Quantum @ DU

White Paper submission, University of Denver 2023, *Ideas to Impact*

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Current Additional Team Members: Note we continue to grow our list of participants as the project moves through the *Ideas to Impact* process. *Physics & Astronomy*: Assoc. Prof. Xin Fan, Asst. Prof. Pavel Salev, Assoc. Prof. and Chair Davor Balzar; *Chemistry & Biochemistry*: Assoc. Prof. Michelle Knowles, Asst. Prof. Scott Horowitz, Assoc. Prof. Brian Michel, Prof. Gareth Eaton, Prof. Sandy Eaton. *Biological Sciences*: Asst. Prof. Erich Kushner. *Sturm School of Law*: Asst. Prof. Zahra Takhshid. *Emergent Digital Practices:* Teaching Prof. and Program Director Bill Depper; *Philosophy:* Assoc. Prof. and Chair Marco Nathan; *Office of Teaching and Learning:* Director of University Teaching Virginia Pitts.

Why this topic?

Society stands on the brink of a transition into a quantum age. Just as the development of digital computer technology based on semiconductors fueled immense growth and change and enabled our current age of information, replacing the simple 1's and 0's of digital technology with the unique laws of quantum mechanics will enable massive leaps in information processing that will reorder life as we know it.

To equip students to excel in this quantum world, DU must grow in research and experiential teaching capabilities across disciplines from Physics and Chemistry to Biology, Psychology, and Law. Just as important, and where our efforts can be most unique, is in supporting and exploring the connections between these disciplines, by not only asking and exploring scholarly questions, but teaching students in Quantum degree programs of these vital intersections.

This *Ideas to Impact* project will require infrastructure investment, faculty development, and student support, with the possibility to build new degree programs at every level and across a broad range of disciplines. Quantum @ DU will catalyze our unique opportunity to build programs on cutting edge quantum research that explore the entangled impacts across every area of the human experience.

In the near term, Quantum @ DU will support critical "shovel-ready" needs of the faculty, students, and staff already working in quantum related areas. These include: Laboratory Infrastructure for Quantum Materials and Information, Postdoctoral Fellowships in Quantum Concepts, Endowed Faculty Positions, Education and Interdisciplinarity in Quantum Concepts and Connections, and administrative and staff support to build interdisciplinary quantum connections.

Why now? What will be the outcomes and impacts of this initiative on society?
Quantum Information and Computing have already begun to change the world. Just the past few years have seen milestone developments in the fundamental science, such as the first truly secure quantum communication from earth to a satellite (achieved by Chinese scientists in 2020), and the first commercial implementation of quantum computers (claimed by several companies starting around 2019 including IBM and D-wave), leaving countries scrambling to compete in this new realm to assure their geopolitical and economic stability and security. In part in response to Chinese investments and advances in quantum science, the United States has sharply ramped up federal spending in quantum areas, including the National Quantum Initiative Act (2018, $1.2 Billion in investments in quantum information science) the "Endless Frontier Act", S.1260 - United States Innovation and Competition Act (2021, >$100 Billion channeled through the NSF), and the recent CHIPS act (2022, $280 Billion for advanced semiconductor manufacturing, research and development, and workforce development).

Such large investments are understandably motivated by the simple promise and myriad impacts of computers thousands of times more powerful than the current state-of-the-art, and communications secured by the fundamental physics of quantum mechanics, rather than simple complexity of classical calculations.

