ECE 5/7383 Introduction to Quantum Informatics
Homework 5

1.0 OVERALL DESCRIPTION OF THE ASSIGNMENT

This homework assignment is related to your final examination for the class. The final examination is in the form of a final project and requires that you engage in an individual project regarding applications or theory of quantum informatics. More details on the requirements for the final project will be forthcoming; however, in a broad sense the final project will require that you prepare a final project report in the format of an IEEE conference paper and it will also require that you prepare a presentation slide deck that you would use if you were giving a 20 to 30 minute talk describing your project and its outcomes to other engineers and scientists who did not necessarily have background knowledge in quantum informatics.

For this homework, you are to choose a topic for your final project, propose it in a written report, and turn in the proposal for grading as your homework 5 assignment. An important aspect of the practice of engineering and science is to the generation of proposals, final reports, and presentations describing your work. As such, there is a pseudo-standard for such reports, typically that varies from company to company. In the academic world, that pseudo-standard is in the form of conference papers and in particular conferences sponsored by professional societies such as the IEEE and ACM. For this reason, your proposal and final report will be in the form of a typical six to ten page conference paper in IEEE format. Fortunately, there are templates available for these documents and they will be provided to you in a later section of this assignment document. Because communication skills and strictly following directions are very important aspects of the practice of good engineering and science, I will likewise be strict in grading your proposal and report in terms of adhering to the format, spelling, grammar, and logical presentation of your ideas in your proposals and final report. If you take the proposal effort seriously and expend a suitable amount of effort, you will have also essentially also written several major sections of your final project report.

The proposal and final report is intended to be an individual effort. If you have a large project and wish to form a team, I MAY allow it under certain circumstances. Those circumstances will require that there is a clear description of individual and independent contributions that, when combined, lead to overall project goals. In any event, I will still require that each student submit their own proposal and final report/presentation. There should not be significant overlap in each student's activities and there must be a good explanation of how each team member's efforts combine to meet the project goal. If you decide to propose a team project, you must include a section in your proposal justifying why more than one person is required to perform the project, how the individual efforts will be combined and verified to meet the project goals, and how each member's efforts are partitioned and differ.

2.0 PROPOSAL FORMAT AND STRUCTURE

Regarding format, you must strictly adhere to the prescribed document formats in the template files, available in MS Word and LaTeX formats. You may not change margin sizes, font sizes and types or other document formatting parameters. I will be extremely strict regarding plagiarism. Common mistakes that are found in some student submissions

are the inclusion of ragged edges in the columns, not adhering to the two-column format, and mixing of different font types in your text. All mathematical equations and symbols should be in the Times New Roman font with variables being italicized and numbers and symbols being in the regular (un-italicized) font. This includes mathematical expressions embedded inside paragraphs as well as stand-alone equations.

2.1 PLAGIARISM

Plagiarism will not be tolerated. If I find that you have copied figures and/or text from another source, you will receive a zero for this part of the class credit. This includes figures and text from my online class notes. I will use academic instructor tools to check for instances of plagiarism for both your proposal and final report. For example, copying and pasting a diagram from my online slides is as much an act of plagiarism as is the copying of text and figures from a published paper. I expect that, as upper-class undergraduate and graduate students, that you will have a command of the written English language commensurate with your academic standing. There is little excuse for poor spelling and grammar given the online proofing tools available to you. Even if you decide to use a figure that is substantially the same as one from my notes or other sources, you need to at least re-draw it in your own style and you should attempt to change it (at least slightly) so that you will not be accused of plagiarism. I am happy to provide more explanation of plagiarism and answer questions in class if you have them. I will not accept any hand-written figures, equations, notes, or other scanned materials inside your proposal or project. There are many ways to generate figures and equations using online sources or MS Powerpoint/Vision that are freely available to SMU students. You can download these from the SMU OIT website if you do not have them installed.

3.0 PROPOSAL/PROJECT EXAMPLES AND IDEAS

I am providing some example topics for your consideration as a choice for your final project. You may, alternatively, choose a different topic not listed if you wish to do so. I will only give you permission to proceed with a topic after I have graded your proposal. So, in a sense, homework 5 is truly a proposal in that you are convincing me that your proposed project is worthy of pursuing.

