

# **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

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# IU Bloomington Calendar

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# INDIANA UNIVERSITY

# **IU Bloomington Calendar**

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IU Only Events Login January 2023

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

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- Art and museum exhibitions
- Career development
- Culture and languages
- Functions, festivals, and celebrations
- Health and wellness
- Lectures, talks, seminars, and conferences



# Quantum Day 2023

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

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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

Add to my calendar  $\vee$ 

# Quantum Computer Music

Eduardo Reck Miranda Editor

Foundations, Methods and Advanced Concepts

🖄 Springer

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# Eduardo Reck Miranda Editor

# Quantum Computer Music

Foundations, Methods and Advanced Concepts

🖉 Springer



# Session 1 Agenda (Tuesday, September 27, 2022)

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)

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 SIC Steering Committee:

- President: Arpan Ojha (Data Science Program)
- Vice-President: Alex Alani (IU School of Music)
- Secretary: Thomas Burkle (MS in OIS 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)

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



Available via Zoom

Hybrid: Zoom and Luddy 2069

# 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 <u>Schroedinger's Class</u> (IPP welcome book) **IOC** 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 <u>little report</u>.

Find more about Schroedinger's Class here (look under June 8).





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Waterloo, Ontario, Canada

Available via Zoom

Video recording of the talk.

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Hybrid: Zoom and Luddy 20

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# Session 4 Agenda (Tuesday, December 13, 2022)

Today's Zoom link will be available from the host Arpan Ojha (IU QISE SJC President)

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.

# We gratefuly acknowledge Dr. Demid Sychev's presentation today: Dr. Demid Sychev

Postdoc at Purdue University QSEI joint appointment between the groups of Vladimir Shalaev and Yong P. Chen

# Session 5 Agenda (Tue, Jan 24, 2023)

7-8pm EST

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



This will be an interactive tutorial for all club members.

Outreach and Competitions (MIT iQuHack 2023)

A club logo is currently being designed.

Jan 27-29, 2023





# Myles Brand I107 (and via Zoom Video recording of today's talk.









Quantum Education Workshop (Thu-Mon, November 17-21, 2022)



11/18-20/2022 Three of us will take part in this year's <u>Schroedinger's Class</u> ( **IOC** 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 www. automatic entry our little report. Find more about Schroedinger's Class here (look under June 8).



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

Available via Zoom Video recording of the talk.





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Waterloo, Ontario, Canad

Available via Zoom

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\* click ( 🛐 ) readout

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7-8pm EST IU OSEc 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)

A club logo is currently being designed.

Jan 27-29, 2023

### Available via Zoom Session 6 Agenda (Tentatively Tue, Feb 21, 2023)

Prof. Ricardo Decca has agreed to give a lightning talk to our club next semester. Video recording of the talk.

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

In person and via Zoom

Available in person and via Zoom

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

# Session 7 Agenda (Hopefully Tue, Mar 21, 2023)

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



In person and via Zoom

Myles Brand 1107 (and via Zoom The talk will be followed by a Q&A session.

### Video recording of today's talk Quantum Day (April 15, 2023)



Full-Day Event IBM Quantum Distinguished Speaker James Weaver, Quantum Developer Advocate at IBM and Brian Ingmanson, Education Engagement Lead, IBM Quantum

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



Oiskit 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).

### Boston, MA and Bloomington, IN Our goal is for this event to be a full-day campus-wide event.

Quantum Music Playground

Link to chapter in new Springer book, the



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).

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

The goal is to try to establish a similar outreach program here in Indiana. Back in Indiana from the workshop here's work our little report. Find more about Schroedinger's Class here (look under June 8).





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| Brian Ingmanson                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 1 2 2                                                                                                                            | 3 -24 4 -24 5                                                                                            | - 24 6 - 24 7 - 24 8                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | - 24                                         |                                   |                        |
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|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | A clip represents a piece of audio or MDI<br>that can be played by clicking the Launch<br>button at its left, or by pressing the | Cycle A Scales Transported                                                                               |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Claves<br>Cow Bell                           |                                   |                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | computer or MIDI key that is assigned to<br>the slot which holds the clip.                                                       | Legato<br>Quantize 2<br>Stochastic Cuin 8                                                                | 42 ···· · · · · · · · · · · · · · · · ·                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Hi Tan<br>Open Hi<br>Mid Tan                 | Drop an instrument or Sample Here |                        |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | Clips can be moved to other slots via<br>dreg-and-drop or copy/paste.<br>Double-click to view and edit this clip in              | Velocity<br>One shot<br>Rest p15                                                                         |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Kill Congs<br>Closed Hi<br>Mid Cong          |                                   |                        |
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Create Quantum Dance Music- a musical journey into quantum computing: James Weaver & Brian Ingmanson



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



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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...

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# 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.





# 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 . . .. 





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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# **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  $e^{--a^2}$ , where t is a length scale, and  $\alpha$  is some positive constant. In contrast, the  $q^{r}$  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







# Email: zou@iupui.edu

Research Areas: Atomic, Molecular and Optical Physics

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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. Th title of the talk was: A Quantum Computational View of the Origin of Randomness, Classicality and Complexity in the World.







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 @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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Capacity of the Universe (cf. his recent book, at the time, Programming the Universe, A Quantum Computer Scientist Takes on the Cosmos).



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 Wolfmam, 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 Fredixin 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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Two months earlier, in October 2019, IU's quantum expertise had been on disc

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Over the last 20 ye **Ouantum** Informatio Gerardo Ortiz (Physic computing industry t opportunity, in Indian MS degree with tracks business to bridge stu degree program in the is clear. Indiana Univer year (March 11, 2020, i have accelerated collab but also with Rose-Hulm IU QSEc researchers wer



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.



Capacity of the Universe (cf. his recent book, at the time, Programming the Universe, A Quantum Computer Spientist Takes on the Cosmos)

A COMPUTABLE UNIVERSE Understanding and Exploring Nature as Computation Foreword by SIR ROGER PENROSE Hector Zenil World Scientific





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



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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| Academics<br>QISMS CLASSES<br>Specialized courses provide you with opportunities to apply quantum concepts and/or to<br>learn about the science and technology where quantum processes are hosted.                                                                   | Contact                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
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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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| a University, Bloomington, QIS MS Degree. October 8, 2020                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                         |                           |                                  |
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- Quantum Information and Simulation: including mathematical and computational
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- Quantum Materials and Sensing: including topological electron systems, strange metals, superconductors, theoretical physics and chemistry, photonics, nanoengineering, 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                              | + |
|------------------------------------------|---|
| Computation and Optimization Courses     | + |
| Solid-State and Nano-Engineering Courses | + |
| Management and Entrepreneurship Courses  | + |
| The Research Component                   | + |
| Tracks                                   | + |
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6 new degrees approved, including graduate degrees in biostatist<u>ics and quantum information science</u>



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Wednesday, November 4, 2020

The Indiana Commission for Higher Education recently approved a new professional MS degree program at Indiana University/Bloomington in quantum information science (QIS). This new MS degree program will start in fall 2021 and will be housed



in the IUB graduate school, with participation from the College of Arts and Sciences, the Luddy School of Informatics, Computing, and Engineering, and the Kelley School of Business. It is designed as a "bridge" degree program for BS-level students without training in physics to get up to speed in QIS. This new degree program complements other recent activity in QIS, including the successful proposal to the IUB Emerging Areas of Research Competition and the recent foundation of the IU Quantum Science and Engineering center (QSEc) and builds upon previous QISrelated course development in physics and computer science. W. M. Snow led the effort to organize the new degree program with help from several IUB faculty in physics, mathematics, chemistry, CISE, and business.





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|                  | Solid-State and Nano-Engineering Courses                        | +                 |                 |
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# IU Bloomington, IUPUI part of coalition to develop quantum technologies

FOR IMMEDIATE RELEASE Jul 8, 2021



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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3 research universities to collaborate with industry, government to develop quantum technologies Scientists at Ir higher education

FOR IMMEDIATE RELEASE Aug 29, 2022 The new Center

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# the National Sc partners would

findings applica BLOOMINGTON, Ind. – Quantum science and engineering can save energy, speed up Notre Dame. 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."

"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

**Bay Studios** 



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

INDUSTRY/UNIVERSITY COOPERATIVE RESEARCH CENTER FOR QUANTUM TECHNOLOGIES Background | What is | Program Goals | Framework | Membership | Outlook | Future Plans | Contact

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



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



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Industry/University Cooperative Research Center (IUCRC) Workshop

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



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| Center for Q        | uantum Technologies (CQT)                                                                                                                                                                                                                                                                                                                                              |                                                                       |
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| Day 1 Agenda (      | This is now just a li                                                                                                                                                                                                                                                                                                                                                  | ocal copy of the <u>official workshop agenda</u> .<br>Moderator: IURU |
| Today's proceedings | s will be moderated by Prof. Babak Anasori from Indiana University-Purdue University Ind                                                                                                                                                                                                                                                                               | lianapolis (IUPUI)                                                    |
| 10:00-10:05am       | Welcome                                                                                                                                                                                                                                                                                                                                                                |                                                                       |
|                     | Dr. David Stewart (Purdue University)<br>Overview of IUCRCs and the COT                                                                                                                                                                                                                                                                                                |                                                                       |
| 10:05-10:35am       | Dr. Sabre Kais and Dr. Yong Chen (both Purdue University)                                                                                                                                                                                                                                                                                                              | (15971) (199715)                                                      |
| 10:40-10:55am       | The Quantum Landscape in the United States<br>Dr. Celia Merzbacher (SRI International and QED-C)                                                                                                                                                                                                                                                                       | QED.C SRI                                                             |
| 11:00-11:15am       | Majorana Quantum Computing<br>Chetan Nayak (GM of Quantum Hardware, Microsoft)                                                                                                                                                                                                                                                                                         | Microsoft                                                             |
| 11:20-11:35am       | Challenges and Opportunities for Low-Depth Quantum Machine Learn<br>Dr. Masoud Mohseni (Google AI) This talk was moved to Thu @11:50am                                                                                                                                                                                                                                 | ing Google Al                                                         |
| 11:40-11:45am       | Break                                                                                                                                                                                                                                                                                                                                                                  |                                                                       |
| 11:45-12:00pm       | Quantum Computing in the Cloud<br>Michael Brett (SVP of Applications, Rigetti)                                                                                                                                                                                                                                                                                         | rigetti                                                               |
| 12:05-12:20pm       | Enterprise Solutions for Quantum Computing<br>Yianni Gamvros (Head of Business Development, QCWare)                                                                                                                                                                                                                                                                    | CWARE                                                                 |
| 12:25-12:40pm       | Photonic Quantum Computing in the Cloud<br>Rafal Janik (Head of Operations & Customer Solutions, Xanadu)                                                                                                                                                                                                                                                               | XANADU                                                                |
| 12:45-01:40pm       | Panel Discussion<br>Moderator: Prof. Ricardo Decca (IUPUI)                                                                                                                                                                                                                                                                                                             |                                                                       |
| 01:40-01:45pm       | (Daily) Wrap                                                                                                                                                                                                                                                                                                                                                           |                                                                       |
| Day 2 Agenda (      | wednesday, June 17)<br>s will be moderated by Profs. Jacek Nabrzyski and Marina Vauchimus from the University of                                                                                                                                                                                                                                                       | Moderator: Notre Dame                                                 |
| 10:00-10:05am       | Welcome<br>Dr. David Stewart (Purdue University)                                                                                                                                                                                                                                                                                                                       | o roome danne                                                         |
| 10:05-10:20am       | Compilation for the NISQ Era<br>Dr. Ross Duncan (Cambridge Quantum Computing, Ltd.)                                                                                                                                                                                                                                                                                    | 300                                                                   |
| 10:25-10:40am       | Quantum Information Science at AFRL - The Way Forward<br>Dr. Michael Hayduk (Deputy Director, AFRL Directorate)                                                                                                                                                                                                                                                        | AFRE                                                                  |
| 10:45-11:00am       | Quantum at GE Research<br>Dr. Loucas Tsakalakos (Business Program Manager, GE Global Research)<br>Dr. Steven Bush (Senior Scientist, GE Global Research)                                                                                                                                                                                                               | æ                                                                     |
| 11:05-11:20am       | Advancing the Quantum Computing Ecosystem<br>Dr. Yudong Cao (CTO, Zapata Computing, Inc.)                                                                                                                                                                                                                                                                              |                                                                       |
| 11:25-11:30am       | Break                                                                                                                                                                                                                                                                                                                                                                  |                                                                       |
| 11:30-11:45am       | Software and Practical Computing<br>Steve Reinhardt (VP Product Development, Quantum Computing Inc.)                                                                                                                                                                                                                                                                   | C Quantum                                                             |
| 11:50-12:05am       | IBM Quantum University Programs<br>Sebastian Hassinger (Quantum Computing Academic Program Leader, I                                                                                                                                                                                                                                                                   | BM) IBW                                                               |
| 12:10-12:25pm       | Scalable and High-Performance Quantum Computers<br>Dr. Christopher Monroe (Chief Scientist and co-Founder, IonQ)                                                                                                                                                                                                                                                       |                                                                       |
| 12:30-01:25pm       | Panel Discussion<br>Moderator: Prof. Peter Kogge (University of Notre Dame)                                                                                                                                                                                                                                                                                            |                                                                       |
| 01:25-01:30pm       | (Daily) Wrap                                                                                                                                                                                                                                                                                                                                                           |                                                                       |
| Day 5 Agenda (      | mursday, June 18)<br>s will be moderated by Prof. Phil Richerme from Invitional University                                                                                                                                                                                                                                                                             | Moderator: Indiana University                                         |
| 10:00-10:05am       | Welcome<br>Dr. David Stewart (Purdue University)                                                                                                                                                                                                                                                                                                                       |                                                                       |
| 10:05-10:20am       | L3Harris Quantum Interests<br>Dr. Rachele Cocks (Principal Scientist, L3Harris)                                                                                                                                                                                                                                                                                        | B L3HARRIS"                                                           |
| 10:25-10:40am       | Quantum at Sea<br>Dr. Tim Morgan (Scientist, NSWC Crane)                                                                                                                                                                                                                                                                                                               |                                                                       |
| 10:45-11:00am       | Information Needed to Determine When and How Quantum Computing<br>Dr. Wayne Eckerle (VP of Research & Technology, Cummins, Inc.)                                                                                                                                                                                                                                       | g can Help Cummins 🧉                                                  |
| 11:05-11:20am       | Opportunities for QM Methodologies in Pharmaceutical Development<br>Dr. Jeff Tan (Director, Eli Lilly and Company)                                                                                                                                                                                                                                                     | Lilly                                                                 |
| 11:25-11:30pm       | Break                                                                                                                                                                                                                                                                                                                                                                  |                                                                       |
| 11:30-11:45am       | Quantum Computing at Accenture<br>Shreyas Ramesh (Senior Manager for Quantum Computing – Artificia                                                                                                                                                                                                                                                                     | l Intelligence, Accenture) >                                          |
| 11:50-12:05pm       | Challenges and Opportunities for Low-Depth Quantum Machine Learn<br>Dr. Masoud Mohseni (Google Al) This talk moved from Tue @11:20am                                                                                                                                                                                                                                   | ing Google Al                                                         |
| 12:10-12:40pm       | Building the Quantum Workforce of the Future<br><u>Dr.W. Michael Snaw</u> (Professor of Physics, Indiana University)<br><u>Dr. Alexandra Boltasseva</u> (Professor of Electrical and Computer Enginee<br><u>Dr. Pramey Upadhysya</u> (Assistant Professor of Electrical and Computer E<br><u>Dr. William D. Oliver</u> (Director, Center for Quantum Engineering, MIT) | ring, Purdue University)<br>ngineering, Purdue University)            |
| 12:40-01:40pm       | Panel Discussion<br>Moderator: Prof. Gerardo Ortiz (Indiana University)                                                                                                                                                                                                                                                                                                |                                                                       |
| 01-40-01-45pm       | Workshon Wran-I in                                                                                                                                                                                                                                                                                                                                                     |                                                                       |

