Quantum mechanics: a systemic component of the modern physics paradigm

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This article presents an epistemological approach to quantum mechanics teaching.

The 20th century is characterized by the prevalence of a radically new scientific viewpoint for physical phenomena, a new 'paradigm' in physics, according to Kuhn's epistemological perception. In particular, the development of quantum mechanics (QM) shapes a *new worldview* as it introduces basic assumptions and images that provide a totally new way of thinking about the world.

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We consider that physics education has to meet today's demand for a qualitative approach to the QM worldview. An effective answer to the corresponding instructional problem might allow the basic ideas of QM to be accessed at a very early stage of physics education. This fact (i) might prevent the introduction of the scientific content of modern physics in ways that provoke serious misconceptions, (ii) might enable students who are not willing to attend specialized science training to reach the core ideas of a theory that introduced radical modifications into human thought and (iii) might lead students to form a *unified image* of microscopic and macroscopic phenomena, compatible with the scientific one.

We believe that an educational strategy aiming at a qualitative approach to QM needs a stable epistemological and educational foundation. We aim to show here that such a strategy has the potential to overcome the difficulties that characterize the whole task.

Motivation and data

Considering that the first step in an effort to reform science education is the development of teachers' efficiency, we carried out a project in the Pedagogical Department of Athens University aiming to lead teachers to a qualitative approach to the QM conceptual system.

The investigation of teachers–learners' initial knowledge confirmed the results of other relevant projects, indicating that their main misconceptions appear to be the result of their pre-/in-university traditional instruction, which provokes the overlapping or mixing-up of the conceptual frameworks of classical physics (CP) and QM and which imposes the deterministic worldview stemming from Newtonian physics.

We consider that these misconceptions form, by nature, *epistemological obstacles* to the acquisition of modern physics knowledge.

Aiming to overcome these obstacles, we created an *instructional model* based on premises that meet an almost general acceptance in the area of cognitive science and on a deep research process into two parallel fields: the field of history and philosophy of science and the field of modern technology.

The empirical implementation of the model and its evaluation process have lasted three years and led us to a quite global approach to physics instruction that comprises QM teaching. In this paper we describe:

- the basic 'cognitive' assumptions on which our instructional proposal is founded,
- the epistemological–pedagogical view that forms the context of our proposal,
- the basic points of our gradually formatted theory labelled 'Levels of Reality',
- the design of the instructional process permitting the implementation of our theory into concrete training courses, and
- a brief description of the implementation process and some general conclusions.

The leading assumptions for the learning process

The conclusions of cognitive science led us to accept the following assumptions concerning the learning process:

(a) Learning is a *search for meaning*. Therefore, the instructional process should start with learners' already formed mental-cognitive structures in order to achieve 'meaning construction'.

(b) Learners' initial cognitive structures might be compared to inaccurate but more or less *coherent* 'scientific theories' as they consist of assumptions and images that provide the explanatory context for thinking about the world. Consequently, the instruction process has to replace them with structures of scientific content that ensure a relevant context.

(c) Based on sensory perceptions and widely spread social beliefs, the initial assumptions and presuppositions of learners are strongly held.

(d) The instructional process should lead learners to 'build' their new 'scientific-cognitive structures' by means of a *radical* or *weak* reconstruction. The kind of reconstruction demanded is defined by the characteristics of their initial knowledge. If that knowledge is inadequate or, moreover, prevents the acquisition of new knowledge, a total/radical reconstruction of learners' initial knowledge should take place. On the contrary, if that knowledge is sufficient to deal with new scientific content, new information can be added to the poor knowledge background during a weak reconstruction process.

(e) Meaning requires understanding *wholes* as well as *parts*. Thus, parts might be understood in the context of wholes. Therefore, the learning process focuses on *primary concepts*, in the context of a concrete scientific theory, not isolated facts.

General epistemological thesis

The following assumptions underlie our entire educational perception and shape its epistemological framework.

