The emerging commercial landscape of quantum computing

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Quantum computing technologies are advancing, and the class of addressable problems is expanding. Together with the emergence of new ventures and government-sponsored partnerships, these trends will help to lower the barrier for adoption of new technology and provide stability in an uncertain market. Until then, quantum computing presents an exciting testbed for different strategies in an emerging market.

Despite scientific advances and a wave of investment, the emerging quantum computing (QC) commercial market still faces a high level of both technological and market uncertainty. The opportunity present in this technological uncertainty has led to a rapid growth in the number of active QC ventures, and as research intensity increases to address outstanding technical challenges, various business strategies have also emerged to tackle the market uncertainty. We examine the recent growth in the commercial QC market through the lens of dominant product design, and we contrast emerging strategies for developing the QC market.

Market evolution
The emergence of a new market is often rife with uncertainty, and predictors of how such markets will evolve have been heavily studied. The dominant design model of market evolution holds that the number of firms active in a sector provides a strong indicator of where market sits in its life cycle. The number of firms increases as ventures are drawn to the opportunity present in the technological uncertainty. Once a dominant design emerges, however, the number of firms shrinks through a process of consolidation and exit.

From the number of incumbent firms and private start-ups active in the field, we see that over the past two decades incumbent firms have been laying the foundations for commercializing QC with the number of start-up ventures lagging behind. However, the number of start-up companies began increasing in 2011 when D-Wave Systems sold its first quantum annealing system. By 2015 — 1 year before IBM’s release of the first commercial cloud quantum computer — the number of start-ups surpassed the number of incumbents active in the field, and that number has been growing rapidly ever since.

The trend in Fig. 1a suggests that the wealth of resources of incumbent firms provided the extra stability necessary to endure the years of basic research that demonstrated that commercial QC could be viable. As soon as that was demonstrated, however, private ventures began to flood the sector with new technologies and ambitions. This is an interesting demonstration of the idea that new ventures are more likely to pursue the commercialization of highly uncertain technologies. According to dominant design trends, we can expect that in the future standard practices will emerge, technical uncertainty will dissipate, and there will eventually be fewer market entries and a consolidation of firms. For the time being, however, the opportunity in QC and the uncertainty behind which designs will become dominant continue to motivate new ventures to enter the industry.

An interesting variant of this trend appears in the number of firms actively involved in developing what we have termed QC software (Fig. 1b), which includes algorithms, applications, simulators and interfaces. These technologies require less capital to develop than hardware ventures, which allowed software firms to proliferate once commercial cloud QC could provide a platform on which to develop their technologies.

Patent trends
Further insight into this rapid expansion of the quantum industry can be gained by looking at the number of patent applications by different firms across the globe. Following the search methodology detailed in Supplementary Information, we plotted the number of patent applications by incumbent firms in the North American (Fig. 1c) and Asian (Fig. 1d) markets and those of several start-up firms (Fig. 1e). These plots reveal a stark contrast between Asian and American firms, where the majority of Asian incumbents have steadily grown their patent portfolios over two decades of developmental research. Apart from HP’s early entrance and subsequent exit from the market, the American incumbents emerged much later but developed more quickly after IBM’s 2016 commercial release. The Asian incumbents have not mirrored this reaction to the release of a commercial QC platform. With D-Wave Systems as the notable exception, start-up ventures across the globe have only recently emerged on the market, but are rapidly patenting technologies to stake out their competitive advantage.

Emergent strategies
Despite this boom, the total number of users on commercial platforms remains a small fraction of the expected market. As efforts to advance the technology continue, firms have simultaneously expanded their push to validate their technologies and grow the QC market. As with other breakthrough technologies, governments have also played a significant role in funding the basic and applied research enabling the emergent industry. Governments around the world continue to make significant investments in the technological developments behind quantum hardware and software advances. Innovation policy can also support the development of emergent business strategies. For example, the National Science Foundation (NSF) recently announced a coordinated programme with cloud QC providers IBM, Amazon Web Services and Microsoft Azure. Under this
programme, the NSF will provide additional funding for graduate students, and these providers will offer those students free access to their quantum cloud. Within this triumvirate of North American quantum companies, we have observed the emergence of two markedly different strategies for managing the QC value chain: the full-stack approach and structural open innovation.

