

# What is the nature of theory in science? Critically evaluate this in relation to the National Curriculum and how science is taught in schools.

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## Abstract

Some of the qualities that are generally associated with a good theory are presented. Quantum mechanics is presented as a theory that does not have all of these qualities. The problems associated with this are discussed. Misleading rhetoric and philosophical arguments are highlighted as particular are highlighted in particular. This is put in the context of the current understanding of quantum theory of those in the field, and of others. Consideration of this is used in analysis of how quantum theory is covered in KS5 curriculae, and a suggested alternative scheme is proposed.

## Introduction

Apart from the rather prosaic requirement of 'agreement with observation', there are many other qualities that a good scientific theory should possess. Many of these are personal to the scientist judging the theory, though some are shared by most. Occam's razor is often quoted in its various forms. Another way of stating Occam's razor is that a good theory should have the minimal number of parameters needing to be experimentally measured before the theory may become predictive. Every first year physicist knows that they can fit a curve through every one of  $n$  arbitrarily placed points of a graph with only a  $(n - 1)$ th order polynomial. They also know that this is a completely pointless exercise, as the curve will mostly vary wildly either side of the two outermost points meaning theory of the relationship between  $x$  and  $y$  will have no predictive qualities once extrapolated.

Prediction is perhaps the most important quality. A theory that cannot make predictions is surely just a description. Even if a theory does not agree with experiment, the study of its predictions can give clues of how a better theory may be constructed. Such a theory often gets branded a model; something with which to play; something from which to learn. Occasionally a theory has very, or exceptionally accurate predictive powers, though nevertheless may not satisfy

other requirements to make it a good theory. In this essay I will argue that perhaps the most successful physical theory of the twentieth century, one which accounts for an estimated 30% of the American gross national product (Folger 2009) is such a theory. I will then consider what this, and recent scientific debate on this means for education.

A theory which is to be an accurate description of nature needs not only to describe it's own specific phenomena well, but to 'fit' well with other theories. Generally this requires it fitting into some epistemological system, having the same assumptions, whether they be axioms, principles, laws, theories, or indeed approximations. As Isham (1995) puts it

An exposition of any area of physics will inevitably contain terms that form part of the general scientific background of the age and culture within which they are employed. The meaningfulness and applicability of such terms is usually deemed to be 'obvious', and therefore not worthy of further explication. . . . . Examples of seemingly innocuous terms that arise in discussions of quantum theory include 'system', 'observable', 'property', 'physical quantity', 'measurement', 'state', 'causality', 'determinism'.  
-Isham (1995)

An interesting example of 'fit' is classical mechanics, which has three equivalent formulations, namely the Newtonian, Hamiltonian, and Hamilton-Jacobian formulations. These theories define three different epistemological systems: the former a system based upon second order differential equations, and the two latter upon a variational calculus based approach, second and first order respectively. Though the three formulations are equivalent, the Hamiltonian formulation fits into the language of symmetries, and as such was adopted by field theorists, and is now the system upon which the standard model of particle physics is based.

This idea of good theories fitting together is rather more important than it may seem at first. Central to modern physics is the concept of a unified theory, unification being nothing more than a slight extension of this idea of fit. String theory is essentially born out of a collective desire to unify gravity with quantum theory.

The fitting into an epistemological system aids somewhat with another important quality, that of consistency. Consistency is one of the more fundamental and necessary qualities, meaning simply that by deductive reasoning, one may not find any contradictions. What good is a theory that contradicts itself? Deductive reasoning is generally a much simpler task in maths, where one's assumption are very well defined. I think it likely that this is one of the main factors that has lead to mathematisation of modern physics. Physics however,

by its very nature must be linked to the real world, and it is often at these points (what Isham (1995) referred to as innocuous terms) that consistency breaks down.

The final criteria of a good theory, that I will mention, is particularly prevalent in physicists; the quality of aesthetics. Aesthetics, probably the most personal and subjective of all these qualities, I believe extend beyond the simplicity and familiarity of Occam's razor. It is certainly true that vast, and rich theories have been developed with little, if any, justification save mathematical grace *cf.* supersymmetry. Aesthetics often get associated with a particular philosophical viewpoint, something that may be very productive as it was for Einstein when developing his general theory of relativity (Carroll 2003). In the case of quantum theory, I will argue that the philosophy was extremely destructive.

Once I have provided my critique of modern quantum theory I shall then move on to consider how the lessons picked up from this may be applied to when teaching wave-particle duality, and how the structure of the curriculum may change in future to take advantage of this.

