Twentieth Century Dichotomic Physical World
Classical and Quantum

Lajos Diósi*
Institute for Advanced Study Berlin

May 11, 1999

Classical Physics (sentimental introduction)
The Great Schism (quantum physics registers)
Paradox Quantum (quantum is totally heretic)
Which is the basic one? (to swallow the other)

*E-mail: diosi@rmki.kfki.hu

1 Introduction

Dear Fellows, dear Colleagues from other disciplines and from my discipline! In fact I should give a bilingual talk. First in mathematical terms and of references to standards of natural sciences and in particular of physics. Second, in common language to please everybody. I prefer to please everybody and I avoid blue puritanic mathematical equations. I show you only a few and just for illustration. I mean to illustrate the lapidarity of fundamental principles which are thought to govern the physical world.

I start with a sentimental introduction to what is called Classical Physics. As always in my talk, I introduce you into the notion of the discipline rather than into the discipline itself. I continue with the Great Schism caused by the appearance of Quantum Physics nearly 100 years ago. Again, I restrict myself to report the fact of the Schism rather than its breathtaking history of the schism. Then, an intensive course follows: I try to visualise the fatality of the schism, convincing you that quantum world is terribly different from ours. Finally, I talk about the emerging beleif that the quantum world is the basic one and it is more likely to swallow the old good classical principles.

2 Classical Physics

Let me awake your fellow-feelings for physics.

Do you know, what happens to a packing-cord when you stretch it out at both ends? It totally straightens, of course. It takes the same shape whatever material it is made of and whenever and wherever you stretch it again and again. What happens to a bullet when it is shot along the cord? It keeps going along it, whatever material the bullet is made of. But this is also what the light is doing. It goes along with the cord, the bullett, the fast foot- or biliard ball, the water-stream emerging from a jet. Everybody is doing the same: traveling along the same path. No wonder that this path has a distinguished name: STRAIGHTLINE, the second among the basic abstractions in natural sciences (If the more divine geometry itself is included into the family of natural sciences. Of course, the POINT is the first abstraction.)

First digression. The above flying things choose the straightline in the ideal cases. You should not snap the cord, you must consider the initial quick part of flights of the bullet or of the foot/biliard balls, and, in general, you must keep off objects from the path of them. SKILL AND GOOD TASTE are needed to make proper idealizations and to single out basic phenomena from the manifold of occasional ones. Physics, even theoretical physics, is an experimental science. Digression ends.

Coming back to our little ideal things mentioned just before, any curious intellectual must ask her/himself:

Why will all these so much different thinghs travel along the same line?

If you realize that this question is relevant then your symphaty for physics has been awakening. For it is physics where the issue and the answer belong to.

So, ask this relevant question again! Why will all these so much different thinghs travel along the same straightline?

The answer took centuries of observations and speculations. They have boiled down to a single principle governing the whole physical world:

EVERYTHING GOES ALONG THE SHORTEST PATH

Transparency: Hamilton, "Equations are nice!"

Enjoy this rule. In the ideal cases, this rule explaines why things [water drops, light, bullet, shape of cord] go along straightlines. But the basic principle tells you the trajectories for the non-ideal cases as well.

Transparency: shortest paths

Example 1.: stretched cord with obstacles (per definition)

Example 2.: biliard balls

Example 3.: light with reflecting obstacles

Example 4.: light with refracting obstacles

Transparency: Hamilton back

It is really amazing that we can cast our whole knowledge about physics into a single principle. Of course, if you memorize the principle EVERYTHING GOES ALONG THE SHORTEST PATH you cannot sit back and think that you know physics. You must learn (remember: skill and good taste) how to adapt the principle to less ideal cases, including cases which are far more generic then you could have any clear vision of straight motion in them. But the mathematical analysis shows that dynamics will always go back to motions along shortest paths in the properly defined abstract spaces.

