The future of quantum computing

As Moore's law reaches its inevitable denouement—because increasing the number of transistors on a chip implies that the transistors themselves become smaller, and there are fundamental lower limits to the size of a transistor working in the conventional manner[1]—attention is being turned to whether computational power can continue to increase. The matter is of extreme importance because of the singular relationship between humanity and computing. It is not simply another example of "mechanically extended man", which is in essence no different from Goethe's "Wenn ich sechs Hengste zahlen kann, Sind ihre Kräfte nicht die meine?"; Licklider has called it man–computer *symbiosis*;[2] he is said to have remarked that "Computers are destined to become interactive intellectual amplifiers for all humans pervasively worldwide".[3] In the same vein, H. Simon has remarked that "Progress depends on our ability to devise better and more powerful thinking programs for man and machine",[4] and, even more succinctly, the ethos of Bret Victor's Dynamicland is that computing will transform humanity.[5] In complete contrast, the economist Tyler Cowen sees stagnation in technology in general,[6] and although he concedes that "the Internet is wonderful", he does not see it as offering economic salvation; in fact he sees growth—progress—in the USA and presumably elsewhere in the Western world ending in the early 1970s—just as the computer era was gathering momentum.

In 1948 the National Physical Laboratory published a report by Alan Turing that may be taken to have initiated cultivation of the field of artificial intelligence (AI).[7] Similar developments were taking place in the USSR;[8] the roots everywhere go back earlier still. In the

1 For elaboration of this point, see e.g. ch. 7 of J.J. Ramsden, *Nanotechnology: An Introduction*, 2nd edn (Elsevier, 2016). Moore's law is, in fact, just a particular example of the customary exponential growth of technology. It could be extended—in terms of computational operations per unit time—backwards to encompass electromechanical machines, relays and vacuum tubes, and doubtless forwards to encompass quantum computing. In fact, the increase is actually superexponential (see M. Roser and H. Ritchie, Technological progress https://ourworldindata.org/technological-progress).

2 J.C.R. Licklider, Man–computer symbiosis. *IRE Trans. Human Factors Electronics* (March 1960) 4–11.

3 Reported by A. Kay at the Ellen MacArthur Foundation Summit, 13 June 2019.

4 H. Simon, Designing organizations for an information-rich world. In: M. Greenberger (ed.), *Computers, Communications, and the Public Interest*, pp. 38–72. Baltimore: The Johns Hopkins Press (1971).

5 https://dynamicland.org

6 T. Cowen, *The Great Stagnation*. New York: Dutton (2011). He does not seem to have modified his views subsequently (e.g., lecture at the Friedberg Economic Institute, Tel Aviv, 20 June 2019).

7 A.M. Turing, *Intelligent Machinery*. Teddington: National Physical Laboratory (1948).

8 K.M. Golubev, Overview of AI research history in USSR and Ukraine: up-to-date just-in-time knowledge concept. In: E. Mercier-Laurent and D. Boulanger (eds), *Artificial Intelligence for Knowledge Management* (AI4KM 2012). *IFIP Advances in Information and Communication Technology*, vol. 42. Springer (2014). This article is very Ukraine-centric and ignores many Russian contributions (Adelson-Velskii, Arlazarov, Khachiyan, Kronrod , Landis, Leman and Weisfeiler to name just a few) and Georgia is wholly neglected (Tkemaladze among others).

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USA, John McCarthy set up an AI laboratory in 1964 at Stanford University, but this research was rather strongly criticized by Lighthill in 1973,[9] in a report that categorized AI into: A, advanced automation; C, computer-based central nervous system research; and B, building robots, a bridge activity between A and C. McCarthy subsequently rebutted some of the criticism, in particular Lighthill's categorization, pointing out that the main activity of AI research is "studying the structure of information and the structure of problem-solving processes independently of applications and independently of its realization in animals or humans" and emphasized that the big challenge is finding out how to *represent* knowledge. Clearly some of Lighthill's scepticism has been refuted by outstanding progress in chess-playing, and even wei ch'i-playing, programs and self-driving automobiles.

