Opinion Article

Advances in Modern Physics: Transition from Positivism to Post-positivism in Education and Research

Abstract

Advances in quantum physics in the first quarter of the twentieth century dramatically influenced perspectives in science and philosophy. This paper discusses why a shift towards post-positivism in the philosophy of science is necessary, taking a novel perspective using the basic principles of quantum physics and its implications. Given the fundamental *limitations* of observation and evaluation in science as elucidated by quantum mechanics, we need to question the meanings of objectivity and truth, and therefore our entire present knowledge base. This results in a *re-alignment* of *ontology, epistemology* and *methodology* in the philosophy of research. The comparison of quantum mechanics and post-positivism leads us to relativism and critical realism. It is proposed that the right way to approach the acquisition of knowledge is to have an overall perspective of post-positivism that parallels the basic principles of modern physics. It is suggested that this new approach would be an appropriate framework also for higher education, leading to *interdisciplinary, constructive* and *active learning* instead of the *traditional* prescriptive approach.

Introduction

Transformation of knowledge, during the two important stages of the learning process—*education* and *research*—results in the continuous development of science and technology (see also Steinke 1994 and Sadler-Smith, 1996). As a result, advancement in science and technology in turn also encourages science to modify or entirely change the *philosophical, epistemological* and *methodological* approaches used in these two stages. Undoubtedly advances in modern physics have been of great importance in the evolution of the philosophy of science. World views at the beginning of the twentieth century were dramatically influenced by new perspectives in physics such as *the Planck radiation law* (see for instance Pyle, 1985), *Bohr's atomic model* (see for instance Willden, 2001) and later the development of *the band theory of solids* (see for instance Blakemore 1989), entirely changing the outlook on the *atomic* and *electromagnetic nature* of the universe (Kragh, 2002). Some new ideas and perspectives towards physical phenomena were so successfully introduced and developed up to the mid-century that the birth of *quantum physics* provided great insights to scientists who could hardly have imagined a better understanding of the microscopic and therefore of matter as a whole.

Towards the end of the nineteenth century, some physicists started to think that most of the issues underlying the topic were totally understood, and the rest of physics would only involve modifications in the details. The revolutionary discoveries of classical physics such as Oersted's discovery of electromagnetic relations (1820), followed by Ampere's (1826) and Faraday's (1831) Laws of *electromagnetism*, the construction of *classical electromagnetic theory* by Maxwell (1850), and finally Thomson's (1896) *discovery of electrons,* had according to this view all already taken place. However, some modern theories and experiments by other great scientists such as Planck, Einstein, Bohr, de Broglie, Heisenberg, Schrödinger and Born proved that their predecessors could be wrong: a lesson also for modern science. Quantum mechanics remains an incomplete science that has evolved from *Schrödinger's and Dirac's formalism* to the *quantum* *electrodynamics* (QED) of Feynman, a more general view of quantum mechanics combining *quantum field theory* (QFT) with *special relativity*, and that this process continues.

The success of these revolutionary physicists was in having a *deep knowledge* of what had been achieved in the past and to have a *critical perspective* on what was happening at the time without discounting a single detail or observation. Faraday (Özdemir, 2015) had great success in postulating *electromagnetic induction*, which later on resulted in many important applications such as *electric generators and engines.* And this was because he did not ignore five seconds of observation during his lifelong experiments.

Novel perspectives and achievements of modern physics such as Planck's (1900) explanation of *the black body radiation*, Einstein's (1905) *photoelectric phenomena and relativity theories* (Penrose 2009), and *Heisenberg's Uncertainty principle* (1925) have ultimately led to a transition in the philosophy of science from *positivism* to *post-positivism* after the mid-twentieth century. This included scientists realigning their *epistemology* and *methodology* in research and education, which has eventually led to new methods of education (Warwick & Stephenson, 2002).