Second disgression. In other disciplines, too, it happens that a single principle is proposed to explain everything and the diversity of detailed rules is left to the adaptation of the given principle to concrete and non-ideal cases. However, the original principle will often be dissolved in proliferating particularities and the whole deduction-adaptation process turns into an ad hoc phenomenology.

Why does deduction work better in physics? Certainly there are many reasons. I dont know them explicitely. But I point out certain useful conditions which hold in physics and perhaps nowhere else. Every physical PROPERTY has its MEASURE and this measure takes a REAL NUMBER as its VALUE. This value is unique upto the units we use (grams, kilograms, tones, for instance). This nice uniqueness does not usually exist for other disciplines. They study phemomena where properties sometimes have no measures, or the measure is not unique or, in many cases, the measure is just a matter of convention. Basic physical properties are, per definition, described by unique measures.

This helps a lot. The basic principle expands itself into mathematical equations. We compare the mathematical predictions to the real physical phenomenon which is described by measured values of physical properties. These latters are never measured with total precision. They are measured with finite precision and we always know this precision, too. The theoretical predictions fit to the measured real phenomena within the tolerance of the measurement precisions. If the measurement precision increases and new precise data would contradict to the theory then the theory should be corrected. This leads to more and more precise theories as well. In the past few centuries, the new precise theories did not deny the old ones. They incorporated them, and generalized them. Typically to the current state of art of physics during the past few centuries, a tremendous amount of phenomena used to be perfectly described by the contemporary theories according to the contemporary measurement precisions. Sometimes, physical principles are just slightly inferior to the contemporary precision of measurements and notions.

Digression ends.

Dear colleagues from all disciplines, this is what theoretical physics offers: a single compact powerful lapidary principle leading to 'perfect' theoretical predictions. We call it classical physics. It was achieved by Newton, Maxwell, and Einsein, to name the greatest heroes.

Speak about transparency

The adjective 'classical' celebrates, like in many other disciplines, the completeness, perfectness, and eternity claimed for the principles. But soon in our twentieth century, this noble adjective became just a restrictive category.

And now I arrive at the first milestone of my talk.

The decent principle EVERYTHING ... of classical physics holds for the so called macroscopic systems: planets, gun bullets, biliard and footballs, water drops, steam engine, human body and dust particles. Classical physics holds for whatever visible common objects, for the visible light itself, as well as for the invisible X or radio waves, electric currents, for all things which share one relevant common feature: ROBUSTNESS. Classical physics does hold for ROBUST phenomena. It does not hold for tiny FRAGILE microscopic, i.e. atomic and subatomic phenomena. ROBUSTNESS OR FRAGILITY, remember please this distinction.

Erstwhile, scientists learned distinguished atomic phenomena which did not fit to the classical principles. In classical physics the physical quantities take continuous values and their change in time is also continuous. In the world of atoms this is not so. Most typically, the energy of an atom or molecule does not take arbitrary values. It may take discrete [QUANTIZED] values which can not change continuously in time but jump suddenly into other discrete values. The classical physics explains but continuous values and continuous evolution in time. You can imagine how tremendous modification should have been done to the principles of classical physics in order to enable them to hold for these strange atoms as well.

Transparency: von Neumann, not yet, take in hand!

What happened in realty was a nightmare for the classical physics. It was being modified several times, deeper and deeper. Finally, a completely new principle emerged. The new principle, the so called quantum physics, describes the fragile atomic world 'perfectly', in the same sense as classical physics describes 'perfectly' the robust macroworld.

Speak about transparency

In the past century, the new quantum theory explained the whole of atomic, nuclear, and elementary particle physics, as well as the behavior of photons which are the elementary particles of visible light. The technological outcome is just as miraculous as the power of the theory itself. Think of electronics, computer-electronics, lasers, computer-tomographs, etc. These benefits are totally due to our knowledge of quantum physics.