AI is a kind of apotheosis of ever-increasing computing power, qualitatively extending what can be done with it beyond simply faster arithmetic. Already we have tantalizing glimpses of what might be achieved by even greater computing power. Large industries have been built up thanks to a competitive edge given by clever algorithms for scheduling deliveries, essentially all variants of the "traveling salesman problem",[9] but in some ways their operations are still quite primitive. A very big field of activity depends on pattern recognition:[10] examples include automated medical diagnosis and drug discovery. Much activity in these two areas seems to be based on trawling through journal papers[11]—a problem of knowledge representation before one starts trying to recognize patterns.[12,13] Unless the reliability of each piece of published work be assessed, however, one can easily be led astray, although contradictions will at least generate an alert that something needs to be checked. A more insightful approach would be to relate medical symptoms to the underlying physiology; we are still far from being able to do this in general, but AI can help to parse chemical space to infer drug candidate properties, now even extending to dynamic aspects of the interface between drug and target.[14] Combining diagnosis and drug design into truly personalized medicine might be a substantial advance.[15] Another example is real-time health monitoring.[16] Modern techniques of DNA sequencing rely on the ability to solve combinatorially heavy

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9 D.L. Applegate, R.E. Bixby, V. Chvátal and W.J. Cook, *The Traveling Salesman Problem*. Princeton: University Press (2007).

10 N. Tkemaladze, On the problems of an automated system of pattern recognition with learning. *J. Biol. Phys. Chem.* **2** (2002) 80–84. Simon[4] remarks that "Progress lies in the direction of extracting and exploiting the patterns of the world...".

11 V.S. Pendyala and S. Figueira, Automated medical diagnosis from clinical data. *Proc. IEEE 3rd Intl Conf. On Big Data Computing Services and Applications* (2017) 185–190.

12 D. Qi, R.D. King, A.L. Hopkins, G.R. Bickerton and L.N. Soldatova, An ontology for description of drug discovery investigations. *J. Integrative Bioinformatics* **7** (2010) 126.

13 S. Orchard et al., Minimum information about a bioactive entity (MIABE). *Nature Rev. Drug Discovery* **10** (2011) 661–669.

14 A. Fernández, *Artificial Intelligence Platform for Molecular Targeted Therapy: a Translational Science Approach*. Singapore: World Scientific (2021).

15 F. Vogenberg, C.I. Barash and M. Pursel, Personalized medicine. Part 1: Evolution and development into theranostics. *P & T* **35** (2010) 560–567, 576; Part 2: Ethical, legal, and regulatory issues. *ibid.*, pp. 624–631, 642; Part 3: Challenges facing health care plans in implementing coverage policies for pharmacogenomic and genetic testing. *ibid.*, pp. 670–675.

16 L. Pearce, Applying digital early warning systems to healthcare. *Nanotechnol. Perceptions* **13** (2017) 25–60.

computational problems.[17] A notable recent success has been the detection of unreported discharges of effluent into rivers using AI.[18] Ultimately, some predict that AI will even surpass human intelligence (Kurzweil's "singularity").

Quantum computing provides hope that computational power can continue to be increased. Quantum logic[19] based on superposition and entanglement enables devices to be created without the limitations of energy dissipation and the perturbation of conventional transistor logic devices by quantum effects. A great technical difficulty is how to avoid entanglement of the qubits (the quantum-computational equivalent of the conventional bits—binary digits—of information) with the environment.[20] Presently, the largest quantum computer in the world, made by IBM, embodies 65 qubits, already a magnificent technological achievement, and similarly sized devices are operational around the world, including at D-Wave, Google, the University of Science and Technology (USTC) in Hefei (Luzhou), Xanadu in Toronto, etc. In solving certain problems, these devices can be as much as ten orders of magnitude faster than conventional computers. Enlargement to ~1000 qubits is foreseen, which will open the door to realistically tackling a host of hugely intricate problems of great practical importance, such as materials for electric storage batteries, fuel cells and CO_2 capture; the relative lack of success in these endeavours until now stems from the inability to encompass them in the nanoscale. The intractability—until now—of another set of problems, such as understanding Earth's climate system, arises from their very large scale and the need to represent them dynamically with a fineness of detail computationally unattainable with present capabilities. Another example of this kind is the introduction of a sustainable system of resource production and consumption based on the concept of rent-a-molecule.[21] As well as AI applied to the problems in medicine already mentioned, perhaps quantum computation-enabled AI will even enable a more rational approach to policy and decision-making in government to be taken, freeing it from the constant need to oversimplify.[22] Certainly governments have shown themselves eager to launch their own programmes, such as UK National Quantum Technologies (UKNQT), which started in 2014; in the USA, the National Quantum Initiative Act came into being in 2018. Doubtless the desire to maintain or achieve military supremacy underlies these State initiatives.

