DOE Study Group Report

Grand Challenges

at the Interface of

Quantum Information Science, Particle Physics, and Computing

Edward Farhi, Stephen Jordan, Patrick Hayden (co-chair),

Mikhail Lukin, Juan Maldacena, John Preskill (co-chair),

Peter Shor, Jacob Taylor, Carl Williams

17 January 2015

The Study Group on Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing, convened by Advanced Scientific Computing Research (ASCR) and High Energy Physics (HEP) Programs in the Office of Science, DOE met on December 11th, 2014 at Germantown, MD. All Study Group members made presentations, with representatives from DOE and other US government agencies also participating. This report was distilled from the presentations and discussions and presents the Grand Challenges formulated by the group.

Study Group Report:
Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing

Edward Farhi, Stephen Jordan, Patrick Hayden (co-chair),
Mikhail Lukin, Juan Maldacena, John Preskill (co-chair),
Peter Shor, Jacob Taylor, Carl Williams

17 January 2015

Introduction

Quantum information science (QIS) is a rapidly developing interdisciplinary field of science and technology, drawing from physical science, computer science, mathematics, and engineering, which addresses how the fundamental laws of quantum physics can be exploited to achieve dramatic improvements in how information is acquired, transmitted, and processed. Theoretical research indicates that large-scale quantum computers will be capable of solving some otherwise intractable problems with far-reaching applications to, for example, cryptology, chemistry, materials science, and fundamental physical science. Experimental efforts to manipulate quantum states are achieving steadily improving results using a variety of physical platforms, such as superconducting circuits, spins of electrons and nuclei, atoms, and photons. Though large scale general purpose quantum computers may still be decades away, quantum information processing is already being exploited in some of the world's most accurate clocks, and in magnetic sensors that achieve an unprecedented combination of sensitivity and spatial resolution; meanwhile new experimental tools are being harnessed to simulate models of quantum many-body physics that are beyond the reach of today's digital computers.

Central to QIS research is the concept of quantum entanglement, the characteristic correlations among parts of a quantum system which have no classical analog. For a highly entangled quantum system, information stored in the system cannot be accessed by interacting with small parts of the system one at a time, because the information is encoded not in the individual parts but rather in the correlations among the parts. By manipulating highly entangled quantum states, a quantum computer performs tasks which cannot be emulated by ordinary digital computers, because such quantum states admit no succinct classical description. Quantum entanglement also underlies quantum error correction procedures which protect quantum states from the destructive effects of decoherence.

Aside from setting the stage for revolutionary future technologies, research on quantum entanglement, quantum information processing, and quantum error correction is also establishing new tools and approaches for deepening our understanding of fundamental physical phenomena. For example, in quantum condensed matter physics, concepts arising from the study of quantum computing and quantum entanglement have spurred the development of powerful methods for classifying quantum phases of matter and more efficient schemes for simulating entangled quantum many-body systems using digital computers. In addition, exciting new scientific opportunities are arising at the interface of QIS with high energy physics. For example, advances in precision measurement exploiting entangled quantum states may enable unprecedented tests of fundamental symmetries, or new strategies for probing dark matter and dark energy. Quantum simulators and quantum computers may provide new insights regarding the behavior of strongly-coupled quantum field theories. Ideas from quantum information theory and quantum complexity theory may deepen our understanding of the quantum structure of spacetime. Furthermore, concepts from particle physics and quantum field theory may suggest new applications for quantum computers, and new ways to make quantum systems more robust against noise.

Despite its scientific promise and relevance to US national security and future economic competitiveness, research on the foundations of QIS has been hampered by unsteady support from US government agencies, contributing to a "brain drain" in which some of the most able and successful scientists working in the US have been attracted to institutions in Canada, Europe, Asia, Australia, and Israel. This problem has been exacerbated by the interdisciplinary character of QIS research, which sometimes leaves the field without a natural home among agency programs or academic departments.

The challenges and opportunities afforded by QIS provide a particularly good fit with the goal-oriented approach to basic science pursued by the DOE Office of Science, as QIS intersects particularly strongly with DOE programs in Advanced Scientific Computing Research (ASCR), Basic Energy Sciences (BES), and High Energy Physics (HEP). While some parts of the QIS research agenda fit best with just one of these programs, other research goals straddle more than one program, or reach into areas that are attracting attention beyond DOE. For example, similar concepts, techniques, and tools are shared by those using quantum simulators or quantum computers for studying physical systems of interest to ASCR, BES, and HEP. Likewise progress in high-precision measurement arising from QIS research can have a broad impact felt in many areas of science. Therefore thoughtful coordination among programs and agencies can help to foster a well conceived research portfolio.

Having noted these significant overlaps with other fields, in this report we emphasize the potential for transformative scientific advances at the interface of QIS with HEP. Both HEP and QIS strive for an understanding of the universe at the most fundamental level. Indeed, just as particle physics probes the structure of matter at shorter and shorter distance, and cosmology probes the history of the universe at earlier and earlier times, we are now for the first time in human history developing the capability to create and control quantum states of matter with greater and greater complexity. This "entanglement frontier" is exciting because, knowing that highly entangled systems of many particles are hard to simulate with digital computers, we may anticipate that surprising, illuminating, and useful new phenomena will occur in sufficiently complex quantum systems.

