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SIGCSE TS 2024 Submission 917

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Submission Information

Submission 917	
Title	A Quantum Abacus for Teaching Quantum Algorithms

Track	Workshops
Author keywords	quantum algorithms string rewriting systems computational thinking
Topics	ACM/IEEE-CS/AAAI Computer Science Curricula, Algorithms, Computational Thinking, CSforAll, Discrete Mathematics
Abstract	At the time of this writing more than 60 (sixty) companies in the world are building quantum computers. The natural language of their quantum gates is that of linear algebra in a complex (Hilbert) vector space. Since 2017 it is known that it is possible to replace the linear algebra with some string-rewriting rules which are no more complicated than the basic rules of arithmetic. The original system was introduced by Terry Rudolph and has been promoted and disseminated in large-scale outreach projects (among others) by Diana Franklin (University of Chicago) and Sofia Economou and Ed Barnes (Virginia Tech) as well as several other educators at the high-school level. In this tutorial we show how a slightly modified (though still very elementary) system can be used to communicate a visual and entirely operational understanding of key quantum computation concepts such as: superposition, probability, entanglement, phase, interference and unitary state evolution, as they occur in well-known quantum algorithms. Examples include the phase kickback phenomenon, teleportation, and the well known Deutsch-Josza, Bernstein-Vazirani and Grover algorithms along with the GHZ game. We work out concrete examples of proving properties for quantum gates and quantum circuits without resorting at all to complex numbers or matrix multiplication. Only simple, abacus-like operations are used--hence the title of the tutorial. We show how this approach can create a genuine bridge to the mathematics of quantum computation, that is, of vector and tensor algebras in complex spaces for students who may have little or no proper mathematical background.
Submitted	Aug 19, 04:48 GMT
Last update	
Designated Reviewer	dgerman@indiana.edu
ACM Authorship Policy	In 2021 the ACM Board of Education has teamed up with the QED-C Workforce Development TAC and has developed (for the first time ever and over a period of 18 months) a Quantum Architectures Knowledge Unit for CS2023. The paper was presented at SIGCSE 2023: https://dl.acm.org/doi/pdf/10.1145/3545945.3569845 In November 2022 we asked the QED-C members (industry, academia, national labs, and government agencies) to comment on the proposed competency-based curricular plans along with the selected topics and learning outcomes. The analysis was communicated at ITiCSE 2023. https://legacy.cs.indiana.edu/~dgerman/2023/materials/V2itipp417-german.pdf It presented three different curricular maps (aimed for distinct, different instructional purposes) representing the core of our SIGCSE 2023 proposal which was itself the result of a task force working closely with a loosely selected (and somewhat fluid) focus group of experts. We propose a tutorial session at SIGCSE 2024 structured (as a workshop) around the shortest of these three curricular maps (and suitable for an eight weeks, half-semester class) that offers a complete and entirely operational approach to teaching quantum computation concepts using only rules of elementary, basic arithmetic. A shorter version of this workshop (one hour) is being presented at QSEEC 2023 during the IEEE Quantum Week Conference (09/17-22/2023, Bellevue, WA): https://legacy.cs.indiana.edu/~dgerman/2023/qseec/outline.pdf The core paper is being presented at FIE 2023 in October (College Station, TX): https://legacy.cs.indiana.edu/~dgerman/2023/qseec/proposal.pdf Two more papers are in development (one co-authored with Terry Rudolph): https://legacy.cs.indiana.edu/~dgerman/2023/qseec/ghz-game-with-misty-states.pdf https://legacy.cs.indiana.edu/~dgerman/2023/qseec/ghz-game-in-black-and-white.pdf One more paper dedicated to Grover's algorithm is also being worked on.
Research Involving Human Participants and Subjects	This work does not directly involve human participants.
Human Subjects - More Details	
Context	If you have tried teaching yourself (or others) the basics of Quantum Computing (or Quantum Information Science) using one of the many already available wonderful textbooks (e.g., by McMahon, Kaye Laflamme and Mosca, Mermin, Nielsen and Chuang, Rieffel and Polak, and others) only to feel overwhelmed by the mathematical apparatus (or just its syntax), then this workshop is for you. In just three hours we outline an approach and a curriculum for an eight weeks long class, that acts as a bridge to the standard quantum computation curriculum in which the math starts to feel supportive, organic and helpful, instead of oppressive. We should stress here that, in our view, there is nothing wrong with mathematics; mathematics by itself is not oppressive. We use mathematics to help describe things going on in the physical world around us. To a physicist, the math is an inextricable part of our understanding. Unfortunately, not everyone is good at mathematics, and most have little, if any, training in physics. The abacus operations you will see and learn during the workshop are indeed mathematics. They are symbols on paper that we manipulate according to fixed rules. But the rules are elementary. To get the most out of this workshop we will provide three things: a free copy of "Q is for Quantum" by Terry Rudolph, complete set of papers and worksheets developed for this workshop, and links to Quantum Country (as an example of standard material taught in an introductory quantum

