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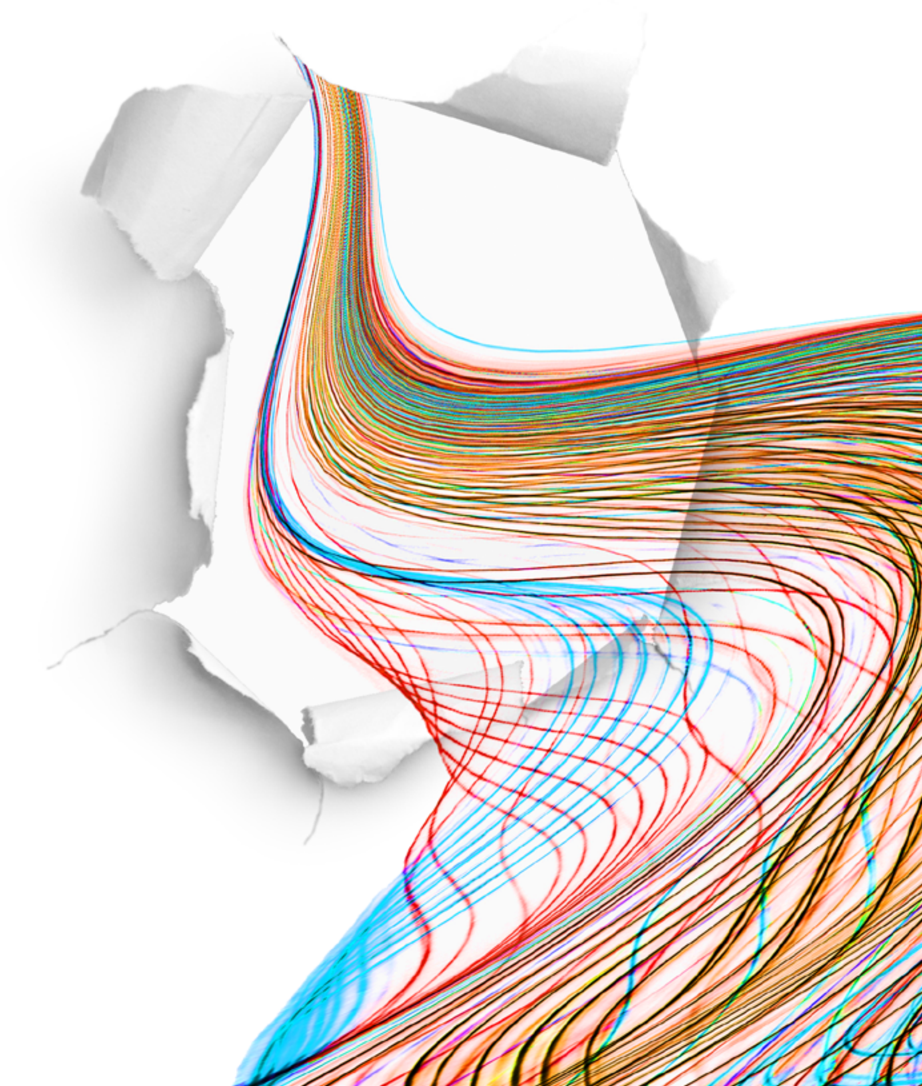
THINK BEYOND ONES AND ZEROS

QUANTUM COMPUTING. NOW.



Accenture Labs

EXECUTIVE SUMMARY

Recent developments have propelled quantum computing from a theoretical concept into a tangible computing option for enterprises—one with the potential to deliver business value by solving difficult subsets of problems in entirely new ways. Although the marketplace is growing and Accenture estimates **$1 billion was invested through public and private initiatives in 2016,** consistent enterprise use of quantum hardware is still two to five years out. However, businesses can start innovating now by accessing existing commercial quantum computing capabilities through newly available quantum hardware platforms and software applications.

Accenture Labs is actively collaborating with industry leaders to explore the types of algorithms for which quantum computing is best suited—optimization, sampling and machine learning—across multiple industries. Enterprises that begin their quantum computing journey now will be best positioned when the emerging technology reaches maturity.

