Teaching Quantum Theory with a Compositional Lens

Experimental Evidence Supporting the Effectiveness of Quantum Picturalism

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Thirteenth Symposium on Compositional Structures (SYCO 13)
London, UK
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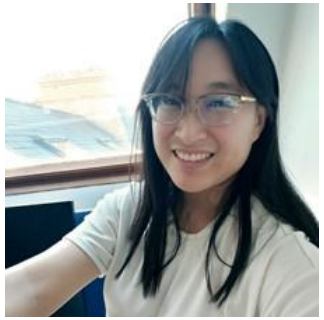
QUANTINUUM UNIVERSITY OF OXFORD IBM Quantum

The Team



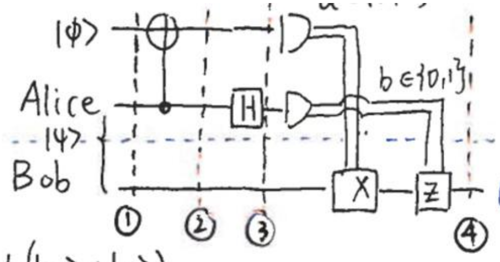









How quantum teleportation is typically taught



$|\phi\rangle^{(1)} = \frac{1}{2\sqrt{2}}(|00\rangle+|11\rangle)(\alpha|0\rangle+\beta|1\rangle) + \frac{1}{2\sqrt{2}}(|00\rangle-|11\rangle)(\alpha|0\rangle-\beta|1\rangle) +$

$\frac{1}{2\sqrt{2}}(|01\rangle+|10\rangle)(\alpha|1\rangle+\beta|0\rangle) + \frac{1}{2\sqrt{2}}(|01\rangle-|10\rangle)(\alpha|1\rangle-\beta|0\rangle)$

$|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle+|11\rangle)$

$|\phi\rangle = \alpha|0\rangle+\beta|1\rangle, \ \alpha, \beta \in \mathbb{C}$

Time slice ① $|\phi\rangle|\psi\rangle = (\alpha|0\rangle+\beta|1\rangle)\otimes\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle) = \frac{\alpha}{\sqrt{2}}|000\rangle + \frac{\alpha}{\sqrt{2}}|011\rangle + \frac{\beta}{\sqrt{2}}|100\rangle + \frac{\beta}{\sqrt{2}}|111\rangle \quad (1)$

Time slice ② $(CNOT_{21}\otimes I)|\phi\rangle|\psi\rangle = \frac{1}{2\sqrt{2}}(|00\rangle+|01\rangle)(\alpha|0\rangle+\beta|1\rangle) + \frac{1}{2\sqrt{2}}(|00\rangle-|01\rangle)(\alpha|0\rangle-\beta|1\rangle) +$

$\frac{1}{2\sqrt{2}}(|11\rangle+|10\rangle)(\alpha|1\rangle+\beta|0\rangle) + \frac{1}{2\sqrt{2}}(|11\rangle-|10\rangle)(\alpha|1\rangle-\beta|0\rangle)$

$= \frac{1}{2}|0\rangle|+\rangle(\alpha|0\rangle+\beta|1\rangle) + \frac{1}{2}|0\rangle|-\rangle(\alpha|0\rangle-\beta|1\rangle) + \frac{1}{2}|1\rangle|+\rangle(\alpha|1\rangle+\beta|0\rangle).$

$-\frac{1}{2}|1\rangle|-\rangle(\alpha|1\rangle-\beta|0\rangle) \quad = |\delta\rangle$

Time slice ③ $(I\otimes H\otimes I)|\delta\rangle = \frac{1}{2}|0\rangle|0\rangle(\alpha|0\rangle+\beta|1\rangle) + \frac{1}{2}|0\rangle|1\rangle(\alpha|0\rangle-\beta|1\rangle + \frac{1}{2}|1\rangle|0\rangle(\alpha|1\rangle+\beta|0\rangle) \ \frac{1}{2}|1\rangle|1\rangle(\alpha|1\rangle-\beta|0$

Time slice ④: Case 1: $\langle 00|$ Outcome $\begin{cases} a=0 \\ b=0 \end{cases}$ $Z^0X^0(\alpha|0\rangle+\beta|1\rangle) = |\phi\rangle.$

Case 2: $\langle 01|$ Outcome $\begin{cases} a=0 \\ b=1 \end{cases}$ $Z^1X^0(\alpha|0\rangle-\beta|1\rangle) = \alpha|0\rangle+\beta|1\rangle = |\phi\rangle$

Case 3: $\langle 10|$ Outcom $\begin{cases} a=1 \\ b=0 \end{cases}$ $Z^0X^1(\alpha|1\rangle+\beta|0\rangle) = \alpha|0\rangle+\beta|1\rangle = |\phi\rangle$

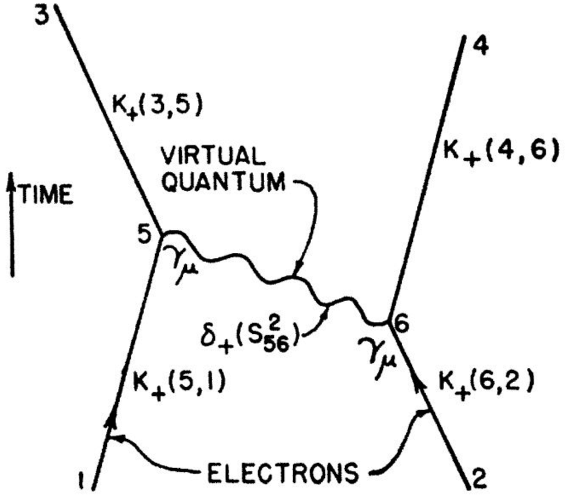
Case 4: $\langle 11|$ Outcome $\begin{cases} a=1 \\ b=1 \end{cases}$ $Z^1X^1(\alpha|1\rangle-\beta|0\rangle) = \alpha|0\rangle+\beta|1\rangle = |\phi\rangle$

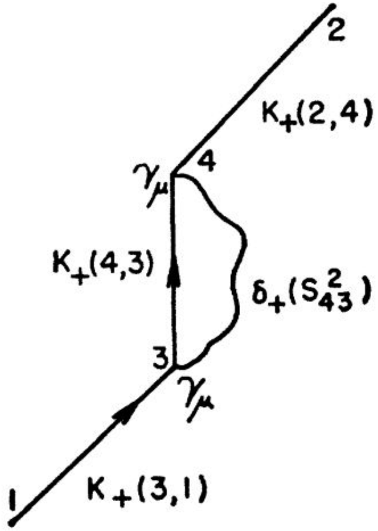
A master's student's notes on quantum teleportation in a graduate course

Physics done with diagrams

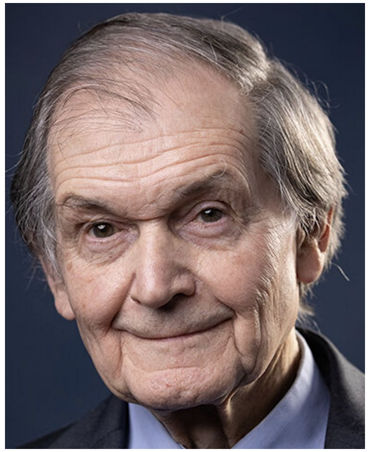
Richard Feynman

1965 Nobel Prize in Physics for
“contribut[ing] to creating a new
quantum electrodynamics by
introducing Feynman diagrams”