Appropriate topics can involve theoretical or implementation studies. Your proposal is meant to be more than just a description of your chosen topic. You need to demonstrate that you have done some background research in your topic so that you are aware of the major contributions and state-of-the-art in the area. This is a crucial aspect of any study as it is a waste of time, effort, and resources when we "re-invent the wheel." Furthermore, becoming familiar with the state-of-the-art often causes new ideas to occur and can help you in deciding upon or narrowing in on your eventual topic. The proposal is also important so that I can judge the probability of success for your final project. Often times, students may propose to engage in a topic that is too large in scope for the result to be practical. I am aware that you only have a couple of weeks until the due date for the final project and that you have other classes, so I will judge your proposal on the merit of the project, the background work you have put in to choosing a topic, the likelihood of success, and determination if the topic is well-known and really does not warrant further study. While I am not expecting altogether new breakthroughs our ground-breaking research, I do expect that you will choose a topic that requires some amount of your own effort in development and is not simply a survey of past results. Even if your project results in a

complete failure of obtaining your goals, if you have followed a sound and logical method of formulating a hypothesis, conducting some form of evaluation or experiment, and properly documented your results, you will have a successful project outcome for the class. The proposal and final project are meant to be an opportunity for you to demonstrate to me that you understand the material and are capable of independent thought and logical reasoning in developing your own ideas and practices. This is NOT a "book report" or topical "survey" assignment. I want you to show me that you can exercise your own analysis and design skills.

Finally, I would encourage you to budget your time carefully. A common mistake is to work on the actual project up until the due date. This means that you have little time left to generate the final report and presentation. When this happens, students often may not receive all the credit they are due since it is the report and presentation that is ultimately graded. If you do not have time to do a good job in preparing your documentation, I have no way of appreciating all the time and effort you expended in actually doing the project. A good rule-of-thumb is to set a personal due date for finishing your project work that leaves at least two or three days to generate the final report and presentation. That way you can finish a first draft and then "sleep on it." You will often find that picking up your first draft and reading through it the next day leads to substantial improvements in the final product. Although this varies based on your own personality, I personally find it useful to build my presentation first, going heavy on figures and equations and less so on bullet lists and text. Then the report can be composed by inserting text to describe the figures and equations.

3.1 SPECIFIC EXAMPLE TOPICS

Some example topics follow:

1. Describe and thoroughly analyze a quantum informatics implementation technology. This will include a description of the technology as well as its mathematical model. The limitations and advantages of your chosen technology must also be included. Some examples of technologies include: superconducting solid-state semiconductor (SSC) qubits such as the transmon, or other charge or flux-based qubits including how they can be made to interact with one another, ion trap based qubits and systems, topological qubits based on anyons and braid groups for operations (such as that being employed by Microsoft for their quantum computer), spin-based systems, quantum dots, nuclear magnetic resonance, diamond-based nitrogen-vacancy qubits, using phonons as qubits, etc. You may also focus on aspects of the implementation. For example a deep and thorough analysis of the underlying SQUID-based circuitry that serves as a basis for some SSC qubits, or the mechanisms of coupling SSC qubits may be a topic of interest. I would expect to see analyses using Hamiltonian mechanics and perhaps simulations with SMU-available software tools for such a project.
2. Describe and thoroughly analyze special-purpose quantum informatics implementations for metrology, sensing, communications, informatics, or computing. Some examples include quantum radar, quantum networks, navigational aids involving quantum informatics, quantum crypto systems, continuous qubit communications, etc.

