Bridge to Quantum STEM

Workshop on Quantum Education for Quantum Workforce Development

January 30-31
Hyatt Centric Hotel
Arlington, VA

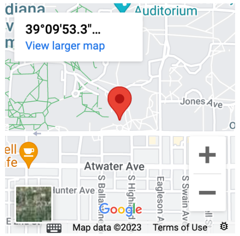
Adrian German

Indiana University Bloomington

IU Bloomington Calendar

APRIL 15, 2023

1:00 PM – 5:00 PM / MERRILL HALL (MUSIC) / MUSIC, JACOBS SCHOOL OF



Location: Merrill Hall (Music) / Music, Jacobs School of

View on Campus Map

Quantum Day 2023

The World Quantum Day is an initiative from quantum scientists from 65+ countries.

The World Quantum Day is a decentralized and bottom-up initiative, inviting all quantum scientists, engineers, educators, communicators, entrepreneurs, technologists, historians, philosophers, artists, and their organizations, to organize their own activities, such as outreach talks, exhibitions, lab tours, panel discussions, debates, interviews, etc., to celebrate the World Quantum Day around the World.

Free

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January 2023
Today
Day
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Month
All
APRIL 15, 2023
1:00 PM – 5:00 PM / MERRILL HALL (MUSIC) / MUSIC, JACOBS SCHOOL OF
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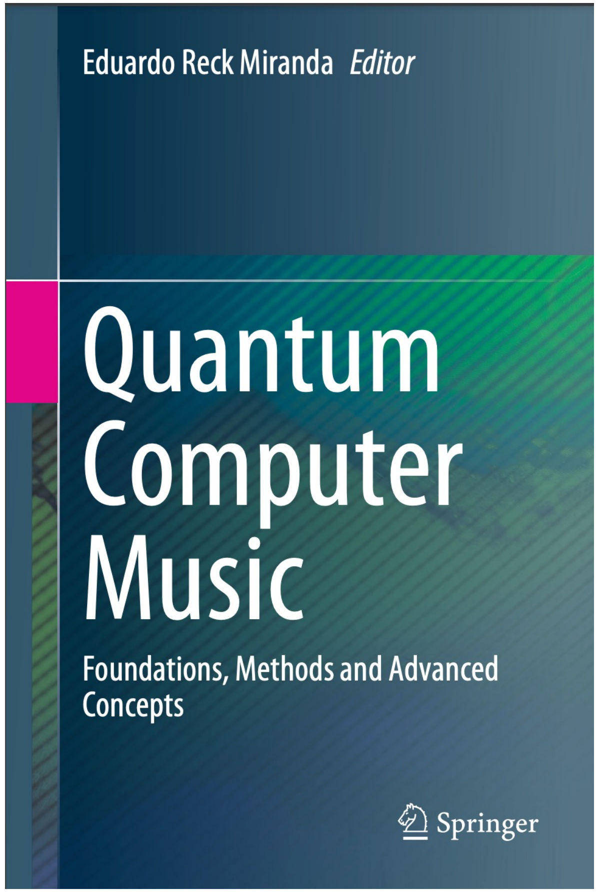
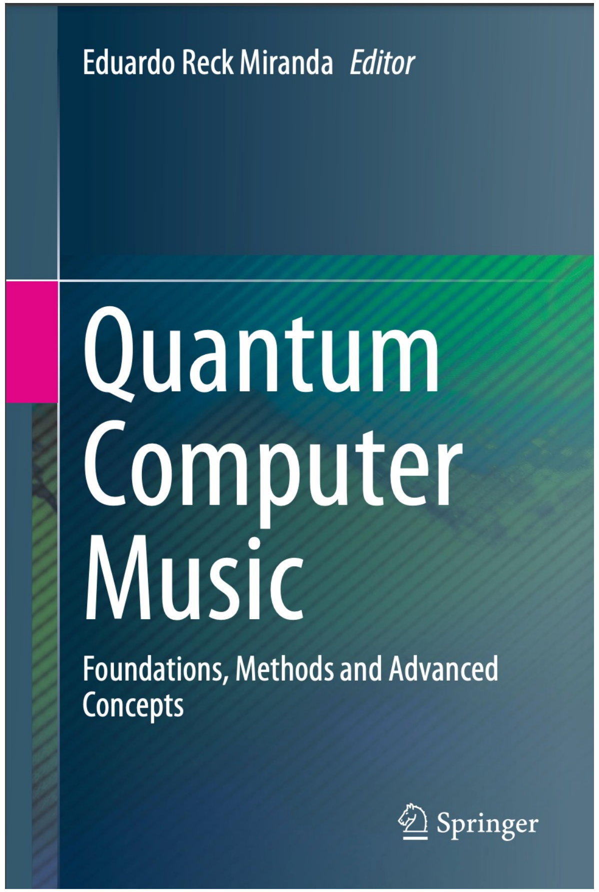
View on Campus Map
Online events
Event type:
Academic calendar
Art and museum exhibitions
Career development
Culture and languages
Functions, festivals, and celebrations
Health and wellness
Lectures, talks, seminars, and conferences


Eduardo Reck Miranda Editor
Quantum Computer Music
Foundations, Methods and Advanced Concepts
Springer

Contents



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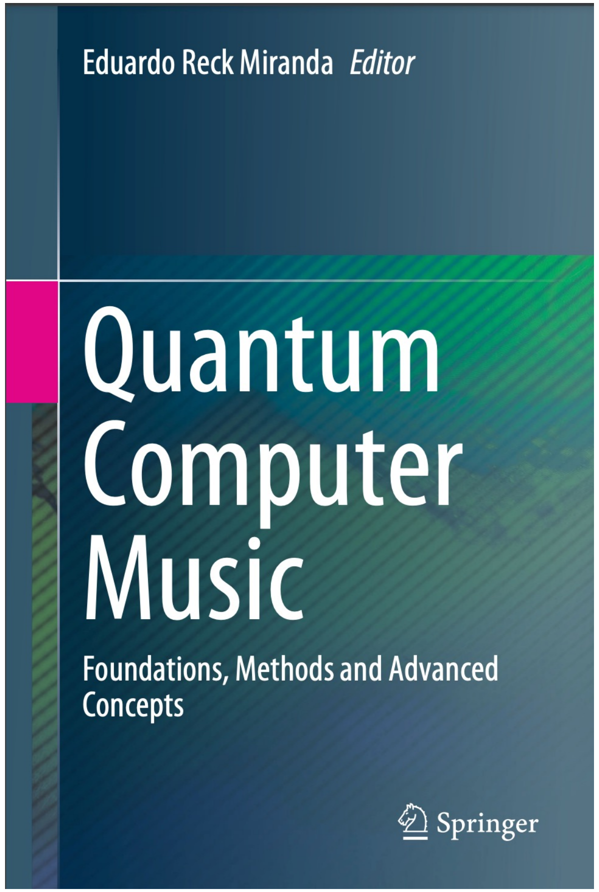

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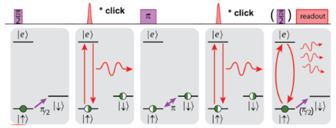
Indiana University Quantum Information Science and Engineering (IU QISE) Student Journal Club

Online Proceedings and Calendar



Session 1 Agenda (Tuesday, September 27, 2022) — **Shoemaker Innovation Center**

Today's proceedings will be moderated by Arpan Ojha (Graduate Student in Data Science, Club President)

07:00-08:30pm This was the first meeting of the year, focused on club structure and goals.
Not everybody could make it. Discord channel, hybrid modality discussed.

Session 2 Agenda (Tuesday, October 11, 2022) — **Hybrid: Zoom and Luddy 2069**

Today's proceedings will try to establish a Steering Committee for this club

07:00-08:30pm The following have agreed to serve on the IU QISE SJC Steering Committee:

- President: Arpan Ojha (Data Science Program)
- Vice-President: Alex Alani (IU School of Music)
- Secretary: Thomas Burkle (MS in QIS Program)
- Faculty Liaison: Shawn Gibford (MS in QIS Program)
- Treasurer: Micah Roberson (Finance, Kelly School of Business)
- Faculty Sponsor: Adrian German (Computer Science)

Additional positions remain available for the asking.

Session 3 Agenda (Tuesday, November 15, 2022) — **Available via Zoom**

Today's Zoom link will be available from the host Arpan Ojha (IU QISE SJC President) — Video recording of the talk.

07:10-07:25pm CQT and IU QSEc Distinguished Speaker
Prof. Alexander Gumennik
Director of ISE FAMES Lab
Assistant Professor of Intelligent Systems Engineering
Quantum Hardware and Quantum-Enabling Systems at IU FAMES

The talk will be followed by a Q&A session.

Quantum Education Workshop (Thu-Mon, November 17-21, 2022) — **Waterloo, Ontario, Canada**

11/18-20/2022 Three of us will take part in this year's Schroedinger's Class (welcome book)
Workshop held at the Institute of Quantum Computation on the University of Waterloo Campus.
The goal is to try to establish a similar outreach program here in Indiana.
Back in Indiana from the workshop here's our little report.
Find more about Schroedinger's Class here (look under June 8).

legacy.cs.indiana.edu/~dgerman/2022/qis-student-journal-club/

Indiana University Quantum Information Science and Engineering IU QISE Student Journal Club

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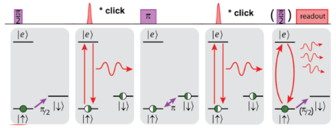

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Session 4 Agenda (Tuesday, December 13, 2022) — Available via Zoom

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Video recording of the talk.

07:10-07:25pm CQT and PQSEI Distinguished Speaker
Prof. Sasha Boltasseva
Ron and Dotty Garvin Tonjes Professor Of Electrical and Computer Engineering
Courtesy Appointment in Materials Engineering
Purdue University Quantum Science Center, Workforce Development Lead
Using Classical Machine Learning to Improve Quantum Photonics

The talk will be followed by a Q&A session. Some materials to review before the talk are listed here.

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Dr. Demid Sychev

Postdoc at Purdue University QSEI
joint appointment between the groups
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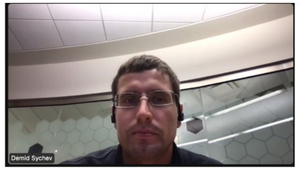


Session 5 Agenda (Tue, Jan 24, 2023) — Myles Brand I107 (and via Zoom)

This is the first in a series of interactive tutorials hosted by AJ Rasmusson (Phil Richerme Group)

Video recording of today's talk.

7-8pm EST IU QSEc Distinguished Speaker
AJ Rasmusson (Grad Student in Phil Richerme's Group)
Also part-time Intern with IBM Quantum (new paper here)
Learning Experiences for New Researchers
Steps needed for a trotterized time evolution on noisy hardware.
Error mitigation and optimization of quantum circuits.

This will be an interactive tutorial for all club members.

Outreach and Competitions (MIT iQuHack 2023) — Boston, MA and Bloomington, IN

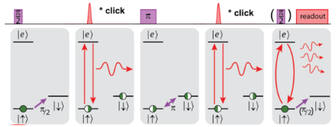
A club logo is currently being designed.

Jan 27-29, 2023

Our club is taking part (remotely and in person) in the MIT Quantum Hackathon legacy.cs.indiana.edu/~dgerman/2022/qis-student-journal-club/

Indiana University Quantum Information Science and Engineering IU QISE Student Journal Club

Online Proceedings and Calendar



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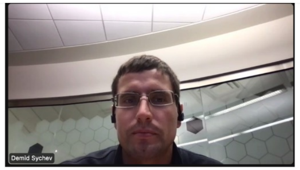

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Jan 27-29, 2023

Our club is taking part (remotely and in person) in the MIT Quantum Hackathon

Session 6 Agenda (Tentatively Tue, Feb 21, 2023) — Available in person and via Zoom

Prof. Ricardo Decca has agreed to give a lightning talk to our club next semester.

07:10-07:40pm CQT and IUPUI Nanoscale Imaging Center Distinguished Speaker
Prof. Ricardo Decca, IUPUI School of Science
Professor and Department Chair, Physics
Co-Director of Nanoscale Imaging Center
Hardware for Quantum Sensing

The talk will be followed by a Q&A session.

Session 7 Agenda (Hopefully Tue, Mar 21, 2023) — In person and via Zoom

In talks with Prof. Peter Kogge for a talk to our club on this date.

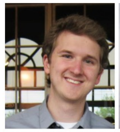
07:10-07:40pm CQT and University of Notre Dame Distinguished Speaker
Prof. Peter M. Kogge, IBM Fellow, IEEE Fellow
McCourtney Professor of Computer Science and Engineering
Department of Computer Science and Engineering
CQT Site Director for the University of Notre Dame
Quantum Computing Playbook

The talk will be followed by a Q&A session.

Quantum Day (April 15, 2023) — In person and via Zoom

This will be a ☞ campus event entitled Quantum Day (co-hosted with Jacobs School of Music for outreach and recruiting).

Full-Day Event IBM Quantum Distinguished Speaker
James Weaver, Quantum Developer Advocate at IBM and
Brian Ingmanson, Education Engagement Lead, IBM Quantum
Quantum Music Playground
Link to chapter in new Springer book, the
Qiskit Pocket Guide and Devoxx UK video.



Tentative location for this event is the most outstanding IU Jacobs School of Music's MAC 070 (panoramic view).

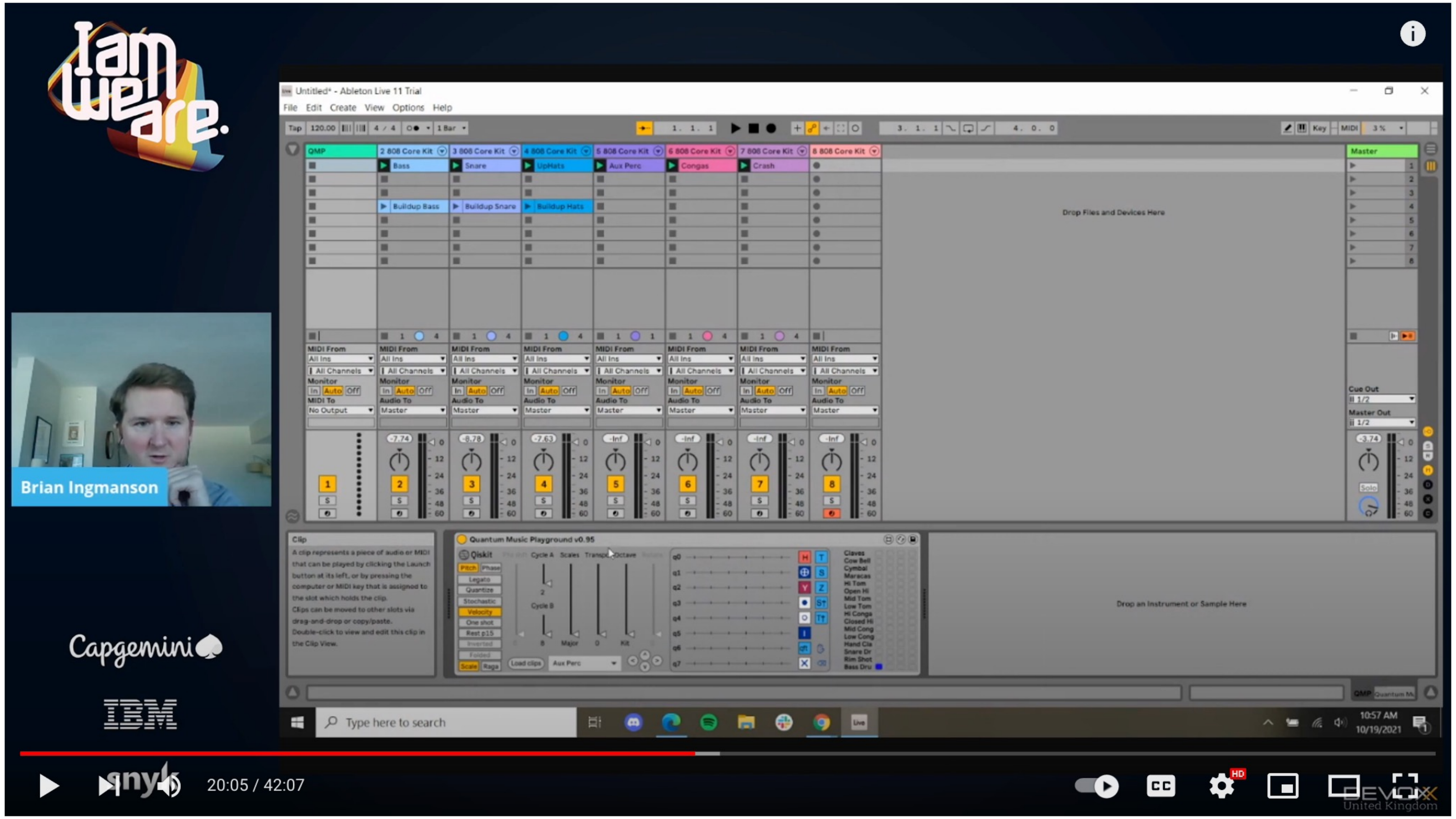
Our goal is for this event to be a full-day campus-wide event.

Goal remains increased collaboration between students at IU QSEc and the rest of the CQT.

Going back to Indiana National Lab Day (in October 2019) here's a video with Jeff Zaleski (IU) and Yong Chen (Purdue QSEI).

We have a few other distinguished guests from Canada, the UK and the CQT that we've invited for this event (so watch this space for updates).

In addition to these milestones any additional events that develop will be indexed/recorded here as they occur.



