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The Evolution of Computation from Classical Models to Quantum Computing: The Impact on Business and the Economy

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Abstract

Aim/Purpose: This paper aims to describe the current computational models of knowledge and (big) data, based on classical physics (classical computing), prior to outlining the concepts of the quantum computational model (quantum computing).

Design/Methodology: The research methodology applied is that of a historical review of classical models, followed by a review of the limited, relevant literature available on the evolving field of quantum computing.

Findings: Results take the form of comparisons of how the state-space and the associated combinatorial explosion are addressed by models; from causal reasoning and statistical approaches, to Artificial Intelligence and Big Data, and those inferred for quantum computing, and the implications for the research paradigm. There follows a discussion on current quantum computational exemplars.

Conclusion: Conclusions drawn encompass suggestions for the future of knowledge derivation and computation within the state-space, and the potential of quantum for real world applications for business, and the economy.

Limitation: Available and relevant literature on the evolving field of quantum computing.

Implication: Implications for reaching definitive conclusions.

Originality: The objectives of this paper are to compare and contrast classical and quantum computation, in relation to both knowledge and state-space.

Keywords: classical computing, quantum computing, artificial intelligence, data analytics.

Introduction

At present, computational models and computers are based on classical physics. Quantum computational models and computers, as the name suggests, are based on quantum physics. This paper aims to describe the current computational models of knowledge and (big) data, based on classical physics (classical models), prior to outlining the concepts of quantum computational models (quantum computing).

The objectives are to compare and contrast classical and quantum computation, in relation to both knowledge and state-space.

The research methodology applied is that of secondary research, through a historic review of classical models, and a review of the limited, relevant literature available on the quantum model.

Results take the form of comparisons on how the state-space and the associated combinatorial explosion are addressed by models; from causal reasoning and statistical approaches, to Artificial Intelligence (AI) and Big Data, and those inferred for quantum computing, and the implications for the research paradigm. There follows a discussion on current quantum computational exemplars.

Conclusions drawn encompass suggestions for the future of knowledge derivation and computation within the state-space, and the potential of quantum for real world applications for business, and the economy.

Methodology

The methodology applied is that of secondary research (literature review). Firstly, definitions of classical models: causal, statistical, heuristic, and big data are revisited in the context of knowledge representation and search. The limited, relevant literature on the evolving field of quantum computational models is then reviewed in this context.

Results

Characteristics of Classical Computing and Classical Computational Models

Types of classical computational models include Causal, Statistical, Heuristic and Big Data (Graham, 2014).

An example of causal reasoning is Automatic Test Equipment (ATE) for computer hardware fault diagnosis (Graham, 1990). Knowledge is described as a hierarchy of descriptions (behaviours) linking cause (faults) and effect (symptoms). Causal reasoning, or reasoning from first principles, often uses simulation to obtain the entire set of causes and effects for a complex structure leading to a hierarchy of descriptions. Causal reasoning models are domain specific and numeric data hierarchies, generating and applying simple numerical files.

"Knowledge-based (or Expert) systems provide clear and logical explanations of their reasoning, use a control structure appropriate to the specific problem domain, and identify criteria to reliably evaluate its performance" (Luger, 2002:20-21). Knowledge-based (Heuristic) reasoning tries to emulate the knowledge and experience that an expert applies (the heuristics) in diagnostics obtained through knowledge elicitation techniques such as interview, acquiring both qualitative and quantitative values. Knowledge is expressed in the form of rules. Backwards or forwards chaining through these rules should lead to one or more solution candidates. Knowledge-based systems separate the domain expertise and knowledge (knowledge-base) from the mechanism (a forward or backward chaining inference engine). They employ propositional logic or predicate calculus to reach one or more conclusions based on evidence with degrees of statistical confidence (confidence factors), as well as "How" and "Why" queries. Such systems have difficulty in capturing deep knowledge and are not truly intelligent, but do attempt to encapsulate knowledge and expertise.

The statistical model is purely numeric and quantitative, acquired from multiple sources, particularly databases, spreadsheets and questionnaires, with further statistics generated by the application of mathematical formulae, there is no single knowledge acquisition approach. Most statistical knowledge is obtained through analysis of statistical information and is domain specific. Statistics may aid the identification of knowledge by statistical weighting (such as confidence factors) for search.

