Kuhn and Quantum Information Science

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Quantum Information Science is described in terms of Kuhn’s ideas on scientific theories and scientific development, following very closely the standard formulation in The Structure of Scientific Revolutions and later works. In particular, important Kuhnian concepts such as “scientific revolution”, “paradigm”, “normal science”, “anomaly” or “scientific community” are revisited and somehow tested in the context of the emergence and development of this novel area of contemporary science.

1. Introduction

It is a commonplace in the literature to introduce Kuhn’s book The Structure of Scientific Revolutions with some laudatory comments. Let us proceed with this essay accordingly, by saying that this work not only is one of the most influential books on the philosophy of science, but also one of the most widely read. Key concepts like ‘paradigm’ or ‘incommensurability’ have been studied and used beyond the realm of philosophical and historical studies of science, and now are part of the jargon in many other disciplines. Specifically in the field of the philosophy and history of science, Kuhn’s theories in this book, and their subsequent re-elaboration (in later accounts) constitute an interesting body of knowledge, an interesting framework in which the emergence of new scientific theories, the idea of scientific progress, the development of science in general, may be interpreted.

In this essay we will apply some of these ideas to a new emergent field in modern physics, relevant enough, in our opinion, to demand the attention of historians and philosophers of science. In a certain sense, this exercise would be a good way of testing Kuhn’s hypotheses in a contemporary context. This new emerging field does not have a proper name; it is constituted by many intermingled fields: Quantum Optics, Information Science, Laser Science, Quantum Computing, etc. This is an indication of its lack of complete definition; it is a paradigm in the making, in progress, as we will see. For the purpose of this essay we will use the term Quantum Information Science (QIS), one of the most common names for this new type of discipline.

1 Email: joserra.marcaida@gmail.com

2 Kuhn, Thomas S.; The Structure of Scientific Revolutions (3rd ed., University of Chicago Press, London, 1996). In the footnotes, we will write SSR.

3 See Bibliography for the main texts consulted. We have decided to exclude Kuhn’s book Black-Body Theory and the Quantum Discontinuity, 1894-1912 (Clarendon Press, Oxford, 1978), since, as Peter Galison suggests in his review of the book (see Bibliography), Kuhn is writing as a historian, not as a philosopher of science, and he does not even mention his other works.
This essay, in a sense, is more an application and evaluation of Kuhn’s model to a specific area of contemporary science, rather than a straightforward philosophical discussion about the model per se. In particular, we leave aside very interesting discussions on the notion of science, its institutional dimensions and its relation to technology, from the post-war period to the present day (the idea of Big Science, the new philosophical problems related to technoscience, etc.). However, it is important to frame this evaluation according to certain philosophical ideas; in many occasions we will be guided by Paul Hoyningen-Huene’s thorough account, Reconstructing Scientific Revolutions.

In the first place, we agree with Hoyningen on the claim that the topic of Kuhn’s philosophy of science is, essentially, scientific development. This is relevant as a starting point, because this essay, in a non-explicit but noticeable sense, is also the story of a developing scientific discipline. Regarding the question about the domain of science in the Kuhnian model, and more specifically, the choice of QIS as the subject under scrutiny, we can argue that this scientific discipline, even though is not one of the so called “uncontroversial” cases, at the same time is definitely not one of the “controversial” ones. In other words, QIS qualifies as “pure science”, Kuhn’s privileged domain for his studies. (However, we disagree with Hoyningen when he opposes this domain to the one of the applied sciences or technological invention; Kuhn himself had doubts about this divide.) In this sense, according to the three conceptions of science that Hoyningen describes, QIS would belong to the ‘epistemic or theoretical’ conception (“that which captures only those aspects pertaining to science qua form of knowledge”), the other two being more oriented towards the social and socio-cultural aspects of knowledge. At the end of the essay we will question if this requirement (that only the epistemic sense counts for the Kuhnian model) is a limiting factor. Kuhn himself, Hoyningen notes, was “aware that this approach leaves a question open: whether the corpus of scientific knowledge itself provides enough for this explanatory task (of scientific development) or whether social, economic, political, psychological and other factors must also be taken into consideration.”

The general structure and the main line of argument of the essay will be the following. The starting point will be the assumption that QIS constitutes a paradigm nowadays, insofar as it more or less satisfies two conditions stated by Kuhn in one of his multiple accounts on the concept of paradigm. These two ‘essential characteristics’ as he calls them are the following. On one side, the achievements of QIS are “sufficiently unprecedented to attract an enduring group of adherents away from competing modes of scientific activity”; and, on the other hand, this new field is “sufficiently open-minded to leave all sorts of problems for the redefined group of

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4 This is an important area of my own research nowadays: to characterise QIS as a technoscience.
5 Hoyningen-Huene, P.: Reconstructing Scientific Revolutions (University of Chicago Press, Chicago, 1993). From now on, in the text we will refer to him as Hoyningen; in the footnotes, we will refer to his book as RSR.
6 RSR, p. 3.
7 RSR, p. 4.
8 RSR, p. 5.
9 The scientific community sometimes appears to be divided: some people think that QIS, particularly in the case of Quantum Computing, is just speculation, pure fantasy.
10 See the discussion in RSR, p. 6.
11 RSR, p. 6.
12 RSR, p. 6.
13 RSR, p. 7.
practitioners to resolve.\textsuperscript{14} We will argue that this paradigm has emerged, through a process of evolution, rather than revolution, from other paradigm, that of Quantum Physics.