Industry/University Cooperative Research Center (IUCRC) Workshop

# Center for Quantum Technologies CQT

**NSP** An NSF Industry/University Cooperative Research Center (IUCRC)

HOME ABOUT V RESEARCH MEMBERS WORKFORCE DEVELOPMENT



Four Indiana research partners are leading efforts to establish the National Science Foundation-backed Center for Quantum Technologies (CQT) to develop novel quantum technologies to address significant industry challenges.

University of Notre Dame IUPUI

Indiana University

The CQT founding partners include Purdue University, Indiana University Bloomington, the University of Notre Dame, and Indiana University Purdue University-Indianapolis (IUPUI). Industry partners will provide funding to the center's researchers and will obtain early

access to findings applicable to their businesses.

News

Three Indiana research universities to collaborate with industry and government to develop quantum technologies in new NSFfunded center

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

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

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



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|  | 10:00-10:05am       | Welcome<br>Dr. David Stewart (Purdue University)                                                                                                                                                                                                                                                                                                                                |                                                       |
|--|---------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|
|  | 10:05-10:35am       | Overview of IUCRCs and the CQT<br>Dr. Sabre Kais and Dr. Yong Chen (both Purdue University)                                                                                                                                                                                                                                                                                     |                                                       |
|  | 10:40-10:55am       | The Quantum Landscape in the United States<br>Dr. Celia Merzbacher (SRI International and QED-C)                                                                                                                                                                                                                                                                                | QED.C SRI                                             |
|  | 11:00-11:15am       | Majorana Quantum Computing<br>Chetan Nayak (GM of Quantum Hardware, Microsoft)                                                                                                                                                                                                                                                                                                  | Microsof                                              |
|  | 11:20-11:35am       | Challenges and Opportunities for Low-Depth Quantum Machine Learning Dr. Masoud Mohseni (Google AI) This talk was moved to Thu @11:50am                                                                                                                                                                                                                                          | Google A                                              |
|  | 11:40-11:45am       | Break                                                                                                                                                                                                                                                                                                                                                                           |                                                       |
|  | 11:45-12:00pm       | Quantum Computing in the Cloud<br>Michael Brett (SVP of Applications, Rigetti)                                                                                                                                                                                                                                                                                                  | rigetti                                               |
|  | 12:05-12:20pm       | Enterprise Solutions for Quantum Computing<br>Yianni Gamvros (Head of Business Development, QCWare)                                                                                                                                                                                                                                                                             | CWAR                                                  |
|  | 12:25-12:40pm       | Photonic Quantum Computing in the Cloud<br>Rafal Janik (Head of Operations & Customer Solutions, Xanadu)                                                                                                                                                                                                                                                                        | XANADU                                                |
|  | 12:45-01:40pm       | Panel Discussion<br>Moderator: Prof. Ricardo Decca (IUPUI)                                                                                                                                                                                                                                                                                                                      |                                                       |
|  | 01:40-01:45pm       | (Daily) Wrap                                                                                                                                                                                                                                                                                                                                                                    |                                                       |
|  | Day 2 Agenda (      | Wednesday, June 17)                                                                                                                                                                                                                                                                                                                                                             | Moderator: Notre Dam                                  |
|  | Today's proceeding: | s will be moderated by Profs. Jarek Nabrzyski and Mariya Vyushkova from the University of No                                                                                                                                                                                                                                                                                    | otre Dame                                             |
|  | 10:00-10:05am       | Welcome<br>Dr. David Stewart (Purdue University)                                                                                                                                                                                                                                                                                                                                |                                                       |
|  | 10:05-10:20am       | <u>Compilation for the NISQ Era</u><br>Dr. Ross Duncan (Cambridge Quantum Computing, Ltd.)                                                                                                                                                                                                                                                                                      | <b>CO</b>                                             |
|  | 10:25-10:40am       | Quantum Information Science at AFRL - The Way Forward<br>Dr. Michael Hayduk (Deputy Director, AFRL Directorate)                                                                                                                                                                                                                                                                 | AFRE                                                  |
|  | 10:45-11:00am       | Quantum at GE Research<br>Dr. Loucas Tsakalakos (Business Program Manager, GE Global Research)<br>Dr. Steven Bush (Senior Scientist, GE Global Research)                                                                                                                                                                                                                        |                                                       |
|  | 11:05-11:20am       | Advancing the Quantum Computing Ecosystem<br>Dr. Yudong Cao (CTO, Zapata Computing, Inc.)                                                                                                                                                                                                                                                                                       |                                                       |
|  | 11:25-11:30am       | Break                                                                                                                                                                                                                                                                                                                                                                           |                                                       |
|  | 11:30-11:45am       | Software and Practical Computing<br>Steve Reinhardt (VP Product Development, Quantum Computing Inc.)                                                                                                                                                                                                                                                                            | C Quantun                                             |
|  | 11:50-12:05am       | IBM Quantum University Programs<br>Sebastian Hassinger (Quantum Computing Academic Program Leader, IBM                                                                                                                                                                                                                                                                          | , IBM                                                 |
|  | 12:10-12:25pm       | Scalable and High-Performance Quantum Computers<br>Dr. Christopher Monroe (Chief Scientist and co-Founder, IonQ)                                                                                                                                                                                                                                                                | ONQ IONQ                                              |
|  | 12:30-01:25pm       | Panel Discussion<br>Moderator: Prof. Peter Kogge (University of Notre Dame)                                                                                                                                                                                                                                                                                                     |                                                       |
|  | 01:25-01:30pm       | (Daily) Wrap                                                                                                                                                                                                                                                                                                                                                                    |                                                       |
|  | Day 3 Agenda (      | Thursday, June 18)                                                                                                                                                                                                                                                                                                                                                              | Moderator: Indiana Universit                          |
|  | Today's proceeding: | s will be moderated by Prof. Phil Richerme from Indiana University                                                                                                                                                                                                                                                                                                              |                                                       |
|  | 10:00-10:05am       | Dr. David Stewart (Purdue University)                                                                                                                                                                                                                                                                                                                                           |                                                       |
|  | 10:05-10:20am       | L3Harris Quantum Interests<br>Dr. Rachele Cocks (Principal Scientist, L3Harris)                                                                                                                                                                                                                                                                                                 | BL3HARRIS"                                            |
|  | 10:25-10:40am       | Quantum at Sea<br>Dr. Tim Morgan (Scientist, NSWC Crane)                                                                                                                                                                                                                                                                                                                        | NAVSEA<br>NOTICE CONTROL                              |
|  | 10:45-11:00am       | Information Needed to Determine When and How Quantum Computing ca<br>Dr. Wayne Eckerle (VP of Research & Technology, Cummins, Inc.)                                                                                                                                                                                                                                             | in Help Cummins 🧲                                     |
|  | 11:05-11:20am       | Opportunities for QM Methodologies in Pharmaceutical Development<br>Dr. Jeff Tan (Director, Eli Lilly and Company)                                                                                                                                                                                                                                                              | Lilly                                                 |
|  | 11:25-11:30pm       | Break                                                                                                                                                                                                                                                                                                                                                                           |                                                       |
|  | 11:30-11:45am       | Quantum Computing at Accenture<br>Shreyas Ramesh (Senior Manager for Quantum Computing 倓 Artificial In                                                                                                                                                                                                                                                                          | telligence, Accenture) >                              |
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|  | 12:10-12:40pm       | Building the Quantum Workforce of the Future<br><u>Dr.W. Michael Snow</u> (Professor of Physics, Indiana University))<br><u>Dr. Alexandra Botasseva</u> (Professor of Electrical and Computer Engineering,<br><u>Dr. Pramery Upadhynya</u> (Assistant Professor of Electrical and Computer Engi<br><u>Dr. William D. Oliver</u> (Director, Center for Quantum Engineering, MIT) | g, Purdue University)<br>ineering, Purdue University) |
|  | 12:40-01:40pm       | Panel Discussion                                                                                                                                                                                                                                                                                                                                                                |                                                       |
|  | 01-40-01-45         | Moderator: Prof. Gerardo Ortiz (Indiana University)<br>Workshop Wran-Lip                                                                                                                                                                                                                                                                                                        |                                                       |
|  | 01.40.01.45pm       | ποικοιομ πιαρ-ομ                                                                                                                                                                                                                                                                                                                                                                |                                                       |

Industry/University Cooperative Research Center (IUCRC) Workshop

Today's proceedings will be moderated by Prof. Babak Anasori from Indiana University-Purdue University Indianapolis (IUPUI)

This is now just a local copy of the official workshop agenda

Moderator: IUPUI

Center for Quantum Technologies (CQT)

All times EDT

Day 1 Agenda (Tuesday, June 16)

# Center for Quantum Technologies CQT

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HOME ABOUT V RESEARCH MEMBERS WORKFORCE DEVELOPMENT



Four Indiana research partners are leading efforts to establish the Purdue University National Science Foundation-backed Center for Quantum Technologies (CQT) to develop novel quantum technologies to Indiana University address significant industry challenges. The CQT founding partners include Purdue University, Indiana University of Notre Dame

University Bloomington, the University of Notre Dame, and Indiana University Purdue University-Indianapolis (IUPUI). Industry partners will provide funding to the center's researchers and will obtain early access to findings applicable to their businesses.