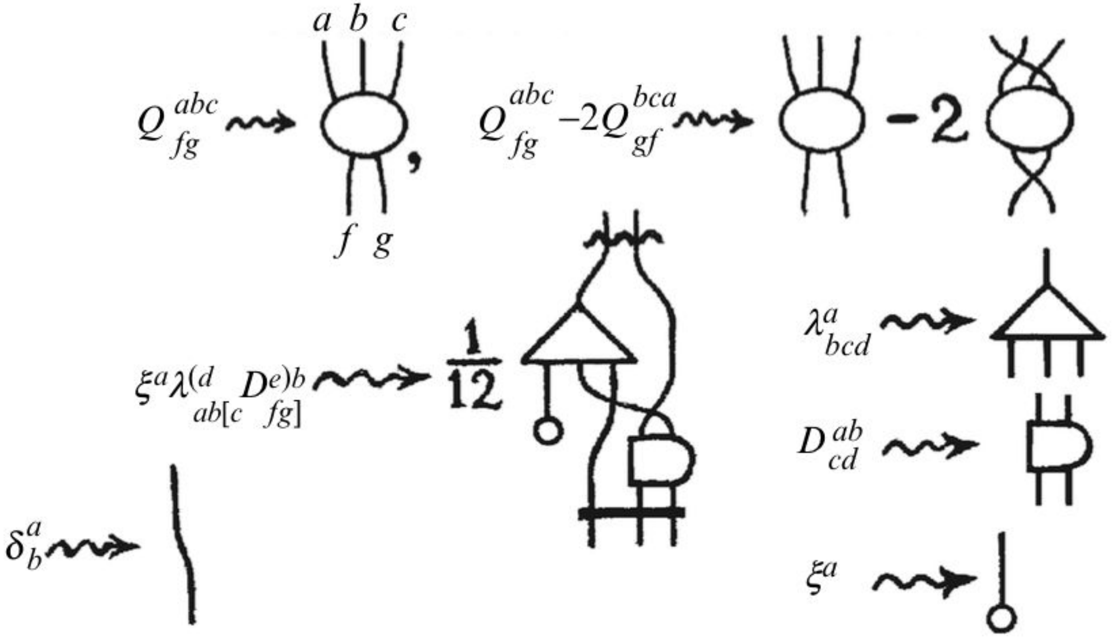


Physics done with diagrams

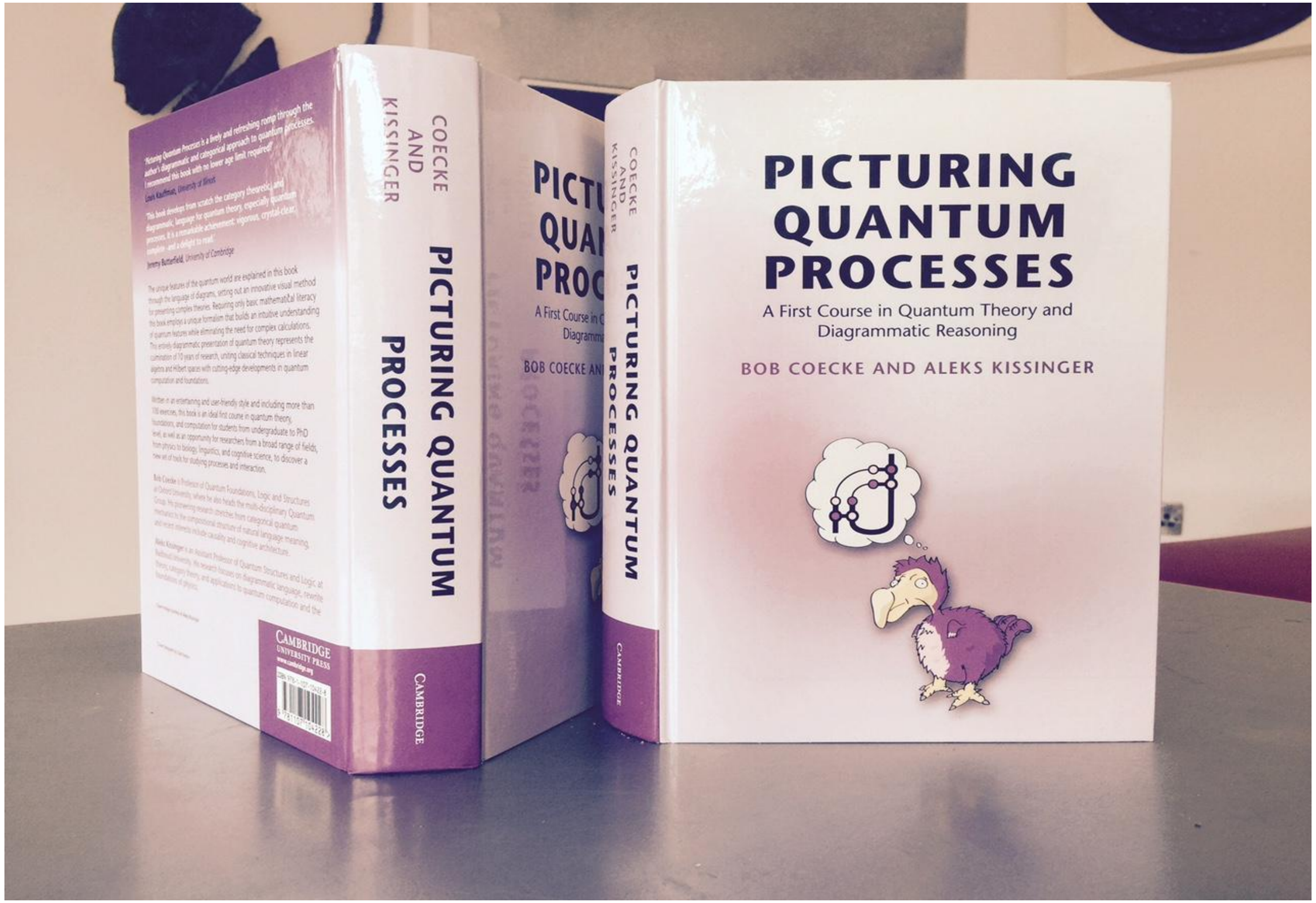


Roger Penrose

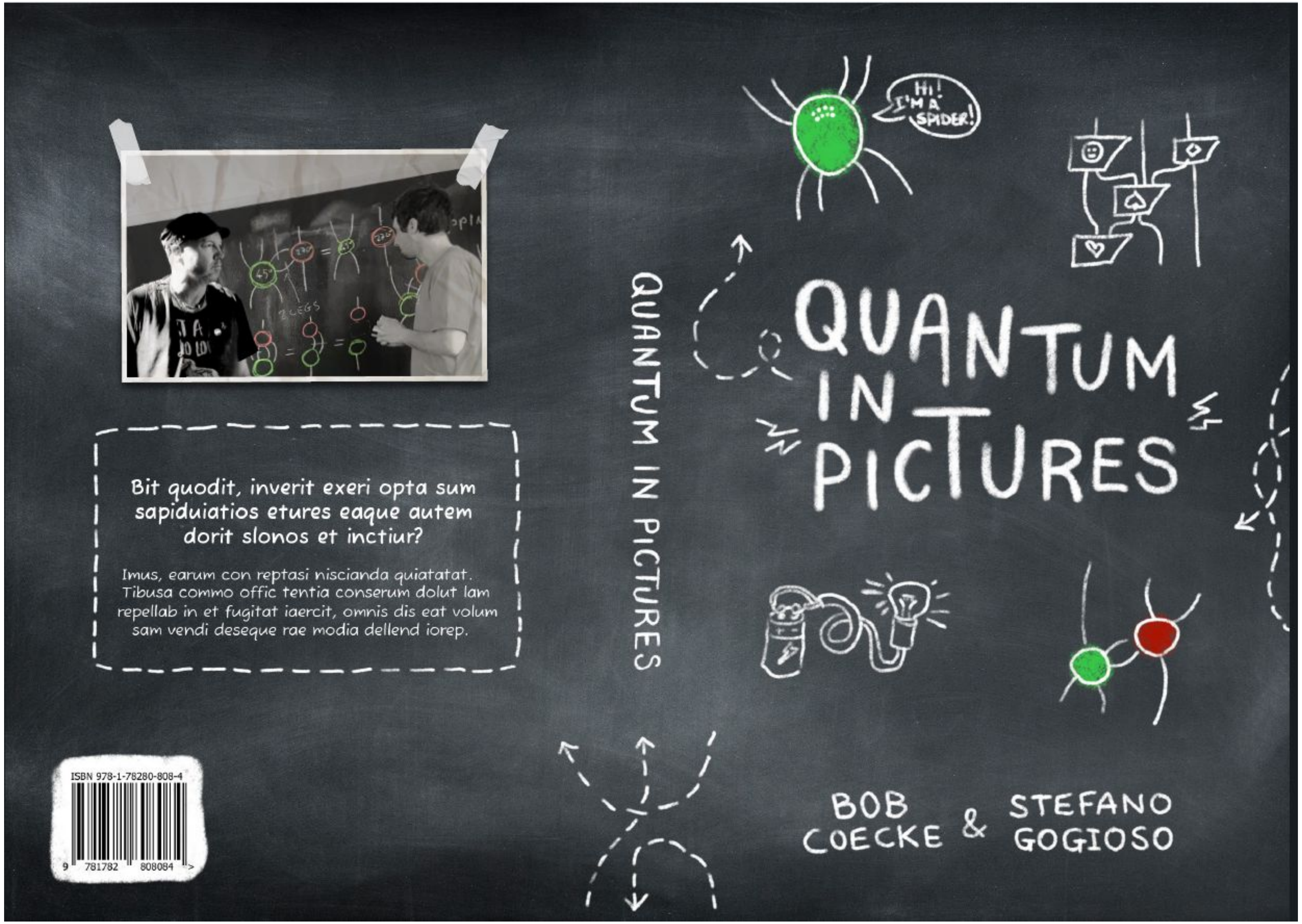
2020 Nobel Prize in Physics for "propos[ing] critical mathematical tools to describe black holes"



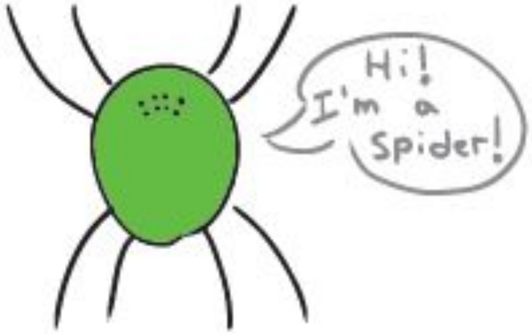
The “dodo book”