We have classical principles for the ROBUST macroscopic phenomena and we have quantum principles for the FRAGILE microscopic phenomena. We dont have a unified principle for the whole of the physical world. We have two basic principles instead of one. Nearly 100 years ago the physical world (in our understanding) became dichotomic. And it has remained so. This is the Great Schism, end of first act, curtain falls!

Whiteboard: C and Q PRINCIPLES

In a peaceful scene of the second act, we do justice to the newcomer quantized principles and put them side by side with the old classical ones. Remind the classical ones:

EVERYTHING [ROBUST] IS DESCRIBED BY REAL NUMBERS AND GOES ALONG THE SHORTEST PATH IN AN ABSTRACT SPACE

This is valid for the robust part of the world. And now, behold, come the principles governing the tiny FRAGILE quantum phenomena:

EVERYTHING [FRAGILE] IS DESCRIBED BY MATRICES OF NUMBERS AND GOES ALONG THE SHORTEST PATH IN AN ABSTRACT SPACE

BUT:

THE MATRICES ARE NOT TESTABLE CONTINUOUSLY IN TIME

WHEN TESTED, THEY JUMP INSTANTANEOUSLY AND RANDOMLY

REAL VALUES OF PROPERTIES ARE OBTAINED FROM SUCH TESTS (MEASUREMENTS)

OUTCOMES ARE RANDOM, STATISTICS IS NEEDED

MOREOVER:

THERE ARE INCOMPATIBLE TESTS and INCOMPATIBLE PROPERTIES

PROPERTIES DONT HAVE ANY REAL VALUES BEFORE TESTS

What is that scandalous mess, compared to the clarity of classical principles? Why is that we cannot formulate the quantum principles in a more concievable way?

Whiteboard: Penrose, take him!

We are classical beings. We sense and manipulate robust macroscopic things, we dont sense tiny atoms. For us, classical physics is the natural one. The quantum physics is particularly strange from the classical viewpoint. Our mind is being in trouble to conceive the abstractness of quantum world. It is not possible to give an easier form to the quantum principles without restricting their generality or without running into controversies. Quantum world is really so deeply different from the classical world that the governing principles can not be told on the same language.

Allow me a pa'rabola: We discovered a tribe (the fragile atomic world) which speaks a strange language that we ourselves can never talk. Talking TO these foreign beings we use always our human language and we know how they will react because we learned their foreign logic. We also learned the structure of their language, and we can translate well defined fragments of their speach. Complete texts are not transferable into human language. But these laconic fragments, used systematically, can succesfully disclose the tribal life for us. Still we are desperately unable to speak their language, not because of organic reasons but because of our different logical systems. This is why we are terrified by the quantum language.

We dont take language courses this time. I'm only trying to guarantee for you that you will sense that the quantum world is so fatally different. For the past century, there have been a successful scientfic RACE to find PARADOXical predictions and phenomena in quantum physics. Who can produce the most incredible quantum features or even effects? I mention two very recent ones which have practical implications, and I end up with two other ones wich have the deepest conceptual implications.

1) *Quantum cryptography is perfectly safe.* Cryptography is the art of transmitting information in such a way that in cannot be understood by an op-

ponent who might intercept it. The problem is that we have to distribute a cryptographic key (a secret sequence of numbers) to several people, by using an insecure communication channel subject to inspection by a hostile evesdropper. If only classical means are used, this is an impossible task. Quantum phenomena, however, provide various solutions. For instance, using single photons to transmit the secret data can be made completely secure. No eavesdropper can steel the information because single photons are so fragile that no interception would remained unnoticed. If you are the eavesdropper, you intercept a secret letter, you break the seal, read it, then you have to re-seal and forward it to the original adressee. Otherwise he disclose that something wrong happened. If the letter contained suitably prepared fragile photons, you can not re-seal it, you will always be disclosed. Such cryptographycal methods are being under development, secret "photons" are being sent through commertial optical cables some 10km's away.

2) Quantum computers are a different cake. They have not been built so far. But, in principle, their capacity would open a new era of computation and problem solving. There are speculations that our brain is a quantum computer. In any case, mathematical evidences show that the 'heretic' logic of the quantum makes it possible that we run such effective algorithms which were not possible on classical computers.

