From Classical to Quantum Information Science: Shifts to New Theories, New Applications

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ABSTRACT

Information is an idea created in human brain. But information has physical aspects too. Emergence of new theory and technology in physical science always contribute to shape various theories, models and services in LIS. Shannon's mathematical formula derives strength from the physical aspect of data or information and gives a new information theoretic approach to communication model by introducing concepts of bit and entropy. With the advancement of Quantum mechanics a new quantum mechanical model is under preparation. Phenomenon like quantum entanglement is successfully being used in computer technology which in turn helps reshape many LIS services. Quantum information science is a newly flourishing field which is expected to bring great advancements in information organization, processing, retrieval, automatic classification, NLP and other LIS related problems.

Keywords: Bit, Classical Information, Quantum Information, Quantum Superposition, Quantum Entanglement, Quantum Cryptography, Quantum Computing, Trans-border Data Flow.

1. INFORMATION IS PHYSICAL

The main issues related to information science and the techniques of communication is how to transport information between two points - one is the source and the other the receiver, the accuracy of the data or information transported, the security of the data, and also the speed of transportation. The term *transportation* sounds somewhat materialistic as it reminds us of something concrete or tangible or physical. The common view of information is non-physical; information is thought to be just an idea, a creation of the human intellect, and thus abstract in nature. But no single definition fits the concept satisfactorily. Non-physical concept of information is both an interdisciplinary and poly-semantic in character. (Capurro & Hjørland,2003; Floridi, 2002). Sometimes it is *meaningful data*(Devlin, 1999). Sometimes it is the communicated message that shapes the receiver (The Information Philosopher Home Page). In some context information is a commodity, and in some other it is a kind of resource.

But scientific outlook assigns a physical entity to information. Theoretically, information is a physical entity (Landauer, 1999), and no information is possible without representation (Landauer, 1996). In fact, the axiom information is physical a phrase borrowed from the title of one of Landauer's earlier papers, is the *mantra* that governs the view of natural science about information.

This physical nature of information is also manifested in such pragmatic issues as the processing and communicating of information. It involves some physical medium, and some physical entity to make journey from source to receiver. In verbal communication it is air pressure propagating in the form of wave, and in other cases it is electrical charges or sequences of light pulses through some appropriate medium like optical fibre, etc. In other words, in communicating messages it is not the abstract idea itself but some real physical entity that travels.

2. CLASSICAL VIS-A VIS QUANTUM REPRESENTATION OF INFORMATION

The axiom information is physical implies that the laws of information processing and communication are a subset of the physical laws in general. In other words, there are some physical limits to information processing or computation, as computation has been defined as nothing but information processing. (Dodig-Crnkovic, 2011).

Using binary code is characteristic of the classical way of representing data or information (sometimes used interchangeably), which is subjected to logical operations using Boolean logic. And modern information communication technology has traditionally depended upon the laws of classical (as opposed to quantum) physics for data or information representation, processing and communication. This is commonly called digital data.On the other hand, data can also be represented in a non classical, quantum mechanical way depending on some fundamental laws of quantum mechanics. The quantum representation of information can be called a paradigm shift in the concept of information because quantum mechanics assigns some unique characteristics to information, following that it seems possible to bring revolutionary changes in the science of information processing and communication in the near future.

3. OBJECTIVE

The objective of the present paper is to bringthe significant paradigm shift in the scientific concept of information into the consideration of the reader community of library and information scientists: what today's science thinks about information and how it is different from the notions of yesterday's science. Secondly, this paper aims at forecasting how this change can influence several issues of long standing concern for LIS professionals. Both classical and quantum information theories involve many mathematical formalisms and physical theories which are not the concern of this paper, and therefore they have been discussed as non-technically as possible. The discussions will only corroborate the elementary theories of quantum physics, and a theory will be invoked at all only in order that the different concepts of information are well understood.

