UNIVERSITÉ DE SHERBROOKE
Faculté des sciences
Département de physique

PHY745 — Modélisation de la matière et calcul quantique

Course details

Course type: optional
Prerequisites: PHQ430 or equivalent
Credits: 3
Time: Thursday 10:30-12:20, Friday 10:30-12:20
Place: MS Teams channel

Instructor

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1 Context and motivation

Since Feynman's proposal of a universal quantum simulator[1], the simulation of quantum matter has been a cornerstone of quantum computation. This course aims to illustrate why this is the case, particularly how the physical properties of quantum condensed matter systems, as studied with toy models of spins and particles, translate to key concepts of quantum information and quantum computation.

2 Learning outcomes

Main goal — to become familiar with the notions of *quantum entanglement* and *entanglement entropy* and their importance in the modelling of quantum condensed matter and quantum computation.

Specific objectives — By the end of the course, students will be able to:

- employ the density matrix formalism to treat pure and mixed quantum states;
- quantify entropy and entanglement in quantum states;
- express unitary evolution and measurement with quantum circuits;
- elucidate the link between quantum computation and quantum simulation of matter;
- use entanglement area and volume laws to categorize quantum states of matter;
- compute properties of quantum systems in the formalism of matrix product states.

3 Activities

- *Video lectures*: weekly lecture to be reviewed *before* weekly walkthrough and Q&A sessions.
- *Readings*: weekly material to be reviewed *before* weekly walkthrough and Q&A sessions.
- *Walkthroughs*: in-depth elaboration and examples of key concepts; once a week on MS Teams. **NB: this is a crucial part of the course and essential preparation for homeworks and exam**.
- *Q&A sessions*: small-group meetings with instructor; once a week on MS Teams.
- *Weekly homework*: problems on the material covered each week.
- *Quizzes*: interspersed between the video lectures.

[1] R. P. Feynman, *Simulating Physics with Computers*, International Journal of Theoretical Physics **21**, 467 [pdf]

4 Evaluation

- Weekly homework: 50% of the final grade.
- Final exam: 40% of the final grade.
- Participation: 10% of the final grade.

Remarks:

- The date of the final exam is determined by the Faculté des sciences.
- Homework problems are made available every week and due Sunday 23:59 of the *following* week.
- Homework problems are graded ✓ / ✗; any problem graded ✗ can be reworked and resubmitted.
- Participation entails (a) active presence in walkthroughs, and (b) completion of quizzes.
- Quizzes are *not* graded.

5 Plan

Part I: Building blocks of quantum information

- *Week 1*: review of probability theory (random variables, correlations, Shannon entropy) and linear algebra (Hilbert space, Hermitian operators, spectral decomposition).
- *Week 2*: the postulates of quantum mechanics, Schmidt decomposition, entanglement, no-cloning theorem.
- *Weeks 3-4*: the postulates of quantum mechanics in terms of density matrices, density matrix kung fu, von Neumann entropy, entanglement entropy.

Part II: (Quantum) matter meets (quantum) information meets (quantum) computation

- *Week 5*: quantum gates, gate set universality.
- *Week 6*: (quantum) computational complexity, circuit model of quantum computation.
- *Week 7*: quantum simulation, adiabatic quantum optimization.

Part III: Entanglement volume and area laws and matrix product states

- *Weeks 8-9*: volume and area laws of entanglement.
- *Weeks 10-11*: matrix product state formalism, applications to modelling of quantum matter and quantum information.
- *Week 12*: revision.

6 Course material

The course follows chapters from the following works:

- M. Mézard and A. Montanari, *Information, Physics, and Computation*, Oxford Graduate Texts (2009); preprint version available at https://web.stanford.edu/~montanar/RESEARCH/book.html.
- M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information*, 10th Anniversary Edition, Cambridge University Press (2010). [relevant pages available on Moodle]
- A. Childs, *Lecture Notes on Quantum Algorithms*; available at https://www.cs.umd.edu/~amchilds/qa/.
- J. C. Bridgeman and C. T. Chubb, *Hand-waving and Interpretive Dance: An Introductory Course on Tensor Networks*, Journal of Physics A: Mathematical and Theoretical **50**, 223001 (2017); full text freely available on publisher's website.

Supplementary references:

- M. M. Wilde, *Quantum Information Theory*, 2nd Edition, Cambridge University Press (2017); pre-publication version available at https://arxiv.org/abs/1106.1445
- B. Zeng, X. Chen, D.-L. Zhou, X.-G. Wen, *Quantum Information Meets Quantum Matter*, Springer, New York, NY (2019); full text at https://link.springer.com/book/10.1007/978-1-4939-9084-9; full text freely available on publisher's website.
- V. Vedral, *Quantifying entanglement in macroscopic systems*, Nature **453**, 1004 (2008); full text at https://vlatkovedral.physics.ox.ac.uk/nature07124.pdf.
- L. Amico, R. Fazio, A. Osterloh, and V. Vedral, *Entanglement in many-body systems*, Reviews of Modern Physics **80**, 517 (2008); full preprint text at https://arxiv.org/abs/quant-ph/0703044.
- U. Schollwöck, *The density-matrix renormalization group in the age of matrix product states*, Annals of Physics **326**, 96 (2011), full preprint text at https://arxiv.org/abs/1008.3477.
- J. Preskill, *Lecture notes on quantum computation*, available at http://www.theory.caltech.edu/people/preskill/ph229/.