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# Making Introductory Quantum Physics Understandable and Interesting

**It is well known that the average student of physics finds quantum physics (QP) difficult. Special efforts are therefore needed to make the subject both understandable and interesting.**

**To make QP more easily understandable, we identify the main elements of cognition involved in the study of QP, and point out how they are different from those involved in the study of classical physics. We find that drawing the student's attention to the special features of the very act of cognition in QP makes the subject more comprehensible.**

**To make QP interesting and exciting, we feel it is essential to give the subject a human touch, e.g. by integrating into the process of teaching biographical notes on the discoverers of the subject.**

## Introduction

Quantum theory is one of the foundations of physics. Yet the average student finds it extremely difficult to understand. Incomprehension leads to lack of enthusiasm and to the complaint that the "teacher does not know whether he knows what he is talking about".

The difficulty in learning QP is primarily due to the following reasons:

1) The student is brought up in the tradition of classical physics (CP), the fundamental concepts of which – determinism, causality, etc – are very convincing. Having accepted the fundamental concepts of CP, he finds it difficult to adjust to those of QP – uncertainty, probability, etc.

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Teaching quantum physics, elements of cognition.

2) The two standard mathematical approaches to QP – Heisenberg's matrix mechanics and Schrödinger's wave

mechanics – are so different that the student finds it difficult to understand how they can describe the same physics.

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3) In general no reliable visual images can be formed of the processes described by QP.

4) QP is often usually taught historically, and the beginner finds it difficult to connect the various stages in the evolution of the subject into a coherent whole.

Keeping these difficulties in mind, various groups in different parts of the world are carrying out research on making QP both understandable and interesting. The University of Maryland Physics Teaching Research Group is involved in two projects to study student understanding of QP and to build a model course for scientists and engineers [1]. The Visual Quantum Mechanics project at Kansas State University is concerned with presenting QP using aids other than classroom lectures, e.g. interactive visualizations and activity-based environments [2].

The scope of this article is restricted to suggestions on making QP more easily understandable and interesting in the usual classroom-teaching approach.

## 2. Making Quantum Physics Understandable

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A typical classical phenomenon may be understood as follows – various manifestations of a single phenomenon, e.g., apples falling, stones following certain trajectories, planetary motion, are experienced directly through sensory perception. Then experiments under controlled conditions may be performed to isolate and better appreciate certain aspects of the phenomenon, and if possible to see the unity between different manifestations of it. This gives rise to a certain image of the phenomenon – motion of massive objects under the influence of a mass-related force. The next step is the development of something like Kepler's laws, which embodies in mathematical form the essence of some manifestation of the phenomenon, e.g., planetary motion, without providing any conceptual basis for it. Then comes the discovery of the concept that underlies the phenomenon, e.g., gravity. This concept is given mathematical form, i.e. it becomes a theory, and this mathematical theory is united with other theories related to the motion of objects, e.g. Newton's laws of motion, leading to a complete description of all manifestations of the phenomenon. This theoretical framework now suggests various experiments that can be done to corroborate it or to refute it.

Thus the classical chain of cognition is as follows:

Phenomenon → Controlled Observations → Image → Formula → Concept → Theory → Experiments

Consider, on the other hand, what happens when we try to understand a phenomenon that is essentially quantum in nature, e.g. transitions between energy levels in an atom. The phenomenon itself is inaccessible to human sensory perception. What is observed is a manifestation of the phenomenon, e.g. spectral lines. At this stage, the phenomenon itself is unknown. Controlled observations lead to a working formula, e.g. Rydberg's formula, but there is as yet no understanding of why this formula holds. Then comes a concept, the Bohr model of the atom, which, though it is deeper than the working formula that preceded it, is recognized as incomplete by its very discoverer. It nevertheless is fundamental in that it connects the manifestation, spectral lines, with the phenomenon underlying it, atomic transitions. Eventually, there comes a definitive theory of the atom. It comes originally in two forms, Heisenberg's matrix mechanics and Schrödinger's wave mechanics, the connection between which is far from obvious. Their unity is finally shown by Schrödinger himself. They are then interpreted in an attempt to form an image of the phenomenon. The image suggested by Bohr's model is found to be incorrect: the reality is far more subtle, so subtle in fact that no completely reliable image of the phenomenon of atomic transitions has ever been found.

In the quantum chain of cognition, the image of the phenomenon, which is so essential to the classical chain of cognition, comes not just at the end but turns out to be unreliable.

The quantum chain of cognition is thus seen to be as follows:

Phenomenon "Image" ← Experiments ← Theory ← Concept ←
Formula ←Controlled Observations on
Manifestation of the Phenomenon
↑

In the quantum chain of cognition, the image of the phenomenon, which is so essential to the classical chain of cognition, comes not just at the end but turns out to be unreliable. To someone trained in CP, the absence of a reliable image in QP is the biggest hurdle to its comprehension.

## 3. The Elements of Cognition

In this section we touch upon some of the elements of the classical and quantum chains of cognition, highlighting the important differences that the teacher should point out to the student.

