How To Guides

Home Page

Syllabus, Contacts, Schedule, and Office Hours: lab.krastanov.org/grad-qis (https://lab.krastanov.org/grad-qis/)

Lecture recordings: echo360 (https://echo360.org/section/23260368-5df1-4508-ba79-806d7e3fce39/public) and personal archive; you can also see the archived **undergrad version of the class (https://presentations.krastanov.org/2024-490Q_Intro_QIS/)** (many advanced topics were skipped)

Please use the **Piazza discussion board (https://piazza.com/class/m0vf0utw3e13f5)** for questions related to the material. Forum discussions are strongly preferred over email, as they give opportunity to everyone in the class to learn from the questions.

Week 1 - Lecture 1

In the first week, we will discuss the nature of probability both in computation and in physics. We will formalize how probabilistic effects are described in these domains.

We will begin covering the following topics in the first few weeks:

- Classical Probability Theory
  - Bayesian vs Frequentist views
  - parametrization of ignorance
  - stochastic matrices
  - probability in physics
  - probability in computation
- Quantum Probability Amplitudes
  - classical vs quantum correlation
  - Unitary matrices
  - particles or waves
  - observer effect
  - delayed choice experiment
  - bomb defusing 💣

Consult the **prerequisites quiz (https://lab.krastanov.org/undergrad-qis-quiz/#do-i-have-the-prerequisites)** , a set of problems that would let you gauge whether you have the prerequisites to succeed in the class.

To hone your skills, consult the following practice problems:

- **classical probability (https://lab.krastanov.org/undergrad-qis-quiz/#classical-probability)**

Necessary Readings:

- Lectures 1, 2, 3, and 4 of **Aaronson's lecture notes (https://www.scottaaronson.com/qclec.pdf)** .

TA-led Discussion Section: Linear Algebra Review, **drive link (https://drive.google.com/file/d/17CX2m043749qN9cs-qh7QBJAQzYn-2qL/view?usp=drive_link)** , **zoom recording (https://umass-amherst.zoom.us/rec/share/BYyFsdfrIr9QxafXtRgtzLQF7JB8JixqKljDpTE0vmsOT8J2cbjVqeJlusdcdCq5.ARvWGVJsClr1E5YK?startTime=1725643857000)** , **feedback form (https://forms.gle/S7hqJnKi7BzLnjEC6)**

Week 2 - Lectures 2 and 3

Finally, we will begin introducing how probability theory is not an accurate description of our physical world and how a modified version of probability theory is necessary to describe nature (and computation) at a fundamental level.

Continuing with the discussion of quantum theory and its relationship to probability.

Introducing side-by-side the classical and quantum abstractions for state representation, rule for probability of observation, state after observation, and general linear operations corresponding to evolve a state. Showcasing the example of interaction-free measurement.

Introducing circuit notation.

Beginning discussion of entanglement vs classical correlation.

Consult the **prerequisites quiz (https://lab.krastanov.org/undergrad-qis-quiz/#do-i-have-the-prerequisites)** , a set of problems that would let you gauge whether you have the prerequisites to succeed in the class.

To hone your skills, consult the following practice problems:

- **classical probability** (https://lab.krastanov.org/undergrad-qis-quiz/#classical-probability)
- (https://lab.krastanov.org/undergrad-qis-quiz/#classical-probability) **quantum probability amplitudes** (https://lab.krastanov.org/undergrad-qis-quiz/#quantum-probability-amplitude)

Necessary Readings:

- Lectures 1, 2, 3, and 4 of **Aaronson's lecture notes** (https://www.scottaaronson.com/qclec.pdf) .
- Minute Physics "Bell's Theorem" **https://www.youtube.com/watch?v=zcqZHYo7ONs** (https://www.youtube.com/watch?v=zcqZHYo7ONs)
  
  (https://www.youtube.com/watch?v=zcqZHYo7ONs)
- 3blue1brown "Some light quantum mechanics" **https://www.youtube.com/watch?v=MzRCDLre1b4** (https://www.youtube.com/watch?v=MzRCDLre1b4)
  
  (https://www.youtube.com/watch?v=MzRCDLre1b4)
- On your own practice exercises from Nielsen & Chuang's.
- If you have forgotten a lot of your linear algebra, watch the youtube series on linear algebra by 3blue1brown.