In the first part of the essay, we will look back at the paradigm of Quantum Physics, and in particular, at the problematic idea of quantum entanglement, one of the most famous anomalies in modern physics. We will describe how the perception of this anomaly has changed, from being a real complication for Einstein, Schrödinger, etc., to being the most important concept in many disciplines today, most notably, QIS. In the second part, we will describe QIS in terms of Kuhn’s notion of normal science. We will begin with the idea of puzzle solving activity, and then proceed by focusing on “normal science type” of strategies with regard to education and community gathering. In the third part, will describe how the development of this new paradigm has not been preceded by a scientific revolution in the ordinary sense (in Kuhn’s original account). In contrast, we will refer to Kuhn’s later reflections on the issue of scientific progress, in which the notion of evolution plays a crucial role. Finally, in the fourth part, we will try to describe one aspect which, in our opinion, is not reflected in Kuhn’s account. At the centre of this last issue is the idea of fascination.\textsuperscript{15}

\textbf{2. Anomalies in the Kuhnian model: the case of quantum entanglement}

A prominent (and controversial) concept in The Structure of Scientific Revolutions is the idea of normal science. According to Kuhn, once a new paradigm, after a period of crisis and subsequent “scientific” revolution, is established, the new defined scientific community embarks into what is defined as “normal science”, a problem-solving activity which extends “the knowledge of those facts that the paradigm displays as particularly revealing, by increasing the extent of the match between those facts and the paradigm’s predictions, and by further articulation of the paradigm itself.”\textsuperscript{16}

One of the most interesting aspects of normal science is its production of novelties. Kuhn puts in a lot of effort into clarifying this issue, for novelties are, potentially, the origins of anomalies\textsuperscript{17}, and these, in part, are responsible of crises. Since we are interested in entanglement as one such anomaly, we should focus on these ideas for a while before considering other issues.

According to Kuhn, one particular feature of scientific activity in normal science is how little it aims to produce conceptual or phenomenal novelties,\textsuperscript{18} in other words, “normal science does not aim at novelties of fact or theory, and when successful finds

\textsuperscript{14} SSR, p. 10.
\textsuperscript{15} This, together with the study of QIS as a technoscience, constitutes the main line of enquiry of my own research. I am currently studying the notion of wonder and wonders in the context of the Scientific Revolution, with the aim of trying to find out if these features of early modern science have been kept at the heart of scientific practice, even up to its present (and radically different) format. An example of this approach would be to try to characterise quantum entanglement as one among many contemporary “wonders” driving scientific practice, or even to characterise the general attitude of Quantum Information scientists as “wonder”. This approach will become clear in the last section of this work.
\textsuperscript{16} SSR, p. 24
\textsuperscript{17} “Kuhn calls observations or experimental and theoretical findings that are surprising relative to normal-scientific expectations, and appear to contradict them, anomalies” RSR, p. 224. Hoyningen reminds us some of their attributes: “serious”, “meaningful”, “troublesome”, “especially compelling”, “admittedly fundamental”, “crisis-provoking”, “significant” anomalies. RSR, p. 225.
\textsuperscript{18} SSR, p. 35
Novelties, however, do appear in science; at least, we can deduce so retrospectively. Kuhn is well aware of that fact: “New and unsuspected phenomena are, however, repeatedly uncovered by scientific research and radical new theories have again and again been invented by scientists.” Kuhn goes on explaining the difference between discoveries as ‘novelties of facts’, and inventions as ‘novelties of theories’, but the interesting point is that a novelty is almost immediately associated with the anomalous, the unrepresentative with respect to the paradigm. Particularly in the case of discoveries, this awareness of anomaly in certain facts suggests that the paradigm-dominated expectations that govern normal science have somehow failed.

However, once the paradigm has been adjusted and the anomalous ceases to be the unexpected, the problem is solved. Nevertheless, as we will see now, this readaptation process is not unproblematic. In some cases, as Kuhn says, “assimilating a new sort of fact demands a more than additive adjustment of theory.” These are the cases when the anomaly is persistent, and the paradigm does not seem able to cope with it.

These extraordinary problems, according to Kuhn, emerge only in special circumstances, brought about by the advance of normal research. They are not necessarily something bad for the scientific community: “it may well be their resolution that makes the scientific enterprise as a whole so particularly worthwhile.” But in many occasions, these persistent problems do incite scientists to desert the paradigm (“to desert the paradigm is to cease practicing the science it defines”). This is an indication of the beginning of a crisis: “When an anomaly comes to seem more than just another puzzle of normal science, the transition to crisis and to extraordinary science has begun.”

At this stage, the anomaly seems to get some prominence, and, as Kuhn says, it comes to be more generally recognized as such by the profession, particularly by the most eminent members in the field, to the extent that many of them may come to consider its resolution as the subject matter of their discipline.

