CHEMISTRY'S QUANTUM AGE IS NEARLY HERE. WHAT'S ON THE HORIZON?

When new technologies emerge, chemistry evolves and grows along with those technologies. In the 1950s, computational chemistry emerged amid the rise of electronic computers. Supercomputers later allowed scientists to simulate individual atoms and molecules with unprecedented precision. Today, many believe that quantum computers have the potential to usher in a new generation of computational chemistry.

Quantum computers have long been anticipated, and while the field still has a long way to go, researchers have made significant practical advances in the last several years. Quantum algorithms and hardware have become more reliable, and engineers are developing quantum bits (qubits) and architectures that tap into more quantum computational power. In 2024, Microsoft and Atom Computing announced a machine with 28 error-correcting "logical qubits"—the largest number on record at the time.

Such milestones are quickly ushering in a time when quantum computers can solve problems more efficiently and effectively than classical computers. "We're interested in a practical, real-world advantage" from quantum computing, says Nathan Baker, who leads the applications engineering team at Microsoft.

Quantum mechanical simulation of chemical systems is one of the most promising avenues for achieving this advantage. Simulating a chemical system represents a complex problem with interconnected variables but one that also relies on a relatively small dataset—a type of problem that is ideal for quantum computers.[1] Improving chemical simulations with quantum computing has practical outcomes.

"Think about the challenges facing the planet; most of those challenges have solutions that are rooted in chemistry and material science," says Karol

Kowalski, a computational chemist with Pacific Northwest National Laboratory (PNNL).

To achieve practical advantages from quantum computing in chemistry, researchers specializing in different aspects of research, including hardware, software, and applications, must work together to overcome existing obstacles. These groups also need to agree on destinations for the field to benchmark success[2] and to answer questions such as the following:

- What types of chemistry problems would benefit most from quantum advantage?
- Where do quantum algorithms still fall short compared to classical ones? How can having dozens of "logical qubits" enable new applications?
- How can researchers across the quantum computing landscape collaboratively design practical quantum computing systems?

In April 2025, Microsoft and PNNL cohosted a two-day workshop for scientists to discuss how quantum computers can benefit research in chemistry and materials science. They gathered to identify the key challenges and opportunities the field will face in the coming years and to foster collaboration among diverse experts to drive the field forward. Experts from multiple disciplines and countries working in academia, industry, and government institutions attended. "We're fortunate to be joined by some world leaders, not just in the fields of quantum computing and quantum chemistry but also in artificial intelligence, computational mathematics, and high-performance computing," says Steven Ashby, director of PNNL.

BITS, QUBITS, AND LOGICAL QUBITS

Quantum computers are fundamentally different from classical computers. By using quantum mechanical principles such as superposition and entanglement, quantum computers can significantly reduce the time it takes to work through complex, multidimensional problems.

Modeling important chemical systems—like nitrogen fixation in enzymes or the electronic choreography happening inside photovoltaic cells—requires computational models that account for the quantum mechanics governing these systems. But certain problems in quantum mechanics, such as calculating the energy states of atoms and molecules, rely on math that quickly scales to intractable dimensions. Classical computers can solve small, approximate versions of these problems.[3] But as the systems expand in detail and size, the time required by classical algorithms to model and solve these problems increases *exponentially*.

In contrast, quantum computations of molecular systems scale polynomially. This distinction makes an enormous difference in complex systems: a quantum algorithm might require slightly more computational resources as atoms are added to a simulation, whereas a classical computation may require double the

By improving the computational modeling of chemical systems, quantum computing has the potential to help solve long-standing global challenges rooted in chemistry, including sustainable manufacturing and energy storage.

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resources for each atom added.[4] Quantum computing, therefore, is poised to provide a real advantage over classical computing by reducing the time required to solve complex problems in chemistry.

But quantum computers face practical limits that have prevented them from outcompeting classical computers.

The fundamental unit of a quantum computer is a qubit. Qubits are analogous to "bits" in classical computers that flip between two states, 0 and 1, to encode information. But qubits can exist in two states *simultaneously* due to quantum superposition. Quantum computers also benefit from quantum entanglement—a situation where otherwise independent qubits affect their entangled partners' states.

Classical machines can pack more and more bits into their hardware to improve computing speed. So far, quantum machines have been restricted by small numbers of qubits. Additionally, most types of qubits are extremely vulnerable to environmental interference and errors, resulting in flipped bits and decoherence. This fragility makes it extremely difficult to measure a quantum computer's answers and to achieve reliable results.

Logical qubits—networks of tens to thousands of physical qubits that work together to detect and correct errors—are overcoming those limits. These "fault-tolerant" computational units are crucial for creating practical and reliable quantum computers.

THE FUTURE IS HERE

Last year, a team from Microsoft and Quantinuum demonstrated logical qubits that outperform physical qubits, reducing error rates by a factor of 800. A few months later, the team connected 12 of these logical qubits to carry out

a first-of-its-kind chemistry computation. "Logical qubits are here," says Baker. "We don't have a thousand of them yet. But we have a path to get there."

A machine with hundreds of error-correcting qubits is fast approaching: Microsoft and Atom Computing plan to launch a quantum computer with 50 logical qubits by the end of 2025. Quantum computers will likely need hundreds or thousands of logical qubits to simulate complex chemical reactions and systems, such as the active sites of important enzymes like nitrogenase.[5] But given the rapid advancements in the field, those attending the workshop believe that now is the time to imagine, design, and benchmark use cases for quantum computing in chemistry and materials science in preparation for those future machines.

"Time is ticking," says Kowalski, who participated in the April 2025 workshop. "We can't afford to delay too long—we need to move from discussions about quantum to taking action."