TA-led Discussion Section: **PDF Drive Link** (https://drive.google.com/file/d/1DTVV2tsqOn-i2s-1pojqH7mCMuJqQsxE/view?usp=sharing) , **Zoom Recording** (https://umass-amherst.zoom.us/rec/share/8HIPPN4ZC8urbWcUSi6Q3EoAcRsiWP6mBQlvnlH1J30g9rOlvQV207DFJqDE8od7.nZ2VPXY831ygCd2D)

As a side note, someone had a question on derandomization and expander graphs: this is a **good fun resource** (https://www.cs.princeton.edu/~zdvir/expanders/avi-book.pdf) . As a second side note, Scott Aaronson's "Quantum Computing Since Democritus" is a great book to read independently of this class.

Homework 1 is assigned

Week 3 - Lectures 4 and 5

Delving deeper in the discussion of classical correlation and quantum entanglement and its use in communication. Topics covered include:

- Representing states of multiple (qu)bits (tensor products)
- Measurement of a single qubit out of a system of multiple qubits
- Measurement in an arbitrary basis
- Entanglement and its non-classical applications
  - superdense coding
  - quantum key distribution
  - state and gate teleportation

Necessary Readings: Lectures 8, 9, and 10 of **Aaronson's lecture notes** (https://www.scottaaronson.com/qclec.pdf) . On your own practice exercises from Nielsen & Chuang's.

Homework 2 is assigned

Week 4 - Lectures 6 and 7

Entanglement and its non-classical applications, including the three most important quantum communication primitives.

- superdense coding
- quantum key distribution

- state and gate teleportation

Necessary Readings: Lectures 8, 9, and 10 of **Aaronson's lecture notes** (https://www.scottaaronson.com/qclec.pdf) . On your own practice exercises from Nielsen & Chuang's.

TA-led Discussion: **PDF Notes** (https://drive.google.com/file/d/1wUKdPHhJu4huSFs-JmeiMoPWAeFpnnQm/view?usp=sharing)

Week 5 - Lectures 8 and 9

A brief review of measurements and probabilities, chiefly looking at how the bra-ket notation makes it easy to go between "inner product", "outer product", and "trace" versions of various formulas.

A guest lecture on Bell's inequality and non-local games.

We introduced the query complexity measure and the notion of oracles (in particular Phase and XOR quantum oracles).

We started covering our first quantum algorithms, mostly exploiting the fact that a bit of global information (e.g. parity) can be extracted quantumly in a single query without needing to extract all possible bit values (the Deutsch algorithm). We then started turning to its more powerful version, the Deutsch-Josza algorithm. The general motif we followed is to prepare queries that will provide an interesting "superposition" in the answer and then perform some additional interference in the answer state in order to extract a useful result with high probability.

Then we investigate Simon's algorithm: still a contrived algorithm with little practical use, however, it is the first algorithm that shows exponential advantage for a quantum computer over a classical one. Simon's algorithm is also the basis on which more practically useful algorithms are constructed.

Necessary Readings: Lectures 17 and 18 from Aaronson's lecture notes. On your own practice exercises from Nielsen & Chuang's.

Homework 3 is assigned

Week 6 - Lectures 10 and 11

Fourier Transforms and Period Finding.

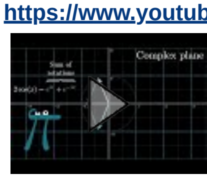
Then we discussed how the difficulty of factoring an integer can provide a good trapdoor function for asymmetric encryption purposes. We then also showed that finding the prime factors of an integer is equivalent to finding the period of a related function. Finding periods of unstructured functions is as difficult as finding any collision classically, namely exponentially difficult with quadratic speedup thanks to birthday attacks. On the other hand, as seen last time, Simon's algorithm provides an efficient quantum method for finding collisions. We are now modifying it into Shor's algorithm, which is a slight modification that lets us find the period of a function (thus breaking common asymmetric encryption standards). Period-finding is also related to Fourier transforms, thus we will discuss the Quantum Fourier transform as an important component of the algorithm.

Necessary Readings:

- Lectures 19, 20, and optionally 21 from Scott Aaronson's notes cover this weeks topic well.
- Fourier transform by 3blue1brown:
  - **https://www.youtube.com/watch?v=spUNpyF58BY** (https://www.youtube.com/watch?v=spUNpyF58BY)

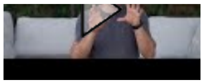
    

    (https://www.youtube.com/watch?v=spUNpyF58BY)
  - **https://www.youtube.com/watch?v=r6sGWTCMz2k** (https://www.youtube.com/watch?v=r6sGWTCMz2k)

    (https://www.youtube.com/watch?v=r6sGWTCMz2k)
- Fourier transform by Veritasium:
  https://www.youtube.com/watch?v=nmgFG7PUHfo (https://www.youtube.com/watch?v=nmgFG7PUHfo)



[(https://www.youtube.com/watch?v=nmgFG7PUHfo)](https://www.youtube.com/watch?v=nmgFG7PUHfo)

Homework 4 is assigned (over the weekend)

Week 7 - Lectures 12 and 13

Grover search algorithm on the first lecture of the week.