3. Alternative forms of quantum computing paradigms and hybrid systems. We have focused on the gate-based or the Feynman-Deutsch model, but there are many others of interest. Examples include quantum annealing (like the DWave computers), topological computation based on braid group operators, one-way/cluster-state, or measurement-based computation, adiabatic quantum computing, continuous qubit computation, etc. An example may be to focus on quantum annealing and to describe the class of suitable problems, survey the state-of-the-art and perhaps include implementaitons using the DWave machines.
4. Quantum cryptography topics. Survey and thorough analysis of new "super-encryption" methods using quantum informatics. Another topic could be post-quantum encryption (PQC) that includes newly proposed classical encryption techniques that are not vulnerable to quantum attacks. Why are they superior? What makes PQC non-vulnerable? Or perhaps, the threat of quantum computation to modern encryption (not just Shor's algorithm and RSA, but other types of encryption). Or perhaps, how new quantum-based encryption protocols could be implemented, how they work, what makes them superior to classical methods.
5. Development of a functionally complete set of quantum computational operators/gates/primitives for a specific technology. This would involve choosing one or more implementation technologies and showing how a set of operators could be implemented using that technology that are functionally complete in the sense that using that set of operations allows any arbitrary computation to be implemented. This is similar to the concept that the use of the AND, OR, and NOT gates in digital electronics are sufficient to implement any arbitrary switching function. As an example, classes of operators based on anyons, continuous qubits, photonic observables such as OAM.
6. Quantum error detection and correction. Survey and thoroughly analyze different methods for quantum error correction. This is considered to be an enabling technology to combat the effects of decoherence and other probabilistic errors that occur in the implementation of quantum informatics systems. You must include a discussion of fault models (the "stuck-at" model for digital electronics is not applicable to quantum informatics) as well as the underlying theoretical mechanisms that enable fault tolerance.
7. Implementation and experimentation of a suitably complex quantum algorithm on an available quantum computer. For example, IBM offers free accounts on there IBMQ machines and you can freely obtain an account and write programs to run on the IBMQ computers. Your algorithms must not be too complex or too simple. Preferably, you may also consider developing a new algorithm that has not been previously published, but an implementation and analysis of an existing algorithm may be permitted if your proposal is accepted.
8. Development a quantum device or system simulator. That is, you could choose to develop a technology-specific method that takes into account the characteristics of a particular technology, or you could develop comparison of your approach to those in the literature. Alternatively, a behavioral simulator that operates at a higher level of abstraction and is technology independent.

9. Simulate a quantum communications system including the transceivers and channel. Thoroughly describe the transmitter, receiver (or transceiver) as well as the channel. Describe how you simulate the effects of loss and decoherence. You may choose to focus on a single subsystem in more detail (i.e., the receiver, transmitter, encoding, compression, error detection/correction, channel) or utilize a broader overall system as a subject of study. An example may be to choose a quantum channel where you compare and contrast different quantum informatics technologies as related to the channel. You may decide to focus on wired, wireless, or both channels.
10. Thorough description and analysis of quantum complexity classes. The well-known computational theory for classical computers based on the Turing machine model falls apart for quantum computation since they are not modeled as Turing machines. New complexity classes have been proposed. you should describe these new complexity classes and describe how to perform complexity analyses (with examples) for quantum algorithms. A tradeoff and description of the advantages and disadvantages of algorithms implemented in quantum versus classical computers should be included.
11. Applications of quantum informatics to other areas. For example, many people hypothesize that one of the most promising applications of quantum informatics will be in the area of new medicines and quantum biochemistry. An analysis of how quantum informatics can be applied and how the area will benefit. Another example is the use of quantum informatics in the financial area. How will new quant methods be improved if quantum computers are available? How can quantum computers be used to predict financial market behavior and to enhance trading decisions? Alternatively, the interplay of quantum technologies with conventional cybersecurity, data science, or other fields.
12. Quantum data science and machine learning. An emerging field is the application of quantum informatics to data science and machine learning. The HHL algorithm for solving linear systems is an example of one of these new advances. How can data be represented in the form of qubits? And how can quantum data be processed with machine learning methods that enhance prediction/classification accuracy or yield improved performance? This is a new field with many opportunities for advancement and the field has many undefined and ill-defined concepts.
13. Quantum networking. We have seen that data compression of quantum data is theoretically superior to any possible compression of classical data. The promise of a "quantum Internet" is very exciting and alluring. What are the technological hurdles of implementing a quantum network? How can a superimposed and or entangled quantum state be transmitted without performing a measurement and thus destroying the information content? How can a quantum state be transferred from one technology to another without measurement? The proposal, design, and analysis/simulation of a new protocol at various network layers that supports quantum information would be a great project.
14. Quantum memory and RAM-based systems. A big problem is the lack of a quantum state memory. In a sense, superconducting solid-state qubits do serve

as short-term quantum state memories, but how can these be scaled, how can error correction be incorporated, how can volatility due to decoherence be improved? What technologies are most promising and what are the limitations and advantages of each in terms of their use to construct a quantum memory? How can quantum states stored in a quantum memory be read, written, refreshed and converted from stationary qubits (like transmons, trapped ions) into "flying" qubits (like photons)?