3) Quantum non-locality was discussed by the the late John Stuart Bell. First, he formulated his (famous) inequalities for certain type of statistical correlations between two distant classical systems. If two systems do not communicate with each other, these correlations must not exceed a certain limit. This is valid for classical systems. In the quantum world, quantum properties of distant systems MAY be correlated stronger. No classical properties could ever exceed the limit established by Bell, but quantum properties do. This is a fancy

4) Quantum properties

With this item, we return to the most heretic feature of the FRAGILE quantum world. As I mentioned already, there are properties in quantum world which are not compatible with each other, i.e. we can not test them simultaneously. The notorious example is the position and the velocity of an atomic particle. If I test the position I can not test the velocity and vica versa. If in a test I ascertain the value of position then the velocity will be left totally uncertain, and vica versa. Most of you have heard about the corresponding Heisenberg uncertainty relation. This is a generic rule of the quantum world that from a given set of properties, say A,B,... some are not testable simultaneously.

Such things make quantum world really different. You are nodding, dont you? But this is not the end of the story! This is not the deepest difference.

ASSUME that nine fellows have questions, each has one question, and the questions concern the properties A, B, ... I, J. I arrange them in a 'matrix':

$$\begin{matrix} A & B & C \\ D & E & F \\ G & I & J \end{matrix} \tag{1}$$

The possible answers are YES or NO for each queries, for example this

$$\begin{matrix} Y & Y & Y \\ Y & Y & Y \\ Y & Y & Y \end{matrix} \qquad \begin{matrix} Y & N & Y \\ N & Y & Y \\ Y & Y & Y \end{matrix} \qquad \begin{matrix} Y & N & Y \\ Y & N & Y \\ Y & Y & Y \end{matrix} \tag{2}$$

All 9 fellows are equally curious but their questions can not be put simultanesously. ASSUME that the compatibility rules are the following: all 3 questions in one row or in one column are compatible. No other combinations are compatible. So they can ask only 3 questions at a time. ASSUME, on the other hand, that the fellows questions are not independent, they are redundant. Two questions are independent, the third answer follows from the two. For A, B, C the possible results are always constrained for minimum 2 YES's, i.e. maximum 1 NO. All other triple queries are constrained in the same way. Then, before anyone of the 9 fellows would ask anything, it is sure that the first and second sets of values are possible while the third set is a priori not.

Let us play with assumed redundancies. If we change one of them, sometimes we get contradictions. The simplest case is the following. We change only one redundancy constraint, namely for the fellows who ask for the properties C, F, J, i.e. in the last column. We ASSUME that their questions are redundant in such a way that the answers are always minimum 2 NO's and maximum 1 YES. All the other constraints be as before: minimum 2 YES's and maximum 1 NO. This is a contradictory, incompatible set of constraints. It is simply impossible to fill in the matrix in such a way that each row and column contains maximum 1 NO but the last column contains maximum 1 YES. Try it, you'll fail.

Our natural conclusion must be this: Such 9 questions, asking for such 9 constrained properties, do not co-exist. This is totally a right conclusion when the properties belong to Robust classical systems. But for the tiny quantum systems it turns out to be that such 9 questions concerning the 9 (interdepent) properties do exist! The logical resolution of this apparent controversy is possible. But you have to be very patient, you have to give up something extremely natural. In the robust classical world, the test of a property gives the value (i.e. a number) of the property but, be sure, the property's value existed already before the test. In the tiny quantum world the properties have usually no values before they are tested. Their values only emerge by the tests themselves.