Create Quantum Dance Music- a musical journey into quantum computing: James Weaver & Brian Ingmanson

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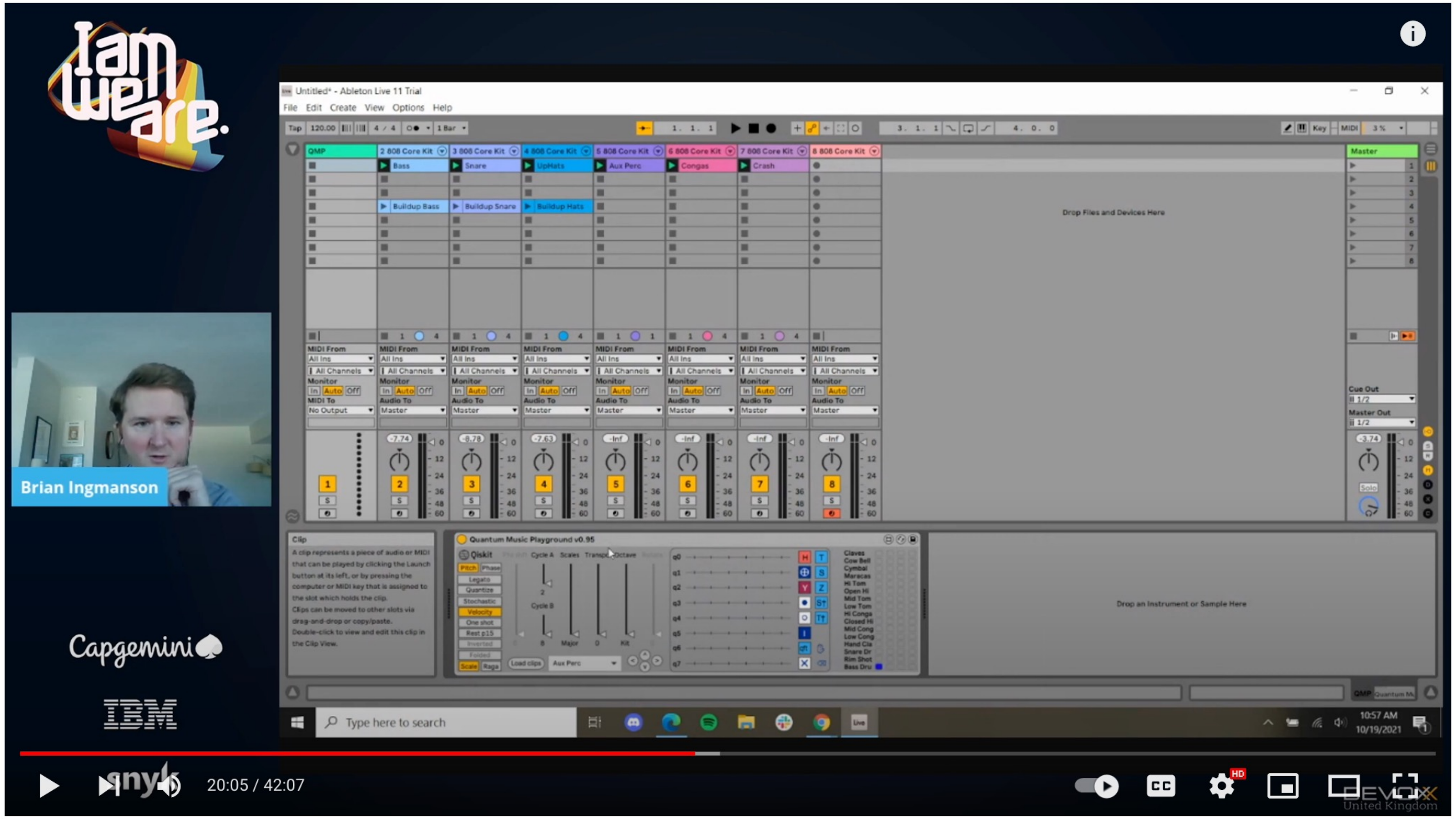

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James Weaver
JavaFXpert

Pinned

quantum-toy-piano-ibmq Public
Quantum Music Composer for IBM quantum computers
JavaScript ☆ 55 ⑂ 16

QiskitBlocks Public
Game that teaches quantum computing using Qiskit (http://qiskit.org) in a Minetest (http://minetest.net) block world. Works on Windows, macOS, GNU/Linux, FreeBSD, OpenBSD, DragonFly BSD, and Androi...
Lua ☆ 190 ⑂ 44

Quantum Music Composer for IBM quantum computers

The Quantum Music Composer application enables a user to compose music that is performed by a quantum computer or quantum simulator. The musical *composition* consists of a series of quantum circuits. Each quantum musical tone [1] in the *performance* of a composition is a quantum state, which when measured, results in a pitch determined by quantum mechanical behavior. This normally results in unique melodies and harmonies each time a given composition is performed by a quantum computer or simulator. Fig. 1 contains a musical score captured from one such performance.

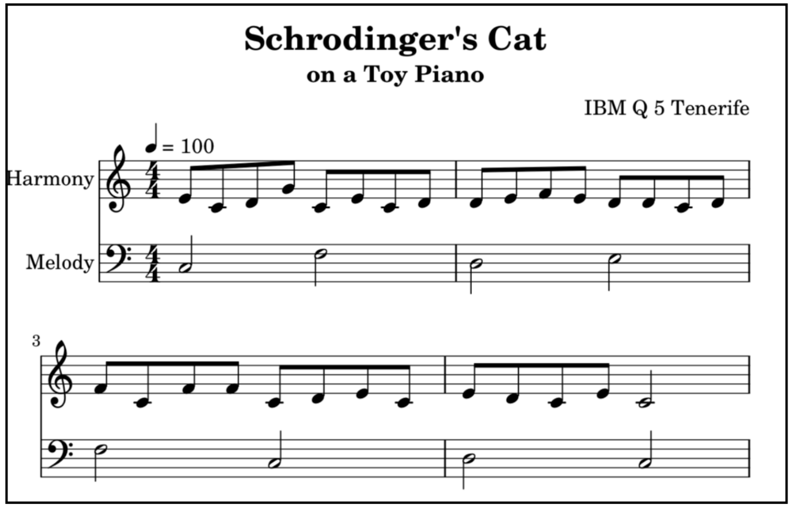
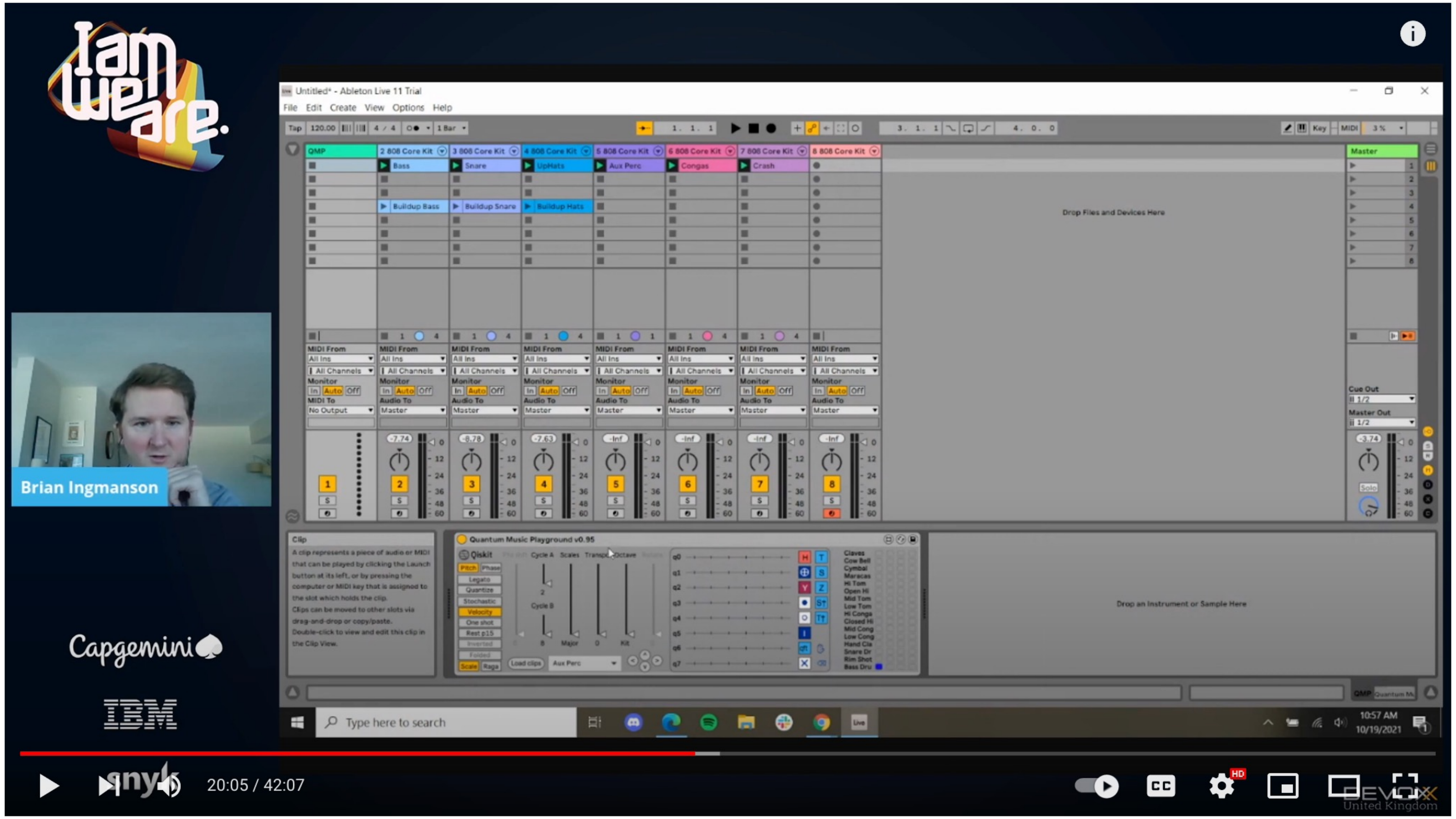


FIG. 1. Musical score captured from the performance of a quantum musical composition [play]

Creating a quantum musical composition

To create a quantum musical composition, the user first supplies the desired probabilities for a given pitch to follow another given pitch *melodically*. Take a moment to examine the music score in Fig. 1 and notice that the staff labeled **Melody** contains a melody with eight notes. Please also realize that the staff labeled **Harmony** actually



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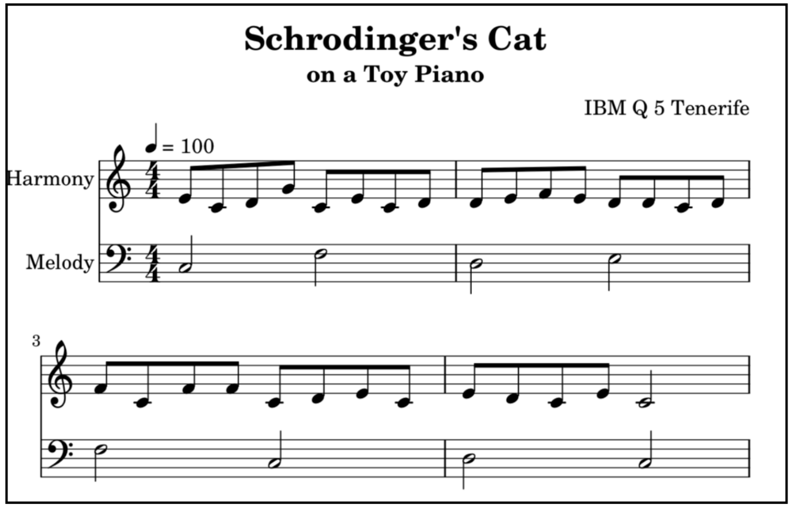

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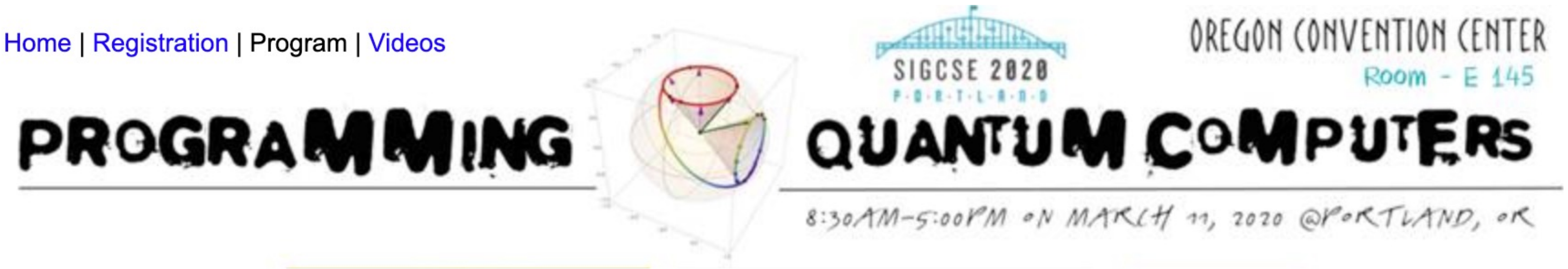

QSEc

Quantum Science and Engineering Center

History

On August 23, 2016, Indiana University welcomed its inaugural group of engineering students. The 25 undergraduate and 20 PhD students joined IU's intelligent systems engineering program, which is focused on the development of small scale, networked and mobile technology. This marked a turning point for IU as it launched the first engineering program in its history. In February, 2018, the Emerging Areas of Research (EAR) program, created as part of the Bicentennial Strategic Plan for IU Bloomington, selected for awards two of the 21 proposals submitted for that year's competition and representing nearly 250 faculty at IU Bloomington. One of them was the "Center for Quantum Information Science and Engineering" initiative led by Gerardo Ortiz, along with David Baxter, Alexander Gumennik (Engineering), Roger Pynn, Phil Richerme, Amr Sabry (Computer Science), Mike Snow and Shixiong Zang among others. In addition to the grant from the EAR program in 2018 the center has received additional external funding (from NSF and DoE) and in January 2020 the center was rededicated. The new center will develop technologies and materials made possible by the 'second quantum revolution' while also offering several educational opportunities for IU students, including new undergraduate courses and possibly one of the country's first quantum engineering programs.

Two months earlier, in October 2019, IU's quantum expertise had been on display at Indiana National Lab Day held in Indianapolis. The event connected IU, IUPUI, the University of Notre Dame and Purdue University researchers with representatives from ten US National Laboratories to highlight unique research capabilities and opportunities as well as potential federal research collaborations. Though NSF had only recently established a foundation for the Big Ideas challenge through pioneering research and pilot activities (which includes the Quantum Leap challenge) Indiana has long had a standing commitment to innovation. Indiana University is still the home of mathematician Michael Larsen who in 2002 with co-authors Zhenghan Wang (at IU at the time), Alexei Kitaev (in Moscow then, now at Caltech and Microsoft) and Michael Freedman (at Microsoft Q Station in Santa Barbara) first introduced the world to topological quantum computation. In 2009 Zhenghan Wang (by now also at Microsoft and UC Santa Barbara) returned for a summer to host with logicians Michael Dunn and Larry Moss an international workshop on Quantum Logic Inspired by Quantum Computation.

Over the last 20 years Indiana University students have had the opportunity to take graduate seminars and classes in Quantum Information Science and Quantum Computation, mainly through the efforts of Amr Sabry (Computer Science) and Gerardo Ortiz (Physics). Recently, however, recognizing the national imperative of solving the talent shortage in the quantum computing industry the Indiana University QSEc, led by Mike Snow, has been working on establishing a unique educational opportunity, in Indiana and anywhere else in the nation, by setting the foundations of an intensive one-year, multi-disciplinary MS degree with tracks which thread as needed through physics, chemistry, mathematics, computer science, engineering, and business to bridge students with a broad distribution of previous training into QIS-related opportunities. There is no MS degree program in the US of this type, but the need for a program which does not assume previous BS-level training in physics is clear. Indiana University was also the catalyst for the first (and so far the only) ever symposium event at SIGCSE earlier this year (March 11, 2020, in Portland, Oregon) dedicated to quantum programming for undergraduates. This and other initiatives have accelerated collaboration with other higher-education institutions in Indiana (most notably Purdue, Notre Dame, IUPUI, but also with Rose-Hulman and others). As an example, at the exact same time with the SIGCSE 2020 symposium in Portland, IU QSEc researchers were hosting in Bloomington their colleagues from Purdue QSEI for a mini-symposium.

[Submitted on 4 Jan 2001 (v1), last revised 20 Sep 2002 (this version, v2)]

Topological Quantum Computation

Michael H. Freedman, Alexei Kitaev, Michael J. Larsen, Zhenghan Wang

The theory of quantum computation can be constructed from the abstract study of anyonic systems. In mathematical terms, these are unitary topological modular functors. They underlie the Jones polynomial and arise in Witten-Chern-Simons theory. The braiding and fusion of anyonic excitations in quantum Hall electron liquids and 2D-magnets are modeled by modular functors, opening a new possibility for the realization of quantum computers. The chief advantage of anyonic computation would be physical error correction: An error rate scaling like $e^{-\al}$, where ł is a length scale, and α is some positive constant. In contrast, the $\q$ presumptive" qubit-model of quantum computation, which repairs errors combinatorically, requires a fantastically low initial error rate (about 10^{-4}) before computation can be stabilized.

Subjects: **Quantum Physics (quant-ph)**; Geometric Topology (math.GT)
Cite as: arXiv:quant-ph/0101025
(or arXiv:quant-ph/0101025v2 for this version)
https://doi.org/10.48550/arXiv.quant-ph/0101025

Zhe-Yu Jeff Ou, Ph.D.

Professor Emeritus
Physics

Email: zou@iupui.edu

Research Areas: Atomic, Molecular and Optical Physics

INDIANA UNIVERSITY BLOOMINGTON

QSEc

Quantum Science and Engineering Center

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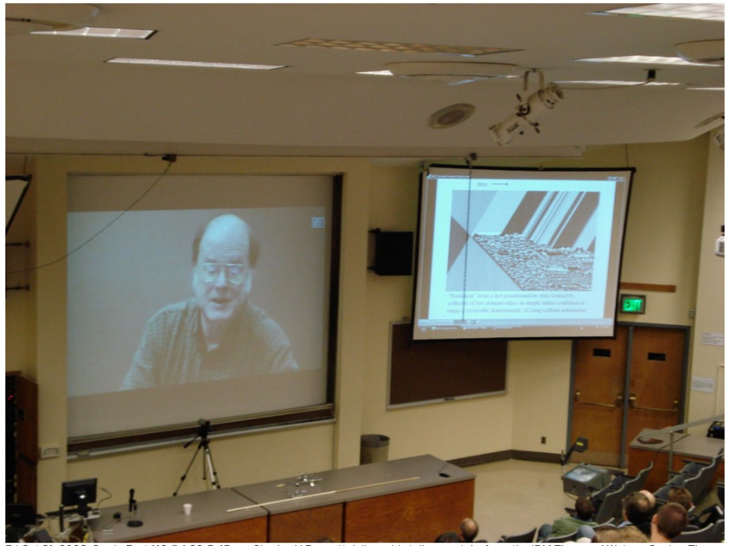

Fri Oct 31, 2008, Swain East 119 @4:30-5:45pm: Charles H Bennett delivers his talk, remotely, from the IBM Thomas J Watson Center. The title of the talk was: A Quantum Computational View of the Origin of Randomness, Classicality and Complexity in the World.

Sat Nov 1, 2008, Frangipani (IMU) @11:30am-12:30pm: Sir Anthony J Leggett delivers, in person, his talk entitled: What Exactly is the Predictive Success of Quantum Mechanics (to Date) Telling Us About the Phisical World? (Second from left, 2nd row: Gregory J Chaitin).