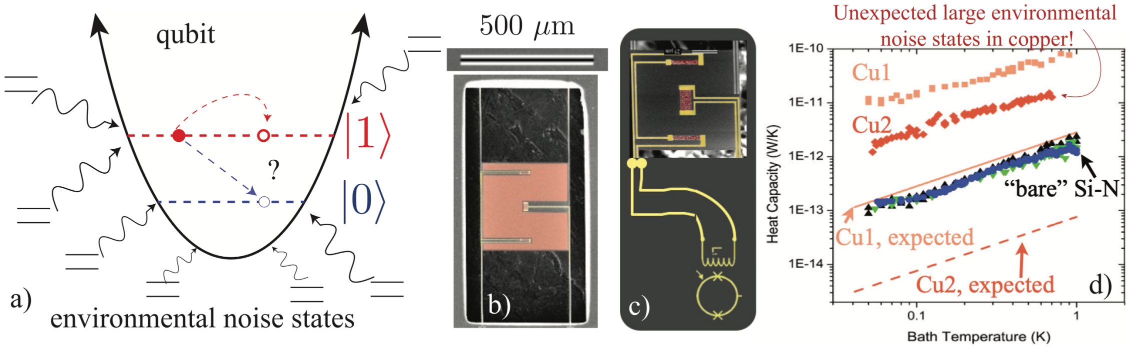
The Quantum @ DU initiative will provide necessary infrastructure and resources for DU faculty and other researchers to be competitive for this research funding. In particular, it will catalyze the existing seeds of quantum research across campus to form a unique center for cross-disciplinary quantum science and societal implications. Additionally, the infrastructure, equipment, and novel educational programs from Quantum @ DU will equip DU students to compete for jobs as leaders in new companies and industries that will form as quantum ideas reorder society, and provide resources and general education to all DU students so that they are comfortable with quantum applications in diverse contexts, and judging potential implications.

Why DU? What are DU's current strengths in the area of focus? How does DU compare/ compete locally and nationally on this subject matter domain?
While quantum research is booming across the country, and CU-Boulder has traditionally led the region in this area, DU is in a unique position that can be leveraged for tremendous growth and impact in quantum science research and education. First, the current research efforts in Quantum concepts at DU are unique and creative in ways that complement, rather than compete with, the work done at other Colorado schools. The work at DU is poised for rapid and cohesive growth, given strategic investment and intentional design of planned interdisciplinarity. Second, the existing DU culture, grounded in the liberal arts ethos, allows flexibility and lowers institutional barriers for exploring meaningful interactions across disciplines. We will be able to build on this culture to create a truly unique environment where students and faculty in dramatically different areas of study can identify and study the impacts of their work across fields. For example, students in a future degree program in Quantum Materials and Information Science could take required courses in the legal and social impacts of quantum technology, and in the effective teaching and learning of quantum concepts at all levels. Third, our smaller size also

helps enable participation of more diverse faculty and student populations. This pattern has already been demonstrated in several DU programs, which often produce higher percentage of graduates from underrepresented groups in STEM, for example.

Research and teaching in Quantum concepts is already ongoing across a range of schools and colleges at the University of Denver, including Natural Sciences and Mathematics, Law, Humanities and Social Science, and others. Some specific areas of excellence in Quantum @ DU are highlighted below.

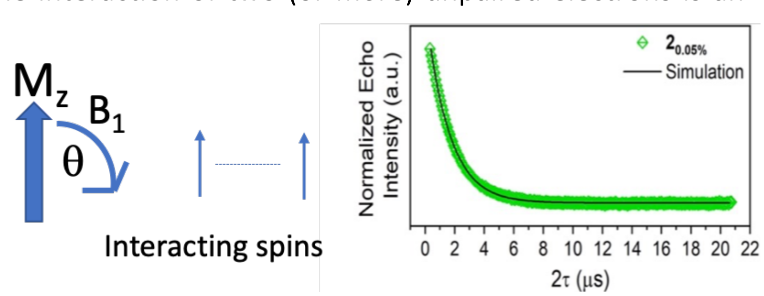
Research highlight 1: Thermal probes of decoherence in qubit materials



