Top Priority Idea

Quantum Science, Engineering, and Materials

Can we harness the power of the quantum?

The science and technology associated with quantum-mechanical phenomena have emerged in the 21st century as a new frontier of fundamental knowledge about how the universe works. All aspects of "Quantum" are rapidly becoming a radically new source of practical technologies. Many of the most famously perplexing and counterintuitive aspects of quantum mechanics do not represent limitations on our ability to understand and control the world around us, but rather–surprisingly–a powerful new set of resources that can be exploited to remarkable advantage in applications at the cutting edge of many disciplines.

One of the key insights that has opened this frontier is that information plays a fundamental role in our understanding and analysis of physical systems. As a result, we have realized that physical systems can control information in a much more powerful fashion than had previously been conceivable. The quantum information perspective has given us a completely new way to teach quantum mechanics that truly ignites students' imaginations.

The scientific and technological resources emerging from these insights are not specific to subatomic particles or isolated physics experiments. Rather, they apply broadly to all physical systems and phenomena (e.g., molecules, liquids and solids; light, sound, heat, motion; electricity and magnetism) and are now being studied and exploited in ever-larger and more complex systems, relevant to a much wider range of science and engineering. This 'second quantum revolution' is resulting in transformational advances in astronomy, cosmology, physics and applied physics, chemistry, materials science, electrical engineering, biology and biomedical engineering, computation, and communication. Importantly, this progress not only enables, but is enabled by, remarkable advances in new materials and in the manipulation of atoms and materials at the atomic and nanometer scale. In order for Yale to excel in Quantum, we need to build both directly in support of quantum science and engineering and in the broader areas associated with materials – only through excellence in both will Yale be able to excel in quantum technology.

We envision three closely related and mutually supporting pillars of intellectual activity in Quantum.

1. Quantum Computation, Communication, and Data Security

Can we build the ultimate computer? Quantum information, the study of the information content of quantum systems, has futuristic potential applications in information security, data science, machine learning and computation. The creation of revolutionary quantum computers—able to carry out extremely difficult computations (e.g., detailed predictions of molecular and material properties, quantum-enhanced machine learning and database manipulations), possibly far beyond the scales that will ever be achievable with ordinary high-performance computers—is on the horizon, enabled by novel materials and nanoscale engineering.

Can we enhance privacy through the power of the quantum? Quantum information can be transmitted but, paradoxically, cannot be copied. This means that future quantum technologies could enhance information security and privacy. Preliminary examples of this technology have already been deployed in small private networks, but the development of these ideas to transform worldwide information security will take place in academic quantum science and engineering labs in the coming decades.

2. Quantum-Enabled Sensors and Measurement Techniques

Can we detect the tiniest signals from distant galaxies and from individual living cells? Devices whose operations are based on quantum principles include not just computers and communication channels, but also the potential for radically new measurement devices and sensing techniques able to focus on tiny signals and (partially) ignore noise. Such 'quantum-enabled' devices and sensors, enabled by deep understanding of materials and device engineering, are beginning to even surpass the standard limit expected from naïve application of the famous Heisenberg uncertainty principle.

These advances are enabling the development of new research tools in physics, engineering, cell biology, neuroscience, astronomy, and beyond. Examples currently under development include: nanoscale sensors of temperature and magnetic field for measuring the structure and dynamics of individual cells and potentially individual molecules; single-photon detectors to receive light from remote planets, stars and galaxies as well as weak fluorescence signals from biological tissues; sensors for gravity, both real world (detection of underground structures and mineral deposits) and fundamental (gravitational waves); 'table-top' quantum experiments to detect new particles even more massive than can be created at the world's largest colliders; and possibly to detect dark energy, the mysterious force causing the expansion of the universe to accelerate.

3. Quantum Materials

Can we design and synthesize materials that were never before possible? A room-temperature superconductor? An anti-cancer molecule? A catalyst to turn pollutants into useful products? A new material for solar cells?

Advances in materials science, and quantum science in particular, will lead to greater understanding of many-electron systems, and thus to new abilities to understand, measure, design, synthesize and predict the properties of novel solids, as well as to create completely new artificial materials that do not naturally occur. These new capabilities will advance both fundamental science and practical applications in fields such as solar energy, catalysis, magnetism and drug design. The ability to design 'picomaterials' in which atomic placement is controlled with picometer resolution fundamentally depends on understanding the quantum world, as does the ability to measure and characterize the results of picometer-level changes in structure. In turn, strong control of materials enables the design and fabrication of quantum devices and sensors.

This moment in the history of Quantum is special in that a virtuous cycle is underway, in which new ideas in each of the three pillar areas summarized above are feeding back to bring advances to the others. For example, materials scientists are embedding single-atom defects into optical materials in search of the best possible properties for quantum sensing. Development of new quantum measurement and sensing methods is intimately related to the development of devices used as quantum bits ('qubits') for computation, and the resulting computers in turn will help predict and develop better materials properties for manifold applications. This synergy will provide a path for rapid growth in the field. A second example is that ideas from quantum information theory have already improved the accuracy of atomic clocks and enabled nuclear magnetic resonance (NMR) spectroscopy on small groups of individual nuclear spins – a capability that may someday allow us to directly determine the structure of a single molecule, with revolutionary impact on biology and medicine. Other ideas about the information content of quantum states have shown us how to dramatically improve current algorithms for solving the equations of quantum mechanics on ordinary computers. This in turn is beginning to have an impact on theoretical studies of quantum materials and molecules. Finally, a local example is the use of new optical clocks that are helping Yale astronomers in their search for exoplanets orbiting distant stars.

