"Potentialities or possibilities": Towards quantum information science?

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Abstract
The use of quantum concepts and formalism in the information sciences is assessed through an analysis of published literature. Five categories are identified: use of loose analogies and metaphors between concepts in quantum physics and library/information science; use of quantum concepts and formalisms in information retrieval; use of quantum concepts and formalisms in studying meaning and concepts; quantum social science, in areas adjacent to information science; and the qualitative application of quantum concepts in the information disciplines. Quantum issues have led to demonstrable progress has been made in information retrieval and semantic modelling, with less clear cut progress elsewhere. Whether there may be a future 'quantum turn' in the information sciences is debated, the implications of such a turn considered, and a research agenda outlined.

Introduction

Over a period of many years, and with increasing frequency in the past decade, quantum concepts have appeared in the literature of the social sciences in general, and the library/information sciences (LIS) in particular. This manifestation has taken several forms. Many have been passing mentions: loose analogies and empty metaphors. Some have applied a mathematical formalism, sometimes with a clear justification, sometimes just because it works. Some have used detailed and rich metaphors and analogies, linking concepts from the physical world with the social and informational realm, and some have claimed that such a linkage is 'real'. Others have argued that there is a general intellectual movement, a *zeitgeist*, centred around quantum concepts, and that the social sciences, including LIS, should partake in this.

This review provides a selective literature review and analysis of quantum ideas in the context of LIS, and related areas, with the intention of clarifying the relevance and significance of such ideas, and suggesting a direction for future research.

Quantum theory

Quantum theory became established in the 1920s as our most fundamental approach to understanding nature, and specifically matter and energy, at very small scales. Space does not permit a detailed review here. For popular, though still scientifically reliable, accounts see Al-Khalili (2004), Cox and Forshaw (2011), Kakalios (2010), Albert (1992) and Polkinghorne (2002), also Kragh (1999) and Baggott (2011) for a historical dimension; for a more rigorous treatment see Penrose (2004), Rae (2007) and Fayngold and Fayngold (2013).

In essence, quantum theory provides a mathematical description of a world very different from that which we experience on the macroscopic scale. Aspects of this mathematical description have been applied within LIS, as will be discussed. Some qualitative concepts, emerging from the mathematics, are associated with the quantum view of the world, and some of these have also been applied in LIS. Among the most significant for our purposes, very briefly and crudely explained here, are as follows (see any of the texts suggested above for fuller description):

- indeterminism / probability – quantum theory does not provide exact deterministic predictions, but only probable outcomes; and quantum probabilities are of a different nature from classical probability
- complimentarity/duality – quantum systems may have two distinct and incompatible natures at once; the wave/particle duality is best known
- measurement – any measurement may affect and change a quantum system
- superposition – quantum systems may be in multiple states at once
- entanglement – properties of two or more quantum systems become correlated
- non-locality – a part of a quantum system may be affected instantly by changes to a remote part of the system

- interference – interaction between two quantum systems, or a system and itself, not possible in a classical system
- indeterminacy/uncertainty – there is a limit to what can be known about a quantum system
- contextuality – the nature of a quantum system varies according to its context

Quantum mechanics remains counter-intuitive in nature, and no single interpretation is accepted. The aspects which led Einstein to describe it as 'spooky', and to refuse to believe that it could be a final theory, are now generally accepted as simply the way the world is. The idea of 'decoherence' - by which the weirder quantum effects, such as Schrödinger's cat, which is simultaneously alive and dead, are almost immediately removed by the interaction of the quantum system with the complex world around them – is believed by many physicists to have removed many of the counter-intuitive and anti-realistic aspects of quantum theory. However, there remain various incompatible, and hotly contested, interpretations, as set out in the sources noted above.

Formally, the applications of quantum theory described here involve operations on abstract mathematical spaces, using quantum probability formalisms, specifically so-called Hilbert and Fock spaces; clear descriptions are given by van Rijsbergen (2004), Widdows (2004), Aerts and Gabora (2005), Aerts (2009), Busemeyer and Bruza (2012) and Melucci (2012). The mathematics of quantum theory can appear abstruse and difficult to the uninitiated, but their application to the kind of situations described here is quite straightforward. As Widdows and Peters (2003, p. 142) write of one such study: "An introduction to the full machinery of quantum logic would defeat [the goal of making the paper accessible] before the reader has a chance to realise that the techniques and equations … are really quite elementary".

While the mathematical formalism of quantum theory is not in doubt, and has proved remarkably successful as a physical theory, there is no satisfactory and generally accepted explanation, giving an understanding of what the theory means. Rather there are a series of competing 'interpretations'; all involve information and knowledge as fundamental features in various ways (Bawden and Robinson 2013, Siddiqui 2013; see also Roederer 2010). It is not necessary to adhere to any particular interpretation to use quantum theory in physics, since the mathematical procedures are the same, and nor is it necessary to do so to apply quantum ideas to the social and information sciences. However, it is notable that several such applications, as noted below, use a rather unfashionable quantum interpretation; the Bohmian, or de Broglie-Bohm, interpretation. This interpretation seeks to retain the classical idea of 'real' particles, guided by a wave of 'active information', and is thus arguably a particularly attractive interpretation for those applying quantum ideas to information problems in the macro-world.

Indeed, although all laws of physics, including classical laws, are informational statements (Davies 2011), quantum mechanics is thoroughly infused by information concepts (Bawden and Robinson 2013). Some protagonists argue that quantum mechanics is in itself a theory of information (e.g. Zeilinger 2000).

Quantum theory has the reputation of being counter-intuitive and difficult to comprehend as anything other than a mathematical 'toolkit' which gives very precisely correct answers to physical questions. Many leading physicists have commented on its lack of qualitative comprehensibility (see accounts of quantum theory mentioned earlier): Richard Feynman wrote that it was safe to say that no-one understood it, Niels Bohr that anyone who was not profoundly shocked by it had not understood it, Sir Roger Penrose that it makes absolutely no sense, and John Wheeler that if you are not completely confused by it then you do not understand it. Lee Smolin suggests that "Perhaps we can't make sense of [quantum mechanics] simply because it isn't true. It is instead likely to be an approximation to a deeper theory that will be easier to make sense of" (Smolin 2013, p. 141).

