Quantum Information and Computation
Final Project Guideline

(Report Due: 23:30, June 8, 2022)

1 General Rules

Goal: Self-study or research on a topic related to *Quantum Information and Computation* .

What to do: Students may choose either of the following items or *beyond*[1].

- Read and summarize current development of a subject related to *Quantum Information and Computation* . This involving elaborations of the central ideas/concepts, reading milestone research papers and explaining what have they done. (Some sample but no limited topics and papers can be found in Section 3; Also stay turned on the NTUCOOL course website.)
- Propose and do a research problem. Formally state the research problem you aim to solve and explain the proposed methodology for it. You may not have enough time to completely solve a problem by the deadline yet. It is OK; do present your method and why you think it should work. Finding a decent research problem is a highly non-trivial task; it will be much appreciated. Please do literature survey to make sure that your target problem is really new before diving into it.
- Initiate a new interdisciplinary field that involves *Quantum Information and Computation* and others. Carefully describe how you conduct tools and machinery of *Quantum Information and Computation* in an academic or industrial field that could benefit each other. Provide evidences for your assertion. Please do sufficient literature survey to make sure that your idea is new.
- Invent a novel algorithm and perform numerical implementations. This is a theory course, so numerical experiments are not so encouraged, unless your novel algorithm can beat the state-of-the-art methods in *Quantum Information and Computation* .

Paperwork presentation. There is no hard requirement on how you present the paperwork report of the final project. Either using English or Mandarin for the write-up are fine; but English is preferred. There are NO page limits nor template limits. Imagine you are the author, and prepare to submit your result to a top conference, or an academic journal, or applying an Intellectual Property Patent. As such, your report should contain a clear and insightful description of what you have done, your ideas, their potential impact, and their importance to *Quantum Information and Computation* . The report should be presented in a professional and decent way to facilitate an intuitive understanding of your project that the reader can easily learn from it and assess the importance. More importantly, you have to write the report *in your own voice* independently. All sources in helping on your project should be cited, and DO NOT copy the content of anything you do not own the authorship. **Academic offense and plagiarism are strictly forbidden**.

[1]Please do not set limit on yourself. You are highly welcomed to push it forward and strive for excellence. It is not merely a final project report; rather, it is encouraged to extend it to a practical research work, a publishable academic paper, an Intellectual Property Patent.

Video or in class presentation. A recorded video presentation is required. If the situation is allowed, in class presentation is highly encouraged. We will choose and propose a some well-presented videos on the NTUCOOL, so other student can learn from it. The video is preferable not longer than 30 minutes.

2 Grading Policy and Submission Formats

Submission formats. The main paperwork report (in the PDF format only) and other supporting materials (if any) have to be submitted to the NTUCOOL by 23:30, June 8, 2022. No late submission is allowed. If there are many students asking for more time, then a two-day extension might be possible. If you also prepare a recorded video presentation, please make sure that the format is MP4. It is preferable that you send me a download link of your video as early as possible (say, e.g. before one week of the deadline) so that we can access your content and further propose it on the NTUCOOL.

Grading Policy. The final project report constitutes 40 % of the total points of the course (see Table 2). The report will be judged by the following reference points (see also Table 1):

- *Readability/Clarity*. The report should be well-written and clearly readable.
- *Literature survey*. Relevant literature or existing works should be surveyed in the report.
- *Broadness*. It means your report has covered broad and comprehensive aspects within the topic.
- *Technical depth*. You might spend more time on the project if the topic is technical demanding.
- *Impact/Contribution/Novelty*. The importance (in any reasonable sense) of your report should be addressed.
- *Video presentation (flexible)*. The video presentation is not mandatory but it is beneficial to the total points.

Note that the above grading criteria are basic reference but not strict. For example, if you have solved a specific research open problem in the final project. Though it might not be *broad* enough, it is fine since the technical depth and the contribution might be overly excess (i.e. 爆表, 外溢).

Grading Reference	Percentage
Readability/Clarity	30 %
Survey on relevant literature or topics	30 %
Broadness	10 %
Technical depth	10 %
Impact/Contribution/Novelty of your project	20 %
Video presentation (flexible not mandatory)	(25 %)
Total	100 %

Table 1: Grading policy for the final project.

HW0	HW1	HW2	HW3	Mid-Term Exam	Final Project	**Total**
0 %	15%	15%	15%	25%	30%	100 %

Table 2: Grading Percentage for the course *Quantum Information and Computation* .

3 Possible Topics and Related Papers

This is not an exhaustive list. If you want a subject not on this list and not sure if it is related to *Quantum Information and Computation* , just send Instructor an email for a discussion to see if it is acceptable.

(a) Quantum Entanglement [1].
  - Embezzlement of entanglement.
  - Entanglement Distillation.
  - Entanglement Witness.
  - Entanglement Monotone.

(b) Quantum Nonlocality [2]:

(c) Local quantum operations and classical communication (LOCC) [3].