4. CLASSICAL INFORMATION: SHANNON'S MATHEMATICAL THEORY

In 1948 Claude E Shannon working at the famous Bell Labs published his seminal paper called *A Mathematical Theory of Communication* in which he for the first time raised the issue of communicating messages to the level of a pure engineering problem, leaving the semantic aspect aside. According to Shannon (1948), "The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point." It is evident from Shannon's proposition that it is only at the two terminal points at which one is concerned with the message, in between no message is found. We also learn from Shannon's paper the detailed theoretical knowledge of data communication. Some of the key features are:

- The message is channelized in an encoded form and is decoded at the receiving end,
- The decoding and reconstruction of the original message at the receiving end must depend on the degree of efficiency of encoding,
- Noise is almost always a staple thing with any medium and has to be taken into account for any reliable communication,

Additionally, the question of data encryption may be thought of as one important thing to maintain data secrecy and security in communication.

Shannon's paper has been the most influential to the practical field of data communication since. He was chiefly concerned with digital communication and the unit of information in Shannon's theory is *bit*. Although Shannon's equations can fit theoretically into any mode and medium of data transfer, the field of application is in electronics. One can read Shannon's paper for details.

4.1 Measurement of Information

Shannon used *bit* as the fundamental unit of information content of a message and interestingly this measure is in perfect accordance with the binary functioning of a digital computer as *bit* is known to be a short form of *binary digit* introduced by J.W.Tukey.It was no coincidence after all as Shannon was interested in computer processing of information and its transmission in digital form. Shannon described information content (I) of a message source in terms of the *surpriseeffect*(Gleick, 2012; Klir & Folger, 2000)which means the more an incident is unlikely to happen for the recipient the greater amount of information the message carries to him/her. He used logarithmic function instead of decimal to arrive at the convenient unit *bit*. In his paper he mentioned advantages of logarithmic function with base 2 (Shannon, 1948). Shannon measured the average information content per message emitting from an information source capable of a total of X-alternative messages. Out of these alternatives only one message may be emitted at a time, or seen from the recipient's point of view he/she can identify only one message at a time. But until the particular message is identified the information content of that message cannot be measured. However, the average information content of the source can be given by a property called Shannon entropy (Klir & Folger, 2000).

$H = -\sum p(x) - \log_2 p(x)$ where $\mathbf{x} \in \mathbf{X}$

When a particular message x is received the information content of this fact is expressed as

$I_x = -\log_2 p(x)$ bits

Evidently, the entropy of the source and the information content of the individual potential messages both are functions of the corresponding probabilities of the occurrence of events. It can be shown that actually Information content of a message x- varies inversely with the probability of x

$I \propto 1/p(x) - \log_2 p(x)$

Using logarithmic function as did Shannon,$I = \log_2 (1/p(x))$, where clearly Information content is proportional to the surprise, which means that when $p(x) = 1$, i.e., a certain event then $I=0$, meaning information content is nil.

5. THE QUANTUM MECHANICS AND THE QUANTUM REPRESENTATION OF INFORMATION

With the significant advancement achieved in the field of quantum mechanics, the concept of information too has changed significantly. New theory of information and communication is now modelled on quantum theories, in which one can see prospects for the more powerful and versatile information processing and retrieval systems.The two most important quantum phenomena on which quantum representation of information fundamentally rests and which have no classical analogy are super-positional states of the quantum particles and quantum entanglement. Following are the very brief descriptions of the two.

5.1 Quantum Superposition

The basic idea of superposition in Quantum physics is that a physical system, conveniently thought as composed of particles, can exist simultaneously at a number of theoretically possible states which are without mutual interference and contradictions. Quantum theory claims to be a mathematical model of the physical universe and a state is a complete description of a physical system. In the words of Paul Dirac, there exists a 'peculiar relationships such that whenever the system is definitely in one state we can consider it as being partly in each of two or more other states. The original state must be regarded as the result of a kind of *superposition* of the two or more new states…'.

Just as any single quantum state can be seen as a superposition of two or more quantum states, two or more states, in a converse manner, can give a new superposed state.