Big data are commonly described as massive heterogeneous data (unstructured, semi-structured and structured) sets, not solvable (manageable data analysis) using conventional data models, such as relational databases. Big data originates from multiple, often ad hoc sources, and can be a bi-product of other things; data stored in conventional databases, in public, private, hybrid or community clouds (Chang and Wills, 2013, pp. 233-234). It may be gleaned through social media interactions, or sensor data generated as a result of the Internet of Things (IoT) (Palmer, 2015a, p. 14), for example, a Smart Meter (BritishGas, 2015). Embedded "things" lead to the generation, and usually the recording, of significant amounts of data (often from sensors) that are amenable to analytics. Analytics can exploit data held in the cloud and cloud storage, adding public cloud data to private cloud data (Gordon, 2013). McKinsey Global Institute (Neaga and Hao, 2013) suggests models for big data characteristics based on the source, with the main key characteristics being those of Volume, Velocity, Variety and Value, plus the characteristic of Veracity. Additional characteristics are those of Variability and Complexity (SAS, 2012).

The role of Artificial Intelligence and Analytics in Classical Computational Models

Artificial Intelligence is an umbrella term for a multi-disciplinary approach to making things smarter (intelligent); Interaction Design, Natural Language Processing, Knowledge-Based Systems, Robotics, Machine Learning (ML). ML is often used wrongly as a synonym for AI. Arguably, the main problems that AI addresses are viewed to be those of Knowledge Representation and Search, or Search and more Search. Practical applications of AI include search engines, speech recognition, industrial robots, Computer-Aided Learning (CAL), and interfaces such as Alexa. Machine Learning aims to emulate human learning through deep learning, Artificial Neural Networks (ANNs), and the realisation of meta-knowledge. Such knowledge or expertise is the basis of knowledge-based systems and heuristic knowledge models.

Analytics refers to the analysis of data to identify patterns or anomalies, and so to provide descriptions, diagnoses, prescriptions, or to make predictions, using artificial intelligence techniques such as machine learning, e.g., ANNs, regression, etc. Analytics can be described by their use; Descriptive, Diagnostic, Prescriptive or Predictive, or categorised by their data format and origin; Text analytics, Speech analytics, Video/image analytics and Combined analytics (Marr, 2015, pp. 105-149). Analytic techniques may lead to the application of established models, such as mathematical (possibly statistical) models or decision trees (which may be part of a knowledge-based model), post processing (filtering, etc.). Analytics are essentially the application of a set of processes (algorithms) and technologies (systems), plus people (skills), to make sense of data (Heger, 2014). For example, ML algorithms are a process of learning a model of the world to predict future outcomes. The type of analytics used is based on the outcome, e.g., classification or clustering (if the outcome is discrete) for a numerical regression problem. Not all big data is stored, as it is not normally possible or desirable. Current applications of analytics include medical applications, such as the Human Genome Project, with Genomics becoming increasingly important (Palmer, 2015). The use of analytics for an earthquake aftershocks mathematical prediction model, has been applied to the unrelated domain of crime prediction in Los Angeles (MIT, 2013), possibly establishing generic patterns analogous to fractals (Graham, 2017).

Characteristics of Quantum Computing and Quantum Computational Models

As the name suggests, quantum computation (and computers), is based on quantum physics and the principles of quantum mechanics. Unlike classical systems, "a quantum system can be in a superposition of many different states at the same time, and can exhibit interference effects during the course of its evolution. Moreover, spatially separated quantum systems may be entangled with each other and may have 'non-local' effects because of this" (de Wolf, 2022).

Quantum computers "work in a fundamentally different way to classic computers, using qubits (quantum bits) as the basic building blocks of computing. Unlike regular binary digits (bits) for classical computers, that store information as either a zero or one, qubits can store a combination of both through superposition. For a quantum computer to work properly, qubits have to remain 'entangled' with each other, meaning that the state of one qubit instantaneously affects the state of another, even when they are physically separate" (Computing, 2022a).