Followed by a lighter slide-show lecture on different hardware implementations of early quantum computers.

Necessary Readings: Lectures 22 (and optionally 23 and 24) from Aaronson's lecture notes. On your own practice exercises from Nielsen & Chuang's.

Notes on how the Quantum Fourier Transform and the Grover Diffusion Operator are implemented: **note_on_compilation.pdf (https://umamherst.instructure.com/courses/23137/files/9286051?wrap=1)** **(https://umamherst.instructure.com/courses/23137/files/9286051/download?download_frd=1)**

Midterm Exam

Week 8 - Lectures 14 and 15 (15 was canceled and rescheduled)

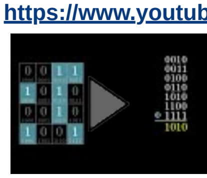
For lecture 15 we transition from the discussion of algorithms to the discussion of error-correcting codes and how they can be used to turn unreliable noisy hardware into something resembling the abstract perfect circuits we have been studying. In particular, on the first day of "Error Correction Codes" we ran some numerical experiments working with classical linear binary error correcting codes, we defined the notion of a generator matrix (used for encoding) and parity check matrix (used for error detection and potentially for correction), as well as the notions of logical and physical bits, syndromes, and we alluded to what "rate" and "distance" are. We tried to interpret the parity check matrix as the object that most clearly informs us about the redundancies introduced by a code as a way to fight noise. We discussed the interesting property that a parity check matrix can extract an error-syndrome that depends only on the error that has occurred, not on the codeword that was transmitted. Finally, we showcased one single quantum error correcting code, as the composition of two classical codes, one for checking X errors and one for checking Z errors.

Necessary Readings:

- The Nielsen and Chuang chapter on error correction is a valuable resource for these few weeks. We will not rely much on Aaronson's lecture notes for this part of the class.
- These 3blue1brown videos are also a good intro to classical error correction:
  - **https://www.youtube.com/watch?v=X8jsijhllIA** **(https://www.youtube.com/watch?v=X8jsijhllIA)**

    (https://www.youtube.com/watch?v=X8jsijhllIA)
  - **https://www.youtube.com/watch?v=b3NxrZOu_CE** **(https://www.youtube.com/watch?v=b3NxrZOu_CE)**

    (https://www.youtube.com/watch?v=b3NxrZOu_CE)
- CQN Winter School lecture: **https://www.youtube.com/watch?v=u2N4MlpgVUY** **(https://www.youtube.com/watch?v=u2N4MlpgVUY)**

  (https://www.youtube.com/watch?v=u2N4MlpgVUY)

Code notebook used in the class: **Error_Correction_Tutorial_draft.ipynb (https://umamherst.instructure.com/courses/23137/files/9930231?**

Week 9 - Lectures 15 and 16 (should have been 16 and 17)

We continued the discussion of error correction, focusing on how the syndrome measurements are performed. Then we used error-correction as an excuse to talk about the "stabilizer formalism".

The "Stabilizer formalism", a.k.a. "Clifford Circuit" formalism was discussed. It is an extremely important technique for efficiently modeling a subset of quantum dynamics on a classical computer. It is the tool that has permitted us to study quantum ECC and entanglement purification/distribution, without having to first build a quantum computer. In terms of computational complexity it is also an interesting construction because it showcases how putting some restrictions on the states we want to represent makes everything simple enough to simulate efficiently on a classical computer. Studying more sophisticated examples of this border between "truly quantum" and "classical" enables us to gain insight about where the "quantum advantage" comes from (and it even occasionally lets use "dequantize" algorithms, leading to better classical algorithms inspired by quantum computing).

First, we discussed describing a quantum state not as a state vector, rather as a list of observables. Then we track how these observables evolve instead of tracking each state (physicists call this the "Heisenberg" picture, while our usual approach with state vectors is called the "Schroedinger" picture). The naive example of such observables we gave simply used an exponentially long list of projectors, each projecting on a different bitstring state.

