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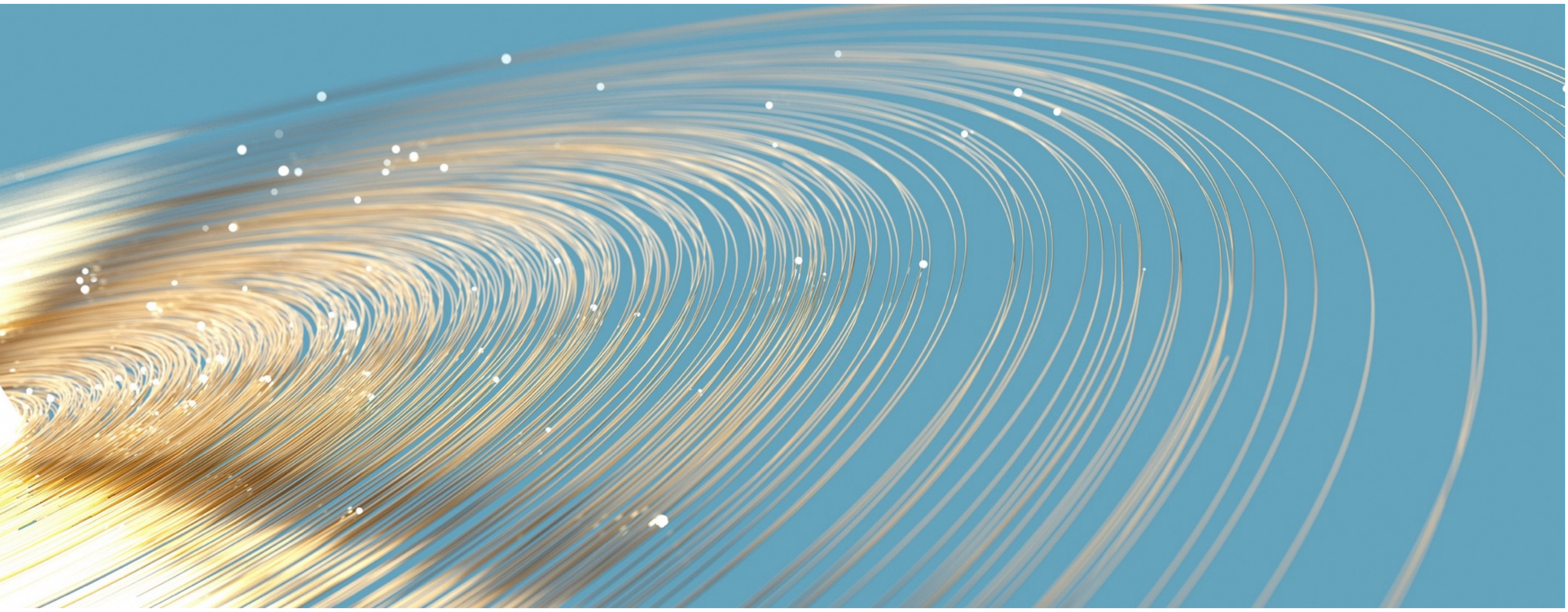

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Problem-solving Using Quantum Annealing

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Why you should care

Quantum is high on the list for anyone following "buzz" terms. It certainly raises a sci-fi feel and creates natural skepticism. However, it is real, it is here, and it is evolving rapidly. In its evolution, a critical step is the development of quantum annealing. This approach, while not new to some, will be very new to others and will redefine how we view complex problem-solving.

Specific industries will have a way to approach computational problems that have previously been unsolvable or prohibitively expensive to address with classical systems. The technology's potential lies in optimization, logistics, financial modeling, machine learning, and even complex chemistry simulations, a field that genuinely needs quantum computing innovation. For companies involved in these places, such as logistics providers, pharmaceutical companies, and energy producers, quantum annealing presents a potentially advantageous approach, providing access to solutions at speeds and scales that classical methods have trouble competing with.