Kuhn suggests three possible outcomes for this problematic situation. On one hand, it may be the case that normal science manages to overcome the crisis by solving the problem that started it, “despite the despair of those who have seen it as the end of an existing paradigm.” On the other hand, if normal science fails so solve the problem, the paradigm in crisis may be eventually replaced by a new paradigm capable of providing a solution. This is undoubtedly Kuhn’s favourite case, and the notion of ‘scientific revolution’ is introduced in this context. In fact, most of the text in The Structure of Scientific Revolutions is devoted to this issue. “The transition from a paradigm in crisis to a new one from which a new tradition of normal science can emerge”, Kuhn writes, “is far from a cumulative process […] it is a reconstruction of

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19 SSR, p. 52
20 SSR, p. 52
21 SSR, p. 52
22 SSR, p. 53
23 SSR, p. 53
24 SSR, p. 34
25 SSR, p. 34
26 SSR, p. 82
27 SSR, p. 82
28 SSR, p. 84
the field from new fundamentals, a reconstruction that changes some of the field’s most elementary theoretical generalizations as well as many of its paradigm methods and applications."\textsuperscript{30}

Finally, there is a third possibility, which Kuhn mentions briefly, but which is very interesting for the purpose of this essay. The scientific community in a certain paradigm, unable to solve the anomalous problem, “conclude that no solution will be forthcoming in the present state of their field. The problem is labelled and set aside for a future generation with more developed tools.”\textsuperscript{31} In the case of quantum entanglement, this is more or less what has happened.

2.1 Quantum Entanglement

The term ‘entanglement’ was coined by Erwin Schrödinger; he first used the German expression, ‘Verschrankung’, in his paper of 1935 “The present situation in quantum mechanics”\textsuperscript{32}, and later introduced the English translation (most widely used ever since) in a later paper, also written in 1935.\textsuperscript{33} Although it has been argued that the idea occurred to him long before 1935, this notion of entanglement was first introduced in the context of the debate provoked by the Einstein-Podolsky-Rosen paper\textsuperscript{34}, published earlier that year. The EPR paper suggested very strongly that the inability of quantum mechanics to account for locality was an indication of the incomplete nature of the theory. The paradox of quantum non-locality was precisely due to this phenomenon that Schrödinger called ‘entanglement’ and, which Einstein later referred to as “that spooky action at distance”.

At this time, 1935, the conceptual interpretation of the quantum theory was dominated by Bohr's ideas, or what is also known as the Copenhagen Interpretation. Einstein was not convinced by many assumptions and consequences of this approach, most notably, the statistical character of quantum theory. His reservations pointed towards the issue of whether the quantum mechanical description of reality was complete or not, in a local, deterministic, and realistic fashion. The EPR paper was intended to put forward these concerns.\textsuperscript{35}

The suggestion that quantum theory, at that stage of its development, was incomplete because of a strange phenomenon, sparked an spirited debate among physicists, most notably between Einstein and Bohr. Some supported the theory and tried to preserve its integrity, others saw the paradox introduced by the EPR paper as a serious challenge. The crisis affected the foundations of quantum mechanics, and its interpretation. Some of the best scientist of the time, as we have said, took the matter

\textsuperscript{30} SSR, p. 84-85
\textsuperscript{31} SSR, p. 84
\textsuperscript{34} Einstein, A., B. Podolsky, and N. Rosen; “Can quantum-mechanical description of physical reality be considered complete?”, Phys. Rev. 47, 777-780 (1935)
as a personal challenge. But the crisis, however notorious, did not stop other areas of quantum theory from developing. Even if it affected the core of quantum mechanics and its interpretation, for practical purposes the theory, in its normal science puzzle-solving activities, was giving promising results. As a consequence, the anomaly of entanglement was recognized as such, but, as Kuhn writes, it was “set aside for a future generation with more developed tools” to resolve it. Indeed, the question of entanglement ceased to be a paradigm threatening anomaly. It still occupied the minds of many scientist, like von Neumann or Bohm, which continued with the debate, but not anymore as crisis producing novelty.

Entanglement re-emerged as a relevant (and controversial) topic again in 1964, with the work of John Bell on ‘hidden variable’ theories, in which phenomena like quantum entanglement are explained in terms of unknown deterministic microscopic parameters. Bell’s most important result, his inequality relations ("Bell's inequalities"), were designed to provide a decisive test about the paradoxical nature of quantum theory. The inequalities were in principle experimentally testable, so the debate about the foundations of quantum theory, merely theoretical in its origins, became also experimental. After the publication of Bell’s papers, several experiments were conducted over the years to test Bell’s inequalities, and their result overwhelmingly supported the predictions of quantum mechanics.

Bell’s work generated an ongoing debate on the foundations of quantum mechanics, but it was not until the 1980s that physicists (and scientist in other disciplines such as computer science and information theory) began to regard the peculiar features of entangled quantum states as a new conceptual tool that could be applied to a number of fields. This is the case of Quantum Information Science. Given the impossibility to get into details, let us simply state that the notion of entanglement in this discipline is one of the foundation stones.

With this lengthy description of its development and reception as an anomaly, we have tried to show how the notion of entanglement, originally belonging to the paradigm of Quantum Physics, has been translated into other fields (where it plays a fundamental role), in a process that seems to be more of an evolutionary nature rather than revolutionary.

3. Normal Science: puzzle solving activity and education

As Kuhn suggests, at the time of its first appearance, we must notice how very limited in both scope and precision a paradigm can be; it is largely (or merely) a promise of success. As the paradigm develops into normal science, it requires not only “the construction of elaborate equipment, the development of an esoteric vocabulary and skills, and a refinement of concepts” but also some sort of organising structure, and a community; in other words, “normal science consists in the actualisation of that

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37 For a good summary, see Aspect, A. Bell’s inequality test: more ideal than ever, Nature 398 189 (1999).