# News

Three Indiana research universities to collaborate with industry and government to develop quantum technologies in new NSFfunded center

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

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











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



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Industry/University Cooperative Research Center (IUCRC) Workshop

This is now just a local copy of the official workshop agend

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Center for Quantum Technologies (COT)

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Day 1 Agenda (Tuesday, June 16)

### Center for CQT Quantum Technologies

**NSF** An NSF Industry/University Cooperative Research Center (IUCRC)

HOME ABOUT V RESEARCH MEMBERS WORKFORCE DEVELOPMENT



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

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IBM Quantum

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**GRUMMAN** 





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



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| Industry/University<br>Center for Quantum                          | Cooperative Research Center (IUCRC) Workshop<br>n Technologies (CQT)                                                                                                                                                                                                                 |                                                  |
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| All times EDT                                                      |                                                                                                                                                                                                                                                                                      |                                                  |
|                                                                    | This is now just a local co                                                                                                                                                                                                                                                          | opy of the official workshop agenda.             |
| Day 1 Agenda (Tuesday, Ju<br>Today's proceedings will be more      | u <mark>ne 16)</mark><br>derated by Prof. Babak Anasori from Indiana University-Purdue University Indianapi                                                                                                                                                                          | Moderator: IUPUI<br>olis (IUPUI)                 |
| 10:00-10:05am Welcome<br>Dr. David                                 | Stewart (Purdue University)                                                                                                                                                                                                                                                          |                                                  |
| 10:05-10:35am Overview<br>Dr. Sabre                                | r of IUCRCs and the CQT<br>Kais and Dr. Yong Chen (both Purdue University)                                                                                                                                                                                                           |                                                  |
| 10:40-10:55am The Qua<br>Dr. Celia                                 | ntum Landscape in the United States<br>Merzbacher (SRI International and QED-C)                                                                                                                                                                                                      |                                                  |
| 11:00-11:15am Majorana<br>Chetan M                                 | a Quantum Computing<br>Nayak (GM of Quantum Hardware, Microsoft)                                                                                                                                                                                                                     | Microsoft                                        |
| 11:20-11:35am Challeng<br>Dr. Maso                                 | ues and Opportunities for Low-Depth Quantum Machine Learning<br>ud Mohseni (Google AI) This talk was moved to Thu @11:50am                                                                                                                                                           | Google Al                                        |
| 11:40-11:45am Break                                                |                                                                                                                                                                                                                                                                                      |                                                  |
| 11:45-12:00pm Quantum<br>Michael                                   | n Computing in the Cloud<br>Brett (SVP of Applications Rigetti)                                                                                                                                                                                                                      | rigetti                                          |
| 12:05-12:20pm Enterpris                                            | se Solutions for Quantum Computing                                                                                                                                                                                                                                                   | 835                                              |
| 12:25-12:40pm Photonic                                             | : Quantum Computing in the Cloud                                                                                                                                                                                                                                                     |                                                  |
| Ratal Jan<br>12:45-01:40pm                                         | in (near or Operations & Customer Solutions, Xanadu)<br>scussion                                                                                                                                                                                                                     | ~                                                |
| Moderato                                                           | r: Prof. Ricardo Decca (IUPUI)                                                                                                                                                                                                                                                       |                                                  |
| 01:40-01:45pm (Daily) W                                            | rap                                                                                                                                                                                                                                                                                  |                                                  |
| Day 2 Agenda (Wednesda                                             | y,June 17)                                                                                                                                                                                                                                                                           | Moderator: Notre Dame                            |
| Today's proceedings will be more                                   | derated by Profs. Jarek Nabrzyski and Mariya Vyushkova from the University of Notr                                                                                                                                                                                                   | re Dame                                          |
| 10:00-10:05am Welcome<br>Dr. David                                 | Stewart (Purdue University)                                                                                                                                                                                                                                                          |                                                  |
| 10:05-10:20am Compilat<br>Dr. Ross I                               | <u>tion for the NISQ Era</u><br>Duncan (Cambridge Quantum Computing, Ltd.)                                                                                                                                                                                                           | <u> 2</u>                                        |
| 10:25-10:40am Quantum<br>Dr. Micha                                 | n Information Science at AFRL - The Way Forward<br>ael Hayduk (Deputy Director, AFRL Directorate)                                                                                                                                                                                    | AFRE                                             |
| Quantum<br>10:45-11:00am Dr. Louca<br>Dr. Steve                    | n at GE Research<br>1s Tsakalakos (Business Program Manager, GE Global Research)<br>11 Bush (Senior Scientist, GE Global Research)                                                                                                                                                   | <b>96</b> )                                      |
| 11:05-11:20am Advancir<br>Dr. Yudor                                | ng the Quantum Computing Ecosystem<br>ng Cao (CTO, Zapata Computing, Inc.)                                                                                                                                                                                                           |                                                  |
| 11:25-11:30am Break                                                |                                                                                                                                                                                                                                                                                      |                                                  |
| 11:30-11:45am Software<br>Steve Re                                 | and Practical Computing einhardt (VP Product Development, Quantum Computing Inc.)                                                                                                                                                                                                    |                                                  |
| 11:50-12:05am IBM Qua<br>Sebastia                                  | ntum University Programs<br>n Hassinger (Quantum Computing Academic Program Leader, IBM)                                                                                                                                                                                             | IBM                                              |
| 12:10-12:25pm Scalable<br>Dr. Christ                               | and High-Performance Quantum Computers<br>topher Monroe (Chief Scientist and co-Founder, IonQ)                                                                                                                                                                                       |                                                  |
| 12:30-01:25pm Panel Dis<br>Moderato                                | cussion<br>pr: Prof. Peter Kogge (University of Notre Dame)                                                                                                                                                                                                                          |                                                  |
| 01:25-01:30pm (Daily) W                                            | rap                                                                                                                                                                                                                                                                                  |                                                  |
| Day 3 Agenda (Thursday,                                            | June 18) M                                                                                                                                                                                                                                                                           | loderator: Indiana University                    |
| Today's proceedings will be more                                   | derated by Prof. Phil Richerme from Indiana University                                                                                                                                                                                                                               |                                                  |
| 10:00-10:05am Welcome<br>Dr. David                                 | Stewart (Purdue University)                                                                                                                                                                                                                                                          |                                                  |
| 10:05-10:20am L3Harris<br>Dr. Rache                                | Quantum Interests<br>ele Cocks (Principal Scientist, L3Harris)                                                                                                                                                                                                                       | 🛞 L3HARRIS"                                      |
| 10:25-10:40am Quantum<br>Dr. Tim N                                 | n at Sea<br>Aorgan (Scientist, NSWC Crane)                                                                                                                                                                                                                                           |                                                  |
| 10:45-11:00am Informat<br>Dr. Wayn                                 | ion Needed to Determine When and How Quantum Computing can<br>e Eckerle (VP of Research & Technology, Cummins, Inc.)                                                                                                                                                                 | Help Cummins 🧲                                   |
| 11:05-11:20am Opportu<br>Dr. Jeff Ta                               | nities for QM Methodologies in Pharmaceutical Development<br>an (Director, Eli Lilly and Company)                                                                                                                                                                                    | Lilly                                            |
| 11:25-11:30pm Break                                                |                                                                                                                                                                                                                                                                                      |                                                  |
| 11:30-11:45am Quantum<br>Shreyas I                                 | n computing at Accenture<br>Ramesh (Senior Manager for Quantum Computing – Artificial Inte                                                                                                                                                                                           | elligence, Accenture) >                          |
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| Building                                                           | the Quantum Workforce of the Future                                                                                                                                                                                                                                                  |                                                  |
| Dr. W. Mic<br>12:10-12:40pm Dr. Alexar<br>Dr. Prame<br>Dr. Willian | hael Snow (Professor of Physics, Indiana University)<br><u>ndra Boltasseva</u> (Professor of Electrical and Computer Engineering,<br><u>ey Upadhyaya</u> (Assistant Professor of Electrical and Computer Engin<br><u>m D. Oliver</u> (Director, Center for Quantum Engineerina, MIT) | Purdue University)<br>eering, Purdue University) |
| 12:40-01:40pm Panel Dis<br>Moderato                                | icussion<br>pr: Prof. Gerardo Ortiz (Indiana University)                                                                                                                                                                                                                             |                                                  |

01:40-01:45pm Workshop Wrap-Up

# Center for Quantum Technologies COT

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The Quantum Computing Company



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







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01:40-01:45pm Workshop Wrap-Up







| Industry/University Cooperative Research Center (IUCRC) Workshop<br>Center for Ouantum Technologies (COT)                                                                                                                                                                                                                                                                                                                                |                                             | 0.01  | –   Cente      | er for          |              |
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| All times EDT                                                                                                                                                                                                                                                                                                                                                                                                                            |                                             | CQ    | Quan           | tum Techn       | ologie       |
| This is now just a local copy                                                                                                                                                                                                                                                                                                                                                                                                            | of the official workshop agenda.            |       |                |                 |              |
| Day 1 Agenda (Tuesday, June 16)<br>Today's proceedings will be moderated by Prof. Babak Anasori from Indiana University-Purdue University Indianapolis                                                                                                                                                                                                                                                                                   | Moderator: IUPUI<br>(IUPUI)                 | HOME  | ABOUT 🗸        | RESEARCH        | MEMB         |
| 10:00-10:05am Dr. David Staupet (Durdue University)                                                                                                                                                                                                                                                                                                                                                                                      |                                             |       |                |                 |              |
| 0.5 and Stewart (Fundue University)<br>Overview of IUCRCs and the CQT<br>Dr. Sabre Kais and Dr. Yong Chen (both Purdue University)                                                                                                                                                                                                                                                                                                       |                                             | 6.8   |                | 1/ J.A.         |              |
| 10:40-10:55am The Quantum Landscape in the United States Dr. Celia Merzbacher (SRI International and QED-C)                                                                                                                                                                                                                                                                                                                              |                                             | T.    |                |                 | (A)          |
| 11:00-11:15am Majorana Quantum Computing<br>Chetan Nayak (GM of Quantum Hardware, Microsoft)                                                                                                                                                                                                                                                                                                                                             | Microsoft                                   | -     |                |                 |              |
| 11:20-11:35am Challenges and Opportunities for Low-Depth Quantum Machine Learning<br>Dr. Masoud Mohseni (Google Al) This talk was moved to Thu @11:50am                                                                                                                                                                                                                                                                                  | Google Al                                   |       |                |                 |              |
| 11:40-11:45am Break                                                                                                                                                                                                                                                                                                                                                                                                                      |                                             | - to  |                |                 |              |
| 11:45-12:00pm Quantum Computing in the Cloud<br>Michael Brett (SVP of Applications, Rigetti)                                                                                                                                                                                                                                                                                                                                             | rigetti                                     | 👻 Th  | e Center fo    | r Quantum       | Techno       |
| 12:05-12:20pm Enterprise Solutions for Quantum Computing<br>Yianni Gamvros (Head of Business Development, QCWare)                                                                                                                                                                                                                                                                                                                        | QC WARE                                     | Dev   | veloping novel | l quantum techi | nologies     |
| 12:25-12:40pm Photonic Quantum Computing in the Cloud<br>Rafal Janik (Head of Operations & Customer Solutions, Xanadu)                                                                                                                                                                                                                                                                                                                   | ⊗x∧n∧du                                     |       |                |                 | E            |
| 12:45-01:40pm Panel Discussion<br>Moderator: Prof. Ricardo Decca (IUPUI)                                                                                                                                                                                                                                                                                                                                                                 |                                             | Р     | urdue Univ     | versity         | Fou<br>Nati  |
| 01:40-01:45pm (Daily) Wrap                                                                                                                                                                                                                                                                                                                                                                                                               |                                             | -     |                |                 | Tech         |
| Day 2 Agenda (Wednesday, June 17)                                                                                                                                                                                                                                                                                                                                                                                                        | Moderator: Notre Dame                       | Ir    | ndiana Univ    | versity         | add          |
| iodays proceedings will be moderated by irors, Jarek Nabrzyski and Manya Vyushkova from the University of Notre U<br>10:00-10:05am Welcome<br>Dr. David Stewart (Purdue University)                                                                                                                                                                                                                                                      | ame                                         | Unive | ersity of N    | otre Dame       | The          |
| 10:05-10:20am Compilation for the NISO Era<br>Dr. Ross Duncan (Cambridge Quantum Computing, Ltd.)                                                                                                                                                                                                                                                                                                                                        | 300                                         |       |                |                 | Univ         |
| 10:25-10:40am Quantum Information Science at AFRL - The Way Forward<br>Dr. Michael Hayduk (Deputy Director, AFRL Directorate)                                                                                                                                                                                                                                                                                                            | AFRE                                        |       | IUPUI          |                 | acce         |
| Quantum at GE Research<br>10:45-11:00am Dr. Loucas Tsakalakos (Business Program Manager, GE Global Research)<br>Dr. Steven Bush (Senior Scientist, GE Global Research)                                                                                                                                                                                                                                                                   | <b>36</b>                                   |       |                |                 |              |
| 11:05-11:20am Advancing the Quantum Computing Ecosystem<br>Dr. Yudong Cao (CTO, Zapata Computing, Inc.)                                                                                                                                                                                                                                                                                                                                  |                                             |       |                |                 |              |
| 11:25-11:30am Break                                                                                                                                                                                                                                                                                                                                                                                                                      |                                             |       |                |                 |              |
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| 11:50-12:05am IBM Quantum University Programs<br>Sebastian Hassinger (Quantum Computing Academic Program Leader, IBM)                                                                                                                                                                                                                                                                                                                    | IBM                                         |       | ENT            | ANGLEN          | -<br>1 E N T |
| 12:10-12:25pm Scalable and High-Performance Quantum Computers<br>Dr. Christopher Monroe (Chief Scientist and co-Founder, IonQ)                                                                                                                                                                                                                                                                                                           |                                             |       |                |                 |              |
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| 10:00-10:05am Dr. David Stewart (Purdue University)                                                                                                                                                                                                                                                                                                                                                                                      |                                             |       | Enter          | prise           |              |
| 10:05-10:20am L3Harris Quantum Interests<br>Dr. Rachele Cocks (Principal Scientist, L3Harris)                                                                                                                                                                                                                                                                                                                                            | S L3HARRIS                                  |       | Lincer         | prise           |              |
| 10:25-10:40am Quantum at Sea<br>Dr. Tim Morgan (Scientist, NSWC Crane)                                                                                                                                                                                                                                                                                                                                                                   |                                             |       |                |                 |              |
| 10:45-11:00am Information Needed to Determine When and How Quantum Computing can He<br>Dr. Wayne Eckerle (VP of Research & Technology, Cummins, Inc.)                                                                                                                                                                                                                                                                                    | lp Cummins 🧲                                | TI    | BM (           | Oua             | nti          |
| 11:05-11:20am Opportunities for QM Methodologies in Pharmaceutical Development<br>Dr. Jeff Tan (Director, Eli Lilly and Company)                                                                                                                                                                                                                                                                                                         | Lilly                                       |       |                | τ               |              |
| 11:25-11:30pm Break                                                                                                                                                                                                                                                                                                                                                                                                                      | 10                                          |       |                |                 |              |
| 11:30-11:45am Quantum Computing at Accenture Shreyas Ramesh (Senior Manager for Quantum Computing à€"Artificial Intellig                                                                                                                                                                                                                                                                                                                 | gence, Accenture) >                         |       |                |                 |              |
| 11:50-12:05pm Challenges and Opportunities for Low-Depth Quantum Machine Learning<br>Dr. Masoud Mohseni (Google AI) This talk moved from Tue @11:20am                                                                                                                                                                                                                                                                                    | Google Al                                   | N     |                | HKC             | )<br> <br>   |
| Building the Quantum Workforce of the Future<br><u>Dr.W. Michael Snow</u> (Professor of Physics, Indiana University)<br>12:10-12:40pm <u>Dr. Alexandra Bollaszave</u> (Professor of Exterinal and Computer Engineering, Puu<br><u>Dr. Pramey Upadhyaya</u> (Assistant Professor of Electrical and Computer Engineering, <u>Puu<br/><u>Dr. William J. Oliver</u> (Director, Center for Quantum Engineering, MIT)<br/>Desch Instantion</u> | rdue University)<br>ing, Purdue University) |       | GRU            | JMM             |              |
| Panel Discussion<br>12:40-01:40pm Moderator: Prof. Gerardo Ortiz (Indiana University)                                                                                                                                                                                                                                                                                                                                                    |                                             |       |                |                 |              |