5.2 Quantum Entanglement

Quantum entanglement is the name of a curious quantum phenomenon and was called the very characteristic nature of quantum mechanics bySchrödinger (Quantum entanglement, 2013). It says that there can be a pair of such particles which are so fundamentally and complementarily associated to each other that any measurement done upon one can cause a correlated response in the other particle, no matter how far apart these two entangled particles are separated. To illustrate this property in lucid terms a pair of entangle particles like electron or photon exhibit such a correlation between them as to share a common quantum state. Quantum states are properties like spin, polarization, (Spin (physics), 2013; Polarization (waves), 2013) etc. that help to describe quanta. However, for entangled particles "they have a definite state as a pair even while neither has a measureable state on its own." (Gleick J. , The Information:a history, a theory, a flood, 2012). When the quantum state, say polarization of any one of such entangled photons is detected to be $+45^0$ for example, or the spin of one of the entangled electrons is measured to be *|1/2⟩*↓ then one can tell for certain that the polarization or spin of the other particle of the pair must be $-45^{\,0}$ *or |1/2⟩*↑ respectively(Quantum entanglement, 2013).

5.3 Qubit as a Measure of Quantum Information

As mentioned above, the quantum state of a particle is able to be superpositional. And it is usual to write the quantum state of a particle in a two dimensional Hilbert space in Dirac notation as a vector

$$|\psi\rangle = \alpha|x\rangle + \beta|y\rangle$$

-where $|\alpha|^2 + |\beta|^2 = 1$.

In classical information theory the smallest unit or a bit of information is represented by (0,1). Using the quantum formalism a *qubit* is represented as

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

It is a quantum counterpart of a classical bit. It describes a state in the simplest possible quantum system. (Preskill, 1998). | ⟩might represent a superposition of the two spins of an electron,

| ⟩ = α|↑⟩ + β|↓⟩

Or it may represent a photon in a superposition of two different polarizations, e.g.

| ⟩ = α| H⟩ + β| V ⟩

where**| H⟩**and **| V ⟩** represent the horizontal and vertical polarizations, respectively. Qubit can be written for any higher dimension too. (Vedral, Introduction to Quantum Information Science, 2006).

In other words when such quantum mechanical properties of particles are used to replace bits they are called quantum bits or qubits.The concept of qubit allows quantum computers to store and represent information depending on the spinor polarization of entangled elementary particles. For concrete example, electrons are particles with spin 1/2, and can have spins of opposite directions up and down denoted as |1/2⟩ ↑ and |1/2⟩ ↓ respectively(Beiser, 1981). It is clear that this spin or intrinsic angular momentum property (Goldstein, 1986)can be used for data representation and can replace the binary 0, 1 model which means that instead of strings of 0s and 1s, data can be coded as strings of particles with opposite spins.

5.4 No Cloning of Quantum Information

Two most fundamental traits of quantum information are that any attempt to acquire information about a quantum system or state of a system must disturb the state of the system itself. In other words, it is not possible to get information about the system without disturbing it. This follows from the uncertainty principle. This also follows from quantum entanglement where any attempt to measure one of the entangled particles' any one state has a corresponding bearing on the others' that state. There is no such necessary condition for classical information.

Another fundamental characteristic that too follows from the property called entanglement is that quantum information cannot be cloned or be copied (Preskill, 1998). This is also in sharp contrast with classical information that can always be copied as many times.

6. APPLICATIONS

The properties of quantum representation of information are not only just theoretical approximation now but it has already been entrusted with experimental results. Here the attempt of the author would be to point out some areas where researches are on, and to suggest some areas in LIS where there is ample scope of its applications.

6.1 Birth of Quantum Information Science or QIS

Strongly appended to the pure theoretical research of Quantum Mechanics (QM) is Quantum Information Science (QIS) which is an interdisciplinary field comprise many branches of science. In the *Report of the Workshop on Quantum InformationScience* (1 July, 2009) it has been described that Quantum information science (QIS) is "a relatively new and rapidly developing interdisciplinary field of science and technology, drawing from physical science, computer science, mathematics, and engineering, which addresses how the fundamental laws of quantum physics can exploited to achieve dramatic improvements in how information is acquired, transmitted, and processed"(Report of the workshop on quantum information science, 2009).