38 See some of the references in the Bibliography.

39 SSR, p. 23

40 SSR, p. 64
In this sense, the new paradigm of QIS has just provided the outlines of this promise and it is beginning to fulfil it. To put it in another way: once a paradigm, according to Kuhn, stands out and gains its status because it is more successful than its competitors in solving a few crucial problems, it then starts to develop itself into the puzzle solving and community gathering activity called normal science. Here we will try to show how QIS has demonstrated, during the last two decades, that it can deal with information (be it in computing, in secure communication, etc) in a novel and promising manner; and how, since a decade or so, it has started to structure and extend these ideas into a normal science format, and it is still in the process of doing so.

Hoyningen suggests that the set of attributes of a scientific community in the Kuhnian model can be divided in two subsets, the first one being used to identify the community (particularly focusing on education and communication) and the second one as an explanation of the attributes in the first subset. In the following section, we will focus on the first subset, and in particular, in the questions about puzzle solving activity and education. We would like to argue that QIS is today a normal science in the making, and for this purpose we will try to relate some of its present features with various ideas concerning normal science in the Kuhnian model.

3.1 Puzzle solving activity

As we have seen in the previous paragraphs, Kuhn insists that even though novelties are not the aim of normal science (on the contrary, “they are necessarily subversive”), “the very nature of normal research ensures that novelty shall not be suppressed for very long.” These novelties can be either the origin of a crisis, or, as in the case of entanglement, the area of research of a temporarily scattered minority of the scientific community. In this last case, the anomaly does not produce a crisis, there is no paradigm change, and no scientific revolution; normal science proceeds as usual.

According to Kuhn, puzzle solving is the main activity of normal science. Turning back to our chosen example for this essay, we can notice, for the last thirty years but particularly in the last decade, a burst of frantic problem solving activity in all the disciplines that constitute QIS. Fields like optics, information theory, computer science, have all experienced a sudden change, and are developing rapidly into new directions, with very promising results. As we have mentioned already, the main idea driving this activity is quantum entanglement, no longer seen as a theoretical hindrance, but as a valuable resource for new approaches in these disciplines. We can illustrate this point with a reference to two of this emergent areas of research: Quantum Cryptography and Quantum Computing.

According to the most optimistic predications, qualitatively new algorithms based on quantum principles and quantum units of information (q-bits), supported by the appropriate quantum technology, will allow a new type of computational devices, the

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41 SSR, p. 24
42 SSR, p. 23
43 More historical work is needed here; this is just an outline.
44 RSR, p. 9
45 SSR, p. 5
46 See Bibliography for some relevant texts about these topics.
so called quantum computers. These computers could, in principle (the theoretical aspects are being calculated, the practical are still a chimera) perform different type of computations, as well as classical computations in a much faster way. Belonging to the latter group is the problem of factorising large numbers. Interestingly enough, the security of most of the cryptographic systems used today is based on the difficulty of factoring large integers. This means that if quantum computers were able to factorise large integers much faster than classical computers (as it has been theoretically proven), the privacy of most cryptosystems would be at risk; in other words, classical cryptography would no longer be secure. In contrast, a new way of thinking about cryptography, based on quantum principles, provides, in theory, means for complete secure communication. This is Quantum Cryptography, where the process of information transfer is secured and protected by the same quantum laws that make it possible.

For the purpose of this essay, it is interesting to note that the puzzle solving activity of one discipline (computing) has produced a decisive crisis in the other one (cryptography). At the same time, the solution of the crisis (quantum cryptographic protocols) derive from the same principles that made possible the crisis-producing novelty (quantum computations). Needless to say, the phenomenon of quantum entanglement and the exploitation of entangled states lie behind the puzzle solving activity of both disciplines.

Another sign of puzzle solving activity is the production of technologies; this does not apply, for the moment, to the case Quantum Computing, but it does in the case of Quantum Cryptography, which has been successfully implemented in many occasions.

Puzzle solving activity is, as we have said, one of the defining features of normal science. It would require a longer text to give a detailed account of this activity as far as QIS is concerned; but with these two examples we have tried to show that the paradigm is moving towards this status. Other important aspects of normal science, which are useful to illustrate our point, are related to the issue of education.

### 3.2 Education

Educational strategies play a crucial role in normal science, in particular, when the scientific community is formed. As Hoyningen points out, scientists share a similar education, a similar professional initiation; they absorb the same technical literature and draw many of the same lessons from it. We will try to show that this is the case for QIS.

In the first place, one of the most relevant aspects of normal science, according to Kuhn, is the fact that once a paradigm is taken for granted, the scientist “need no longer, in his major works, attempt to build his field anew, starting from first

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48 RSR, p. 9. Hoyningen suggests that this approach might be a bit narrow, and too contemporary (p. 11). In our case, this criticism is not relevant.
principles and justifying the use of each concept introduced.\textsuperscript{49} In the case of QIS, this is not exactly true; however, it is gradually looking like Kuhn’s description. On one hand, even though most of the first principles are well established, there is still plenty of work being done in formulating them in a coherent way. On the other hand, most of the major works (both seminal papers and books) still include a conceptual justification as an introduction to their main arguments; in particular, these preliminary texts insist on the novelty of these ideas and their enormous potential. A good example is the book Quantum [Un]speakables. From Bell to Quantum Information\textsuperscript{50}, where the aim of the work is to pay tribute to John Bell, and, at the same time, a good introduction to QIS is provided and justified.

In the second place, another important aspect in Kuhn’s conception of normal science is the role played by text books. Scientist, according to Kuhn, “work from models acquired through education and through subsequent exposure to the literature”; they do not necessarily need to know the reasons why these models are given the status of community paradigms.\textsuperscript{51} In the present situation of QIS, these models are still being constructed, so it is important to provide good grounding for the support of the new paradigm. In other words, authority resides in the hands of the pioneering scientists who witnessed the first stages of the paradigm. This is particularly clear when we look at the editors and contributors to textbooks,\textsuperscript{52} not very abundant in the case of QIS.