This report examines the science behind quantum computing; recent hardware and software advancements; and potential use cases by problem type and industry, such as portfolio risk optimization in Financial Services or protein folding in Healthcare. It also recommends steps to prepare for the arrival of mainstream quantum computing by conducting business experiments using quantum computation through APIs.

A LOOK INSIDE QUANTUM COMPUTING

Quantum computing, which harnesses quantum mechanical phenomena to greatly enhance the way in which information is stored and processed, lending itself to performing more efficient algorithms than possible in classical computing, has been an area of ongoing research for more than 30 years. Although physicists and mathematicians were able to theorize three decades ago how a quantum computer could work, scientists and engineers had difficulty building one. In the last five years, we have seen the hardware and software capability move out of university labs and into tangible business products; however, the technology still needs to mature in order for it to become fully enterprise-ready and deliver meaningful, cost-effective business results.

One of the best ways to begin to understand quantum computing is to compare it to classical computing. Although it is not a new model of computation (i.e., it is equivalent to Turing machines or the lambda calculus), the hardware for the two methods operates in very different ways. (See "Quantum 101" sidebar to learn more.) In a classical computer, the basic unit of information is a bit, which can have only one of two values—0 or 1. In a quantum computer, the basic unit of information is known as a quantum bit or "qubit." Through quantum mechanical phenomena, these qubits can perform many computations simultaneously, which theoretically allows the quantum computer to solve a difficult subset of problems much faster than a classical computer.

Given this prospect, there are many hyped statements being made about the capabilities of quantum computing to do tasks such as breaking modern encryption methods in seconds and solving intractable problems in minutes. While in theory this is possible, the reality today is that quantum computers have yet to achieve these types of results.[1]

As such, it is unlikely classical computing will be replaced any time soon by quantum computing. The more likely future scenario is that quantum computing will augment subroutines of classical algorithms that can be efficiently run on quantum computers, such as sampling, to tackle specific business problems. For instance, a company seeking to find the ideal route for retail deliveries could split the problem into two parts and leverage each computer for its strengths. Theoretically, the quantum computer could be used to identify high efficient routes, which is the most computationally expensive portion, and then a high-performance classical computer could be used to pick the most optimal of the efficient routes.

Quantum computing cost per unit of performance is also still a factor, although this will change as quantum computers improve and become easier to access. Currently, due to the abundance of classical computing in the cloud and scarcity of quantum computers, it is estimated to be between 1,000 and 10,000 times more expensive per query to use quantum computers over their classical alternatives, thus making quantum impractical for bulk commodity workloads. However, problems that cannot be solved on classical computers but can potentially be solved on quantum computers are likely worth the expense in the near term.

> **The more likely future scenario is that quantum computing will augment subroutines of classical algorithms that can be efficiently run on quantum computers, such as sampling, to tackle specific business problems.**

Many people believe that quantum computing is one of several technologies that will enable the “fifth generation” of computers.

present
and beyond
Quantum computers
FIFTH GENERATION

1971–present
Microprocessors
FOURTH GENERATION

1964-1971
Integrated circuits
THIRD GENERATION

1956-1964
Transistors
SECOND GENERATION

1940-1956
Vacuum tubes
FIRST GENERATION

QUANTUM **101**

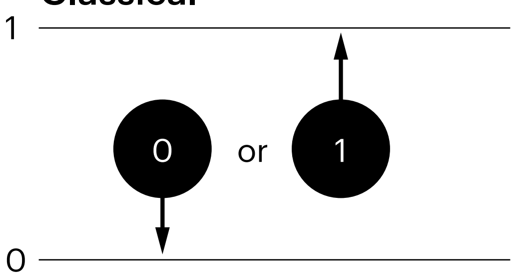
The innovation behind quantum computing is in the way it takes advantage of certain phenomena that occur at the subatomic level. To understand how it works, it helps to describe some fundamental differences between classical and quantum computing.

Information representation—In classical computing, a computer runs on bits that have a value of either 0 or 1. Quantum bits or "qubits" are similar in that for practical purposes we read them as a value of 0 or 1, but they can also hold much more complex information, or even be negative values. Before we read their value they are in an indeterminate state called superposition (see graphic below) and can be influenced by other qubits (this is called entanglement). Qubits can be realized in a variety of ways (electron spin, light polarization, super conducting circuits, etc.) but the results of quantum theory hold independently of the specific mechanism of information storage and processing.