(d) Quantum Error Correction [4, 5]:
  - Fault-tolerant quantum computation [6].
  - Surface codes; topological codes [7].
  - Quantum polar codes; quantum LDPC codes.
  - Holographic codes.
  - Complexity of decoding quantum codes.
  - Self-correcting quantum memories.

(e) Continuous Variables in Quantum Information [8, 9, 10, 11].

(f) Quantum Cryptography [12].
  - Entropy accumulation [13].
  - Information-theoretic security proof for quantum-key distributions [14].

(g) Quantum Sensing and Metrology [15, 16].

(h) Quantum Tomography [17, 18, 19, 20, 21, 22].

(i) Quantum Markov State [23, 24].

(j) Quantum Machine Learning [25].
  - Barren Plateaus.
  - Quantum no-free-lunch theorem.
  - Quantum Boltzmann machines.
  - Quantum PAC learning.
  - Advantages of quantum machine learning.

(k) Quantum communication and information complexity [26, 27, 28].

(l) Quantum Algorithms [29].

(m) Quantum Communication Theory [30].

- Quantum reverse Shannon theory.
- Finite blocklength analysis.
- Error exponent analysis.

(n) Quantum Information-Theoretic Protocols [31].

(o) Quantum Channel Capacities [32].

- Holevo quantity is not additive [33].
- Continuity of quantum channel capacities [34].
- Classical, private, quantum, zero-error, and entanglement-assisted capacities.
- Hardness of calculating quantum channel capacities [35].

(p) Quantum Entropy Inequalities.

- Strong subadditivity [36].
- Entropy power inequalities.

(q) Quantum Resource Theories [37, 38, 39].

(r) Quantum Computer Architecture [40].

(s) Other applications:

- Measure concentration and randomized techniques in quantum information.
- Quantum control.
- Quantum finance.
- Quantum simulations.

References

[1] R. Horodecki, P. Horodecki, M. Horodecki, and K. Horodecki, "Quantum entanglement," *Reviews of Modern Physics*, vol. 81, no. 2, pp. 865–942, jun 2009.

[2] N. Brunner, D. Cavalcanti, S. Pironio, V. Scarani, and S. Wehner, "Bell nonlocality," *Reviews of Modern Physics*, vol. 86, no. 2, pp. 419–478, apr 2014.

[3] E. Chitambar, D. Leung, L. Mančinska, M. Ozols, and A. Winter, "Everything you always wanted to know about LOCC (but were afraid to ask)," *Communications in Mathematical Physics*, vol. 328, no. 1, pp. 303–326, mar 2014.

[4] D. Gottesman, "An introduction to quantum error correction and fault-tolerant quantum computation." [Online]. Available: https://arxiv.org/abs/0904.2557

[5] B. M. Terhal, "Quantum error correction for quantum memories," *Reviews of Modern Physics*, vol. 87, no. 2, pp. 307–346, apr 2015.

[6] E. T. Campbell, B. M. Terhal, and C. Vuillot, "Roads towards fault-tolerant universal quantum computation," *Nature*, vol. 549, no. 7671, pp. 172–179, sep 2017.

[7] A. G. Fowler, M. Mariantoni, J. M. Martinis, and A. N. Cleland, "Surface codes: Towards practical large-scale quantum computation," *Physical Review A*, vol. 86, no. 3, sep 2012.

[8] S. L. Braunstein and P. van Loock, "Quantum information with continuous variables," *Reviews of Modern Physics*, vol. 77, no. 2, pp. 513–577, jun 2005.

[9] A. Ferraro, S. Olivares, and M. G. A. Paris, "Gaussian states in continuous variable quantum information." [Online]. Available: https://arxiv.org/abs/quant-ph/0503237

[10] C. Weedbrook, S. Pirandola, R. García-Patrón, N. J. Cerf, T. C. Ralph, J. H. Shapiro, and S. Lloyd, "Gaussian quantum information," *Reviews of Modern Physics*, vol. 84, no. 2, pp. 621–669, may 2012.

[11] G. Adesso, S. Ragy, and A. R. Lee, "Continuous variable quantum information: Gaussian states and beyond," *Open Systems & Information Dynamics*, vol. 21, no. 01n02, p. 1440001, mar 2014.

[12] S. Pirandola, U. L. Andersen, L. Banchi, M. Berta, D. Bunandar, R. Colbeck, D. Englund, T. Gehring, C. Lupo, C. Ottaviani, J. L. Pereira, M. Razavi, J. S. Shaari, M. Tomamichel, V. C. Usenko, G. Vallone, P. Villoresi, and P. Wallden, "Advances in quantum cryptography," *Advances in Optics and Photonics*, vol. 12, no. 4, p. 1012, dec 2020.

[13] F. Dupuis, O. Fawzi, and R. Renner, "Entropy accumulation," *Communications in Mathematical Physics*, vol. 379, pp. 867–913, 2020.