Classical and Quantum Computational models and their relationship to State-Space and the Combinatorial Explosion

Classical and quantum computational models can be evaluated by their relationship to state-space and the combinatorial explosion. The state-space refers to the space of allowed problem states. State-space may take the form of a tree, or (when it is possible to return to a previously visited state) a graph. In all but trivial cases, for classical computational models, it is not possible to explore state-space fully (until every path reaches a goal state or a dead end). If the branching factor (the number of successors of a given state) is b and the tree is explored to depth n, there will be b^n nodes at the nth level. The classic example is the Chess Board. The resulting total size of the state-space is known as the combinatorial explosion.

The Causal Model would consider every possible outcome from every possible combination of moves, i.e., the entire state-space. The highly domain specific nature of any causal model (for a single electronics component for instance) is the main constraint to the growth of state-space and the accompanying combinatorial explosion.

The heuristic approach applies 'rules of thumb', such as set pieces in chess (case-based reasoning), using knowledge to guide the search (of the state-space). Knowledge-based reasoning has the opposite issues to causal reasoning; its heuristic approach effectively contracts the state-space, but the heuristics may not be as well defined. The domain specific nature of knowledge-based systems, and their use as front-ends to databases, constrain the size of the generated state-space (search), and therefore, reduce the resulting combinatorial explosion.

The statistical view covers both causal and heuristic models. The heuristics are also likely to map against probabilities (of decision and goal outcomes) which would be experientially reached by human experts, in guiding search. The main advantage of the statistical model is its simplicity; purely numeric and quantitative, it is usually combined with other models to provide information (to guide search and thus contract the state-space). For example, knowledge bases where statistical probabilities are employed to provide confidence factors (the measurement of confidence or belief in a given solution (Graham, 2014, p.9)). Again, domain specificity and weighted search reduces the state-space and combinatorial explosion.

Because of the very nature of the big data model, the state-space and combinatorial explosion are large. Here, analytics and artificial intelligence are the means by which the state-space and combinatorial explosion are constrained.

Value is obtained by the application of analytics to big data, effectively reducing the state space, "converting" the data into information (contemporary), or knowledge (future predictive) by making it domain specific. This reduction in state-space naturally impacts on the combinatorial explosion.

There is a temporal element to data, information and knowledge. Data is absolute and temporally independent. This is important when considering classical and quantum computation.

The advent of quantum computational models and quantum computing represents a complete paradigm shift. The need to manage, or reduce the state-space may be more an ideal, rather than a necessity. This is due to the quantum characteristics of superposition and entanglement and, therefore, the ability to represent more of the state-space without some of the physical constraints of classical systems. In all but the most trivial of cases, it would be physically impossible to model the entire state-space using classical computational models based on classical physics. It is also likely that the combinatorial explosion is of lesser concern for quantum physics-based models.

Discussion

In theory and in practice, current computers and computational systems are largely classical, founded on classical physics. Operations in classical systems only have local effects, so limited by locality, as well as being limited to being in only one state at a time. This is not case for quantum computers and quantum computational systems, as modern quantum mechanics informs us (de Wolf, 2022).

Quantum systems offer significant opportunities, for instance, in the development of a quantum internet. Researchers from Delft University of Technology in the Netherlands have sent data across three physical locations using what they have dubbed qubit teleportation. This constitutes a major step forward in enabling a future quantum internet, by teleporting quantum information between two network nodes that were not directly linked to each other. In a study, researchers describe how they accomplished a breakthrough in qubit teleportation across non-adjacent nodes, or rather, over a network.

"The new technique will enable information to be transported in an instant, they say, paving the way for a quantum computing revolution as well as a major shift in network architecture. The scientists used a nitrogen vacancy system, which is essentially a tiny empty space inside a synthetic diamond that can be used to trap electrons. The team created three such systems, which they dubbed Alice, Bob, and Charlie, and then entangled these systems by sending individual photons between them. The researchers first entangled two electrons, one belonging to Alice and the other to Bob. Both electrons had the same spin and were therefore entangled in the same quantum state, with each holding the same information. This quantum state was then transferred to another qubit, a carbon nucleus, inside Bob's synthetic diamond. By doing so, researchers were able to entangle Bob's electron with another electron belonging to Charlie. By performing a specific quantum operation on both of Bob's qubits — the electron and the carbon nucleus — the researchers were able to glue the two entanglements together: Alice plus Bob glued to Bob plus Charlie. Due to the fact that Alice and Charlie were indirectly entangled with one another, the researchers were able to transported data from Alice to Charlie. The state, or information, disappears on one side and appears on the other side, and because it's not travelling the space in between, [the data] can also not get lost" (Computing, 2022a).