Grand Challenges

To focus our discussion, we formulate here a set of Grand Challenge questions providing particularly enticing opportunities, though of course our list is far from complete. One thing these questions have in common is that people with a deep understanding of more than one area will be especially well positioned to lead future developments. Not many scientists are experts on both quantum complexity and quantum gravity, or on both quantum simulation platforms and nonperturbative quantum field theory, or on both quantum limited measurement and dark matter. Well crafted support from visionary funding agencies can motivate a new generation of scientists to acquire the interdisciplinary training needed to face these challenges.

What new measurement strategies, exploiting quantum coherence and entanglement, can probe fundamental physics with unprecedented precision?

QIS has provided new tools and strategies for enhancing measurement sensitivity. For example, clocks and sensors which exploit entangled states achieve an accuracy which scales favorably with the number of entangled particles. New quantum information paradigms such as quantum sensor networks may yield powerful precision measurement tools capable of, among other things, imaging single molecules and probing complex materials with unprecedented spatial resolution.

Aside from their other exciting applications, such ultra-precise instruments can provide new windows on fundamental physics. Sensing with entangled states could improve limits on electric dipole moments of atoms and molecules, providing more stringent tests for models of CP violation beyond the standard model. Advances in precision measurement could facilitate detection of axion dark matter or time variations of fundamental constants predicted by some models of dark energy or dark matter. Extensive collaboration between the QIS and HEP communities, involving both theorists and experimentalists, will be needed to conceive and realize a new generation of experiments at the entanglement frontier of particle physics, a daunting technical challenge for which DOE laboratories can provide valuable expertise.

What credible deviations from conventional quantum theory are experimentally testable?

It has long been anticipated that experiments may reveal shortcomings in currently accepted ideas about quantum physics, and there are ambitious experimental programs to probe the limitations of conventional quantum theory. Eventually, quantum computers will test quantum mechanics in a new regime by studying the properties of profoundly entangled states of many particles under highly controllable conditions. In the nearer term, experimental advances are making it possible to search with greater precision for nonlinear corrections to the Schrödinger equation and spontaneous collapse of macroscopic superpositions due to intrinsic decoherence. Optomechanical interference experiments, in particular, may be able to test models of new physics associated with energy scales well beyond the reach of present day accelerator experiments. Because of their technical complexity and fundamental importance, experimental tests of quantum theory may fit with the goals and expertise of high energy physicists and DOE laboratories.

But all efforts to test quantum mechanics are hampered by a dearth of credible alternatives. The HEP community can enhance the scientific value of experimental searches for violations of quantum mechanics by proposing deformations from standard quantum theory which make sense as fundamental theories and are also compatible with everything we currently know about physics. Or perhaps we can find new arguments to strengthen the widely held suspicion that such deformations cannot exist.

What physics insights can inspire new applications for quantum computers?

Quantum computers have remarkable capabilities, but they also have limitations; for example, we do not expect quantum computers to be able to solve the hardest instances of NP-complete problems in polynomial time. Even so, quantum algorithms might find exact or approximate solutions to NP-hard problems with significant speedups compared to classical algorithms. Since quantum computing is an entirely new computational paradigm, challenging our meager imaginations, most likely many unanticipated applications will be discovered by experimenting with quantum devices as they become available. A quantum computer with just hundreds of physical qubits, which may be available relatively soon, could be a very instructive testbed for exploring potential quantum speedups and inspiring new algorithms.

Physicists, and high energy physicists in particular, can draw upon their deep understanding of quantum phenomena to conceive and develop new quantum algorithms. For example, topological quantum field theory (TQFT), originally developed by particle theorists, has inspired an especially elegant approach to achieving error-resistant quantum computing, and thinking about how to simulate TQFTs has led to powerful new quantum algorithms for approximating topological invariants of links and manifolds. Applications of scattering theory to quantum walks on graphs have spawned new computational models and algorithms for evaluating Boolean formulas. Physicists also proposed the adiabatic quantum computing model, which can be adapted to run any quantum algorithm, though at a substantial overhead cost; understanding the applications of adiabatic quantum computing to combinatorial search problems remains a compelling theoretical problem and a promising arena for technological development and experimentation. Many more seminal insights can be expected as more HEP physicists join the quest for new quantum algorithms.

Can quantum computers efficiently simulate all physical phenomena?

Though we don't yet know for sure, it seems plausible that a general purpose quantum computer will be able to simulate efficiently any process that occurs in Nature, something that can't be claimed for classical digital computers. What makes this possible is that the Hilbert space of any realizable physical system has a decomposition as a tensor product of simple subsystems, and the Hamiltonian which dictates the system's Schrödinger evolution can be expressed in a "local" form, as a sum of terms where each acts on a small number of these subsystems. In some cases, preparing a ground state or finite-temperature equilibrium state of the Hamiltonian may be a hard problem even for a quantum computer, but in that event we expect that Nature, too, is incapable of solving the hard state-preparation problem.