[14] R. Renner, N. Gisin, and B. Kraus, "Information-theoretic security proof for quantum-key-distribution protocols," *Physical Review A*, vol. 72, no. 1, jul 2005.

[15] V. Giovannetti, S. Lloyd, and L. Maccone, "Advances in quantum metrology," *Nature Photonics*, vol. 5, no. 4, pp. 222–229, mar 2011.

[16] C. L. Degen, F. Reinhard, and P. Cappellaro, "Quantum sensing," *Reviews of Modern Physics*, vol. 89, no. 3, jul 2017.

[17] G. M. D'Ariano, M. G. Paris, and M. F. Sacchi, "Quantum tomography," in *Advances in Imaging and Electron Physics*. Elsevier, 2003, pp. 205–308.

[18] K. Banaszek, M. Cramer, and D. Gross, "Focus on quantum tomography," *New Journal of Physics*, vol. 15, no. 12, p. 125020, dec 2013.

[19] I. L. Chuang and M. A. Nielsen, "Prescription for experimental determination of the dynamics of a quantum black box," *Journal of Modern Optics*, vol. 44, no. 11-12, pp. 2455–2467, nov 1997.

[20] J. F. Poyatos, J. I. Cirac, and P. Zoller, "Complete characterization of a quantum process: The two-bit quantum gate," *Physical Review Letters*, vol. 78, no. 2, pp. 390–393, jan 1997.

[21] M. Mohseni, A. T. Rezakhani, and D. A. Lidar, "Quantum-process tomography: Resource analysis of different strategies," *Physical Review A*, vol. 77, no. 3, mar 2008.

[22] M. P. da Silva, O. Landon-Cardinal, and D. Poulin, "Practical characterization of quantum devices without tomography," *Physical Review Letters*, vol. 107, no. 21, nov 2011.

[23] O. Fawzi and R. Renner, "Quantum conditional mutual information and approximate markov chains," *Communications in Mathematical Physics*, vol. 340, no. 2, pp. 575–611, sep 2015.

[24] D. Sutter, *Approximate Quantum Markov Chains*. Springer International Publishing, 2018.

[25] S. Arunachalam and R. de Wolf, "Guest column: a survey on quantum learning theory," *ACM SIGACT News*, vol. 48, no. 2, pp. 41–67, jun 2017.

[26] R. de Wolf. [Online]. Available: https://homepages.cwi.nl/~rdewolf/qcommcompl.pdf

[27] H. Buhrman, R. Cleve, S. Massar, and R. de Wolf, "Nonlocality and communication complexity," *Reviews of Modern Physics*, vol. 82, no. 1, pp. 665–698, mar 2010.

[28] D. Touchette, "Quantum information complexity and amortized communication." [Online]. Available: https://arxiv.org/pdf/1404.3733

[29] A. K. T. I. L. C. John M. Martyn, Zane M. Rossi, "A grand unification of quantum algorithms." [Online]. Available: https://arxiv.org/abs/2105.02859

[30] "Principles of quantum communication theory: A modern approach." [Online]. Available: https//arxiv.org/pdf/2011.04672

[31] A. Abeyesinghe, I. Devetak, P. Hayden, and A. Winter, "The mother of all protocols: restructuring quantum information's family tree," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 465, no. 2108, pp. 2537–2563, jun 2009.

[32] M. M. Wilde, *Quantum Information Theory*. Cambridge University Press, 2016.

[33] G. Aubrun, S. Szarek, and E. Werner, "Hastings's additivity counterexample via dvoretzky's theorem," *Communications in Mathematical Physics*, vol. 305, no. 1, pp. 85–97, nov 2010.

[34] D. Leung and G. Smith, "Continuity of quantum channel capacities," *Communications in Mathematical Physics*, vol. 292, no. 1, pp. 201–215, may 2009.

[35] T. Cubitt, D. Elkouss, W. Matthews, M. Ozols, D. Pérez-García, and S. Strelchuk, "Unbounded number of channel uses may be required to detect quantum capacity," *Nature Communications*, vol. 6, no. 1, mar 2015.

[36] I. H. Kim, "Operator extension of strong subadditivity of entropy," *Journal of Mathematical Physics*, vol. 53, no. 12, p. 122204, dec 2012.

[37] E. Chitambar and G. Gour, "Quantum resource theories," *Reviews of Modern Physics*, vol. 91, no. 2, apr 2019.

[38] K. Kuroiwa and H. Yamasaki, "General quantum resource theories: Distillation, formation and consistent resource measures," *Quantum*, vol. 4, p. 355, nov 2020.

[39] I. Devetak, A. W. Harrow, and A. J. Winter, "A resource framework for quantum shannon theory," *IEEE Transactions on Information Theory*, vol. 54, no. 10, pp. 4587–4618, oct 2008.

[40] Y. Ding and C. T. Frederic, *Quantum Computer Systems: Research for Noisy Intermediate-Scale Quantum Computers*. Morgan & Claypool Publishers.