What makes quantum annealing particularly relevant today is its availability: different from general-purpose quantum computing (which remains experimental mainly but soon to be practical – as I have noted in past papers, until around 2030), companies are investing in a range of approaches. As the only practical example, D-Wave has built a commercially available quantum annealer capable of solving real-world problems. For decision-makers in R&D, strategy, and technology, quantum annealing in specific use cases can solve complex problems today. Those problems tend to lean toward breakthroughs in optimization and cost efficiency across critical industries such as those already mentioned. These examples are tangible evidence that quantum-based problem-solving must be addressed today versus believing it is a long way into the future.

What you need to know

Specifically, quantum annealing is a specialized form of quantum computing designed primarily to solve optimization problems. It uses quantum mechanical effects to explore a solution space more efficiently than classical algorithms, which often have difficulty finding global optima in highly complex systems.

It is helpful to pull apart the technical process of quantum annealing and how it operates better to appreciate the challenges today and in the near future:

- **Quantum bits (qubits) and superposition:** In classical computing, bits are binary; they can exist in one of two states, either 0 or 1. However, as with all quantum computing methods, we use qubits in quantum annealing. Thanks to the principle of superposition, a qubit can exist in a state that represents both 0 and 1 simultaneously, meaning that quantum systems can explore multiple solutions at the same time. This simultaneous policy allows quantum annealers to evaluate many possibilities significantly faster than classical systems.

- **Energy states and Hamiltonian optimization:** At its foundation, the process is designed to evolve a quantum system to its lowest-energy state, representing the optimal solution. The process begins by initializing all qubits in a simple, low-energy configuration. Over time, the system evolves based on a Hamiltonian effect, a mathematical function that describes the system's total energy. The goal is for the qubits to transition toward a state that minimizes this energy use.
- **Quantum tunneling:** One of the most important features of quantum annealing is quantum tunneling. In classical systems, optimization algorithms can get stuck in local minima, suboptimal solutions in which a small change increases the problem's energy use, clearly a point of failure. Quantum tunneling allows qubits to bypass these local minima by "tunneling" through the energy barrier versus attempting to move over or around it, drastically increasing the chances of finding the global minimum or the best possible solution.
- **Adiabatic evolution:** The quantum annealing process relies on adiabatic evolution. The system starts in an easy-to-solve configuration and slowly shifts to a more complex problem representing the real-world optimization challenge. If the process is slow enough, the system remains in its lowest-energy state throughout the evolution, eventually reaching the optimal solution to the problem.
- **Quadratic Unconstrained Binary Optimization (QUBO)**: Most problems that quantum annealers solve are considered QUBO problems. In a QUBO formulation, variables are represented as binary (0 or 1), and the goal is to minimize a quadratic objective function. Problems such as route optimization, resource allocation, and machine learning model tuning can all be expressed as QUBO problems, making them strong application cases for quantum annealing.
- **Decoherence and noise**: One of the biggest challenges in quantum computing, including annealing, is *decoherence*, where qubits lose their quantum properties due to environmental interactions. Quantum annealers are designed to minimize decoherence by operating at extremely low temperatures (close to absolute zero) and in highly controlled environments. Regardless, noise and errors can affect the performance of these machines, and current research focuses heavily on improving error correction techniques. Our team is currently working on a detailed report to address this topic.
- **Hybrid systems**: In current cases, quantum annealers are often used with classical systems. The quantum annealer handles the most computationally intensive parts of the problem (e.g., optimization), while the classical system deals with data management, input/output, and preprocessing tasks. This approach ensures the best of both available approaches, high-performance quantum processing where needed most, and the robustness of classical computation for other tasks.

Examples in motion

While quantum annealing remains specialized, its adoption has potential across many industries that require the kind of problem-solving discussed. Below, we explore a few case studies to illustrate its potential and current application.

Case study 1: Volkswagen's quantum traffic management breakthrough

Volkswagen has been one of the earliest and most visible adopters of quantum annealing, leveraging D-Wave's system for optimizing urban traffic management. In 2019, during the Web Summit event, Volkswagen announced a project to use quantum annealing to optimize taxi routes in Lisbon, Portugal.

Traffic congestion can be a significant problem in cities during large-scale events. Existing classical algorithms for optimizing routes are limited by the number of variables they can manage simultaneously, often leading to suboptimal routing and longer delays than desired.