### Center for Quantum Technologies OT

**NSF** An NSF Industry/University Cooperative Research Center (IUCRC)

RESEARCH MEMBERS WORKFORCE DEVELOPMENT



University Bloomington, the University of Notre Dame, and Indiana University Purdue University-Indianapolis (IUPUI). Industry partners will provide funding to the center's researchers and will obtain early access to findings applicable to their businesses.

funded center

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

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



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The Ouantum Computing Company



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



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<sup>1</sup> (approved<sup>2</sup> 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<sup>3</sup>) and sustained with year-round internships with any of the industrial members in our new Center for Quantum Technologies<sup>4</sup> (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.



| Day 1 Agenda (laced y, Lune 16)       Moderator: IURUI         Mary I precedings will be moderad by Mr. Baka Ausori from Indiana University Packa University Indianapolis (IUPU)       Indiana University Packa University Indianapolis (IUPU)         10.00-10.05am       Dr. David Stewart (Pardia University)       Overview of ULCRs and Dr. Kong Chen (Doth Pardiae University)       Indiana University Packa University       Indiana University Packa University       Indiana U                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | nu unies ED         | This is now just a local                                                                                                                                                                                                                                                                                                                                                   | copy of the <u>official workshop agenda</u> .       |
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| Barb preceding will be nederated fyretic blak Ausor from Indiau University Audae University Hadaupolis (UPU)<br>10:00-10:05 km (Version Particle University)<br>10:00-10:55 km (Version Particle University)<br>10:0                                                                                                                                                                                                                     | Day 1 Agenda (1     | uesday, June 16)                                                                                                                                                                                                                                                                                                                                                           | Moderator: IUPUI                                    |
| 1000-11030a       Dr. David Stewart (Purdue University)         1005-10-135a       Dre Sabre Kais and Dr. Yong Chen (poth Purdue University)         10140-10155a       Dre Sabre Kais and Dr. Yong Chen (poth Purdue University)         10140-10155a       Dre Guantum Indracage in the United States         10140-10155a       Microsoft         10140-10155a       Microsoft         10140-10155a       Ciele Merzaber(ER) (KM / Quantum Hardware, Microsoft)         10140-11155a       Google All         10140-11155a       Google All         10141-1125a       Brake         Quantum Computing in the Cloud       Google All         10141-1125a       Brake         Quantum Computing in the Cloud       Google All         10141-1145a       Brake         10141-1145a       Brake <th>Today's proceedings</th> <th>will be moderated by Prof. Babak Anasori from Indiana University-Purdue University Indiana<br/>Welcome</th> <th>polis (IUPUI)</th>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Today's proceedings | will be moderated by Prof. Babak Anasori from Indiana University-Purdue University Indiana<br>Welcome                                                                                                                                                                                                                                                                      | polis (IUPUI)                                       |
| 10.40-10.55am       The Quantum Landscape in the United States<br>Dr. Ceila Metrobacher (SR International and QEL-C)       Image: Ceila Metrobacher (SR International and QEL-C)         11.00-11.15am       Chainerga Quantum Computing<br>Chatan Nayak (6M of Quantum Hardware, Microsoft)       Image: Ceila Metrobacher (SR International and QEL-C)         11.10-11.15am       Chainerga Quantum Computing<br>Chainerga Quantum Computing in the Cloud<br>Mathum Computing in the Cloud<br>Chainerga Computing in the Cloud<br>Chainer Cloud Computing in the Cloud<br>Fatal Lank (Med of Oparitonis R light))       Image: Ceila Metrobacher (Computing<br>Yanni Camwros (Med of Business Development, QCWare)         11.20-11.2009       Photonic Quantum Computing in the Cloud<br>Fatal Lank (Med of Oparitons & Customer Solutions, Xanadu)       Image: Ceila Metrobacher (Med OP<br>Fatal Lank (Med of Oparitons & Customer Solutions, Xanadu)         11.20-11.2009       Photonic Quantum Computing in the Cloud<br>Fatal Lank (Med of Decar (UPU)       Image: Ceila Metrobacher (Med OP<br>Fatal Computing Inthe Cloud<br>Fatal Lank (Med of Decar (UPU)         11.20-11.2000       Report Computing Inthe Cloud<br>Fatal Lank (Med of Decar (UPU)       Image: Ceila Metrobacher (Med OP<br>Fatal Computing Inthe Cloud<br>Fatal Lank (Med of Decar (UPU)         11.20-11.2000       Report Computing Inthe Cloud<br>Fatal Lank (Med of Decar (UPU)       Image: Ceila Metrobacher (Med OP<br>Fatal Computing Inthe Cloud<br>Fatal Lank (Med of Decar (UPU)         12.40-11.2001       Decar Metrobacher (Med Computing Inthe Cloud<br>Decar Metrobacher (Med Computing Inthe Cloud<br>Decar Metrobacher (Med Computing Inthe Cloud<br>Decar Metrobacher (Med Conthe Inthe Inthe Inthe Inthe Inthe Inthe Inthe                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 10:00-10:05am       | Dr. David Stewart (Purdue University)<br>Overview of IUCRCs and the CQT<br>Dr. Sabre Kais and Dr. Yong Chen (both Purdue University)                                                                                                                                                                                                                                       |                                                     |
| 1130-1135an       Majorana Quantum Computing<br>Chetan Nayk (OH of Quantum Hardware, Microsoft)       Microsoft         1120-1135an       De Masoud Motseni (Google A) This tak was moved to The @1150an       Checanologie Coople A)         1140-1145an       De Masoud Motseni (Google A) This tak was moved to The @1150an       Checanologie Coople A)         1140-1145an       Det Masoud Motseni (Google A) This tak was moved to The @1150an       Coople A)         1140-1145an       Det Masoud Motseni (Google A) This tak was moved to The @1150an       Coople A)         1140-1145an       Det Masoud Motseni (Google A) This tak was moved to The @1150an       Coople A)         1140-1145an       Det Masoud Motseni (Google A) This tak was moved to The @1150an       Coople A)         1140-1145an       Det Masoud Motseni (Google A)       Coople A)         1120-1140p       Panel Discussion       Masoura Coople A)       Coople A)         1120-1140p       Panel Discussion       Masoura Coople A)       Coople A)         1120-1140p       Panel Discussion       Moderator: Note Dane       Coople A)         1120-1140p       Panel Discussion       Moderator: Note Dane       Coople A)         1120-1140p       Panel Discussion       Coople A)       Coople A)         1120-1140p       Panel Discussion       Coople A)       Coople A)         1120-1140p <td>10:40-10:55am</td> <td>The Quantum Landscape in the United States<br/>Dr. Celia Merzbacher (SRI International and QED-C)</td> <td></td>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 10:40-10:55am       | The Quantum Landscape in the United States<br>Dr. Celia Merzbacher (SRI International and QED-C)                                                                                                                                                                                                                                                                           |                                                     |
| 1140-1145an Collenges and Opportunities for Law-Depth Quantum Machine Learning Coogle Al<br>1140-1145an Brek<br>U145-1240p Reprint Solutions for Quantum Computing<br>1265-1240p Reprints Solutions for Quantum Computing<br>1265-1240p Reprint Solutions for Quantum Computing<br>1265-1240p Reprint Solutions (Statistics Xanadu)<br>1245-0140p Reprint Solutions (Statistics Xanadu)<br>1245-11000 Disson (Statistics Views Solutions, Xanadu)<br>1245-11000 Disson (Statistics Views Solutions, Xanadu)<br>1255-11000 Disson (Statistics Views Solutions, Xanadu)<br>1265-11000 Disson (Statistics Views Solutions)<br>1265-11000 Disson (Statistics Views Solutions)<br>1265-11000 Disson (Statistics Views Solutions)<br>1265-11000 Disson (Statistics Statistics Ciolobal Research)<br>Disson (Control Statistics Ciolobal Research)<br>1265-11200 Disson (Control Statistics Ciolobal Research)<br>1265-11200 Disson (Control Statistics Ciolobal Research)<br>1265-11200 Disson (Marantu University Program<br>1266-11200 Disson (Control Development, Quantum Computing Inc.)<br>1261-11200 Disson (Control Development, Quantum Computing Inc.)<br>1261-1225 Disson (Marantu University Program<br>1261-1225 Disson (Marantu University)<br>1260-1250 Disson (Marantu Computing Statistics Ciolobal Research)<br>1260-1250 Disson (Marantu University)<br>1261-1260 Disson (Marantu University)<br>1261-1260 Disson (Marantu University)<br>1261-1260 Disson (Marantu University)<br>1261-1260 Disson (Marantu University)<br>126                                                                                                                                                                                                                           | 11:00-11:15am       | Majorana Quantum Computing<br>Chetan Nayak (GM of Quantum Hardware, Microsoft)                                                                                                                                                                                                                                                                                             | Microsoft                                           |
| 1140-1145am Break<br>1145-1200p, Quartum Computing in the Cloud<br>Minister Berts (VP Applications, Rigetti)<br>1205-1220p, Temprise Studions for Quantum Computing<br>1215-1220p, Panel Discussion<br>Montecture Profile Cloud Computing in the Cloud<br>Panel Discussion<br>Melcone<br>D. David Stewart (Purdue University)<br>1005-1020m<br>Compliation for the NISO Era<br>Dr. Ross Durana (Cambridge Quantum Computing, Ltd.)<br>Compliation for the NISO Era<br>Dr. Ross Durana (Cambridge Quantum Computing, Ltd.)<br>Compliation for the NISO Era<br>Dr. Ross Durana (Cambridge Quantum Computing, Ltd.)<br>Dr. Steven Bush (Serior Science at AFEL - The Way Forward<br>Dr. Michael Hayduk (Deputy Director, AFRL Directorate)<br>Quantum at CE Research<br>Directoreas Taskalaka (Subines Program Manager, CE Global Research)<br>Dr. Steven Bush (Serior Sciencia, Cambridge Cloud Research)<br>Dr. Steven Bush (Serior Sciencia, Cambridge Cloud Research)<br>Dr. Steven Bush (Serior Sciencia, Cambridge Cloud Research)<br>Dr. Steven Bush (Serior Sciencia, Camputing, Inc.)<br>1125-1130m<br>Reak<br>1130-1125bm<br>Dr. Christopher Monroe (Chief Scientist and co-Founder, Iong)<br>Panel Discussion<br>Montector: Prof. Peter Kogge (University of Notre Dame)<br>Dr. Dr. Notopher Monroe (Chief Scientist, L3Harris)<br>Dr. Branel Discussion<br>Montector, Prof. Peter Kogge (University)<br>125-11300m<br>Dr. Tim Morgan (Scientist, L3Harris)<br>Dr. Tim Morgan (Scientist, L3Harris)<br>Dr. Tim Morgan (Scientist, NSWC Cane)<br>Dr. Tim Morgan (Scientist, NSWC Cane)                                                                                                                                                                                                | 11:20-11:35am       | Challenges and Opportunities for Low-Depth Quantum Machine Learning<br>Dr. Masoud Mohseni (Google Al) This talk was moved to Thu @11:50am                                                                                                                                                                                                                                  | Google Al                                           |