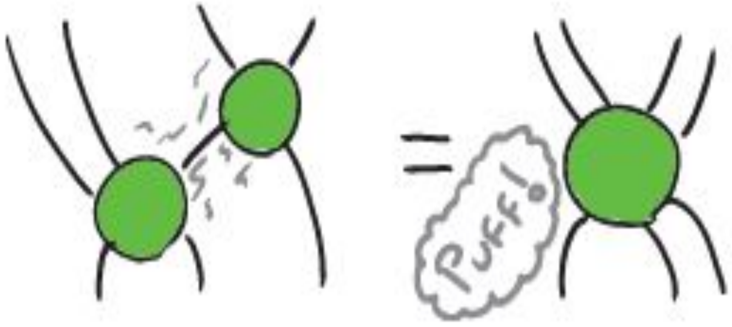


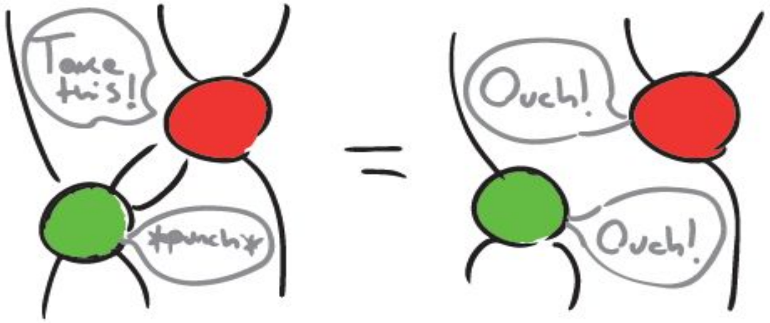
A textbook for all ages



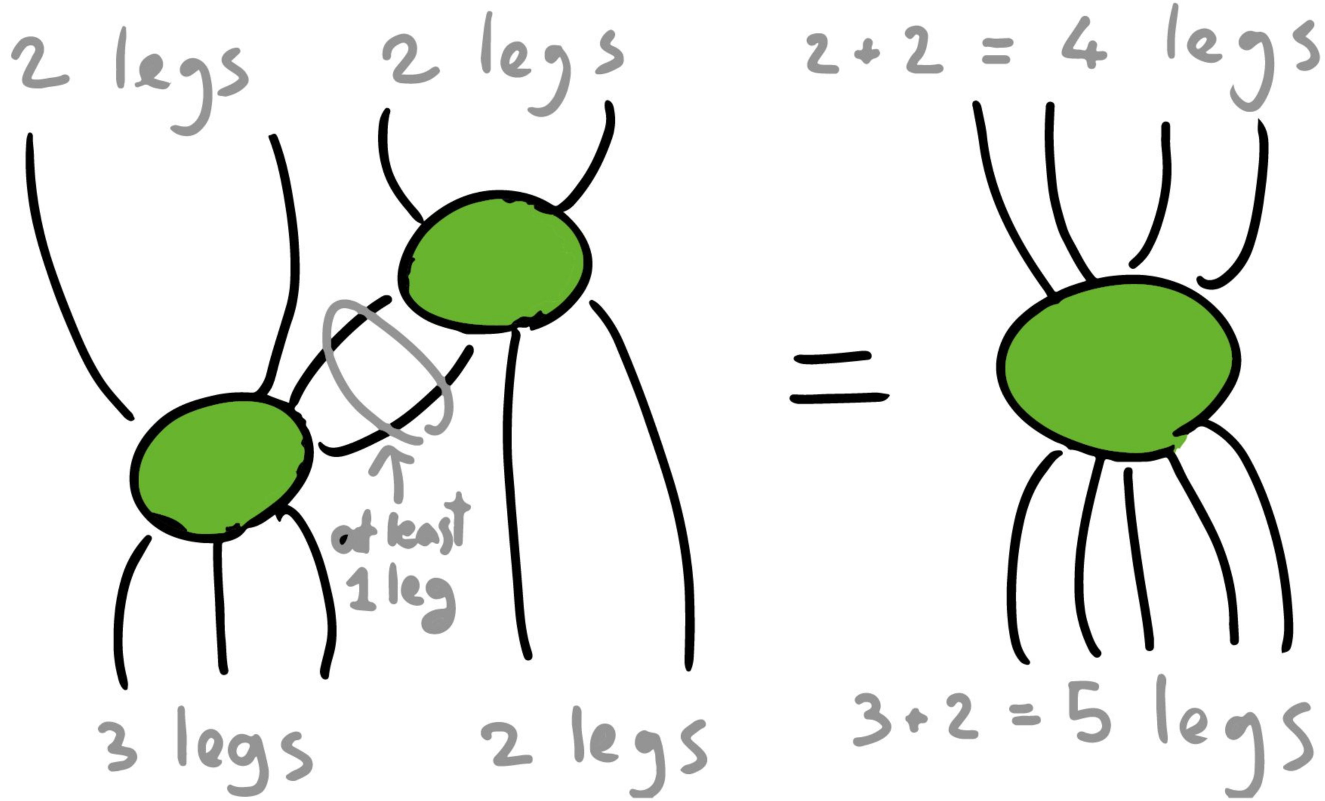
What's in the book?



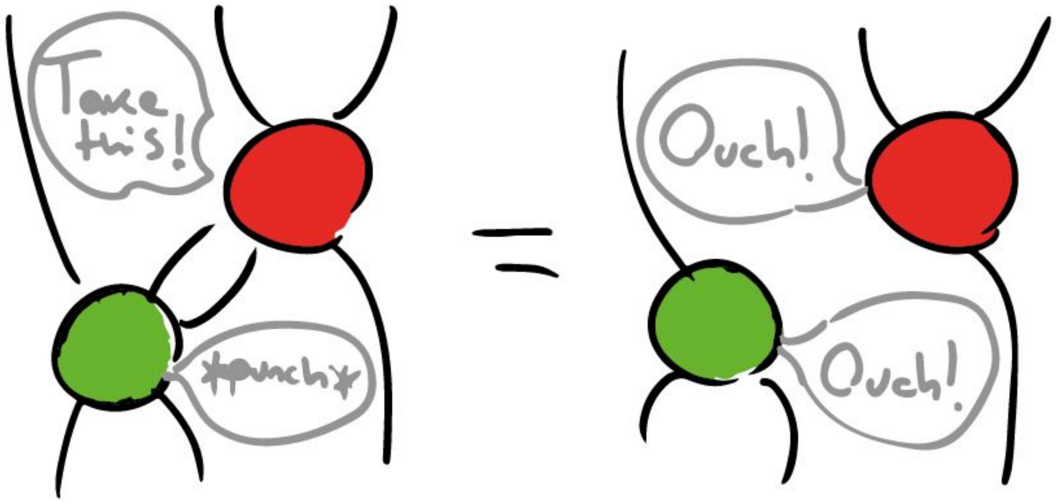




Spider Fusion



Leg-chopping



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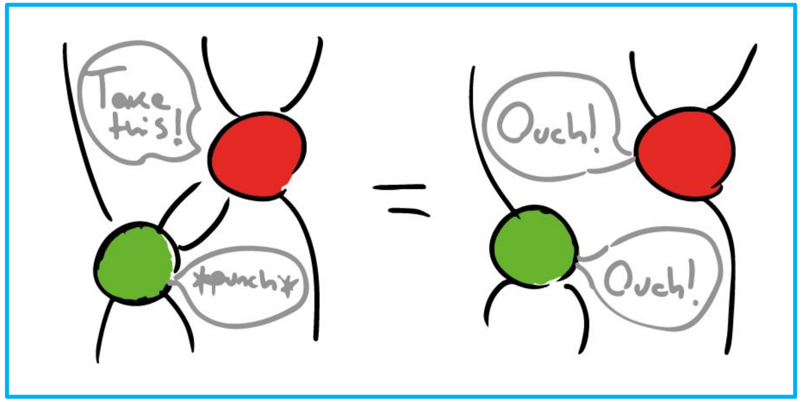

