Make Your Business Quantum-Ready Today

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FORTHCOMING: ***MANAGEMENT AND BUSINESS REVIEW (mbrjournal.com)***

DRAFT: 10 APRIL 2022

Executive Summary

Quantum computing is a different way of computation that merges quantum mechanics with computer science and information theory, with a large enough payoff for managers to feel compelled to invest. At the same time, it is also uncertain when – if at all -- quantum computing will become widely available for mainstream business applications. Thus, managers will find themselves torn between 1) waiting for the technology to mature and risking competitors taking the lead and 2) investing now but with no sight of returns on this investment. This article provides a way out: Executives can invest today in quantum-inspired computing that emulates quantum computing on existing specialized digital computers. Any investment today will carry over to (true) quantum computing when it becomes available, and there are computational gains to be had right away for certain architectures and specific business applications. To get quantum ready, first, managers can use the information on providers and use cases in the existing computing ecosystem. Second, they should take stock of their companies' needs for advanced computing to gauge the fit of quantum applications with their business requirements. Finally, they should try out pilot studies with quantum-inspired computing.

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How can executives capitalize on the promise of quantum computing for their businesses? ManMohan Sodhi and Sridhar Tayur suggest a low-risk approach based on quantum-inspired computing.

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The history of the computer precedes the announcement of the first programmable digital computer, the ENIAC, in 1946.[1] Before that, a 'computer' was a person employed during WWII to, well, compute. In the 20th century, quantum mechanics brought on the *first quantum revolution*, transforming computation with the invention of the transistor and the integrated circuit unit (ICU) currently used in computers ranging from handheld devices to supercomputers.

In the 2020s, we are on the cusp of a *second quantum revolution*, with the reimagined usage of quantum mechanics[2] with computer science[3] and information theory.[4] Business leaders have the chance to become the co-creators of this new future. Quantum computing is gaining importance not just in research journals but also with articles appearing in mainstream business journals.[5, 6] Indeed, application providers have made a strong case that the payoff is large enough[7] that many managers will feel compelled to be involved.[8]

Quantum computing was proposed by Paul Benioff,[9] Yuri Manin,[10] and Richard Feynman[11] to get past the limitations of digital computing for the emulation of nature, which is quantum. Unlike the binary (0/1) bits of digital technology, quantum computing uses 'qubits' that can take many different states simultaneously, enabling much faster computing, say, with complex combinatorial problems. Moreover, many problems like simulating materials at the molecular level are solvable only when computing with qubits. Thus, besides fast computation – potentially containing the exponential explosion of the solution time for practical-sized combinatorial problems[12] – quantum computing is expected to solve simulation problems at the molecular or atomic level that would otherwise not be possible.

While there appears to be treasure at this frontier of computing, it is also highly uncertain[13] when quantum computing will become widely available for mainstream business applications – if at all. Many tech giants and well-funded startups are working on different ideas for quantum computers, but commercial quantum computers might become available only in the late 2020s or early 2030s. Besides, many computer architectures require temperatures of nearly absolute zero (0.15 K or below), which would require much energy.

Thus, senior managers find themselves on the twin horns of a dilemma: 1) wait for the technology to become mature but potentially lose out on competitive advantage while others invest and learn the use of quantum computing, or 2) invest in quantum computing right away and then worry about frittering resources in a wild goose chase, with no sight of returns on this investment.

Executives have a way out of this dilemma: they can invest in quantum-*inspired* computing today

However, executives have a way out of this dilemma: they can invest in quantum-*inspired* computing today. Such computing is already available via the cloud on digital computers such as Digital Annealer from Fujitsu and Simulated Bifurcation Machine (SBM) from Toshiba. Quantum-inspired computing takes a problem formulated as a quantum computing problem and then runs it on a specially architected classical (digital) computer. Thus, quantum-inspired computing comprises (1) formulating the problem in a way that is amenable to quantum computing and then (2) solving the formulation using an algorithm inspired by the principles of quantum mechanics. The first two steps are identical to those for quantum computing – but the next step is different: (3) running the algorithm on this formulation using digital computers specially architected to optimize such algorithms.