Science's present knowledge base is a result of learning, and represents a collection of individuals' worldviews. As Coll and Taylor (2001) stated "individuals' worldviews construct *paradigms*, which are some combinations of basic beliefs, concerning ultimate or first principles." It is personally interpreted that paradigms are *intellectual developments* involving the essence of philosophy of science such as *ontology*, *epistemology* and *methodology.* Paradigms can change in the course of time, because science is always potentially on the edge of revolution, as also stated by Williams (1982). From the author's point of view, science is continuously evolving since its nature consists of proofs and refutations. As stated by Pickstone (2001): the ways of knowing are based on the ways of production.

This paper discusses how and why advances in physics have in due course led to a transformation in the philosophy of science and learning, and therefore in education. The way of thinking in post-positivism will be combined with the ideas of quantum physics. In connection with this, one suggests that the difference between positivism and post-positivism can well be understood when we analyze the conflicting views between classical physics and quantum physics.

Basics of Quantum Theory

Deterministic views of classical theory started to come up against statistics in thermodynamic phenomenon where the repetition of the same event and the multiplicity of different events comes into play. Consequently multiple recurrences of one particular phenomenon in many microscopic and macroscopic events need not end up with the same results. The first comprehensive theory was the *Maxwell-Boltzmann Statistics* (1871), evaluating the possible ensembles of an isolated thermodynamic system with particular values of a continuous energy range.

Planck in 1900 introduced the term *quanta* by explaining the quantum behavior of thermal or *blackbody* radiation. According to classical beliefs thermal radiation should have been infinite when the temperature of metals continually increased. However Planck's quantum theory suggested that electromagnetic radiation could be dispersed by energy quanta of $E=h \times \nu$ called *photons* where E is the energy of a photon with ν frequency and h the Planck constant. This was the first such theory, which suggested that something with no mass (like a photon) could have energy (Tekeli et. al., 1999). It combined energy and frequency with particle and wave behavior, respectively (for further reading, see also Einstein and Infeld foreword by Isaacson, 2007).

This eventually led to a well-known fact called the *wave-particle dilemma* as follows: When Planck mathematically formulated the semi-classical *black body*, more generally known as the *thermal radiation* problem in 1900, he was not quite aware of the fact that this invention was going to revolutionize physics and lead to a new type of version of it—*Quantum Physics*—without which today's globalization would not have been possible (Loudon, 2000). In 1905, Einstein showed that a photon could act as a particle in the photoelectric effect. He demonstrated that photon energy could be converted to the kinetic energy of electrons. Bohr's atomic model in 1913 generalized the idea of *quantized electronic energy levels* in an atom that can be changed by either the emission or absorption of photons. This was the first modern atomic model (Thornton and Rex, 2002). Contrarily, de Broglie postulated the wave nature of electrons in 1923. This assigns electrons with a wave parameter called the *de Broglie wavelength (de Broglie, 1970), resulting in an important term "matter wave"*. This conflict between the idea of the a photon as a particle of light and the matter wave of each quantum system is the famous wave-particle dilemma of quantum physics.

This dilemma was formalized by Schrödinger in 1925 with the fundamental equation named after him in which every quantum mechanical system needs to have a waveform (Bransden and Joachain, 1990). This formulation established a new type of mechanics called *wave mechanics* that differs from the *Newton mechanics*. Wave mechanics calculates the accompanying wave functions for individual quantum systems giving the probabilities of where quantum mechanical species may be situated in space, as shown by Born in 1926, whereas Newton mechanics gives the exact positions.

We would not like to be misunderstood by the readers by suggesting that Newton mechanics is more comprehensive than the quantum mechanics just because the former is more deterministic. The latter is a result of experimental facts that are more explanatory and appropriate for us to understand the microscopic world and macroscopic world as a whole. Predictions of quantum mechanics are also valid in the macroscopic world. However they approximate Newton mechanics in the macroscopic limit so that the full application of them becomes dispensable. A detailed discussion on how quantum mechanical implications construct macroscopic phenomena in real world is given in the philosophical section.