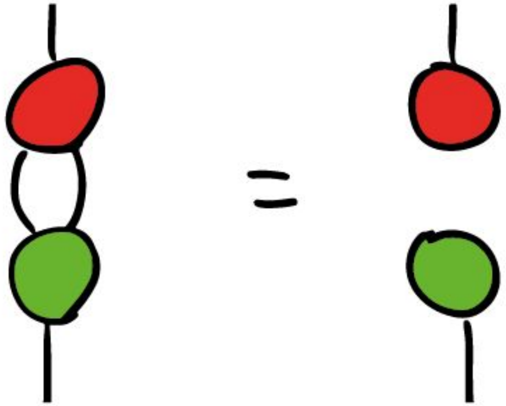

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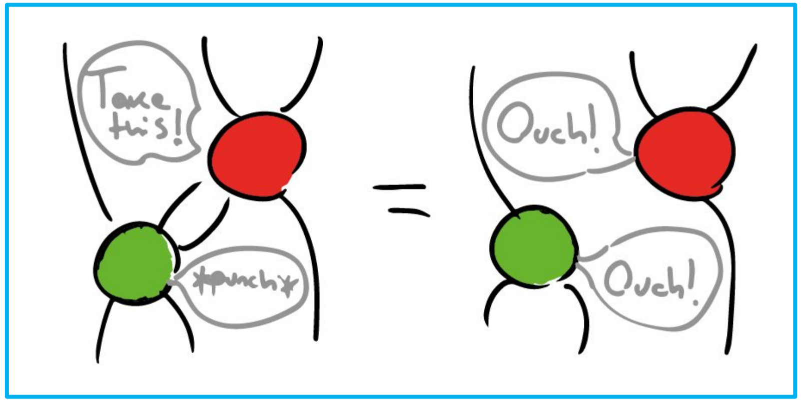
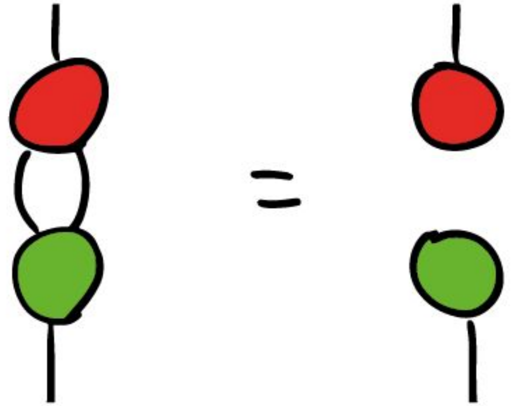
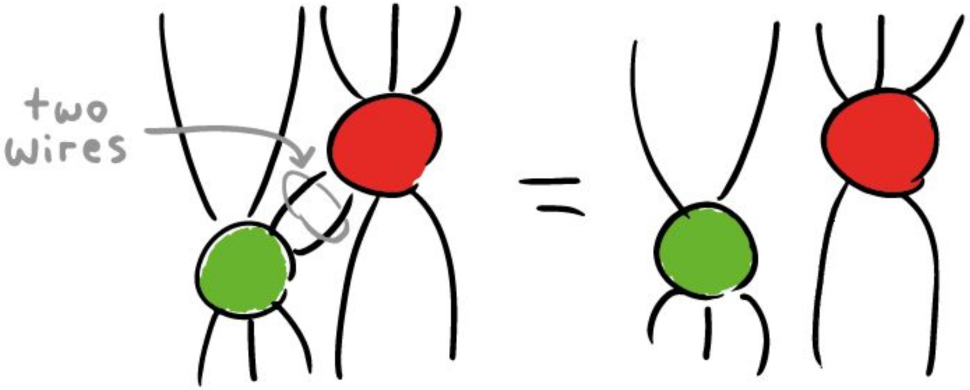
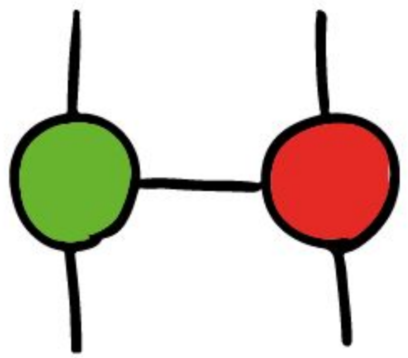


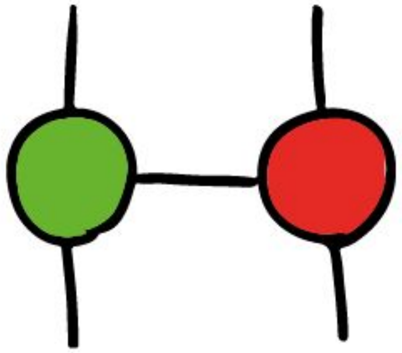


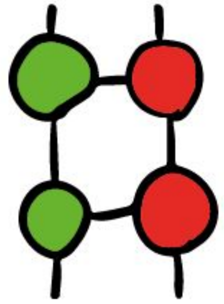


CNOT Gate



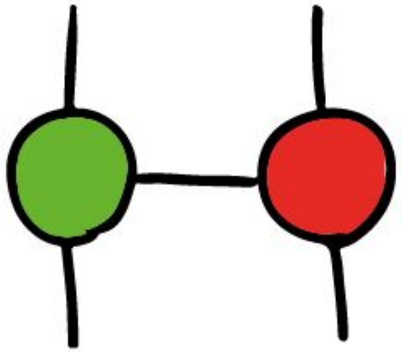
CNOT Gate

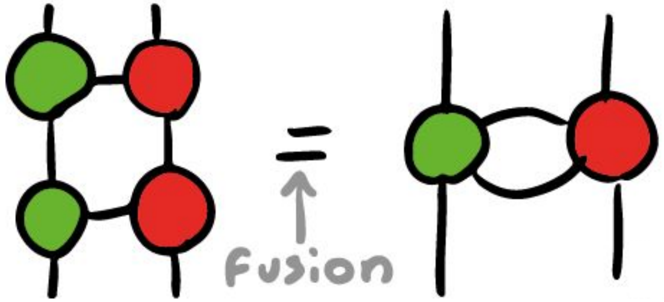




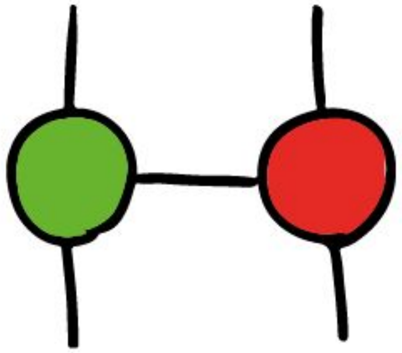
<- What happens if we apply the CNOT gate twice in a row?