This should give us cause to be cautious in seeking to adapt its precepts more widely, and particularly in seeking to apply its concepts in a qualitative way.

It is, of course, necessary to take great care when trying to apply the principles of science, and of quantum theory in particular, outside the domain in which they were created, and especially when considering qualitative concepts apart from their mathematical formalism. There is a long history of misleading and confusing misuse of quantum concepts, ranging from popular semi-mystical interpretations, of which Capra's *Tao of physics* and Zukav's *Dancing Wu Li masters* are among the best known, and arguably also among the more scientifically respectable (Capra 1975, Zukav 1979). Capra's book has had a remarkable longevity, going through over forty editions, and remaining a best-seller, despite its detailed arguments being initially to a large extent based on a model of particle physics, the 'bootstrap' model, which was losing favour in science at the time the book was first published. We may view this as an example of the compelling influence of quantum metaphors, even if the detailed analogies behind them are lacking in rigour. It is also a reminder that it is essential that those making use of scientific concepts in other domains must keep up-to-date with the science. Capra has, it is fair to say, updated his comments on the scientific content in later editions.

The tendency to misuse qualitative quantum concepts was most notoriously exposed in a hoax perpetrated by Alan Sokal, an American physicist, who, in 1996, submitted an article offering seemingly blatantly spurious links between quantum physics and social issues (Sokal 2008). The article was accepted, and received a degree of praise, even after it was known it was a hoax.

Against this may be said that it is well-known that several of the originators of quantum mechanics, including Bohr, Schrödinger, Heisenberg and Pauli, were interested in such

extensions of their ideas, as have been more recently active quantum scientists, such as Bohm. Heisenberg (2000, p.128), for example, memorably stated that quantum entities "form a world of potentialities or possibilities rather than one of things or facts", while there is an interpretation of quantum theory originally promoted by John von Neumann, which holds that the consciousness of an observer determines the outcome of experiments in the quantum realm, and in a sense creates reality. This latter is now generally not accepted - though see Rosenblum and Kuttner (2011) for a recent espousal - but has been adopted as the basis for a wide, and arguably misplaced, application of quantum ideas.

With these caveats in mind, an analysis of a wide spectrum of literature was carried out, to identify ways in which quantum concepts have entered the literature of the information sciences and closely related subjects.

Literature analysis
The analysis was based on searches of bibliographic databases (Library and Information Science Abstracts, Library and Information Science and Technology Abstracts, and Web of Science), Google Scholar, internet search engines, and library catalogues; relevant material was followed up through prior references and subsequent citations. Themes and categories were drawn out by interpretive synthesis (Bawden 2012).

The choice of material for analysis was selective rather than comprehensive. The majority of items to be found with some reference to 'quantum' matters in the literature of the information sciences and related disciplines offer only trivial uses of quantum terminology. A new library system offers a "quantum jump" in performance, while a new search function gives a "quantum leap" in capability. The only thing we can conclude from these, and from the increasing use of the q-word in the names of systems and services, is that quantum concepts, in a very general sense, have entered the consciousness of the information disciplines and professions. This may have some relevance to the general intellectual climate, as we will note.

We also excluded the burgeoning area of quantum computing and quantum information science, in which entangled particles are used as processing units, handling quantum bits, q-bits, rather than classical bits (Vedral 2006, Mermin 2007, Gribbin 2013). While this new technology is indisputably an application of quantum theory relevant to information science, it is only considered here in so far as it contributes new concepts or perspectives.

Five general themes or categories emerged, which we term loose analogy and metaphor; information retrieval (IR); concepts and meaning; quantum social science; and quantum information science. Each will now be considered in turn.

1 Loose analogy and metaphor

In some cases, a rather shallow form of qualitative analogy or metaphor is taken further, sometimes taking up much of a publication. An example of this, applied specifically to the management of library/information services, is given by Pienaar, Russell, Roets, Kriel and Grimbeck (1999). They start from the basis that management processes in organizations can receive insight from new scientific theories and concepts, and mention specifically quantum mechanics (along with chaos theory and complexity theory, other sources of metaphor which space does not allow us to discuss here) as having "opened new avenues of thought about organizational life (p. 272). Quantum theory is claimed to have a particular relation to the managerial concept of the client-centred team. However, quantum theory here is reduced to the single qualitative idea that "the quantum world is a web of relationships. Everything is inter-connected like vast network of interference patterns" (p.268). From this drastically simplified version of non-locality, the authors think it reasonable to state, without any discussion or analysis, that "when systems and business processes are viewed as part of a quantum world … no one exists independently of relationships with other people. Each of us is a different person in each organizational context or place" (p268). From this, we learn that "the quantum mechanics theory demonstrates seven principles [including that] the era of the individual has been replaced by the era of the team player [and] instead of detailed planning and analysis, structures that foster relationships become important" (p. 268).

As a further example, we can take the development of a strategic plan for urban transportation, which uses a methodology based loosely on quantum mechanics in a knowledge management context (Zanotti 2012). This relies on "quantum systematics", a version of systems theory, which utilizes what the author describes as "models and metaphors both of quantum mechanics and quantum field theory" (p. 214). Again, these are exceedingly loose analogies: for example, the idea, prevalent in some, typically older, interpretations of quantum mechanics that the observer creates reality is related to the idea that an entrepreneur creates their own market, while the idea of the energy of the quantum vacuum is related to the active influence of the environment on a system. A similar proposal, is given by Bisconti, Corallo, De Maggio, Grippa and Totaro (2010), who propose to analyse knowledge production and innovation potential using models from quantum mechanics to analyse social phenomena characterized by indeterminacy.

