Statement of Research

A quantum approach to natural language/cognition

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My research interest is a novel formal approach to natural language and cognition that sees human brain as a *quantum* physical system and contends the correspondence between the formulation of a state of affairs and the measurement of its physical embodiment [1]. According to this assumption, symbols are eigenstates* of a quantum physical measurement associated with an experimental arrangement†. The measurement corresponds to the cognitive formulation of a state of affairs. I argue that the underlying physical system is quantum mechanical‡; and the core issue of cognition or intelligence is not about the static representation of states of affairs and the manipulation thereof, but about the active measuring and the dynamic evolution of superposed physical states (for details, see [1]). For example, the emotional response of a person to an event can be represented by a superposition: $c_1|excited\rangle + c_2|frustrated\rangle + c_3|anxious\rangle + c_4|angry\rangle \cdots$, where $|\cdot\rangle$ is the eigenstates of the emotion-formulation operator§; $c_i \in \mathbb{C}$ being a complex number; $\sum_i |c_i|^2 = 1$; and $|c_1|^2$ is the probability of recognizing/formulating/measuring *excited* as the attribute, etc. When we think of the situation (in terms of the emotion the event aroused), however, the emotion does not have to be explicitly recognized. In fact, this example also marks a significant difference between classical approaches and the quantum approach. According to conventional computational theories, which are non-stochastic¶, even if we do not explicitly make statements about the properties the decomposition is nevertheless well-defined and the computational results do not depend on whether we have made an explicit decomposition. In other words, according to conventional computational theories, an analysis of the knowledge does not change the knowledge itself; by putting together the analyzed parts one gets the whole again —- there is a referentially transparent global reference frame. *This is not the case in the quantum framework:* the physical states are in general *not* the same after measurement. The question asking what the physical property really is without physical measurement is pointless. The central issue of quantum physics – being *non-deterministic* – is *epistemology*, not ontology.

As far as the non-deterministic property is concerned, the quantum approach is similar to stochastic approaches. However, a stochastic approach employs a collection of real parameters but the operations on real numbers are "monotonic"‖. A stochastic approach can therefore *not*

*An eigenstate is one of the possible measurement outcomes in of an experiment. Although eigenstates can be either continuous or discrete, the discrete eigenstates are more interesting. For instance, the bounded electron in the hydrogen atom can only be found in discrete orbits. The energy states are eigenstates. Since electromagnetic wave is to be described by a wave function of photons, the discrete modes in a wave guide or a cavity are also eigenstates. This may be similar to the firing "modes" of electro-chemical activities in the brain.

†The dependence of physical properties on experimental arrangement is a crucial difference between quantum and classical physics. For instance, although there is no preference of orientation in nature, the spin angular momentum of an electron *is* either *up* or *down* according to the alignment of measuring instrument (chosen arbitrarily by a physicist).

‡Classical physics is, after all, a special case of quantum physics. The laws in classical physics are aggregate behavior of quantum physics. This is called the *correspondence principle*.

§An operator is the mathematical formalism of a measurement in quantum physics.

¶The underlying mechanism of conventional computational theories are deterministic Turing machine.

‖For example, for addition: if $a, b \in \mathbb{R}$, either we have $|a+2b| \geq |a+b| \geq |a|$ or $|a+2b| \leq |a+b| \leq |a|$. However, if $a, b \in \mathbb{C}$, we may have $|a+2b| \geq |a+b|$ but $|a+b| \leq |a|$.

account for "interference" patterns of a *single* object (a marvelous example is the interference of one single electron, see [2]). In quantum physics, we need *complex probability amplitude*. So if the mental states do follow quantum mechanics, we need complex numbers to describe the mental processes. In fact, since all real numbers are also complex numbers, the quantum approach can be demonstrated to *subsume* stochastic approaches. If we interpret the member function in fuzzy logic as stochastic, the criticism of stochastic approach applies to fuzzy logic as well. Moreover, the quantum approach is better physically grounded. In this regard, being more related to engineering, the stochastic approaches and fuzzy logic employ many *ad hoc* modelling techniques which may attain a certain goal but fail in explaining why it is the case.

In comparison with classical connectionism (Artificial Neural Networks with real connection weights), the quantum framework is based on a more exact theory of the underlying physical substrate. In the quantum approach the eigenstates in a brain correspond to the firing patterns of *a huge number* of neurons in the brain, there is no approximation involved as in modelling individual neuron. It is like to solve a periodic wave function in the solid-state substrate involving a huge number of atoms without resorting to the solution of the wave function of all individual atoms: what is of interest is the *modes*[**]. Furthermore, it is not clear how the activations are related to probabilities (if any), not to mention how to account for higher-level discrete computation based on the activities on the lower-level continuous substrate in connectionism. Being a physicalist account like connectionism, the quantum does not have the drawback of over-simplification. More importantly, it can accommodate "subjectivity" without resorting to dubious emergentism[††] [1].