Information processing—In a classical computer, at the fundamental level, bits are processed sequentially, which is similar to the way a person would solve a math problem by hand, one step at a time. In quantum computation, qubits are entangled together so changing the state of one qubit influences the state of others regardless of their physical distance. This allows quantum computers to intrinsically converge on the right answer to a problem very quickly. As a result, qubits working together to find the optimal solution are more efficient than certain classical approaches.

QUBIT SUPERPOSITION:

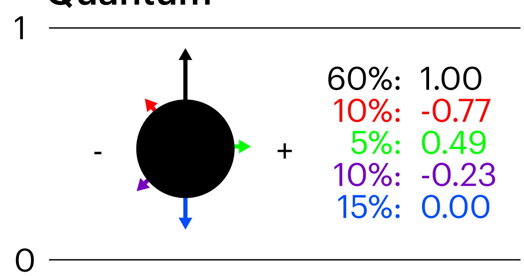
Classical



Discrete number of possible states: 0 or 1.

Deterministic: repeated computations on the same input will lead to the same output.

Quantum



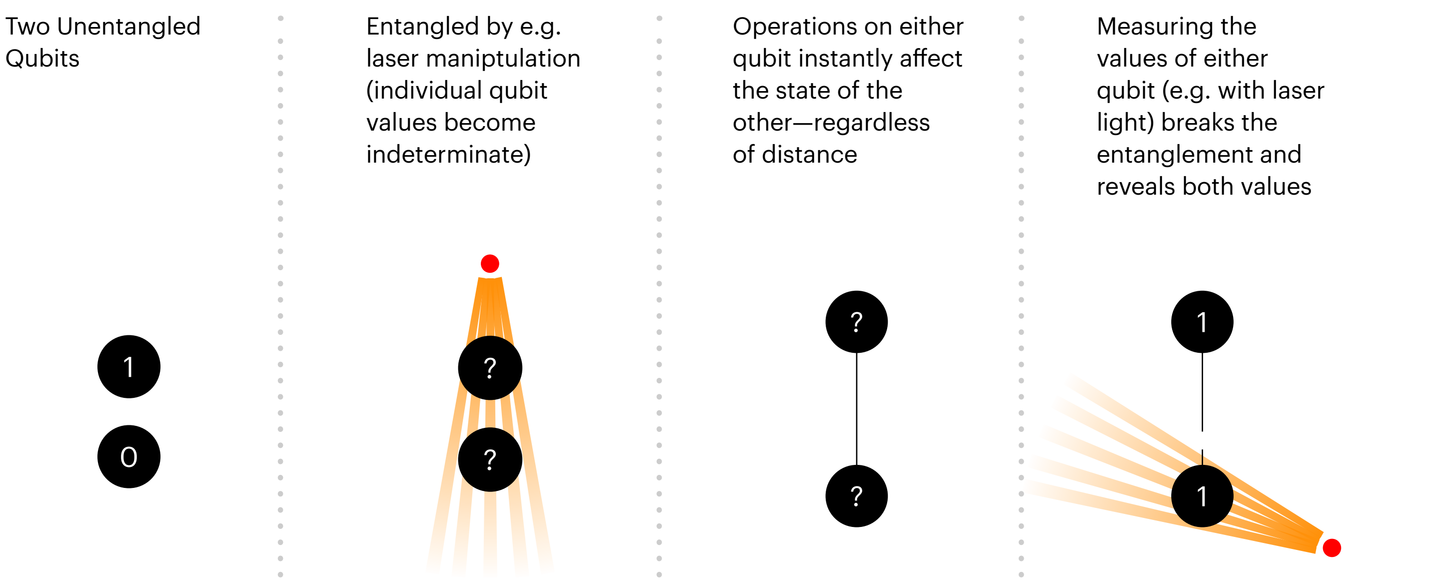
Infinite (continuous) number of possible states.

Probabilistic: measurements on superposed states yield probabilistic answers (our confidence in these answers builds up through repeated computations) then reduced to 0 or 1.