A third, and final, example is that of James (2012), who discusses a perceived shift to accessing and using information in smaller, more elemental, units than traditional books, reports and other document formats. He proposes " a new metaphor for the coming shift in style – Quantum Information – the shift from files and books (our particles) to sentences, paragraphs and tweets (our waves)" (p. 163). The meaning of this is not entirely clear, however. At one point we are told that we are moving from "information as files to information as waves" (p. 163). At another, we learn that "the Quantum Information metaphor describes the shift to handling small elemental pieces of information irrespective of their type and devoid of their 'container' – the file, the book or the article" (p.165); this sound as more like an atomic metaphor than a

quantum one. A later section (p.166) is enticingly titled "Developing the information wave equation: so what does an information quantum look like?"; sadly no equation is developed, and the only information on what the quantum looks like refers to a format "yet to be developed".

It would be easy to conclude that these, and similar offerings, are simply a misuse by trivialization of the ideas of quantum theory, leading to rather trite ideas, that do not need support from any scientific theory. A more charitable conclusion is that contributions such as these are appreciating and taking advantage of, however imperfectly, a new worldview, inspired by quantum theory. They may enable progress to be made by aligning the ways in which information science concepts are expressed with current intellectual currents of thought; though it is necessary to avoid overly shallow analogy, and particularly necessary to avoid adherence to views and interpretations which a physicist would regard as charmingly old-fashioned. And they may, if developed rigorously, lead to involvement of the information sciences in a new 'quantum social science', which will be discussed here.

2 Information retrieval
In contrast to the last section, we look here at an area studied rigorously and quantitatively. Although Melucci and van Rijsbergen (2011, p.154) comment modestly that "the study of the presence of quantum phenomena in IR and in general the evaluation of quantum-like models are still at the beginning", a considerable amount of work has been done and success achieved in this topic in the decade or so that it has been an active research area. Concise reviews and commentaries on the development of the field are given by Song, Lalmas, van Rijsbergen, Frommloz, Piwowarski, Wang, Zhang, Zuccon, Bruza, Arafat, Azzopardi, Di Buccio, Huertas-Rosero, Hou, Melucci and Rüger (2010), by Piwowarski, Frommholz, Lalmas, and van Rijsbergen (2010A), by Melucci and van Rijsbergen (2011) and by Arafat (2011).

In brief, application of quantum ideas to IR relies on three ideas: that there are significant similarities between the formal methods adopted in IR and in quantum mechanics; that there are similar phenomena to be observed in quantum physics and in IR, and related areas such as natural language, cognition and decision making; and that the form of non-classical probability used in quantum physics may be appropriate in the IR context.

This quantum approach to IR was introduced by van Rijsbergen's influential book *The geometry of information retrieval* (2004); though its proposals were entirely novel, the author noted earlier suggestions of the approach in the writings of MacKay (1950, 1969) and Maron (1964). This falls within the scope of the new area of 'information geometry', a theoretical framework applicable across the information sciences where probability is a significant factor; for a recent overview of current thought in this area, albeit at a high level of mathematical rigour and with limited relevant examples, see the articles in the

volume edited by Nielsen and Barbaresco (2013). van Rijsbergen's book introduced a formalism based on Hilbert spaces for representing IR models within a uniform framework, and in effect combining the probabilistic, logical and vector space approaches to IR.

A Hilbert space, named after the German mathematician David Hilbert, may be regarded simply, if crudely, as an abstract mathematical space, which generalizes the familiar notion of three-dimensional Euclidean space, and extends to an arbitrarily large number of dimensions. It is referred to as a vector space, since it incorporates the concepts of magnitude and direction, so that points in such a space represent every possible state that a system may be in. The definition of a Hilbert space, as distinct from other abstract spaces, gives it properties which make it an ideal mathematical environment for a quantum-like formalism.

Because the same formalism is applicable to both, it is natural to speculate that quantum phenomena may have analogues in IR. The link between the two is probability; one of the most important issues in both IR and quantum theory. As van Rijsbergen (2004, p. 26) summarizes it "this kind of probability assignment in Hilbert space is a suitable way of describing interaction for information retrieval".

Probability space represents the probability of events and combinations of events. Hilbert spaces are used to represent probability spaces in an algebraic form – as vectors, matrices and operators between them. A central concept is the density matrix, or density operator. In quantum physics, this represents the state of a system, something for which the structure is unknown and one makes measurements, which are subject to error and to interference between the system and the measuring apparatus. In IR, it encapsulates a probability space, where the probabilities refer to term occurrence, document relevance and aboutness, and more particularly to pairs of events, for example term occurrence in a document and relevance of that document. This density matrix representation of probability is a more general theory than classical probability, as it encapsulates all the information about a probability space; see Piwowarski, Frommholz, Lalmas, and van Rijsbergen (2010A) and Melucci (2012) for detailed accounts.

Beyond the formal mathematical representation of probability, there has been for the beginning an interest in examining analogies with the concepts of quantum physics: "Those who introduced the quantum view of probability in IR have supposed that at least one the three notions, i.e. superposition, interference and entanglement studied in physics for a long time, may have their analogues in IR or can be leveraged to make a significant breakthrough at the theoretical level" (Melucci and van Rijsbergen 2011, p. 133). In the IR context, superposition occurs when there is uncertainty in assessment of, for example, relevance, interference when a document is judged relevant and not relevant simultaneously, and entanglement when two terms are co-joined in a way

more fundamental than simple co-occurrence, e.g. 'retrieval system', which in quantum probability does not imply simply 'retrieval' and 'system'.

Following Melucci and van Rijsbergen (2011), we can say that research on this topic has followed two lines: the investigation of the value of abstract vector spaces in general, and Hilbert spaces in particular, in IR, but without any particular focus on quantum concepts; and the use of specifically quantum concepts to model IR issues.

The first approach incorporates a number of somewhat different formalisms and applications. One relatively long-established method is Latent Semantic Analysis, originally a model for experimental studies of use and ambiguity of words, later adapted for IR, and extended to incorporate Latent Semantic Indexing (Dearwester, Dumais and Harshman 1990, Ding 2005, Landauer, McNamara, Dennis and Kintsch 2007). In essence, these methods deal with 'sparse' document-term matrices, i.e. where each document has only a very few of the terms present in all the collection, by reducing the dimensionality to a much smaller number of 'latent variables'. A quantum probability model of IR can subsume these methods, using the weights (measures of the contributions of two terms for describing a document or query) to measure associations between the uses rather than the semantics of terms (Piwowarski, Amini and Lalmas (2012).