To help solve this complex problem, Volkswagen partnered with D-Wave's quantum annealer to simulate thousands of potential routes and recommend best-case paths for taxi drivers. The quantum annealer rapidly evaluated various simulations, considering real-time traffic data and predicted congestion. When taking these issues into account, the quantum system provided routes that minimized travel time while avoiding congestion, showing how quantum annealing can outperform classical optimization techniques, particularly in dynamic environments with very large datasets.

Case study 2: Unisys – enhancing supply chain optimization

Unisys is another company that has used quantum annealing to optimize supply chains. This very complex problem set involves managing inventory levels, transportation logistics, and supplier coordination. In supply chains, companies must enhance and optimize multiple variables such as cost, time, inventory levels, and route efficiency. Traditional methods are notoriously slow and computationally expensive, mainly when dealing with a large number of suppliers, products, and transportation routes.

Unisys turned to quantum annealing to solve these optimization problems. Again, using D-Wave's quantum processor (you will notice a trend here for good reason that we will discuss later), the company tackled specific use cases, such as minimizing transportation costs while maximizing the freshness of goods in food supply chains. The system evaluated many potential supply routes, inventory levels, and warehouse locations to find the most cost-effective and efficient distribution strategy.

Quantum annealing helped Unisys significantly reduce transportation costs while improving inventory turnover rates. By optimizing the entire supply chain simultaneously rather than through a series of siloed optimizations, Unisys provided its clients with a more agile and responsive supply chain capable of more effectively adapting to demand fluctuations and disruptions.

Case study 3: D-Wave's work with Recruit in financial optimization

Recruit, a Japanese financial services company, partnered with D-Wave to explore how quantum annealing could improve financial portfolio optimization. Due to the number of potential variables, classical algorithms often needed help. Recruit needed to optimize a portfolio of financial assets to maximize returns while reducing risk to the lowest acceptable levels. Classical algorithms, such as those used in traditional financial modeling, often get stuck in local minima, especially when balancing trade-offs such as risk and reward in a highly volatile market.

Using a quantum annealing approach, Recruit was able to rapidly simulate various portfolio configurations, accounting for asset correlations, market conditions, and risk tolerance fluctuations. The quantum annealer explored many more possibilities in less time than classical systems, enabling more accurate and diversified portfolio construction. Recruit reported improvements in portfolio performance and risk management. Quantum annealing allowed them to explore a wider range of asset combinations, helping them to identify portfolios that would have been computationally impossible to explore with classical systems.

Case study 4: Pharmaceutical discovery – Biogen's approach

In the pharmaceutical industry, quantum annealing has shown promise in accelerating drug discovery. Biogen, a leading biotechnology firm, has worked with quantum computing startups to simulate molecular structures, where quantum annealing excels at handling combinatorial problems.

Traditional drug discovery methods involve testing hundreds of thousands of compounds against target molecules. The complexity of molecular interactions means that classical computers cannot deliver the power to assess the exponential number of possible configurations and folding patterns of proteins and molecules. Biogen realized they could significantly accelerate the modeling of potential drug candidates by applying quantum annealing. As such, the annealer explored various molecular structures to predict how different compounds would bind to proteins associated with diseases such as Alzheimer's.

The speed and accuracy of quantum annealing allowed Biogen to narrow drug candidates more efficiently, cutting down research times and costs, clearly illustrating the potential to significantly accelerate the drug discovery pipeline timeline and efficacy.

Where is the pulse heading?

As mentioned earlier, D-Wave dominates this space and remains the only viable commercial-grade provider of quantum annealing systems. However, several alternate approaches from other highly reputable companies are worthy of mention. It is, however, important to point out that D-Wave's approach is based on proper quantum annealing versus a more widely used gate-model quantum computing approach, which has been popularized by the likes of IBM, Microsoft, and Google, which have decided to focus more on approaches to universal quantum computing. Notably, Fujitsu offers a digital annealer, but it is not a quantum-based approach, but "quantum-inspired" that uses a classical system design. It does more directly compete with D-Wave for optimization challenges.

Critical developments are taking place in three areas within most approaches: scalability, hybridization with classical systems, and broader industry adoption, which are shaping the future of quantum annealing.