Microsoft and PNNL convened their recent workshop to reach a collective understanding of the road ahead for quantum chemistry and to answer the question: With 25 or 50 logical-qubit machines on the near horizon, what applications can the field begin developing for the 100-plus logical-qubit machines that will soon follow?

Use Case #1: Strong electronic correlations

Traditional computational methods like basic density functional theory (DFT) struggle to simulate systems where electrons interact strongly with each other—known as highly correlated systems.[6] These systems include metal-organic frameworks (MOFs), aromatic compounds, and stacked DNA bases. Quantum computing could improve the modeling of such systems, enabling chemists to more accurately and efficiently model systems related to energy storage (such as energy transfer at metal active sites in chlorophyll) or design more efficient catalyst materials (like MOFs for methanol conversion).

In a recent study that was presented at the workshop, researchers described the development of hybrid quantum-classical algorithms to calculate electronic coupling values between two strongly correlated metal centers in a dichromium complex.[7] This new algorithm reduced the computational infrastructure required to carry out this calculation by nearly 90% compared to an earlier quantum-classical algorithm. This work shows that it's possible to significantly improve how quantum algorithms use quantum computing hardware for eventually modeling relatively complex chemical systems.

Use Case #2: Describing and understanding catalysts

Chemists want to better predict the behavior of subtly different active sites to identify catalysts that are potentially more efficient, more selective, or more stable. Improvements to industrial catalysts could reduce waste and CO_2 emissions produced during chemical transformations and cut down on the energy needed to carry out these transformations.

For example, a catalyst like zinc oxide (ZnO) is deceptively complex: it includes an oxygen-rich surface layer, a stoichiometric ZnO section, and clusters of ZnO with stepped structures. Each section has its own properties and chemical behavior. In the catalytic conversion of methane to methanol, the ZnO clusters provide the greatest selectivity for methanol and minimize the complete oxidation to carbon dioxide.[8] Selective oxidation of methane to methanol converts a potent greenhouse gas—and major component of natural gas—into a valuable liquid fuel and feedstock chemical.

Classical methods, such as the combination of DFT and machine learning, can provide qualitative descriptions of these systems as well as some guidance on how to improve materials. But quantitative comparison is still lacking. Precise energy calculations are crucial here because miniscule overestimates or underestimates will significantly distort the materials' predicted properties. Researchers at the workshop are exploring whether quantum computers with 50 to 100 logical qubits will allow better simulation of diverse active sites and, eventually, their reactive environments.

Use Case #3: Simulating benzene

Benzene—the quintessential aromatic molecule—and its derivatives are important building blocks in a range of chemical compounds, from pharmaceuticals to industrial materials like polymers. The planar and electronic structure of aromatic compounds gives them unique properties for controlling how effectively a drug candidate interacts with a target protein or for creating tunable and energy-efficient electronic devices like organic light-emitting diodes. Accurately predicting how benzene interacts with biomolecules and other compounds, as well as how modifying benzene affects its properties in various systems, is therefore of significant interest.

But benzene's electrons exhibit complex behavior. The molecule contains π electrons above and below its carbon ring. When quantum chemists try to model this behavior with classical computing methods, they encounter correlation difficulties. For example, benzene's electrons interact with each other and influence each other's movement. "You might think benzene is a simple molecule," says Kowalski. "This is far from the truth."

While DFT can make reasonable approximations of the behavior of benzene's electrons, the classical method struggles with quantum effects important for computing excited energy states and reactions. When quantum computers achieve greater accuracy, researchers may unlock more accurate predictions of how benzene (and other aromatic compounds) interact with other chemical structures and systems.

COLLABORATING ACROSS BOUNDARIES IS CRITICAL

Attaining quantum machines and quantum chemistry algorithms that outperform classical ones will require a collective effort. No one person or organization will have all the answers, which is why interdisciplinary

workshops, like the one hosted by Microsoft and PNNL, are beneficial. Nearly every discussion during the workshop highlighted the need to simultaneously pursue improvements in quantum computing applications, algorithms, and architectures that organize hardware and software. "All three points in this 'triangle' are critical," says Baker. There is a need to create algorithms for fault-tolerant, logical qubit-based quantum computers that are relevant to chemical systems. New algorithms are one solution, although workshop attendees also discussed that there are opportunities to revisit older algorithms. In the earliest days of quantum chemistry research, there may have been relevant algorithms written that were passed over due to hardware limitations of the time.

Academic and government researchers attending the conference also called on industry participants to prioritize collaborative design in quantum hardware and large-scale architectures—areas where industry currently holds the most expertise. "We have to make sure that we are cognizant of the hardware specifications, so I see a huge role for industry to provide us with enough guidance," says Kowalski. "It's the only way."

Everyone involved in solving these problems and applying quantum computing to chemistry problems needs to have a shared vision and language. Tools that make it easier for chemists and quantum computing experts to collaborate and bridge the inevitable knowledge gaps with new technologies are critical. Workshop attendees discussed tools that could help chemists with limited computational training understand how quantum computers can address their research question or help chemists distill systems into formats that a quantum architect could understand and examine.

Attendees also agreed that classical technologies such as high-performance computing and machine learning will continue to evolve in parallel with quantum computing, creating yet another opportunity for codesign across fields of expertise. "The race may never stop," says Baker. "The killer applications of quantum computing will likely be applications that join the best of all these technologies."

"It's not like the development of one of these technologies has ended, and we drew a line in the sand to say, 'Once you pass this line, you have quantum advantage,'" adds Baker. "These are all living, growing things where innovation is happening. And I think that's what makes it exciting."

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