| 1145-1200p       Quartum Computing in the Cloud         1145-1200p       Futerprise Solutions for Quartum Computing         1225-1220p       Futerprise Solutions for Quartum Computing         1225-1220p       Refail Lank (Head of Decreations & Customer Solutions, Xanadu)         1225-1240p       Phenel Discussion         Moderator: Prof. Ricardo Decca (UPU)       Distribution         1245-0140p       Moderator: Prof. Ricardo Decca (UPU)         1246-0140p       Moderator: Prof. Ricardo Decca (UPU)         1000-1005am       Welcome         Dr. David Stewart (Purdue University)       Concern         1000-1005am       Welcome         Dr. David Stewart (Purdue University)       Concern         1000-1005am       Welcome       Dr. David Stewart (Purdue University)         1000-1005am       Contact (Cambridge Quantum Computing, Ltd.)       Concern         1005-1120am       Quantum Information Science at AFL - The Way Forward       Concern         1005-1120am       Discussi Takalakos (Business Program Manager, GE Global Research)       Concern         1015-1120am       Discussi Takalakos (Business Program Manager, GE Global Research)       Concern         1015-1120am       Bek Quantum Computing Inc.)       Eileenee Athle Check Quantum Computing Inc.)       Eileenee Athle There Kreenee Athle Check Quantum Computing Inc.) <td< td=""><td>11:40-11:45am</td><td>Break</td><td></td></td<>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 11:40-11:45am       | Break                                                                                                                                                                                                                                                                                                                                                                      |                                                     |
| 1205-1220pm       Enterprise Solutions for Quantum Computing       CONVERE         1225-12240pm       Photonic Quantum Computing in the Cloud       CONVERE         1225-1240pm       Photonic Quantum Computing in the Cloud       CONVERE         1225-1240pm       Photonic Quantum Computing in the Cloud       CONVERE         1245-0140pm       Moderator: Prof. Ricardo Decca (IUPU)       0         0140-01455pm       Daily Wap       Moderator: Note Dame         1030-1005am       Welcome       D.       Consolidation forth Jiste Natoryski and Marja Yushkova from the University of Nore Dame         1030-1005am       Welcome       D.       Consolidation forth Jiste Natoryski and Marja Yushkova from the University of Nore Dame         1030-1002am       Welcome       D.       Consolidation forth Jiste Natoryski and Marja Yushkova from the University of Nore Dame         1030-1020am       Quantum Information Science at AFRL - The Way Forward D.       Concertification for Yushkova (Reputing Jiste Natoryski and Marja Yushkova Ion the University Programs         1130-1120am       Advancing the Quantum Computing Ecosystem       Concertification for Yushkova Cloude Development, Quantum Computing Inc.)         1130-11225pm       Scalable and High-Performance Quantum Computing Academic Program Leader, IBM)       Concertification For Peter Kogge (University O Notre Dame)         1130-11225pm       Scalable and High-Performance Quantum Computing Ion                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 11:45-12:00pm       | Quantum Computing in the Cloud<br>Michael Brett (SVP of Applications, Rigetti)                                                                                                                                                                                                                                                                                             | rigetti                                             |
| 12:25:12:40pm       Photonic Quantum Computing in the Cloud         12:45:01:40pm       Panel Discussion         Moderator: Prof. Ricardo Decca (UPUI)       Moderator: Notice Dame         12:45:01:40pm       Panel Discussion         Moderator: Prof. Ricardo Decca (UPUI)       Moderator: Notice Dame         Ubio: 10:00:50pm       Compilation for the NISO Era       Moderator: Notice Dame         Ubio: 10:00:50pm       Compilation for the NISO Era       Compilation for the NISO Era         Ubio: 10:00:510:20pm       Compilation for the NISO Era       Compilation for the NISO Era         Uautum at GE Research       Quantum Information Science at AFRL - The Way Forward       Compilation for the NISO Era         Ubio: 51:1000m       Dicussis Stalaback Sciencis Scientist, GE Global Research)       Compilation Science Back Sciences Program Manager, GE Global Research)       Compilation Science Back Sciences Program Manager, GE Global Research)         10:45:11:20pm       Advancing the Quantum Computing Inc.)       Computing Inc.)       Computing Inc.)         11:25:11:20pm       Reak       Computing Ecosystem       Computing Inc.)       Computing Inc.)         11:25:11:20pm       Sciabale and High-Performance Quantum Computing Inc.)       Computing Inc.)       Computing Inc.)       Computing Inc.)         12:10:22:25pm       Sciabale and High-Performance Quantum Computing Inc.)       Computing Inc.) </td <td>12:05-12:20pm</td> <td>Enterprise Solutions for Quantum Computing<br/>Yianni Gamvros (Head of Business Development, QCWare)</td> <td>ocware</td>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 12:05-12:20pm       | Enterprise Solutions for Quantum Computing<br>Yianni Gamvros (Head of Business Development, QCWare)                                                                                                                                                                                                                                                                        | ocware                                              |
| 1245-0140pm       Panel Uscussion         0140-0145pm       Daily Wap         1247-0145pm       Daily Wap         1000-1005am       Welcome         1000-1005am       Welcome         1000-1005am       Welcome         1000-1005am       Welcome         1000-1005am       Welcome         1001-1005am       David Stewart (Purdue University)         1001-1005am       David Stewart (Purdue University)         1001-1005am       Quantum Information Science at AFRL - The Way Forward         1005-1020am       Quantum at GE Research       Welcome         1005-1120am       Quantum Computing Loto, AFRL Directorate)       Welcome         1005-1120am       Advancing the Quantum Computing Ecosystem       Welcome         1105-1120am       Advancing the Quantum Computing Ecosystem       Welcome         1120-1145am       Software and Practical Computing       Generating         1121-1120am       Reak       Welcome       Welcome         1120-11205am       BM Quantum University Programs       Welcome       Welcome         1120-11205am       Panel Discussion       Welcome       Welcome       Welcome         1120-11205am       Moderator Prof. Peter Kooge (University of Notre Dame)       UDiversity Programs       Welcome </td <td>12:25-12:40pm</td> <td>Photonic Quantum Computing in the Cloud<br/>Rafal Janik (Head of Operations &amp; Customer Solutions, Xanadu)</td> <td>XANADU</td>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | 12:25-12:40pm       | Photonic Quantum Computing in the Cloud<br>Rafal Janik (Head of Operations & Customer Solutions, Xanadu)                                                                                                                                                                                                                                                                   | XANADU                                              |
| Value Variant (Very) (Hardy       Moderator, Notre Dame         ID32 Japand (Verkedsdy, Lune 17)       Moderator, Notre Dame         ID30-10.05sa       Diversity (Pardue University)         ID30-10.05sa       Diversity (Pardue University)         ID30-10.05sa       Diversity (Pardue University)         ID30-10.05sa       Diversity (Pardue University)         ID30-10.05a       Diversity (Pardue University)         ID35-10.04a       Diversity (Pardue University)         Quantum Information Science at FRL - The Way Forward       Diversity (Pardue University)         Quantum Information Science at FRL - The Way Forward       Diversity (Pardue University)         Quantum Information Science at FRL - The Way Forward       Diversity (Pardue University)         Diversity (Pardue University) (Pardue University)       Diversity (Pardue University)         Diversity (Pardue Unive                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 12:45-01:40pm       | Panel Uiscussion<br>Moderator: Prof. Ricardo Decca (IUPUI)<br>(Daily) Wran                                                                                                                                                                                                                                                                                                 |                                                     |
| Idady Sproceedings will be moderated by Pols Jarek Nakoryski and Mariya Vyashkova from the University P Note Dame<br>Welcome<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development<br>Development | Day 2 Agenda (V     | Vednesdav, June 17)                                                                                                                                                                                                                                                                                                                                                        | Moderator: Notre Dame                               |
| 10:00-10:05am       Wetcome         Dor. David Stewart (Purdue University)       Compilation for the NISQ Era         Dir. Ross Durana (Cambridge Quantum Computing, Ltd.)       Compilation for the NISQ Era         Dir. Ross Durana (Cambridge Quantum Computing, Ltd.)       Compilation for the NISQ Era         Dir. Ross Durana (Cambridge Quantum Computing, Ltd.)       Compilation for the NISQ Era         Dir. Ross Durana (Cambridge Quantum Computing, Ltd.)       Compilation for the NISQ Era         Dir. Durana Takalakos (Business Program Manager, GE Global Research)       Compilation for the NISQ Era         Dir. Steven Bush (Senior Scientist, CE Global Research)       Compilation for the NISQ Era         Dir. Vudong Gao (CTO, Zapata Computing, Inc.)       Steven Bush (Senior Scientist, GE Global Research)       Compilation for the NISQ Era         Dir. Vudong Gao (CTO, Zapata Computing, Inc.)       Steven Bush (Review Program Brack       Compilation for the NISQ Era         Dir. Dir. Vudong Cao (CTO, Zapata Computing, Inc.)       Steven Bush (Review Program Brack       Compilation for the NISQ Era         Dir. David Stewart Brack       Steven Bush (Review Program Brack       Compilation for the NISQ Era         Dir. David Stewart Brack       Steven Bush (Review Program Brack       Compilation for the NISQ Era         Dir. David Stewart Brack       Steven Bush (Review Program Brack       Compilation for the NISQ Era         Dir. David Stewart Brack                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Today's proceedings | will be moderated by Profs. Jarek Nabrzyski and Mariya Vyushkova from the University of No                                                                                                                                                                                                                                                                                 | tre Dame                                            |
| 10.05-10.20an       Concellation for the NISO Era       COC         10.05-10.20an       Dr. Ross Duncan (Cambridge Quantum Computing, Ltd.)       COC         10.25-10.40an       Quantum Information Science at AFRL - The Way Forward       Concentration         10.25-10.40an       Quantum Information Science at AFRL - The Way Forward       Concentration         10.45-11.100an       Dr. Louars Takalabako (Seniors Scientist, CE Global Research)       Coc         10.45-11.100an       Dr. Louars Takalabako (Seniors Scientist, CE Global Research)       Coc         11.05-11.20an       Advancing the Quantum Computing, Inc.)       Coc         11.125-11.30an       Break       Constaption of Product Development, Quantum Computing Inc.)       Coc         11.125-11.30an       Break       Software and Practical Computing       Coc       Coc         11.125-11.30an       Break       Software and Practical Computing Academic Program Leader, IBM)       Coc       Concentration         11.125-11.30an       Break       Software and Practical Computing Academic Program Leader, IBM)       Coc       Concentration         11.125-11.30an       Break       Coc       Concentration       Coc       Concentration         12.10-12.25pm       Software and Practical Computing Academic Program Leader, IBM)       Coc       Concentration       Coc       Concentration<                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 10:00-10:05am       | Welcome<br>Dr. David Stewart (Purdue University)                                                                                                                                                                                                                                                                                                                           |                                                     |