Sat Nov 1, 2008, Rawles 100 @2:00-2:45pm: David Deutsch delivers his talk, remotely, from Oxford University's Clarendon Laboratory. The title of his talk eventually became the theme of the conference: What is Computation? (How) Does Nature Compute?

Sat Nov 1, 2008, Rawles 100 @3:00-3:45pm: Lov K Grover delivers, remotely, from Bell Labs, his talk entitled: Can Quantum Search Take Place in Nature? From left to right in this picture: Andy Hanson (taking notes), Gerardo Ortiz (third row) and Hector Zenil (white shirt).

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Sun Nov 2, 2008, Frangipani Room (Indiana Memorial Union) @9:00-10:30am and 10:45am-12:15pm: round-table discussion with (from left to right) Greg Chaitin, Ed Fredkin, Rob de Ruyter van Steveninck, Tony Leggett, Cristian Calude, Tom Toffoli (of Toffoli gate fame) and Stephen Wolfram, moderated by (from left to right, with their backs towards the camera) Hector Zenil, George Johnson and Gerardo Ortiz.

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The round table from the other side of the room. See books listed below for transcripts of all these talks.

Sat Nov 1, 2008, on the steps of Lindley Hall around 4:15pm. Front row, left to right: Tom Toffoli, Tony Leggett, Rob de Ruyter, Greg Chaitin, Stephen Wolfram, Cris Calude, Ed Fredkin and (last, on the right) George Johnson. Hector Zenil and Gerardo Ortiz are visible in the second row on the left. Mike Dunn is visible between Rob de Ruyter and Greg Chaitin and right above him (next to Gerardo) is Andy Hanson.

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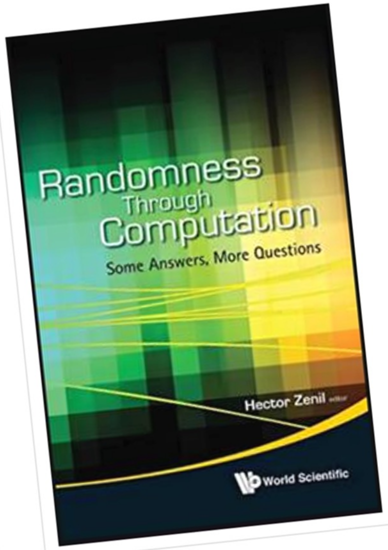
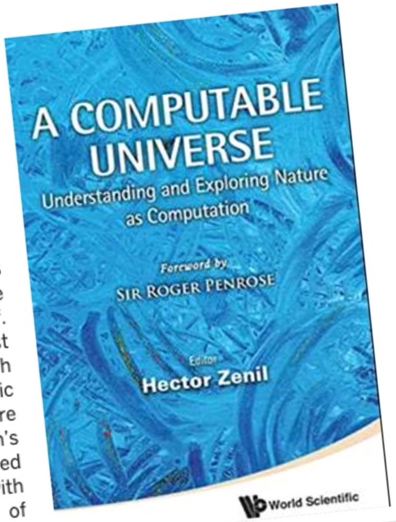


These two books contain most of the talks from the 2008 and 2005 conferences. "Randomness Through Computation (Some Answers, More Questions)" was published first, on Feb 11, 2011. The second one, "A Computable Universe (Understanding and Exploring Nature as Computation)" followed on Oct 30, 2012, and contains a foreword written by Sir Roger Penrose (who wanted but wasn't able to attend our 2008 conference neither in person nor via remote video due to a prior engagement; Prof. Penrose had in fact visited Bloomington just a few months earlier to present the Joseph and Sophia Konopinski Memorial Public Lecture in Physics (and a separate lecture on Twistor Theory) at Tim Londergan's invite). The 2005 conference also featured Ray J Solomonoff, one of the founders (with Greg Chaitin and Andrey Kolmogorov) of Algorithmic Information Theory.



Quantum Information Science

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Specialized courses provide you with opportunities to apply quantum concepts and/or to learn about the science and technology where quantum processes are hosted.

Specializations include:

- Quantum Information and Simulation: including mathematical and computational models of quantum computation and simulation, and complexity theory.
- Quantum Materials and Sensing: including topological electron systems, strange metals, superconductors, theoretical physics and chemistry, photonics, nano-engineering, and quantum measurement.
- Quantum Applications and Operations: including optimization problems, quantum algorithms, logistics, operations research, and machine learning.

A capstone project involving research on a mutually-agreed-upon QIS topic will be supervised by the research advisor. It will consist of a written report to be reviewed by the advisor, the track manager, and the program director.

In the subsections below, we list all the classes relevant towards satisfying the above specializations. In addition we also imagine novel tracks you may follow for further specialization. “Track managers” will advise you and guide you along these paths.

- Core Course +
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Wednesday, November 4, 2020

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“IU Physics should take more credit for inventing the professional MS degree idea before it was named in Shelia Tobias's book and funded for study/promotion by various foundations grants. I am referring to the US Particle Accelerator School (USPAS) MS degree program in accelerator physics which we (IU) have run for two decades in collaboration with Fermilab. This program is a successful example of a set of stakeholders (US national labs in this case, rather than QIS industry) getting together to support a sustained educational activity that has succeeded to efficiently educate not only MS students but also PhD students in accelerator physics as well who go on to positions in industry and national labs. The point is that this USPAS activity has both the MS and PhD aspects and it offers a counterexample to the "MS only" push that I can see from some quarters. We can state based on our own pioneering experience that doing something that serves both MS and existing/prospective PhD students is the right way to go to stay flexible. It is a crime that this program is not listed prominently in the "official" PSM degree program list because it was too far ahead of its time."

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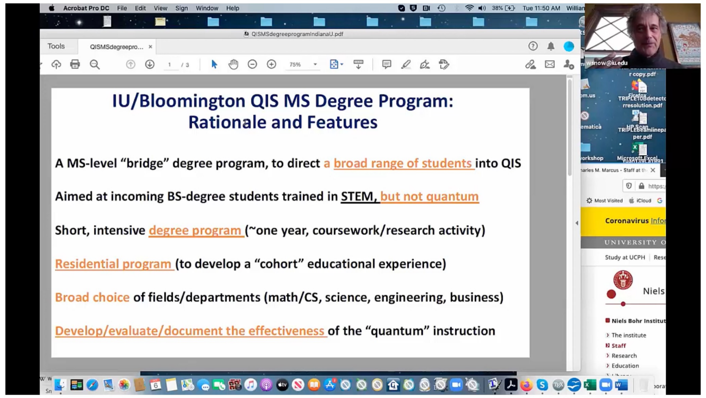

Indiana University, Bloomington, QIS MS Degree. October 8, 2020

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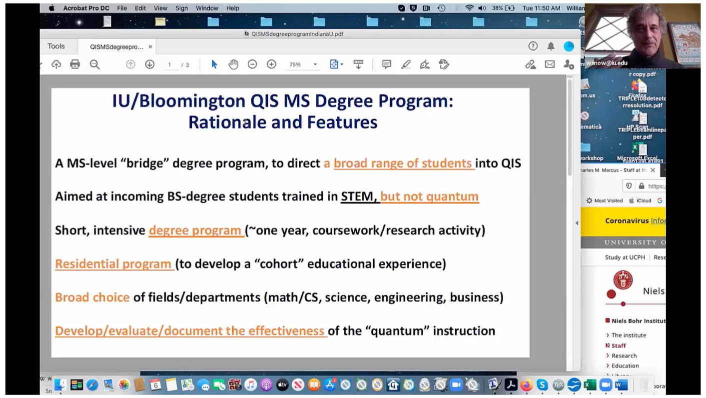

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Wednesday, November 4, 2020

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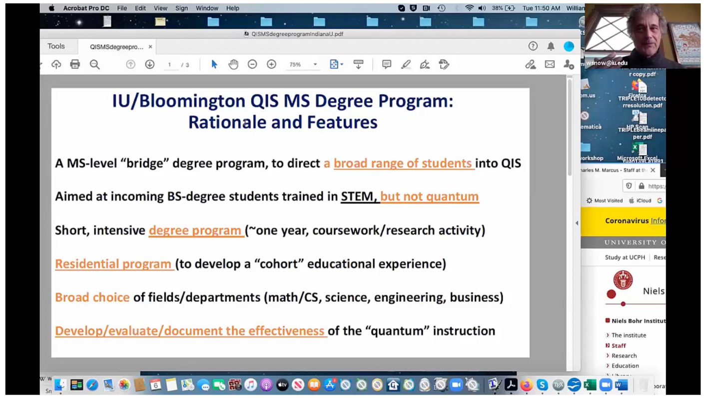

Indiana University, Bloomington, QIS MS Degree. October 8, 2020

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IU Bloomington, IUPUI part of coalition to develop quantum technologies

FOR IMMEDIATE RELEASE | Jul 8, 2021

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Scientists at Indiana University Bloomington and IUPUI are partnering with two other institutes of higher education in Indiana to establish a quantum research center in the state.

The new Center for Quantum Technologies, led by Purdue University, will be established through the National Science Foundation's Industry-University Cooperative Research program. Industry partners would provide research funding to the center's scientists and gain early access to findings applicable to their businesses. The other university in the partnership is the University of Notre Dame.

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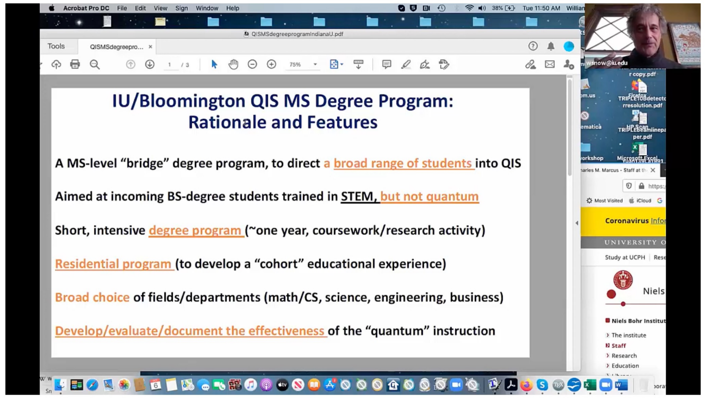

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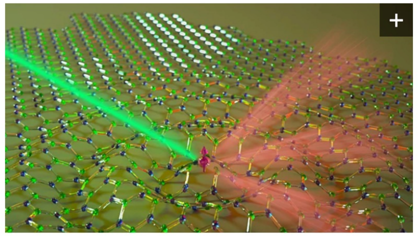
3 research universities to collaborate with industry, government to develop quantum technologies

FOR IMMEDIATE RELEASE | Aug 29, 2022 | Twitter | Facebook

BLOOMINGTON, Ind. – Quantum science and engineering can save energy, speed up computation, enhance national security and defense, and innovate health care. With a grant from the National Science Foundation, researchers from Indiana University (both Bloomington and IUPUI campuses), Purdue University and the University of Notre Dame will develop industry- and government-relevant quantum technologies as part of the Center for Quantum Technologies. Purdue will serve as the lead site.

"The Center for Quantum Technologies is based on the collaboration between world experts whose collective mission is to deliver frontier research addressing the quantum technological challenges facing industry and government agencies," said Gerardo Ortiz, Indiana University site director, scientific director of the IU Quantum Science and Engineering Center and professor of physics. "It represents a unique opportunity for the state of Indiana to become a national and international leader in technologies that can shape our future."



The Center for Quantum Technologies will develop foundational knowledge into industry-friendly quantum devices, systems and algorithms and will train future quantum scientists and engineers to fill the need for a robust quantum workforce. Image courtesy of Second Bay Studios

"This newly formed center is unique in many aspects," said Ricardo Decca, professor and chair of the Department of Physics at IUPUI. "It brings together experts in many scientific

Overview of the Industry/University Cooperative Research Center for Quantum Technologies

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IUPUI

Industry/University Cooperative Research Center for Quantum Technologies

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CQT | Center for Quantum Technologies

An NSF Industry/University Cooperative Research Center (IUCRC)

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The Center for Quantum Technologies

Developing novel quantum technologies to address significant industry challenges

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New center aims to apply quantum science to real-world problems

INDUSTRY/UNIVERSITY COOPERATIVE RESEARCH CENTER FOR QUANTUM TECHNOLOGIES

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New center aims to apply quantum science to real-world problems

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The Center for Quantum Technologies

Developing novel quantum technologies to address significant industry challenges

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1. The absence of any serious education in QM in a large fraction of traditional US engineering programs, including computer engineering and the closely related computer science and data science programs, presents many BS degree STEM graduates with the daunting problem of how to get trained quickly and efficiently to pursue the new opportunities in quantum information sciences (QIS). Since Fall 2021 Indiana University has an intensive MS program[1] (approved[2] in October 2020 at the state level) that delivers parallel tracks in quantum mechanics/quantum information combined with an intensive research experience in a QIS-related activity supervised closely by faculty in our Quantum Science and Engineering Center (IU QSEc[3]) and sustained with year-round internships with any of the industrial members in our new Center for Quantum Technologies[4] (CQT). Our program is truly inter-disciplinary and aimed at STEM undergraduates that were not majors of Physics. I would like to describe the challenges and opportunities associated with such a unique project.

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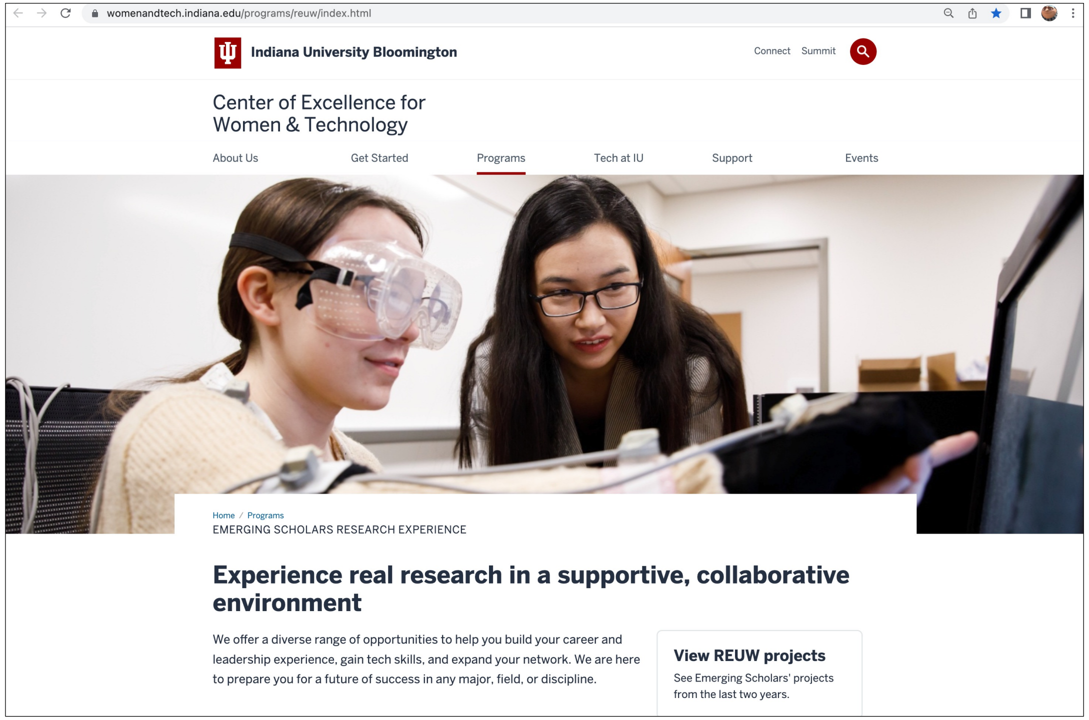

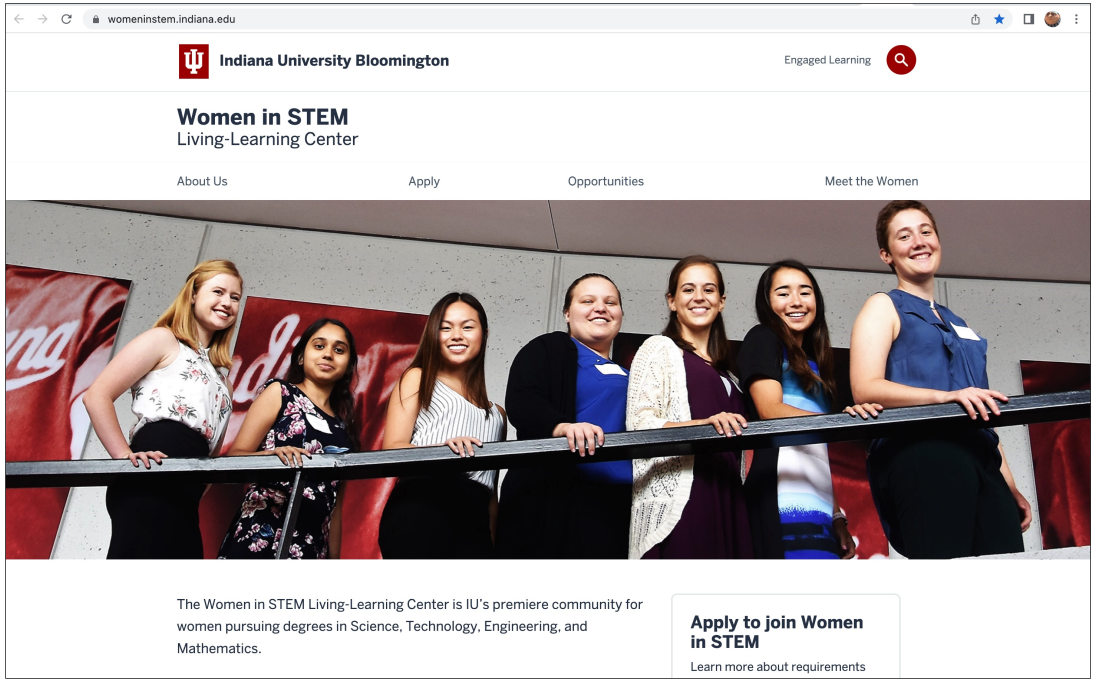

Indiana University Bloomington

Center for Evaluation, Policy, & Research

In Summer 2021 our instructional team has designed and implemented an online learning experience (a Boot Camp, now offered via IU Expand, as a MOOC) that addresses the needs of diverse QIS learning communities through approaches that value diversity, equity and inclusion.

The Boot Camp is a short, intensive training meant to prepare students for continued learning, growth and making a long-lasting impact. Its purpose is to create and sustain an inclusive, student-centered learning environment for the benefits of recruitment and retention especially of students from underrepresented and underserved minority demographics and by capitalizing on prior or existing initiatives on the Bloomington campus such as: (a) the IU-MSI STEM Initiative, the (b) Women in STEM Living-Learning Center and (c) The Center of Excellence for Women and Technology.