### 3.1. *Phenomena*

In CP the phenomenon itself is accessible to sensory perception whereas in QP only a manifestation of the phenomenon can be observed. The boundary between these realms can be thought of in terms of a fundamental constant that emerges in QP alone. Quantum phenomena, from this point of view, are seen to be those in which Planck's constant $h$ plays an important role. The trajectory of a cricket ball is described by CP because its action is much larger than $h$ whereas the 'trajectory' of an electron is described by QP because its action is comparable to $h$. CP is in this sense recoverable from QP in the limit $h \to 0$. Depending on the level of sophistication of the student, the connections between QP and CP can be made in different ways: perhaps the most

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beautiful, powerful and intuitive way to bring out the essentially quantum nature of the world, from which the classical world emerges as a limit, is to talk about the path-integral formulation of QP.

### 3.2. *Experiments and Observations*

Experiments and observations entail measurements, and the very concept of measurement is profoundly different in QP and CP. In CP what is measured is already there, whereas in QP it comes into existence, in some sense, during measurement. The 'collapse of the wave-function' associated with the measurement process in QP is still not completely understood. The student can at this juncture be introduced to various ideas of what happens when a measurement is made in QP, e.g., decoherence, the many-universe interpretation, etc.

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The uncertainty principle, wave-particle duality, and the impossibility of measuring both position and momentum simultaneously should be discussed not just as theoretical ideas but in light of experiments that can be done to illustrate them, e.g., experiments on electron diffraction. Some of the experiments that were seminal to the development of QP, e.g., G P Thomson's experiment on the wave nature of electrons, can now be done in an undergraduate laboratory. Wherever possible, demonstrations on fundamental ideas like the wave nature of particles should be integrated into the teaching programme.

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Another kind of 'experiment' that the student of QP needs to get used to is the 'thought experiment' (gedanken experiment). The gedanken experiments that Einstein devised to refute QP, in his debates with Niels Bohr on the ultimate truth of the quantum approach to physics, have become a part of the lore of the subject. Other famous thought experiments include Jeans' cube, to argue for the equipartition theorem in thermal radiation, Heisenberg's gamma-ray microscope, to disprove the concept of a trajectory for an atomic object, Schrödinger's cat, to highlight the paradoxical nature of macroscopic superpositions in QP, and Bohr's ideal box, to disprove Einstein's objection to the time-energy uncertainty relation, etc. [3].

Doing a thought experiment is necessarily an act of imagination. An average student of physics finds this difficult and the teacher must therefore take him through it very carefully, explaining the background and the circumstances in which the need for them is felt.

In qauntum physics complex numbers are used not to achieve economy and elegance but because they are essential to the theory.

### 3.3. *Formulas and Equations*

To most students who encounter QP after introductory courses in classical physics, it is mathematically formidable. We list below some of the mathematical concepts that most students find difficult.

The wave function is necessarily a complex quantity. It is important to emphasize that in QP, unlike in classical theories like that of electromagnetic radiation, complex numbers are used not to achieve economy and elegance but because they are essential to the theory.

Wave mechanics is perhaps the most accessible of the various approaches to QP, since it describes QP using the kind of mathematics that a student should have encountered already in classical electrodynamics and optics – partial differential equations, boundary-value problems, and Fourier analysis.

In more advanced treatments of QP the student encounters difficult ideas like Hilbert spaces, operators, etc., the connection between which and the physics they describe are far from obvious.

### 3.4. *Concepts*

Far more difficult than the mathematics of QP are its concepts. We list below some of the concepts that most students find especially difficult to understand.

Some concepts peculiar to QP, unconnected with anything encountered in CP, are matter waves, representation of particles as wave packets, interpretation of the wave function as a probability amplitude, representation of dynamical variables as operators, probability current density, tunnelling, and uncertainty relations.

Some concepts learnt earlier in CP take on new meanings – an atom is no longer a hard spherical object, light is no longer the classical wave of Maxwell's electromagnetic theory, motion is no longer what it was in Newton's mechanics.

Some concepts essential to CP are discarded in QP, e.g., the idea of the trajectory itself is no longer meaningful in QP.

Concepts that are completely different in CP come together in QP, e.g., wave and particle.

Some concepts become much deeper in QP, such as the principle of linear superposition. In CP, an oscillating string is usefully regarded as being in a superposition of its eigenstates or normal modes. In QP we think of a physical system as existing in a superposition of the eigenstates of the operator corresponding to the dynamical variable that we seek to measure – until the moment when a measurement is made, when it collapses to one of the eigenstates of the operator. This idea is directly connected with three other important concepts in QP: representation of dynamical variables as operators, the uncertainty relations corresponding to non-commuting operators, and measurement.

The representation of dynamical variables as operators is perhaps one of the biggest stumbling blocks for a beginning student of QP. It is important to emphasize that what is measured is not the operator but one of its eigenvalues – it is in a sense the spectrum of measurable eigenvalues of a dynamical variable along with the eigenfunctions that defines the operator corresponding to it.