	computation course) and Martin LaForest's excellent booklet prepared for young (high-school) students enrolled in summer programs at IQC Waterloo in Ontario, Canada (as a most meritorious example and useful reference of how one might try introducing the actual mathematical concepts needed for a standard class). We will then proceed to show you how one can use Terry Rudolph's rewriting system (which we call the "Quantum Abacus") to guide their students to the place where we would all like them to be, no less, but going through a stage where they would feel indeed that they "really understand" what our mathematics "means" in terms of stuff that goes on in the physical world.
Agenda	-----(First hour: Basic Tools) Bits + superposition = qubits. Phase and interference. One-qubit gates. Two qubits and entanglement. Two qubit gates. -----(Second hour: Quantum Circuits) Quantum circuits. Phase kickback phenomenon. Quantum teleportation. -----(Third hour: Famous Algorithms and Non-Locality) Deutsch-Josza Bernstein-Vazirani Grover's algorithm The GHZ Game (entanglement as "quantum telepathy")
Activities	Participants will receive free copies of "Q is for Quantum" the book by Terry Rudolph and a complete set of worksheets based on the papers that describe the content and rationale for this tutorial, along with the papers themselves. The goal for the tutorial being for the participants to leave with a working knowledge of the main ideas behind this approach and materials that can be used directly in the classroom, our tutorial will be structured following the principles of active and team-based learning. Participants will be organized in groups using an approach developed about 10 years ago by the first author and presented at ITiCSE 2013: https://legacy.cs.indiana.edu/~dgerman/2023/materials/2462476.2466516.pdf The teams will work together through scaffolded challenges designed to illustrate the following successive stages and concepts: one qubit gates, phase and superposition; destructive and constructive interference; two qubit gates and entanglement; the phase kickback phenomenon; the teleportation protocol; early quantum algorithms (Deutsch-Josza, Bernstein-Vazirani, Grover's); and non-locality (the GHZ game). Since there is no way to effectively flip a classroom that meets only once (as is the case with the session that we are proposing) we will try to offer the next best thing by guiding the participants through a sequence of examples that they need to complete following another methodology developed for a similar purpose and presented at ECEL (10th European Conference on e-Learning) in 2011. https://legacy.cs.indiana.edu/~dgerman/ecel2011/dgermanPaper.pdf The session will indeed be coordinated by us using slides; however, the goal is to just act a catalyst and following the principles of active learning, we'll strive to be mostly "a guide on the side" rather than "the sage on the stage".
Workshop Leadership	We had a very successful pre-symposium event at SIGCSE 2020: https://legacy.cs.indiana.edu/~dgerman/quantum-computing-for-undergrads/videos.html Right when our event ended the conference was canceled. Story here: https://legacy.cs.indiana.edu/~dgerman/quantum-computing-for-undergrads/tcNickolas.html In 2022 the second and third authors organized another very successful event: https://dl.acm.org/doi/10.1145/3478432.3499201 We now focus on qualifications and background for the first author. Dan-Adrian German is a Senior Lecturer in Computer Science with the Luddy School of Informatics, Computing and Engineering at Indiana University (IU)in Bloomington. At IU he is the recipient of several teaching awards at the departmental and university level; his interests include learner-sighted teaching practices and maker-centered learning. He is also Acting Organizing (and Outreach) Manager and Industry Liaison for the Indiana University Quantum Science and Engineering Center. In 2021 he served as Chair for the Technical Advisory Committee (TAC) on Workforce Development in the Quantum Economic Development Consortium (QED-C). Since 2022 he is a member of the ACM/IEEE-CSCI/AAAI CS2023 Curricular Guidelines and a Faculty Advisor to the new Self-Governed IUB Student Organization "Quantum Technologies for Everyone" (QuTE). He is the organizer of several successful symposia and conference workshops and has had presentations at various national and international conferences (SIGCSE, SIGITE, ITiCSE, ISSOTL, FIE, ECEL, QSEEC and others). In 2021 he was the organizer and co-chair of the Q2E Track at Q2B 2021, in Santa Clara, California. He remains active in the QED-C Workforce TAC where he continues to be the organizer of the Quantum Talent Showcase bi-monthly sessions and has co-authored "Assessing the Needs of the Quantum Industry" a paper1 published in the IEEE Transactions on Education last year (2022). The Quantum Economic Development Consortium (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.
Audience	Undergraduate Computer Science Faculty including HS teachers
Expected Capacity	30
Workshop Room	Round tables with chairs for all