The design of our Boot Camp identified three aspects of diversity, equity and inclusion we wanted cultivated: (a) addressing social inequalities, (b) valuing individuals, and (c) finding common ground. Long ago, Indiana University Bloomington has made a long-term commitment to making and keeping our residential campus more diverse, equitable and inclusive. It follows that these goals should also be espoused by, and conspicuously represented in, our online education programs, both traditional (fee-based degree courses) and open. The Boot Camp is free of charge and access is granted via an open registration process; anybody can sign up, from HS students and/or HS teachers to any prospective student from anywhere in the world, including existing industry workforce interested in retraining or upskilling in the new field of QIS.

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Diversity is composed of individual and group/social differences; equity refers to ensuring historically underrepresented populations have equal access and opportunities for participation in educational programs; inclusion is intentional, and on-going engagement with diversity: in the curriculum, in the co-curriculum, and in the communities with which individuals might connect that help members increase their awareness of the complexity of interactions among individuals, institutions and systems. A question we had in mind from the outset was: how will our MOOC Boot Camp course continue to further the university's diversity, equity and inclusion goals?

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To this purpose we first developed a plan to engage in a more systematic and purposeful approach for the realization of these goals within course design. To achieve that, we first examined existing online learning experiences where creators had identified specific aspects of diversity, equity and inclusion they wanted to cultivate. Then, we identified specific approaches that instructional teams used to realize their goals. Finally, we extracted design principles for DEI that could be taken up by our team of instructors (and the design team) within online learning spaces. There is always room for improvement and one important conclusion that we came to here is that within (as part of) any design process the faculty and design teams can and should hold themselves accountable for enacting the DEI goals stated within the original proposals. And although further investigation is necessary to fully understand the ways in which dynamics within a design team impacts the realization of DEI goals, we think that the implementation of our current Boot Camp has been, and remains by and large a success story.

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Motivations for designing and creating MOOCs by faculty frequently include: (a) the social value of learning, (b) the dissemination of specific knowledge for a general audience and (c) the opportunity to teach a relevant subject in an attractive and entertaining way. Finding value in social learning is important when considering the social-constructivist nature of intercultural education. There is a need for MOOC spaces to foster intercultural competence in learners to engage in successful and meaningful interactions that not only transmit knowledge, but also cultivate learner interactions in the development of networked engagement of peers across diverse language and cultural backgrounds.

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A Sense of Safety and Trust. The learning environment should promote a sense of safety and trust for sharing ideas and critical reflections related to content and tasks that welcome diverse perspectives and multiple literacies. To that end we replaced the traditional web forums in the Boot Camp with dedicated channels on a Discord server, where learners have control over their identity being anonymous or not, and thus implementing the "lurking as learning" concept known to foster intercultural competence while respecting learners' prior experiences and beliefs regarding communicative norms.

ground. Long ago, Indiana University Bloomington has made a long-term commitment to making and keeping our residential campus more diverse, equitable and inclusive. It follows that these goals should also be espoused by, and conspicuously represented in, our online education programs, both traditional (fee-based degree courses) and open. The Boot Camp is free of charge and access is granted via an open registration process; anybody can sign up, from HS students and/or HS teachers to any prospective student from anywhere in the world, including existing industry workforce interested in retraining or upskilling in the new field of QIS.

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ss the faculty and design teams can and should
hold themselves accountable for enacting the DEI goals stated within the original proposals. And although further investigation is necessary to fully understand the ways in which dynamics within a design team impacts the realization of DEI goals, we think that the implementation of our current Boot Camp has been, and remains by and large a success story.

Diversity is composed of individual and group/social differences; equity refers to ensuring historically underrepresented populations have equal access and opportunities for participation in educational programs; inclusion is intentional, and on-going engagement with diversity: in the curriculum, in the co-curriculum, and in the communities with which individuals might connect that help members increase their awareness of the complexity of interactions among individuals, institutions and systems. A question we had in mind from the outset was: how will our MOOC Boot Camp course continue to further the university's diversity, equity and inclusion goals?

Motivations for designing and creating MOOCs by faculty frequently include: (a) the social value of learning, (b) the dissemination of specific knowledge for a general audience and (c) the opportunity to teach a relevant subject in an attractive and entertaining way. Finding value in social learning is important when considering the social-constructivist nature of intercultural education. There is a need for MOOC spaces to foster intercultural competence in learners to engage in successful and meaningful interactions that not only transmit knowledge, but also cultivate learner interactions in the development of networked engagement of peers across diverse language and cultural backgrounds.

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Addressing Social Inequalities. Our QIS Boot Camp has an open content since there virtually are no restrictions on enrollment. Within the Boot Camp, one proposed goal (that falls under the theme of Addressing Social Inequality) speaks to leveling the playing field by offering easing transitions to college-level rigor. The most notable instances of this particular aspect of the goal involves lecture videos that include examples and procedures for a variety of QIS concepts, code demonstrations for any exercises that admit such an approach, and scaffolded assignments with demonstrations and/or code samples for learners to review prior to completing assignments. Overall, through our videos and content we continually and explicitly reinforce this proposed goal of opening access to courses for underrepresented students within this field.

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Valuing Individuals. The Boot Camp is structured to offer different entry points depending on the previous background of the learner. Its set of reconfigurable modules based on short videos and associated interactive assessment supports our goal for differentiated instruction to create personalized learning experiences. To support this theme the Boot Camp models and encourages multiple, alternative approaches and solutions to a problem. If one solves a problem in more than one way and obtains the same result one gains increased confidence that the result is correct.

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The **Finding Common Ground** theme comes into play when learners are being asked explicitly to engage with each other via a peer-review graded assignment or ungraded external tool allowing learners to share and comment on each other's work. Encouraging collaboration beyond platforms and relying on some form of peer review for assignments also builds intercultural competencies for learners to have space to reinforce content and expand their worldviews through collaborative interactions.

Home • Workshop on Quantum Education for Quantum Workforce Development

WORKSHOP ON QUANTUM EDUCATION FOR QUANTUM WORKFORCE DEVELOPMENT

ABOUT THE WORKSHOP

The United States Government is concerned about the workforce needs for quantum information science and has been developing numerous programs to create opportunities to increase quantum education in the K-16 pipeline. Nevertheless, conventional quantum instruction within the disciplines remains deeply rooted in a pedagogy developed in the late 1940s with the emergence of Dirac's third edition of his quantum mechanics textbook and of Schiff's quantum text. Even though there are hundreds of quantum mechanics textbooks, most continue to follow a very similar pedagogy based on differential equation in position space (sometimes altering the ordering of topics to teach spins first). This is much less so in quantum computing and quantum communication education, where newer paradigms have been developed, primarily from the Computer Science realm (such as teaching quantum mechanics from the lens of a novel theory for probability). The NSF QLCI Conceptualization Grant team, centered at the University of Florida, is hosting a workshop on quantum education for quantum workforce development, exploring ideas for approaches to teach at the K-12 level, at the undergraduate level, and at the graduate level. We are interested in bringing in a diverse group of people interested in re-examining how we teach quantum mechanics and how we can improve on student learning, with a focus on preparing students for careers in quantum computing, quantum communication, and quantum sensing.

UF UNIVERSITY OF FLORIDA
Quantum Information Systems //// NSF QLCI: Conceptualizing an Institute for Quantum Biology
PROJECT SUMMARY PEOPLE EVENTS LITERATURE RELATED ORGANIZATIONS

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"Quantum theory and Einstein's general theory of relativity are the two great fundamental theories of contemporary physics. Between them they provide the conceptual framework and the mathematical language in which we express all other theories in physics, and they provide the basic principles to which all known laws of nature conform." -- Lectures on Quantum Computation David Deutsch, 2006 (sponsored by Quiprocone, HP Labs Bristol)

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"Sixteen years ago, Scott Aaronson remarked (in the presence of Ray Laflamme) that quantum mechanics (QM) resembles an operating system on which the rest of Physics is running its application software (except for general relativity "which has not yet been successfully ported to this particular OS").

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"I like to say that, after all the forbidding–sounding verbiage you read in popular books, quantum mechanics is astonishingly simple—once you take the physics out of it! In fact, QM isn't even 'physics' in the usual sense: it's more like an operating system that the rest of physics runs on as application software."

SCIENTIFIC AMERICAN.

Scott Aaronson Answers Every Ridiculously Big Question I Throw at Him

By John Horgan on April 21, 2016

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He then goes on to explain what he thinks is at the heart of it all:

"[QM i]s a certain generalization of the laws of probability. It says nothing directly about electrons, photons, or anything like that. It just talks about lists of complex numbers called amplitudes: how these amplitudes change as a physical system evolves, and how to convert them into the probability of seeing this or that result when you measure the system."

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Such a pragmatic point of view has always been intrinsic to CSCI:

"And everything you've ever heard about the 'weirdness of the quantum world,' is simply different logical consequences of this one change to the rules of probability.

This makes QM, as a subject, possibly more computer-science friendly than any other part of physics."

On the Design and Implementation of a Quantum Architectures Knowledge Unit for a CS Curriculum

For a theoretical computer scientist, he says, QM is a logical necessity: "In fact, even if our universe hadn't been described by QM, I suspect theoretical computer scientists would have eventually needed to invent quantum computing anyway, just for internal mathematical reasons. Of course, the fact that our universe is [in fact, quantum mechanical] does heighten the interest!"

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the conflict is only superficial? It was then that we remembered a quote from Richard Feynman from the 1964 Messenger Lectures at Cornell, later published as the book "The Character of Physical Law":

> "It always bothers me that, according to the laws as we understand them today, it takes a computing machine an infinite number of logical operations to figure out what goes on in no matter how tiny a region of space, and no matter how tiny a region of time. So I have often made the hypothesis that ultimately physics will not require a mathematical statement, that in the end the machinery will be revealed, and the laws will turn out to be simple, like the chequerboard with all its apparent complexities[b]."

all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy. Thank you.

Simulating Physics with Computers

Received May 7, 1981 *International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982*

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measurement and so on, which computers have stimulated us to think about anew, with new types of thinking. And all I was doing was hoping that the computer-type of thinking would give us some new ideas, if any are really needed. I don't know, maybe physics is absolutely OK the way it is. The program that Fredkin is always pushing, about trying to find a computer simulation of physics, seem to me to be an excellent program to follow out. He and I have had wonderful, intense, and interminable arguments, and my argument is always that the real use of it would be with quantum mechanics, and therefore full attention and acceptance of the quantum mechanical phenomena—the challenge of explaining quantum mechanical phenomena —has to be put into the argument, and therefore these phenomena have to be understood very well in analyzing the situation. And I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy. Thank you.

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measurement and so on, which computers have stimulated us to think about anew, with new types of thinking. And all I was doing was hoping that the

anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with computers and I mean that in a specific way which I am going to explain. The reason for doing this is something that I learned about from Ed Fredkin, and my entire interest in the subject has been inspired by him. It has to do with learning something about the possibilities of computers, and also something about possibilities in physics. If we suppose that we know all

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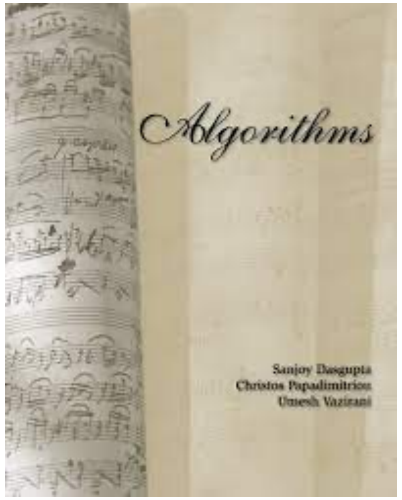
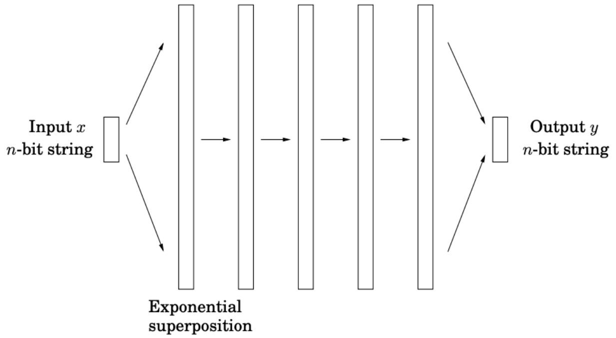
A different, more powerful way of computing

Quantum mechanics provides the basis for a new paradigm of computing. Since the 1940s, the rules of computing have not changed. Computers have continued to get smaller and faster year after year, but their fundamental operations remain the same. They still obey the laws of information processing, and process information by performing operations on bits. Quantum computers manipulate qubits instead of bits. With superposition and entanglement, the states of multiple qubits become very complex. By harnessing these complex states, quantum computers will be able to solve many problems much faster than today's computers.



On the Design and Implementation of a Quantum Architectures Knowledge Unit for a CS Curriculum

Figure 10.3 A quantum algorithm takes n "classical" bits as its input, manipulates them so as to create a superposition of their 2^n possible states, manipulates this exponentially large superposition to obtain the final quantum result, and then measures the result to get (with the appropriate probability distribution) the n output bits. For the middle phase, there are elementary operations which count as one step and yet manipulate all the exponentially many amplitudes of the superposition.



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A quantum algorithm is unlike any you have seen so far. Its structure reflects the tension between the exponential "private workspace" of an n-qubit system and the mere n bits that can be obtained through measurement.

The input to a quantum algorithm consists of n classical bits, and the output also consists of n classical bits. It is while the quantum system is not being watched that the quantum effects take over and we have the benefit of Nature working exponentially hard on our behalf.

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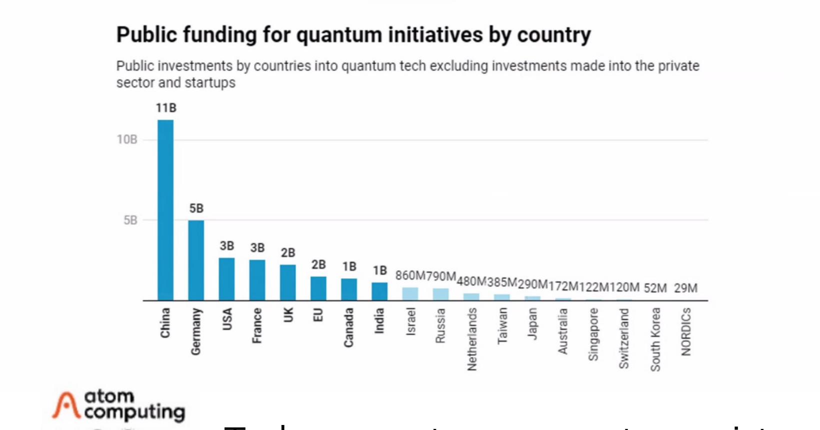
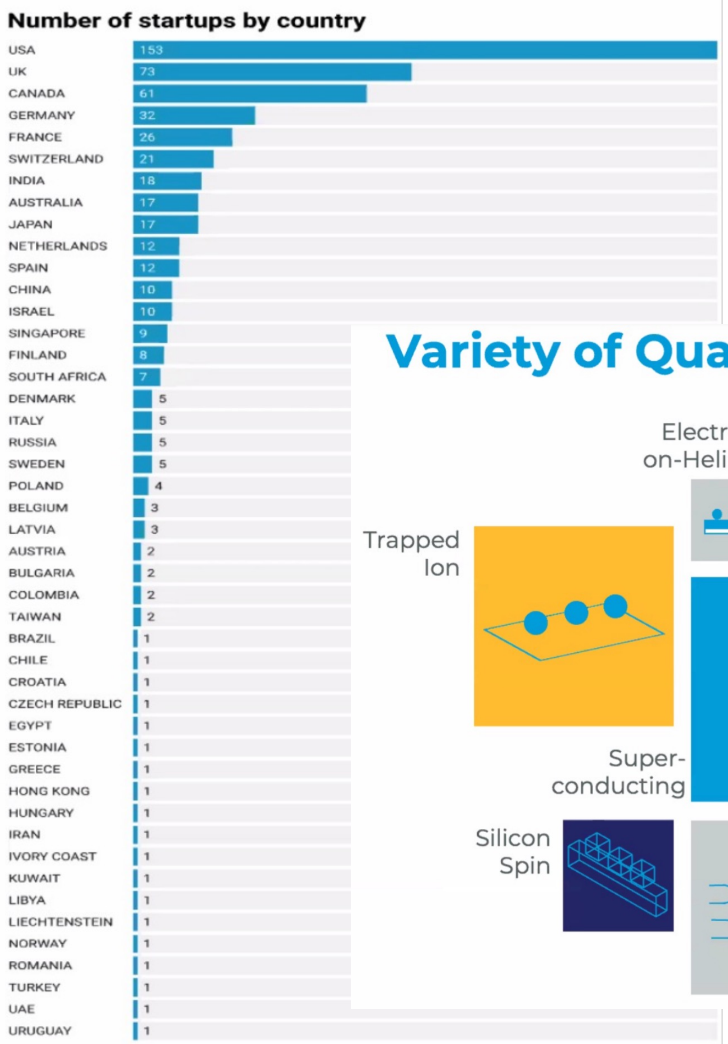
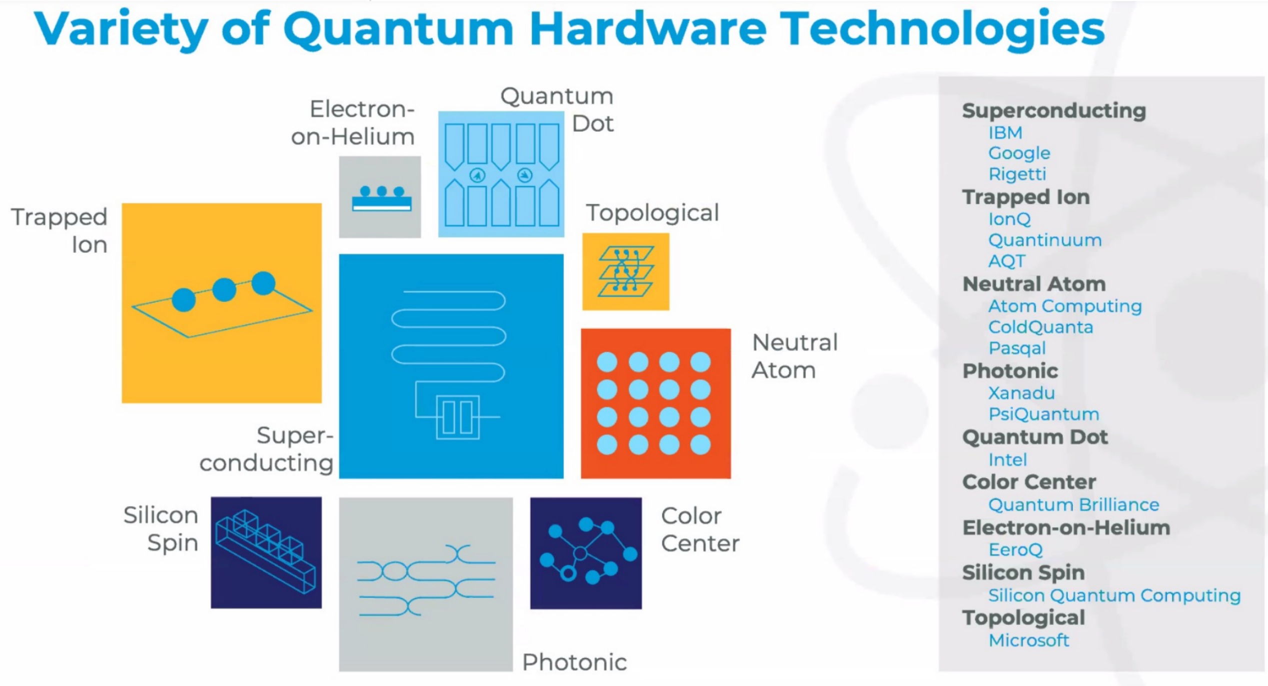
Government Programs for Quantum Computing





WOMEN IN QUANTUM



Today, quantum computers exist, access to them via the cloud is affordable, university and industry developed education is increasing, and government funding was approved to further research and focus on needed workforce development. Worldwide, there is growing excitement, investment, and competition in the area of QIST. A technological ecosystem is being shaped by public and private investment in North America, Asia and Europe.

