. Physics indeed is a magic window, our everyday reality is an illusion, and the quantum mechanical "illusion" is a reality. It is all marvellous and probably undeserved. As it often happens, the last words goes to Albert Einstein:

> *The most incomprehensible thing about the world is that it is comprehensible.*

Scientific Notation and a Glimpse at Infinity

In any discussion of Nature, we need to be able to deal with an extremely large range of physical quantities. For some strange reason, most authors of popular books seem convinced that the general public is not capable of comprehending a simple system of powers of 10, known as the "scientific notation". Even more bizarre is the apparent belief that expressing large numbers in the "ordinary way" such as "1,000,000,000,000,000,000" or "one hundred billion billion billion" provides any useful information at all. In this book, we use the scientific notation frequently and consistently. Readers who never encountered this reasoning should be prepared to spend some time digesting the subject matter in this Appendix: please be assured that it is most definitely worth your while!

The whole affair is very simple indeed:

$$10^2 = 10.10 \qquad 10^3 = 10.10.10 \qquad 10^5 = 10.10.10.10.10$$

and so on. Inversely:

$$10^{-2} = \frac{1}{10.10} \qquad 10^{-3} = \frac{1}{10.10.10} \qquad 10^{-5} = \frac{1}{10.10.10.10.10}$$

It is easy to see that each additional power of 10 means adding a zero, so that the large number 1,000,000,000,000,000,000 in the first paragraph is nothing but simply 10^{18} (just count the zeros).

It is also easy to see that multiplying two powers of ten is just addition of the powers: for example

$$10^2.10^3 = (10.10).(10.10.10) = 10^{2+3} = 10^5$$

Therefore, the second large number in the first paragraph above is one hundred billion billion billion $= 10^2.10^9.10^9.10^9 = 10^{2+9+9+9} = 10^{29}$.

For numbers smaller than 1.0, it is equally easy to see that it is the position of the first non-zero digit after the decimal point which gives the correct (negative) power of 10, so that for example:

$10^{-3} = 0.001 =$ one thousandth,

$10^{-6} = 0.000,001 =$ one millionth and so on.

And finally, any division by a power of 10 corresponds to subtraction of the powers, as in

$$10^6/10^2 = \frac{10.10.10.10.10.10}{10.10} = 10.10.10.10 = 10^4 = 10^{6-2}$$

We can summarize our results so far

$$10^2 10^3 = 10^{2+3} = x^5 \qquad \frac{10^6}{10^2} = 10^{6-2} = 10^4$$

by two general equations[3]:

$$10^n 10^m = 10^{n+m} \qquad \frac{10^n}{10^m} = 10^{n-m}$$

As an exercise, you should be able to evaluate

$$\frac{2 \times 10^{12} \times 6 \times 10^{-9}}{3 \times 10^{-7}} =$$

and express in plain English the numbers:

$$\frac{10^4}{2} = \qquad \textit{and} \qquad \frac{10^{-2}}{2} =$$

Some powers of 10 have nicknames (see below) but for really large or really small numbers there are no names - just the scientific notation.

Standard names and prefixes:

factor	name	prefix	example
10^{12}	trillion	Tera	TeV (tera-electronVolt)
10^9	billion	Giga	GW (gigawatt)
10^6	million	Mega	MΩ (megaOhm)
10^3	thousand	kilo	kg (kilogram)
10^{-1}	tenth	deci	dl (deci-liter)
10^{-2}	hundredth	centi	cm (centimeter)
10^{-3}	thousandth	milli	ms (millisecond)
10^{-6}	millionth	micro (μ)	μ g (microgram)
10^{-9}	billionth	nano	nm (nanometer)
10^{-10}			Angstrom (A)
10^{-12}	trillionth	pico	ps (picosecond)
10^{-15}		femto	fm (1 Fermi = femtometer)

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[3] Note the special case when $m = n$ in the second equation, which immediately leads to the otherwise hard-to-explain fact that $x^0 = 1$ for any value of x