Interpreting results—In classical computing, only specifically defined results are available, inherently limited by an algorithm's design. Quantum answers (which are in quantity called amplitudes) are probabilistic, meaning that because of superposition and entanglement multiple possible answers are considered in a given computation. Problems are run multiple times, giving a sample of possible answers and increasing confidence in the best answer provided. Statistics are used to rank from 0 to 100 percent the likelihood an answer is the correct one. This confidence threshold is balanced to provide the optimal speed and accuracy.

These factors allow quantum computers to solve certain classes of complex problems much more efficiently than classical computers. While classical computers would take more and more time for each variable added (e.g., exponential time), quantum computers can harness the properties mentioned above to solve complex problems in a way that increasing the problem size causes a far smaller increase in the time required to solve the problem.

QUBIT SUPERPOSITION:



TYPES OF QUANTUM COMPUTERS

There are several approaches to building quantum computers. The most business-relevant types today are the adiabatic quantum computer and the gate model quantum computer. These two methods have been explored using various hardware implementations and both have strengths and weaknesses.

Adiabatic (aka annealer): Adiabatic quantum computers, a special case of quantum annealers, use a result known as the adiabatic theorem[2] to perform calculations. They are best suited for solving optimization problems, which are ubiquitous across industries and resources to solve by classical computing methods. There are also opportunities to apply adiabatic quantum computing methods to sampling and machine learning problems.

Gate model (aka circuit model or standard model): Technically challenging to build because they are extremely hardware specific, gate model quantum computers perform calculations by manipulating quantum states via application of gates—a basic quantum circuit operating on a number of individual qubits. These quantum gates form building blocks of quantum circuits in a manner similar to how classical logic gates form the building blocks of conventional digital circuits. When quantum computers were first proposed, gate model quantum computers were what was envisioned.

Quantum technology is still maturing and there are some hurdles left to overcome in order to build fully scalable quantum computers. As just one example, quantum systems are much more sensitive than classical computers to noise (i.e., factors that the system adjusts for on a regular basis). Noise causes a quantum system to decohere and lose its quantum properties. There is a lot of room for progress in devising quantum error correction schemes (also known as fault-tolerant quantum computing), as well as engineering advancements toward suppressing noise effects. Nonetheless, the number of qubits in today's adiabatic quantum computers is currently keeping pace with Moore's Law, and we expect the first enterprise applications leveraging adiabatic quantum computers (as well as the subsequent adoption in business) to come in the next two to five years. (See Table 1 for nearer-term opportunity areas for quantum computing by industry.)

Although the timeframe for gate model quantum computer is longer—the technology is at least five to 10 years away from capabilities that could trigger major business and societal transformation—the potential is vast. In a quantum-enabled future, quantum computing could fundamentally revolutionize the way that businesses operate and technology works. Imagine being able to design a room-temperature superconductor that transmits energy and information much more efficiently than any computing technology in existence today. And most importantly for the benefit of all humankind, quantum computing could increasingly be used to solve globally intractable challenges. Climate change, for example, could be addressed much more quickly by developing a catalyst for carbon sequestration; and world hunger could be minimized by creating a nitrogen fixation (fertilizer) solution that greatly improves agricultural methods. These prospects will be much more likely through continued quantum computing research and experimentation conducted by a collaborative of educational institutions, businesses and governments.

IDENTIFYING THE "RIGHT" PROBLEMS TO ADDRESS WITH QUANTUM

At this point in time, quantum computing is best suited to solving problems using three types of algorithms: optimization, sampling and machine learning. For the more technically inclined, these are non-linear polynomial optimization problems with discrete variables.

Optimization—The primary area of focus in quantum computing now, optimization problems are challenges where the goal is to find the best decision out of a large number of possible decisions. **Optimization problems are typically difficult yet valuable real-world problems to solve, and they exist in almost every field in which businesses operate.** Examples of optimization problems include finding the most cost-effective route for shipping goods, determining the most efficient way to extract resources from a mine, seeking the most productive resource allocation involved in a production line, looking for innovative pharmaceutical drug discovery methods, or identifying a better way to manage risk in financial portfolios.