The textbook is, then, the typical medium of instruction for normal science\textsuperscript{53}. If, according to Kuhn, textbooks “are produced only in the aftermath of a scientific revolution” and “they are the bases for a new tradition of normal science”\textsuperscript{54}, in the case of QIS this tradition is now being designed.\textsuperscript{55} Hoyningen suggests that a good way of approaching the issue of textbooks is by analysing “what is not learnt” through their use\textsuperscript{56}. In general, the student does not get a proper view of the past in his field, not even a general overview of the present situation of research in the field. The use of textbooks usually implies that the student is isolated from the primary sources: he does not read original work. QIS has not arrived at this stage yet, but it is very close to it. Students do get a general overview of the past and present of their research, principally because this research is relatively recent and needs to establish itself on firm grounds. Students do read primary sources, because the development of textbooks, as we have just said, is still in progress.

Directly related to this, Kuhn suggests the importance of foundational texts for the change in paradigm and the posterior consolidation of normal science. These are the famous classics of science\textsuperscript{57}. In the case of QIS, certain texts, particularly papers, are being promoted to the level of classics in the field. See for example, the Einstein-Podolsky-Rosen paper of 1935, John Bell’s papers, Aspect’s results, Bennet and

\textsuperscript{49} SSR, p. 19
\textsuperscript{51} SSR, p. 46
\textsuperscript{52} A good example is Boumeester, D., Ekert, A., and Zeilinger, A.(Eds.); The Physics of Quantum Information (Springer, London, 2001)
\textsuperscript{53} RSR, p. 186 Hoyningen dedicates a lot pages to this issue.
\textsuperscript{54} SSR, p. 144
\textsuperscript{55} In our case, as we will see, no revolution but evolution
\textsuperscript{56} RSR, p. 187
\textsuperscript{57} SSR, p. 10
Brassard^{58}, Ekert^{59}, etc. These texts are beginning to give shape to the classic corpus of the paradigm.

Besides this, it is worth noting the increasing importance of the Internet as community gathering tool. (Let us take the Centre for Quantum Computation^{60} based in Oxford, as an example.) Firstly, online lecture notes (in various formats, from PDF files to Power Point presentations and videos) are being made available, and are becoming a new form of textbook. These materials, which often include exercises and solutions, are usually accompanied by online tutorials, general introductions to the subjects and bibliographies. In particular, the possibility of linking materials and WebPages through hypertexts permits greater accessibility and mobility.^{61} These materials, indirectly, help to bridge the gap between institutions and their often different educational systems and standards, creating this sense of community that is so relevant in the Kuhnian model. Moreover, through the use of hypertexts but specially with the email, the Internet has provided a good ground for the creation of an efficient and far reaching correspondence network. Now more than ever, documents, letters, papers, any kind of material and information, become easily available and exchangeable. At a bigger scale, a scientific community is being created through this use of websites. These are often departmental websites based on universities, so the idea of science, community of practitioner, and indoctrination is all united. This unity is reinforced through meetings in conferences, workshops and symposiums (which are usually conveniently displayed in special sections of the WebPages) and through the mobility of the job market (with references also included in websites). The Centre for Quantum Computation, for example, even provides a World Map showing where Quantum Computing is being studied.

4. Quantum Information Science: a paradigm without revolution

In the previous sections we have tried to argue that QIS may be suitably described as a new emerging scientific field, a new paradigm with normal science activity, according to the model introduced for the first time in *The Structure of Scientific Revolutions*. In this section, we will study the ways in which the model can account for the development of QIS as a paradigm, a process that took place no through a revolutionary change in the usual sense. For this purpose, we will look at Kuhn’s thoughts on the idea of scientific development as an evolutionary process hinted at the end of *The Structure of Scientific Revolutions*; we will also look at his very last thoughts on the matter, included in the posthumously published work, *The Road since Structure.*^{62}

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^{60} www.qubit.org

^{61} Interestingly enough, Kuhn mentions the importance of referencing (SSR, p. 178). This is a non trivial way of creating a rich information network, particularly nowadays, with the use of hyperlinks.

In the first place, we must go back to the agreed idea, at the beginning of this essay, that the topic of Kuhn’s philosophy of science is, essentially, scientific development. Moreover, as Hoyningen suggests, in the context of a new historiography of science which does not hold the view of scientific development as a cumulative process, “Kuhn’s goal is to propose a new picture of science and scientific development, in particular of scientific progress, grounded in this new historiography.” Kuhn does not deny the presence in science of this kind of cumulative progress, he considers it appropriate of normal science. But in order to oppose the idea of progress through accumulation, he famously introduced the idea of scientific revolutions, which are essentially, as Hoyningen suggests, constructive-destructive events. (As well as the notion of cumulative progress, Kuhn rejects the idea of science developing towards a goal, a sort of objective truth. He insists, at the end of The Structure of Scientific Revolutions: “We may have to relinquish the notion, explicit or implicit, that changes of paradigm carry scientists and those who learn from them closer and closer to the truth. We will go back to this issue at the end of the section.)

