Course Syllabus

18819F: *Introduction to Quantum Computing*
47779/47785: *Quantum Integer Programming and Quantum Machine Learning*
Fall 2022 (MW: 4:40-6:30 pm; Room 2701 Tepper Quad)

Instructor: Prof. Elias Towe
Office Location: 147 Roberts Hall
Email Address: towe@cmu.edu
Office Hours: Tue 1:30-2:30 pm (In-person/Online)

Instructor: Prof. Sridhar Tayur
Office Location: 4216 Tepper Quad
Email Address: stayur@cmu.edu
Office Hours: By appointment only

Instructor: Dr. David Bernal
Office Location: Virtual
Email Address: bernalde@cmu.edu
Office Hours: By appointment only

Instructor: Dr. Davide Venturelli
Office Location: Virtual
Email Address: DVenturelli@usra.edu
Office Hours: By appointment only

Teaching Assistant: Pruthviraj Gampalwar
Office Location: https://cmu.zoom.us/my/pruthvirajg
Email: pgampalw@andrew.cmu.edu
Office Hours: Wed 10:15 – 11:15 am
Teaching Assistant: Jiaqi Guo
Office Location: https://cmu.zoom.us/j/4793550860?pwd=YndLZXRWYkNFdlhYeWtoOXpXQzJ1QT09
Email: jiaqiguo@andrew.cmu.edu
Office Hours: Wed 10:15 – 11:15 am

Course Management Assistant: Michele Passerrello
Email: mpasserr@andrew.cmu.edu
Office Location: HH 1113

Course Description:

This course is primarily designed for graduate and advanced undergraduate students. It covers recent developments in Quantum Computing for solution of combinatorial optimization problems and machine learning. The course covers integer programming and machine learning, their non-quantum (classical) solution methods, and concepts that take advantage of near-term quantum and quantum-inspired computing. The annealing and circuit model of quantum computing that are currently implemented in various hardware incarnations will be explained. The course explores how these machines will potentially be used for hardware-tailored machine learning algorithms to solve problems that classical computers struggle with. The course contains a series of lectures that expose students to practical exercises using quantum resources such as quantum annealing and gate-based computers to gain exposure to these novel computational models, all through the cloud-based Quantum Computing access platform at Amazon Web Services. The main deliverable of the course is a final group project that offers students an opportunity to thoroughly familiarize themselves with a problem of their interest and apply classical and unconventional (quantum and quantum-inspired) computing tools to address the problem in a specific application.

Number of Units: 12

Pre-requisites: None

Graduate Area: Applied Physics

Lectures: Tepper Room: 2701: Mondays/Wednesdays 4:40-6:30 PM.

Required Textbook:

Suggested Reading:

- Isaac Chuang and Michael Nielsen, Quantum Computation and Quantum Information, Cambridge University Press, 2000.
- David Mermin, Quantum Computer Science: An Introduction, Cambridge University Press, 2012.
- Georges Irfah, The Universal History of Computing, John Wiley & Sons, 2001.
- A. Das and B.K. Chakrabarti (Eds.). Quantum Annealing and Related Optimization Methods, Springer-Verlag,2005.
- Eleanor G. Rieffel and Wolfgang H. Polak, Quantum Computing: A Gentle Introduction, MIT Press, 2011.
- Richard J. Lipton and Kenneth W. Regan, Quantum Algorithms via Linear Algebra. A Primer, MIT Press,2014.