With the first two steps shared with (true) quantum computing, any investment in quantum-inspired computing will carry over to quantum computing in a straightforward manner when the latter becomes practical and widely accessible. Thus, the effort invested would not be in a throw-away “science project.” Notably, there are computational gains right away for certain architectures and specific business applications.

Overall, we seek to guide managers in three steps with this article. *First*, we provide a glimpse of the business applications that providers and users are developing using quantum computing. Managers can use this information to scan the computing ecosystem for what is available that is relevant to their firms. *Second*, we ask executives to take stock of their companies' needs for advanced computing to gauge the fit of quantum applications with their business requirements. *Finally*, we encourage executives to get their organizations quantum-ready with quantum-*inspired* computing on specialized digital architectures that are already available.

Step 1. Scan for quantum computing business applications and providers

There are different types of quantum architectures (Table 1). *Quantum computing* is split into two categories: quantum annealing (a type of adiabatic quantum computing) used by D-Wave and Honeywell, gate (circuit) model systems being developed by Google, IBM, IonQ, and Rigetti. A fundamentally different approach is *quantum-inspired computing* with hardware by Hitachi, Fujitsu, and Toshiba, all available today for business applications. Amazon is providing access to a variety of hardware through its cloud-based service, Amazon Braket, from startups IonQ and Rigetti machines, quantum annealing company D-Wave, and quantum-inspired hardware Toshiba SBM.

Table 1: Companies offering quantum-inspired and quantum computing, the latter in two fundamentally different ways

Quantum computing		**Quantum-inspired computing**
Adiabatic quantum computing (including quantum annealing)	*Gate-based quantum computing*	
D-Wave Honeywell	Google IBM IonQ Rigetti	Hitachi Fujitsu Toshiba

Rather than concern themselves about which architectures might 'win,' managers should focus on the business applications

Indeed, at this early stage of quantum computing development, executives should expect there will be different approaches. Only in the long term will we find out which approaches – and companies – will succeed. However, managers should focus on the business applications and be agnostic to architectures rather than concern themselves about which architectures might 'win.'[14] This is why we suggest that managers look at the quantum-inspired computers available today and move to (true) quantum computing – whether quantum annealing or gate-based – when that becomes widely available.

As a sampling of applications suggests (Table 2), there are potential gains from quantum computing's capability to solve complex combinatorial problems and run huge numbers of simulations. Some applications for designing new materials or new products for the aerospace, automotive, and pharma industries have to create and evaluate billions and trillions of combinations. Artificial intelligence and machine learning are already benefiting many industries, particularly healthcare. Quantum computing can help in the computationally intensive training phase of such applications. Running simulations in parallel is critical for pricing and design of instruments in finance and insurance sectors, so those sectors are also keen on developing quantum applications that can potentially solve problems in seconds rather than days. Finance also benefits from the parallel evaluation of combinations to find optimal portfolios.

Table 2: A sample of business applications for some sectors

Sector	Application	Examples of companies
Aerospace and Defense	Materials, component design Defense and security applications	Lockheed, Airbus, Boeing
Automotive	Materials, component design Automated vehicles	Volkswagen, Diamler, Toyota, BMW, Denso
Chemicals	Computational fluid dynamics Designing new materials Designing new batteries	Exxon Mobil, Mitsubishi Chemicals

	Logistics and Supply Chain	
Finance	AI/Machine Learning for fraud Pricing of derivatives Portfolio optimization Monte-Carlo Simulation of Risk	Goldman, JP Morgan Chase, BBVA, Bankia
Pharmaceutical	Drug discovery	GSK, Astex Pharmaceuticals

Step 2. Identify your need for advanced computing

Managers need to evaluate the fit of quantum computing to their organizations. This is best done by identifying a) which computing-intensive applications you currently use, b) computing bottlenecks, and c) what computational and data capabilities are in-house, and which are outsourced. Let us consider each in turn.

a) ***Identify the computing-intensive applications in use today and computing bottlenecks***

While you may be familiar with your organization's enterprise systems like ERP (enterprise resource planning) or CRM (customer relationship management), you may need to dig deeper into function-specific applications in use in R&D, manufacturing, or risk management. The sampling of applications presented earlier (Table 2) can give you a good start for what to look for in your organization.