| 10:25-10:40am       Quantum Information Science at AFRL - The Way Forward       Image: Construction of the second of the                                                                                                                                                                                                                                                                                                                                                             | 10:05-10:20am       | Compilation for the NISQ Era<br>Dr. Ross Duncan (Cambridge Quantum Computing, Ltd.)                                                                                                                                                                                                                                                                                        | 300                                                 |
| Quantum at GE Research<br>Dids5-110000 Dr. Louxas Takalabako Biskinese Program Manager, GE Global Research)<br>Dr. Steven Bush (Senior Scientist, CE Global Research)<br>Dr. Yudong Cao (CTO, Zapata Computing, Inc.)<br>1125-113000<br>Break<br>1130-1145500<br>Bibl Quantum University Programs<br>Steve Reinhardt (VP Product Development, Quantum Computing Inc.)<br>EGE Quantum Christopher Monore (Chief Scientist and co-Founder, Iong)<br>1210-1225000<br>Dr. Stable and High-Performance Quantum Computing Academic Program Leader, IBM)<br>1210-1225000<br>Dr. Salable and High-Performance Quantum Computers<br>Dr. Christopher Monore (Chief Scientist and co-Founder, Iong)<br>1230-0125000<br>Panel Discussion<br>Moderator: Prof. Peter Kogge (University of Notre Dame)<br>1025-0130000<br>Discussion<br>Dr. David Stewart (Purdue University)<br>1030-102000<br>Dr. David Stewart (Purdue University)<br>1035-102000<br>Dr. David Stewart (Purdue University)<br>1045-110000<br>Information Needed to Determine When and How Quantum Computing can Help Cummins<br>Comport University (Pf of Research St. Edetonlogy, Cummins, Inc.)<br>1105-1120500<br>Dr. David Stewart (Purdue University)<br>1125-113000<br>Dr. David Stewart (Purdue University)<br>1125-113000<br>Dr. Sareyas Ramesh, Cencity Company<br>1125-113000<br>Dr. Break<br>1130-1145500<br>Dr. Hankensh, Cencity (Por Research & Technology, Cummins, Inc.)<br>Dr. Hankensh, Cencity (Por Research & Technology, Cummins, Inc.)<br>Dr. Hankensh, Cencity (Por Research & Technology, Cummins, Inc.)<br>1130-1145500<br>Dr. Maxoud Mohzeni (Coogle AI)<br>Dr. Maxoud Mohzeni (Coogle AI)                                                                                                                                                                                             | 10:25-10:40am       | Quantum Information Science at AFRL - The Way Forward<br>Dr. Michael Hayduk (Deputy Director, AFRL Directorate)                                                                                                                                                                                                                                                            | AFRE                                                |
| 11105-11120an<br>Advancing the Quantum Computing Ecosystem<br>Dr. Yudong Cao (CTO, Zapata Computing, Inc.)<br>1125-1130an<br>Break<br>1130-1145an<br>Software and Practical Computing<br>Steve Reinhardt (YP Product Development, Quantum Computing Inc.)<br>1130-1145an<br>Software and Practical Computing<br>Steve Reinhardt (YP Product Development, Quantum Computing Inc.)<br>1130-1145an<br>Software and High-Performance Quantum Computing Academic Program Leader, IBM)<br>1130-11225an<br>Scalable and High-Performance Quantum Computers<br>Dr. Christopher Monroe (Chief Scientist and co-Founder, IonQ)<br>1230-0125pm<br>Panel Discussion<br>Moderator: Prof. Peter Kogge (University of Notre Dame)<br>10125-01300p<br>10125-01300p<br>10125-01300p<br>10125-01300p<br>Diay J Agenda (Thursday, June 15)<br>Moderator: Prof. Peter Kogge (University of Notre Dame)<br>10125-10140an<br>Dr. David Stewart (Purdue University)<br>1025-1040an<br>Quantum Interests<br>Dr. Ravid Stewart (Purdue University)<br>1035-1020an<br>Information Needed to Determine When and How Quantum Computing can Help Cummins<br>Quantum at Sea<br>Dr. Tim Morgan (Scientist, ISX Crane)<br>1105-1120an<br>Information Needed to Determine When and How Quantum Computing can Help Cummins<br>Quantum at Sea<br>Dr. Tim Morgan (Scientist, ISX Crane)<br>1105-1120an<br>Discussion<br>Moderator: Prof. Peter View Computing at Accenture<br>Streyas Ramesh (Ferior Manager for Quantum Computing de' Artificial Intelligence, Accenture)<br>Dr. Masoud Moliseri (Google AI) This tak more famile @1120an<br>Building the Quantum Workforce of the Future<br>Dr. Masoud Moliseri (Google AI) This tak more famile @1120an<br>Building the Quantum Workforce of the Future<br>Dr. Masoud Moliseri (Google AI) This tak more famile @1120an<br>Building the Quantum Workforce of the Future<br>Dr. Masoud Moliseri (Google AI) This tak more famile @1120an<br>Building the Quantum Workforce of the Future<br>Dr. Masoud Moliseri (Google AI) This tak more famile @1120an<br>Building the Quantum Workforce of the Future<br>Dr. Masoud Moliseri (Google AI) This tak more familereing, Purdue University)<br>Dr. Masoud Moliseri (Google A                                                                                                                                                                                                 | 10:45-11:00am       | Quantum at GE Research<br>Dr. Loucas Tsakalakos (Business Program Manager, GE Global Research)<br>Dr. Steven Bush (Senior Scientist, GE Global Research)                                                                                                                                                                                                                   | Æ                                                   |
| 11:25-11:30am Break<br>11:30-11:45am Software and Practical Computing<br>Software we Reinbardt (VP Product Development, Quantum Computing Inc.)<br>BM Quantum University Programs<br>Sebastian Hassinger Quantum Computing Academic Program Leader, IBM)<br>12:10-12:25pm Software (Product Development, Quantum Computing Inc.)<br>Software Reinbardt (VP Product Development, Quantum Computing Inc.)<br>12:00-12:50m Panel Discussion<br>Moderator: Prof. Peter Kogge (University of Notre Dame)<br>10:25-01:30pm (Daily) Wrap<br>DM 3 Agenda (Thursday, Jume 18)<br>DM Vectore<br>10:00-10:55m Wectore<br>10:00-10:55m Discussion<br>Moderator: Prof. Peter Kogge (University of Notre Dame)<br>10:00-10:55m Discussion<br>Moderator: Prof. Peter Kogge (University of Notre Dame)<br>10:00-10:55m Discussion<br>Moderator: Prof. Peter Kogge (University)<br>10:00-10:55m Discussion<br>Moderator: Prof. Peter Kogge (University)<br>11:00-11:25m Discussion<br>Moderator: Prof. Peter Kogge (University)<br>11:00-11:25m Discussion<br>Moderator: Prof. Peter Manager for Quantum Computing can Help Cummins<br>Discussion<br>Moderator: Prof. Peter Tan (Director, Ell Lilly and Company)<br>11:00-11:25m Discussion<br>Moderator: Prof. Peter Sorger for Quantum Machine Learning<br>Building the Quantum Workforce of the Future<br>Dr. Massud Mohseni (Google AI) This tak moved from Tue @11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Massud Mohseni (Google AI) This tak moved from Tue @11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Massud Mohseni (Google AI) This tak moved from Tue @11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Massud Mohseni (Google AI) This tak moved from Tue @11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Massud Mohseni (Google AI                                                                                                                                                                                                           | 11:05-11:20am       | Advancing the Quantum Computing Ecosystem<br>Dr. Yudong Cao (CTO, Zapata Computing, Inc.)                                                                                                                                                                                                                                                                                  |                                                     |
| 1130-1145an Software and Practical Computing<br>Sreve Reinhardt (VP Product Development, Quantum Computing Inc.)<br>BM Quantum University Programs<br>Seabatian Hassinger Quantum Computing Academic Program Leader, IBM)<br>1210-1225pm Scalable and High-Performance Quantum Computing Academic Program Leader, IBM)<br>1210-1225pm Scalable and High-Performance Quantum Computing Academic Program Leader, IBM)<br>1210-1225pm Scalable and High-Performance Quantum Computing Academic Program Leader, IBM)<br>1210-1225pm Scalable and High-Performance Quantum Computers<br>Di 25-01:30pm Quality Wrap<br>Day 3 Agenda (Thursday, June 18) Moderator: Indiana University<br>Welcome<br>Di 25-01:30pm Quality Wrap<br>Day 3 Agenda (Thursday, June 18) Moderator: Indiana University<br>Welcome<br>Di 25-01:40am Quantum Interests<br>Di 25-10:40am Quantum Sea<br>Dr. Tim Morgan (Scientist, ISWC Crane)<br>Di 25-11:300m Break<br>11:30-11:45am Quantum Interests<br>Dr. Wayne Eckerie (VP of Research & Technology, Cummins, Inc.)<br>Dr. Wayne Eckerie (VP of Methodologies in Pharmaceutical Development<br>Dr. Wayne Eckerie (VP of Methodologies in Pharmaceutical Development<br>Dr. Wayne Eckerie (VP of Methodologies in Pharmaceutical Development<br>Dr. Wayne Eckerie (VP of Research & Technology, Cummins, Inc.)<br>Dr. Wayne Eckerie (VP of Research & Technology, Cummins, Inc.)<br>Dr. Wayne Eckerie (VP of Research & Technology, Cummins, Inc.)<br>Dr. Wayne Eckerie (VP of Research & Technology, Cummins, Inc.)<br>Dr. Wayne Eckerie (VP of Research & Technology, Cummins, Inc.)<br>Dr. Wayne Eckerie (VP of Research & Technology, Cummins, Inc.)<br>Dr. Wayne Eckerie (VP of Research & Technology, Cummins, Inc.)<br>Dr. Wayne Break<br>11:30-11:45am Quantum Workforce of the Fruitare<br>Dr. Wathale Lingent (Rodersor of Phicist, Indiana University)<br>Dr. Masoud Mohseni (Google AI) This Lik moved from Ture (11:20am<br>Building the Quantum Workforce of the Fruitare<br>Dr. Masoud Mohseni (Google AI) This Lik moved from Ture (11:20am<br>Building the Quantum                                                                                                                                                                                   | 11:25-11:30am       | Break                                                                                                                                                                                                                                                                                                                                                                      |                                                     |
| 1150-1205an       IBM Quantum University Programs         Sebastian Hassinger (Quantum Computing Academic Program Leader, IBM)       Image: Computing Academic Program Leader, IBM)         1210-1225pm       Dc. Christopher Monroe (Chief Scientist and co-Founder, Iong)       Image: Computing Academic Program Leader, IBM)         1230-0125pm       Panel Discussion       Panel Discussion         0125-01203pm       Panel Discussion       Moderator: Prof. Peter Kogge (University of Notre Dame)         0125-01203pm       Daily Wap       Moderator: Prof. Peter Kogge (University of Notre Dame)         0125-0120am       Daily Wap       Moderator: Prof. Peter Kogge (University of Notre Dame)         0125-0120am       Daily Wap       Moderator: Prof. Peter Kogge (University)         1130-120am       Welcome       Dr. David Stewart (Purdue University)         1005-1020am       Dr. Rachele Cocks (Principal Scientist, LSHarris)       Image: LSHARRIST         1025-1040am       Quantum at Sea       Dr. Tim Morgan (Scientist, NSWC Crane)       Image: Cock Crane)         1045-1120am       Doportunities for (M Methodologies in Pharmacutical Development Dr. Wayne Eckerle (VP of Research & Technology, Cummins, Inc.)       Image: Cock Crane)       Image: Cock Crane)         1130-1120am       Dr. Tim Morgan Zia Accentre       Streeyas Ramesh (Senior Maager for Quantum Computing & Artificial Intelligence, Accentre)       Image: Cock Crane) <t< td=""><td>11:30-11:45am</td><td>Software and Practical Computing<br/>Steve Reinhardt (VP Product Development, Quantum Computing Inc.)</td><td></td></t<>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 11:30-11:45am       | Software and Practical Computing<br>Steve Reinhardt (VP Product Development, Quantum Computing Inc.)                                                                                                                                                                                                                                                                       |                                                     |