A careful analysis leads to an ultimate verdict: NO VALUES OF PROPERTIES IN THE FRAGILE MICROWORLD EXIST PRIOR TO TESTS. This is the shearest contradiction to the concept of classical physics of ROBUST phenomena where EVERYTHING is always having a measure, a value. But if you are careful listeners to my talk, you may go further: THE LACK OF OBJECTIVE VAULES OF PROPERTIES IN THE FRAGILE MICROWORLD is the shearest contradiction not just with classical physics but with our common logics, too. The logics of the FRAGILE quantum world challenges our naiv notion of objectivity. So heretic is the quantum. This century has seen no reconciliation with the classical. The second act is ending now.

In the third act we see again the dichotomic fin-du-siecle physical world. On the left, there is the ROBUST world of the macrocosmos, including galaxies, planets, but also the apple falling from the tree, the waterflow, the wind, the electricity, even the heat, ... all thought to be governed by the same fundamental principle. And here is the human being, as well. He knows his body belongs to the robust classical world. But in his robust body he has got tiny fragile brain functions. So he seems a bit helpless. Roger Penrose wish definitely to get away from the classical world into the quantum.

On the right, there is the FRAGILE microcosmos, single atomes, molecules, nuclear particles, a few photons, but also tiny FRAGILE phenomena occuring in otherwise ROBUST bodies, for instance the very tiny and fragile collective motion of billions of atoms in a piece of solid at low temperatures. All these FRAGILE phenomena are governed by the same heretic quantum principles.

In the center, we see the wall, dividing our beloved world into two. We talked about the particularly interesting way how things communicate through the wall. It used to be a complicated task. Conveying the ROBUST influence of the ROBUST classical world upon the FRAGILE atomic world makes little problem. But the interpretation of the influence of the FRAGILE world upon the ROBUST one is an issue. Indeed, the present principles of quantum physics refer to something strangely subjectiv. The ROBUST world is only influenced if it applies TESTS or MEASUREMENTS on the properties of the FRAGILE quantum world. The concept of TEST or MEASUREMENT may be unrelated to the human subject, it may even be spontaneously arranged by the Nature, TESTs and MEASUREMENTs in this sense are continuously being done and assuring the spontaneous communication between the two worlds. But their internal rules are totally different, which makes the world dichotomic. And, to be honnest, the funny 'anthropic' reference to TESTS and MEASUREMENTS can not really be removed from an axiomatizable (lapidary) theory.

How can we copy with our dichotomic understanding of the phyical world? How are we doing and where are we going? In the early days of the Great Schism, it was really thought that small atomic systems, or even subatomic structures and elementary particles, obey the quantum principles while the 'bigger' sructures remain under the rule of the classical physics. However, the notions of fragility and robustness have never been uniquely defined. The wall between the robust and fragile is movable. Quantum principles are being extended for larger and larger number of atoms and the results are in perfect agreement with the experiments. In short: we believe that the quantum principles can be extended for any large systems. The robust properties of large systems can equally be calculated from the quantum principles in spite of the fact that these principles were originally recognised for the fragile microworld. And this leads to an extreme hypotheses: the quantum principles are the only real (and necessary) ones. The whole physical world is quantum. The classical principle EVERYTHING ... follows from the quantum principles if we ASK for the ROBUST properies of the quantum world. The quantum world swallows the old classical one.

If this hypotheses becomes true, heretic rules will govern everything. There is a little problem, however. Now the old good classical properties of planets, soccer and biliard balls, water drops and flows, X and radio waves, heat, the human body and the dust particle become quantum properties. While we know that they are genuin ROBUST phenomena with ROBUST properties, in the quantum world these properties have no real values. They must be tested first. But, as a rule, tests should be made by ROBUST classical things which, since everything is quantum, dont exist at all. Who or what makes the first test? Who or what will build up the ROBUST classical things from the potentiality of the FRAGILE ones? If everything were submitted to the heretic rules then all classical entities (physical properties, events, time, *etc.*) would disappear as fundamental entities. To recover them, this is a hottest issue in contemporary theoretical physics. Which latter is also being bilingual but its first language is blue puritanic mathematical equations and only its second language is the one on which I gave my talk.

Transparency: Helgoland????