Certainly, there will be improvement in productivity from running these applications if digital computers became 2x or even 10x as fast, with the same data sources and the same personnel. Indeed, with graphics processing units (GPU) and the "elastic cloud" you can already expect 2x-10x parallel speedup today, albeit at a proportional 2x-10x higher cost as well.

b) Identify bottlenecks to computing

One question that follows is about the scenario where computing became 100x-1000x faster but at the same cost (and energy usage) as before: What applications could (and would) you deploy then? The applications you identified above are what your organization is already using, but you could also identify what you are *not* doing owing to computing bottlenecks.

Quantum computing is not just a faster desktop or engineering workstation

Just like an airplane is not (just) a faster car, quantum computing is not just a faster desktop or engineering workstation. Quantum computing will reveal new vistas, which is why it is good to conceive new applications currently not being used or developed but may be entirely possible with quantum computing. At this time, there are problems in pattern recognition via machine learning that are outside the capabilities of classical computers in science and engineering that would be solvable on a quantum computer.[15] The reason is that we anticipate that a quantum computer will readily identify unusual patterns for machine learning or other applications, which may well be beyond the ability of digital computers. Understanding the structure of such applications might encourage imaginatively identifying business opportunities well outside the scope of current-day problems.

The key consideration then is the cost of quantum computing (per instructions per second/scale) relative to the *opportunity* cost of not having certainly applications.
Thinking in these terms of these opportunity costs can also help you explore alternative computing solutions that exist today such as a GPU cloud.

c) Identify computational and data capabilities in-house and outsourced

Take inventory of your capabilities---data, software, and hardware including its use on the cloud. The most expedient way to get going is to use data already in use (or at least available, even if it is not being used), and identify a problem that might benefit from quantum computing.

Strategically, quantum computing will mean more hardware access via the cloud and so a concern maybe more dependence on the cloud provider.

Step 3. Get quantum-ready now

Rather than wait for these innovators to make quantum computing widely accessible for business applications, managers can invest in presently available quantum-inspired computing and gain competitive advantage. When quantum computing becomes widely available, these managers will be able to take advantage of it much faster. Among the companies that have made such computers available are Toshiba, Hitachi, and Fujitsu, available on the cloud directly from the manufacturer or, in the case of Toshiba at least, accessible via Amazon Braket. An advantage such computation provides, besides potentially faster computing, is that multiple "good" solutions can be obtained in a short period rather than spinning wheels on traditional computers searching for a single near-optimal solution and yet settling down for a sub-optimal one due to limitations on solution time.

Consider how Quantbot Technolgies LP, a multi-billion-dollar hedge fund manager, became quantum ready in 2021 using the Toshiba SBM quantum-inspired computing on the cloud. In portfolio applications, machine-learning algorithms provide candidates for alphas, the signals that correlate to higher returns. However, these signals are noisy and may be correlated to each other. Quantbot's Alpha Optimal Combination (AOC) problem is how to best combine these signals to maximize return while containing risk to an acceptable level.

Using existing data used to solve the AOC problem, a Quantbot team comprising of data scientists (reporting to the Chief Investment Officer) and a technologist (reporting to the Chief Technology Officer) adapted the open-source code of Graver Augmented Multi-seed Algorithm (GAMA) available from the Quantum Integer Programming (QuIP) course (https://bernalde.github.io/QuIP/) in collaboration with Carnegie Mellon University.