(a) The educational process should communicate the contemporary *'unified scientific paradigm'* that includes: first, the *scientific content*, that is, the body of knowledge accepted by the contemporary scientific community and, second, the *scientific inquiry*, that is, the methods and activities that lead to the acquisition and development of scientific knowledge.
(b) The scientific content is the central focus of the instruction. It forms our understanding of nature on the basis of science.
(c) An adequate design of the educational process should accurately determine the basic characteristics of the structure of the scientific content which is intended to replace the learners' initial cognitive structures or which forms the Structure–Target of the instruction.
(d) The educational 'building' of the scientific content has to be founded on the basic aspects of the nature of science and to be influenced by the history of science. The whole structure has to promote the understanding of the values/assumptions of scientific knowledge and the processes by which that knowledge was created and developed.

Levels of reality

An epistemological–instructional 'building' of the scientific content

As already mentioned, the basic misconceptions of teachers–learners' knowledge on QM items appear to stem from the overlapping or the mixing-up of the conceptual frameworks of CP and QM. We considered that a possible way to deal with that situation was to form a structure of the selected scientific content that introduces CP and QM as two *totally independent conceptual systems* and, at the same time, relates these conceptual systems in such a way as to make visible the unified image of the natural world accepted by modern science.

In order to solve that problem, we carried out wide epistemological research on the diverse ways in which scientists study natural phenomena and propose explanations. The whole process led us to a *context approach* to physics knowledge.

The structure of the scientific content that we propose [1] classifies physical phenomena into distinct 'Levels of Reality'. The following analysis refers to the 'Newtonian Physics Level' (NPL) and 'Quantum Physics Level' (QPL).

(a) Each level forms a distinct *conceptual network* corresponding to a particular *scientific paradigm*. A conceptual network is a system of concepts (*nodes* of the network) and of relations among them (*links* of the network). Each concept acquires its meaning only in terms of the relations that the system itself *as a whole* institutes between it and the other concepts. For example, in NPL, which corresponds to the Newtonian physics paradigm, the concept of 'force' acquires its meaning through its intrasystemic relations to the concepts of 'material point', 'mass', 'instantaneous acceleration', 'momentum', etc.
(b) *Physical laws* are mathematical expressions that represent the relations that tie together the physical concepts into a system. The theory corresponding to each level imposes a *covering law* or a limited number of covering laws (for example, Newton's laws in NPL and the Heisenberg Uncertainty Principle or Schrödinger equation in QPL) that form the *explanatory framework* of that level and they impose adequate *reasoning pathways* for the interpretation of physical phenomena.
(c) Each level contains *secondary laws* that particularize the *covering law(s)* and associate them with *concrete aspects of reality* by forming appropriate *theoretical models*. For example, in NPL, Newton's inverse square gravitational law, stemming from Newton's covering laws, forms the theoretical model of the planetary system.
(d) The theory of each level adapts natural objects into a particular *ontological status*, lending them special properties and behaviour. Later in this paper we give an account of the 'ontological properties' of 'Newtonian objects' and 'quantum objects' belonging to NPL and QPL respectively.
(e) The proposed structure of the scientific content permits a *reducing explanation* inside the *same* Level of Reality because all secondary laws are reduced to the covering laws of that level.
(f) The reducing explanation is not allowed between the different levels because each of them forms a conceptual network, totally independent from the others, imposing on the concepts a precisely determined meaning. Conse-

quently, we cannot use classical analogies for the interpretation of microscopic phenomena.

(g) The level of reality that corresponds to modern physics theory defines the *limits of validity* of the other levels. For example, modern science knows, from the vantage point of its present knowledge, that Newtonian objects constitute a mis-presentation of the world but, at the same time, it determines precisely the series of natural phenomena and the boundary conditions for which Newtonian physics offers a rather correct—and simpler—description.

(h) As the conceptual systems of the different levels are essentially incompatible their association becomes possible only through an understanding of the 'crisis process' that led to the abandonment of the older conceptual system and the acceptance of the modern one.