| 12:10-12:25pm Scalable and High-Performance Quantum Computers<br>21:10-12:25pm Scalable and High-Performance Quantum Computers<br>Moderator: Not Peter Kogge (University of Notre Dame)<br>12:30-01:25pm Panel Discussion<br>Moderator: Not Peter Kogge (University of Notre Dame)<br>12:30-01:25pm Panel Discussion<br>Moderator: Not Peter Kogge (University of Notre Dame)<br>12:30-01:25pm Panel Discussion<br>Day 3 Agenda (Thursday, June 18)<br>Moderator: Not Peter Kogge (University of Notre Dame)<br>10:30-10:05am<br>Dr. David Stewart (Purdue University)<br>10:35-10:20am<br>Dr. David Stewart (Purdue University)<br>10:35-10:20am<br>Dr. Rachele Cocks (Principal Scientist, L3Harris)<br>10:25-10:40am<br>Dr. Tim Morgan (Scientist, NSWC Crane)<br>11:05-11:20am<br>Dr. Jerrit an (Director, Eli Lilly and Company)<br>11:25-11:30pm Break<br>11:30-11:45am<br>Quantum Computing at Accenture<br>Streyas Ramesh (Fenior Manager for Quantum Machine Learning<br>Dr. Maxoud Mohseni (Google AI) This talk more from Tie @ 11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Maxoud Mohseni (Google AI) This talk more from Tie @ 11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Maxoud Mohseni (Google AI) This talk more from Tie @ 11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Maxoud Mohseni (Google AI) This talk more from Tie @ 11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Maxoud Mohseni (Google AI) This talk more from Tie @ 11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Maxoud Mohseni (Google AI) This talk more from Tie @ 11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Maxoud Mohseni (Google AI) This talk more from Tie @ 11:20am<br>Building the Quantum Workforce of the Future<br>Dr. Maxoud Mohseni (Google AI) This talk more from Tie @ 11:20am<br>Building the Quantum Workforce of The Future<br>Dr. Maxoud Mohseni (Google AI) This talk more from Tie @ 11:20am<br>Building the Quantum Workforce of The Future<br>Dr. Maxoud Mohseni (Google AI) This talk more from Tie @ 11:20am<br>Building the Quantum Workforce of The Future<br>Dr. Maxoud Mohseni (Coreardo                                                                                                                                                                                                                   | 11:50-12:05am       | IBM Quantum University Programs<br>Sebastian Hassinger (Quantum Computing Academic Program Leader, IBM)                                                                                                                                                                                                                                                                    | IBM                                                 |
| 12:30-01:25m Anel Discussion<br>Moderator: Prof. Peter Kogge (University of Notre Dame)<br>D1:25-01:30pm (Daily) Wrap<br>Day 3 Jagenda (Thursday, June 18) Moderator: Indiana University<br>Day 3 Jagenda (Thursday, June 18) Moderator: Indiana University<br>D1:00-01:05am Discussion (Scientist, L3Harris) Discussion (Scientist, L3Harris)<br>D: Rachele Cocks (Principal Scientist, L3Harris) Discussion<br>D: Tim Morgan (Scientist, NSWC Crane)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Wayne Eckerle (VP of Research & Technology, Curmins, Inc.)<br>D: Web of the Carmon Computing at Accenture<br>D: Wayne Beak<br>D: Masoud Mohseni (Googie AI) This tak moved from Tue @ 11:20am<br>D: Masoud Mohseni (Googie AI) This tak moved from Tue @ 11:20am<br>D: Masoud Mohseni (Googie AI) This tak moved from Tue @ 11:20am<br>D: Masoud Mohseni (Coogie AI) This tak moved from Tue @ 11:20am<br>D: Masoud Mohseni (Coogie AI) This tak moved fro                                                                                                                                                                                                                                       | 12:10-12:25pm       | Scalable and High-Performance Quantum Computers<br>Dr. Christopher Monroe (Chief Scientist and co-Founder, IonQ)                                                                                                                                                                                                                                                           | Q IONQ                                              |
| 01.279-20400       Moderator: Indiana University         Day 3 Agenda (Thursday, June 18)       Moderator: Indiana University         01005 10:005m       Welcome         Dr. D avid Stewart (Purdue University)       Usaturation (Purdue University)         10:05-10:20am       Dr. Rachele Cocks (Principal Scientist, L3Harris)         D0:25-10:40am       Dr. Rachele Cocks (Principal Scientist, L3Harris)         D0:45-11:00am       Diantum at Sea         D:45-11:00am       Difformation Needed to Determine When and How Quantum Computing can Help Cummins         D:10:51:120am       Difformation Needed to Determine When and How Quantum Computing can Help Cummins         D:11:05-11:20am       Difformation Needed to Determine When and How Quantum Computing can Help Cummins         D:11:05-11:20am       Difformation Needed to Determine When and How Quantum Computing can Help Cummins         D:11:05-11:20am       Diff Tan Difficutor, Eil Lilly and Company)         11:10:51:120am       Quantum Gomputing at Accenture         Shreyas Ramesh (Senior Manager for Quantum Machine Learning       Scoogle Al         11:50:12:05pm       Challenges and Opportunities for Low-Depth Quantum Machine Learning       Google Al         Building the Quantum Workforce of the Future       Dr. Masoud Mohemi (Google J) Nis tuk moved from Twe @11:20am       Google Al         Building the Quantum Workforce of the future       Diff Reary Undive                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 12:30-01:25pm       | Panel Discussion<br>Moderator: Prof. Peter Kogge (University of Notre Dame)<br>(Daily) Wran                                                                                                                                                                                                                                                                                |                                                     |
| IodayS proceedings will be moderated by Prof. Phil Richerme from Indana University         Welcome         D10-010.05am         Welcome         Dr. D-wid Steward (Purdue University)         U33-Brits Quantum Interests         Dr. Bachele Cocks (Principal Scientist, L3Harris)         Duartum at Sea         Dr. Marcine Cocks (Principal Scientist, L3Harris)         Dird Steward (Dr. Marcine)         Dird Tim Morgan (Scientist, NSWC Crane)         Dird Tim Tim Korgan (Scientist, NSWC Crane)         Dird Tim Tim Korgan (Scientist, NSWC Crane)         Dird Tim Tim Korgan (Scientist, NSWC Crane)         Dird Tim Tim Tim Korgan (Scientist, NSWC Crane)         Dird Tim                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         | Day 3 Agenda (1     | hursday June 18)                                                                                                                                                                                                                                                                                                                                                           | Moderator: Indiana University                       |
| 10:00-10:05am<br>Dc.David Stewart (Purdue University)<br>10:05-10:20am<br>Dr.Rachele Cocks (Principal Scientist, L3Harris)<br>Dr.Rachele Cocks (Principal Scientist, L3Harris)<br>Dr.Rachele Cocks (Principal Scientist, L3Harris)<br>Dr.Rachele Cocks (Principal Scientist, L3Harris)<br>Dr.Rachele Cocks (Principal Scientist, L3Harris)<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison<br>Dr.Barrison                    | Today's proceedings | will be moderated by Prof. Phil Richerme from Indiana University                                                                                                                                                                                                                                                                                                           |                                                     |
| 10.95-10:20a       L3Haris Quantum Interests       Call Lance Cocks (Principal Scientist, L3Haris)       Call Lance Lance Cocks (Principal Scientist, L3Haris)         10:25-10:40a       Dur. Tim Morgan (Scientist, SWC Crane)       Information Needed to Determine When and How Quantum Computing can Help Cummins         10:45-11:00a       Dr. Tim Morgan (Scientist, NSWC Crane)       Information Needed to Determine When and How Quantum Computing can Help Cummins         10:45-11:00a       Dr. Doportunities for QM Methodologies in Pharmaceutical Development       Dur. Computing and Company)         11:05-11:20a       Opportunities for QM Methodologies in Pharmaceutical Development       Dur. Computing at Accenture         11:05-11:20a       Marce Science (F) of Research & Technology, Cummins, Inc.)       Computing at Accenture         11:05-11:20b       Reak       Computing at Accenture         11:05-11:20b       Challenges and Opportunities for Low-Oepth Quantum Machine Learning       Coogle Al         11:05-12:05pm       Challenges and Opportunities for Low-Oepth Quantum Machine Learning       Coogle Al         11:05-12:05pm       Challenges and Opportunities for Low-Oepth Quantum Machine Learning       Coogle Al         11:05-12:05pm       Challenges and Opportunities for Low-Oepth Quantum Machine Learning       Coogle Al         11:05-12:05pm       Challenges and Opportunities for Low-Oepth Quantum Machine Learning       Coogle Al         11:05-12:05pm <td>10:00-10:05am</td> <td>Welcome<br/>Dr. David Stewart (Purdue University)</td> <td></td>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 10:00-10:05am       | Welcome<br>Dr. David Stewart (Purdue University)                                                                                                                                                                                                                                                                                                                           |                                                     |
| 10:25-10:40am Quantum at Sea<br>Dr. Tim Morgan (Scientist, NSWC Crane)<br>Dr. Wayne Eckerle (VP of Research & Technology, Curmmins, Inc.)<br>Dr. Wayne Eckerle (VP of Research & Technology, Curmmins, Inc.)<br>Dr. Wayne Eckerle (VP of Research & Technology, Curmmins, Inc.)<br>Dr. Wayne Eckerle (VP of Research & Technology, Curmmins, Inc.)<br>Dr. Wayne Eckerle (VP of Research & Technology, Curmmins, Inc.)<br>Dr. Wayne Eckerle (VP of Research & Technology, Curmmins, Inc.)<br>Dr. Wayne Eckerle (VP of Research & Technology, Curmmins, Inc.)<br>Dr. Wayne Eckerle (VP of Research & Technology, Curmmins, Inc.)<br>Dr. Wayne Eckerle (VP of Research & Technology, Curmmins, Inc.)<br>Dr. Wayne Eckerle (VP of Research & Technology, Curmmins, Inc.)<br>Dr. Hasoud Mohseni (Googie AI) This tak moved from Tue @11:20am<br>Building the Quantum Workforce of the Future<br>Dr. W. Wichael. Song (Westistant Poffessor of Flicticical and Computer Engineering, Purdue University)<br>Dr. Hasoud Robaseni (Resion of Electrical and Computer Engineering, Purdue University)<br>Dr. William D. Oliver (Director, Center for Quantum Engineering, MIT)<br>12:40-01:40pm Prate Discussion<br>Mediater: Prof. Gerardo Ortiz (Indiana University)<br>D1:40-01:45pm Workshop Wap-Up                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 10:05-10:20am       | L3Harris Quantum Interests<br>Dr. Rachele Cocks (Principal Scientist, L3Harris)                                                                                                                                                                                                                                                                                            | 🛞 L3HARRIS"                                         |
| 10:45-11:00an Information Needed to Determine When and How Quantum Computing can Help Cummins<br>Dr. Wayne Eckerle (VP of Research & Technology, Cummins, Inc.)<br>Dr. Jeff Tan (Director, Eli Lilly and Company)<br>11:25-11:30pm Break<br>U1:30-11:45am Quantum Computing at Accenture<br>Swreyas Ramesh (Senior Manager for Quantum Computing Jef Artificial Intelligence, Accenture)<br>Dr. Mascud Mohseni (Googie Al) This tulk moved from the @11:20am<br>Building the Quantum Workforce of the Future<br>Dr. W. Michael Sance (Horseor of Hysics, Indiana University)<br>12:10-12:20pm Zhexandra Botasseva (Professor of Flycis, Indiana University)<br>Dr. Mascud Mohseni (Coegie Al) (Asistant Professor of Electrical and Computer Engineering, Purdue University)<br>Dr. William D. Oliver (Director, Center for Quantum Engineering, MIT)<br>12:40-01:45pm Workshops Wap-Up                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  | 10:25-10:40am       | Quantum at Sea<br>Dr. Tim Morgan (Scientist, NSWC Crane)                                                                                                                                                                                                                                                                                                                   |                                                     |
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NORTHROP GRUMMAN