The teleportation occurred at a distance of only 60 feet, but the researchers are optimistic that this can be achieved over a distance of several miles. In the long run, it could help create a new network of quantum computers or a quantum internet that is exceptionally safe, trustworthy, and secure. The researchers are now building small quantum networks in the lab, but the idea is to eventually build a quantum internet (Computing, 2022a).

Another exemplar is that of the Borealis quantum computer which, it is claimed, performs 9,000 years of calculation in microseconds.

"Researchers at Canadian firm Xanadu claim to have developed a quantum computer capable of doing a computation in a fraction of a second that would take a traditional computer 9,000 years to finish. This illustrates the superiority of quantum computing over conventional computers for certain tasks, a concept called quantum supremacy or quantum advantage. Quantum supremacy refers to the notion that a quantum computer can solve tasks that conventional computers cannot perform in a reasonable period of time. In December 2019, Google claimed quantum supremacy by demonstrating Sycamore, an early quantum computer, which solved a computational challenge in about 200 seconds with 54 qubits, compared to 10,000 years estimated for a conventional supercomputer (Computing, 2022b)". It should be noted, however, that IBM, which has a stake in the quantum computing race, vehemently refuted the claim.

"The Quantum Processing Unit (QPU) engineered at Xanadu is named Borealis. In order to solve a problem known as boson sampling, Borealis uses light particles, or photons, which are sent through a network of fibre-optic loops. The process involves measuring the properties of a large group of entangled, or quantum-linked, photons separated by beam splitters. Ordinary computers have difficulty accomplishing the job of boson sampling because the complexity of the computations significantly increases as the number of photons in the sample grows. Borealis, however, computes the answer by directly measuring the behaviour of as many as 216 entangled photons. Borealis accomplished a computing work based on Gaussian Boson sampling (GBS) in only 36 microseconds, while today's algorithms and supercomputers would take 9,000 years to complete the same operation. This runtime advantage is over 50 million times as extreme as that reported from earlier photonic machines and constitutes a very large GBS experiment, registering events with up to 219 photons and a mean photon number of 125. According to Xanadu, Borealis is the world's first photonic quantum computer capable of quantum computing advantage and with complete programmability over all of its gates. Borealis is now accessible through Xanadu Cloud or Amazon Braket, according to the Canadian firm" (Computing, 2022b).

A further exemplar of the potential of quantum computing is the Orca Computing's quantum computer that can apparently operate at room temperature, unlike its peers that need freezing temperatures to keep their qubits cool.

"The MoD is working with Orca to explore applications for quantum computing in the defence space. Quantum computers can be disruptive in nearly every industry sector, and, within defence, there's a lot of problems where optimisation can play a huge and very important role. The MoD will work with Orca's small PT-1 quantum computer, which is distinct from its peers in that it doesn't have to operate at sub-zero temperatures. The Orca system is expected to provide significantly improved latency - the speed at which we can read and write to the quantum computer" (Computing 2022c).

Research is also on going into other problems in quantum computation, namely, to find a stochastic archetype of quantum probability (Jenkins, 2022).

Quantum computing may present solutions to long standing classical problems, such as Complexity theory and Moore's Law. Almost all search problems belong to the Nondeterministically Polynomial (NP) class of problems that may not be solved in less than exponential time, i.e., intractable. NP problems are currently ameliorated by resorting to the use of heuristics, advocating Occam's (1324) Razor:

"It is vain to do with more what can be done with less … Entities should not be multiplied beyond necessity".

Moore's Law is not a law of physics, just an observation about the number of transistors on a chip. Moore (BBC Science Focus Magazine, 2022) suggested that as advances were made, the power of the average computer processor would double every year. In this regard, trends have in fact exceeded expectations. However, although Moore's Law still has relevance today, its relevance is waning. This is because of physical limits, as well as economic ones, for two-dimensional chips and physics, now leading to a move towards three-dimensional chips and physics. Perhaps quantum computational models may lead to four-dimensional "chips" and four-dimensional physics?