Brief List of Topics Covered:

- Introduction to Linear Algebra for Quantum Mechanics and Machine Learning: Complex numbers, vectors and vector spaces, functions as vectors, inner product, norms, projections, Hilbert spaces, basis vectors, matrices, Hermitian operators, and special matrices
- Basic classical machine learning: Support vector machine model; Deep learning neural networks; Running classical machine learning algorithms on computing systems with accelerators; Challenges of running machine learning algorithms on current state-of-the-art classical computing hardware
- Introduction to Mathematical Programming methods: Linear Programming; Integer Programming; Nonlinear Programming; Mixed-Integer Nonlinear Programming; Introduction to computational complexity.
- Ising, Quadratic Unconstrained Binary Optimization (QUBO); Ising model basics; Simulated Annealing, Markov-chain Monte Carlo methods, benchmarking classical methods, Formulating combinatorial problems as QUBOs.
- Introduction to Test Sets; Groebner basis; Graver basis; GAMA: Graver Augmented Multiseed algorithm; Applications: Portfolio Optimization, Cancer Genomics
- Axioms of Quantum Mechanics; Postulates of quantum mechanics, review of classical bits (cbits), the single quantum state and the quantum bit (qubit); Quantum measurement, quantum operations; Multiple quantum states, observables
- Qubit Gate model of quantum computing; Reversible operations on qubits, logic gates and quantum circuits; Qubits for information processing; general quantum computation process; Example of the power of quantum computing, Deutsch's problem

- Quantum methods for solving Ising/QUBO in the NISQ Era; Adiabatic Quantum Computing, Quantum Annealing and D-Wave; QAOA: Quantum Alternating (Approximate) Optimization Ansatz (Algorithm); Exercises on Amazon Bracket
- Physics-Inspired Hardware for solving Ising/QUBO; Graphical Processing Units; Tensor Processing Units; Complementary metal-oxide-semiconductors (CMOS); Digital Annealers; Oscillator Based Computing; Coherent Ising Machines
- Quantum Algorithms for future quantum processors; HHL Algorithms for solving a system of linear equations (Ax = b); Factorizing large numbers; period finding; quantum Fourier Transform; Quantum shell game; Grover's search algorithm
- Noise in quantum computing and quantum error correction; Review of classical error correction methods; quantum error correction

Course Canvas :
Canvas login page : https://cmu.instructure.com/. You should check the course Canvas daily for announcements and handouts.

Course Website: The content will be handled via Canvas.

Homework Project:
Projects will be completed by groups of 2-4 students and will reflect understanding of material covered in the lectures. Components of the project including:

- Identifying a problem that can be posed as an Integer Optimization Problem or a Machine Learning Problem. Discussion of the importance of the problem.
- Summary of the literature relevant to the problem. How is the problem currently solved? Which computational methods are employed to tackle the problem?
- Finding or generating a family of instances or input data for the problem to test solution algorithms on it (consistent with literature or industrial application).
- Attempt to reproduce the state-of-the-art approach for addressing the problem using classical computing approaches. Identify the sources of complexity while solving the problem that might benefit from quantum/quantum-inspired/unconventional (physics-inspired) methods.
- Map the problem and solve it using physics-inspired methods:
  - If you choose an Integer Optimization Problem:
    - Model the problem as a Quadratic Unconstrained Binary Optimization (QUBO). Verify that the reformulation of the problem is valid in the sense that it represents the original problem.
    - Solve the problem using simulated annealing as a benchmark.
  - If you choose a Machine Learning Problem:
    - Formulate a machine learning problem that is amenable to solution by a noisy intermediate-scale quantum (NISQ) processor such as those available in a computing cloud (e.g., Amazon Could Services).
    - Solve the problem using neural networks and classical computing methods (consider solving it without using GPUs as a baseline for the comparison) as a benchmark
- Perform simulations of NISQ devices and/or analytical resource estimates for this problem (so that we know what would be needed at scale when more mature NISQ processors become available in the future).

- If you choose an Integer Optimization Problem:
  - Tackle the resulting QUBO problem using unconventional methods, e.g. Quantum Annealing, QAOA, simulated annealing in GPUs/TPUs, etc. Compare at least two different methods.
- If you choose a Machine Learning Problem:
  - Solve the learning task using hardware accelerators, e.g., GPUs or TPUs. Perform simulations or runs in limited-sized instances in NISQ processors.