On the other hand, Heisenberg in 1925 highlighted an important reality in quantum physics—*the uncertainty principle* (Fujikawa, 2012): Let us first state that this is a most unconventional aspect of quantum physics at the microscopic scale that differs from classical physics at the macroscopic scale. However we should not forget the fact that the microscopic world form the elementary components of the macroscopic environment. The motions of species in physics can be characterized by two basic parameters of a physical event. The basic parameters are;

1. Position (where something is)
2. Velocity or more specifically momentum (momentum=(mass) x (velocity))

In classical theory, i.e., in the Newton mechanics or from the macroscopic perspective, we can measure these two quantities more or less precisely, in theory there is no doubt where something is and what its momentum is. However in quantum mechanics or from the microscopic perspective this principle that we can measure things a hundred percent ceases to apply. Let us suppose a particle such as an electron has a momentum **p** and a position **x**. Position and momentum couple, or correspondingly energy and time. The basic quantities of a physical event, must have uncertainties delta(**x**) and delta(**p**) or corresponding uncertainties in energy and time; delta(**E**) and delta(**t**), respectively. If one can measure or calculate the former preisely one has to give up any certainty as to the latter. In between there always exist possibilities of uncertainties in both, even in a perfect experiment. Sizes of uncertainties are not independent, they are related by delta(**p**) x delta(**x**) > (h = Planck’s constant). So for instance if we can measure **x** exactly, the uncertainty in **p** (delta(**p**)) must be infinite, in order to keep the product constant.

These uncertainties lead to many strange things: for example in a quantum mechanical world, we cannot predict where a particle will be with 100% certainty. We can only speak in terms of probabilities. We can say that an electron will be at one location with a 95% probability, but there will be a 5% probability that it will be somewhere else. No one has definitively demonstrated a correct interpretation on this uncertainty, so for example it may be a fundamental way that the universe works, or it may be an artifact of the fact that whenever we make a measurement we must interfere with the system that is measured. Whatever it is, it is a fact that it happens. We have to live with this reality. On the other hand, this is a real controversy that disproves a positivistic, realist approach towards scientific phenomena and this behavior of the microscopic world completely breaks down the deterministic view of philosophy in science—positivism. Later in 1954, as Einstein stated, “it is difficult to attach a precise meaning to the term scientific truth” (Coll & Taylor 2001). A unique interpretation of the uncertainty principle by Penrose (2011) is also given in the references.

Although quantum physics involves some novel and very sophisticated theories and principles, this has not caused a complete break with the past. For instance, Newton mechanics still concretely stands in the macroscopic world, and Faraday’s *induction law* remains the basis of producing electricity. Quantum mechanics is so comprehensive that its principles can be reduced to *classical* Newton mechanics under special conditions where classical phenomena can satisfactorily be applied. This is in general called the *Bohr Correspondence Principal* (see for example Bransden and Joachain, 1990). For example, the *Fermi-Dirac statistics* of modern physics that is applied to the microscopic phenomena of *fermions* is reduced to classical Maxwell-*Boltzmann statistics,* which can quite happily be applied to the systems in the *classical regime,* such as an *ideal gas* (see for example Kittel, 1969).

We can summarize the basic unconventional phenomena of quantum physics that haven’t been noticed in classical physics, as follows:

a0 Quantum behavior of electromagnetic radiation (light as photons, Planck, 1900)

b0 Particle behavior of photons (photoelectric effect, Einstein, 1905) and wave nature of electrons (de Broglie, 1923), resulting in wave-particle duality

c0 The uncertainty principle (Heisenberg, 1925) d0 Accompanying wave functions for quantum mechanical species (wave mechanics, Schrödinger, 1925) and the absolute square of wave functions as probabilities (Born, 1926).