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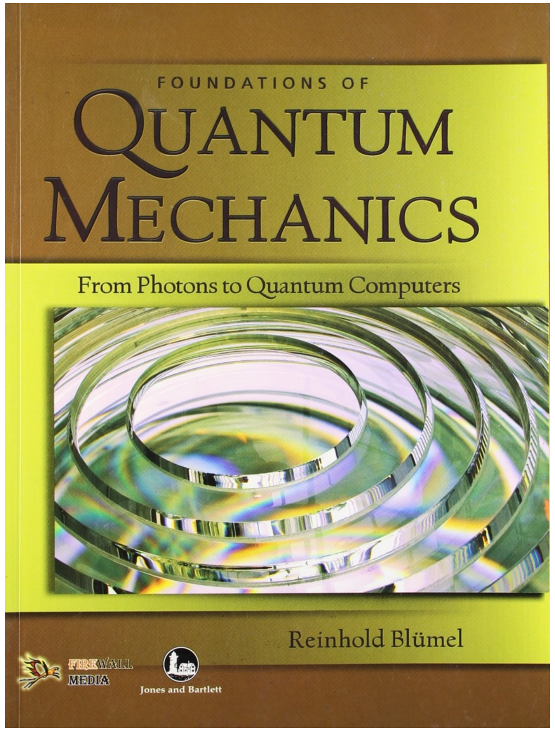
The conceptual basis for the new quantum technology consists of

(a) superposition,
(b) entanglement, and
(c) quantum measurement (i.e., the collapse of the wave function).

In connection with matter, these concepts simply do not exist in the classical description of our world and are not used in any of the "classical" machines and appliances around us. Thus, quantum technology is not just better, it is different.



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(a) superposition

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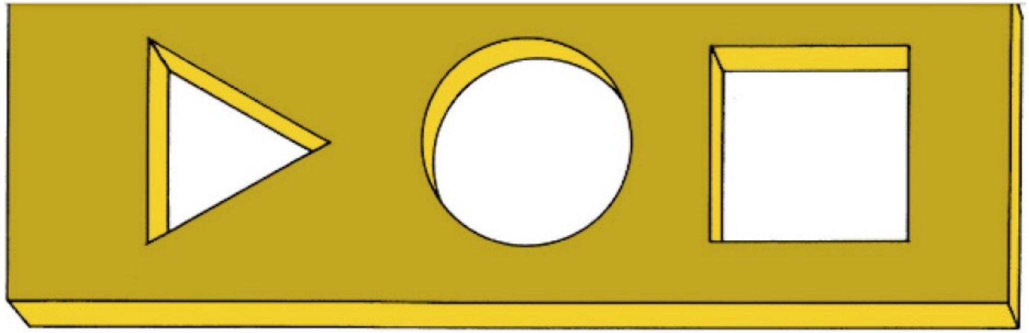
Is there an object that could fit these openings perfectly?



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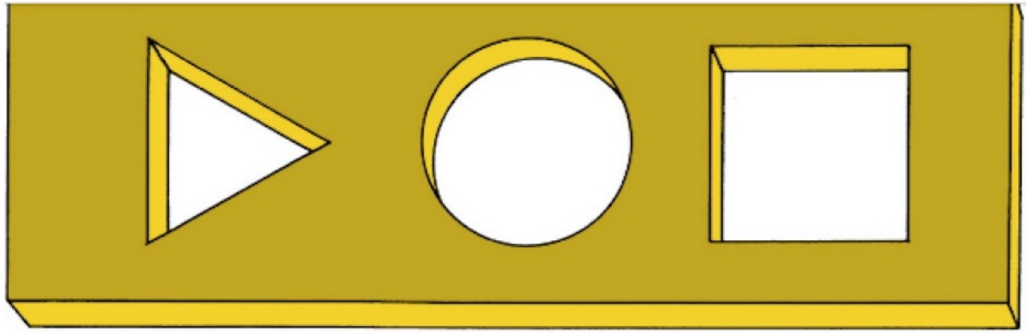
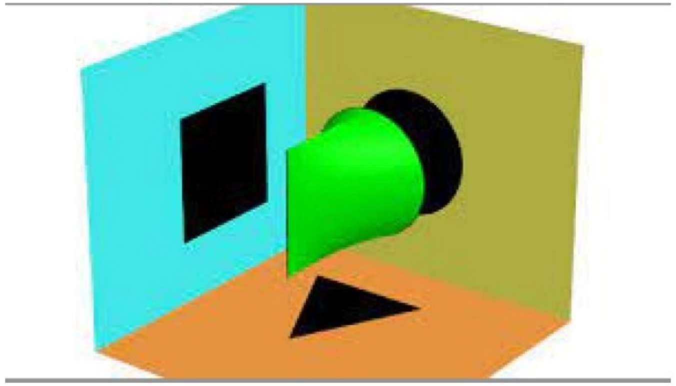
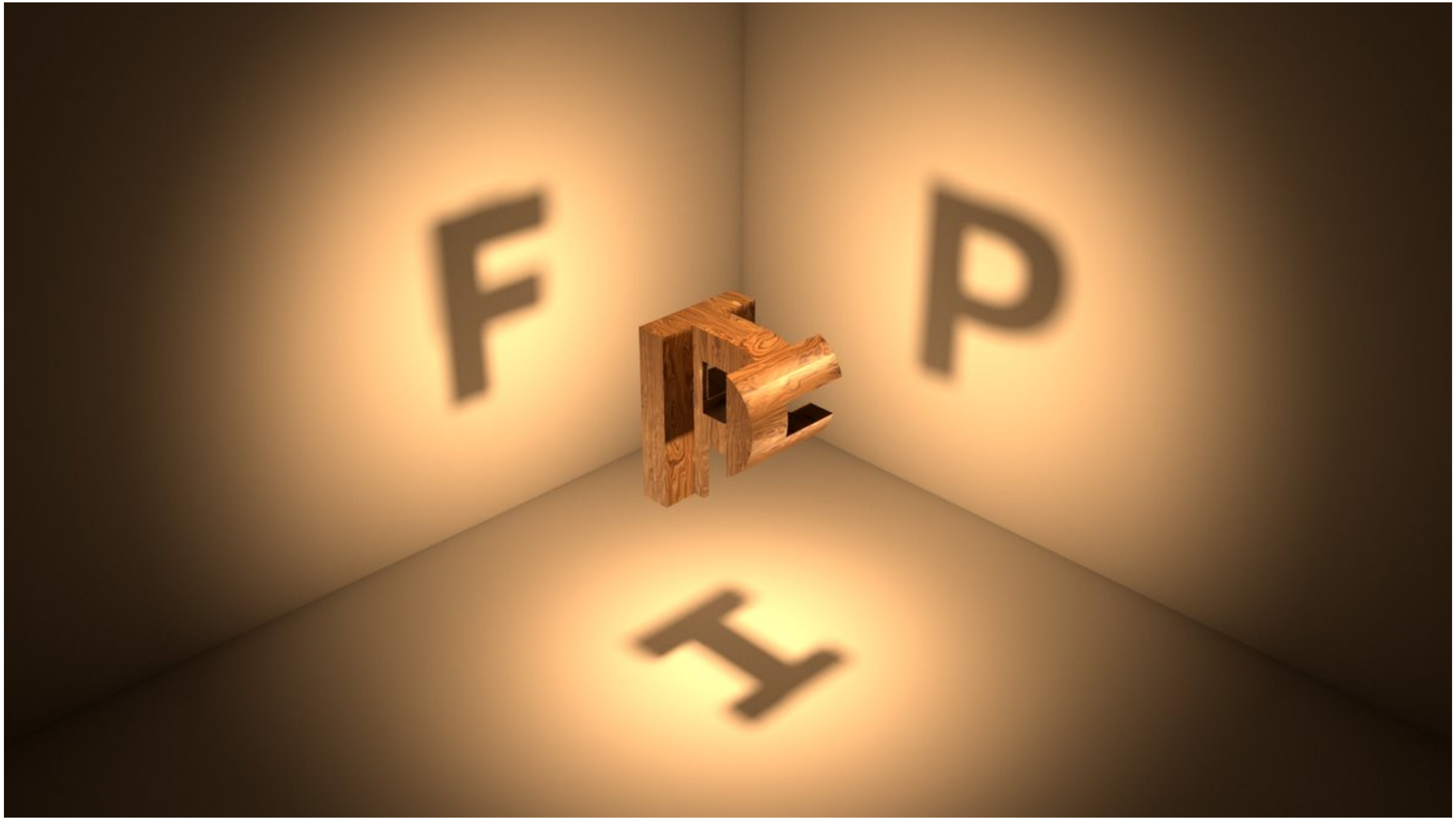


Answer: yes.

This is called superposition.

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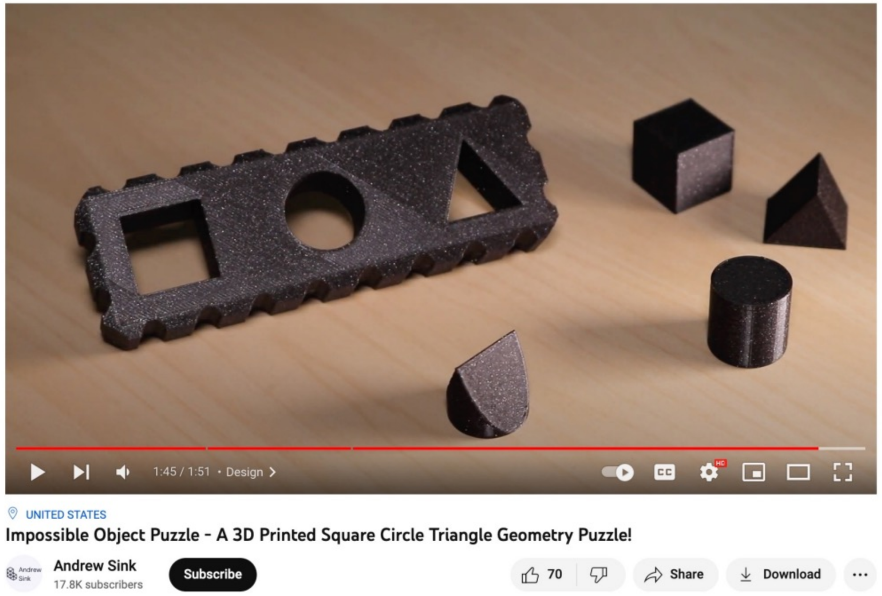

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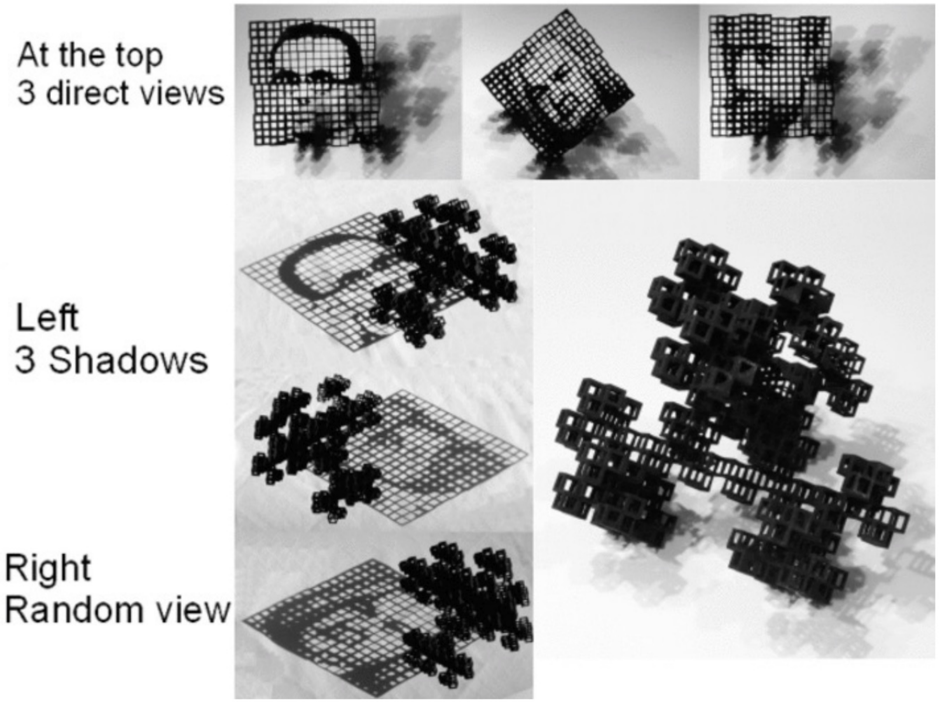
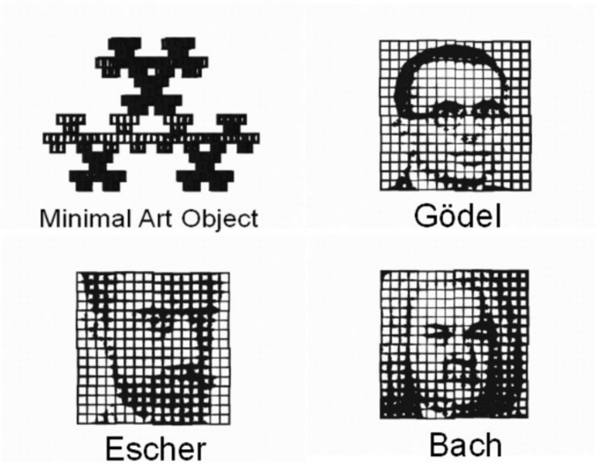
Same idea taken to the extreme:

shapeways.com/product/T8GLAXEJH/godel-escher-bach-3-faces-in-a-minimal-object



Gödel, Escher, Bach: 3 faces in a Minimal Object

Made by
Kuiper & van Ballegooijen Math Art



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1 INTRODUCTION

From the outset, we need to distinguish between Quantum Mechanics (QM) and Quantum Information Science and Technology (QIST). QM is the science describing the behavior of matter and light on the atomic and subatomic scale. QIST is an emerging interdisciplinary academic discipline concerned with studying the new possibilities QM offers for acquiring, transmitting, and processing information. Fields under QIST include quantum computing (QC), quantum sensing (ultrasensitive precision measurements), quantum communication, quantum cryptography, materials for quantum information and more. Specifically, quantum computing is a type of computation whose operations can harness quantum mechanical phenomena such as *superposition, interference and entanglement.*

Worldwide, there is growing excitement, investment, and competition in the area of QIST. A technological ecosystem is being shaped by public and private investment in North America, Asia and Europe. The potential implications of QIST are broad; quantum technology may eventually underlie a new technological infrastructure, much like the semiconductor revolution changed everything in the second half of the last century. With this growth, there has been a steady demand for QIST-trained professionals. Recognizing that the impact on the CS undergraduate curriculum is imminent, our paper aims to answer the following questions:

(1) What is the minimum set of topics (knowledge unit - KU) that a CS undergraduate should be taught in a Quantum Architectures course?
(2) What is the interface for this knowledge unit (where input: required skills, and output: learning outcomes)?
(3) What is the tension between disciplines such as math, physics, engineering and computer science? How do we get a genuinely trans-disciplinary learning program off the ground?
(4) What is the theoretical minimum that captures the essence without overwhelming details in physics and maths?
(5) How can we ensure a 10-15 years horizon shelf life for this knowledge unit (including concrete recommendations for a CS undergraduate "quantum hardware lab")?

1. Why do we need such a knowledge unit?
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3. How do we know it's what we need?

On the Design and Implementation of a Quantum Architectures Knowledge Unit for a CS Curriculum

Figure 1: Schematic overview of the three curricular plans with specific sample instantiations.

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2 QUANTUM MECHANICS (QM)

QIST has three pillars: quantum sensing, quantum networking and quantum computing (collectively known as quantum technology).

The learner should realize that we can address quantum technology only because of QM. And the reason for QM is Nature. Thus, from the start, the learner needs to develop a qualitative appreciation for the quantum nature of our world. Understanding what we

2.1 A Quantum Intuition

Dirac taught us that a minimum disturbance accompanies a measurement (inherent in the nature of things, and that cannot be overcome by improved experimental technique). If the minimum

5.3 Implementing Qubits

We acknowledge nine current modalities [36, 37]: superconducting, silicon spin, optical (photonics), quantum dots, trapped ions, color centers in diamond, neutral atoms in an optical tweezer array, topological and electron on helium.

3 QUANTUM COMPUTING

Classically, the time it takes to do specific computations can be decreased by using parallel processors. To achieve an exponential decrease in time requires an exponential increase in the number of processors and hence an exponential increase in the amount of physical space needed. In quantum systems, the amount of parallelism increases exponentially with the size of the system. Thus, an exponential increase in parallelism requires only a linear increase in the amount of physical space needed. This effect is called quantum parallelism [40, 41]. However, there is a catch: while a quantum system can perform massive parallel computation, access to the computation results is restricted. Accessing the results is equivalent to making a measurement, which disturbs the quantum state. This problem makes the situation seem even worse than the classical situation; we can only read the result of one parallel thread, and because the measurement is probabilistic, we cannot even choose which one we get. But in the past few years, a few researchers have found efficient ways of finessing the measurement problem to exploit the power of quantum parallelism. This type of manipulation has no classical analog, and requires non-traditional programming techniques.