Setup	
Special Equipment Needs	We still need to coordinate the workshop via Powerpoint slides on a projector (so please provide that in the room) but it's crucial for participants to be able to work together in teams at tables in a team-based learning (TBL) context.
Participant Laptop Requirements	Laptop Not Required
Prior Workshop Experience	As I said a one-hour long version of this workshop is being offered (on Sep 17, 2023) at The 2nd Quantum Science and Engineering Education Conference (QSEEC) 2023
Modality	I would prefer to offer this workshop twice, once in-person and once online; if I am only selected for one modality, I would prefer in-person
Advertisement	If you have tried teaching yourself (or others) the basics of Quantum Computing (or Quantum Information Science) using one of the many already available wonderful textbooks only to feel overwhelmed by the mathematical apparatus (or just its syntax) then this workshop is for you. In just three hours we outline an approach and a curriculum for an eight weeks long class, that acts as a bridge to the standard quantum computation curriculum but in which the math starts to feel supportive, organic and helpful, instead of oppressive. We should stress here that, in our view, there is nothing wrong with mathematics; mathematics by itself is not oppressive. We use mathematics to help describe things going on in the physical world around us. To a physicist, the math is an inextricable part of our understanding. Unfortunately, not everyone is good at mathematics, and most have little, if any, training in physics. We give concrete examples of proving properties for quantum gates and quantum circuits (and describe completely well-known, fundamental quantum algorithms) without resorting at all to complex numbers or matrix multiplication. Yet the abacus operations you will see and learn during the workshop are indeed mathematics (albeit extremely elementary). They are symbols on paper that we manipulate according to fixed rules. We will provide three things: free copies of "Q is for Quantum" by Terry Rudolph, complete printed set of papers and worksheets developed for this workshop, and links to Quantum Country (as an example of the standard material taught in an introductory quantum computation course) and Martin LaForest's excellent booklet prepared for young (high-school) students enrolled in summer programs at IQC Waterloo in Ontario, Canada (as a reference). We will then proceed to show you how one can use Terry Rudolph's rewriting system (which we call the "Quantum Abacus") to guide their students to the place where we would all like them to be, no less, but going through a stage where they would feel indeed that they "really understand" what our mathematics "means" in terms of stuff that goes on in the physical world.
Author conflicts	none

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