Philosophical Aspects

Let us have a look at the definitions of ontology, epistemology and methodology which are the main constituents of the philosophy of science and paradigms in order to understand why philosophical approaches have to change while science is advancing or evolving. The question as to what is the form or nature of reality or what is there that can be known is referred to as *ontology* (Coll & Taylor, 2001). *Epistemology* is simply the philosophy of knowledge or of how we come to know (Hofer and Pintrich 2004, and Trochim 2000). *Methodology* is a set of tools involving methods and techniques that enable us to get information in a more practical manner. In general a particular scientific research has to involve these three important issues, which are continuously affected by scientific innovations. Methodological approaches of a particular topic is very much dependent upon the views regarding ontological and epistemological questions. For example, according to Coll and Taylor (2001), "those subscribing to realist ontology and objectivist epistemology rely on inquiry that is experimental and manipulative, in which questions and hypotheses are stated and are evaluated by empirical testing. In this approach careful control of experimental conditions is necessary to prevent outcomes being subject to extraneous influences." This is more likely to be a positivistic approach, proposing that what science deals with is that which can be directly observed and measured. This is in a sense a true approach if everything was directly observable and measurable as in the classical physicists' worldview.

Now, let me return to quantum mechanics and attempt to discuss what are the new aspects that differ from classical ones (for further reading see also Murdoch, 1989). As far as the ontological aspects are concerned in quantum physics, we cannot establish the form of a species whether they best treated as waves or as particles prior to experiment. Only upon experiment does the issue become meaningful. I propose that this reality in quantum physics invokes the *relativist ontology* whilst classical physics is based on the *realist ontology*. *Einstein's relativity theory* also supports this assumption for modern science. This exemplifies the required transition from a positivistic to post-positivistic worldview. According to the positivistic view, the experimental parameters are fully defined a priori. However, as in the Heisenberg uncertainty principle, quantum mechanics has produced evidence contradicting the realist ontology of positivism.

One might speculate that the predictions of quantum physics are only valid for ontological issues in the microscopic world of atoms, molecules and elementary particles, and that the outcomes of these predictions cannot be applied to the macroscopic scale. However this is not correct (Vedral, 2011).

Let us now explain this important matter with a few examples. These examples are stunning examples of how the microscopic quantum world constitutes the macroscopic. First of all let us start with one of the most incredible birds, robins. It has been determined by Wiltschkos (1972) that robins, when they migrate to warmer Mediterranean coasts, escaping from the harsh winter conditions of Scandinavia, seem to be able to detect one hundredth of the very small fluctuations in the orientations of the Earth's magnetic field via a process called "*quantum entanglement*" (Gauger et. al., 2011). The birds somehow build a sort of biological compass, "the quantum sixth sense" using one of the strangest features of quantum mechanic. Einstein called such effects 'spooky'. This extraordinary phenomenon was first pointed out with a thought experiment of Einstein and his colleagues Podolsky and Rosen in 1935 as a paradox called "*EPR paradox*", however it was eventually proved to be a reality (Freedman and Clauser, 1972 and Blaylock, 2010). It describes how two separate and isolated particles have instantaneous connections via a weird quantum link. In the case of robins, the best explanation is that the spin entanglement of electrons occurs within a protein in the bird's eyes due to the Earth's magnetic field, and that makes the entangled electron pairs highly sensitive to any direction variations of the Earth's magnetic field, allowing the bird to "sense" in which direction it should migrate. The amazing discovery eventually led to the development of "quantum biology".

Another important implication of a different quantum phenomena is the "*quantum tunneling*" (a kind of quantum teleportation) of enzymes (Carlo 2012) inside living cells, accelerating the chemical processes so that it would otherwise take so much time that life wouldn't have been possible without this quantum process.

On the other hand, one of the most tangible applications of quantum physics is *quantum computing* that makes direct use of quantum mechanical phenomena, such as superposition and entanglement, to perform fast and efficient acquisition and processing of data (Gershenfeld and Chuang, 1998).

As seen from these examples taken from real life, maybe all quantum behavior are not only applied in the microscopic world but also in bigger objects such as birds' eyes and living cells, surprising scientists who believed that the quantum laws were only valid at microscopic scale.