A second example is the study of the 'geometry of word meaning' (Widdows 2004, Widdows and Peters 2003), which has considerable overlap with the study of quantum approaches to concepts discussed later. The classical vector space models for IR, as developed by Salton and McGill (1983), lack any form of logic, such as Boolean: the geometry of meaning approach uses quantum logic, which differs significantly from Boolean, to establish how words are related, and hence how documents and queries are represented for IR purposes.

A third, and final, example of the first approach is the abstract vector space model for contextual IR, i.e. the style of IR that recognizes that information which is useful to one person at one place at one time may not be useful if any factors change. To develop a model which determines the probability that a document will be useful in any particular context, quantum context factors have been developed for objects -documents and queries - and for operators - relevance and aboutness (Melucci 2008). The strength of this model is that there is a uniform representation for objects and for contextual factors.

The second approach involves use of one of the key concepts of quantum theory, identified by Melucci and van Rijsbergen (2011) as superposition, interference and entanglement to model IR issues. This is most commonly seen in the development of various approaches to representation and ranking of documents; see Melucci and van Rijsbergen (2011) and Arafat (2011) for details and examples. We might cite, as one interesting example, the representation of documents and information needs as

subspaces spanned by vectors and density matrices, where the ill-defined needs and probability of document relevance may be represented by superposition (Piwowarski, Frommholz, Lalmas, and van Rijsbergen 2010B). As a second, we can mention a model which uses the concept of interference to model the way in which relevance judgements of any document are affected by similar judgements of other documents (Zuccon and Azzopardi 2010); another analysis of interference is given by Melucci (2010). A third example is the modeling of users' relevance states by quantum probability (Di Buccio, Melucci and Song 2011). A relevance state is an individual's internal subjective assessment of relevance, which only appears as an objective relevance assessment when a final judgement has been reached; a process analogous to the "collapse" of a physical quantum superposition. An individual's uncertainty as to the relevance of a document may be modeled as a superposition with interference. An IR system operating with such a model could detect interference and help a user clarify their state, by, for example, suggesting example documents or giving an alternative presentation of results. These are all examples where studies can show the superiority in practice of a retrieval system based on a quantum formalism.

Other concepts from quantum physics have been used in this connection. Retrieval of documents is modeled by analogy with quantum measurements of polarized particles (Zhao, Zhang, Song and Hou 2011), while Wittek and Darányi (2011A) use what they describe as a metaphor relating the detection of elements in a chemical sample by spectral analysis (the spectral lines being ultimately a quantum phenomenon) to a 'spectrum' of word meaning in a text collection.

Another strand of the application of quantum ideas in IR is the development of 'semantic spaces', by which the formalisms are used to model meaning. This involves, for example, word correlation matrices, where different vectors give different meanings, where compound terms are represented through the concepts of superposition and entanglement, and where quantum-like interference can be detected in the interaction of concepts (see, for example, Aerts and Gabora 2005). While noting the clear relevance of this to IR, we will consider it in the next section, dealing with quantum approaches to meaning and context.

3 Concepts and meaning

The idea of a 'concept' is of evident importance to LIS, underpinning *inter alia* information needs and users' questions, information retrieval and knowledge organization: concepts "seem to be all-present and pervasive in library and information science" (Hjørland 2009, p.1527). But – other than that they are something to do with meaning - there is little consensus as to what concepts actually are.

Quantum ideas have been used recently to provide new perspectives on the nature of concepts, and of meaning, following their introduction by Widdows (2004). These studies have taken a quantitative approach to defining concepts, and there is

considerable similarity with the quantum IR studies described earlier; indeed, the two may be seen as closely interrelated, in as much as retrieval of documents is closely aligned to the meaning of terms defining their aboutness. The most extensive research on this topic has been carried out by Aerts and colleagues, within the broader area they have called 'quantum cognition'. A brief overview, with discussion of related application of quantum formalism including information retrieval and topics discussed below under the heading of quantum social science, is given by Aerts, Broakaert, Sozzo and Veloz (2013); fuller details and examples are given by Aerts, Gabora and Sozzo (2013) and, from somewhat different perspectives, by Wittek and Darányi (2011B) and by Busemeyer and Bruza (2012).

This approach rejects the traditional 'container' views of concepts, and sees concepts as 'meaning entities' in particular states; these states may be changed by the context. This is referred to as the SCOP (state context property) theory of concepts. A concept here is a cognitive entity, and these ideas are validated by experiments asking individual people of their idea of a concept. Such opinions can be modeled using the quantum mechanical formalisms, representing concepts in Hilbert and Fock spaces. This is elaborated in the Quantum Model Theory (QMod), which is presented as "a modeling theory worked out to describe situations entailing effects such as, *interference*, *contextuality*, *emergence* and *entanglement*, which are typical of the micro-world but also occur at macroscopic level and even outside physics" [original authors' italics] (Aerts and Sozzo 2012B, p. 125).

The quantum features displayed here are reasonably clearly understood in qualitative terms. Contextuality implies changes of meaning according to context, emergence implies the conjugation of two concepts giving rise to a third, not implicit in the originals, interference implies the meaning of one concept affected by the meaning of another in a particular way, and entanglement (and sometimes also interference) indicates the combinations of two or more concepts becoming an undivided whole: for details and examples, see Aerts and Sozzo (2011, 2012A, 2012B), Aerts, Broekaert, Gabora and Veloz (2012) and Atmanspacher, Graben and Filk (2011).

There is, in this approach, a direct analogy between physical particles and these meaning entities, and a particle trajectory corresponds to meaning in a document. This justifies the use of the same mathematical formalism. Aerts, Gabora and Sozzo (2013) give a more detailed justification of this, on the basis of a similarity in the kind of probabilities which are appropriate; in both quantum mechanics and in conceptual meaning, one is dealing with probabilities representing open-ended potentiality, rather than a lack of knowledge, and this accounts for the applicability of the same mathematics. As with quantum IR, other quantum concepts have been used in this connection; for example, the wave-particle duality of quantum physics has been suggested to be a useful metaphor in modeling semantic content (Darányi and Wittek 2012).