Linking up the epistemological and cognitive requirements

As mentioned before, we accept the perception that learners' conceptual structures might be paralleled to scientific theories. Driven by the already exposed epistemological and cognitive approach, we came to the following central assumptions.

(a) In case that the learners' knowledge indicates a mixing-up of two paradigms' concepts, the instructional process should provoke a 'crisis' situation, similar to the Kuhnian period of crisis in science. The whole process has to lead to a complete distinction of the conceptual systems of CP and QM and a parallel explicit clarification of the meaning of the concepts inside the corresponding conceptual network. The expected result is the construction of a self-consistent new 'theory', relevant to the scientific theory that arises after a 'scientific revolution', possessing the characteristics of the described structure of 'Levels of Reality'. The cognitive change that takes place corresponds to a radical reconstruction of learners' knowledge.

(b) As long as learners acquire a new way of 'seeing' phenomena, they will probably be able to use new concepts for the interpretation of other related problems and to add new information in a way consistent with their new conceptual structure. That procedure, including activities relevant to the scientific ones during a period of 'normal' science, corresponds to learners' conceptual weak reconstruction.

Design and targets of the instructional process

Radical reconstruction: toward a complete distinction between NPL and QPL

The informal interviews that we carried out before the design of the instructional process made clear the following [2, 3].

(a) A number of QM concepts such as electron [orbit, cloud, orbital, shell], energy levels, ground state etc, which learners 'have learned' during their secondary school studies might be characterized as 'incompatible concepts', that is concepts whose true ontological status mismatches students' initial conceptions. Thus: *a radical reconstruction should be related to an 'ontological shift'*.

Intending to provoke such a shift, we determined the special properties and behaviour that might characterize the objects belonging to NPL and QPL respectively.

Ontological status of Newtonian objects. (i) A rigidly fixed 'state' of an object/system: a set of numbers that measure the physical quantities possessed by the system; (ii) predictability of the evolution of physical phenomena stemming from the time-reversible Newtonian laws of motion; (iii) distinguishability of identical physical objects.

Ontological status of quantum objects. (i) The Heisenberg Uncertainty Principle (HUP) sets the limits of our feasible knowledge for a microscopic system; (ii) the classical concept of 'state' is replaced by the superposition principle; (iii) it is the measurement that transforms the possibility to certainty; (iv) partial unpredictability of the physical world; (v) indistinguishability of identical physical objects.

(b) The behaviour of quantum objects is usually interpreted by means of the Newtonian/deterministic way of thinking. Thus: *a radical reconstruction should lead learners to the recognition of the different 'explanatory* *frameworks' and 'thinking pathways' that each 'level of reality'/conceptual system imposes*. Furthermore, they should become conscious of the fact that the basic concepts of each level, functioning as the nodes of the relevant conceptual network, acquire their meaning *as parts of the whole system.*

A weak reconstruction follows: the 'building' of the conceptual system of QPL

We accept that if the evaluation of the instructional process ascertains learners' radical reconstruction, their new conceptual structure has the potential for further enlargement and new information can be added in a cumulative way—by new nodes and new links—during a weak reconstruction process.

Instructional tools

The initial knowledge of teachers/learners is characterized by a restricted background in science and mathematics. Intending to attain a *qualitative* approach to the scientific content, we decided to support the whole task by drawing on *instructional tools* from two parallel fields:

(a) The field of *history and philosophy of science* [4], which can provide a *key topic* connected with a 'crisis' period. This topic has the potential to associate the scientific content with the real problems that gave birth to it.

The key topic: the hydrogen atom
We selected as a key topic of the instructional process the model of the hydrogen atom because: (i) it is connected with a 'crisis period' as far as the rejection of Bohr's model and the acceptance of the modern model of the atom might be considered as the 'signal point' of the 'scientific revolution'/'paradigm shift' of 20th century physics, (ii) it can be used as the reference point of learners' thinking as it is a subject familiar to them from their secondary school studies, (iii) it lays the foundations of QM on *a 'matter-based'* perception. We selected electrons—and not photons—to represent the ontological status of quantum objects because they are already classified in learners' initial knowledge as *material* objects. Thus, the fact that it is the *matter* that displays a different behaviour depending on the macroscopic or microscopic point of view is easily accepted.