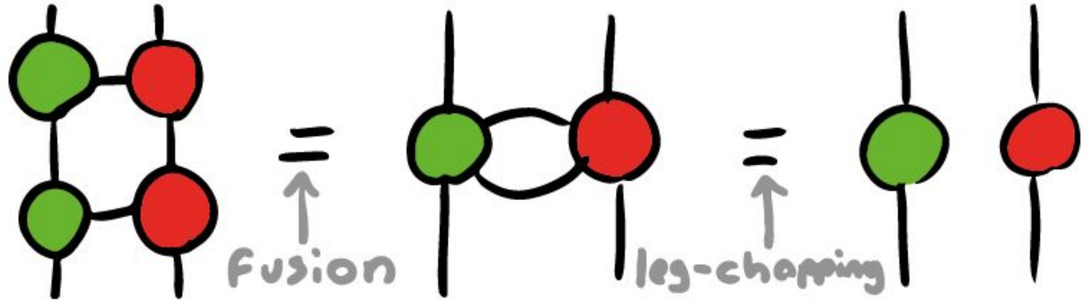
CNOT Gate



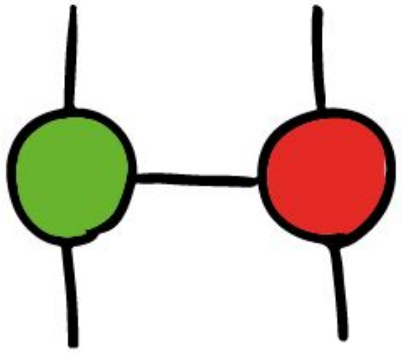


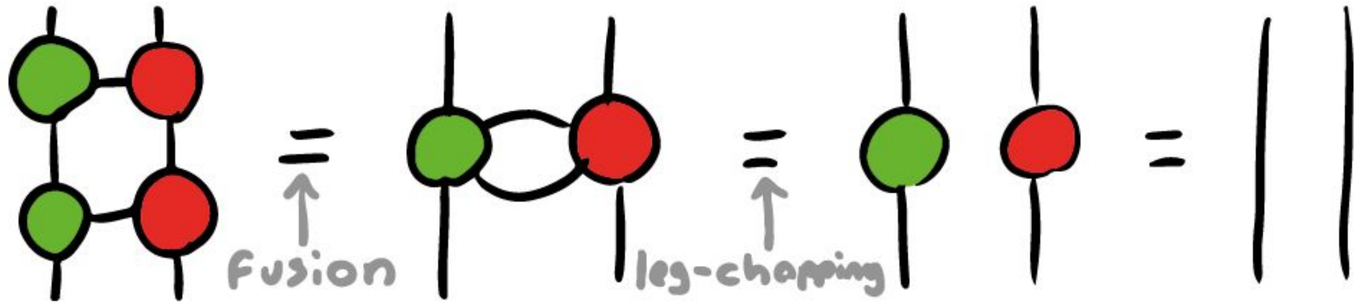
CNOT Gate



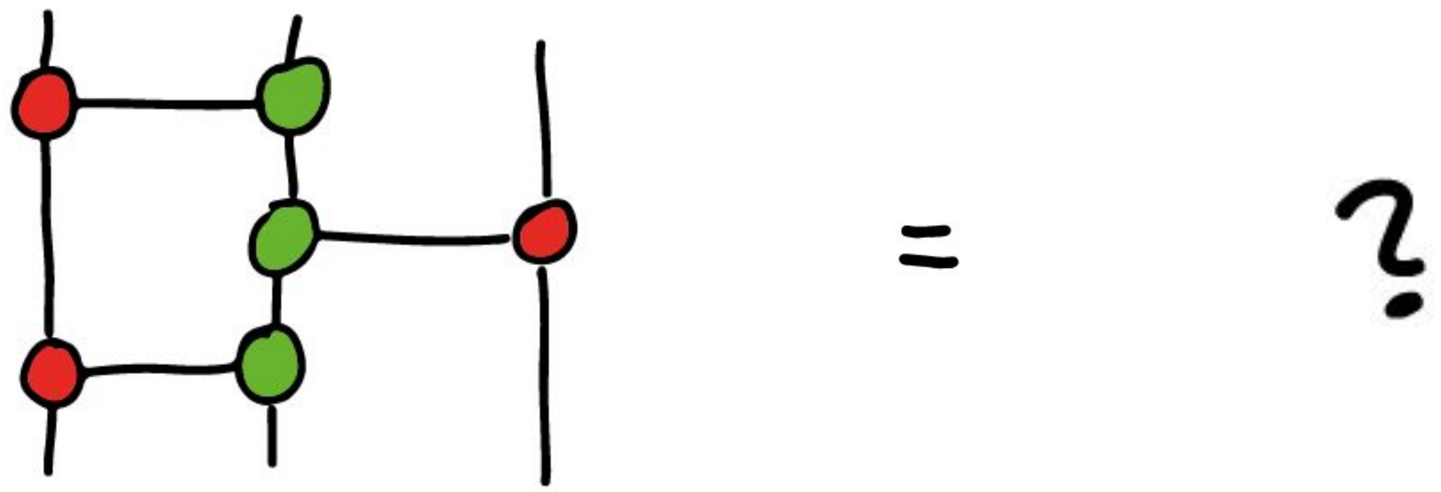


CNOT Gate

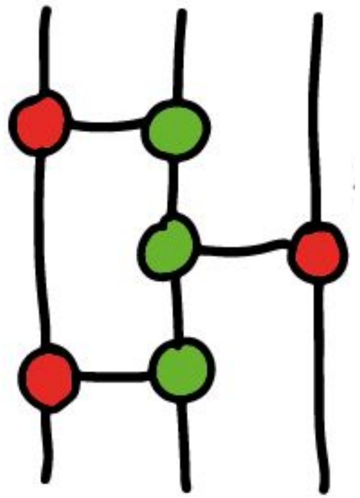




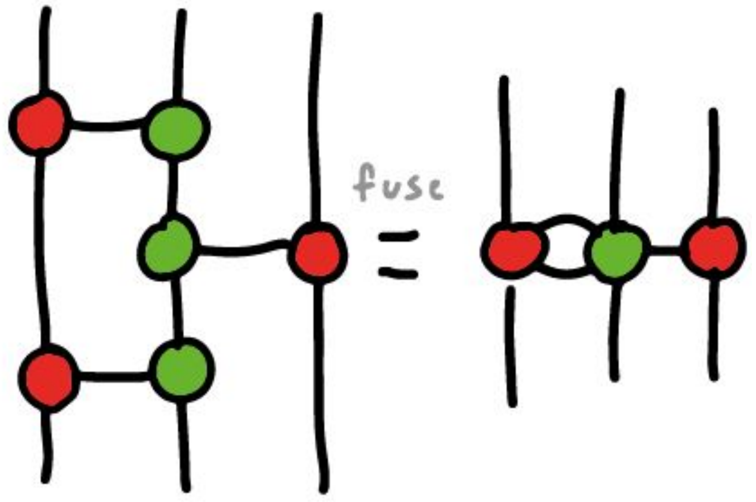
Simplifying a Quantum Circuit



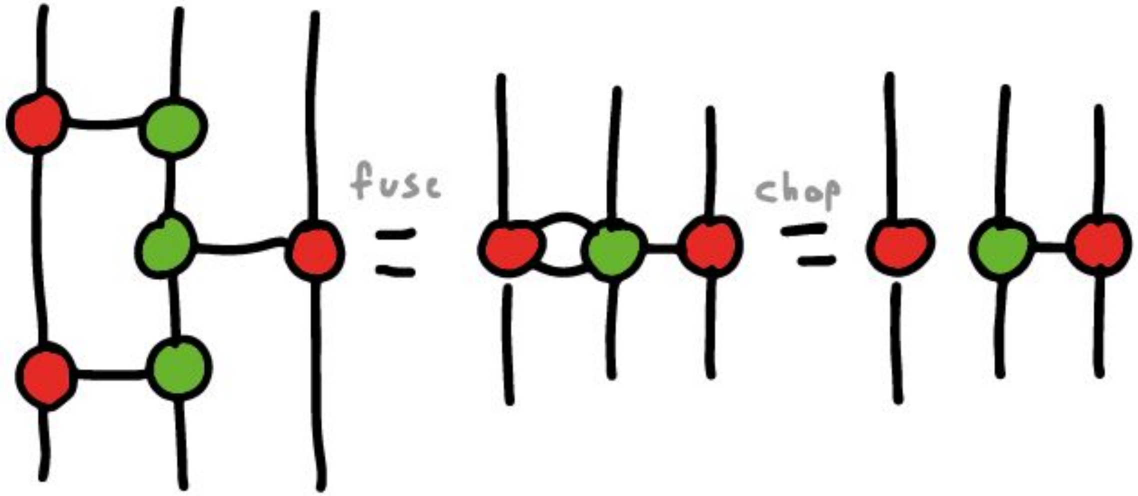
Simplifying a Quantum Circuit



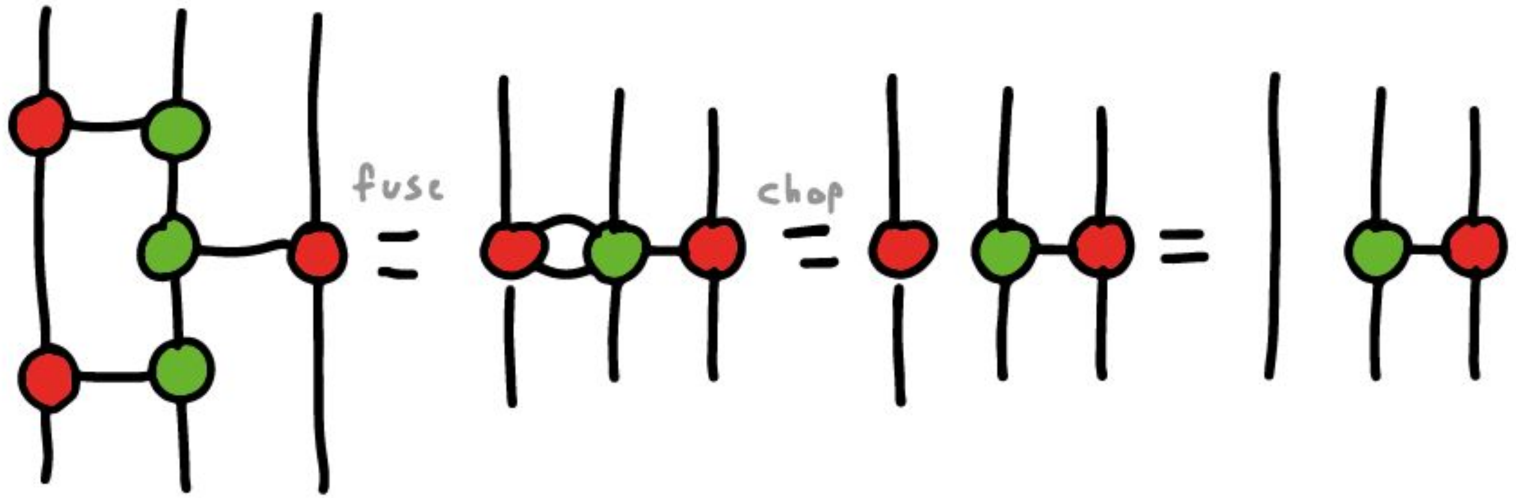
Simplifying a Quantum Circuit



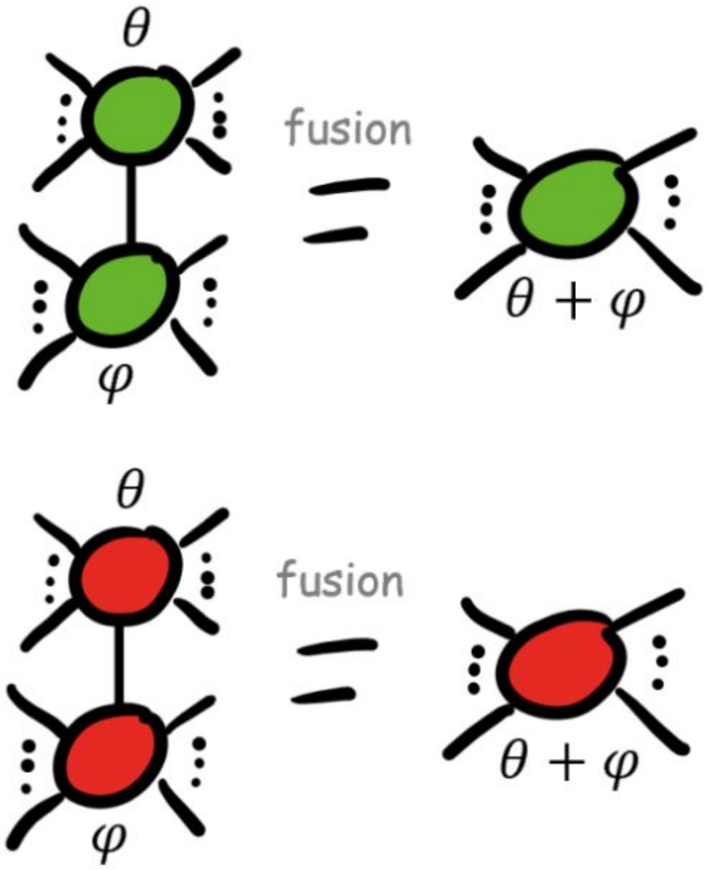
Simplifying a Quantum Circuit

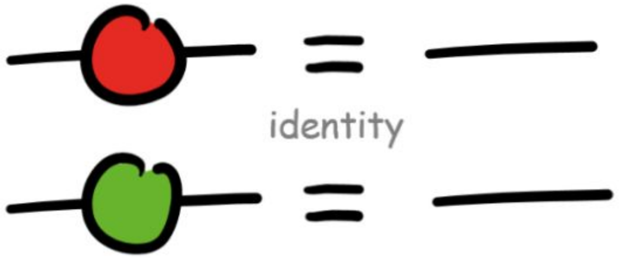


Simplifying a Quantum Circuit

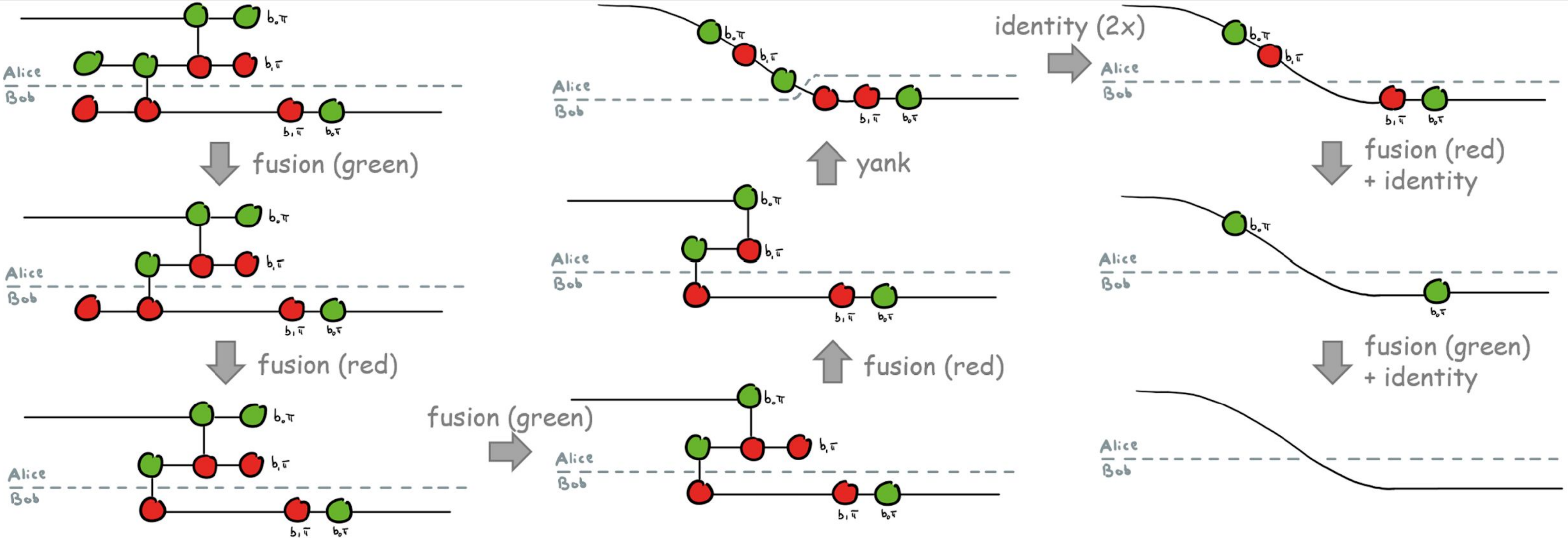


Two Rules