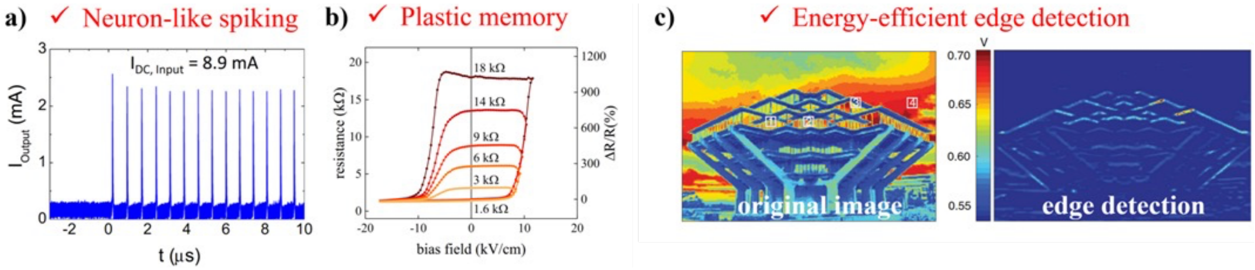
The Zink lab has developed unique tools to study the fundamental physics of noise sources in materials at temperatures well below 1 Kelvin, where quantum bits formed from superconducting circuits are often operated. Panel a) of the figure above depicts the interference of environmental noise states with the two state system that forms a qubit. These interactions cause *decoherence,* where the qubit prepared in a given state (here the |1> state) forgets it's quantum information due to environmental interactions. The Zink group, with collaborators at NIST Boulder, developed micromachined thermal platforms (seen in SEM micrographs in panels b and c) measured with SQUID noise thermometry, to study heat capacity and thermal conductivity between 50 mK and 4 K. Panel d shows that even a simple metal such as copper can show an unexpectedly large heat capacity, indicating unexpected environmental noise states.

Research highlight 2: Resonant probes of decoherence in qubit materials

The Eaton lab at DU is one of the world leaders in measuring spin decoherence via electron paramagnetic resonance (EPR) spectroscopy. Their results are used by other labs around the world to design quantum "qubits." The interaction of two (or more) unpaired electrons is an example of quantum entanglement. Building on basic understanding of spin-spin interactions the DU EPR Center is poised to contribute to development of quantum computing. Informal, noncredit instruction in this area has been a feature of the EPR Center for over a decade and could be incorporated into a coherent program of instruction in quantum computing. This could be expanded to include undergraduate laboratory instruction.

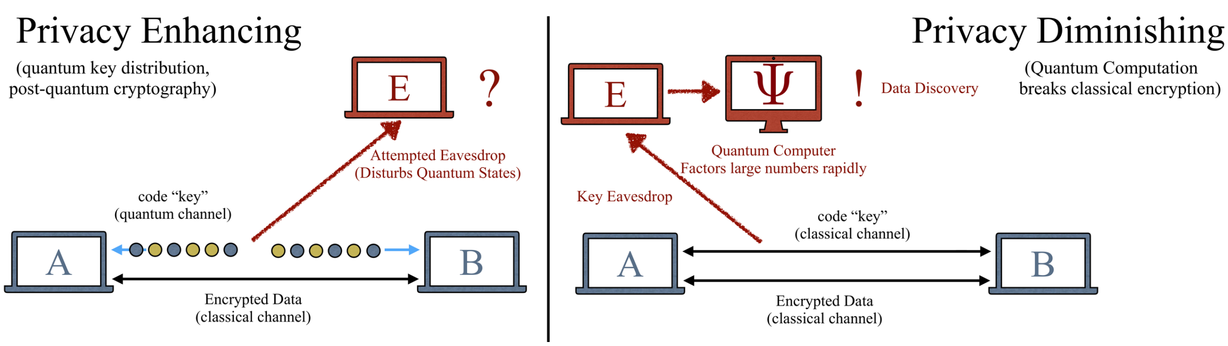


Research highlight 3: Quantum materials for advanced computing



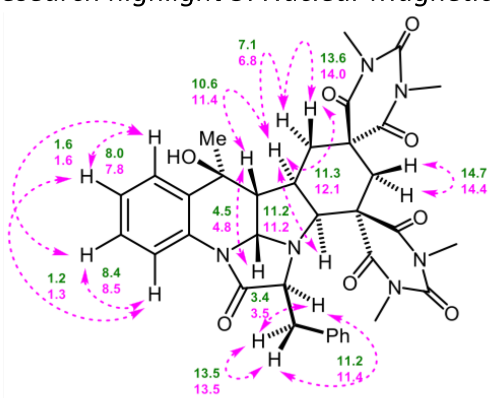
Asst. Prof. Pavel Salev is building a new experimental lab that will explore quantum materials as novel computational platforms. In recent years, there has been tremendous progress in the development of artificial intelligence algorithms, including neuromorphic and reservoir computing. Large-scale implementation of such algorithms is hindered, however, by the limitations of silicon-based technologies. Because of the high-power consumption and large number of components in transistor circuits, building a computer that can rival the complexity of the human brain necessitates the search for new material platforms beyond traditional semiconductors. Quantum materials exhibit a plethora of exotic physical properties stemming from the fundamental electronic interactions at the atomic scale. Utilizing the functional properties of these unusual systems enables the design of unconventional computing elements that can replace complex transistor circuits. The figure above highlights some of Prof. Salev's work: a) demonstrating quantum-material-based devices that can mimic the spiking of biological neurons: b) emulate the memory plasticity of biological synapses, and c) provide the energy-efficient hardware implementation of the edge detection algorithms used in the neural networks. Quantum materials research is a rapidly growing field that challenges the established approaches of electronics design. The unique work at DU will focus on enabling (spin + charge) computing platforms in magnetically ordered metal-insulator transition systems – a special class of quantum materials where the electrical conductivity can be changed by orders of magnitude by controlling the electronic interactions.