- Provide a mid-term report with initial results and plan (15/70) with a short presentation (10/70).
  - Literature review, test instances selection, and initial classical results.
- Write a report outlining strengths-limitations-functional requirements-opportunities of the different approaches used, highlighting the knowledge obtained while developing the project supported by computational results (25/70).
- Make a final presentation to the class reporting the findings of the project (20/70).

There will be an ungraded submission at the beginning of week 3 with the proposed problem to be solved (we can guide you in case you are out of ideas). There is a presentation at the middle of the semester (when the mid-term report is submitted) allowing students to present in front of the class their partial progress and receive feedback.

Much of the second half of the course is devoted to the final project completion, with the office hours aimed at each final project group.

Project groups will be self-created although we will support you in finding a group in case you want to join one. Individual projects are only allowed under exceptional cases. One of the important learning objectives of this course is completing the project in a group (with a considerable amount of work distributed among several individuals).

Reading Assignments:
Specific published articles which will be provided on Canvas from time to time.

Grading Algorithm:

The final course grade will be based on a term project accounting for 70% of the grade and periodic quizzes accounting for 30% of the grade. There will be 4 quizzes, each worth 10 points. Only the best 3 quizzes will count toward the 30%.

Note: While lower cut-offs may be used, the following cut-offs are guaranteed.

Final Grade	Points
A	89 – 100%
B	79 – 88%
C	69 – 78%

The project accounts for 70% of the total grade (30% for weekly short quizzes).

Tentative Course Calendar

Date	Day	Class Activity	Reading Assignment	HW (or Project) Assignment
Aug				
29	Mon	1. Course Overview and Introduction		
31	Wed	2. Review of Linear Algebra Part I: complex numbers, vectors, vector spaces, functions as vectors, inner product, norms, projections, Hilbert space, basis vectors, matrices, Hermitian operators, and special matrices.		
Sep				
5	Mon	Labor Day - No Classes		
7	Wed	3. Review of Linear Algebra Part II: complex numbers, vectors, vector spaces, functions as vectors, inner product, norms, projections, Hilbert spaces, basis vectors, matrices, Hermitian operators, and special matrices.		
12	Mon	4. Basic classical machine learning and its relationship to linear algebra; support vector machine model; deep learning neural networks; Running classical machine learning algorithms on computing systems with accelerators, challenges of running machine learning algorithms on current state-of-the-art classical computing hardware – Part I		
14	Wed	5. Basic classical machine learning and its relationship to linear algebra; support vector machine model; deep learning neural networks; Running classical machine learning algorithms on computing systems with accelerators, challenges of running machine learning algorithms on current state-of-the-art classical computing hardware - Part II		
19	Mon	6. Basic classical Machine Learning and its relationship to linear algebra; support vector machine model; deep learning neural networks; Running classical machine learning algorithms on computing systems with accelerators, challenges of running machine learning algorithms on current state-of-the-art classical computing hardware - Part III		Quiz I (10%)
21	Wed	7. Mathematical Programming basics, linear, nonlinear, continuous, and		

		discrete optimization. Integer Programming classical solution techniques: Cutting plane theory and relaxations		
26	Mon	8. GAMA: Graver Augmented Multiseed algorithm Introduction to Test Sets; Groebner basis; Graver basis GAMA; Applications: Portfolio Optimization, Cancer Genomics; Quantum Inspired: Cardinality Quadratic Binary Problem		
28	Wed	9. Ising, Quadratic Unconstrained Binary Optimization (QUBO); Ising model basics; Simulated Annealing, Markov-chain Monte Carlo methods. Formulating combinatorial problems as QUBOs		Quiz II (10%)
Oct				
3	Mon	10. Benchmarking stochastic solvers such as Physics-Inspired Hardware for solving Ising/QUBO; Digital Annealers; Oscillator Based Computing; Coherent Ising Machines; Quantum Annealers; Gate-based Quantum Algorithms for Optimization		Project proposal due
5	Wed	11. Axioms of Quantum Mechanics; Postulates of quantum mechanics, review of classical bits (cbits), the single quantum state and the quantum bit (qubit); Quantum measurement, quantum operations; Multiple quantum states, observables		
10	Mon	12. Qubit Gate model of quantum computing; Reversible operations on qubits, logic gates, and quantum circuits; Qubits for information processing; general quantum computation process; Example of the power of quantum computing, Deutsch's problem Part I		
12	Wed	13. Qubit Gate model of quantum computing; Reversible operations on qubits, logic gates, and quantum circuits; Qubits for information processing; general quantum computation process; Example of the power of quantum computing, Deutsch's problem Part II		Midterm Project report due (15%) Quiz III (10%)
17	Mon	Fall Break		
19	Wed	Fall Break		
24	Mon	14. Midterm Project Presentations		