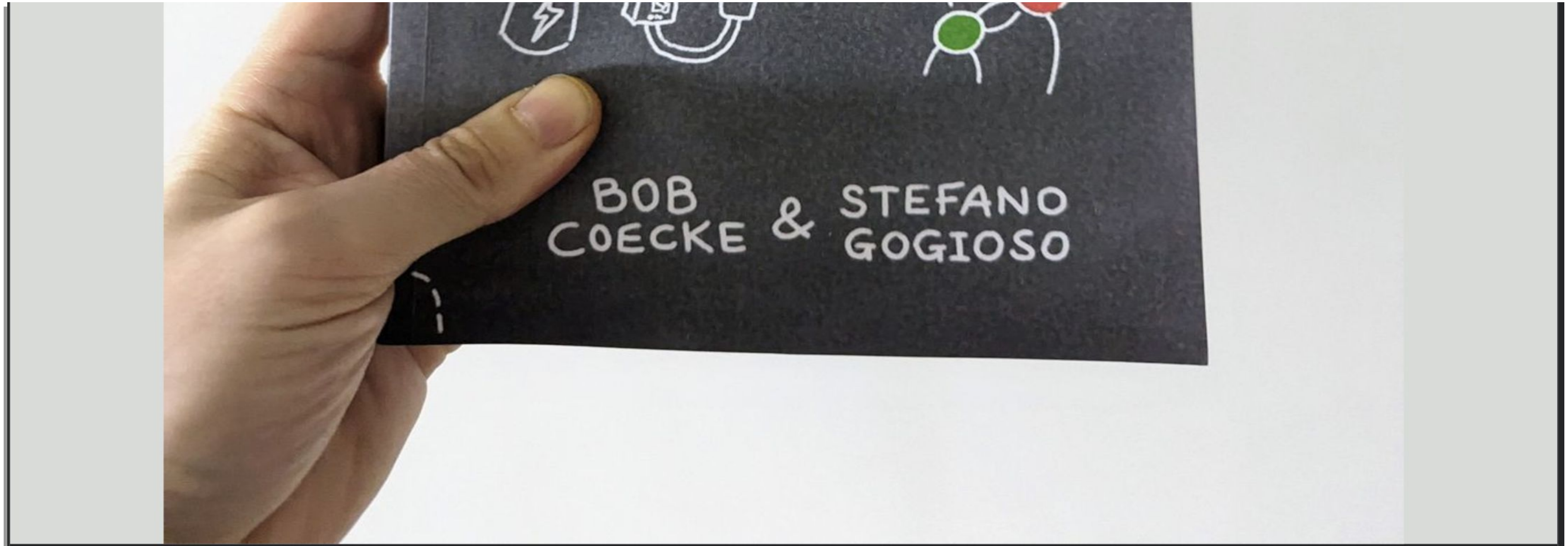




Quantum Teleportation



More in the book, approved by kids

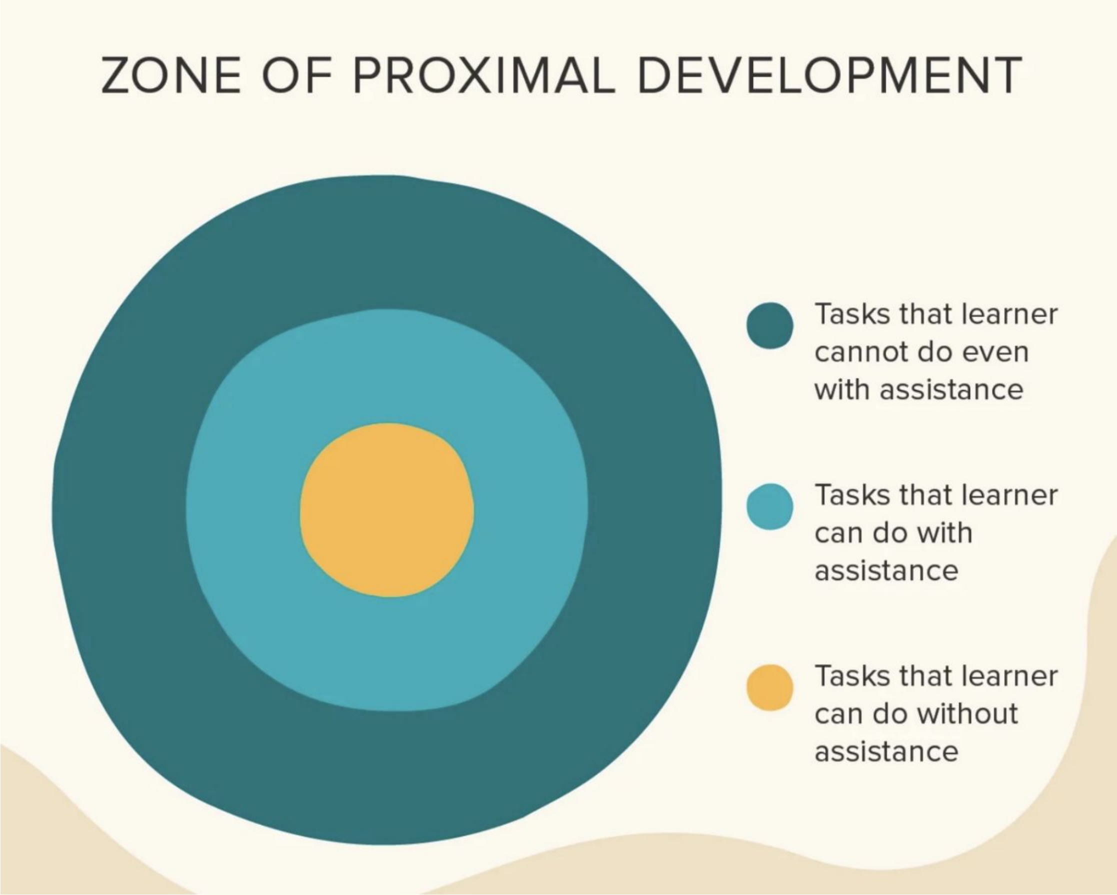


Dan Razvan Ghica
Yesterday at 07:45 ·

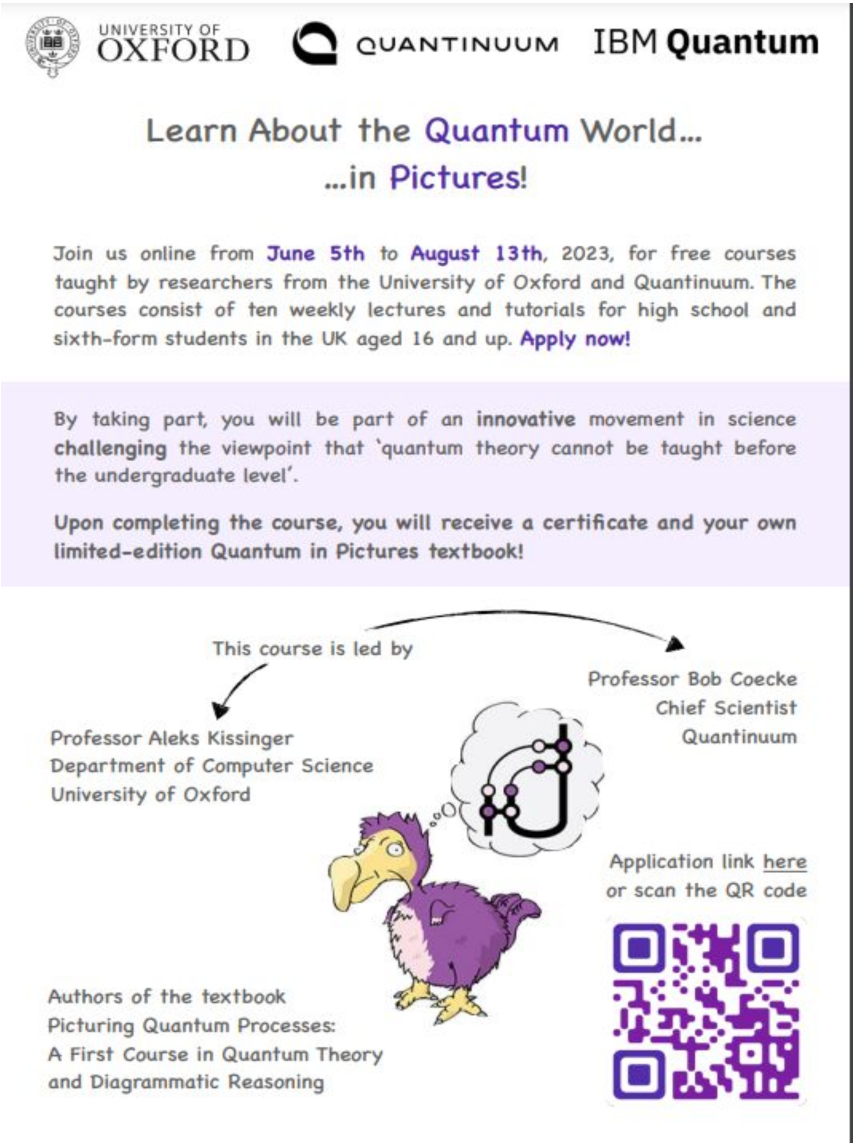
Strong positive reviews from Alexander Ghica (age 10) on Bob Coecke 's new book. "Very clear", "very well structured" (yeah, he actually said that 😅) and "easier to understand than science YouTube videos".

Quantum Picturalism (QPic) for high schoolers

- **Key Research Objective**: demonstrate learnability of QPic for the age group 16-18, keeping QPic within the zone of proximal development (ZPD)
- **Key Performance Indicator**: performance on Oxford post-grad level exam