The team accessed Toshiba SBM on the cloud (directly from Toshiba) and obtained twenty near-optimal solutions within two minutes compared to finding sub-optimal solutions after hours on a traditional computer using a classical solver. A retrospective simulation of 252 trading days of decision making in rolling horizon compared the 20 new 'near-optimal' solutions with the existing past solutions and tracks metrics (Risk, Return, Sharpe Ratio). All 20 solutions dominated the current heuristic solution on these metrics (Figures 1 and 2). This dominance was not surprising because solutions were obtained in the past on a traditional computer using a heuristic, as finding an optimal solution would be too difficult to obtain even after hours of computation. The surprising finding was the quality of the solutions obtained from the quantum-inspired approach in just a couple of minutes.

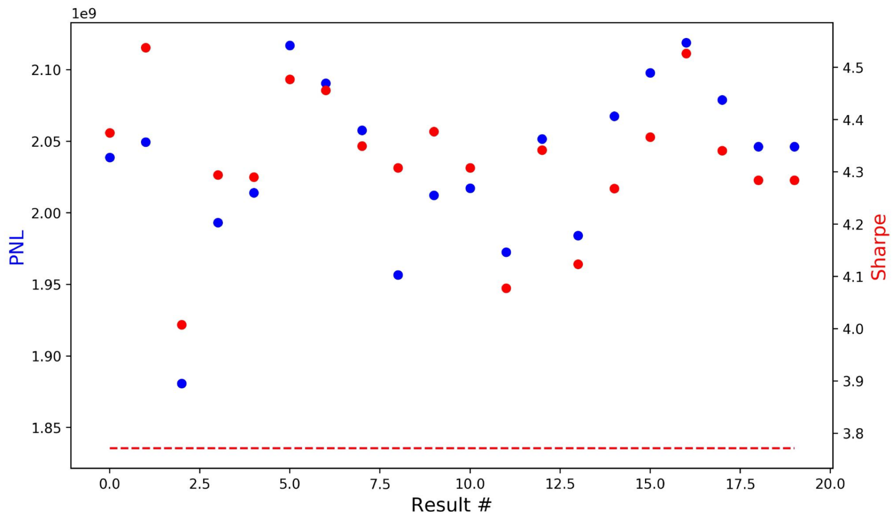

Figure 1: All twenty quantum solutions provided higher returns (PNL, blue dots) and Sharpe ratios (red dots) than the solutions obtained via traditional computing using a proprietary heuristic (normalized with red dashed line) that was currently in use.

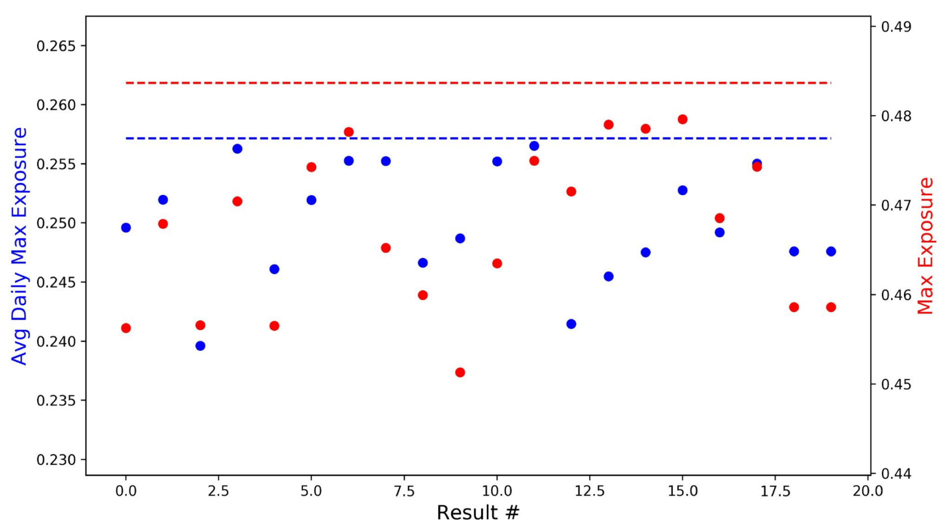

Figure 2: All 20 quantum solutions provided lower average (blue dots) and lower maximum daily risk exposure (red dots) than the solutions via traditional computing using a proprietary heuristic (dashed blue and red lines) that was currently in use.