26	Wed	15. Exercise session, other midterm project presentations, or Guest speaker potentially on hardware solvers		Midterm Project presentation I (10%)
31	Mon	16. Quantum Methods for solving Ising/QUBO in the NISQ Era; QAOA: Quantum Alternating (Approximate) Optimization Ansatz (Algorithm); Quantum Optimization methods		
Nov				
2	Wed	17. Quantum Algorithms for future quantum processors; the HHL Algorithm for solving a system of linear equations (Ax = b); Factorizing large numbers; period finding; quantum Fourier Transform		
7	Mon	18. Quantum Algorithms for future quantum processors; HHL Algorithms for solving a system of linear equations (Ax = b); Factorizing large numbers; period finding; quantum Fourier Transform.		Quiz IV (10%)
9	Wed	19. Guest speaker: Noise in quantum computing and quantum error correction; Review of classical error correction methods; quantum error correction		
14	Mon	20. Guest speaker on Neutral Atoms for implementation of physical qubits (Dr. K. Pudenz of Atom Computing Inc.)		
16	Wed	21. Physics-Inspired Hardware for solving Ising/QUBO; Adiabatic Quantum Computing, Quantum Annealing, and D-Wave; Graphical Processing Units; Tensor Processing Units; Complementary metal-oxide-semiconductors (CMOS); Digital Annealers; Oscillator Based Computing; Coherent Ising Machines. (Potentially Peter McMahon or physics inspired NN)		
21	Mon	22. Recent advances and other topics		
23	Wed	**Thanksgiving Holiday – No Classes**		
28	Mon	23. Recent advances and other topics		
Dec				
30	Wed	24. Recent advances and other topics		
5	Mon	25. Term Project Presentations		Term Project presentation I (20%)
7	Wed	26. Term Project Presentations		Term Project presentation II (20%)

Education Objectives (Relationship of Course to Program Outcomes)

The ECE department is accredited by ABET to ensure the quality of your education. ABET defines 7 Educational Objectives that are fulfilled by the sum of all the courses you take. The following list describes which objectives are fulfilled by this course and in what manner they are fulfilled. The objectives are numbered from "1" through "7" in the standard ABET parlance. Those objectives not fulfilled by this course have been omitted from the following list:

1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics. This ability will be developed by solving regularly assigned homework problem sets.

2. An ability to communicate effectively with a range of audiences. This ability will be developed by making oral presentations in class and by writing a paper/report on a term project worked on by a team of 2 to 4 people.

3. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives. This ability will be developed by working with other students on a term project; a team of at least 2 to 4 students is required.

4. An ability to acquire and apply new knowledge as needed, using appropriate learning strategies. This ability will be developed by reading assigned papers selected from the literature of the field. Knowledge acquired is expected to help develop strategies for the term project.

ECE Academic Integrity Policy
(http://www.ece.cmu.edu/programs-admissions/masters/academic-integrity.html**):**

The Department of Electrical and Computer Engineering adheres to the academic integrity policies set forth by Carnegie Mellon University and by the College of Engineering. ECE students should review fully and carefully Carnegie Mellon University's policies regarding Cheating and Plagiarism; Undergraduate Academic Discipline; and Graduate Academic Discipline. ECE graduate student should further review the Penalties for Graduate Student Academic Integrity Violations in CIT outlined in the CIT Policy on Graduate Student Academic Integrity Violations. In addition to the above university and college-level policies, it is ECE's policy that an ECE graduate student may not drop a course in which a disciplinary action is assessed or pending without the course instructor's explicit approval. Further, an ECE course instructor may set his/her own course-specific academic integrity policies that do not conflict with university and college-level policies; course-specific policies should be made available to the students in writing in the first week of class.