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The Women in STEM Living-Learning Center is IU's premiere community for women pursuing degrees in Science, Technology, Engineering, and Mathematics.

Apply to join Women in STEM 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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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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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 The Bo growth perspectives and multiple literacies. To that end we replaced the traditional web forums in the studen Boot Camp with dedicated channels on a Discord server, where learners have control over their of stud on prio identity being anonymous or not, and thus implementing the "lurking as learning" concept known the (b) Techno to foster intercultural competence while respecting learners' prior experiences and beliefs regarding communicative norms. The de

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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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Diversity is composed of individual and group/so historically underrepresented populations have equa in educational programs; inclusion is intentional, and curriculum, in the co-curriculum, and in the commu

that help member institutions and sy Boot Camp course

Valuing Individua the previous back and associated int personalized learr multiple, alternati one way and obta 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.

Addressing Social Inequalities. Our QIS Boot Camp has an open content since there virtually are

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.

# 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.

|   | UNIVERSITY OF FLORIDA |            |                                                                 |            |                       |  |  |  |
|---|-----------------------|------------|-----------------------------------------------------------------|------------|-----------------------|--|--|--|
| F | Quantum Informati     | on Systems | //// NSF QLCI: Conceptualizing an Institute for Quantum Biology |            |                       |  |  |  |
|   | PROJECT SUMMARY       | PEOPLE     | EVENTS                                                          | LITERATURE | RELATED ORGANIZATIONS |  |  |  |



Adrian German dgerman@indiana.edu Indiana University Bloomington, Indiana, USA Marcelo Pias Federal University of Rio Grande Rio Grande, Brazil mpias@furg.br Qiao Xiang Xiamen University Xiamen, Fujian, China xiangq27@gmail.com



- 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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"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<sub>®</sub>

#### 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."





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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!"





Technical Symposium

- 1. Why do we need such a knowledge unit?
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# On the Design and Implementation of a Quantum Architectures Knowledge Unit for a CS Curriculum

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<sup>b</sup>."

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 ComputersReceived May 7, 1981International 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. 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

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

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,

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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.



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**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.



#### **Government Programs for Quantum Computing**

#### 

#### Acomputing

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 Number of startups by country



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.

Is there an object that could fit these openings perfectly?

This is called superposition.









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♥ UNITED STATES Impossible Object Puzzle - A 3D Printed Square Circle Triangle Geometry Puzzle!





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#### Same idea taken to the extreme:

■ shapeways.com/product/T8GLAXEJH/godel-escher-bach-3-faces-in-a-minimal-object  $\leftarrow \rightarrow$ C

At the top 3 direct views

Left 3 Shadows

Right

Random view

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

Made by Kuiper & van Ballegooijen Math Art





Bach



- 1. Why do we need such a knowledge unit?
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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")?



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



Technical Symposium

1. Why do we need such a knowledge unit?

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

#### 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.



From Photons to Quantum Computers

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#### **Kindergarten Quantum Mechanics** — lecture notes —

**Bob Coecke** 

Oxford University Computing Laboratory, Wolfson Building, Parks rd, OX1 3QD Oxford, UK. coecke@comlab.ox.ac.uk

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 Ouantum mechanics. 03.67.-a Ouantum 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,





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:

#### **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.

| "GOOD QM"      |  | HIGH-LEVEL language |   |
|----------------|--|---------------------|---|
| von Neumann QM |  | 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!



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?
- 2. What does it look like?
- How do we know it's what we need? 3.



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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 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

Lecture 09: Quantum Fourier Transform

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# **Diana Franklin**

Associate Professor of Computer Science at University of Chicago

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| THE UNIVERSITY OF       | THE UNIVERSITY OF        |
|-------------------------|--------------------------|
| CHICAGO                 | CHICAGO                  |
| Introduction to Quantum | Introduction to Quantum  |
| Computing for Everyone  | Computing for Everyone 2 |
| UChicagoX               | UChicagoX                |
| Course                  | Course                   |

# a quantum abacus

It's time to prove our theorem:

۲



We start by reminding ourselves that  $|+\rangle = \{\bigcirc, \bigoplus\}$  and  $|-\rangle = \{\bigcirc, \overline{\bigoplus}\}$ So now we need to calculate:

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



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|------------------|-----------------------|------------------|
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Quantum Computing Realities Quantum Computing Fundamentals















- 1. Why do we need such a knowledge unit?
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The why and what of CS202X Curricular Guidelines. Continuing a process that began 50+ years ago with the publication<sup>1</sup> of Curriculum 68 (computing in 1968 was perhaps ahead<sup>2</sup> 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<sup>3</sup> 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





- 1. Why do we need such a knowledge unit?
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TOOLS AND TECHNIQUES FOR THE SCIENCE UNDERGRADUATE FACULTY





ABSTRACT

- 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?

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

### 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)
  Auth
- 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)

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

| ors: | <u>Marcelo Pias</u> , | <u>Brett Becker</u> , | <u>Qiao Xiang</u> , | 0 | Mohamed Zahran |
|------|-----------------------|-----------------------|---------------------|---|----------------|
|      |                       |                       |                     |   |                |

| Monica Anderson | Authors Info & Claims |
|-----------------|-----------------------|
|                 |                       |

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





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- Security (SEC)
- Society, Ethics and Professionalism (SEP)
- Software Development Fundamentals (SDF)
- Software Engineering (SE)
- Specialized Platform Development (SPD)
- Systems Fundamentals (SF)

### **Architecture and Organization**

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



### Computer Science Curricula 2013

Curriculum Guidelines for Undergraduate Degree Programs in Computer Science

December 20, 2013

The Joint Task Force on Computing Curricula Association for Computing Machinery (ACM) IEEE Computer Society

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.



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?

# 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)



1. Why do we need such a knowledge unit?

2. What does it look like?

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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.



- 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?





Adrian German dgerman@indiana.edu Marcelo Pias Qiao Xiang Xiamen University Federal University of Rio Grande Indiana University Rio Grande, Brazil Xiamen Fujian China Bloomington, Indiana, USA mpias@furg.br xiangq27@gmail.com



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Sixteen years ago, Scott Aaronson remarked (in the presence of Ray Laflamme) that quantum mechanics (QM) resembles an operat ing system on which the rest of Physics is running its application ing system on which the rest of Physics in running in application software (except for general relativity which has not yet been accessfully speed to this particular OS'). Firsts to that, it took variantly to realize that a complete and construct instructions the QM can be given via the language of ophits and quantum gates. Cases to the greense, it is oblig provided initiation chandler physics bases to the green via the language of ophits and quantum gates. Cases to the greense, it is oblig provided initiation chandler physics before the physical tracks and physical values of the sample reversing systems cases blue on build school takens. Reversing systems are at the foundation of Computer Science, they are in fact, as there are very fortunat development. Therefore, a linear to these are very fortunate development. Therefore, a linear CCS CONCEPTS KEYWORDS ACM Reference Format: so these are very fortunate developments. Furthermore, a linea

algebra prerequisite is now shared firmly in the CS undergraduate

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#### curriculum. Such plans have been constructed with a preliminar consultation with QED-C members (industry, academia, national labs, and government agencies) asking for comments, suggestions and general input on these three curricular plans.

 Hardware → Quantum computation. quantum information science, quantum computation, quantum processing unit, undergraduate curriculum, quantum architectures

Service 1

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ACM Reference Format: Addran German, Marcelo Pias, and Qiao Xiang. 2023. On the Design and Implementation of a Quantum Architectures Knowledge Unit for a CS Cur-riculum. In Proceedings of the 54th ACM Technical Symposium on Computer Science Education V. (SIGCSE 2023), March 15–18, 2023. Theoreto, ON Canada. ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3545945.350845

#### INTRODUCTION

algebra perrequisité is now shared firmly in the CS undergradaule curriculum with Machine Learning, a topic that has known a very deep and sudden revival. Quantum Information Science and Tech-nology (QIST) is inherently interdisciplinary and apane physics, computer science, mathematics, engineering, chemistry and mate-rials science. We presend three curricular plans for incorporating QIST topics (via Quantum Computing) into the CS undergraduate

From the outset, we need to distinguish between Quantum Me-chanics (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 inter-disciplinary 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 quantum sensing (ultrasensitive precision measurements), quantum communication, quantum cryptography, materials for quantum in formation and more. Specifically, quantum computing is a type of computation whose operations can harness quantum mechanical whether the sense of t phenomena such as superposition, interference and entanglement

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

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.

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

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.

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

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

**Regulatory** issues



#### On the Design and Implementation of a Quantum Architectures **Knowledge Unit for a CS Curriculum** Marcelo Pias Federal University of Rio Grande

Rio Grande, Brazil

Adrian German

dgerman@indiana.edu

Indiana University

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.

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

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

Quantum Internet concepts



Figure 1: Schematic overview of the three curricular plans with specific sample instantiati ABSTRACT

curriculum. Such plans have been constructed with a prelimination of the second s ansultation with OED-C members (industry academia natio Sixteen years ago, Scott Aaronson remarked (in the presence o Ray Laflamme) that quantum mechanics (QM) resembles an operat ing system on which the rest of Physics is running its application and general input on these three c ing 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'). Prior to that, it took the insight of an educator and eminent computer scientist (Umesh Varirani) to realize that a complete and consistent infroduction to QM can be given via the language of qubits and quantum gates. CCS CONCEPTS Hardware → Quantum computation KEYWORDS Closer to the present, it took the profound intuition of another poly math (Terry Rudolph) to realize that the linear algebra normally at quantum information science, quantum computation, quantu math (ferry Rudolph) to realize that the linear algebra normally at the foundation of such an approach can be replaced with a simple rewriting system accessible to middle school students. Rewriting systems are at the foundation of Computer Science, they are, in fact the very fabric of it (e.g., Turing machines and lambda calculus) ssing unit, undergraduat

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Qiao Xiang Xiamen University

Xiamen Fujian China

1 (SIGCSE 2023), March 15-18, 2023, Toronto, ON, Canad algebra prerequisite is now shared firmly in the CS undergraduat Science Education V. 1 (SIGCSE 2023), March 15–18, 2023, 107 ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/ algebra prerequisite is now shared firmly in the CS undergraduate curriculum with Machine Learning, a topk that has known a very deep and sudden revival. Quantum Information Science and Tech-nology (QIST) is inherently interdisciplinary and spans physics, computer science, mathematics, engineering, chemistry and mate-rials science. We present three curricular plans for incorporating INTRODUCTION

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- Understand that a quantum object (a) is produced as a particle, (b) propagates like a wave, 58.75 and (c) is detected as a particle with a probability distribution that corresponds to a wave.
- 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 72.50 no way to use quantum entanglement to send messages faster than the speed of light.
- 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
- Understand the power and idiosyncrasies of quantum communication. 31.256.
- 7. Understand the power of quantum parallelism and the role of constructive vs destructive 56.25 interference in quantum algorithms given the probabilistic nature of measurement(s).
- 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 78.75
- 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
- 21.25 12. Understand phase inversion and inversion around the mean in Grover's algorithm.
- 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, 32.50 topological, color center, electron-on-helium, etc.).
- 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







Figure 1: Schematic overview of the three curricular plans with specific sample instantiation ABSTRACT

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Hardware → Quantum computation.

KEYWORDS quantum information science, quantum computation, quantur

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Scores are in the range [-100, 100]

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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)

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.

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

Quantum Internet (Nitrogen Vacancy Centers or other transportation techniques)



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.

Native quantum language fluency.



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





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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.

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.





- 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?



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

### 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. Crosscampus, 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].



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 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





### IBM Quantum



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

### ACKNOWLEDGMENTS

This work was done as part of CS2023: ACM/IEEE-CS/AAAI Computer Science Curricula (csed.acm.org). We thank the other members of the Architecture and Organization (AR) Knowledge Area Committee for feedback and support. Thanks also to Prof. Anthony Laing from the Quantum Engineering Technology center at the Univ of Bristol and Michael Biercuk from the Univ of Sydney and Q-CTRL as well as Zlatko Minev and Thomas George McConkey from IBM Quantum for conversations on some of the topics discussed in this paper. Doug Finke and Charles Robinson from the QED-C Workforce TAC helped us calibrate the survey and collect the input from the QED-C members. QED-C is a broad international group of stakeholders from industry, academia, national labs and professional organizations that aims to enable and grow the quantum industry and its associated supply chain. QED-C was established with support from NIST as part of the federal strategy for advancing QIST as per the National Quantum Initiative Act in 2018.









Adrian German dgerman@indiana.edu Indiana University Bloomington, Indiana, USA Marcelo Pias Federal University of Rio Grande Rio Grande, Brazil mpias@furg.br Qiao Xiang Xiamen University Xiamen, Fujian, China xiangq27@gmail.com

1 ANK

### 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 <u>self-esteem should not be a goal</u>, <u>but rather</u> a result (or <u>a consequence</u>), 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.