In spite of the impact of such notions as scientific revolution, or paradigm shift (a la Gestalt switch), and their tremendous influence after the publication of The Structure of Scientific Revolutions, it is a common view in the literature about his work that Kuhn’s reflections on The Structure of Scientific Revolutions and on subsequent criticisms constitute a modification of his approach, intended to weaken his original “revolutionary” theses. Kuhn, on the contrary, insisted that these modifications over the years left the core of his theory essentially untouched. In spite of this, as Hoyningen points out, even though Kuhn remained, as before, convinced that crises are usually the prelude to revolution, he acknowledged that revolutions might also, albeit rarely, get started in other ways.

In fact, the first indications of this point of view are included at the end of The Structure of Scientific Revolutions, when Kuhn points towards an evolutionary conception of scientific development. In the same sense as Darwin’s view of evolution suggested the idea of “a process that moved steadily from primitive beginnings but toward no goal”, according to Kuhn “the developmental process described in this essay has been a process of evolution from primitive beginnings-a process whose successive stages are characterized by an increasingly detailed and refined understanding of nature. But nothing that has been or will be said makes it a process of evolution toward anything.” It is this idea of scientific development as an evolutionary process that we may borrow from the Kuhnian system when we try to describe the emergence of QIS as a new paradigm. The idea of a crisis and a scientific revolution in the strict sense would be totally inaccurate.

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63 RSR, p. 3
64 RSR, p. 13
65 RSR, p. 258-259
66 SSR, p. 170 He goes on... “Does it really help to imagine that there is some one full, objective, true account of nature and that the proper measure of scientific achievement is the extent to which it brings us closer to that ultimate goal?”
70 SSR, p. 170-171
Kuhn planned to investigate further this analogy between scientific progress and evolutionary biological development. Instead of just talking about periods of normal science punctuated by revolutions, he also proposed a case in which periods of normal science and normal development are combined with occasional periods of “speciation” into new and distinct scientific “specialties”, for speciation in this context means specialization.

The two main ideas behind his approach towards a viable evolutionary epistemology are the following. On one hand, as we have said above, speciation is specialization. In *The Structure of Scientific Revolutions*, Kuhn points out, there was a distinction between those developments that simply accumulate, add to knowledge, and those which require a partial, sometimes total abandonment of what had been believed before. Kuhn’s idea for the new book was to present a new distinction, between developments which do and developments which do not require local taxonomic change. During this second type of change, Kuhn suggests, something else occurs that in *The Structure of Scientific Revolutions* was mentioned only in passing:

After a revolution there are usually (perhaps always) more cognitive specialties or fields of knowledge than there were before. Either a new branch has split off from the parent, as scientific specialties have repeatedly split off in the past from philosophy and from medicine. Or else a new specialty has been born at an area of apparent overlap between two pre-existing specialties, as occurred, for example, in the cases of physical chemistry and molecular biology. At the time of its occurrence this second sort of split is often hailed as a reunification of the sciences, as was the case in the episodes just mentioned. As time goes on, however, one notices that the new shoot seldom or never gets assimilated to either of its parents. Instead, it becomes one more separate specialty, gradually acquiring its own new specialists’ journal, a new professional society, and often also new university chairs, laboratories, and even departments.

Revolutions, in this new sense, give rise to new divisions between fields in scientific development, much like episodes of speciation in biological evolution. The biological parallel to revolutionary change then is not mutation but speciation.

On the other hand, this idea of a parallelism between scientific and evolutionary developments is in accordance with Kuhn’s rejection of both foundationalism and, in a sense, the standard correspondence theory of truth. Although he was quite aware that the rationality and unity of science are put into question by this approach, he opposed the idea that the aim, when evaluating a particular science, is to determine whether or not it corresponds to an external world and objective truth. He wrote: “It is that notion, whether in an absolute or probabilistic form, that I am persuaded must vanish together with foundationalism. What replaces it will still require a strong conception of truth, but not, except in their most trivial sense, correspondence.

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71 In fact, according to the editors, this was one the three main themes of the book. See the Introduction in *The Road since Structure*. Philosophical Essays, 1970-1993, with an Autobiographical Interview (University of Chicago Press, Chicago, 2000).

72 *The Road since Structure*, p. 3

73 *The Road since Structure*, p. 94

74 *The Road since Structure*, p. 97

75 *The Road since Structure*, p. 97

76 p. 98 road .. “And the problems presented by speciation are very similar to those presented by revolutionary change and by the emergence and individuation of new scientific specialties”

77 “To anyone who values the unity of knowledge, this aspect of specialization- lexical or taxonomic divergence, with consequent limitations on communication- is a condition to be deplored” For Kuhn this limitation is positive, is the essential precondition for what is known as progress in both biological development and the development of knowledge. *The Road since Structure*, p. 99.
truth”. As he hinted at the very end of *The Structure of Scientific Revolutions*, in this last work he still insists that scientific development “must be seen as a process driven from behind, not pulled from ahead- as evolution from , rather than evolution toward”.

Finally, there is a third idea, which we cannot just but mention, behind this parallel between biological and scientific development: the study of the unit that undergoes speciation. According to Kuhn, “in the scientific case, the unit is a community of intercommunicating specialists, a unit whose members share a lexicon that provides the basis for both the conduct and the evaluation of their research and which simultaneously, by barring full communication with those outside the group, maintains their isolation form practitioners of other specialities.”

In conclusion, in this section we have shown how the Kuhnian model, particularly its last version, may in principle accommodate to the idea of QIS emerging from the paradigm of Quantum Physics via a process of evolutionary speciation, rather than revolutionary change.

5. Fascination

The aim of this final section is to point out a question which we think has been crucial for the development of QIS as a revolutionary paradigm, and which the Kuhnian model we have been examining so far cannot fully explain.