The choice for executives

The overall computation environment has been such that speed has been growing exponentially, with flops doubling every 1.3 years, the number of transistors per chip doubling every two years (Moore's Law), and chips becoming more integrated as in Apple's M1 architecture. At the same time, superior software implementations of refined algorithms continue to advance the capabilities of commercially available solvers (Gurobi, CPLEX, and others), taking advantage of new architectures and being made available on the cloud.

Add to this mix various quantum computing architectures, even if these are only in experimental form as of writing and will mature in the future. Competition between these architectures is suitable for users who can seek to benefit from these ongoing enhancements in various quantum-computing approaches.

The question facing executives is why they should seek quantum readiness for their organizations now. After all, their experience with many technologies has been captured by the Gartner hype cycle: unrealistic expectations at the outset followed by a trough of disappointment [16] (Figure 3). So why not wait until others have tried and failed and then learn from their mistakes?

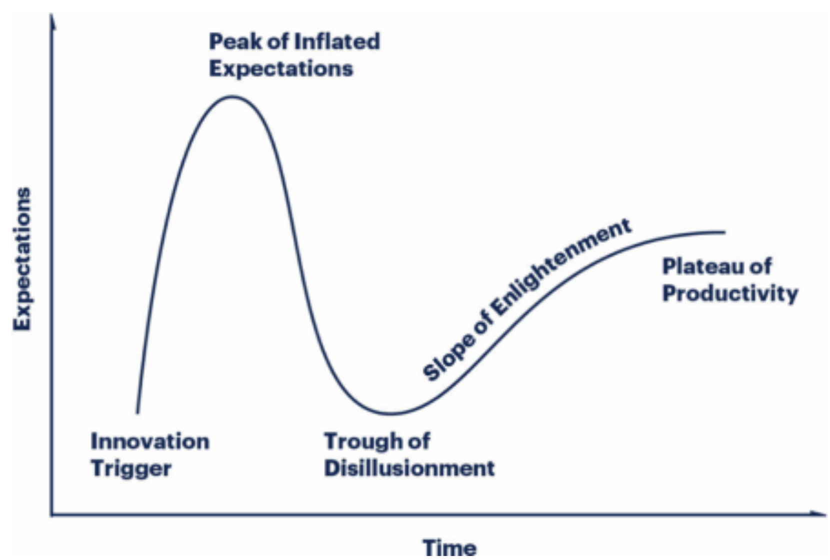

Figure 3: Gartner Hype Cycle expressing inflated expectations followed by disillusionment and the slow learning experience, eventually leading to productivity (Source: Gartner)

The reason is that if a company wishes to have competitive advantage, it must get quantum ready now. As an HBR article argued, IT was eventually like a utility in the long run: having it did not confer competitive advantage, but not having it could be a significant disadvantage.[17] (Figure 4). But that is, in the long run---in the short run, you get competitive advantage if you are ahead of competitors – or face competitive disadvantage if you are behind them (Figure 4).