Research highlight 4: Quantum Privacy at the intersection of commercial law and technology



Asst. Prof. Zahra Takhshid is exploring far-reaching implications of quantum technologies on law, which highlights one of many ways developing quantum technology can impact society far beyond the physics lab. The image above summarizes one area of her focus: exploring which quantum technologies could enhance privacy, and which could diminish or eliminate it. Quantum key distribution uses the essential physics of quantum measurement--the alteration of a quantum system by the act of measuring it-- to ensure data privacy. However, possession of a large scale quantum computer by a potential eavesdropper on classical network communications potentially invalidates even the best classical encryption schemes because quantum computers excel at factoring large numbers, which is the essential mathematics of current classical encryption. As Prof. Takhshid states in a forthcoming review essay (”Quantum Privacy” in *The Cambridge Handbook of Emerging Issues at the Intersection of Commercial Law and Technology*, 2023), equipping legal scholars and practitioners with knowledge of quantum concepts helps reduce their treatment as ”exceptional” technologies, which can prevent thorough and equitable examination of the legal impacts of the technology. She also cites the critical role of interdisciplinary work, such that the legal academy can ”have a hands-on introductory understanding ” of the science behind quantum technologies. This again highlights the unique and impactful role DU can take by enhancing these interactions.

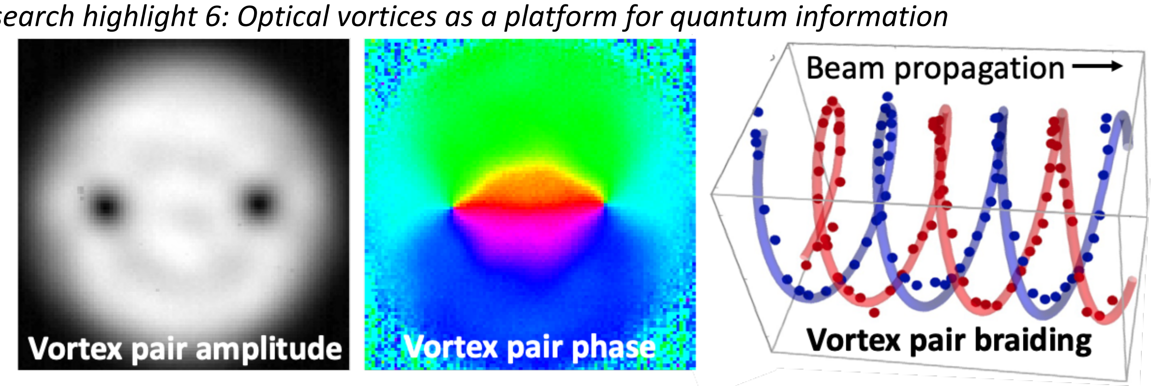
Research highlight 5: Nuclear Magnetic Resonance (NMR) research in using quantum chemistry



Spin-spin coupling (Experimental Calculated) in a polyheterocyde

The Department of Chemistry and Biochemistry at DU has seven faculty currently engaged in research using quantum chemistry via NMR spectroscopy. These faculty include Scott Horowitz (nucleic acid biophysics), Sunil Kumar (aberrant protein-protein interactions), Allegra Aron (metallophore discovery), Andrei Kutateladze (quantum observables predictions for small molecules), Brian Michel (biological catalysts), and Brady Worrell (polymer analysis), and new faculty that will likely be hired to use NMR within the next two years. NMR spectroscopy’s growth at DU outpaces our current instrumentation, and a new spectrometer is needed to allow continued growth in the Chemistry & Biochemistry Department.