Let us now extend the philosophical discussion with a few arguments on fundamental aspects of quantum mechanics between Einstein and other well-known founders of quantum philosophy such as Heisenberg, Bohr and Dirac. Basically Heisenberg noted that there is an unusual relation between the precision of two basic quantities of physics; position and momentum. If we measure the position precisely to a certain accuracy, we can not measure the momentum to a certain accuracy and vice versa. The basic differentiation between the two philosophical views that Einstein and others believed is that whether this uncertainty is a natural way that the universe works or whether instead it is an artifact that appears when measuring these quantities (Penrose 2011). Einstein who said "God does not play dice with the universe" never believed that the uncertainty is natural (see also Natarajan, 2008). If it is not natural we can explain it with the following argument: Observation of a microscopic object is limited by the wavelength of observing light. Reducing the wavelength of the incident light increases the precision of the position but also increase the light energy and therefore reduces the precision of velocity, resulting in more uncertainty in momentum.

However, Heisenberg postulated the uncertainty principal to be a fundamental law of the universe and the lowest product of uncertainties in position and momentum is in the order of the Planck constant which is a universal constant coming from the very early creation of universe; supposedly the Big Bang. The conflict between Einstein and Heisenberg was finalized by Copenhagen interpretation of Bohr's Institute, postulating that we have to recognize this uncertainty without looking at it as natural or as artificial (Murdoch, 1989). It was further developed by Dirac who said; “Shut up and calculate!”, following his great quantum mechanical formalism and Feynman’s *Quantum Field Theory*, all based on the famous uncertainty principle.

I personally believe that this is an uncertainty given to human beings by God. I, in a way, agree with Einstein that “nothing is uncertain for God” but I also agree with Heisenberg that “everything is uncertain for us”.

Following the discussion above, as far as the epistemological and methodological aspects are concerned, we cannot perform ideal experiments or establish ideal theories that uncover the truth contrarily to the objectivist classical view of physics. However we can perform experiments and establish theories that may approach the truth. Since approaching is an infinite process, we cannot know how close we have reached the truth at any one time. This is a true assumption from just a post-positivistic perspective, while positivists believe that the measured or observed values by an appropriate method are a totally definite and correct way to reach the truth (Nevvajai, 2000). In contrast to quantum physics, classical physicists could judge and come to conclusions with their measured or observed values in a positivistic way, because all the parameters of physical phenomena are correctly measurable and observable. However this is not true from the perspective of quantum physics. What positivists or classical physicists did not criticize or ask themselves is; “*what is measurable and observable and to what extent?*” As a matter of fact, the answer to this question should be *nothing* a hundred percent. The discussions on the philosophy of quantum physics and post-positivism must be built on this particular point in epistemology and the methodology of modern sciences.

The first principle alternative to *objectivism* could be seen as *subjectivism*, which states that there is no external reality, but that the findings of an inquiry are produced by the observer. However this is controversial within the post-positivistic worldview, that proffers *critical realism* instead of subjectivism in epistemological and methodological issues. A critical realist believes that there is a reality independent of our thinking about which science can study (Trochim 2000). While positivism strongly insists on realism, post-positivism is rather chary, supporting the philosophy of *critical realism*.

Post-positivists think that all observations could have a possibility of misinterpretation, misunderstanding and error, and that all theory can be improved. As Trochim (2000) stated, “where the positivist believed that the goal of science was to uncover the truth, the post-positivist critical realist believes that the goal of science is to hold steadfastly to the goal of getting it right about reality, even though we can never achieve the goal.” Therefore objectivity in post-positivism is the right approach from a broader perspective including a more comprehensive spectrum of most scientific views, although positivism believes that the objectivity of the individual scientist extracts true information about reality, no matter what their paradigms are. Post-positivism indicates the fact that no individual can see the world perfectly as it really is. The philosophy of quantum physics is based on many parameters with uncertainties and probabilities and that also supports an objectivity of this kind in the epistemological and methodological approaches. Perhaps unfortunately or fortunately, the universe does not look like what we see with our eyes.

The leading physicists of the early twentieth century, whether they were post-positivists or not, led to great changes in our views about the universe, and their ideas and views undoubtedly made us reconsider the philosophy of science and the methods of education. Today reflection on these views of science, technology and education continuously advance our knowledge. Both in modern physics and post-positivism, extending the enquiry may lead to questions, and answers, answers that could result in new types of physics and a new philosophy of science. The future may be formed with these new ideas as it has been presently done by the implications of quantum mechanics.

