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Quantum Computational Intelligence: Answers and Questions

Dan Ventura

In 1994 the discovery by Peter Shor of an algorithm for factoring large numbers in polynomial time using a quantum computer[1] transformed the field of quantum computation from a theoretical curiosity to a potential technology of national interest. The appeal of a computational paradigm with a potentially exponential increase in capacity over classical approaches dramatically increased interest and research in the field. Interestingly, however, discoveries of other useful quantum algorithms have come few and far between. The ramifications of a quantum factoring algorithm on cryptography not withstanding, it is beginning to appear as if quantum computation is an answer looking for a question.

The field of computational intelligence, including the sub-fields of machine learning, neural networks, computational learning theory, evolutionary computation and symbolic artificial intelligence, seeks to produce algorithms for solving problems that are intractable or have no closed form solution or are in some other way unsuitable for traditional computational methods. Many successful applications of such techniques exist; however, due to the nature of the problems to which these technologies are applied, such successes are more often the exception rather than the rule. In other words, we might say that computational intelligence is a question looking for an answer.

Perhaps the two fields can be combined to the advantage of both. Computational intelligence seeks to extend the capabilities of classical computers. As quantum computation begins to mature, is it not natural to attempt to extend its capabilities in a similar fashion, by developing a field of quantum computational intelligence? Conversely, perhaps developing quantum computational intelligence is critical to quantum computation's continued development as a computational science. (It is still very much a developing and valuable science from a physical standpoint, even if no other algorithmic developments occur.)

Quantum computation is probabilistic in nature and is computation based upon the time evolution of a physical system. Further, this physical system obeys the laws of quantum mechanics, which can be extremely counterintuitive. Two important and unusually powerful ideas unique to quantum computation (as opposed to the classical sort) are *quantum parallelism* and *entanglement*. Quantum parallelism refers to the fact that a quantum system exists as a superposition of many states at once, and therefore computation involving the system is simultaneously applied to all states represented in the quantum system. Entanglement describes the non-classical correlations that can exist between different quantum systems through which the systems may be said to communicate. These concepts embody the unique capability that quantum computation has to perform an exponential amount of information processing within a polynomial amount of space and time.

Now, consider for what is this type of computation really suited? We are still trying to figure this out. Quantum computation is very counterintuitive, even unsettling, from a physical standpoint; from a computational standpoint it is not so much unsettling as it is just extremely different. I do not believe anyone really has a handle yet on how to think algorithmically in this way, and so I suspect that we have yet to produce the most important developments in the field. Shor's factoring algorithm is ingenius, and it poses a very real challenge to current standards in cryptography. However, one can always come up with codes that are not based upon the difficulty of factorization. In fact, quantum cryptography, the study of cryptographic systems based on quantum principles, is a burgeoning field in its own right. Also, there is no proof that what Shor did can't be done classically, (though at the moment we suspect that it can not). So then what of quantum computation?

Search is another problem for which interesting quantum computational algorithms have been discovered. For example, Lov Grover produced an algorithm for searching an unordered list of length N in $O(\sqrt{N})$ time[2], whereas classically the same task requires $O(N/2)$ time. In other words, a quantum computer with a quantum phone book can find the name associated with a particular phone number significantly faster than a classical computer with a classical phone book can. As impressive an achievement as Shor's algorithm is, I will argue that Grover's quantum search is even more important because it is more purely quantum in nature and because it is provably super-classical. Further, I believe it is a better indicator of the future of quantum computation.

Of course, search is an extremely common theme in traditional artificial intelligence, and many approaches to computational intelligence suffer from exponential explosions in computational requirements. Quantum computation naturally processes exponential amounts of information. Computational intelligence and quantum computation are both forms of computation that can be described as fuzzy, probabilistic, inexact, nondeterministic, etc. Despite Shor's remarkable success, quantum computation appears, in general, to be much more amenable to computational intelligence type problems rather than to traditional problems requiring exact, deterministic solutions.

In fact, this wedding of quantum computation and computational intelligence is beginning to bear some fruit. Results have been published on quantum associative memories with storage capacities exponentially greater than their classical counterparts[3]; detailing fascinating mathematical analogies between the quantum and neural network theories[4]; on using quantum computation for evaluating decision trees[5]; discussing the construction of quantum bayesian networks[6]; suggesting quantum extensions to genetic algorithms[7]; simulating the implementation of a neural network using quantum dots[8]; presenting a quantum computational learning algorithm for learning DNF formula[9]; investigating the implementation of competitive learning in a quantum system[10]. Research such as this hints at the enormous possibility that a study of quantum computational intelligence possesses. However, the field, as such, is still in its infancy, and really the work cited here, while on the right track, nibbles more around the edges than it does embrace the full potential of this emerging science.

And in fact, there exists an inherent difficulty in the endeavor of communicating across fields with radically different agendas, viewpoints, strategies, nomenclatures, etc. For example, to someone in computational intelligence that is familiar with inductive learning, the value of an algorithm for encoding a set of examples in a quantum state is fundamentally obvious. For a physicist, on the other hand, such an algorithm may seem esoteric at best. The situation gets even more complicated when we consider the fact that computational intelligence itself is extremely interdisciplinary in nature, consisting of ideas from computer science, mathematics, psychology, biology, and statistics to name a few. Thus progress in such an eclectic field as quantum computational intelligence is bound to be slow, especially at first.

This inertial effect is as easy to understand as it is difficult to overcome -- the two fields of quantum mechanics and computational intelligence that must be reconciled to produce useful quantum computational intelligence are disparate almost to the extreme. One can almost be characterized as rigor for the sake of rigor (though physicists will take offense at this), while the other has prospered almost exclusively on empirical success (and computational intelligence practitioners will take offense at this). A less acerbic way to put this is to say that empirical evidence without a theoretical basis is as terrible for a physicist as is a theoretical basis without empirical usefulness for a practitioner of computational intelligence. Although these generalizations are exaggerations, they do help emphasize the difficulty in producing interesting results as a union of the two sciences. Physics demands rigor and theoretical correctness. Computational intelligence demands practical application and empirical benefit. While these two approaches are hardly mutually exclusive, they are rarely considered together even within a single discipline, and the situation is exacerbated by the disparity between the two fields now attempting to unify. The difficulty is all the greater because as is usually the case across disciplines, completely different languages are spoken and results are often needlessly reproduced for lack of sufficient communication.

We are just beginning to glimpse what can be done with quantum computation and so also we are just beginning to glimpse what can be done with quantum computational intelligence. The kinds of problems to which computational intelligence is usually applied are often exponential in nature. Quantum computation performs an exponential amount of information processing in polynomial space and time, but most of this is usually unavailable to us. The trick is figuring out for what kinds of problems we can extract from the quantum computer something more than we could from a classical one. As we learn better how to do that, the field of quantum computational intelligence will become both the question to the answer and the answer to the question.

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