As a better example of such a set of observables, we can think of an "overly restrictive" quantum ECC (i.e. an n-qubit code with n observables (checks) in its parity-check tableau) as the set of constraints that are fulfilled by one (only one) single state vector (i.e. ket). Tracking how these constraints evolve as gates are applied is equivalent to tracking how that single state evolves. Interestingly, we need only linearly many checks in this example, not exponentially many. It is because we restricted ourselves only to Pauli observables and operations (gates) that map Pauli observables to other Pauli observables and because a linearly small set of Pauli group elements can be a generating set for the exponentially large Pauli subgroup (i.e. many observables in the exponentially large set we usually need can be expressed in terms of a much smaller set of observables we have to track).

Necessary Readings:

- Aaronson's lectures 27 and 28
- Nielsen & Chuang's section 10 (also a good source of exercises)
- Steane's well known tutorial on the topic is also worth a read **https://ebooks.iospress.nl/DOI/10.3254/978-1-61499-018-5-1** (https://ebooks.iospress.nl/DOI/10.3254/978-1-61499-018-5-1) (which can be accessed for free from google scholar **https://scholar.google.com/scholar?hl=en&as_sdt=0%2C22&q=A+tutorial+on+quantum+error+correction+steane** (https://scholar.google.com/scholar?hl=en&as_sdt=0%2C22&q=A+tutorial+on+quantum+error+correction+steane))

Reading materials that significantly supplement the lecture content (and will be of great help with homeworks and exams):

- The Heisenberg Representation of Quantum Computers **https://arxiv.org/abs/quant-ph/9807006** (https://arxiv.org/abs/quant-ph/9807006)
- Improved Simulation of Stabilizer Circuits **https://arxiv.org/abs/quant-ph/0406196** (https://arxiv.org/abs/quant-ph/0406196)
- Sparse Graph Codes for Quantum Error-Correction **https://arxiv.org/abs/quant-ph/0304161** (https://arxiv.org/abs/quant-ph/0304161)

Homework 5 is assigned

Week 10 - Lectures 17 and 18 (should have been 18 and 19)

In Lecture 17 we covered how to perform measurements in the stabilizer formalism.

Lecture 18 was dedicated to formalism for dealing with noise and classical probability in quantum information science: density matrices, partial traces, and quantum channels.

On density matrices: a way to track both classical and quantum probability distribution in one object. Concepts discussed today: density matrices, partial traces, the fact that we can write $|\langle\psi|\phi\rangle|^2 = \langle\psi|\phi\rangle\langle\phi|\psi\rangle = \langle\phi|\psi\rangle\langle\psi|\phi\rangle$ and $\mathrm{tr}(\rho|\psi\rangle\langle\psi|) = \langle\psi|\rho|\psi\rangle$ which is useful for transforming between various expressions involving projectors/observables/density matrices/kets, measuring only a single subsystem of a bigger entangled system, the fact that entangling with an untracked part of the environment is the reason for the macroscopic world looking classical.

On quantum channels, a.k.a. quantum operations, a.k.a. CPTP maps: We introduced them in three different ways: axiomatically as the mathematical object that preserves meaningful density matrices (i.e. preserving the trace and the positivity of eigenvalues); as the result of some arbitrary interaction with the environment that then has to be marginalized over (i.e. through a partial trace); as a particular "sum of conjugated operators" expression which is maybe the most opaque representation, but is also the representation that is most useful when modeling noise.

Necessary Readings:

- readings from the previous week on ECC and stabilizer formalism
  - Nielsen & Chuang's sections 10
  - Steane's well known tutorial on the topic is also worth a read **https://ebooks.iospress.nl/DOI/10.3254/978-1-61499-018-5-1 (https://ebooks.iospress.nl/DOI/10.3254/978-1-61499-018-5-1)** (which can be accessed for free from google scholar **https://scholar.google.com/scholar?hl=en&as_sdt=0%2C22&q=A+tutorial+on+quantum+error+correction+steane (https://scholar.google.com/scholar?hl=en&as_sdt=0%2C22&q=A+tutorial+on+quantum+error+correction+steane)**)
- on "open quantum systems":
  - Aaronson lecture 6
  - Nielsen & Chuang's sections 2.4, 8.1, 8.2, 8.3

Homework 6 is assigned

Week 11 - Lectures 19 (19 was longer than usual) (should have been 20)

We finished the discussion of quantum channels and used them to discuss how error correction works even on non-Pauli errors.

On quantum channels, a.k.a. quantum operations, a.k.a. CPTP maps: We introduced them in three different ways: axiomatically as the mathematical object that preserves meaningful density matrices (i.e. preserving the trace and the positivity of eigenvalues); as the result of some arbitrary interaction with the environment that then has to be marginalized over (i.e. through a partial trace); as a particular "sum of conjugated operators" expression which is maybe the most opaque representation, but is also the representation that is most useful when modeling noise.