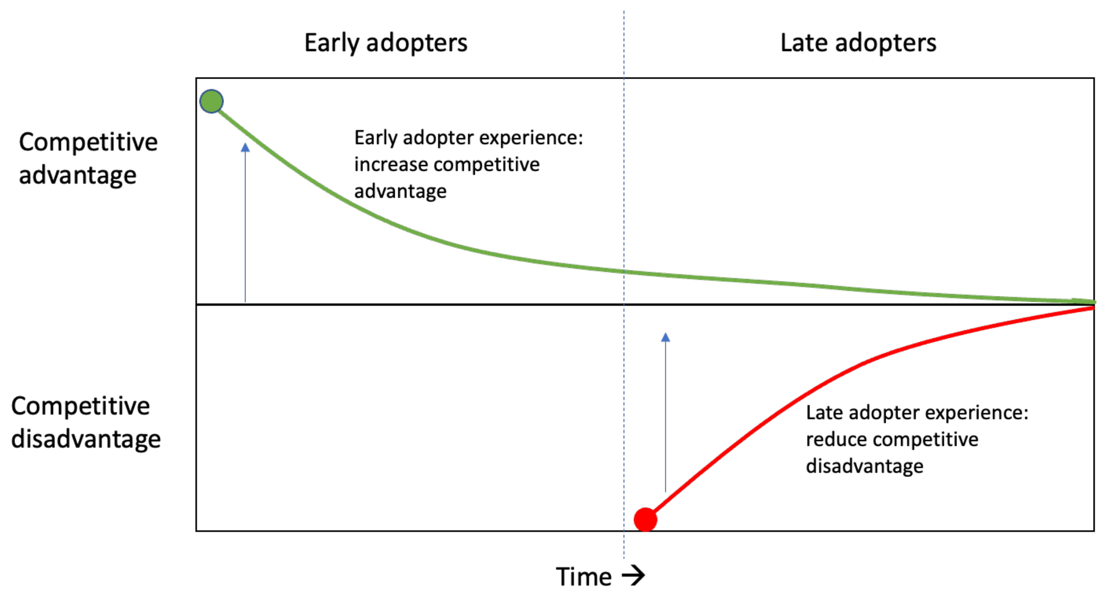

Figure 4: A company may adopt technology early for "greed" to gain a competitive advantage or wait after others have adopted it when competition forces it to adopt the technology for "fear" of being at a competitive disadvantage.

Quantum-inspired computing is already available on digital computers. It is the basis for the low-risk approach we have offered in this article for companies to become quantum-ready now. You may get better and faster solutions today, and when quantum computing becomes widely accessible, you can reuse these algorithms and applications and be ahead of the competition.

Quantum-inspired computing has limitations relative to quantum computing

Of course, the reader may ask why to bother switching to (true) quantum computing if quantum-inspired computing is good enough, especially with the continually increasing speed of chips and thus digital computers? The reason is that quantum-inspired computing has limitations relative to quantum computing. At this time, quantum-inspired computing can tackle a limited set of complex problems, specifically those that naturally can be mapped to Quadratic Unconstrained Binary Optimization (QUBO). Such problems do not require adding too many new variables or approximate continuous variables with discretization, such as Binary Classification in machine learning. Thus, such computing is not suitable for many situations, especially in studying quantum chemistry and materials. It may not be helpful even when unusual patterns exist in data, say, for machine learning. These patterns would exceed the abilities of digital computers even when these are specially architected---and digital computers cannot be specially architected differently for every such problem. Therefore, it makes sense to wait for the real thing, i.e., quantum computers.[18]

A couple of notes of caution are in order, along with a reassurance that digital computers are not going to be replaced by quantum ones. The fastest-growing costs and energy consumption stem from computing---whether from server farms, the notorious bitcoin mining, or the time-consuming financial calculations and simulations. While quantum computing promises speedup, it remains to be seen what the cost and energy consumption will be, depending on the architectures that will become practical. Even when practical quantum computers become widely accessible, digital computers will likely shoulder the vast burden of computational tasks for several decades.

Quantum computing is only one of many quantum technologies

Overall, quantum computing is only one of many quantum technologies, and it is easy to mix these up. Besides computing, these include sensors and communications. Cryptography has been in the news as being vulnerable to quantum computers. Although breaking encryption is theoretically possible, managers need not worry about the government or non-government actors hacking into their computers at the current stage of quantum computing development.

Instead, managers can and should invest in quantum computing today. We have outlined three steps for how they could do so using quantum-inspired computing that is already available.