An important consequence of the quantum approach is the *duality* of symbol and sense, which follows immediately from the *non-commutativeness* of operators (two operators ξ and η do not commute if $\xi\eta \neq \eta\xi$) and Heisenberg's Uncertainty Principle (for more details, see [3]). Instead of being static, the structure of a state of affairs is to be seen as the construction from a series of dynamic quantum measurements. On the one hand, this view challenges the classical symbolic view of well-defined information (boolean or real-valued). On the other, it extends and complements the connectionist/statistical/fuzzy-logic frameworks by using complex numbers instead of real numbers as parameters. It offers a new way to accommodate uncertainty, non-monotonicity and counterfactual reasoning and can bridge the discrepancy between continuous sub-symbolic system and discrete computation "out of the box." In fact, the holistic property of a wave function has led many to argue for the connection between quantum physics and *consciousness* — von Neumann and Penrose [4] among others. Indeed, *intention* plays a crucial part of human mind[‡‡]. So if the quantum theory of mind turns out to be correct (the theory can be experimentally falsified — to be correct means to be able to survive empirical refutation), this uniform framework which subsumes both symbolic AI and everyday reasoning may prove useful in implementations of human-like artificial intelligence and cognitive systems.

The established formalism of quantum mechanics – mathematics of Hilbert space – can be applied straightforwardly to reasoning as well as to natural language processing or understanding. In this formalism, the measurement process is described by an Hermitian operator

[**]It is more plausible that the thinking process is based on the dynamic firing patterns rather than on the activation/deactivation of individual neurons.

[††]In the mainstream of natural science — physics, chemistry and biology — there is no emergentism but only *reductionism*, strictly speaking. For one thing, theory is about *explanations*, not about facts-collecting. We say a theory A can be reduced to theory B in the sense that all basic rules in theory A can be conceptually formulated as special cases in theory B, but not vice versa. In other words, general rules of theory A can be *derived* from that of theory A and there are "anomalies" in theory A which can be accounted for in theory B as regularities. For instance, the chemical properties can be derived from the quantum physical properties of shell electrons; Newtonian mechanics is a special case (an approximation, nevertheless) of the theory of relativity. In this sense, biology can be *reduced* to chemistry and chemistry can be *reduced* to quantum physics.

[‡‡]The classical computational approach sees human-mind as a computer and the classical connectionism sees it as a clockwork. Both are theories of zombies.

(physicists call it an *observable*). Assuming that the brain is a closed quantum physical system with constant energy, a reasoning process is a unitary transformation (a solution of a stationary Schrödinger's equation) applied to an input quantum superposition (the physical embodiment of a state of affairs). Using a training algorithm similar to the back-propagation method in a feed-forward neural network, an optimal solution of a complex-valued Hamiltonian matrix (H: the energy operator) can be obtained to construct the unitary operator ($U = e^{-iH/\hbar}$). The operator is to minimize the difference between the output and the target state of affairs (both are complex-valued vectors). The trained Hamiltonian matrix is then applied to unseen vectors to test the system's generalization ability. The feasibility of this approach — at least in small domains — has been demonstrated in my publications [1, 3, 5]. As far as the further development of the quantum approach is concerned, I am interested in the following theoretical works (in arbitrary order):

- Theoretical extensions of a "flat" treatment of language and logic in my thesis to accommodate structures (grammar and sophisticated reasoning);
- The theoretical investigation into the potential of quantum architectures and to reveal their relationship to existing statistical / connectionist / fuzzy-logic frameworks;
- A more sophisticated quantum computational theory to unify soft information processing with "crisp" classical computation — establishment of the correspondence principle;

Beside theoretical work, there may be practical applications of the quantum approach to Natural Language Processing, Cognitive Science or Artificial Intelligence. Among them are (in arbitrary order):

- Using quantum representation as the final arbitration mechanism to extend the ability of existing intelligent agents and/or robots;
- Using quantum representation to account for *emotion* (in general a superposition of eigenstates pertaining to an emotion-formulation-operator) — useful in user modeling, etc.;
- Hybrid applications combining conventional NLP and/or stochastic NLP (e.g. Hidden Markov Model), on the one side; and a quantum arbitration module, on the other. Preliminary studies have been done in applying quantum architectures to statistical language models (n-gram language models) [6] , which shows in some respect better performance than that of a smoothed statistical algorithm [7].
- Hybrid applications combining conventional data-mining / information retrieval techniques and a quantum arbitration module to build intelligent internet agents;
- Hybrid applications of conventional expert system and a quantum arbitration module. These can be applied to practical areas such as computer-aided diagnosis, computer-aided second-language learning or computer-aided translation, etc.

I am convinced this approach can deliver fruitful research results. Detailed project proposals can be prepared in due course.

References

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