### **The nature of quantum theory**

Quantum mechanics is famous for its own particular brand of mystery and intrigue, for cats being alive and dead at the same time, for gods playing dice and the like. Not all of this, as you might imagine, was entirely incidental. Traditional readings of the events that lead to the inception of the Copenhagen Interpretation as the orthodox tended to focus on the 1927 Solvay conference and the Machean positivist arguments of the victorious Göttingen-Copenhagen group; in particular Werner Heisenberg. The central positivist philosophy supposedly inspiring the epistemological method (or principle) of 'elimination of unobservables' (Beller 1999). Even the traditional readings of the history however, don't accept that Copenhagen hegemony was the logical conclusion to proceedings.

“Many working physicists are seemingly content to accept what Einstein referred to as the ‘gentle pillow’ of the Copenhagen interpretation without asking any further questions, and this has long been accepted as the orthodox position. But if we restrict our attention to physicists (or indeed philosophers) of the first rank, then we see immediately that such an orthodoxy is illusory”

-Hendry (1952)

Several recent historiographical analyses of the birth of quantum mechanics, in particular Beller (1999) and Bacciagaluppi & Valentini (2010) have told a significantly different story. Mara Beller makes an account of the positivist

justifications of Göttingen-Copenhagen in her book *Quantum Dialogue*, not as a “heuristic principle and more a tool with which theoretical advances could be justified *ex post facto*”. It seems the classical Socratic dialogue, fundamental to deductive analysis of new theories, completely broke down, and was confounded in often inconsistent, fluid (Beller 1999), and at times ferocious philosophical rhetoric (Bacciagaluppi & Valentini 2010). As Beller explains,

The ingenious technique was to describe arguments of consistency as those of inevitability.  
-Beller (1999)

Many arguments, and rhetoric, once the predictive power of quantum theory had been established, tended to focus on a kind of protectionism - urging the audience away from analysis and toward a kind of natural reverie.

Do not keep saying to yourself, if you can possibly avoid it, But how can it be like that? because you will get down the drain, into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.  
-Richard Feynman

The practical upshot of which is the ‘Shut up and calculate’ instrumentalist mentality that my (small amount of) research shows is still very prevalent today. My thoughts on the matter are that, though this instrumentalist approach is a prerequisite for a career in many parts of modern research in quantum theory, it needn’t, and shouldn’t be so. The rhetoric that students of physics are subject to from the age of sixteen onwards serves to convince them that the standard analytical tools of science they would normally use somehow do not apply to quantum theory.

The most (in)famous paradox in quantum mechanics is that of the so called measurement problem. The measurement problem arises from the need to place a boundary between the indeterminism of the Copenhagen interpretation, and the determinism of the everyday classical world we live in, hence the role of the observer. Schrödinger’s cat was designed to illustrate this point. By attaching the cat to a quantum device upon which it’s life depends we have moved microscopic indeterminism to the macroscopic level. Furthermore we cannot be sure what counts as an observer. Does the cat count? Or does it require a person? What did the universe then look like before life? Does this undo the Copernican revolution, and place us right back at the centre of the universe? (Towler 2009) All perfectly valid questions to make in a Socratic dialogue. All completely unanswerable with the standard theory.

This supposed role of the observer created much confusion, though the theory evidently, nevertheless flourished.

... this matters not at all in practise. When in doubt, enlarge the quantum system. Then it is found that the division can be so made that moving it further makes very little difference to practical predictions. Indeed good taste and discretion, born of experience, allow us largely to forget, in most calculations, the instruments of observation. . . . . The pragmatic philosophy is, I think, consciously or unconsciously the working philosophy of all who work with quantum theory in a practical way.  
-Bell (1987)

This pragmatic philosophy that Bell describes is undeniably productive. It would be impossible to argue against its use given its success, but equally a good scientist should always be aware of the limitations of the theory which they are using. Other criticisms of Copenhagen have centred around the two ‘principles’ of complementarity and correspondence, and around their fuzzy definitions. Bohr’s complementarity is an extension of his insistence of holding on to classical concepts (Beller 1999), and is large skipped quickly over or omitted by most authors of quantum mechanics textbooks, it not being important to the theory. The correspondence principle on the other hand states that the behaviour of large quantum mechanical systems should closely approximate classical theory. Although this may well be, it is not in fact an element of the theory, but a test of it.