A particularly intriguing question is whether quantum computers can simulate accurately nonperturbative phenomena in quantum gravity, where spacetime is subject to strong quantum fluctuations. If the answer is Yes, then simulating quantum gravity will be an especially worthy application for quantum computers. If the answer is No, then the computational power encoded in the laws of physics surpasses what is captured by our currently accepted quantum computational models. Addressing this question is bound to deepen our understanding of quantum gravity. Just as thinking seriously about how to simulate a quantum field theory on a classical computer led decades ago to deep insights regarding the foundations of quantum field theory, we can anticipate that thinking about how to address open questions about quantum gravity using a quantum computer can bring us closer to answering the vexing question: What is string theory?

How can quantum simulators and quantum computers deepen our understanding of quantum field theory and quantum gravity?

DOE devotes enormous computing resources to lattice gauge theory calculations, which have substantially advanced our knowledge about nonperturbative quantum chromodynamics. But those computations simulate field theories in imaginary time, and hence can explore only static properties like hadron masses and matrix elements. Simulating the real time evolution of quantum field theories is a hard problem classically, yet might be done with a quantum computer using resources that scale reasonably with the energy, number of particles, and the desired precision. Such simulations could explore the behavior of nuclear matter at nonzero density, or far from equilibrium, and could be used to estimate QCD backgrounds with improved accuracy compared to classical methods. Quantum computing may also be a powerful tool for probing nonperturbative string theory, providing valuable guidance concerning the relation of strongly-coupled field theories to their gravitation duals in cases, like non-supersymmetric cosmological spacetimes, where understanding is currently lacking.

Scalable quantum computers capable of simulating quantum field theory or quantum gravity are still far off, but analog quantum simulators for studying such phenomena are becoming feasible today. Digital quantum computers have the advantage that, using suitable error correction protocols, they can simulate a specified Hamiltonian system with excellent accuracy, in contrast to analog quantum simulators which provide an imperfect approximation to ideal quantum systems. But at least some of the properties we hope to probe in a quantum simulation may be robust with respect to imperfect implementation, yet at the same time hard to extract in classical simulations of quantum systems. There are now proposals for simulating dynamical gauge fields using ultracold atoms, superconducting circuits, and other systems, which are promising though dauntingly complex. Finding and executing achievable simulation schemes for extracting useful information about nonperturbative field theory is an important research program, which the HEP community can help to steer in fruitful directions. DOE involvement in developing and testing quantum simulator hardware could accelerate this program and enhance its scientific impact.

Does space emerge from entanglement?

A central mystery about quantum gravity concerns whether and how the geometry of space and time can arise from some more fundamental quantum description. Entanglement theory, a powerful framework for reasoning both operationally and mathematically about correlations in quantum mechanics, provides a fresh approach to such deep questions. Already, there is strong evidence that entanglement can be used to stitch together otherwise disconnected spacetimes. The monogamous character of quantum entanglement is also at the core of the recent "firewall" controversy, which has sharpened Hawking's black hole information paradox and shaken our confidence that black holes even have interiors.

We now know that if a quantum field theory has a dual gravitational description, then the field theory's vacuum entanglement can be computed as the area of a minimal surface in the gravity dual, another strong indication that the geometry of the bulk spacetime has an interpretation in terms of quantum entanglement. Our understanding of this connection remains far from complete, and future progress is likely to rely on concepts and insights from quantum information theory, such as tensor networks, complexity theory, error correction, and information compression. These investigations of the origin of spacetime geometry are bound to raise new questions and precipitate the development of new quantum information theory tools with broad applications extending beyond gravitational physics.

How can entanglement theory be extended?

Quantum entanglement is valuable. In a two-party system it can be used as a resource to perform certain desirable tasks, such as teleporting a quantum state from one party to the other, or generating a secret key shared by the parties. These are tasks that cannot be performed using only quantum operations performed locally by each party, even if augmented by classical communication between the parties. Indeed, the natural way to quantify entanglement is to formulate a *resource theory* in which local operations and classical communication (LOCC) can be regarded as a "free" resource with no inherent value; in particular, LOCC cannot increase the amount of quantum entanglement shared by the two parties.

The resource theory framework has other applications to physics, most notably to thermodynamics. Recently the analogy between entanglement theory and thermodynamics has been strengthened, yielding new tools for exploring the thermodynamics of nanoscale and far-from-equilibrium systems. We anticipate that continuing developments at the interface of quantum information and high energy physics will stimulate further exploration of resource theories shedding light on fundamental issues. For example, entanglement theory so far has little to say about quantum correlations in time rather than space; perhaps the need to quantify correlations and physical constraints in relativistic quantum field theories and their holographic duals will give rise to a more versatile and potent formulation of quantum information theory, which might also shed light on whether and how time could be an emergent rather than a fundamental notion.

The Study Group on Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing met in Germantown, Maryland on 11 December 2014. All Study Group members made presentations, with representatives from DOE and other US government agencies also participating. This report was distilled from the presentations and discussions.