(b) The field of *modern technology* [2, 3], which can provide representations of the microscopic phenomena that might replace the missing sensory experience of the 'quantum world'.

Replacing the sensory experience
Based on the Schrödinger equation, we created [2, 3] a simulation/computer visualization of the hydrogen atom's orbitals (figure 1), aiming to offer an adequate technology-based environment.

Empirical implementation

An instructional model for a radical reconstruction

We created an instructional model [4] whose goal is the radical reconstruction of learners' initial knowledge, which is characterized by the mixing-up of two paradigms' concepts. This model is founded on the assumption that the juxtaposition of two representative theoretical models of the two competitive paradigms might provoke a 'crisis' situation, similar to the historical one, capable of revealing the deep conceptual differences between CP and QM. The rival models should be strongly associated with the selected key topic. We selected:

(a) As representative models of the *competitive paradigms*: (i) Bohr's semi-classical model and (ii) the atom model accepted by modern physics.
(b) As covering laws of CPL and QML the Newtonian laws and HUP respectively.

The successive steps of the teaching proposal aim to lead learners to construct their own knowledge by following the different reasoning pathways that the covering laws impose.

The presentation and the analysis of Bohr's atomic model: on the PC screen the fixed electron orbits, foreseen by Bohr's model, are presented. Bohr adopted Newton's proof for Kepler's planetary system to which he pasted the arbitrary hypothesis of angular momentum quantization. Thus, (i) the Newtonian equations of motion can be written; (ii) we can define, at the same moment, the position and the momentum of the electron, that is, we can define the classical