Are there potential show-stoppers? One is the sheer difficulty of embodying qubits, although progress so far is encouraging, especially compared with another very hard technology, controlled nuclear fusion, which seems as tantalizingly out of reach now as it was 50 years ago (quantum computers may indeed help to solve some of its problems). Another is the possible noncomputability of some aspects at least of human intelligence,[23] implying that

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[17] J.D. Kececioglu and E.W. Myers, Combinatorial algorithms for DNA sequence assembly. *Algorithmica* **13** (1995) 7–51.

[18] P. Hammond, M. Suttie, V.T. Lewis, A.P. Smith and A.C. Singer, Detection of untreated sewage discharges to watercourses using machine learning. *Clean Water* **4** (2021) 18.

[19] S. Gudder, Quantum computation. *Am. Math. Mon.* **110** (2003) 181–201.

[20] §7.3 of J.J. Ramsden, *Nanotechnology: An Introduction*, 2nd edn (Elsevier, 2016).

[21] W.R. Stahel, The circular economy and intelligent decentralization, nanotechnologies and materials, minerals and mining. *Nanotechnol. Perceptions* **16** (2020) 151–168.

[22] J.J. Ramsden, The role of systems thinking in modern society. *Nanotechnol. Perceptions* **14** (2018) 90–98.

[23] J.J. Ramsden, Computational aspects of consciousness. *Psyche: Problems, Perspectives* **1** (2001) 93–100.

even with the power of quantum computation, AI will remain limited in its scope. And there is an inherent contradiction between the fact that the benefits of the Internet (and, more generally, powerful computation) are distributed in proportion to our cognitive abilities to exploit them,[6] whereas enormous and still growing computational efforts are expended on devising sophisticated entertainment that seems to diminish the cognitive abilities of those who are entertained.[24]

This is part of a more general dilemma of the computing revolution. In a simple way it is exemplified by the presence of spam and junk notifications that detract from the usefulness of e-mail. In a more elaborate way it is exemplified by Wikipedia, a true child of the Internet. In its early days, doubtless helped by the novelty, it was widely felt to be useful. As it progressed, however, comprising an increasingly impressive collection of software for automated formatting, indexing, cross-referencing etc., the quality of its content inexorably declined.[25,26] Perhaps the power of quantum computing will rescue it from the fate of irreclaimable mediocrity, by making human writers superfluous—it will be able to automatically trawl the world's literature, summarizing it to create articles perfectly reflecting the current state of popular knowledge, and without the partisan spirit that imbues so many of the present articles. In fact, were this capability to be reached, it would render Wikipedia superfluous because anyone could use the abstracting tools to create personal summaries of any field of knowledge, exactly tailored to personal needs.

Nonetheless the field is pervaded with gigantic optimism. Perhaps the key to understanding this is, as Licklider has remarked, "the self-motivating exhilaration that accompanies truly effective interaction with information and knowledge through a good console connected through a good network to a good computer",[27] and underlying it all is perhaps the thought that ultrapowerful quantum computation will somehow prevent the seemingly inexorable decline that follows the rise of civilizations,[28] and keep us on a permanently high level.

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[24] Computer-based entertainment has grown enormously during the Covid pandemic, which kept many people locked down at home. In many ways it is the apotheosis of the cinema, which "has the doubtful advantage of giving a maximum of recreation at a minimum of mental effort" (Anon., *Where Freedom Falters*, p. 283. London: Scribner's, 1927).

[25] J.J. Ramsden, The future of Wikipedia. *Nanotechnol. Perceptions* **11** (2015) 131–135.

[26] D. Cross, Whither Wikipedia. *Nanotechnol. Perceptions* **12** (2016) 50–52.

[27] J.C.R. Licklider, Computers and Government. In: *The Computer Age: A Twenty-Year View* (eds M.L. Dertouzos and J. Moses), pp. 87–126. Cambridge, Mass.: MIT Press (1980).

[28] Abd Ar Rahman bin Muhammed ibn Khaldun, *The Muqaddimah*. Cairo: (ed.) Muhammad Tawit at-Tanji(1370).