**Full-stack approach**
IBM joins the NSF agreement with the richest pedigree in QC. From their early entry into the field with one of the first experimental executions of a quantum algorithm in 1998 to their current fleet of 28 quantum computers hooked up to the cloud, IBM has been a dominant presence in the community since the beginning. This has allowed them to pursue a ‘full-stack’ business strategy, wherein they produce the entire QC value chain. This value chain consists of the quantum hardware that executes the desired algorithms, classical hardware for controlling the quantum processor and connecting the processor to the cloud, software tools for interfacing with a user with the cloud system, and a portfolio of applications and knowledge that a user can access.

IBM’s strategy aims to fulfill each of these steps while also providing advanced classical simulators for algorithm development on simulated quantum computers. This approach has materialized into their IBM Q Network, a tiered community of companies and research institutions attempting to build the QC community through collaborative R&D and user open innovation. This network aims to support, train and educate users of IBM’s cloud quantum computers while cooperatively developing practical applications for these new tools. Members of the network run the gamut from national laboratories and universities to Fortune 500 companies and QC software start-ups. The IBM Q Network does not contain any QC hardware start-ups or any direct competitors to IBM’s qubit technology. In fact, only one member of the community — advanced materials company Archer Materials Limited — is actively developing competing QC hardware, and Archer’s hardware pursuit is a room temperature hardware approach that does not compete directly with IBM’s qubit technology.

**Structural open innovation**
In contrast to IBM’s full-stack approach, Microsoft and Amazon have opted to pursue structural open innovation. They have launched partnerships to integrate hardware and software quantum start-ups into a packaged value chain that they will deliver to users through their established cloud platforms. Amazon has partnered with hardware start-ups IonQ, Rigetti Computing and D-Wave Systems, each representing a different qubit technology. Similarly, Microsoft has partnered with IonQ and Honeywell, which are both using trapped ions qubits, and Quantum Circuits, Inc., which is developing superconducting qubits. These partnerships supplement the global research network that Microsoft has built to pursue topological QC and their venture investment into the QC start-up PsiQuantum. Amazon has similarly signalled interest in launching their own internal hardware development programme through a recent partnership with Caltech. By integrating both internal and external efforts, Microsoft and Amazon have been able to diversify their investment in different qubit architectures, which could prove beneficial if superconducting qubits hit a barrier that prevents further scaling up. This strategy of structural open innovation has simultaneously allowed them to jump-start their QC offering and leverage their existing cloud computing base to begin a process of user open innovation.

Amazon and Microsoft’s structural open innovation creates a symbiotic approach to market entrance that simultaneously grants start-up companies such as Rigetti and IonQ access to the customers and reputation of well-established firms. With the development of so-called Noisy Intermediate-Scale
Quantum (NISQ) machines, QC is evolving from a challenge in search of a solution to a solution in search of users, and market entrance will become an increasingly important hurdle for start-ups to overcome. Incumbent partnerships such as those Microsoft and Amazon have created could offer a ready-made solution to this challenge.

Outlook
The recent wave of entries into the QC market is not without historical precedent. When the classical supercomputing market was searching for an alternative to the traditional von Neumann architecture, a similar upswell in firms developing massively parallel computers arose. Once a dominant massively parallel computer design emerged, however, the number of firms declined sharply through a process of consolidation and exit. The current QC upswell has been driven by over 100 start-up companies entering the sector. As was previously seen in the emerging nanobiotechnology industry, the diverse range of approaches undertaken by these start-ups precedes the market selection of a dominant design.

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Competing interests
S.-S. and E.-R.M. are employees of the quantum computing start-up company Photonic Inc.

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