5.4 Error Mitigation and Control

The complexity of noise is a crucial issue. Quantum error correction protects quantum information from errors due to decoherence and other quantum noise. Quantum error correction is theorised as essential to achieving fault-tolerant quantum computation that can reduce the effects of noise on stored quantum information, faulty quantum gates, faulty quantum preparation, and inaccurate measurements.

Classical error correction employs redundancy. The simplest albeit inefficient approach is the repetition code. The idea is to store the information multiple times, and—if these copies are later found to disagree—take a majority vote; e.g. suppose we copy a bit in the one state three times, etc. However, copying quantum information is impossible due to the no-cloning theorem. This theorem seems to present an obstacle to formulating a theory of quantum error correction. But it is possible to spread the (logical) information of one qubit onto a highly entangled state of several (physical) qubits. Peter Shor first discovered this method of formulating a quantum error correcting code by storing the information of one qubit onto a highly entangled state of nine qubits.

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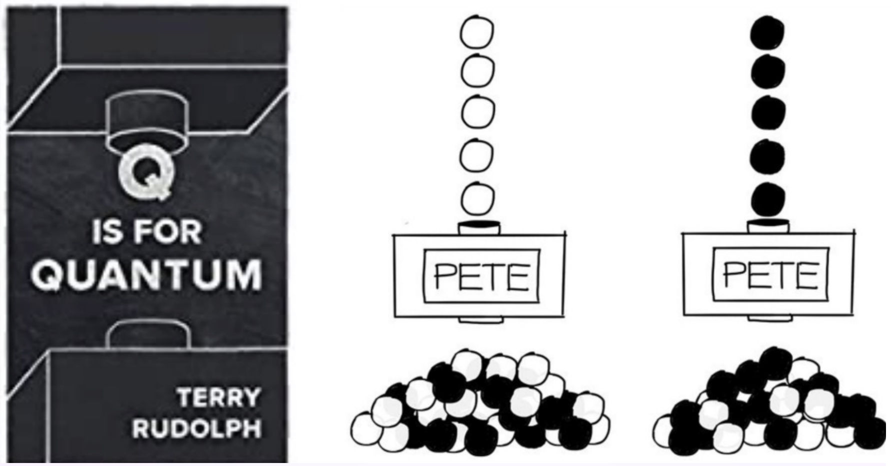
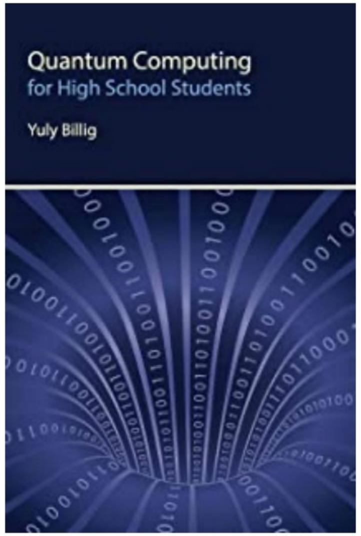
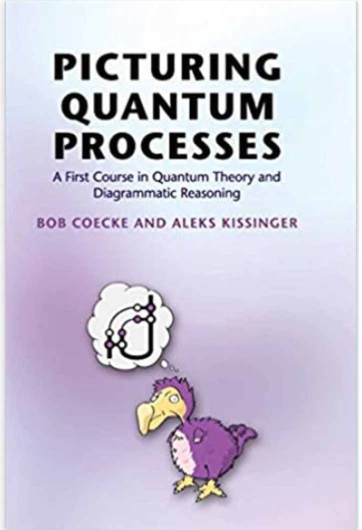
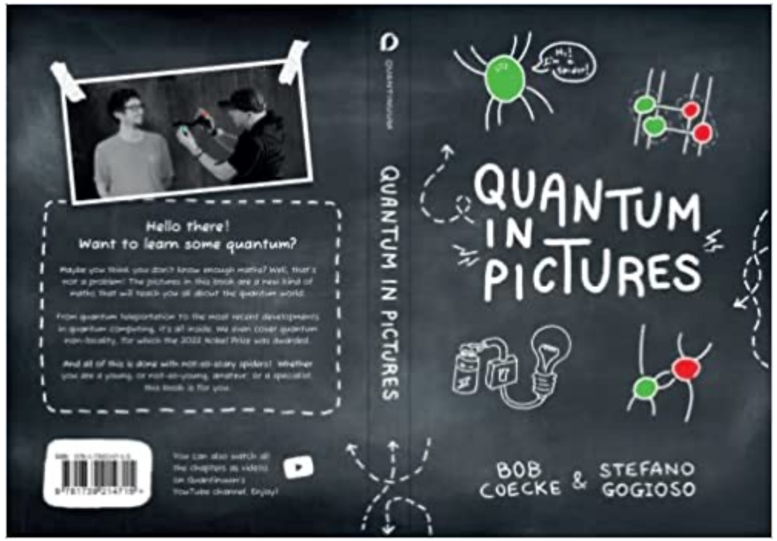






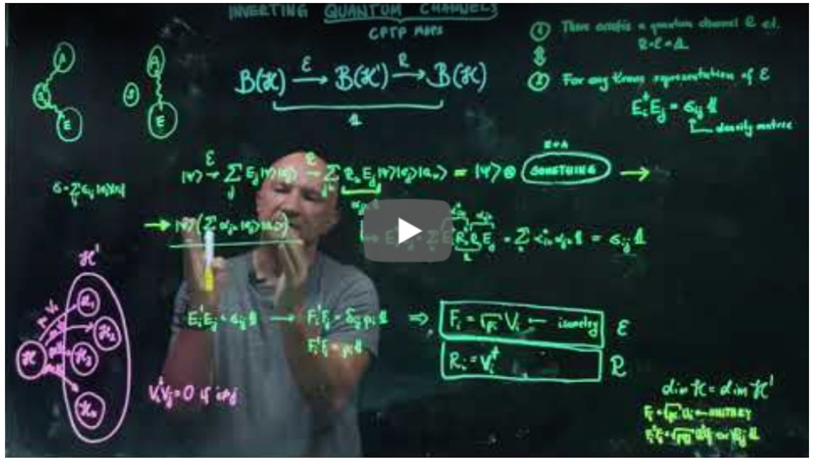


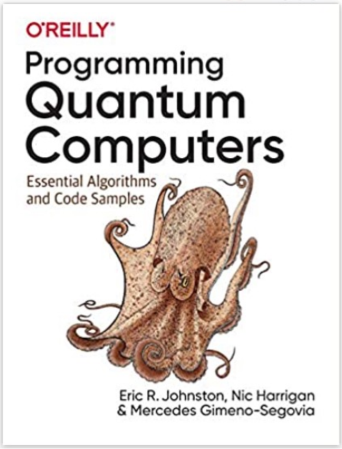
Quantum Country

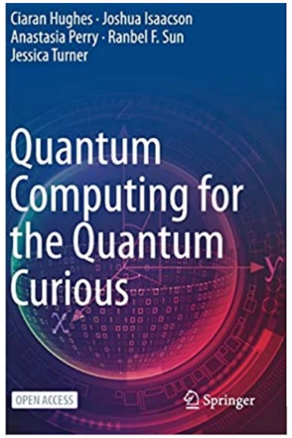
by Andy Matuschak and Michael Nielsen

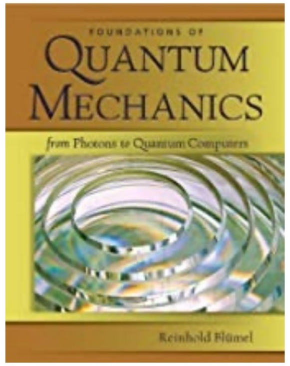
A free introduction to quantum computing and quantum mechanics

Qiskit

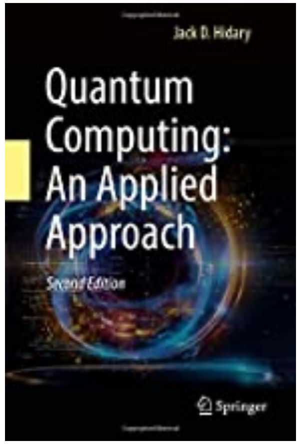








From Photons to Quantum Computers



Kindergarten Quantum Mechanics
— lecture notes —

Bob Coecke

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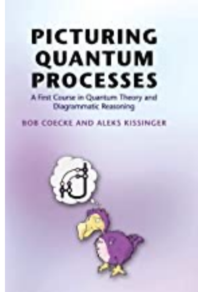
Abstract. These lecture notes survey some joint work with Samson Abramsky as it was presented by me at several conferences in the summer of 2005. It concerns 'doing quantum mechanics using only pictures of lines, squares, triangles and diamonds'. This picture calculus can be seen as a very substantial extension of Dirac's notation, and has a purely algebraic counterpart in terms of so-called Strongly Compact Closed Categories (introduced by Abramsky and I in [3, 4]) which subsumes my Logic of Entanglement [11]. For a survey on the 'what', the 'why' and the 'hows' I refer to a previous set of lecture notes [12, 13]. In a last section we provide some pointers to the body of technical literature on the subject.

Keywords: quantum formalism, graphical calculus, Dirac notation, category theory, logic
PACS: 03.65.-w Quantum mechanics, 03.67.-a Quantum information



The aim of this sequel paper is to say 'here's the beef!', and highlight some of the major results of the approach advocated in Kindergarten Quantum Mechanics, and how they are being applied to tackle practical problems on real quantum computers. Toward that end, we will focus mainly on what has become the Swiss army knife of the pictorial formalism: the *ZX-calculus*, a graphical tool for representing and manipulating complex linear maps on 2^N dimensional space. First we look at some of the ideas behind the ZX-calculus,

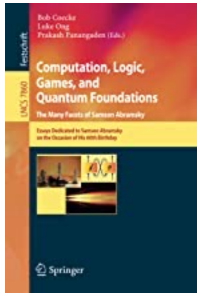
1. THE CHALLENGE

Why did discovering quantum teleportation take 60 year? We claim that this is due to a 'bad quantum formalism' (bad $\neq$ wrong) and this badness is in particular due to the fact that the formalism is 'too low level' cf.

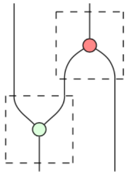
$$\frac{\text{“GOOD QM”}}{\texttt{von Neumann QM}} \simeq \frac{\text{HIGH-LEVEL language}}{\texttt{low-level language}}.$$

Interestingly enough during one of my talks Gilles Brassard (one of the fathers of teleportation) disputed my claim on why teleportation was only discovered in the 1990's. He argued that the reason 'they' only came up with teleportation when they did was due to the fact that the question had never been asked before [15] — and he added that once the question was asked the answer came quite easily (in a couple of hours). But that exactly confirms my claim: the badness of the quantum formalism causes the question not to be asked! Moreover, what is a more compelling argument for the badness of a formalism than having its creator on your side? While von Neumann designed Hilbert space quantum mechanics in 1932 [34] he renounced it 3 years later [10, 31]: "I would like to make a confession which may seem immoral: I do not believe absolutely in Hilbert space no more." (sic.)

- So, wouldn't it be nice to have a 'good' formalism, in which discovering teleportation would be trivial?
- I claim that such a formalism already exist! That's what these notes are all about!
- So you think it must be absurdly abstract coming from guys like us?
- Not at all! In fact, it could be taught in kindergarten!



Spiders are all that the language of ZX-calculus consists of. Why can ZX-calculus get away with only these? Since we can now build the CNOT-gate from these spiders as follows:


(3)

That this is indeed the case is something that can be easily checked using matrices. So in particular, the CNOT-gate doesn't have to be treated as a primitive anymore, but breaks down in two smaller pieces. Once we have phase gates and the CNOT-gate, we know that we can reproduce any quantum circuit made up of any gates.

What is the upshot of doing this? More specifically, why is this better than using standard circuits? The true power of ZX-calculus arises from the fact that these smaller pieces in (3) are very easy to work with, in the sense that the rules that govern them are easy to figure out, remember, and do calculations with. Also, there aren't many of them. In contrast, coming up with all the rules that govern fixed sets of quantum gates is really hard, and little is known beyond the case of very limited gate sets [2] or small fixed numbers of qubits.

1. Why do we need such a knowledge unit?
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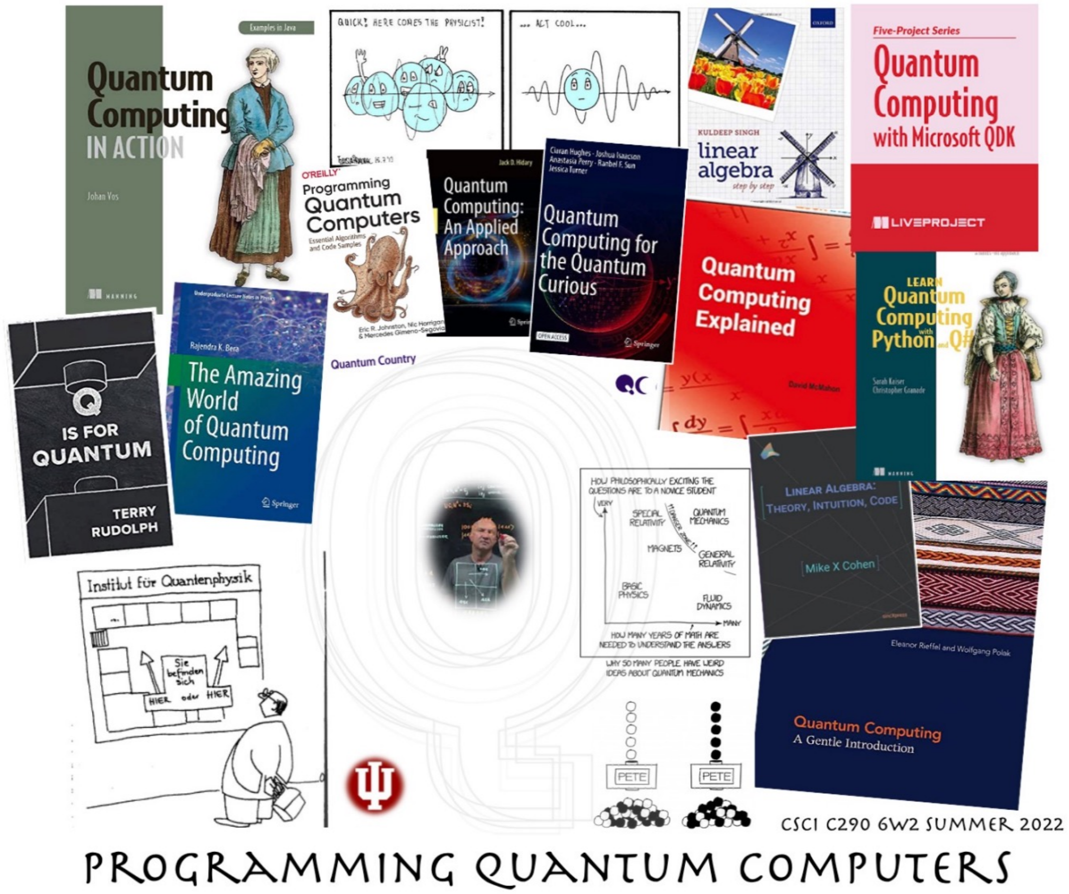

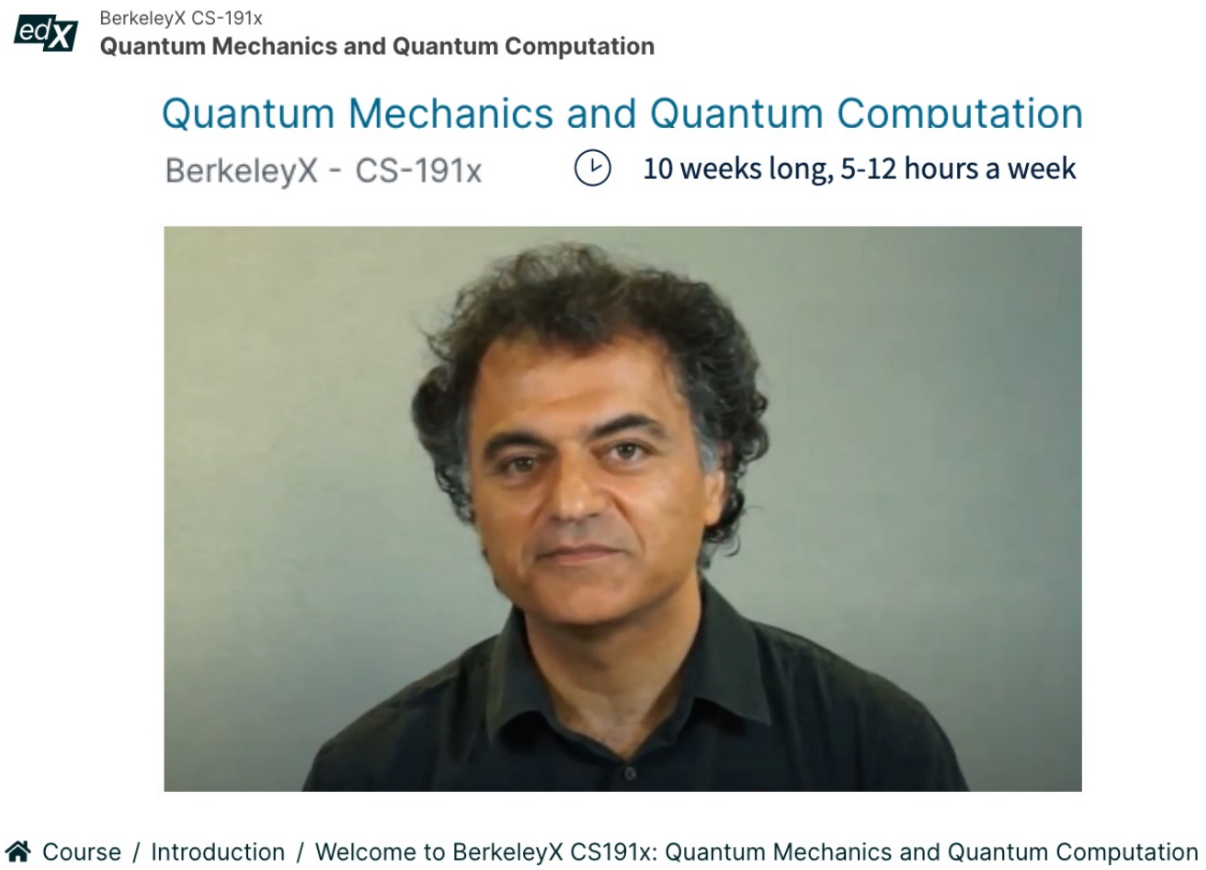

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Introduction and sample Diagnostic Quiz
Lecture 1: Double-Slit Experiment
Lecture 2: Qubits and Uncertainty Principle
Assignment 1
Lecture 3: Axioms of QM, Two Qubits, and Entanglement
Lecture 4: Bell Inequalities. Certifiable Randomness
Assignment 2
Lecture 5: Quantum Gates
Lecture 6: Quantum Teleportation