15. Quantum measurement. We discussed and derived the concepts behind projective quantum measurement in class. However, this is an ideal model that assumes qubits only exist in a closed system. Generalized measurement requires consideration of the environment. A model of measurement is the so-called the use of positive semi-definite operators for positive-operator valued measurement (POVM). Describe and analyze the POVM model. Include a discussion about how POVM can be implemented and its advantages. Give examples and include a POVM-based sample system with a thorough analysis of its operation. Describe how external environmental effects are included in POVMs and/or generalized measurements.
16. Quantum informatics for navigation. How can quantum informatics be used to sense an objects position in latitude, longitude, and height above sea-level? Quantum gravitometers and magnetometers (as well as other sensors) have recently been proposed as implementations for navigational systems that can operate in a GPS-denied environment. Survey the existing approaches and propose new ones. Perform an accuracy study to compare quantum-based navigational aids in comparison to GPS. How can they be implemented and what are the challenges, limitations, and advantages?
17. Use of entanglement and teleportation to enhance communications. These are phenomena unique to quantum mechanical theory that have far-reaching theoretical advantages to quantum communications. In 2017, the Chinese government launched the Micius quantum informatics satellite and demonstrated that entanglement can be used to transfers information through a quantum wireless channel that is secure and over a long distance. Thoroughly analyze the Micius experiments and technology and describe enhancements and ways that this technology can be used in future systems.
18. Higher-radix qudits. We have focused on the use of qubits comprised of wave functions that are confined to two states. How can the use of higher states be incorporated into quantum informatics technology? What are the benefits and technological challenges? Apply higher-radix qudits to applications in communications, sensing, metrology, and computing and show the benefits and limitations. As an example, how could the Micius experiments (describe din the previous topic) be expanded to use higher-dimensional quantum digits? What are the challenges preventing the use of qudits and how could well-known quantum algorithms be implemented more efficiently through the use of qudits?

4.0 PROPOSAL/PROJECT REPORT STRUCTURE

These are just a few examples of possible topics. Each of the above examples encompasses several possible projects. Keep in mind that a more narrow selection from one of the above topics is permissible, but more thorough analysis/implementation/study

would be required. Again, I want to emphasize that a survey of existing technology should only be one portion of your project, I do expect you to demonstrate your ability to hypothesize, experiment, and document with some of your own ideas as well. Unlike a typical academic research project, I do not expect that everyone will successfully come up with an entirely new idea and show it is viable. Even if you ideas do not ultimately succeed, as long as you performed a thorough and rigorous study, you will receive credit. However, if you do happen to propose a new idea and show that is viable, then I would be happy to work with you to transform your work into a publishable contribution that could also potentially turn into a thesis topic for graduate study if you decide to pursue it.

The requirements for a successful proposal, in addition to the issues described above, include the following sections. Your proposal should generally have the following sections, although I am giving them generic subsection titles. I do not expect that you would copy this outline strictly, but it should include these topics:

1. **100-250 word abstract** that serves as a synopsis of your entire proposal (and eventually, your entire final report). This should be written LAST as it is a complete summary of the content of your proposal/project report.

2. **Introduction** that is no more than one to one and half pages in the IEEE format. The introduction describes the subject of your paper, why it is important and of interest, briefly surveys past approaches (with references), and briefly describes what is new, different, or included in the rest of your paper.

3. **Background section**. This section gives a summary of the topics that your reader will need to know to understand the remainder of your paper. For example, if you decide to do a project on sensing/measurement systems using topological anyon based qubits, you might include a subsection that gives a brief introduction to anyon-based qubits including what they are and their mathematical models along with appropriate foundational and tutorial/introductory references. This is a very important part of the proposal as it is your opportunity to show me that you have "done your homework." this should be no more than two pages of your final project paper.

4. **Approach section**. This section describes exactly what you plan to do (proposal), or have accomplished (final report). This should be described in enough detail that another engineer or scientist who is "skilled-in-the-art" could reliably recreate or repeat your approach and recreate your process of experimentation and/or analysis. This section, along with the background section, are likely the two most important parts of your proposal since it will describe to me the work you plan to accomplish for your final project.