- **Training**: A course comprising 8 lectures and live tutorials based on the "Quantum in Pictures" book.



Student recruitment



- UK high school students aged 16 to 18
- 734 applications within 3 weeks
- 76 candidates randomly selected ensuring
  - o Fluency in English
  - o Time commitment
  - o Gender balance
- 54 participants completed the course
- 1 lecture and 1 tutorial each week for 8 weeks, then 2-3 weeks for exam

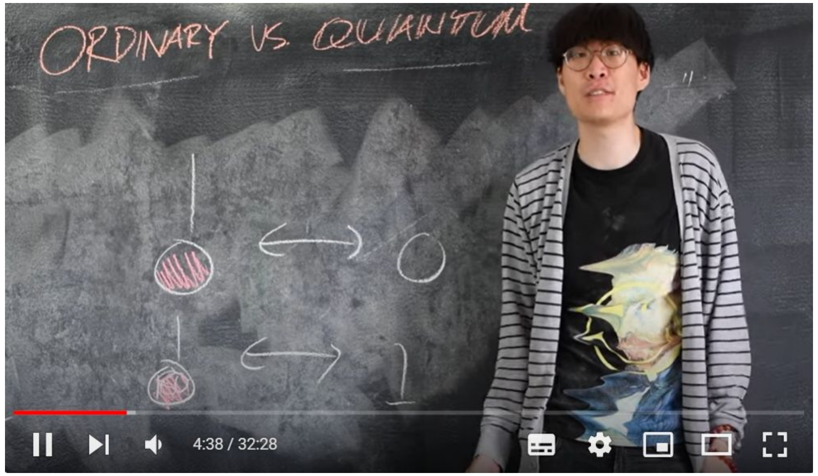
Concepts taught in the 8 weeks' lectures

No mathematical prerequisites:

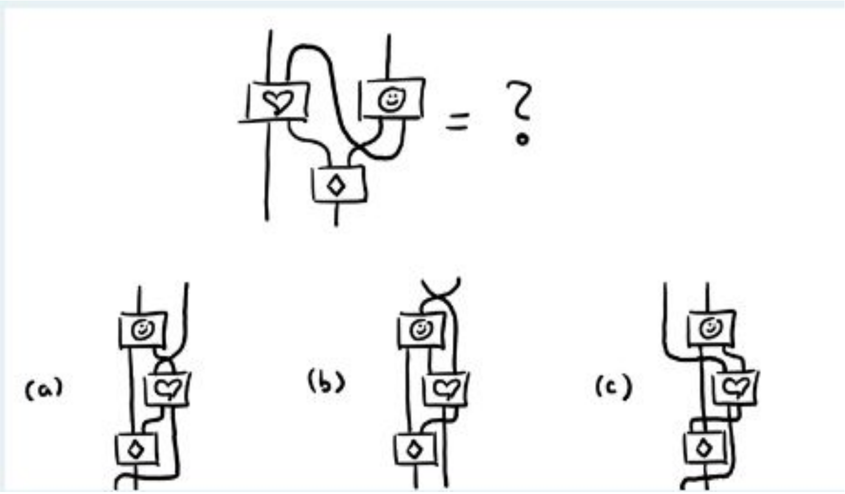
No matrices, No bra-ket, No tensor product, No complex numbers, No trigonometry