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The fact that the uncertainty principle is deeply embedded in QP cannot be understood completely so long as one talks of it only in terms of disturbing the system while making measurements, important though that is. The student must be able to see that an uncertainty relation between two dynamical variables, e.g., momentum and position, is inevitable because the operators representing them are non-commuting.

Measurement is completely different in CP and in QP. In CP measurement reveals the system as it is, whereas in QP measurement causes the system to collapse. How exactly this 'collapse of the wave-function' occurs is still not understood, and this must be emphasized to the student.

The variety and richness of the concepts in QP are such that it took the founders of QP more than twenty-five years to understand them. It is not surprising, therefore, that a beginner should find them confusing. It is important that the teacher takes an approach that logically connects the various concepts into a whole, instead of discussing each one in isolation. They should be seen as arising out of the fundamental principles of QP. At the same time it is important that the students appreciate how the concepts came into being, and this requires some appreciation of their history.

### 3.5. *Images*

In the initial stages of learning QP, it is perhaps inevitable that the student should intuitively form images of the entities and processes involved, e.g., an electron cloud or a matter wave, quantum jumps, etc. However, it is essential that the student eventually be weaned away from such image-making. As physicist Paul Davies has rightly cautioned, "It is impossible to visualize a wave-particle. So do not try." Anyone who wishes to work with QP must eventually teach himself how to cope with image-free concepts and their mathematical representations.

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## 4. Making Quantum Physics Interesting

Considering how difficult it is to understand QP, it is important that the subject be made accessible in every way possible. One way to make it less remote and awesome is to emphasize the human element in the process of its discovery. We can learn much about this element in the discovery and development of QP from the writings of those who contributed to its development, e.g. Einstein [4], de Broglie [5], Heisenberg [6], and Feynman [7]. There are in addition many excellent books on the subject by writers such as Hofmann [8], Gamow [3] and Styer [9]. When we learn about the human beings behind the physics, we learn something about the scientific method that no finished theory can teach us – the mistakes, the confusion, the opposition, the guesswork, the coincidences, and the leaps of imagination that went into the process of discovery.

### 4.1. *Boldness in Hypothesis*

A revolutionary hypothesis always faces opposition in the beginning. What is 'obvious' now might once have been laughable. The path-breaking concept of matter waves due to Louis de Broglie was thought so illogical and amusing that it was dubbed *la comedie francaise.*

The concept of the quantum originated in Planck's theory of radiation. Bohr had the insight to apply it to the apparently unrelated problem of the atom. Planck's own hypothesis, which gave birth to QP, was such a complete break with the classical way of thinking that it must be regarded as one of the boldest scientific steps ever taken.

Einstein's reaction to Bohr's postulates was deeply pessimistic – "If this is correct it signifies the end of physics as a science."

### 4.2. *Coincidences*

Sir J J Thomson established the 'particle nature' of the electron. Thirty years later his son G P Thomson proved the 'wave nature' of the electron. Both were awarded Nobel Prizes for their discoveries.

Schrödinger's discovery of wave mechanics followed Heisenberg's discovery of matrix mechanics but the two were discovered independently of each other. In fact it was not obvious to either creator or to most others working in the area that the two theories were in fact connected. Dirac was aware of Heisenberg's discovery when he wrote his fundamental papers on QP – casting it in the language of vector spaces and operators, with Poisson Brackets as defining quantities – but his approach was so deep and prescient that one gets the feeling that he could well have developed all of QP on his own.

### 4.3. *Guesses, and 'Chance' Discoveries*

Chance discoveries always create a bigger impression than planned ones. Davisson and Germer's discovery of the diffraction patterns of electrons was accidental, but placed de Broglie's matter waves on a firm footing.

When Heisenberg first hit upon the idea of using matrices to represent physical quantities, he did not know what a matrix was! He had to work out the rules for himself on the basis of the physics that the matrices were required to embody.

Schrödinger's equation seems an almost miraculous act of guesswork. He credited Einstein with giving him an opportune 'flick on the nose' by pointing out the importance of de Broglie's matter waves and adding that there must be an equation that governed their evolution.

Lest the student get carried away with the possibilities of chance discoveries and guesses, it may be useful to remind him of what Pasteur said – that chance speaks only to the mind that is ready to hear.

### 4.5. *Assessment of Discoveries in Historical Perspective*

Telling stories about the birth of QP may arouse the interest of the student, but it is important that he should eventually be able to see the theory from the standpoint of today's working physicist – as a working theory, with its strengths understood and its problems appreciated.

## 5. Conclusion

Ponomarev has expressed the importance of studying QP as follows:

> Quantum Physics has given decisive touches to the present picture of physical reality···. In studying quantum physics a person acquires much more than special skills enabling him to design a laser or nuclear reactor···. Knowledge of quantum physics leaves ineradicable traces in one's consciousness. This abstract knowledge once acquired irreversibly influences the whole subsequent life of a person. It influences his attitudes towards physics, towards other sciences and even his moral criteria. [10]

For this to happen, it is important that anyone teaching QP at the introductory level should make every effort to ensure that the student is drawn into the subject rather than being turned off by it.

## Suggested Reading

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