Research highlight 6: Optical vortices as a platform for quantum information



The Siemens lab, in work funded by the NSF and the W. M. Keck Foundation, is pioneering the use of optical vortices for quantum simulation of superfluid hydrodynamics, and also exploring the possibility that these optical vortices could be “anyons” that are the basis for topological quantum computing. They have demonstrated many of the steps required for topological quantum computing: full control over arbitrary vortex lattices (setting up the quantum problem), braiding of vortices (the calculation to be performed), and fusion of vortices (problem readout). This promising approach is also completely novel: they are currently the only ones in the world working on implementing quantum computing algorithms and gates with optical vortices. The optical vortex quantum simulator is low cost, accessible and flexible, room temperature, and robust to errors because of topology and photon insensitivity to the environment; this is in contrast to the current state-of-the-art methods for quantum computing that require ultra-low temperature and vacuum to isolate qubits from the environment – and yet still require a factor of 10 redundancy for error correction.

These highlights feature only a few of the faculty already working on quantum concepts. These faculty are respected leaders in their respective sub-fields, with established track records of obtaining external funding for their research and publishing in high-impact peer-reviewed journals; however the transition to quantum research demands new infrastructure and nanoscience tools that are widely unavailable at DU. The vision of the Quantum @ DU initiative is to provide the infrastructure and institutional support to bring together these individuals into a cohesive and sustainable core of quantum research.

With regard to DEI values and principles, how will this project, if funded, increase compositional diversity at DU as well as inclusiveness and justice at DU?

The society we will face in coming years and decades stands to be shaped and transformed by quantum concepts in ways not yet known. Achieving true equity and inclusion in this society requires empowering a diverse student body and faculty with the knowledge to compete for the best jobs and tools to answer new fundamental questions. Quantum @ DU is an essential component for achieving this equity and inclusion.

To help achieve these goals, we will dedicate one speaker slot each year in the planned Quantum @ DU seminar series to discuss DEI in quantum. Attendance at this seminar will be required for any related degree programs, and DEI concepts will be integrated into the quantum curriculum.

The envisioned Endowed Professorships are an important route toward manifesting our DEI goals in faculty hiring. In recent years hiring excellent diverse faculty is extremely competitive, and DU currently simply cannot compete for these candidates (we have recent direct evidence of this). Philanthropic endowment of competitive named professorships at all seniority levels would help DU compete and take advantage of our possibilities in this area.

How does this topic further DU's commitment to the public good?

As with Diversity, Equity, and Inclusion, quantum concepts have impacts on the public good that are potentially profound, but not yet well understood. The full range of proposed activities to be supported by Quantum @ DU are motivated by the public good: from uncovering new quantum nanoscale phenomena in the physics research lab; to studying the societal or legal ramifications of quantum concepts for privacy, security, or communication; to teaching these concepts and their impacts in the classroom.

Given the life-changing potential of quantum technologies, the public impact of this work is likely to be enormous. One goal will be to prepare DU students to be moral and honest practitioners of quantum science, even in the face of corporate and government pressure. This work toward constructing and understanding quantum ethics is inherently interdisciplinary, and can thrive in DU's environment if institutional structures to support exchange between fields are implemented.

What sources of external funding are available to support this issue area, i.e., federal and state grant funding, philanthropic funding, other?

As stated earlier, there are many new federal funding streams supporting quantum information, quantum materials, and development of a quantum workforce, and these continue to grow. Another important aspect of building our capabilities across a range of fields where quantum concepts are explored is to make teams of DU investigators potentially attractive collaborators for many of the very large scale research centers that NSF, DOE, and DOD currently favor as approaches to "grand challenges" such as quantum materials and information. An example of such a program are the NSF Quantum Leap Challenge Institutes. These are large, often multi-university research centers, dedicated to pushing existing boundaries in quantum research, technology, and workforce development. These funding mechanisms often assume that necessary infrastructure is available, but do not provide funding to improve it. Expanding our infrastructure to support our core of quantum-related faculty and growing this group will let DU compete for larger and more sustainable funding streams than has been ever been possible.