This policy applies, in all respects, to this course.

CMU Academic Integrity Policy (http://www.cmu.edu/academic-integrity/index.html):

In the midst of self-exploration, the high demands of a challenging academic environment can create situations where some students have difficulty exercising good judgment. Academic challenges can provide many opportunities for high standards to evolve if students actively reflect on these challenges and if the community supports discussions to aid in this process. It is the responsibility of the entire community to establish and maintain the integrity of our university.

This site is offered as a comprehensive and accessible resource compiling and organizing the multitude of information pertaining to academic integrity that is available from across the university. These pages include practical information concerning policies, protocols and best practices as well as articulations of the institutional values from which the policies and protocols grew. The Carnegie Mellon Code, while not formally an honor code, serves as the foundation of these values and frames the expectations of our community with regard to personal integrity.

This policy applies, in all respects, to this course.

The Carnegie Mellon Code

Students at Carnegie Mellon, because they are members of an academic community dedicated to the achievement of excellence, are expected to meet the highest standards of personal, ethical and moral conduct possible.

These standards require personal integrity, a commitment to honesty without compromise, as well as truth without equivocation and a willingness to place the good of the community above the good of the self. Obligations once undertaken must be met, commitments kept.

As members of the Carnegie Mellon community, individuals are expected to uphold the standards of the community in addition to holding others accountable for said standards. It is rare that the life of a student in an academic community can be so private that it will not affect the community as a whole or that the above standards do not apply.

The discovery, advancement and communication of knowledge are not possible without a commitment to these standards. Creativity cannot exist without acknowledgment of the creativity of others. New knowledge cannot be developed without credit for prior knowledge. Without the ability to trust that these principles will be observed, an academic community cannot exist.

The commitment of its faculty, staff and students to these standards contributes to the high respect in which the Carnegie Mellon degree is held. Students must not destroy that respect by their failure to meet these standards. Students who cannot meet them should voluntarily withdraw from the university.

This policy applies, in all respects, to this course.

Carnegie Mellon University's Policy on Cheating
(http://www.cmu.edu/academic-integrity/cheating/index.html) states the following:

According to the University Policy on Academic Integrity, cheating "occurs when a student avails her/himself of an unfair or disallowed advantage which includes but is not limited to:

- Theft of or unauthorized access to an exam, answer key or other graded work from previous course offerings.
- Use of an alternate, stand-in or proxy during an examination.
- Copying from the examination or work of another person or source.
- Submission or use of falsified data.
- Using false statements to obtain additional time or other accommodation.
- Falsification of academic credentials."

This policy applies, in all respects, to this course.

Carnegie Mellon University's Policy on Plagiarism
(http://www.cmu.edu/academic-integrity/plagiarism/index.html) states the following:

According to the University Policy on Academic Integrity, plagiarism "is defined as the use of work or concepts contributed by other individuals without proper attribution or citation. Unique ideas or materials taken from another source for either written or oral use must be fully acknowledged in academic work to be graded. Examples of sources expected to be referenced include but are not limited to:

- Text, either written or spoken, quoted directly or paraphrased.
- Graphic elements.
- Passages of music, existing either as sound or as notation.
- Mathematical proofs.
- Scientific data.
- Concepts or material derived from the work, published or unpublished, of another person."

This policy applies, in all respects, to this course.