Finally, the data driven approach of big data analytics has led to the epistemology of knowledge itself being challenged, from theory-based hypothesis and experiment driven, to data synthesis and mining with two perspectives on data; data as research objects and data as scientific methodology. Pale et. al. (Cate, 2016) argue that big data is a new approach to scientific inquiry in which data collection and mining alone (without theories) is a legitimate form of scientific inquiry. With the advent of quantum models of computation and the reduction of state-space inhibitions and the consequences of the combinatorial explosion, this new approach to scientific enquiry could gather momentum.

Conclusions

Classical computational models may be differentiated by characteristics, such as, their origin or mode of generation, their quantitative or qualitative characteristics, format, whether or not domain specific, and their main affinity with data, information or knowledge. Common physical data storage forms include, simple files, spreadsheets, relational or object-oriented databases, knowledge-bases, data centres, many of these may be in the cloud.

All classical models (whether theoretical or applied) are based on classical physics and their physical representation in the form of binary bits, bytes, terabytes and so on, and so forth. Each bit can only store a single value of either zero or one. Classical computers are non-deterministic, finite state automata.

All models, particularly Classical, are abstract, both in their essence and construction, limited by their physical existence in space and time. Quantum models are more natural, comprehensive representations, both spatially and temporally. Quantum computers may be non-deterministic, (almost) infinite state automata. Quantum computational models appear to represent the next logical step in the evolution of computation from big data.

One implication of the exemplars discussed in this paper is that Quantum computers are capable of solving complex calculations much faster than traditional silicon-based devices, as quantum computers work with qubits, which can simultaneously represent both zero and one. This means they can work faster and cope with more uncertainty than those operating on binary systems, solving problems in seconds that would take traditional computers years or centuries.

The relevance of Moore's Law (which is actually an empirical relationship between gains and experience in the production ratio of the number of transistors to chip), which has been slowing down, may become insignificant. The physical limits and economic constraints, for largely two-dimensional chips and two-dimensional physics, mean that Classical models are moving towards operating in three dimensions. Perhaps quantum models may lead to four-dimensional "chips" and four-dimensional physics?

The exemplars suggest that Quantum computing is still under development, quantum machines can't actually solve practical problems yet, they are not at the commercial level, so their potential is yet to be fully realised. What these machines do is to enable the gauging of possibilities of a quantum computer, if scaled-up to really large system sizes. Issues of quantum computers operating at room temperature are reportedly now being addressed.

Quantum computers may potentially speed up the discovery of new medications, lead to improvements in artificial intelligence, and be used to create encryption methods that are even more secure.

In the past, knowledge has been derived through scientific inquiry and approaches such as hypothesis and test. (Big) Data analytics has made the epistemology of knowledge being more the result of synthesis and discovery, although still restricted physically in the classical model. Quantum computing presents an opportunity to reduce or eliminate physical restrictions of this knowledge synthesis. However, the ideal is suggested to be the combination of classical and quantum computational models, within shared memory. Applying analytics and heuristics (Occam's Razor), for the realisation of greater potential in the enhancement of this new approach to scientific enquiry. It should always be noted that any knowledge, however acquired, including such synthesised knowledge, is not infallible and can prove erroneous (extraneous data can produce “red herrings”).

The realisation of the quantum computational model does not necessitate the replacement of classical computational models. Procedural problems should use procedural solutions, etc. A quantum computer is not required to calculate salaries or simple problems with clearly defined inputs and outputs. The adage of “horses for courses” is appropriate, using the significant power of quantum where it is most advantageous to do so, for example, in weather forecasting. Even if all, or most of any state-space for a given domain, can be modelled and computed using quantum computers, such systems would be deemed profligate. There would be no economic or business case for doing so. The better solution being in the form of a unified approach of big data, artificial intelligence, analytics (classical) and the power of quantum, within shared memory.

The potential of quantum computation and quantum computers lies in their application to previously intractable problems, and “quantum leaps” in knowledge acquisition and scientific enquiry.

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