Lastly, now with more in-depth knowledge of how to work with arbitrary errors, we started discussing a more interesting code: the Toric code. We discussed how syndromes are measured and how contractable and non-contractable loops of errors have different effects on the state of the code.

Necessary Readings:

- readings from the previous week on ECC and stabilizer formalism
  - Nielsen & Chuang's sections 10
  - Steane's well known tutorial on the topic is also worth a read **https://ebooks.iospress.nl/DOI/10.3254/978-1-61499-018-5-1 (https://ebooks.iospress.nl/DOI/10.3254/978-1-61499-018-5-1)** (which can be accessed for free from google scholar **https://scholar.google.com/scholar?hl=en&as_sdt=0%2C22&q=A+tutorial+on+quantum+error+correction+steane (https://scholar.google.com/scholar?hl=en&as_sdt=0%2C22&q=A+tutorial+on+quantum+error+correction+steane)**)
- on "open quantum systems":
  - Aaronson lecture 6
  - Nielsen & Chuang's sections 2.4, 8.1, 8.2, 8.3

Week 12 - Lectures 20 and 21 (21 was longer than usual) (should have been 21 and 22)

In lecture 20 we covered the "destabilizer formalism" that improves the performance of the "stabilizer formalism" by precomputing much of the "anticommutativity" structure that otherwise requires an expensive Gaussian elimination. We also used that formalism to talk about the logical operators of an error correcting code and giving more details on how to prove properties of contractable and non-contractable loops of errors in the Toric code.

Necessary Readings:

- Improved Simulation of Stabilizer Circuits **https://arxiv.org/abs/quant-ph/0406196 (https://arxiv.org/abs/quant-ph/0406196)**

In lecture 21 we started discussing Hamiltonians and Schroedinger's equations. Hamiltonians are "generators" of a unitary operation. We introduced the terms Lie group and Lie algebra, the generalized notion of an exponential as the process of following a tangent (generator) on the surface of a group (of unitary operations). The chief insight was based on interpreting a general unitary as the product of many unitaries that differ from the identity by an infinitesimally small generator of evolution.

Necessary Readings:

- Aaronson lecture 25

- Nielsen & Chuang would be a great supplementary resource on this

Week 13 - Lectures 22 (should have been 23)

This week we covered the Adiabatic Algorithm, a new way to run optimization problems. There are two ways to think of it: (1) as the addition of "quantum tunneling" to the typical process of gradient descent (not a formalism we are equipped to work with); and (2) as a slow continuous transformation of the cost function landscape from an "easy and solved" one to the "difficult" one together with a promise that throughout this evolution if we started in the minimum we will always remain in the minimum (the method we chose). We also went through the actual proof that we remain in the ground state (the Adiabatic Theorem).

Necessary Readings:

- Aaronson lecture 26

Homework 7 is assigned

Week 14 - Lectures 23 and 24 (should have been 24 and 25)

We proved the Adiabatic Theorem, the underlying truth that enables the adiabatic algorithm.

Then we discussed the Variational Principle, the other main component of Hamiltonian-based quantum algorithms, leading us to the family of variational quantum algorithms.

This is the last topic that will be included in the final exam.

Afterwards we spent some time on the QAOA as a general form of these Hamiltonian-based algorithms.

We briefly discussed Measurement Based Quantum Computation which ended up being the main topic for lecture 25.

Necessary Readings:

- Aaronson lecture 26
- Blog post by Aaronson with a few references to papers in it: **https://scottaaronson.blog/?p=8375** (https://scottaaronson.blog/?p=8375)
- The introduction and background sections of **https://arxiv.org/abs/2306.09198** (https://arxiv.org/abs/2306.09198)
- Sections 1.1.1-1.1.3 of **https://arxiv.org/abs/1804.09130** (https://arxiv.org/abs/1804.09130)

Week 15 - Lectures 25 (should have been 26)

We saw how to perform gates and measurements in an MBQC model of computation -- a way to perform quantum computation by first preparing a sophisticated resource state and then using only single-qubit gates.

Necessary Readings:

- A helpful overview: **https://arxiv.org/pdf/1208.0041** (https://arxiv.org/pdf/1208.0041)
- Aaronson's advance lecture notes, lecture 17: **https://www.scottaaronson.com/qisii.pdf** (https://www.scottaaronson.com/qisii.pdf)

The content below this line is copied over from last year (mixture of grad and undergrad classes) for reference. It will be updated in real-time as we go through the semester. Not all planned class content is listed below.