Since this model of conceptual meaning shares the same mathematical structure as the information retrieval models noted earlier, there is an evident potential for combining them, to give a kind of semantic retrieval space (Widdows 2004), and indeed Aerts, Gabora and Sozzo (2013) look forward to such a "complex number semantic space scheme".

It is should be noted again, however, that this is a cognitive approach, based on the study of individual understanding of the meaning of concepts; the idea of quantum entanglement has similarly been used in studies of the ways in which individuals recall and associate words (see, for example, Galea, Bruza, Kitto and Nelson 2012). Hjørland (2009) has cautioned against cognitive approaches as providing the best form of concept theory for the information sciences. Whether the quantum formalisms would prove equally appropriate for modeling concepts within a different theoretical framework is an intriguing question.

4 Quantum social science
This term is used to refer to the application of quantum concepts and formalisms to the modeling of social interactions and the exchange of information, particularly where decisions are made on the basis on incomplete or contradictory information, as an alternative to traditional decision theory and game theory; financial trading and stock pricing has been a popular, and potentially lucrative, application. It may be taken to cover some looser and less formal analogies, as in the studies of Bisconti, Corallo, De Maggio, Grippa and Totaro (2010) and of Zanotti (2012) discussed above, but the term is more usually reserved for more detailed and formal analyses. There is some overlap with quantum cognition, where this extends into the social context beyond the individual. Lambert-Mogiliansky and Busemeyer (2011, 2012) report an intriguing intermediate stage, with quantum indeterminacy used to model the 'multiple selves' of an individual making a decision; in effect individual identity is an emergent property of a quantum style of decision making.

The most comprehensive description and analysis of quantum social science is given by Haven and Khrennikov (2013), who give a wide survey of applications of quantum ideas in the social sciences, and some more detailed accounts of their own work. They remind us that the application of models from the physical sciences to social science issues is by no means new; they cite the earliest example as a paper of 1900 using the mathematics of Brownian motion to model asset prices (Baclelier 1900); more recent examples are given by Robinson and Bawden (2013). They suggest that most work in quantum social science can be categorized into one of four groups: financial asset pricing; decision making; quantum game theory; and the investigation of new social science concepts. For more details and examples see Haven and Khrennikov (2013) and also Khrennikov (2010). These are generally situations in which an objective measure – the price of a stock, the change in the price of an insurance policy – are determined by the judgements of, and hence the information available to, the participants, re-emphasising the information orientation of this approach. The central objective of the approach is to

answer the question "How can we model *information* [their italics] in a social science setting?", and it is described as the "modeling of information reality" (Haven and Khrennikov 2013 p. 56; see also Khrennikov 1999, 2004).

Their concept of quantum social science is summarized as that "… we seem to come to the hesitating conclusion that quantum social science seems to have something to do with (i) wave functions, (ii) information connected to such wave functions, and (iii) a very peculiar model which seems to connect particles, wave functions, and information" (Haven and Khrennikov 2013, p. 57). This model is the Bohmian interpretation of quantum mechanics, which – as noted above – is especially 'information laden'.

The 'active information' in the Bohmian pilot wave is interpreted here as the subjective information possessed individuals, which causes measurable effects *en masse*. This might be, for example, information possessed by market participants, which causes prices to change; the 'wave of information' guides the price. On this supposition, a 'financial Schrödinger equation' may be constructed, which yields quantitative predictions; for specific examples, see Haven (2006, 2008) and Choustova (2009) – further examples are given in Haven and Khrennikov (2013).

Of course, the idea that the information available to individuals, and the opinions and beliefs which they develop on the basis of - usually incomplete and sometimes erroneous – information, can affect objective factors in the social world is far from new. Soros' (1987) idea of 'reflexivity' is just one qualitative expression of this idea, which has been quantitatively expressed through the 'active information' concept (Haven and Khrennikov 2013, pp 179-181). There are also echoes of the interpretivist anthropology of Clifford Geertz, with his central concept of "webs of meaning" (Geertz 1973, Alexander, Smith and Norton 2011).

So, for example, insurance rates may be modeled by the Schrödinger equation, with the Bohmian pilot wave, incorporating the relevant information, steering the trajectory, and hence the price changes. It is, of course, necessary that the concepts of physics which appear in the original quantum formalisms, be replaced by a social science equivalent (Khrennikov 1999). In economics, for example, price changes can correspond to position changes in physics, and rate of price change to velocity. Mass can correspond to number of shares held. Together, these two measures can amount to an equivalent to kinetic energy. Potential energy can be equivalenced by interactions between traders, as well as interactions from other factors, such as macro-economic issues.

This application overlaps with the area of 'quantum finance', focused on the setting up and solving of the Schrödinger equation for a variety of financial problems (Baaquie 2007). Although it relates to individual judgements, this approach does not have the same information focus, or generality of approach, as quantum social science, and therefore has less relevance for our purposes. As with the retrieval context, quantum

finance works with the same inputs and outputs as conventional calculations, but using a different underlying mathematical formalism.

Unlike some authors on this topic, Haven and Khrennikov give detailed discussions of the philosophy underlying their approach, and in particular the extent to which the application of such ideas is simply the use of a mathematical formalism which works, as opposed to any suggestion that that quantum principles *per se* are involved. However, the result is a degree of confusion. In support of the former idea, they write "The models presented in this book can be called "quantum-like". They do not have a direct relation to quantum physics. We emphasize that in our approach, the quantum-like behavior of human beings is not a consequence of quantum physical processes in the brain. Our basic premise is that information processing by complex social systems can be described by the mathematical apparatus of quantum mechanics." (p. xviii) and "the reader may want to veer close to mathematics and instead steer away from general physical, metaphysical, and philosophic principles" (p. 6) and "… we use quantum mechanical principles in social science to potentially better explain certain phenomena in that macroscopic setting. This does not mean that anything quantum mechanical is as such manifest in the macroscopic world" (p. 210). However, they also discuss ideas from quantum biology, suggestions that quantum effects may be responsible for consciousness, and Pauli's ideas on an analogy between the complementarity between wave and particle aspects of matter in quantum physics and the complementarity between the conscious and unconscious mind in psychology, suggesting that they leave the door open to some direct causal link. For more discussion of quantum biology, see Ball (2011), for quantum consciousness, see Penrose (1994), Hameroff (2007) and de Barros and Suppes (2009), and for the link with Jung's thought, see Jung, Pauli and Hull (1955), Meier (2001) and Wolfraim (2010).

