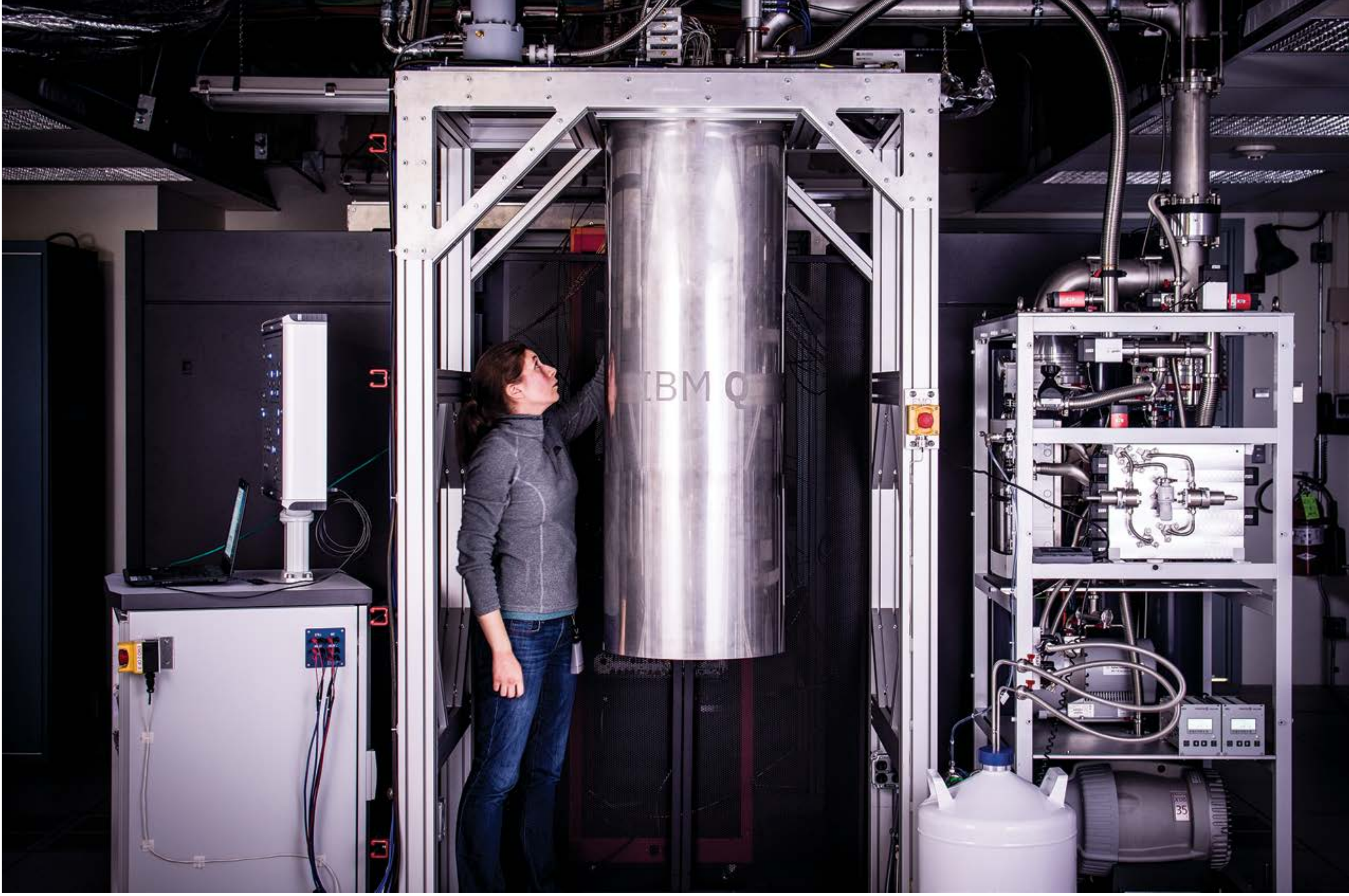


QUANTUM COMPUTING

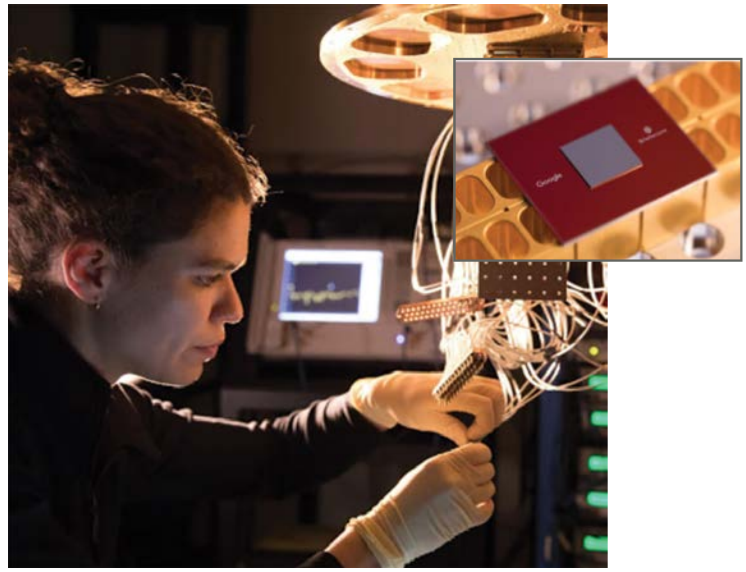
Quantum computers offer transformative power for certain types of problems. Rather than processing data like an ordinary computer with "bits" that can be either 1 or 0, quantum computers process data with devices called "qubits" that can be 1, 0, or both simultaneously—a phenomenon called superposition. That property and another called entanglement (which means that qubits are not independent of each other and in fact can influence neighboring qubits) gives quantum computers unique capabilities. Computer scientists have found numerous examples of problems, including breaking codes and searching massive data files, where a quantum computer would be dramatically faster than the computers of today. Not surprisingly, quantum computers are of intense interest to national security agencies, as well as to major corporations interested in artificial intelligence.