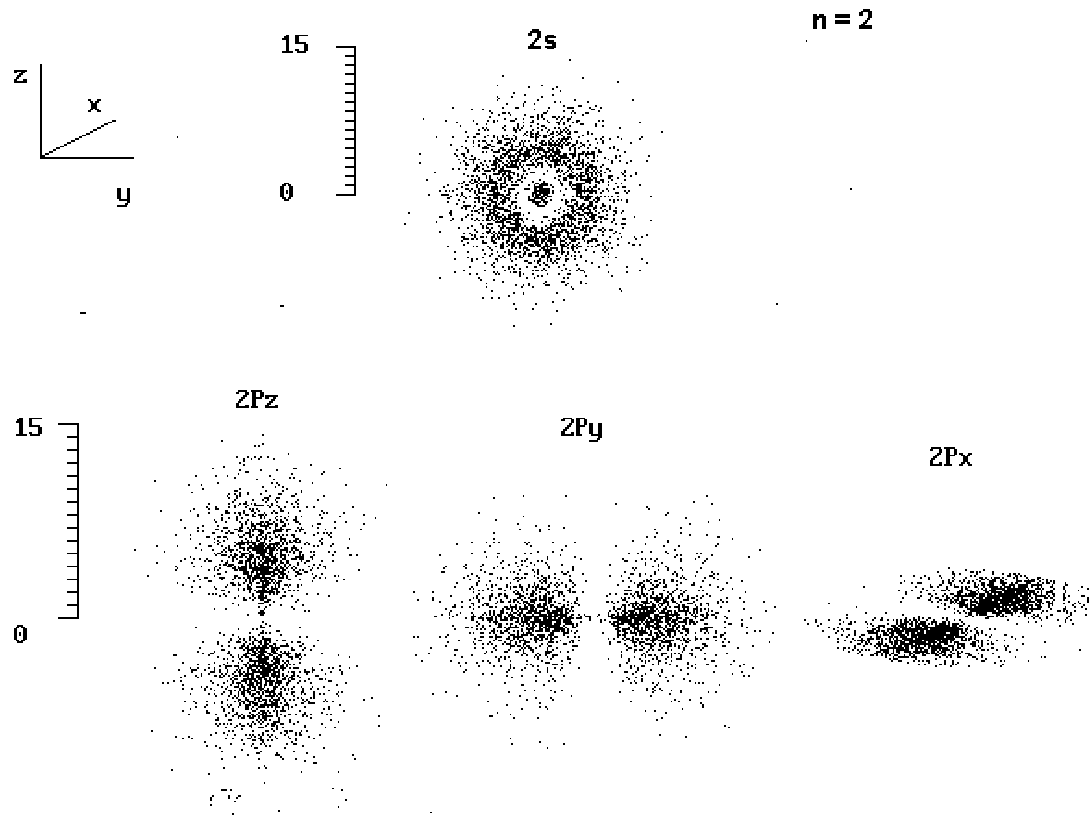

Figure 1. An 'image' of the simulation/visualization of the hydrogen atom orbitals.

'state' of the system; (iii) we can predict the orbit of the electron, its future behaviour is one-way defined.

The presentation (simulation) and the analysis of the hydrogen atom '1s' orbitals: on the PC screen the possible positions at which the electron might be detected are presented. The electron seems to appear at random positions. The visualization illustrates the following facts.

(a) There are limits to our feasible knowledge for a microscopic object/system (HUP: $\Delta x\,\Delta p \geq h$). Thus, (i) the concept of 'state', as it is defined by classical physics, disappears. (ii) If we detect the electron at a certain position, we cannot determine the position it occupied before a time interval Δt. Thus, *reversibility, as accepted by classical physics, does not exist*. (iii) As we cannot define at the same moment the position and the momentum of the electron, we cannot predict its future motion, and the concept of the 'orbit' disappears. Thus, *predictability, as accepted by classical physics, does not exist.*

(b) The impression of a restricted number of the possible electron positions forms an image that *lacks a concrete structure*. Although the image appears to be different every time its formation is repeated—as it consists of different 'points'—the final image always has the same general shape. Thus, (i) 'orbital' is a picture formed by the possible positions of the electron. (ii) These positions follow a *statistical law*. This is the reason why a large number of 'points' is necessary to form the final structure. (iii) We cannot predict the next position of the electron but we can calculate *the probability* of finding it at a particular position in space. (iv) The density of the 'points' per unit volume visualizes the *probability density* of finding the electron inside this volume.

A weak reconstruction

The evaluation of the first part of the project [2, 4] strengthened our opinion of the possibility of enlarging learners' knowledge by a *weak reconstruction* process [5].

We selected wave–particle duality as the first *central node* of QPL construction. As learners became conscious of the fact that the final pattern of orbitals is the result of a large number of stochastically distributed individual processes, we used the empty regions of the '2s', '3s' and 'p' orbitals of the hydrogen atom as a spur to creative thinking. These regions are parts of the *probability space* where the probability of detecting the electron is zero. As probability density is, in our case, a time-independent entity, it is plausible to think about a '*probability standing wave*' that 'follows' the electron and determines its 'appearance density'. Thus, the wave-like representation is the appropriate one when the phenomena it has to interpret owe their appearance to a large number of individual events or to the behaviour of a large number of indistinguishable quantum objects. The potentiality of two complementary descriptions of a physical system appears. The wave-like description corresponds to a holistic point of view and 'observes' the global/collective properties that become non-observable if we focus on the corpuscular ones. The inner meaning of the Complementarity Principle comes to light as a rational result of the QM probabilistic reasoning pattern and it is associated with HUP as far as it refers to the impossibility of specifying, simultaneously, the wave and corpuscular properties of a system.

Conclusions

The instructional requirement for a qualitative approach to the QM worldview led us to acknowledge the importance of an epistemological–educational 'building' of the scientific content corresponding to the modern physics paradigm.

Attempting to respond to such a demand, we centred on the understanding of the nature of science and scientific inquiry as necessary components of science education. As the evaluation process of the implementation courses has justified our choice, we continue our research project on the same basis, aiming at effective approaches to teaching science.

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References

As the present article is a review of our recent research project, we refer only to our own papers, which contain a detailed description of each concrete item. A complete list of references and the relevant bibliography is available in these papers.

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