5. **Results section**. This is the section that describes the outcome of your project. For the proposal, it should describe what you ANTICIPATE will happen including both if your work/hypotheses are successful and if it is not. You should attempt to describe alternative approaches if your primary plan fails or unavoidable roadblocks appear (proposal only). For example, if you propose to do a project using anyons to design a navigational aid and you run into a technological hurdle that you can't overcome, include a backup plan; perhaps using a different technology or perhaps a different application. Some projects may be more on the development/implementation side while others are more theoretical. All engineering and science papers need some form of validation or proof section, but the form of these can vary. For example, a new theoretical principle can be proven with lemmas,

theorems, and corollaries, a new algorithm or method can be demonstrated with a table/plot of empirical results, a case study can be validated with a simulation study, etc. Think about how you will demonstrate the outcome of your project. It is not expected that your proposal will have results, although some preliminary results may be applicable. However, your proposal should have a sound plan for how you will demonstrate outcomes of your study. In the final report, this section should include a comparison of alternative approaches identified in the background section. For the proposal, you may choose to include results from other approaches and point out the limitations of these that you intend to improve upon. A common mistake is to overwhelm the reader with too many results in the final report. When writing the final report, you need to think about how you can provide your results in a comprehensive, but succinct manner. This section should not be much more than two pages.

6. **Summary, conclusion section**. This section should briefly summarize the content of the entire paper. It should briefly describe the overall objective, the motivation for your study, the approach, and a summary of the results with an emphasis on major outcomes. This section is usually one to three paragraphs in length.

7. **References section**. This is a bibliography of important past results, motivating papers/approaches, the background papers, etc. You should try to have results from several different researchers and groups and avoid having numerous citations from closely related work from a single group. Leaving out important past work related to your project is a fatal error and cause your work to not be taken seriously since it indicates to the informed reader that you are apparently not aware of important past work. The references section typically is comprised of 10 to 20 different references and those that are publically available are greatly preferred. For example, including only references to personal communications, class notes, and other private sources is not a good strategy. It is OK to have a few of these references, but you should include sources from publically available sources for the most part. This is another important section for your proposal. Including only web-based sources is also bad practice. It is not good enough to just use Google to find your sources. Some of these are permissible, but I expect to see sources available from IEEEXplore and other publications sources. Also, including too many textbook sources is also bad practice. Textbooks are general and introductory and do not, in general, provide the detail and depth required for a proper references section. A great resource is also the quant-physics arXiv and some citations can certainly include these, although I expect to see some sources from publications cites such as IEEEXplore, ACM digital libraries, Spring-Verlag, Elsevier, and others. These are all available in digital form from the SMU libraries. Sources you need that are not online can be obtained in PDF form by filling out a request form on the SMU library webpage. The librarians are generally very receptive and quick to find the resource, scan it, and email it to your account. I will be checking your references and if I find that they are not well related or have obviously not been read by you, you will lose credit on your proposal and final project. I will finally caution you to ensure that some of references are fairly recent. While the inclusion of seminal papers from years past is acceptable, you should also demonstrate that you have considered more recent work as well. Finally, a great way to find other relevant references is to consider the papers referenced in some of the articles that you find on your own. In particular if a certain paper seems to be heavily referenced in your sources, it is likely worth taking a look at to determine if it is applicable to your project.

5.0 TEMPLATES FOR PROPOSAL/PROJECT FINAL REPORT

Sources for document templates are here:
https://www.ieee.org/conferences/publishing/templates.html

6.0 REFERENCE SOURCES

Important resources for papers are:

IEEEXplore (SMU access):
https://ieeexplore-ieee-org.proxy.libraries.smu.edu/Xplore/home.jsp

ACM Digital Libraries (open access during COVID19 era)
https://dl.acm.org

Access to SMU digital online sources:
https://smu.primo.exlibrisgroup.com/discovery/search?sortby=rank&vid=01SMU_INST:01SMU&lang=en

SMU Inter-library Loan (for papers not present in the collection)
https://www.smu.edu/Libraries/fondren/services/ILL

Quantum Physics arXiv:
https://arxiv.org/archive/quant-ph

7.0 FINAL REMARKS

If you do a good job on your proposal, you will have already written 40-60% of your final report. You will not waste time during the performance of your project in looking up and understanding past work because you will have already accomplished this portion of your project. I am more than happy to discuss other aspects of your proposal and project and I will grade your proposals quickly to provide guidance and feed back. A good way to study the typical structure of engineering and scientific articles is to simply refer to those already published, even if they are in a different subject area. While my own papers are certainly not perfect examples, I do have many of my conference/journal papers online at https://s2.smu.edu/~mitch/publications.html. I do NOT expect to see your reference section heavily populated with my own papers though, although you can use some of them if they are relevant.

While your proposal will only be worth a homework grade, it inherently carries more weight in your final grade since the effort you put into the proposal will directly affect your final project grade and that one is worth more points (the equivalent of a test grade for the final examination).