An IBM researcher examining a cryostat cooling cylinder that contains a prototype of a commercial quantum processor. *(IBM)*

Computing is not the only area where quantum technologies could provide useful solutions. Quantum communications could provide unhackable ways to share information, and quantum measurement devices could provide unparalleled accuracy. Nor will computing be the first practical quantum technology. A device known as a superconducting quantum interference device or SQUID, developed in 1964, can detect magnetic fields 100 billion times smaller than those generated by an ordinary refrigerator magnet. SQUIDs have been widely used in mineral exploration and for imaging the magnetic fields from human brains.

SQUIDs are based on an earlier discovery that electrons in a superconducting material can tunnel through a neighboring layer of an insulating material into a second superconductor, a quantum effect that is called a Josephson junction. Research into this phenomenon supported by DOE's Basic Energy Sciences (BES) office led in 1985 to the discovery that such devices exhibited multiple quantum levels or states—the first time such phenomena, common in atoms, had been observed in much larger, man-made devices. BES-supported research in this and related areas continued for several decades. That research now underlies several of the most promising routes to quantum computing—all of which involve materials that display quantum effects and are candidates for constructing qubits.

The apparent front-runners for commercially-viable qubits include:



Google's newest 72 qubit superconducting quantum processor, the Bristlecone chip (inset), being installed at the Quantum AI Lab in Santa Barbara for testing of both the technology and applications in quantum simulation and machine learning, and to facilitate algorithm development. *(Google)*

- **Superconducting loops.** These consist of a resistance-free current oscillating back and forth around a circuit loop that has three Josephson junctions (a SQUID current loop has two junctions). The devices must be kept cooled to within a few degrees of absolute zero. Both Google and IBM are pursuing this approach.
- **Topological materials.** These depend on quantum effects observed in electrons in novel semiconductor structures, which draw substantially on earlier BES research. Microsoft and Bell Laboratories are pursuing this approach.
- **Silicon Quantum Dots.** These add a single electron to a tiny semiconductor crystal (a quantum dot). BES nanoscale shared research facilities played a key role in the emergence of the underlying quantum dot technology. Intel is pursuing this approach.

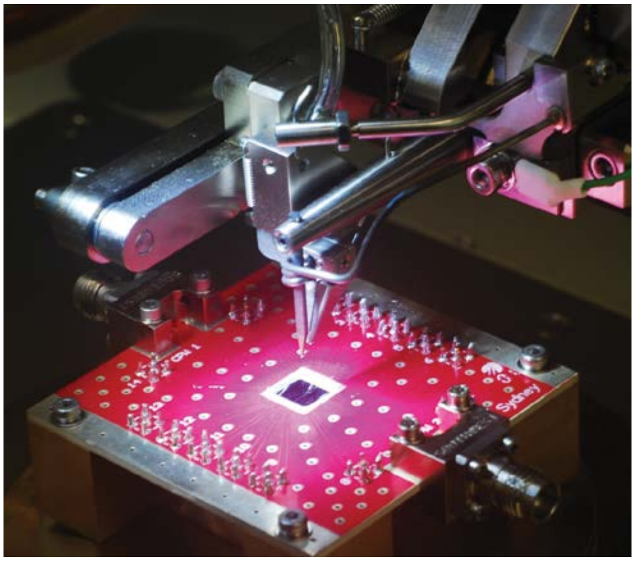
Box

WHAT MAKES QUANTUM COMPUTING SO POTENTIALLY POWERFUL

Two characteristics that make quantum phenomena strange also explain quantum computing's potential: superposition and entanglement. Superposition means that a qubit can represent 0 or 1 or both simultaneously. Moreover, while the bits in conventional computers are completely independent of each other, qubits are not: they are entangled, and the correlations among them contain far more information than any individual qubit. Indeed, the amount of information processed and potentially available grows exponentially with the number of qubits. To get a sense of what that means, Google has described a quantum computer with 22 qubits that could potentially evaluate over a million possibilities simultaneously, and has left space in its design for expanding to 50 qubits, which would mean a capacity for a million billion simultaneous evaluations. By comparison, the most advanced Nvidia graphics card has about 20 billion transistors, and so can process at most that many operations simultaneously. Quantum computers with 100 qubits or more will have capabilities that cannot be matched by any imaginable conventional computer—opening a new era in information processing.

Quantum computers also face software challenges, in part because early quantum computers are likely to be hybrid devices, embedded within a conventional computer. That requires development of algorithms that, as the computation is performed, efficiently pass information between classical methods for the "easy" parts of a problem and quantum hardware for the parts that classical computing cannot handle.

Despite these challenges and the inherent complexity of quantum systems, the field appears to be making rapid progress. Several commercial laboratories have demonstrated prototype systems with 10–20 qubits. Academic experts believe that systems with 100 qubits may be achievable in the near future (see box). If so, then the multiple decades of research supported by BES—basic research, not directly focused on quantum computing—will have paid a big dividend.



Topological materials that create quantum effects through novel semiconductor structures such as those being worked on here offer one possible route to quantum computing. *(Microsoft)*