Return to Top

Yale and the future of Quantum

We envision developing Yale's Quantum efforts into an overarching umbrella program encompassing multiple disciplines. The goal of this program will be to build on Yale's foundational strengths in one of the most important new intellectual frontiers of our lifetime, and to knit these strengths into a unified enterprise that establishes Yale as the internationally recognized center of excellence in Quantum.

Leading this dramatic blossoming represents an opportunity to do something unexpected and explicitly forward-looking that will make a serious statement for and by Yale—a statement that will enhance our ability to recruit top students and faculty and to build technologies with major impact in the world. It will also make Yale the place that is addressing the enormous governmental and corporate interest and concern in workforce development for this field.

The foundation for a world-leading program already exists at Yale and has been recognized with the formation of the Yale Quantum Institute. The University has pillars of excellence in a wide range of departments that can feed into a comprehensive program in Quantum, including in:

- *Quantum computing and quantum information*: Physics and Applied Physics have world-class theory and experimental programs in superconducting quantum circuits that already make Yale the world-leading center for the dominant technology platform in quantum information processing. The first electronic quantum computer was built at Yale, as was the first successful quantum error correction architecture on any technology platform.
- *Materials Science*: Yale has substantial and diverse strengths in materials science spanning Chemistry, all of the SEAS Departments, Applied Physics, Physics, and the West Campus Energy Sciences Institute. Connections to Brookhaven National Laboratory are also strong in support of this area.
- *Quantum-enabled detectors and sensors*: Yale has strong groups in Electrical Engineering, Physics and Applied Physics in this area and is a world-class center for opto-mechanics (the use of quantum light to control and sense quantized mechanical motion).
- *Table-top precision quantum experiments* studying both the microscopic world and the structure of the universe. The Physics Department (the Wright Laboratory in particular) have several superb experimental programs in this area.
- *Quantum condensed matter theory*: Physics and Applied Physics have substantial strengths in the quantum theory of many-electron systems and the study of the entanglement and topological properties of matter. This provides an important intellectual bridge between properties of quantum materials and certain powerful types of quantum error correction in quantum information processing.

These existing exceptional local strengths can be leveraged to recruit outstanding talent in complementary areas. Strong interdisciplinary hiring will help multiple departments (e.g., Physics, Applied Physics, Electrical Engineering, Mechanical Engineering and Materials Science, Chemistry, Computer Science) accelerate their evolution, and modernize and strengthen their research and teaching portfolios.

By enhancing synergy and interactions among faculty, students, and postdocs in diverse departments, Yale has great potential to be the first institution to establish a comprehensive university-wide research and education program in Quantum Science, Engineering and Materials that will advance the frontiers of knowledge and train the next-generation workforce for this burgeoning field. Such a program would be unique among our peer institutions. It would be highly attractive to students (and prospective students) by providing a meeting ground and common language for them to communicate across disparate departments.

To advance Yale's efforts in Quantum Science, Engineering and Materials, we offer the following recommendations:

- *Organizational Structure*: Expand the scope of the existing Quantum Institute into a University-wide Quantum Initiative at a scale that will attract international attention and will place Yale in a position of broad intellectual leadership. The expanded Quantum Institute should create a powerful ecosystem that initiates, enables and sustains both fundamental and applied advances in this burgeoning field and develops the underlying science and engineering disciplines, and materials research.
- *Faculty and Students*: Expand the faculty size in Quantum-related science and engineering departments through strategic hiring. We recommend the use of a pool of half-slots available to departments willing to commit a half-slot to make a hire in Quantum-related fields. We also recommend a subset of full slots be made available for pairs of departments willing to make joint hires in partnership.
    - Key areas for faculty hiring include quantum computer science, quantum materials science, quantum electrical engineering, quantum sensors for real-world applications (particularly in biology and medicine), quantum information theory approaches to fundamental questions about the universe (e.g., gravity, space-time and black holes), and materials science - in a way that builds on the natural intellectual synergies relevant to quantum technologies (e.g., superconductors or topological insulators).
    - As faculty are added, there should be a commensurate increase in the number of graduate students in the relevant host department.
- *Space*: Create a central intellectual hub for the Quantum Initiative, built on the foundation of the existing Yale Quantum Institute, by expanding its intellectual scope to fully include all three pillars discussed above and by expanding its physical scope to include modern high-quality space to house cutting-edge experiments and outstanding new hires.
    - Construct a new building for the physical sciences with the Quantum Initiative and Materials Research among its major foci, and with a goal of occupancy within ten years (by the year 2028). This building should be designed at a scale to support approximately 25 faculty labs, to house core facilities for materials research and nanoscale research and device fabrication, and to allow an expansion of SEAS in this and related areas.
    - In the period before such a building is available, the University should make maximum use of space available on West Campus, particularly in space committed to the Energy Sciences Institute, and in Becton to house incremental faculty hires in this area.
- *Core facilities*: Expand, upgrade and modernize the core facilities and cleanroom that support the Quantum Initiative and the physical sciences (see ***Core Facilities*** recommendation above). This includes nano-fabrication, lithography, instrumentation for materials characterization, high performance computing and modern high-performance electronics expertise.
- *Education*: Create a multi-departmental graduate program in Quantum (perhaps similar to the Biological and Biomedical Sciences umbrella program in the biological sciences and medicine) with a modest number of core introductory courses in a coordinated curriculum common among Physics,

Chemistry, Applied Physics, Electrical Engineering, Mechanical Engineering and Material Science, Computer Science, and other interested departments. Create an undergraduate program in Quantum Engineering (perhaps focusing on quantum computing and information, quantum signal processing, sensing, transduction, devices and measurements) involving Physics, Applied Physics, Electrical Engineering, MEMS, Computer Science and other interested departments.