A glimpse at Infinity

The usefulness of the scientific notation follows from the ease with which we can represent the huge ranges of various quantities mentioned above. So for example, we will soon discuss the range of distances from 10^{-34} meters (the "Planck scale") all the way to 10^{26} meters (the distance to the edge of the observable Universe). So if you start from the Planck scale and increase it million times, your get $10^{-34}10^{6} = 10^{-28}$. If you take *this* distance and increase it billion times, you get $10^{-28}10^{9} = 10^{-19}$ - still a ways from 10^{+26}!

There is an anecdote that nicely illustrates the enormous ranges we deal with. An article on cosmology in a scientific journal was followed by an Errata in a subsequent issue, apologizing for an inadvertent error: the main result was off by a factor of million. However, the Errata says, *this does not change any conclusions of our paper.*

And now, to introduce a *really* large number, I should mention that a well known software company is named after a misspelled nickname for 10^{100} which is called a googol: it is a 1 followed by one hundred zeros. This is a number much, much larger than the number of seconds elapsed since the Big bang (which is only about 10^{17}). You see that a number billion times smaller or billion times larger than a googol is 10^{91} or 10^{109} who cares that it is "not exactly googol".

Now, if you have a tendency for mischief, you might think: what about 10^{googol} ? That would be $10^{10^{100}}$: a 1 followed by a googol of zeros[4]. As you can read in Wikipedia, this number could not be printed even if all matter in the visible Universe was converted into paper and ink. Curiously, such a monster is important enough to have its own name: it is called a "googolplex", and even more curiously, it is (possibly) useful to think about numbers as large as this, as we will now see.

The part of Universe visible to us is called a "Hubble volume", and it is some 10^{27} meters across. In a serious (it is claimed) scientific paper, a calculation is presented showing that if the Universe is infinite, then we can expect, at a distance of some $10^{10^{115}}$ meters from us, A Hubble volume identical in all details to our Hubble volume. This means that in "that Universe" there is a copy of you reading this book and thinking what you are thinking[5]. Now, to get a glimpse at infinity, express that

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[4] Please note that $10^{10^{100}}$ is defined as $10^{(10^{100})}$ which is different from (much larger than) $(10^{10})^{100}$ - the first number has a googol of zeros; the second has "just" 1000 zeros (it is still an obscenely large number)

[5] The article begins like this: *Is there another copy of you reading this article, deciding to put it aside without finishing this sentence while you are reading on? A person living on a planet called Earth, with misty mountains, fertile fields and sprawling cities, in a solar system with eight other*

distance in terms of the size of ”our Universe”, i.e. how many of our Hubble volumes we would have to put next to each other to get to that place. It is a straightforward consequence of our elementary introduction to the scientific notation that instead of

$$10^{(10^{115})}$$

the answer is

$$10^{(10^{115}-27)}$$

Now try to visualize the difference between 10^{115} and $10^{115} - 27$! For “all practical purposes”, they are the same. This means that the distance to that ”mirror” Universe is, for all practical purposes, $10^{10^{115}}$, *independent* of whether you measure it in inches, meters, light years or in Hubble volumes! Billion billion billion times smaller or billion billion billion times larger - does not make any difference.

You may have to spend a few minutes to fully comprehend how incomprehensible this result is. And if you do, you will get a glimpse at the nature of infinity. Galileo, who was not exactly the most modest of scientists, was asked once if he thought the Universe was finite or infinite. He replied that *either* possibility was beyond his imagination.

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planets. The life of this person has been identical to yours in every respect ...

You probably find this idea strange and implausible, and I must confess that this is my gut reaction too. Yet it looks like we will just have to live with it, since the simplest and most popular cosmological model today predicts that this person actually exists ...

Curiously, it is quantum mechanics that allows this calculation to be made - Universe with continuous spectra of physical quantities would be much *more* complicated than our quantum Universe.