If I had not grown up with this theory, and had had it presented to me by a student I was teaching, I feel that I would have no problem criticising it, and trying to help the student discover its flaws. I imagine most science teachers would do the same. I have to admit that I find it rather baffling that Schrödinger’s cat is presented by many authors as *actually* being both dead and alive at the same time, and not as a major problem in an established theory. Upon reflection I think I would put my initial acceptance of the theory down to three main reasons

- As before mentioned, even prior to university level physics, students are aware of the some of the clichés; “I think I can safely say that nobody understands quantum mechanics” - Richard Feynman, or “those who are not shocked when they first come across quantum theory cannot possibly have understood it.” - Neils Bohr. These statements serve to make student question their own understanding of the theory rather than the theory itself.
- Its incredible success, and the dismissive nature with which people tended to talk about competing theories
- The ‘shut up and calculate’ approach to quantum mechanics is unfortunately something that the busy lifestyle of a student breeds. Sometimes

it is easier not to ask difficult questions.

These, I now firmly believe, are analogous to the *barriers to learning* one tends to talk about in secondary education, and should be tackled as such. The late twentieth century and the early twenty-first has seen a revival of the debate on the foundations of quantum mechanics, and a significant range of alternatives are being investigated (Bacciagaluppi & Valentini 2010, Cushing et al. 1996, Holland 1993), many articles published in reputable journals, and books published by reputable publishers. Prominent among alternative theories is one that comes under various different names: pilot-wave theory, Bohmian mechanics, de Broglie-Bohm theory, causal interpretation, hidden variables, ontological interpretation. This provides a completely different view-point on quantum theory, being both causal and ontological. Most interestingly it isn't just an alternative interpretation of quantum mechanics, or an alternative formulation (*cf.* classical mechanics), it is empirically distinct, and as such a completely different theory.

As part of my investigation I decided it would be prudent to have some gauge of the size of the research field of one of the alternative theories currently receiving attention; I chose pilot-wave theory. If time constraints weren't an issue it would have been nice to do a proper scientometric analysis of the field, or at least construct a Price's estimate (de Solla Price 1963, Wray 2010), however that wasn't to be the case, and a little *ad hoc* methodology was in order. I decided to try to estimate how many papers had been published on pilot-wave theory as a proportion of total theory papers. Under consultation with the Imperial College librarians it was judged that the best course of action would be to analyse the number of papers on one of the large internet journal databases; Web of Science, arXiv, Inspec or MathSciNet. ArXiv was chosen as its indexing gave a simple way of determining the number of pilot-wave papers as a proportion of all theory papers. Making sure to include all the various guises of pilot-wave and making sure not to include conference proceedings I plotted the attached chart. It shows a year on year average of about 1% of theory papers, quite a sizable amount, esp. since it was first proposed by de Broglie at the 1927 Solvay conference. It is therefore paramount that one must take care not to include bias in the material and presentation of the theory to students Quantum theory should be presented as just that, a theory, warts and all.

In particular I believe it is vital to include an unbiased discussion on the philosophical arguments used to justify different theories. Without an introduction into such arguments in science, and with young and impressionable minds, it would be easy to be misled.

## School Science

Some of these issues and topics are way beyond further education, and there is certainly a very strong argument to leave any of the issues I've raised until university. Students generally have their first taste of quantum theory while studying As level however, and this would leave two or three years for them to build up a picture of quantum theory based solely on popular science in the media and elsewhere. Personally I think that leaving a discussion on these points until higher education would be leaving too much time for misconceptions to develop, and that if treated carefully, there is a sensible discussion to be had. Certainly I think that if the double slit experiment is used to illustrate wave particle duality, the scientific theories developed to tackle this should be elaborated on.

With the creation of Ofqual over the last couple of years, and the passage of responsibility for publishing subject criteria from QCDA to Ofqual, the criteria for As and A level science has not been modified since 2006. The relevant section of the criteria is appendix 3.7 of QCA (2006) states

### 3.7 Quantum and **nuclear physics**

1. *Photons* photon model to explain observable phenomena evidence supporting the photon model
2. *Particles* evidence supporting the quantum model for particles a study of particle diffraction would provide suitable depth of treatment
3. . . . .

where the standard typeface denotes material to be covered in As level, the bold typeface may be spread between the two years, and together they should account for roughly 60% of the specification. Evidently wave-particle duality needs to be covered at As. I would like to point out however that the requirement is only for evidence supporting quantum theory, rather than any of quantum theory itself. Also electron diffraction is specified, but not the double slit, where the interesting phenomenon is not diffraction, but something akin to interference. The other areas to cover are rudimentary mechanics (energy and force, acceleration as vector quantities), electronics, and a qualitative treatment of waves. The electronics does not fit with the wave-particle duality, but the mechanics, and the treatment of waves cover both bases to an extent, providing quite a timely pocket to touch on quantum theory. This, of course, has been planned in this way - I find it hard to believe that wave-particle duality would be treated so early if it wasn't aptly placed. Also, there is more than enough room

for a concise discussion on controversy over different formulations of quantum theory and their recent revival.