Regardless of this imprecision, Haven and Khrennikov's quantum social science may be summarized as using a mathematical formalism describing results of measurements for systems characterized both by a high sensitivity to external influences, and by the processing of incomplete information. Social systems have developed the ability to use such a "quantum-like" scheme of information processing and decision making (p. 26-28).

Other authors have discussed various quantum-like models for social organization. Lawless and colleagues have developed various quantum approaches to modeling social groups and institutions, in terms of their interactions, decision making and information handling; see, for example, Lawless, Bergman, Louçã, Kriegel and Feltovich (2007). Kitto, Boschetti and Bruza (2012) have shown how a quantum decision-making model, using a Hilbert space formalism, may account for changing attitudes of individuals, and propensity to act, in social settings. It would be intriguing to consider if any such model might have applicability to the study of information behaviour and information practices.

In a more qualitative approach, Vann (1995) suggests that quantum theory can provide a variety of productive language, metaphors and models for anthropology and ethnography. This is because there is a commonality between quantum mechanics and these social sciences in their interest in relationships between organisation and interaction in the microcosm and the macrocosm, and in their recognition that the observer always affects and is affected by the observed. It may be remarked that, like other social applications of quantum ideas, this (like more popular accounts of 'quantum society' such as that of Zohar and Marshall 1995) appears to rely on some rather old-fashioned aspects of the accounts of the physical theory. However, such analyses provide a link to our next topic, quantum information science, because they focus on applications of quantum mechanics to human communication and meaning.

5 Quantum information science

Beyond the limits of the extensive studies of quantum ideas in search, retrieval and semantics described above, there has been little discussion of their applicability to the wider information science discipline. This is a little strange, as factors affecting the information retrieval area, generally accepted as an integral and important part of information science (Bawden and Robinson 2012, Robinson 2009, Stock and Stock 2013), might be expected to have wide applicability within the discipline. Arafat (2011), following van Rijsbergen (2004), notes that quantum ideas are relevant to IR, and perhaps by extension to information science in general; however his detailed analysis of the nature of this relevance is limited to the IR context.

The two most widely known studies of a unified approach to information in the physical and social realms, those of Stonier (1990) and of Bates (2005, 2006), do not introduce any quantum issues, taking a classical approach to physical issues. This is perhaps particularly surprising in the case of Bates, who was one of the first to note that concepts of uncertainty and indeterminism, drawn from quantum physics, should be considered in the design of indexing systems (Bates 1986).

While a number of authors have criticised an approach to information science rooted in a deterministic and objective world view, itself based in classical physics, they have typically recommended as a solution a social and cultural perspective, rather than one involving quantum concepts: early and recent examples are given by Rosenberg (1974) and Hjørland (2007) respectively.

In what seems to be the only paper addressing this issue in detail (our justification for examining in arguments in some detail), John Budd (2013) sets out a vision for a conception of the information studies discipline based on quantum concepts. His aim is "to demonstrate that fundamental aspects of quantum theory can be applied to work in information studies … as a way to shape questions and inquiry" (Budd 2013, p567). ('Information studies' is not defined specifically, but we take it to be the broad field encompassing information science and cognate disciplines, the area covered by this

review.) This, he sees as an essentially qualitative task, proceeding in a way opposite to those who seek to apply the mathematical formalisms of quantum theory to problems of the information sciences, without worrying over much about any lack of qualitative justification. Budd is interested in "most especially, the non- or extra- mathematical components of quantum theory [which may] offer ontological and epistemic modes of thought which apply to information" (Budd 2013, p567). If this is to make any sense, as Budd notes, we have to accept that some of the qualitative concepts encountered in quantum mechanics may have relevance to life on the macro-scale, and specifically to information; concepts such as entanglement and non-locality.

In justifying such an attempt, he argues, citing Lossee (2012) who also remarks on some aspects of quantum physics in respect of information, that the study of information has, to a large extent and with some success, followed the path of the study of physical science; since the study of the physical universe must now deal with quantum concepts, so should that of information. This means that information should be amenable, at least to an extent, to study and analysis by means of the same concepts and mathematical formalisms as physical systems. A second general argument in support of this kind of analysis is that science is showing links between, and common principles joining, the micro- and macro-levels of description, and therefore information studies similarly "has much to gain from the connection of micro- and macro-level conceptions of reality" (Budd 2013, p577). These rather general arguments have some force, but each needs to be examined carefully. It is notable that Budd, like others who have sought links between quantum physics and the social and informational realm, refers specifically to the Bohmian interpretation of quantum mechanics.

Budd points out, correctly, that a problem with any such analysis is that there is disagreement as to exactly what information is. To deal with this, he restricts the idea of information to small linguistic units within texts, which carry meaning, and then "identifying analogues between quantum theory as it has been expressed and the phenomena of these small linguistic elements" (Budd 2013, p568). And he argues that information may be seen to have both an objective and a subjective element; and that exactly the same is true of physical situations according to quantum theory. It should be noted that both of these assertions are rather contentious, the latter particularly so; in some interpretations, quantum theory is entirely objective.