How sustainable is this project? Will it contribute to student interest and enrollments and, ultimately, to tuition revenue?

The dramatic effects of the classical-computation powered developments in artificial intelligence are currently impacting more aspects of society every day, and certainly focus student interest. The coming impact of similar technologies powered by quantum concepts will exceed this, and student interest in these concepts is already ramping up. As mentioned above, the development of a quantum workforce is a central aspect of many of the new federal funding streams focused on quantum concepts, and DU must take advantage of this to assure our relevance to future student interests. In the short term, we are already working to take advantage of this interest by developing Concentrations and Minors related to Quantum Materials and Information Sciences, but see a critical opportunity to develop additional educational programs. One key focus, if we can develop suitable infrastructure and faculty support, is to implement a Professional Masters degree, that would focus on giving students from a wide range of STEM fields practical knowledge required to be effective in quantum technologies. We see a critical role, and an important point of distinction for DU's degree programs, in adding ethics and social impact to the experiential learning of superconducting electronics and low temperature physics that would be offered to these new students.

Likewise, how sustainable is the funding stream after initial investment? Beyond net new tuition, what are the options for grants, contracts, and philanthropy?

One of the main goals of the Quantum @ DU project is to ensure our ability to access sustainable funding streams well into the future. We have provided detailed information in this area earlier, but will reiterate that the options for federal funding are already a strong motivation to continue DU's investment in this area. We also note that if adequate support is focused to develop a Professional Masters program, the graduates would be a potential pool for future philanthropy.

Planned Initial Activities and Thrusts

This project connects a wide range of faculty and units across campus, and it will require significant investment in research equipment and infrastructure, along with other faculty supports. We know of no existing means for the campus to make such a significant and important investment.

Even the near-term needs required to begin the process require very significant investments that require an institutional commitment. We currently envision these taking six thrusts.

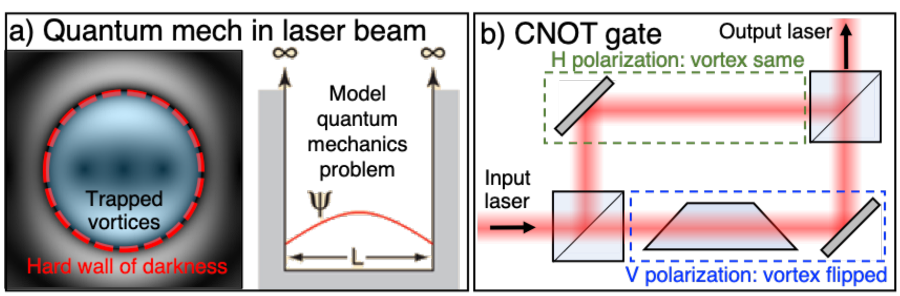
1) *Laboratory Infrastructure for Quantum Materials and Information*. Simply put, the kinds of fundamental questions that are of interest in quantum science related areas require state-of-the-art tools that are often lacking here at DU. One early focus will be on developing a Quantum and Molecular Nanofabrication Facility. This clean-room facility will house tools to produce and study the tiny physical, chemical, and biological structures often required to probe and manipulate the quantum realm. This includes advanced photolithography tools, improved materials growth capabilities, and other advanced processing equipment, along with the physical infrastructure to safely and effectively use these tools (temperature regulation, water cooling, vibration isolation, in addition to the clean environment). This facility (to be located in Knudsen Hall or the Physics building initially, and then integrated into a new STEM building in the next 5-10 years) will be open to student and faculty users from across campus by application to the Quantum @ DU team. This thrust will also support additional experimental tools essential to both research and teaching in Quantum concepts. This likely includes tools to create and manage the low temperature environments that house many manifestations of quantum computers (such as a dilution refrigerator), upgraded imaging and spectroscopy tools (including state-of-the-art Nuclear Magnetic Resonance spectrometer and X-ray diffractometer), and expansion of facilities to sustainably perform research in the low-temperature environments required to access quantum phenomena (including additional facilities to recycle liquid helium).