If we consider the emergence of QIS as a paradigm, together with its tremendous success and popularity, but we do not take into account the puzzle solving capabilities of the paradigm and the results (both theoretical and experimental) that is producing, and, moreover, if we ignore the status of some its major figures, and the increasing number of university departments that work on this area (in other words, if we exclude most of what is usually considered essential for the ‘well being’ of a scientific field) then we are left with a very simple fact, not uncommon in science, but something which usually is not taken seriously in philosophy of science: the fascination that the topic as a whole provokes.

In recent years, the theory of quantum information and the technological applications which derive from it have managed to attract the interest of both the scientific and non-scientific communities in a rather unprecedented way. Expressions like “quantum computer”, “teleportation” or “quantum cryptography” are becoming increasingly popular nowadays. For some people (physicists, computer scientists, engineers) they represent a truly professional challenge. For others, they either epitomize the success of science and its applications as a form of technology (which can be used, which can be sold); or, very simply, these concepts fascinate them in the way new discoveries and creations have always fascinated people throughout history.

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78 *The Road since Structure*, p. 95.
79 *The Road since Structure*, p. 96.
80 Quoted from Marcaida, J.R., “Creating single photons on demand”. Msci Project 2004, Department of Quantum Optics and Quantum Information, Imperial College London.
As far as the Kuhnian model is concerned (particularly in *The Structure of Scientific Revolutions*), this idea of fascination as a determining factor in the development and success of science is present but in an ambiguous sense. On one hand, it is one of its most relevant aspects the fact that, according to the Kuhnian model, there is not a rational way, like a set of universal rules, for choosing between rival theories; that is, it is ultimately a question of subjective preference that transcends rationality. In this sense, psychological and social factors must be taken into account when explaining why certain theories win the allegiance of the scientific community and other do not. Kuhn writes: “Individual scientists embrace a new paradigm for all sorts of reasons and usually for several at once [...] Some depend upon idiosyncrasies of autobiography and personality. Even the nationality or the prior reputation of the innovator and his teachers can sometimes play a significant role.” As we have said above, this issue is also directly related to questions about rationalism, relativism and the unity of science.

Having set the ground for our approach with his view on non-rational preferences, Kuhn, on the other hand, seems to reject our idea of the importance of a ‘fascinating’ topic. In *The Structure of Scientific Revolutions*, Kuhn writes: “to understand why science develops as it does, one need not unravel the details of biography and personality that lead each individual to a particular choice, though that topic has vast fascination.” Hoyningen agrees with this idea when he insists, focusing on normal science activities, that the research problems may be characterised negatively, since they are not selected for social, economic, or other reasons external to science. In other words, as Kuhn defends in other chapter of *The Structure of Scientific Revolutions*, “it is no criterion of goodness in a puzzle that its outcome be intrinsically interesting or important.”

We disagree with these conclusions quite substantially, for several reasons. Firstly, in the case of QIS we think it is important to consider details of biography and personality, from two perspectives, at least. One is related to the personalities and lives of the main scientists involved in the development of the field, not just Bohr, Einstein or Bell, but also Aspect, Ekert, Zeilinger, and many more. The different intellectual trajectories of these scientists contradict Kuhn’s opinion in *The Structure of Scientific Revolutions* that “almost always the men who achieve these fundamental inventions of a new paradigm have been either very young or very new to the field whose paradigm they change.” The other perspective is that of the scientists that join the discipline, particularly students. Many are interested in this field because of the prominence of the scientists that made it possible, and because they will dedicate themselves to discuss and solve the same problems these characters discussed. References to this issue are not infrequent, in an informal way, in departmental interviews as part of the recruitment strategies, when the student is told that he or she will be trying to investigate a question like entanglement, that even Einstein could not manage to explain.

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82 SSR, p. 152.
83 SSR, p. 200.
84 SSR, p. 36.
85 SSR, p. 90.
Secondly, there are, in our opinion, reasons external to science which affect the nature of research problems. For example, the issue of perfectly secure communication in cryptographic schemes (both in classical and quantum protocols) is clearly motivated by non-scientific interests, and in fact, this area of research has been among the first ones in producing fully operational technological applications.

Thirdly, we agree with Kuhn that an interesting or important outcome of a puzzle can not be the criterion of its goodness. But it still is an aspect that surely must be taken into account. The results from the tests of the Bell inequalities may serve as an example: these results, particularly the fact that quantum theory defies the classical notion of locality and reality, and consequently the rejection of hidden variable theories, demonstrate how an interesting (we do not argue if it is expected or not) outcome of a puzzle led scientists in a certain direction with very prosperous results.

Finally, the impact of QIS as a fascinating and promising discipline on the media (particularly in the non strictly academic realm) is also noteworthy. A quick glance at bibliographic indexes will show increasing number of articles, reviews and general references featuring QIS. To put it in simple words, it is becoming “fashionable” to talk about teleportation, quantum cryptography, quantum information, quantum computers. Just to give an example, and as a way to conclude this section, we include here the introductory note of a public lecture at The Royal Institution of Great Britain87, by Professor Peter Knight, Head of the Physics Department, and Head of the Quantum Optics and Quantum Information Group at Imperial College London. The Lecture, scheduled for the 22nd of April, 2005, was entitled “Quantum entanglement: spooky but useful”.