Whereas the processing time required by a classical computer to provide high quality solutions an optimization problem can increase exponentially with the size of the problem, quantum computing will provide a much speedier answer. The implications for such a change will be dramatic as enterprises with increased optimization capabilities will be able to drive new cost savings and revenue generation opportunities using such techniques.

Sampling problems—Another function that adiabatic quantum computers can perform, sampling is the technique of drawing values from a solution space that allow generalizations about the distribution of the population. Classical computers can struggle to efficiently generate random examples of certain types of phenomenon that sampling can handle well. However, if complex quantum states (which are themselves inherently probabilistic) can be controlled, sampling from these states can be done much more efficiently.

Machine learning—Since machine learning is based on both sampling and optimization methods, the ability to improve these techniques will lead to better machine learning capability as an outcome. In particular, sampling technology in quantum computers can provide more distributed, reliable input data for the machine learning algorithms. Each iteration of the new data would help the artificial intelligence to "learn." As for the optimization capabilities of quantum computing, many machine learning techniques boil down to challenging optimization problems. For example, a company could build a probabilistic representation of a certain aspect of the world (customer behavior, for example), use the samples from an adiabatic quantum computer to get information about what the model looks like now, and then use a machine learning algorithm to determine how to improve the model over time.

Accenture Labs has mapped 150+ use cases for quantum computing with a focus on finding those that are the most promising in various industries.

TABLE 1: Opportunities for quantum computing applications by industry

INDUSTRY	SAMPLE OPPORTUNITY AREAS FOR QUANTUM COMPUTING
Financial Services	**Portfolio risk optimization and fraud detection:** Quantum computing shows promise in helping to determine attractive portfolios given thousands of assets with interconnecting dependencies. Additionally, quantum computing techniques could be used to more effectively identify key fraud indicators.
Healthcare	**Protein folding and drug discovery:** Simulated annealing is an algorithm currently used for the prediction of the effects of potential therapeutic approaches while optimizing for non-adverse effects. Quantum computing can replace some of these techniques, and may be able to show improvements at scale in the next few years such as advancing drug design to the point of providing personalized prescription drugs for individual patients.
Manufacturing	**Supply chain and purchasing:** Supply chain optimization problems come in many different forms, such as procurement, production and distribution. As quantum computing improves, it will evolve from being able to solve one-time scenarios like plan-o-grams or truck loads, to large system-wide scenarios like store floor, regional distributions and eventually global supply chains.
Resources	**Asset degradation modeling and utility system distribution optimization:** Today, real-time data for operations is checked against rules, or against machine learning models, to identify issues that might compromise availability. With quantum computing, optimization of key systems could be an ever-present probabilistic recommendation for cost savings. Additionally, optimal product lifecycle and replacement could be determined at a system-wide scale to better understand the implications, and then broken down on a part-by-part basis.
Media and Technology	**Advertising scheduling and ad revenue maximization** systems are often tailored on a per-customer basis. These systems collect hundreds of attributes about a consumer's preferences, which then need to be mapped to product affinities and represented as a graph. Ultimately, the decision on which ad to show a customer is an optimization of this graph, a task that a quantum computer is well-suited to tackle.

OPPORTUNITIES TO APPLY QUANTUM COMPUTATION IN INDUSTRY

In collaboration with 1QBit (see sidebar), Accenture Labs has mapped many possible use cases for quantum computing with a focus on finding those that are the most promising in various industries. The goal is to identify and validate the problems where a quantum algorithm will outpace existing computing methods and improve results. Enterprises that begin business experiments with quantum technology now will be better prepared for major industry changes that could come through the introduction of quantum computing.

QUANTUM HARDWARE AND SOFTWARE ADVANCEMENTS

As fundamental quantum computing research continues, a number of exciting developments are expected on the commercial side. A few leading companies are already using various techniques to make quantum hardware available for purchase and shared use; others are working to offer cloud-based quantum computing platforms and software applications to access quantum computing power.