6.2 Quantum Information and Quantum Computer

The functioning of quantum computer is based on quantum bit or *qubit* as opposed to classical binary bit. In digital computers a bit represents the state either 0 or 1at a moment. Given such n bits we can have as many as 2^ndistinct characters. But in quantum computers the value of a qubit is 0, 1 and any probabilistic quantum superposition (Dirac, 2013) of their quantum states. This means that instead of two distinct binary states a qubit can represent all superpositional states evidently indicating greater capacities for operation on data. More interestingly, where as a digital computer with n bits can be in any one of the total 2^n states at a time a quantum computer with n qubits can be in 2^nstates simultaneously. Gleick writes that, "this gives a quantum computer a potential for parallel processing that has no classical equivalence."(Gleick, 2012).

6.3 Quantum Cryptography and Data Security

Entangled quanta guarantee security of data or information being sent from one point to another. The no cloning property has given quantum information a unique security by way of quantum cryptography where any attempt of eavesdropping must destroy the information itself.

When signals are sent in form of entangled particles measurement of spin or polarization of any of the paired particles at one end can tell the spin or polarization of the other particle. If any third party tries to read the signal by measuring the spin or polarization of a particle its entanglement with the other particle is lost. So it is easy to see why eavesdropping of any quantum message cannot be successful. Gleick(2012) writes, "Where as an object in classical physics, typically composed of billions of particles, can be intercepted, monitored, observed, and passed along, a quantum object cannot. Nor can it be copied or cloned. The act of observation inevitably disrupts the message". This theoretical property can be used for quantum cryptography in which a *quantum key*(Harrison, 2004) is to be constructed for distribution between two authorized parties participating in a communication to achieve the highest level of data security where involvements and interests both are at the governmental level. Security of classified data in a closed network may be maintained with quantum cryptography.

6.4 Transborder or Transfrontier Data Flow

The idea of quantum cryptography can have profitable application in Transborder Data Flow(TDF, Gupta & Gupta, 198?) which may be defined as "units of information transferred and processed in more than one nation state." In other words trans-border data flow occurs when extra- territorial data processing function operate at one or more than one termination point in a communication link." Here the term *data* is synonymous with *information*. "In the present context *data* refers to a set of organised symbols capable of machine processing and transfer."

Four types of data flow (Gupta & Gupta, 198?) have been recognized viz. Operational data including organizational decision and administrative data, financial (and banking data too), personal data, and scientific and technological data. All the four types of data need security as privacy of data is a key issue in today's information industry based on business process out sourcing, knowledge process out sourcing etc. Shielding data against hacking can be done with the help of quantum key distribution (Harrison, 2004).

6.5 Quantum information science in IR system, NLP & AI

Understanding the advantages of quantum computing over classical (digital) computing some further implications of this technology may be suggested in LIS field. Vlatko Vedral (2010), Professor of QIS in the Oxford University affirms that "a quantum computer could be designed to scan any number of database elements much faster than a classical computer."It is because of its capacity to belong to a number of superpositional states at a time that a quantum computer can explore a huge number of alternatives simultaneously. This can be logically expanded to suggest that a much more powerful Information Retrieval system can be achieved based on quantum model. Secondly, Natural Language Processing can be done with greater efficiency with the outcome that both Machine Translation and Automatic Classification can be done with greater level of accuracy. Fortunately, researches have already been started and papers are coming out in all of these areas including Semantic analysis and NLP and IR models, which show positive direction towards their materialization in the future.(Aerts & Czachor, 2004; Aerts, *et al.,* 2013; Melucci, 2012).

7. CONCLUSIONS

Although small scale quantum computers could already been built.Vedral (2010) put the question this way, "How far away are we from fully fledged quantum computers?" He also gave the answer "quite far". But by a fully fledged system he meant a qubit capacity equivalent to today's computer's capacity to work with millions of classical bits-bytes. According to him the current experiment of quantum computation works with 10 to 15 qubits. (Vedral, 2010)But it is a steadily growing field of research. The growth of research and theoretical and experimental advancements are reflected through the retrieval of numerous documents by search engines and more particularly in the webpage of Centre for Quantum Computation at qubit.org(Oxford Quantum, n.d.) with links to arXiv where one can read about different facets of its research. Interestingly, papers more directly related to LIS professionals on topic like QIS-XML and metadata(Heus & Gomez, 2007; Heus & Gomez, 2011) also appear.

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