Assignment 3
Lecture 07: Quantum Circuits
Lecture 08: Early Quantum Algorithms
Assignment 4
Midterm Exam

Lecture 09: Quantum Fourier Transform
Lecture 10: Shor's Factoring Algorithm
Assignment 5
Lecture 11: Quantum Search
Lecture 12: Observables and Schroedinger's Equation
Assignment 6
Lecture 13: Particle in a Box. Implementing Qubits.
Lecture 14: Spin
Assignment 7
Lecture 15: Manipulating Spin
Lecture 16: Supremacy (Advantage)
Assignment 8.1
Assignment 8.2
Final Exam

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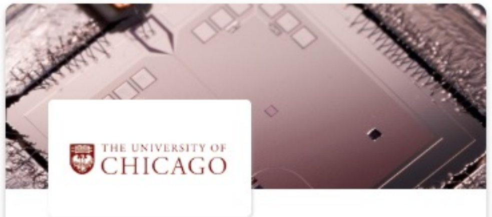
Diana Franklin

Associate Professor of Computer Science at University of Chicago



Introduction to Quantum Computing for Everyone

UChicagoX

Course

Introduction to Quantum Computing for Everyone 2

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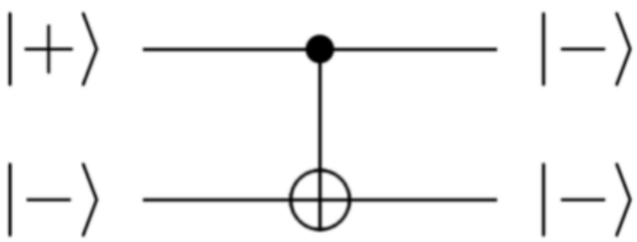
Course

a quantum abacus



It's time to prove our theorem:

$$\looparrowleft\!\rho\,(|{+}{-}\rangle) = |{-}{-}\rangle$$

We start by reminding ourselves that $|+\rangle = \left\{\bigcirc, \bullet\right\}$ and $|-\rangle = \left\{\bigcirc, \overline{\bullet}\right\}$

So now we need to calculate:

$$\begin{aligned}
\looparrowleft\!\rho\,(|{+}{-}\rangle) &= \looparrowleft\!\rho\,(\left\{\bigcirc, \bullet\right\}\left\{\bigcirc, \overline{\bullet}\right\}) \\
&= \looparrowleft\!\rho\,(\left\{\bigcirc\bigcirc, \bigcirc\overline{\bullet}, \bullet\bigcirc, \bullet\overline{\bullet}\right\}) \\
&= \left\{\looparrowleft\!\rho\,(\bigcirc\bigcirc), \looparrowleft\!\rho\,(\bigcirc\overline{\bullet}), \looparrowleft\!\rho\,(\bullet\bigcirc), \looparrowleft\!\rho\,(\bullet\overline{\bullet})\right\} \\
&= \left\{\bigcirc\bigcirc, \bigcirc\overline{\bullet}, \bullet\bullet, \bullet\overline{\bigcirc}\right\} \\
&= \left\{\bigcirc\bigcirc, \bigcirc\overline{\bullet}, \overline{\bullet}\overline{\bullet}, \overline{\bullet}\bigcirc\right\} \\
&= \left\{\bigcirc\bigcirc, \bigcirc\overline{\bullet}, \overline{\bullet}\bigcirc, \overline{\bullet}\overline{\bullet}\right\} \\
&= \left\{\bigcirc\left\{\bigcirc, \overline{\bullet}\right\}, \overline{\bullet}\left\{\bigcirc, \overline{\bullet}\right\}\right\} \\
&= \left\{\bigcirc, \overline{\bullet}\right\}\left\{\bigcirc, \overline{\bullet}\right\} \\
&= |{-}{-}\rangle
\end{aligned}$$

"... [and] in the end the machinery will be revealed ..."

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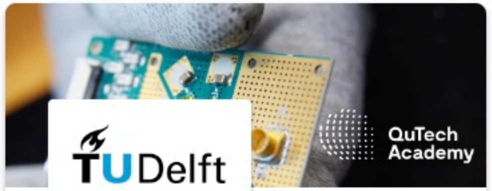

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Fundamentals of Quantum Information

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Quantum Computing Realities

Quantum Computing Fundamentals

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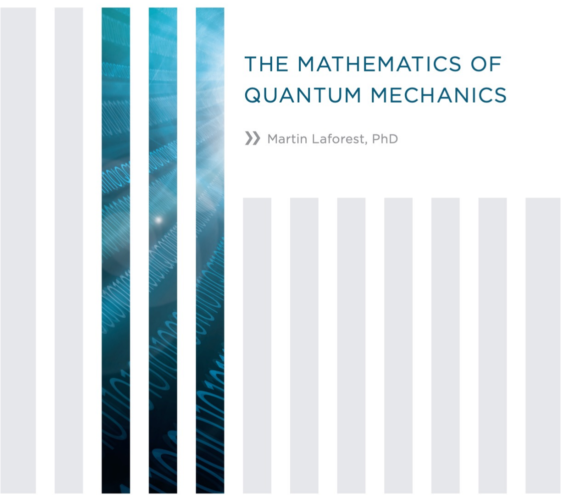

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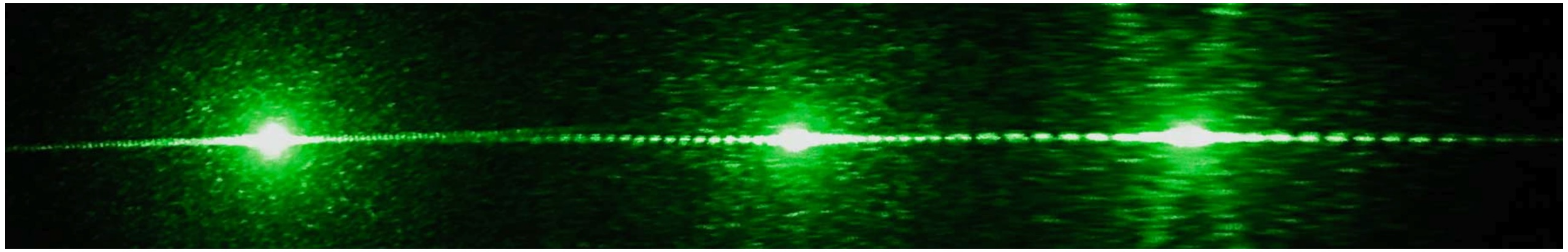

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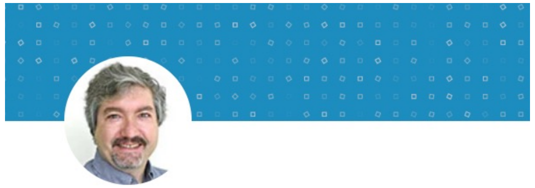

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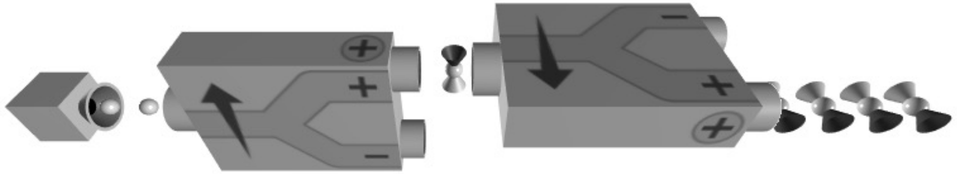

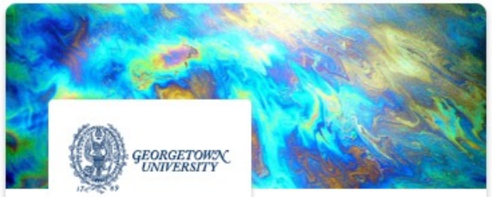

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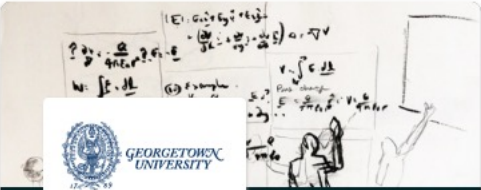

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The why and what of CS202X Curricular Guidelines. Continuing a process that began 50+ years ago with the publication[1] of Curriculum 68 (computing in 1968 was perhaps ahead[2] of where quantum computing is today) the three major professional societies in computing (ACM and IEEE—Computer Society, now joined by AAAI) have sponsored 5 efforts to establish international curricular guidelines for undergraduate programs in computing on a roughly 10-year cycle. The last report came out[3] in 2013. Last year (2021) the QED-C Workforce Development TAC has contacted the ACM/IEEE Boards of Education offering to assist in the proper, accurate inclusion of Quantum Computing (QC) topics and learning outcomes in the CS202X Curricular Guidelines.

CS2023: ACM/IEEE-CS/AAAI Computer Science Curricula

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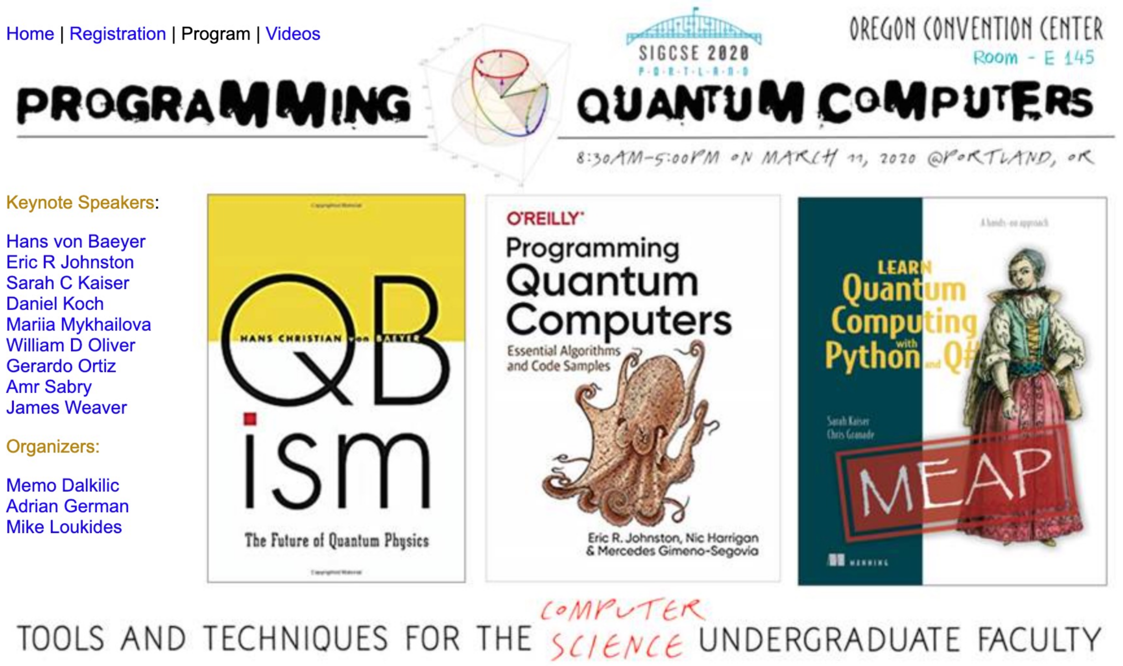

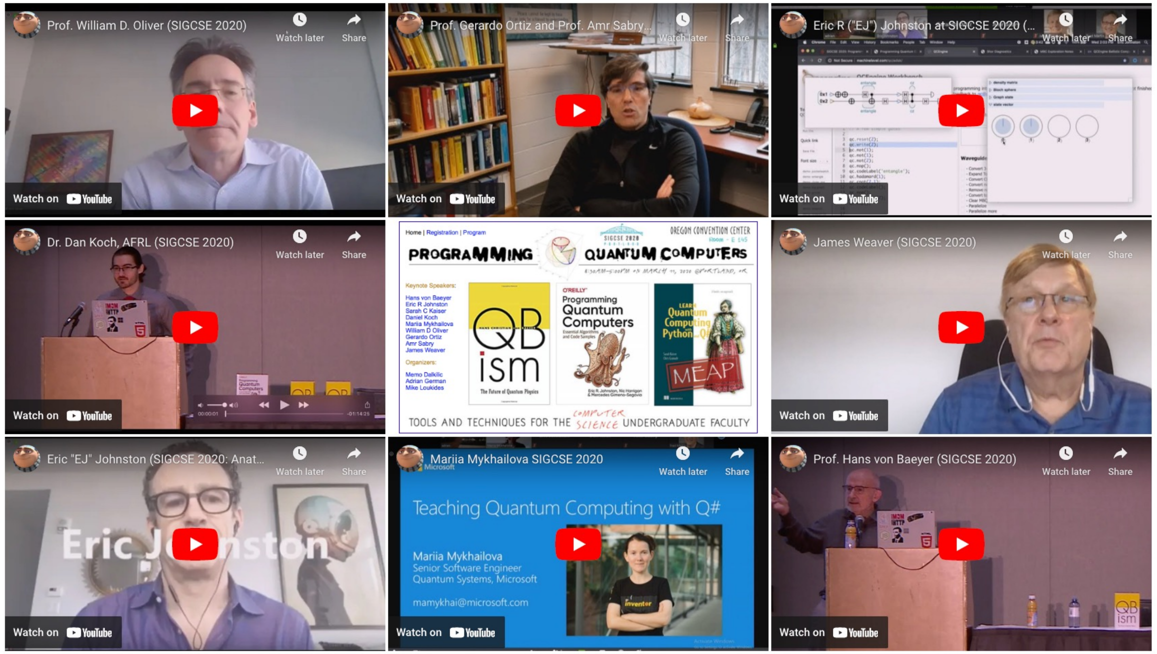

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Knowledge Areas

Knowledge Areas planned for CS2023:

- Algorithms and Complexity (AL)
- Architecture and Organization (AR)
- Artificial Intelligence (AI)
- Data Management (DM)
- Graphics and Interactive Techniques (GIT)
- Human-Computer Interaction (HCI)
- Mathematical and Statistical Foundations (MSF)
- Modeling (MOD)
- Networking and Communication (NC)
- Operating Systems (OS)
- Parallel and Distributed Computing (PDC)
- Programming Languages (PL)
- Security (SEC)
- Society, Ethics and Professionalism (SEP)
- Software Development Fundamentals (SDF)
- Software Engineering (SE)
- Specialized Platform Development (SPD)
- Systems Fundamentals (SF)

ABSTRACT

Should Quantum Processor Design be Considered a Topic in Computer Architecture Education?

Authors: Marcelo Pias, Brett Becker, Qiao Xiang, Mohamed Zahran, Monica Anderson Authors Info & Claims

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QED-C

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Chair: Marcelo Pias, Federal University of Rio Grande (FURG), Brazil

Committee:

- Brett A. Becker, University College Dublin, Ireland
- Monica D. Anderson, University of Alabama, Tuscaloosa, AL, USA
- Qiao Xiang, Xiamen University, China
- Mohamed Zahran, New York University, NY, USA
- Adrian German, Indiana University, Bloomington, IN, USA

Why is Quantum Computing (QC) an Architecture and Organization Topic? Because QC is set to exploit the computational aspects of an entirely new hardware platform (qubits) and because the associated (classical) computer architecture and organizational aspects are non-trivial.

Computer Science Curricula 2013

Curriculum Guidelines for Undergraduate Degree Programs in Computer Science

December 20, 2013

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On the Design and Implementation of a Quantum Architectures Knowledge Unit for a CS Curriculum

5.1.1 List of Topics. This is the list of topics we propose for a one semester class that could be extended to a two-semester sequence if supported by an adequate number of lab sessions:

- The Wave-Particle Duality Principle.
- The Uncertainty Principle in the Double-Slit Experiment.
- Qubits. Superposition. Measurement. Photons as qubits.
- Basic probability, trigonometry, simple vector spaces.
- Supporting formalisms: complex numbers, Euler's formula.
- Systems of two qubits. Entanglement. Bell states.
- The No-Signaling theorem.
- Axioms of QM: the superposition principle, the measurement axiom, and the unitary evolution of quantum states.
- Single qubit gates: X, Z, H, etc.
- Two qubit gates and tensor products. Working with matrices.
- The No-Cloning Theorem.
- The Quantum Teleportation protocol.
- Early quantum algorithms: Deutsch-Josza, Bernstein-Vazirani.
- Simon's algorithm (as a precursor to Shor's algorithm)
- Deutsch-Josza with Mach-Zehnder Interferometers.
- Quantum Factoring (Shor's Algorithm)
- Quantum Search (Grover's Algorithm)
- Physical implementation of qubits.
- The nine qubit modalities currently in use.
- Classical control of a Quantum Processing Unit (QPU)
- Error mitigation and control. NISQ and beyond.
- Post-quantum encryption
- Quantum Key Distribution (QKD).
- The Quantum Internet.
- Adiabatic Quantum Computation (AQC)
- Quantum Annealing (QA)

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On the Design and Implementation of a Quantum Architectures Knowledge Unit for a CS Curriculum

5.1.2 Illustrative Learning Outcomes. With this list of topics in mind, at the end of the course we would want students to Understand that:

- a quantum object (a) is produced as a particle, (b) propagates like a wave, and (c) is detected as a particle with a probability distribution that corresponds to a wave
- at the quantum level nature is inherently probabilistic.
- entanglement can be used to create non-classical correlations, but there is no way to use quantum entanglement to send messages faster than the speed of light.
- nature is inconsistent with any local hidden variable theory.
- quantum gates implement time evolution of a quantum state.

Become aware of the following:

- the power and idiosyncrasies of quantum communication
- the power of quantum parallelism and the role of constructive vs destructive interference in quantum algorithms given the probabilistic nature of measurement(s).

Understand that:

- quantum computation breaks the extended Church-Turing thesis but does not violate the original Church-Turing thesis and what the difference is
- quantum computation already occurs in nature. We are just trying to get better at harnessing it

Understand:

- the role of quantum Fourier sampling and quantum Fourier transform (QFT) in Shor's algorithm
- the classical components/aspects in Shor's algorithm
- the mechanisms of phase inversion and inversion around the mean in Grover's algorithm

Be able to:

- enumerate, compare and contrast the implementation-level specifics of each qubit modality (e.g., trapped ion, superconducting, silicon spin, photonic, quantum dot, neutral atom, topological, color center, electron-on-helium, etc.)
- pinpoint differences between adiabatic quantum computing (AQC, QA) and the gate model of quantum computation and which kind of problems each is better suited to solve

Understand that:

- a QPU is a heterogeneous multicore architecture, similarly to a FPGA or a GPU
- the building blocks of a quantum computer are: a quantum algorithm, a quantum language, a compiler, arithmetic, instruction set, micro-architecture, a quantum to classical conversion and a quantum chip.