> **Software APIs with pre-developed algorithms make it easier for enterprises to define problems to test with quantum computers, and build pilot applications that run on existing quantum computing models.**

On the **hardware** side, D-Wave is currently the sole manufacturer of commercial adiabatic quantum computers, having released three models since 2010. The company recently announced its next-generation quantum computer with 2,000 qubits.[2] There are several other groups, including Google, MIT Lincoln Laboratory and Intelligence Advanced Research Projects Activity (IARPA), working on developing these devices as well. For example, Google recently unveiled a digitized adiabatic quantum computing device that features digital error correction capabilities.[3,4] By more effectively controlling noise than previous adiabatic quantum computers, this kind of hybrid approach should allow for more rapid scaling in problem sizes. Rigetti, a quantum computer start-up, is aiming to produce a complex prototype chip by the end of 2017.[5]

In 2016, Microsoft released its quantum computing simulator, Microsoft LIQUi|>, a software architecture and suite of tools for quantum computing.[6] Simulators are one of the steps needed to move from theoretical to applied quantum testing—and ultimately to making quantum hardware. Microsoft is also exploring topological quantum computing, a specific hardware implementation of quantum computing that has inherent resistance to noise, which in turn should make it able to scale more efficiently. Finally, IBM recently made its five-qubit gate model quantum computer publicly accessible via the cloud; the endeavor is helpful for increasing public understanding of how quantum computing can be used to solve difficult problems.

In terms of **software**, the quantum ecosystem is also growing. Startup companies are emerging to bridge the gap between experimental research and enterprise. Most notably, companies such as 1QBit, QxBranch and QCWare are taking a fresh look at some of the most challenging computational problems today by applying a quantum mindset to the software solution.

For example, the various methods of building a quantum computer have pushed 1QBit to create a hardware-agnostic software platform, which can be used to build many different types of applications. As such, businesses with little to no prior quantum knowledge can begin to take advantage of quantum computing. This also allows businesses to seamlessly switch the underlying hardware powering their applications from classical computers to cloud clusters to different types of quantum devices.

The technical implementation involves using application programming interfaces (APIs) to provide web-based access to quantum computations. These software APIs with pre-developed algorithms are speeding adoption by making it easier for enterprises to define problems to test with quantum computers, experiment with the processing power and build pilot applications that run on the majority of existing quantum computing models.

EVOLUTION OF THE **QUANTUM ECOSYSTEM**

Research partnerships between high-profile companies and top universities are being formed, most notably Google and University of California Santa Barbara (UCSB); Lockheed Martin and University of Maryland; and Intel and Delft University of Technology. Google Research also has a joint initiative with NASA and Universities Space Research Association (USRA) to advance machine learning.[7] In addition, investment funds dedicated to quantum technology, such as Quantum Wave Fund and Quantum Valley Investments, are fueling startups in the field.

Governments around the world are forging ahead with quantum computing initiatives as well.

In early 2016, Australia announced an **AUD$25 million investment** over five years toward the development of a silicon quantum integrated circuit.[8]

The Canadian government committed **$76 million** in September 2016 to the University of Waterloo's Transformative Quantum Technologies program to tackle three challenges in quantum research: to develop a universal quantum processor, quantum sensors and long-distance quantum communications.[9]

The United States **released a report** in mid-2016 from the National Science and Technology Council that "recommends significant and sustained investment in quantum information science by engaging with academia, industry and government in the coming months."[10]

The European Commission announced plans to launch a **US$1.13 billion project,** scheduled to start in 2018, to support a range of quantum technologies.[11]

The Chinese Academy of Sciences is working with China's Internet giant Alibaba to build a **research facility** dedicated to quantum research.[12]

CLOSE UP ON QUANTUM SOFTWARE INNOVATOR 1QBIT

In response to predicted demand for quantum services, software companies are developing hardware-agnostic quantum platforms and applications. Accenture Labs is monitoring the quantum computing ecosystem and collaborating with leading companies such as Vancouver, Canada-based 1QBit. 1QBit is a software company dedicated to building development tools and software to solve the world's most demanding computational challenges. The company's platforms enable the development of hardware agnostic applications that are compatible with both classical and quantum processors.

The 1QBit Quantum-ReadyTM platform helps enable the development and execution of applications on classical computers in familiar environments such as C++ and Python, or through remote calls to a software as a service platform. After a user constructs a problem using 1QBit's platform, the software handles the complexities of translating the problem into a form recognizable by a quantum processor, sending the problem to the processor, retrieving the solution from the processor and reconstructing the solution in a form recognizable by a classical computer. (See Figure 1).