Having justified the approach in general terms, Budd fleshes it out somewhat, by seeking analogies between quantum physics and the concerns of information: "only a very few analogies will be presented here to illustrate some similarities between discoveries related to quantum mechanics and information" (Budd 2013, p570). The analysis is therefore qualitative, and reliant on a perceived similarity in micro-physical and macro-informational situations. These include:
- destructive interference in the wave function depiction of matter having an analogy with confounding and confusion in the understanding of information

- complete understanding of communication being impossible, with linguistic elements regarded as having, in some sense, momentum, and hence their position being impossible to determine, by analogy with Heisenberg's principle
- the fact that words can have more than one meaning being related to the superposition of quantum states, whereby a particle may have more than one possible position and momentum
- the quantum principles of non-locality and entanglement having their analogies in information terms, since information gathering in one part of a system may affect others; "human behaviour, including communicative actions, is nonlocal" (Budd 2013, p576)

In general, these may be seen to follow and endorse the arguments set out earlier in this review, derived from the studies in IR, concepts, and social science.

Budd concludes by arguing for the investigation of a quantum approach within information studies, and refers to the prospect that this could contribute to what others refer to as a "Grand Unified Theory", from physics to consciousness. This seems a suitably ambitious note on which to conclude this five-point survey of quantum applications in information-related areas.

Summary
It will be clear from what has gone before that there is no single 'quantum approach' in information science. Even at the rigorous and formal end of things, the application of quantum mathematics to information retrieval, there are different quantum approaches, as a comparison of geometric and probabilistic quantum approaches shows (Zellhöfer, Frommholz, Schmitt, Lalmas and van Rijsbergen 2011). 'Quantum information science' is therefore a mixed bag of formal and informal, quantitative and qualitative, metaphor and actuality. This is, we think, a desirable state of affairs; the quantum paradigm is so rich that it is undesirable to make the attempt, at least at this stage, to identify a single approach.

It seems well-established that quantum formalisms – Hilbert and Fock spaces, quantum probability and quantum logic – have real and measurable advantages over their classical counterparts, in systems for information retrieval and for capturing semantics. There is some evidence, though less convincing, that the qualitative concepts of quantum theory are valuable, both for systems design and for the study of information in social contexts. And there are tantalising suggestions that a 'quantum approach' could be a valuable basis for developing the information science discipline.

It is unsatisfactory to allow that the mathematical formalisms are helpful, without attempting to ask why (although we must remember that, as previously noted, asking why has not been a particularly successful approach in quantum physics); as Melucci and van Rijbergen (2011, p.155) write "quantum probability is a crucial step to achieve a significant increase of retrieval performance accompanied by the understanding of the

mechanism underlying the retrieval process". Understanding is vital, insofar as it is possible.

However, it remains unclear as to how we should regard the application of quantum ideas in the information sciences, and how their 'quantumness' is regarded. To give just a few examples, it has been described as:

- a metaphor
  (Wittek and Darányi 2011A, 2011B, Bruza, Kitto, Nelson and McEvoy 2009)
- an analogy
  (Widdows 2004, Piwowarski, Frommholz, Lalmas and van Rijsbergen 2010B, Arafat 2011, Zhao, Zhang, Song and Hou 2011)
- inspired by quantum theory
  (Piwowarski, Frommholz, Lalmas and van Rijsbergen 2010B, Piwowarski, Amini and Lalmas 2012, Zhao, Zhang, Song and Hou 2011)
- quantum-like
  (Di Buccio, Melucci and Song 2011, Haven and Khrennikov 2013)
- an abstract framework
  (Bruza, Kitto, Nelson and McEvoy 2009)
- a scientific mirror
  (Arafat 2011)

Nor should we forget that the quantum formalisms were, with some exceptions such as Fock spaces, not derived for quantum issues at all: Hilbert spaces, matrix mechanics, wave equations, Poisson brackets and the rest were derived by nineteenth century pure mathematicians, and adapted by quantum physicists for their purposes. It is therefore perfectly possible to use these mathematical tools without any thought of using quantum theory: indeed Widdows and Peters (2003, p.142) write that "the link with 'quantum logic' was itself only brought to our attention after the bulk of the results ... had been obtained".

Atmanspacher, Graben and Filk (2011), reminding us that that Niels Bohr himself thought it likely that the central qualitative features of quantum theory would have significance in macroscopic, and even non-physical systems (in common with other pioneers of the field, as noted above), find it unsurprising that quantum formalisms have wide applicability. They suggest that the only necessary common features are that the order of operations or activities is of importance (non-commutativity) and that logical divisions are graduated or shaded (no sharp truth values). These conditions, of course, apply to many situations in the human sciences, the information sciences among them. Hence they are best represented by quantum logic, which is neither distributive (it allows for two alternative possibilities at once) nor commutative.

van Rijsbergen (2004, p. 3) summarises the commonality with IR applications as "in quantum mechanics we have the problem of measurement; we don't know how to

model the result of an observation which arises from the interaction of an 'observable' with a piece of reality. In IR we face the same problem when we attempt to model the interaction of a 'user' with an artefact". More generally, Wittek and Darányi (2011B) note that quantum mechanics deals with systems with inherent ambiguity, and hence its formalisms will apply to similar situations. Aerts, Gabora and Sozzo (2013) and Busemeyer (2009) focus on the statistical commonalities. Human systems are very complex, with many states which are unobservable even in principle, and many more that we cannot in practice observe. They are very sensitive to context, their states are easily disturbed by measurement, and the measurements that are obtained are error prone and uncertain and noisy. Classical models of probability, logic and information processing are too restrictive in their assumptions to represent these systems well; a quantum formalism is more appropriate.

Similarly, Widdows (2004, pp 216, 217) argues that "Quantum theory involves dealing with particles which are composed from different pure states, which can be superimposed upon one another to make combined states. In the same way, ambiguous words can be thought of as the sum of different 'pure' meanings, superimposed upon the same word …. The analogy between quantum particles and ambiguous words turns out to be quite strong – as well as being appealing on a general intuitive level, the exact same operations in vector spaces can be used to model both processes." Widdows (2005, pp219-220) also draws attention to the "curiously similar" collapse of the wave function in quantum physics, by which the position of a particle previously indeterminate becomes known, and the ability of humans to determine the particular meaning of an ambiguous word when it is seen in a context.