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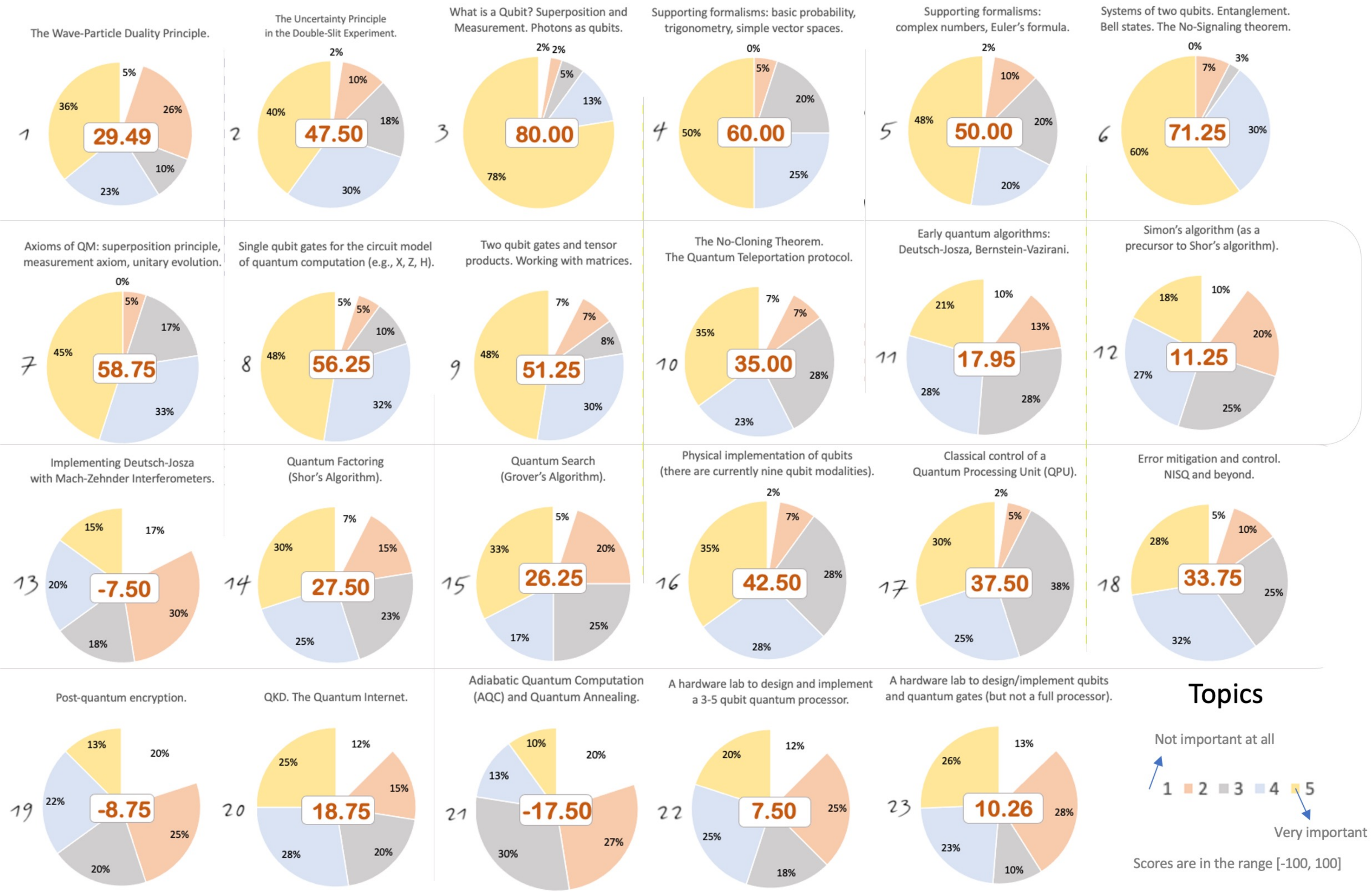
1. Why do we need such a knowledge unit?
2. What does it look like?
3. How do we know it's what we need?



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Technical Symposium

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If any topics should be added to this curriculum, or if you have any qualifications about your answers above, please use the space below to communicate those aspects to us. (100 characters max)

Nonlinear Phenomena for the generation and detection of quantum phenomena. Material and fabrication for quantum platforms.

It seems very challenging (maybe impossible?) to design and implement qubits and quantum gates in a semester-long early undergraduate lab. Though getting this kind of hands-on experience is very important. The skills needed will also be highly depending on the technical job. (I am assuming technical job means a job in quantum computing that would require a bachelor degree.) For example, experimental work will place more emphasis on hardware, while theory work will require more understanding of various algorithms.

Quantum Cryptography, and Post Quantum Cryptographic Algorithm implementation are necessary from a software development perspective.

Regulatory issues

Topics to be added (may be as an advanced materials): Quantum Computer Simulators, Quantum Compiling

Don't waste time going through algorithms that were invented merely to prove that there exist classes of problems for which quantum computation is fast - e.g. Deutsch-Josza. These are much too theoretical given the declared target students. The fundamental theory is all done and this course is not aimed at creating future quantum mechanics math professors. Instead, pick an economically interesting application and show how to map it to a quantum computer. The emerging business need is how to map useful work to a quantum computer. Pick something in quantum chemistry or social media map searching. Don't bother with a decryption example - there is no money to be made. Don't bother with quantum internet - there is no money to be made. I think that probability, trigonometry, simple vector spaces, complex numbers and Euler's formula need to be in pre-requisite courses. Anyone who comes to this course not knowing those has no hope of completing the course materials.

knowledge of classical computers is also important

AQC and Quantum Annealing are extremely under-represented in academia, compared to the volume of research publications using this alternative approach to quantum computation. I believe the problem is not enough university and graduate-level introductory materials. Faculty are unfamiliar with the subject and don't have anything to teach from.

Electromagnetic Theory, Quantum Physics, Quantum Chemistry, Python, Qiskit.

Programming skills to interface with hardware, such as FPGS, and other instruments

Quantum Internet concepts

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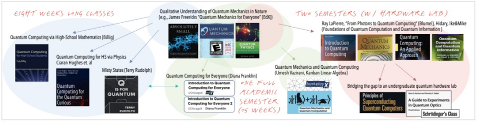

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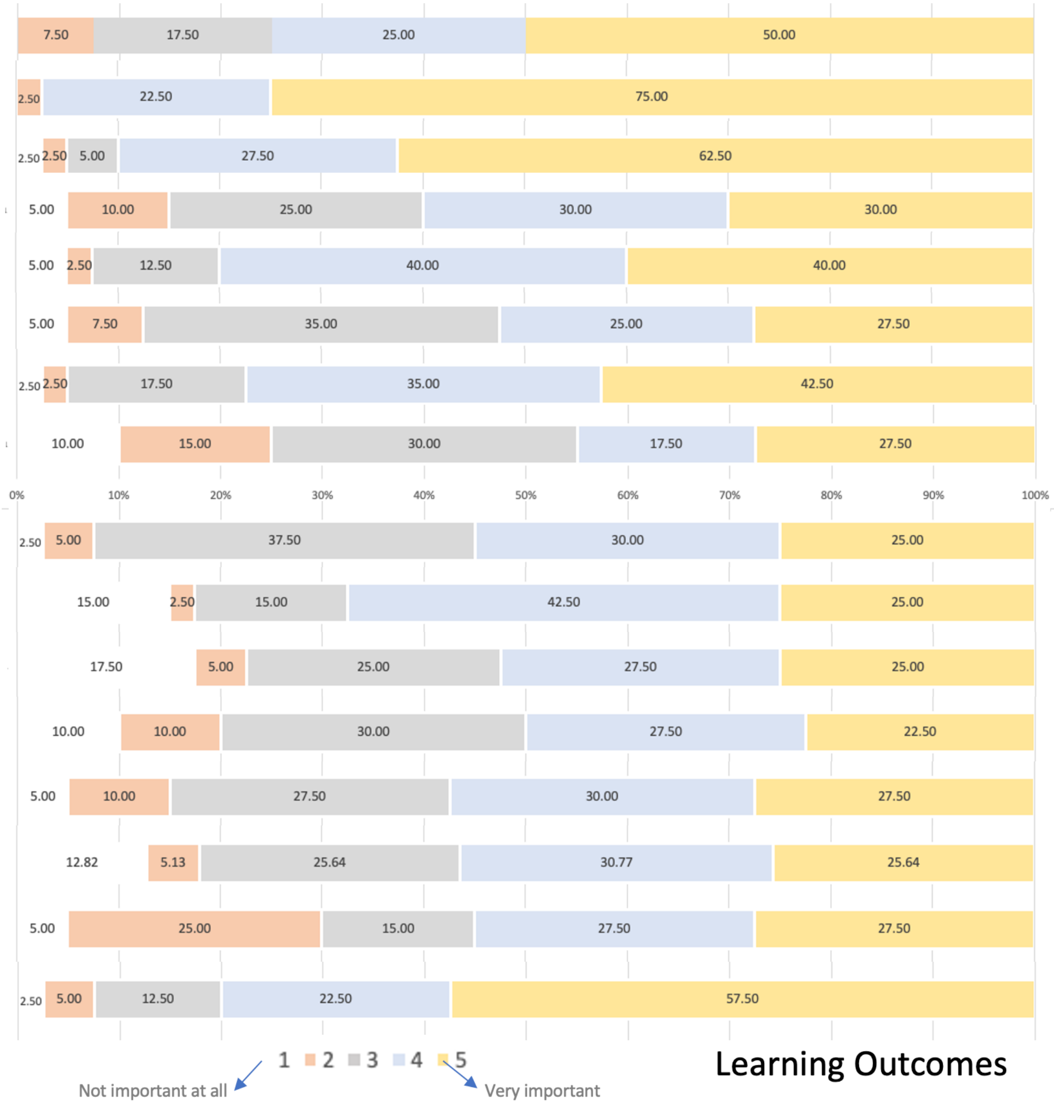
1. Understand that a quantum object (a) is produced as a particle, (b) propagates like a wave, and (c) is detected as a particle with a probability distribution that corresponds to a wave. 58.75
2. Understand that at the quantum level nature is inherently probabilistic. 85.00
3. Understand that entanglement can be used to create non-classical correlations but there is no way to use quantum entanglement to send messages faster than the speed of light. 72.50
4. Understand that nature is in fact inconsistent with any local hidden variable theory. 35.00
5. Understand that quantum gates implement the time evolution of a quantum state. 53.75
6. Understand the power and idiosyncrasies of quantum communication. 31.25
7. Understand the power of quantum parallelism and the role of constructive vs destructive interference in quantum algorithms given the probabilistic nature of measurement(s). 56.25
8. Understand that quantum computation breaks the extended Church-Turing thesis but does not violate the original Church-Turing thesis and what the difference actually is. 18.75
9. Understand that quantum computation already occurs in nature we just try to harness it. 35.00
10. Understand the role of quantum Fourier sampling (QFT) in Shor's algorithm. 30.00
11. Understand the classical components/aspects in Shor's algorithm. 18.75
12. Understand phase inversion and inversion around the mean in Grover's algorithm. 21.25
13. Be able to enumerate, compare and contrast the implementation-level specifics of each qubit modality (e.g., trapped ion, superconducting, silicon spin, photonic, quantum dot, neutral atom, topological, color center, electron-on-helium, etc.). 32.50
14. Be able to pinpoint differences between AQC and the gate model of quantum computation and which kind of problems each is better suited to solve. 25.64
15. Understand that a QPU is a heterogeneous multicore architecture like a FPGA or a GPU. 23.75
16. Understand that the building blocks of a quantum computer are: a quantum algorithm, a quantum language, a compiler, arithmetic, instruction set, micro-architecture, a quantum to classical conversion and a quantum chip. 63.75



Scores are in the range [-100, 100]

Learning Outcomes

SIGCSE 2023 Technical Symposium

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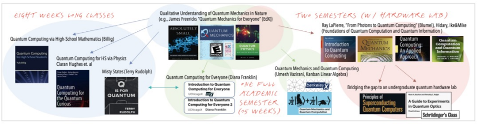

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If any learning outcomes should be added, or if you would like to qualify any of your answers above, please use the space below to communicate that to us.. (100 characters max)

Why are you assuming there is a "quantum chip" vs a trap or atom array?

Platforms and costs for diverse materials. Waste management. Philosophical questions about the meaning of entanglement. Ethical consequences and implications of quantum generation of devices and networks.

Quantum Internet (Nitrogen Vacancy Centers or other transportation techniques)

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The last learning outcome is not quite accurate. In Measurement Based Quantum Computing, there is no single "quantum chip" that contains qubits. Also it is arguable whether ion traps, cold atoms, diamond centres, etc, are in chips, or just housed in some other kind of packaging.

An important concept is that qubits are described by amplitudes, and that we interfere amplitudes that are indistinguishable. If they are distinguishable, nothing interesting normally an be done, you simply have classical probability. the fact the amplitudes are complex gives rise to the interesting quantum effects

Helping students develop an intuitive feel for Quantum Mechanics' non-intuitive idiosyncrasies is very important. Only then will students understand how to fully leverage Quantum Mechanical principles to solve problems not solvable by classical computers today. Some level of complexity theory is necessary as well. To fully grasp this concept.

Native quantum language fluency.

That last statement about components of a quantum computer does not fit AQC/Quantum Annealing. [Yet a]n[other] example of how this topic is under-represented.

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6 CONCLUSIONS

Interest in incorporating quantum architecture topics in the traditional CS curriculum remains high [38]. In this paper, we have argued that there is more than one way to achieve that goal, and we reviewed many available resources. And while none of our questions admits a clear-cut answer, we can try to summarize here our position as follows:

(1) the CS undergraduate should have a proper appreciation for the quantum mechanical nature of our world. They should know that there is more than one way to implement a qubit, that we are currently in the NISQ era, and there is a gate model as well as an alternative, adiabatic model of quantum computation.

(2) there are many entry points in such a program and consequently an equal number of associated prerequisites. The main prerequisite should be a certain intellectual versatility, manifested in a willingness to be exposed to information from more than one domain/discipline.

(3) in quantum computation labs will be quintessential, and they will rely on computer-assisted mathematics (e.g., Wolfram Alpha, `numpy`, Qiskit, `matplotlib`, etc.) software emulation (Qiskit Metal) traditional maths (Google Colab and LaTeX) access to actual quantum computers via various cloud platforms (Amazon Braket, IBM Q, Xanadu Borealis, etc.) and occasionally access to a physics lab, fab or foundry.

(4) a genuine interdisciplinary program can only be built if faculty has wide general support towards such a goal. Cross-campus, inter-departmental communication and cooperation may not be trivial, and faculty need to know that they might have to make a concerted effort to achieve such a beneficial desiderate.

(5) incorporating material about all qubit modalities in the curriculum will ensure the material will remain relevant over a reasonably long period. Some qubit modalities (e.g., photons via bulk optics) might allow more accessible experimental setups than others (trapped ions or superconducting qubits). But the widespread opinion is that students should be exposed to more than one qubit modality, including the design and implementation of qubits (e.g., via Qiskit Metal) and error mitigation and (classical) control.

We live in an era of great promise and consequently a proportionate amount of confusion. More than 60 companies worldwide are building quantum computers at this writing. And while some companies have already started announcing publicly their goals of reaching a million qubits [49] by the end of the decade, one needs to keep in mind that it is normal for a company to have different positions when talking to investors and customers. There is clearly no doubt that there has been significant progress, and with that comes a certain amount of overhype.

But there is also a certain amount of underhype that goes underreported. Witness for example the following interview [13]with David Deutsch in The Economist:

> "Last year I saw their ion-trap experiment, where they were experimenting on a single calcium atom. The idea of not just accessing but manipulating it, in incredibly subtle ways, is something I totally assumed would never happen. Now they do it routinely. [And it] works in a completely different way that cannot be expressed classically. This is a fundamentally new way of harnessing nature. To me, it's secondary how fast it is."

We need to keep an open mind and prepare our students for all their possible futures [44].

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The Economist

Technology Quarterly | Brain scan

David Deutsch, father of quantum computing

A fundamentally new way of harnessing nature

Mar 9th 2017

"I OCCASIONALLY go down and look at the experiments being done in the basement of the Clarendon Lab, and it's incredible." David Deutsch, of the University of Oxford, is the sort of theoretical physicist who comes up with ideas that shock and confound his experimentalist colleagues—and then seems rather endearingly shocked and confounded by what they are doing. "Last year I saw their ion-trap experiment, where they were experimenting on a single calcium atom," he says. "The idea of not just accessing but manipulating it, in incredibly subtle ways, is something I totally assumed would never happen. Now they do it routinely."

Such trapped ions are candidates for the innards of eventual powerful quantum computers. These will be the crowning glory of the quantum theory of computation, a field founded on a 1985 paper by Dr Deutsch. He thinks the widely predicted "quantum supremacy" that eventually puts a quantum computation incontrovertibly ahead of a classical one will be momentous for scientists and laymen alike. He brushes off the fervent debate about whether the commercially available D-Wave computer offers a speed advantage. "If it works, it works in a completely different way that cannot be expressed classically. This is a fundamentally new way of harnessing nature. To me, it's secondary how fast it is."

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IQC

IBM Quantum

Q-CTRL

QED-C®

QET Labs

Association for Computing Machinery

IEEE COMPUTER SOCIETY

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thank you

Wed **Mar 10**

Why there is no curve in this class:

> We hold these truths to be self-evident: (a) That all students are intrinsically motivated to learn but learn to be unmotivated if they repeatedly fail; (b) That every student has the basic needs to belong, to be competent and to influence what happens to them; motivation to learn only exists when these three conditions are satisfied; (c) Learning is hard, expensive (in terms of effort) and involves taking risks, so it is imperative that students need to perceive the classroom as a safe environment both from a physical and psychological perspective. Finally, and this is in fact the crux of the matter here and in the rest of higher-education, high self-esteem should not be a goal, but rather a result (or a consequence), that comes with the mastery of challenging tasks.

We will never curve your scores artificially (either higher or lower). But we will always allow you to make up exams and assignments to score as high as you can in this class. We will never artificially inflate performance (out of respect for you and ourselves) and we will always provide opportunities to show you have grown into a more effective and skilled programmer and problem-solver.