The three specification papers that I have analysed, AQA (2007), EDEXCEL (2008), OCR (2008), all contain the nearly identical phrase “wave nature of electrons/particles”, rather than the phrase “quantum model” used in the Ofqual criteria. It is my impression that this different, though admissible, term has the effect of keeping discussion away from quantum theory. Certainly the discussion of diffraction rather than the double slit does this. This is all very well, and a very defensible pedagogical trick to make (a discussion on quantum theory could be quite counter productive unless properly sculpted) if it weren’t for the nature of physics teachers.

[The double-slit experiment is a] phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality it contains the only mystery.

-Richard Feynman

Demonstrating an experiment showing electron diffraction, and then concluding electrons sometimes behave as if they were waves, without any further explanation, without answering when they do or why, is in my opinion a completely unsatisfactory treatment of the subject. The temptation as a teacher to talk about, or briefly cover the double slit experiment would be too great. But as I have argued, a brief, fleeting glimpse could lead to the students acquiring many misconceptions, especially as most physics teachers are likely to hold many misconceptions themselves having been educated at the height of Copenhagen hegemony.

Each of the three specifications chooses to elaborate on the “wave nature of electrons/particles” in slightly different ways. Both AQA (2007) and OCR (2008) choose to specify the ability to use the formula for the de Broglie wavelength. OCR (2008) goes further by specifying the ability to “explain that electrons travelling through polycrystalline graphite will be diffracted by the atoms and the spacing between the atoms” and “explain that the diffraction of electrons by matter can be used to determine the arrangement of atoms and the size of nuclei”. In contrast to AQA (2007) and OCR (2008), EDEXCEL (2008) does not specify the use of the equation, and instead to specify “discuss how scientific ideas may change over time, for example, our ideas on the particle/wave nature of electrons”.

This, I feel, is something of a missed opportunity. Wave particle duality has been mentioned, and evidence elaborated upon, though a discussion on exactly what wave-particle duality *is* has been avoided. As conceded earlier, there is a

strong case for not discussing the double slit this early in the students' education. If this were to be the case, then I would argue that electron diffraction should be left out. By only including electron diffraction, and including wave-particle duality only in an off hand way, one tempts questions in the pupils minds, only to move on quickly without answering them. Furthermore this is the only time in the specification where wave-particle duality is covered, and as such the students will be left without any idea of what quantum theory really is, or the controversy surrounding it.

In order to evaluate the understanding of the current controversy over quantum mechanics in those who have passed through the educational system I decided to perform standardised interviews on my ex-coursemates at Imperial College London. This course of action was decided upon the advice of Oppenheim (1992) due to the high level of open ended questions required. The six people I interviewed had all completed a MSc in 'Quantum fields and fundamental forces' at Imperial College the previous year after undergraduate physics degrees, three in England and three in Ireland. Due to the subject material, and the intention of gauging confusion and personal ideas on interpretation, the wording of the questions were kept particularly clear and simple. The requirement of stimulus equivalence, as explained in Oppenheim (1992) was taken into account when designing the interview, and the questions were looked over by another of my ex-coursemates to make sure there were no unintentional double-meanings or ambiguity. In particular, the questions were designed to be devoid of philosophical bias, especially in terms of realist or positivist wordings.

I found a mixed response on the interpretation of quantum mechanics. No one had any problem with the statistical interpretation of the wavefunction, though one attributed a meaning that they themselves were uncertain about, stating "[the wavefunction] is more than just...". Two claimed never really to have had a problem with the theory, and just accepted it as fact, one with a half-remembered quote claiming that our generation would be the first to properly understand the theory, having grown up with it. Two identified the measurement problem, but attributed it to an incompleteness of the theory rather than an error in it. All had heard of alternate interpretations of quantum mechanics, though were quite dismissive of their merit. In particular many-worlds was identified, with various synonyms of nonsense used by four. The three Irish-educated people had all heard about Bohmian-mechanics through the work of John Bell, and thought it worthy of research for that reason, though still viewed it as a sideline theory. One mentioned "spontaneous collapse" models, and thought that they were a more likely candidate for a more correct theory.

All remembered studying the double slit experiment before university, though only four remembered it proving the wave nature of electrons. Three identified

(wrongly) the double slit as proof that particle trajectories were impossible. In particular, one of the three to have heard of Bohmian-mechanics was among these, showing some considerable confusion over the matter. When questioned on the double slit experiment, there was no consensus. All associated the wave-nature with the wave properties of the wavefunction, though the nature of the wavefunction was unclear. Two associated a realist viewpoint of it - claiming that the particle goes through both slits, and one claimed that it did not make sense to say where the electron was until it was observed. Three attributed a statistical explanation.