- **Increased scalability and error reduction:** The next generation of quantum annealers will feature larger qubit counts and better coherence times. Current systems developed by D-Wave operate with limited qubits, but ongoing research focuses on creating more stable and error-resistant qubits. Improved quantum error correction techniques and innovations such as topologically protected qubits will allow quantum annealing systems to scale while meeting the required precision. These techniques and innovations will solve even more complex optimization problems, such as large-scale logistics, supply chain networks, and financial portfolio assessments.
- **Hybrid quantum-classical systems:** Quantum annealing systems will increasingly operate alongside classical systems to form hybrid quantum-classical frameworks. This trend is already evident, with quantum systems handling the most computationally intensive aspects of optimization while classical systems perform the necessary preprocessing and data handling. Hybridization allows enterprises to leverage quantum power for specific tasks without replacing their classical infrastructures, making the adoption more practical and cost effective. This approach is ideal for complex logistics, financial modeling, or resource planning industries.
- **Industry-specific applications and partnerships:** Expect to see accelerated development of industry-specific applications for quantum annealing, particularly in fields such as pharmaceuticals, energy, manufacturing, and supply chain management. Industries that depend on solving large-scale, combinatorial optimization problems will increasingly rely on quantum annealers for breakthroughs in efficiency and cost reduction. Partnerships between quantum computing companies and enterprises will likely increase, extending the technology's reach. For instance, D-Wave has already partnered with Volkswagen and Recruit, and future collaborations with firms in healthcare, energy, and aerospace will likely follow.

- **Increased investment and public-private collaboration:** As technology matures, public and private sector investments will drive quantum annealing forward. Countries such as the US, Canada, China, and members of the European Union are providing substantial funding through quantum initiatives. Private enterprises, venture capital, and tech giants such as Google and IBM are expected to continue pouring resources into quantum annealing research and commercial applications. This infusion of capital and interest will further accelerate innovation in both hardware and software.
- **Broader adoption beyond early adopters:** Quantum annealing is used predominantly by large enterprises with significant R&D budgets. However, as costs gradually decline and more user-friendly quantum systems become available, smaller enterprises and a more comprehensive range of industries will adopt quantum annealing solutions. As cloud-based access to quantum computing (via platforms like Amazon Braket and IBM's Quantum Experience) expands, even companies without the resources to purchase dedicated quantum machines can access quantum annealing capabilities.
- **New frontiers in security and cryptography:** Beyond optimization, quantum annealing will play a critical role in cryptography and cybersecurity. Quantum annealing has the potential to revolutionize encryption methods by solving problems that underpin the security of current cryptographic algorithms. Governments and enterprises concerned with next-generation cyber threats are already looking at quantum-resistant algorithms and encryption solutions that exploit quantum capabilities. This shift toward quantum-safe cryptography will become crucial as quantum computers advance and pose risks to traditional encryption methods.

Final word

Quantum annealing is emerging as a significant, near-term tool that provides specialized quantum capabilities, particularly for solving complex optimization problems. As discussed, unlike general-purpose quantum computers, which are still years away from widespread commercial viability, quantum annealers are already solving real-world challenges in logistics, finance, supply chain optimization, and drug discovery. Industries that rely heavily on optimization are positioned to benefit from this technology as it matures.

The value proposition for enterprises is clear: quantum annealing offers a path to speed up problem-solving processes previously constrained by classical systems, allowing businesses to become more agile and competitive. However, to fully embrace the potential, decision-makers, especially R&D leaders and CTOs, need to understand its current limitations, such as the types of problems it can solve (mostly optimization and combinatorial) and the need for hybrid systems that integrate both quantum and classical computing.

In the coming years, we will see advances in qubit stability and the expansion of quantum annealing's applicability as more industries invest in R&D and develop new use cases. Companies that move early to adopt quantum annealing, particularly in partnership with hardware vendors such as D-Wave, will have a significant competitive edge in solving optimization problems faster, more efficiently, and at a grander scale.

It is doubtful that quantum annealing will replace classical computing given that it is a step change to generalized quantum computing. Instead, it provides a substantial jump forward for those coping with complex optimization challenges, offering opportunities to address previously computationally challenging problems. Organizations that can find clear use cases and can afford to integrate this technology into their operations will be better prepared for the quantum future coming from this early-stage innovation, gaining early access to capabilities that will define the future of computational problem-solving.

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