Educational Aspects

We discussed the supporting views of quantum physics for post-positivism as a philosophy of science. In this section let us raise a question as to "*what are the educational aspects that post-positivism foresees?*"

Noe (2001) summarizes the transition from positivism to post-positivism as follows: **"**The positivistic method stemmed from the spirit of experimental philosophy which promoted the scientific revolution. It was this period that the classical positivism emerged and social sciences began to introduce the positivistic method. In the twentieth century, the *Vienna Circle* tried to realize the methodological unification between natural sciences and social sciences under the slogan of unified science. But their radical reductionism which aimed to assimilate social sciences with natural sciences, trying to introduce the unified language of physics, suffered a setback as a result. After that the trend of post-positivism made an important alteration to understanding the positivistic method by proposing new theses on the theory-lead nature of observations, the impossibility of crucial experiments and so on. According to them, the relation between natural sciences and social sciences must be reconsidered not as a hierarchy, but as pluralistic co-existence.**"**

This suggests not a separation of the two kinds of sciences (social and natural sciences) but the need to bring closer both sciences in some core respects. For example, when the modern universities in Turkey were first established in the years 1930-1960, positivistic views were so dominant that the social and natural science curricula had totally different kinds of infrastructure. Today the need for exchange of information has been recognized in higher education. As a result, more and more interdisciplinary programs are developed in individual departments. Nowadays, for instance, physics graduates can find more jobs in projects relating to different fields, not just in their own fields.

As James et al (1997) suggested, "The traditional boundaries of the separate sciences do not accord with contemporary experience; and wider public understanding and interest in science is most likely to be developed through an integrated approach." This kind of *globalization* in science requires *lifelong* and *continuously constructing learning* in most aspects of sciences (van der Molen, 2001). As a result of post-positivistic new thinking, Said (1996) points out the importance of achieving *global understanding* and explains the process of approaching the truth as follows; "we sift from the truth of reason to the truth of images, from the truth of images to the truth of intuition, from the truth of intuition to the truth of feeling and from the truth of feeling to the truth of pattern. We shift from truth to truth. Each one of us possesses a little piece of truth. Total knowing requires an in-gathering of pieces of truth."

Most post-positivists are also *constructivists* in pedagogical terms, because in a post-positivistic view of the world the truth is an external reality that we try to approach and therefore learning about a certain issue can *never* be *complete,* but rather *constructs* our experiences. Accepting constructivist beliefs about the nature of truth and knowledge loads us as university professors with a completely different mission in the teaching methodologies of science, in comparison to conventional positivistic approaches in education, which proposes that scientific knowledge can entirely be transmitted to the learner. Under constructivism, the teacher holds a totally different role; that of a facilitator rather than transmitter of knowledge (Coll and Taylor, 2001), involving students in an active way in the learning process. Teachers' attitudes of this kind in university education would trace a kind of idea in students' mind that the knowledge they receive is not a concrete block of information that cannot be changed or constructed but, nevertheless, it can be modified, added to and even completely changed. Therefore such higher education will produce individuals who can set up their own paradigms in terms of epistemology and methodology, and whose views are critical realism as followed by the leading scientists of modern physics.

Conclusions

Why the transition in the philosophy of science from positivistic to post-positivistic is necessary has been discussed from a novel perspective considering the basic principles of quantum physics. Consideration of the realities of the *limitations* of observation and evaluation in modern sciences leads us to question the meanings of objectivity, truth and therefore our present knowledge base, resulting in a re-alignment of ontological, epistemological and methodological approaches to the philosophy of research. Since post-positivism leads to a relativist and critical realist approach towards the principal issues (ontology, epistemology and methodology) of the philosophy of science, I propose that the right way to approach the truth and build knowledge is to have an overall perspective of post-positivism that parallels the advancement of modern physics. My opinion is that this new approach would be a good framework for higher education, proposing *interdisciplinary, constructive* and *active learning* instead of a *traditional* prescrpitive approach.

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