All in all, I found a mixture of different opinions on the interpretation of quantum mechanics, all along the lines of Copenhagen, but with added confusion and doubt. It was mentioned at four times during the interviews that they never really had had to think about this in any formal way. The assessment of their courses had been focussed on calculation, and using the theory, rather than critiquing it. While I would like to avoid a debate on the implicit value of knowledge and understanding, it is interesting that all claimed to have chosen to study physics in part due to general interest in the theory, rather than its applications.

These interviews can hardly be called a survey however. The sample size was as large as practicable, but still extremely small. There was probably also a large amount of bias in the sample due to their specialism into the theoretical and foundational aspects of physics. In particular I find it very unlikely that a large survey of physics graduates would find 50% had heard of pilot-wave theory (despite the eight page summary in the standard undergraduate text Rae (2008)). I do however feel that the qualitative conclusions that can be drawn from this are in line with my earlier assertions. In particular the general attitude of ignoring the conceptual problems of the theory and accepting it as inevitable that they won't understand the theory, associating it with limitations of human thought. I would like to point out that these interviewees can be fiercely analytical people, most having been through five years of higher education in physics.

As a second part of my research I asked the two physics teachers at my placement school to explain to me how they would teach section 2.5.3 of the OCR specification (OCR 2008). Of course, again this is only two teachers, and is hardly representative of teaching in Britain. It did however agree with my assertion that the double slit experiment is too much of a temptation for teachers to ignore, both of them having taught it. When I asked how they would explain what happens to an electron in the experiment, there was a great deal of ambiguity in their responses. There were, in my opinion, too many questions left unanswered, and mostly due to a lack of time spent on the experiment.

## Conclusions

Point 43 on the Edexcel specification, just under the point concerning the wave nature of electrons states

discuss how scientific ideas may change over time, for example, our ideas on the particle/wave nature of electrons.

I think that it would be useful to keep this in mind when considering the curriculum for A level physics.

My original question related to the nature of theory in science, and how this was reflected in the national curriculum. Through evaluating the birth, and current state of one of the pillars of modern physics, I've shown that theory, and science in general are not as clear cut (and innocent) as is often presented to students. I've identified what I believe are the main barriers to learning: instrumentalist rhetoric, misleading arguments, and what Steven Weinberg called "the unreasonable ineffectiveness of philosophy" (Beller 1999). Central to a constructivist approach to science teaching is the idea of a Socratic dialogue and, as has been argued, this tends to get thwarted by a number of factors for students beginning to learn quantum theory.

My interviews alluded to the misinformed viewpoints of current graduates, something that I believe needs to be tackled. It is true certainly that an good exposition of quantum theory can only take place at a university level, something that is only beginning to happen at the moment *cf.* Towler (2009). I would however advise against the off-hand blurt on wave-particle duality in current curriculae - such an approach would lead to many students relying on, at times very misleading, popular accounts and ultimately many many misconceptions. Conversely, not covering the material wouldn't be much better. Many students enter further education having heard about quantum physics, intrigued as to what the word quantum means, and wishing to know more. Silence wouldn't dampen that.

I conclude, out of absence of other options, that it would be better to cover quantum theory in a controlled way. A qualitative coverage of three or four of the opposing quantum theories, set in the backdrop of the double-slit experiment, and a appraisal of some arguments for and against each one shouldn't take more than three or four lessons. It would give students a sound standing in a very popular, and very misrepresented area of physics. Expanded into more lessons it could cover a depth of how science works not seen in the rest of the curriculum. But, more than that, it would be incredibly engaging, and serve as a very good reason to to keep studying physics.

Unfortunately, the implementation of such a programme nationally wouldn't be simple. Most teachers will be unaware of the recent debate over quantum theory, having completed their degrees in a time when the Copenhagen hegemony was still very real. If such a programme was to be implemented successfully, I would argue that the guidance for the schemes of work couldn't come from the subject criteria, but would need to come from the exam boards. But even then the structure is not there in the specification for the re-education of physics teachers. Something along the lines of the secondary science framework's *barriers to learning* may help, but may well be too sparse and underused to enable the change that would be required.

In conclusion, it seems that change in further education may well have to wait for change in higher education, whether that be a slow reform of teaching practice, or empirical evidence is found clarifying the situation. Until that time it will only be my personal teaching practice that will change.

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Proportion of Papers in arXiv on Pilot-Wave theory compared to all theory papers