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Endnotes

[1] ENIAC, or the Electronic Numerical Integrator and Computer, was the first programmable, general-purpose digital computer made in 1945 that remained in operation until 1956. It had a speed of about 1,000 times that of electro-mechanical machines and 2,400 times faster than a human. Towards the end of its operational use, the ENIAC contained 18,000 vacuum tubes, 7,200 crystal diodes, 1,500 relays, 70,000 resistors, 10,000 capacitors, and approximately 5,000,000 hand-soldered joints. It weighed 27 tons, occupied 1,800 sq feet, and consumed 150 kW of electricity.

[2] Feynman, R.P. Simulating physics with computers. Int J Theor Phys 21, 467–488 (1982). https://doi.org/10.1007/BF02650179

[3] Turing, A.M., 1936. On computable numbers, with an application to the Entscheidungsproblem. J. of Math, 58: 231-265.

[4] Shannon, C.E., 1948. A mathematical theory of communication. The Bell System Technical Journal, 27(3): 379-423. Doi:10.1002/j.1538-7305.1948.tb01338.x

[5] Ghose, S. 2020. Are you ready for the quantum computing revolution? HBR. Sep 17, 2020. Accessed https://hbr.org/2020/09/are-you-ready-for-the-quantum-computing-revolution?autocomplete=true

[6] Ruane, J., McAfee, A., and Oliver, W.D., 2022. Quantum computing for business leaders. HBR. Jan-Feb issue.

[7] Bova, F., Goldfarb, A., and Melko, R. 2021. Quantum Computing Is Coming. What Can It Do? Jul. 16, 2021. Accessed https://hbr.org/2021/07/quantum-computing-is-coming-what-can-it-do?autocomplete=true

[8] Biondi, M. et al. 2021. Quantum computing use cases are getting real—what you need to know. McKinsey Digital. Accessed https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/quantum-computing-use-cases-are-getting-real-what-you-need-to-know?cid=other-eml-alt-mip-mck&hdpid=fabd4b4b-d2ed-4376-8bb8-37c3ac7b7607&hctky=1151117&hlkid=a7a83128cf484597b611c01720d2d79e.

[9] Benioff, P. 1980. The computer as a physical system: A microscopic quantum mechanical Hamiltonian model of computers as represented by Turing machines. Journal of Statistical Physics, 22(5):563– 591.

[10] Manin, Y.I. 1980. Vychislimoe i nevychislimoe (Computable and Noncomputable), Moscow.

[11] Feynman, R.P. Simulating physics with computers. Int J Theor Phys 21, 467–488 (1982). https://doi.org/10.1007/BF02650179

[12] Quantum algorithms may provide polynomial rather than exponential speedup, but this may be adequate for many practical-sized problems. See Aaronson, S. 2005. Guest column: NP-complete problems and physical reality. ACM SIGACT News 36(1):30–52. Accessed at https://doi.org/10.1145/1052796.1052804

[13] Ruane, J., McAfee, A., and Oliver, W.D., 2022. Quantum computing for business leaders. HBR. Jan-Feb issue.

[14] Bova, F., Goldfarb, A., and Melko, R. 2021. Commercial applications of quantum computing. EPJ Quantum Technol. 8, 2. https://doi.org/10.1140/epjqt/s40507-021-00091-1

[15] Bernal, D.E., Ajagekar, A., Harwood, S.M., Stober, S.T., Trenev, D., You, F. 2022. *Perspectives of Quantum Computing for Chemical Engineering*. Accessed at https://doi.org/10.1002/aic.17651

[16] Sodhi, M.S., Seyedghorban, Z., Hossein, T., and Simson, D. 2022. Why emerging supply chain technologies initially disappoint: Blockchain, IoT, and AI. *Production and Operations Management*. Accessed at https://doi.org/10.1111/poms.13694.

[17] Carr, N. 2003. IT doesn't matter. *Harvard Business Review*. Accessed at https://hbr.org/2003/05/it-doesnt-matter.

[18] Bernal, D.E., Ajagekar, A., Harwood, S.M., Stober, S.T., Trenev, D., You, F. 2022. *Perspectives of Quantum Computing for Chemical Engineering*. Accessed at https://doi.org/10.1002/aic.17651