“Entanglement – a concept introduced by Schrödinger and Einstein, and once described as the spookiest part of modern science – is at the heart of quantum mechanics. Yet until quite recently it was often considered fit merely for after-dinner arguments by philosophers. Peter will describe how recent study of entanglement has produced shocks that the science community is only now coming to terms with, for example, the abandonment of ideas we previously took for granted. But it doesn’t end there: entanglement is the enabler of quantum teleportation and of communication links that have quantum security, and are therefore probably immune to eavesdroppers. Entanglement may even provide the engine of quantum computers, able to tackle problems impenetrable even to the largest possible classical computer. Join Peter as we celebrate the ‘International year of physics’, and learn all about what may well be one of Einstein’s most enduring legacies.”

6. Conclusion

The purpose of this essay was to describe the emergence and the progress of a new discipline in contemporary physics, Quantum Information Science, in terms of Kuhn’s now classical model of scientific development. Based mainly on his famous work, The Structure of Scientific Revolutions, this model provides an interesting framework in which scientific disciplines and their activities can be investigated. The idea was to test the accuracy of the Kuhnian model and to try to show if there are certain features about QIS that demand its reformulation. The result is that out of the five topics we

87 www.rigb.org/rimain/index.jsp
have examined in these pages (“entanglement as an anomaly”, “puzzle solving activity”, “educational issues”, “evolution without revolution” and “fascination”) only the last two gave rise to problems for the model. Let us recapitulate starting from these two.

In the case of scientific development as an evolutionary process, Kuhn himself provided a reformulation of his own theory, although he could not but give an outline of his ideas: scientific revolutions are not strictly necessary for the emergence of a revolutionary paradigm. There may be cases, as in QIS, when a new discipline evolves from a paradigm without the break, without the radical change implied by the concept of scientific revolution. This idea of scientific development as evolution and speciation is still against the notion of a cumulative scientific progress, one of Kuhn’s major concerns.

The other problematic aspect of QIS is how to theorise about the interest this discipline on the whole has aroused among scientists and the non-scientific community. As we have tried to show, Kuhn’s model does not account for the influence that a certain topic has on the development and success of a discipline. He favours the idea of certain irrational aspects influencing decisions and affiliations to a particular paradigm, but he does not pay significative attention to the generally non rational (mostly psychological) effects that an interesting discipline with a fascinating topic may have on scientists and non scientists alike. We must indicate that the section in this essay devoted to this issue is merely a sketch, and further work should be done in order to formulate properly this critique to the Kuhnian model. In particular, it would require a certain axiological approach to scientific practice.

As far as the other three main issues in this essay are concerned, in the first part we have described how an anomaly in the strict Kuhnian sense, quantum entanglement, belonging to a different paradigm (Quantum Physics), instead of provoking a crisis leading to a scientific revolution, led to the emergence of a new paradigm, QIS, by a process of evolution and speciation. In fact, the interesting aspect about quantum entanglement as an anomaly is that, in the new paradigm, it has become the key concept behind the most relevant hypotheses.

In the second part of the essay, the aim was to focus on the two aspects of QIS, its puzzle solving activities and its educational strategies, for which the Kuhnian model provided a good description. In fact, we have tried to show that QIS is a paradigm in the making, already beginning to display the typical normal science features suggested by Kuhn. On the whole, the Kuhnian model has been a useful conceptual tool to describe QIS, with the exception of the issue of fascination.

Thinking about this essay (and its aims) from a wider perspective, it is relevant to note that a confused reader may find in this work some of the same mistakes that Kuhn was trying to criticised when writing *The Structure of Scientific Revolutions*. As we have seen already, Kuhn’s work must be understood in the context of (and against) a historiography of science that understands scientific development as a cumulative process. In this essay we also reject this idea of progress. However, Hoyningen, following Kuhn, suggests three characteristics of these “old histories” that could erroneously be attributed to ours. Firstly, their objective is “to clarify and deepen an understanding of contemporary scientific methods or concepts by
displaying their evolution". Secondly, “most authors of such scientific histories were themselves scientists who worked in the field in question." And thirdly, the preferred topic is disciplinary and sub disciplinary history. We must insist that in this essay, as far as scientific development is concerned, scientific progress is not understood as accumulation towards a certain goal, but as a combination of periods of abrupt change (scientific revolutions in the proper sense) and periods of evolutionary speciation.

Let us conclude with a last reference to the question of fascination. In this essay we have described the notion of quantum entanglement not only as an extremely useful resource, but also as an anomaly, as something rare, mysterious, that scientists admire, know how to use, but can not really account for. In recent years, issues such as the notion of wonder in scientific contexts, or the role played by wonders (anomalies, novelties, exceptions) within scientific practice, have attracted the attention of many philosophers, historians and sociologists of science. It seems an interesting fact that at the core of one of the most advanced forms of science we still have these, apparently, non rational, non scientific elements. Perhaps a general revision of the fundamental idea of science is required.

BIBLIOGRAPHY


Bohm, D.; Quantum Theory (Prentice-Hall, NJ, 1951)


89 RSR, p. 14-15
90 RSR, p. 15
91 As we pointed out at the beginning, to try to characterise quantum entanglement as one among many contemporary “wonders” driving scientific practice, or to try to characterise the general attitude of Quantum Information scientists as “wonder” would be examples, from my own perspective, of this approach.


Hoyningen-Huene, P.; Reconstructing Scientific Revolutions (University of Chicago Press, Chicago, 1993)


Musgrave, A. “Kuhn’s Second Thoughts”, in British Journal for the Philosophy of Science, 22, pp. 287-297 (1971)