Carnegie Mellon University's Policy on Unauthorized Assistance
(http://www.cmu.edu/academic-integrity/collaboration/index.html) states the following:

According to the University Policy on Academic Integrity, unauthorized assistance "refers to the use of sources of support that have not been specifically authorized in this policy statement or by the course instructor(s) in the completion of academic work to be graded. Such sources of support may include but are not limited to advice or help provided by another individual, published or unpublished written sources, and electronic sources. Examples of unauthorized assistance include but are not limited to:

- Collaboration on any assignment beyond the standards authorized by this policy statement and the course instructor(s).
- Submission of work completed or edited in whole or in part by another person.
- Supplying or communicating unauthorized information or materials, including graded work and answer keys from previous course offerings, in any way to another student.
- Use of unauthorized information or materials, including graded work and answer keys from previous course offerings.
- Use of unauthorized devices.
- Submission for credit of previously completed graded work in a second course without first obtaining permission from the instructor(s) of the second course. In the case of concurrent courses, permission to submit the same work for credit in two courses must be obtained from the instructors of both courses."

This policy applies, in all respects, to this course.

Carnegie Mellon University's Policy on Research Misconduct (http://www.cmu.edu/academic-integrity/research/index.html) states the following:

According to the University Policy for Handling Alleged Misconduct in Research, "Carnegie Mellon University is responsible for the integrity of research conducted at the university. As a community of scholars, in which truth and integrity are fundamental, the university must establish procedures for the investigation of allegations of misconduct of research with due care to protect the rights of those accused, those making the allegations, and the university. Furthermore, federal regulations require the university to have explicit procedures for addressing incidents in which there are allegations of misconduct in research."

The policy goes on to note that "misconduct means:

- fabrication, falsification, plagiarism, or other serious deviation from accepted practices in proposing, carrying out, or reporting results from research;

- material failure to comply with Federal requirements for the protection of researchers, human subjects, or the public or for ensuring the welfare of laboratory animals; or

- failure to meet other material legal requirements governing research."

"To be deemed misconduct for the purposes of this policy, a 'material failure to comply with Federal requirements' or a 'failure to meet other material legal requirements' must be intentional or grossly negligent."

To become familiar with the expectations around the responsible conduct of research, please review the guidelines for Research Ethics published by the Office of Research Integrity and Compliance.

This policy applies, in all respects, to this course.

Take care of yourself. Do your best to maintain a healthy lifestyle this semester by eating well, exercising, avoiding drugs and alcohol, getting enough sleep and taking some time to relax. This will help you achieve your goals and cope with stress.

All of us benefit from support during times of struggle. You are not alone. There are many helpful resources available on campus and an important part of the college experience is learning how to ask for help. Asking for support sooner rather than later is often helpful.

If you or anyone you know experiences any academic stress, difficult life events, or feelings like anxiety or depression, we strongly encourage you to seek support. Counseling and Psychological Services (CaPS) is here to help: call 412-268-2922 and visit their website at http://www.cmu.edu/counseling/. Consider reaching out to a friend, faculty or family member you trust for help getting connected to the support that can help.

If you have questions about this or your coursework, please let me know.

Every individual must be treated with respect. The ways we are diverse are many and are critical to excellence and an inclusive community. They include but are not limited to: race, color, national origin, sex, disability, age, sexual orientation, gender identity, religion, creed, ancestry, belief, veteran status, or genetic information. We at CMU, will work to promote diversity, equity and inclusion because it is just and necessary for innovation. Therefore, while we are imperfect, we will work inside and outside of our classrooms, to increase our commitment to build and sustain a community that embraces these values.

It is the responsibility of each of us to create a safer and more inclusive environment. Bias incidents, whether intentional or unintentional in their occurrence, contribute to creating an unwelcoming environment for individuals and groups at the university. If you experience or observe unfair or hostile treatment on the basis of identity, we encourage you to speak out for justice and support in the moment and and/or share your experience anonymously using the following resources:
Center for Student Diversity and Inclusion: csdi@andrew.cmu.edu, (412) 268-2150, www.cmu.edu/student-diversity
Report-It online anonymous reporting platform: www.reportit.net username**:** *tartans* password**:** *plaid*

All reports will be acknowledged, documented and a determination will be made regarding a course of action." All experiences shared will be used to transform the campus climate.