FIGURE 1: Enterprises can access quantum processing power through an API from 1QBit.

Part of 1QBit's intellectual property is developing mathematical algorithms, solvers and embedders that companies can use to interface with quantum computing.

Examples of these tools include:

Graph similarity—Compares two or more graphs to detect common patterns (e.g. find shared traits in molecules or find outliers in social networks).

Maximum quasi clique—Identifies a group of densely correlated actors in a set. This can be used to find group of objects that are quasi similar to each other (e.g., users with similar usage patterns or shared interests).

Minimum clique cover—Partitions a network to the minimum number of non-overlapping communities, where each entity highly interacts with other entities in the same community (e.g., detecting influential actors in a social network).

Graph coloring—Assigns the minimum number of colors to the nodes of a network such that no two adjacent nodes have the same color.

Balanced graph partitioning—Breaks problems into equal-size parts (e.g., resource distribution in parallel computing).

Linear knapsack—Determines the combination of items that holds the total greatest value given a limited space. (e.g., allocating investments in a portfolio).

1QBit has applied these and other algorithms in its quantum computing research to solve challenging industry problems.

Examples in the Financial Services industry include:

Dynamic portfolio optimization—Computing a portfolio that is optimal over multiple rebalances is difficult for a traditional computer to manage. Quantum computing can solve this problem, which could generate better portfolios that require less rebalancing and fewer associated costs. (For more information, see Solving the Optimal Trading Trajectory Problem Using a Quantum Annealer).

Clustering—Investors can use the power of quantum computing to group seemingly disparate sets of assets or investors into groups, allowing for the discovery of patterns in areas such as asset performance, consumer sentiment and risk aversion.

Portfolio analysis—Clustering via quantum computing can be used to reduce the dimension of an investment decision, for example, reducing the correlations in a pool of 1,000 assets from 500,000 down to 2,000. This helps reduce the effect of noise in the results and can improve the risk of the portfolio versus conventional methods. (For more information, see Building Diversified Portfolios that Outperform Out-of-Sample).

START INNOVATING WITH QUANTUM COMPUTING NOW

There is no doubt that the quantum revolution is coming. It is imperative for leaders to make sure that their businesses are ready for this cutting edge of technology innovation. Enterprises can start by learning more about the fast-evolving market, identifying where quantum will impact the business and preparing with quantum-ready applications. Accessing the growing set of APIs will enable businesses to more quickly deploy quantum-based optimization, sampling and machine learning pilots in a test, learn and iterate approach.

To help clients gain unique insights into how quantum computing can be applied to their enterprises, Accenture is working with clients to conduct quantum business experiments. The experiments are designed to discover viable quantum problems using a select set of pre-programmed quantum algorithms, identify if these algorithms are effective replacements for existing classical computing implementations and develop a quantum application to demonstrate the functionality.

Enterprises that move ahead with experimentation and innovation at this stage will be prepared to capitalize on the opportunities that the quantum revolution is bound to bring.

> **It is imperative for leaders to make sure that their businesses are ready for this cutting edge of technology innovation.**

SHORT-TERM PLAN

1. Begin learning about quantum computing and the tools available to harness it.
2. Identify areas of the business where today's quantum computers can make a difference.
3. Test initial use cases.
4. Create a timeline for how these use cases will scale with quantum computing advancements.

LONG-TERM PLAN

1. Create a quantum computing roadmap for the business and reevaluate throughout the year.
2. Appoint an employee(s) to monitor trends and report in monthly.
3. Build quantum-ready applications on top of a hardware agnostic interface, to allow for seamless switching between different types of quantum computers as they evolve.

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Accenture Labs is located in seven key research hubs around the world: Silicon Valley, CA; Sophia Antipolis, France; Arlington, Virginia; Beijing, China; Bangalore, India; Herzliya, Israel and Dublin, Ireland. The Labs collaborates extensively with Accenture's network of nearly 400 innovation centers, studios and centers of excellence located in 92 cities and 35 countries globally to deliver cutting-edge research, insights and solutions to clients where they operate and live. For more information, please visit www.accenture.com/labs.

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