2) *Summer Quantum Research Fellowships for Undergraduates*. Research is one of the most powerful parts of the education that DU has to offer. It provides students with relevant experience beyond the classroom and prepares them for meaningful careers. Unfortunately, current mechanisms to support student research (Undergraduate Research Center's Summer Research Grants, PINS) are not enough to support a student for even a complete summer. We will establish competitive summer fellowships to support undergraduates collaborating with DU faculty on a Quantum research problem in science, policy, law, or social impact.

3) *Postdoctoral Fellowships in Quantum Concepts*. To enable and support the exploration of quantum concepts in research across the full range of disciplines at DU, we envision supporting postdoctoral fellowships. This is a very effective and impactful use of institutional resources, with direct impact on building and improving our research profile, and providing a flexible and quick means for faculty to move quickly into new quantum-related fields. A request for proposals for such positions will be advertised across campus, and selected by the core group of faculty associated with Quantum @ DU.

4) *Endowed Faculty Positions*. Though this aspect is likely out of reach of the expected initial institutional investment, future institutional advancement should target several endowed professorships across the disciplines. Well-endowed named professorships, with competitive salaries and initial equipment and personnel (start-up) budgets are essential to bring high impact talent to campus, individuals who will not only establish cutting-edge research and teaching programs in quantum-related fields, but who will improve existing efforts via collaborations and co-learning. This is particularly important for DU to achieve our stated DEI goals. As mentioned earlier, hiring faculty candidates that enhance our diversity (at every level of seniority) is often so competitive that we simply cannot hire these candidates without additional financial, infrastructure and other resources. These Endowed Faculty Positions would be a game-changer.

5) *Education and Interdisciplinarity in Quantum Concepts and Connections:*



Quantum science and information concepts are notoriously difficult to visualize and observe, especially in experiments that are accessible to undergraduate students. The Siemens lab has recently discovered that the tools they developed for controlling, propagating, and measuring optical vortices comprise a unique platform for observing and manipulating quantum phenomena. Even more exciting, the tools are accessible to undergraduate students from any major and inexpensive (a complete laboratory setup could be constructed with $5000, 20x less than the cost of a commercial quantum optics education kit). Two of the quantum concepts that can be easily explored are illustrated above: a) by structuring the beam shape, we can model trapped light that simulates the famous "particle in a box" problem of quantum mechanics, and b) classical entanglement can be implemented with polarization and vortex mode, allowing for real 2-qubit computation. Quantum @ DU will support the development of a series of five hands-on and inquiry-based laboratories. The goal will be to give DU students real intuition in dealing with quantum concepts and computing gates, which will give them a distinct advantage when applying these concepts to real-world challenges.

Consistent with the emerging nature of the field, quantum concepts are taught traditionally in only physics and chemistry departments, and largely ignored in other fields. As society feels the growing pains of the transition to the quantum age, studies of quantum concepts – and their implications – will make their way into many other fields. At DU, we have the opportunity to lead the critical effort to broaden the scope of quantum-related education to other units (such as philosophy, EDP, and Law). We will engage in a redesign of quantum-related education focused on both experiential learning and interdisciplinarity. One particular thrust will be to curricularly design a new quantum game through a multi-college collaboration that attracts students who are not science majors and is both a creative outlet and an educational tool.

If properly supported, Quantum @ DU will build momentum across campus, leading to growing interest in quantum concepts and applications. We envision developing a new SI-Natural sequence of classes "Quantum Science", which would teach non-science majors to do the following: explain essential quantum science concepts, identify the strengths and limitations of quantum computing, categorize common quantum computing platforms, and appraise the social and moral implications of quantum computing. The classes would be taught by faculty from this interdisciplinary team and use laboratory and game design principles described above. This would provide for campus-wide education and uniquely prepare DU students to be engage with the implications of quantum science and computing in their individual fields.

6) *Administrative and Staff Support to build interdisciplinary Quantum @ DU connections*: The early stages of the effort to build and explore the interdisciplinary interactions around quantum concepts will benefit from funding and a staff position to manage programs to connect faculty and students. This could include management of a Quantum @ DU Seminar series to bring internationally prominent speakers to campus to meet students and faculty, support for budget development and grant writing for quantum-related proposals, and travel support for students in quantum-related degree programs to present their research in the academic community. Staff support for management and technical assistance with the Nanofabrication facility is also critical for optimal utilization of this resource.