More ambitiously, we might see this as a link between information processes in different realms. Is any significance, beyond the issues considered above, in the seemingly now well-established fact that patterns in quantum theory - some interpretations of which are, as we have seen, information-laden - seem to mirror those found in the information of meaningful communication. This addresses the issue of potential links between conceptions of information in different realms (Robinson and Bawden 2013). It requires us to consider whether the quantum concepts applied in information science are 'merely' analogies, metaphors and sources of inspiration, or whether they have some 'reality'. Most researchers have preferred to use the formalisms for practical ends; a similarity with quantum physicists, most of whom have a preference for using the formulae without concern for philosophy, crudely characterised as "shut up and calculate" (Al-Khalili 2004). But some have given detailed consideration to the nature of some of the quantum concepts used in an information science context: contexualisation and interference (Aerts 2009), entanglement (Bruza, Kitto, Nelson and McEvoy 2009, Arafat 2011), and superposition (Arafat 2011).

Whilst most studies have focused on providing new and better ways of carrying out practical tasks – information retrieval, natural language processing, decision making, etc. – some have sought more dramatically novel results. Aerts (2009), for example,

proposes that the quantum modelling of concepts reveals a wholly new second form of thought process, 'quantum conceptual thought', which is holistic and indeterminate. If this could be shown to be so, apart from its psychological implications it would have practical implications for the ways in which information is presented.

Still more ambitiously, some have sought a unity between human information and communication and the physical world, using quantum ideas as the bridge. Aerts (2010) proposes to reinterpret quantum physics, with quantum particles regarded as conceptual entities which act as communication vehicles between material entities which acts as a memory structure; a dramatic example of quantum concepts in the social realm reflecting back on their physical origins. Though this may strike many as a metaphor too far, it is merely the latest in a long-established line of thought to the effect that quantum theory in some way links the micro- and macro-worlds, and also links objective and subjective. We have already noted Pauli's ideas on the link between the quantum world and the psyche, while Niels Bohr contended that the quantum idea of complementarity had application in psychological and social realms (Pais 1991, p. 438-447). Another example is David Bohm (1990), who builds on the concept of "active information" in his interpretation of quantum mechanics to propose links, through such information acting at different levels, between larger physical structures, human minds, and perhaps a collective mind. While such grand theories may seem far removed from the concerns of information science, they have a resonance with its core concepts that should not be ignored.

Conclusions

"We must be clear", Niels Bohr told the young Werner Heisenberg, as they walked on Hain Mountain near Göttingen in June 1922, "that, when we speak of atoms, language can only be used as in poetry. The poet, too, is not nearly so concerned with describing facts as with creating images and establishing mental connections" (Heisenberg 1971, p. 41). Perhaps information scientists should try, like quantum physicists, to be more like poets sometimes; using mathematical formalism when appropriate, but establishing a qualitative, perhaps metaphorical, framework when that is more useful.

Quantum concepts have entered several aspects of information science, and the broader discipline of information studies, over the past decade. Their clearest demonstrable success has been in information retrieval, semantic language processing, and decision theory: some interesting ideas have been put forward in information-focused issues in the social sciences; and qualitative analogies, some more interesting and convincing than others, have been put forward across the discipline. It seems reasonable to suggest that this amounts, if not to a new paradigm or 'turn' for the information disciplines, then at least to an interesting new diversion from the main path.

To establish how significant this may be for the discipline as a whole, outside the relatively limited areas of impact to date, we suggest that five research themes should be pursued, since none on its own will give the necessary breadth of understanding:

- a wider application of quantum methods in IR, an specifically contextual and conceptual retrieval, with particular emphasis on comparison with alternative methods, and an emphasis on a qualitative understanding of strengths and weaknesses
- application of the methods used in quantum social science studies to the investigation of information behaviour and information practices, of both groups and individuals
- examination of the validity of quantum concepts, with a specific comparison of concepts derived otherwise
- consider other aspects of quantum formalism, such as the least action principle and the conservation of information, to see if they may have valid application in the information sciences
- examine the biggest picture – what, if anything, does the seeming equivalence of concepts and pattern in quantum theory and in the information sciences tell us about the nature and role of information in the universe (or the multiverse, for adherents of that quantum interpretation).

What would it mean for quantum theory to become a foundation of the information sciences? In one way, it would make it more genuinely scientific, if the emphasis were, as it should be, on rational and scientific quantum ideas. On the other hand, it would introduce an anti-realist element; quantum theory is intrinsically inimical to a naïve realism, and this is shown in its applications to the information sciences, for example the concept that a document may be simultaneously relevant and not relevant in an IR model. This would, somewhat unexpectedly, put a scientific model to some extent at odds with realist approaches to information science (see, for example, Hjørland 2004).

In a thoughtful evaluation of van Rijsbergen's introduction of quantum formalisms into information retrieval, Cornelius (2009), worries that "the assault of a mathematical IR on our areas of interest … could be seen as constituting a threat to the LIS field" (p 331 and 335). His concern is that if a formal and mathematical approach to one core area of information science proves successful, then other parts of the subject will be affected, so that "other aspects of enquiry into information seeking and even general aspects of information behaviour will, at the least, have to take account of this formal language and may find that its own research agenda and methods are colonized by, if not actually taken over by, that approach and method" (p. 334). Information science may no longer be able to operate with a mixed "basket of methodologies" (p. 332). We are unable to empathise overmuch with these concerns, nor with the military terminology in which they are expressed. If these methods are of any value, then they should certainly be taken account of, in a critical way, as this review seeks to do. We can certainly agree with Cornelius when he advocates that "LIS needs to revisit and enhance its methods" (p. 331); inasmuch as quantum ideas help us to do that, so much the better.

Writing on swings in fashion between subjective and objective approaches to information, Marcia Bates (2005) concluded "I believe that we are missing the most important lesson that should be coming out of these historical swings – the recognition that each of these positions has something to teach us and that the long-term goal should be to develop an approach that allows each perspective to give over to us what it has to teach." Perhaps that is how we should best see the incorporation of quantum ideas into LIS.

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