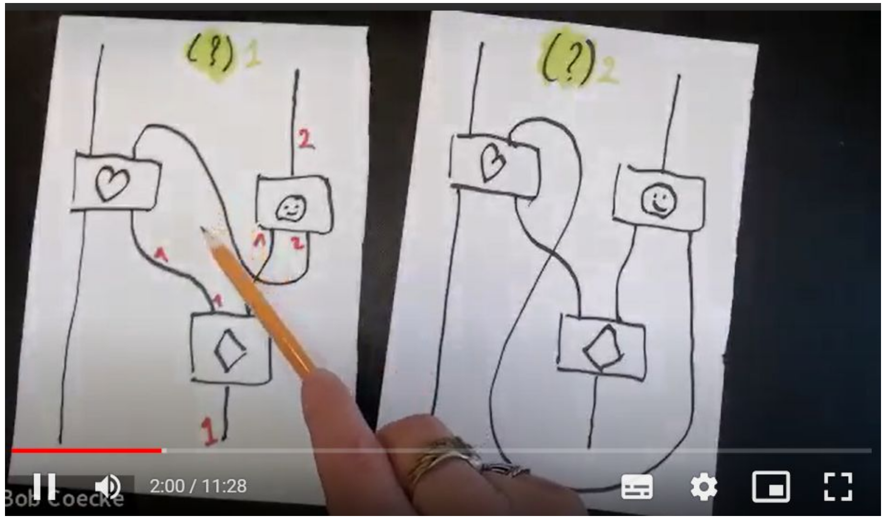
- Spacetime diagrams
- Process theories and Choi-Jamiołkowski isomorphism
- Quantum gates (CNOT, H, Z Phase, X Phase)
- Reversible computation
- States, circuits, measurement, post-selection
- Complementarity of Z and X observables
- Entanglement, Bell state, Bell measurement
- Deterministic vs non-deterministic processes
- Uncertainty principle
- Multi-party quantum communication protocols
- Mixed state quantum information

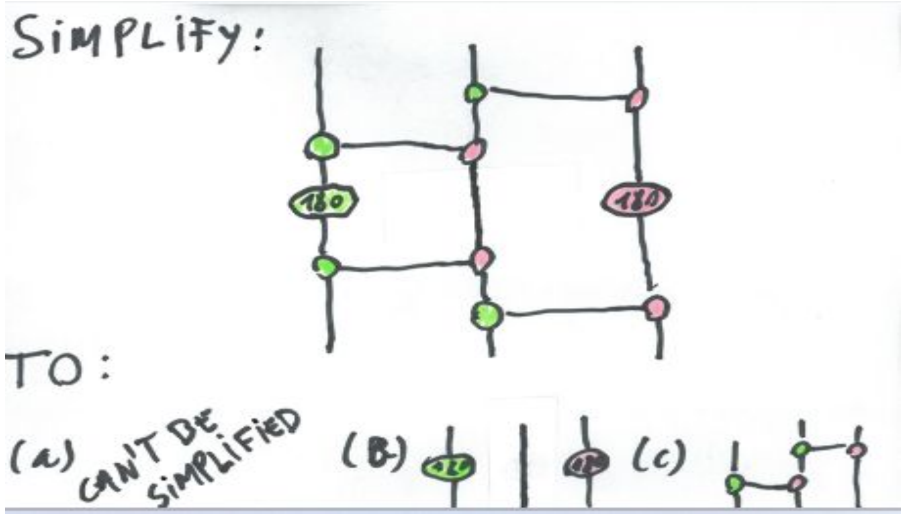
Weekly lectures and live, small-size tutorials

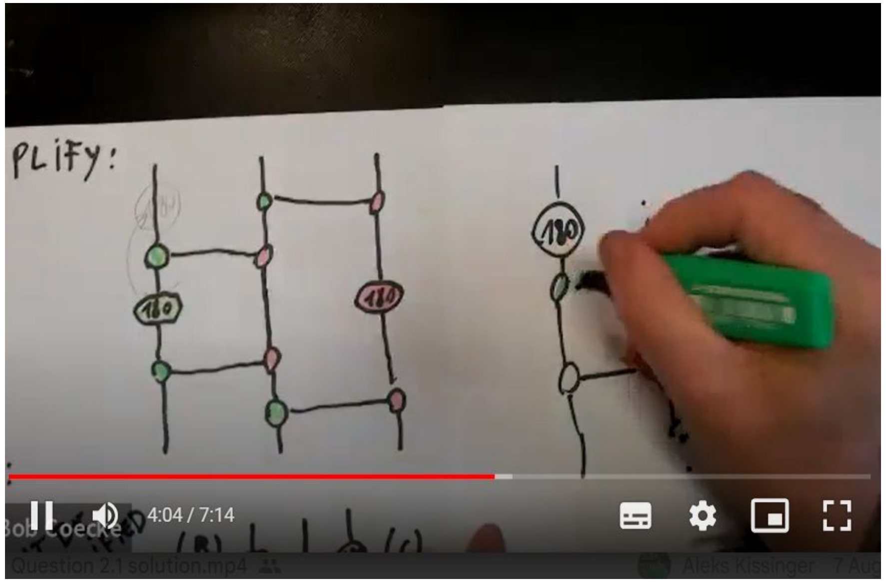


Quizzes


= ?
(a)
(b)
(c)


(?)1
(?)2
2:00 / 11:28
Bob Coecke


SIMPLIFY:
TO:
(a) CAN'T BE SIMPLIFIED
(B)
(c)


PLIFY:
4:04 / 7:14
Bob Coecke

QUANTINUUM UNIVERSITY OF OXFORD IBM **Quantum**

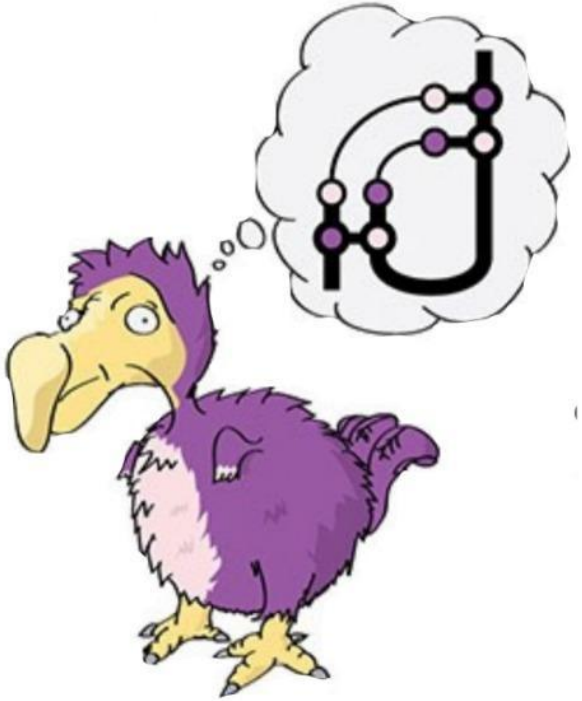
CERTIFICATE

of Appreciation

This certificate is awarded to

Oscar Wilde

for completing the course **Quantum in Pictures** organised from June 2023 to September 2023.



Prof. Bob Coecke
Chief Scientist,
Quantinuum

Prof. Aleks Kissinger
Department of Computer Science,
University of Oxford

The Exam

- Exams double-marked by University of Oxford standards and criteria
- Take-home exam of two weeks

Table D1

This high school exam	*Postgraduate exam at the University of Oxford*
Question 1a	Question 2a, MT2018 MSc Quantum Computer Science
Question 1b	Question 2b, MT2018 MSc Quantum Computer Science
Question 1c	Question 2c, MT2018 MSc Quantum Computer Science
Questions 2a & 2b	Question 2b, MT2021 MSc Quantum Processes and Computation & Question 4, MT2018 MSc Quantum Computer Science
Question 3a	Question 2a, MT2020 MSc Quantum Processes and Computation
Question 3b	Question 2, MT2019 MSc Quantum Processes and Computation

Data

- Demographics
- Qualitative data
  - Weekly attendance
  - Tutor notes
  - Pre- and post-study assessments
- Performance on the final test

Quantum Picturalism: Learning Quantum Theory in High School

Selma Dündar-Coecke, Lia Yeh, Caterina Puca, Sieglinde M.-L. Pfaendler, Muhammad Hamza Waseem, Thomas Cervoni, Aleks Kissinger, Stefano Gogioso, Bob Coecke

Quantum theory is often regarded as challenging to learn and teach, with advanced mathematical prerequisites ranging from complex numbers and probability theory to matrix multiplication, vector space algebra and symbolic manipulation within the Hilbert space formalism. It is traditionally considered an advanced undergraduate or graduate-level subject. In this work, we challenge the conventional view by proposing "Quantum Picturalism" as a new approach to teaching the fundamental concepts of quantum theory and computation. We establish the foundations and methodology for an ongoing educational experiment to investigate the question "From what age can students learn quantum theory if taught using a diagrammatic approach?". We anticipate that the primary benefit of leveraging such a diagrammatic approach, which is conceptually intuitive yet mathematically rigorous, will be eliminating some of the most daunting barriers to teaching and learning this subject while enabling young learners to reason proficiently about high-level problems. We posit that transitioning from symbolic presentations to pictorial ones will increase the appeal of STEM education, attracting more diverse audience.

Comments:	In proceedings of the 2nd Quantum Science and Engineering Education Conference (QSEEC), co-located with the 4th IEEE International Conference on Quantum Computing and Engineering (QCE)
Subjects:	**Physics Education (physics.ed-ph)**; Quantum Physics (quant-ph)
Cite as:	arXiv:2312.03653 **[physics.ed-ph]**
	(or arXiv:2312.03653v1 **[physics.ed-ph]** for this version)
	https://doi.org/10.48550/arXiv.2312.03653
Journal reference:	2023 IEEE International Conference on Quantum Computing and Engineering (QCE), 2023, pp. 21-32
Related DOI:	https://doi.org/10.1109/QCE57702.2023.20321

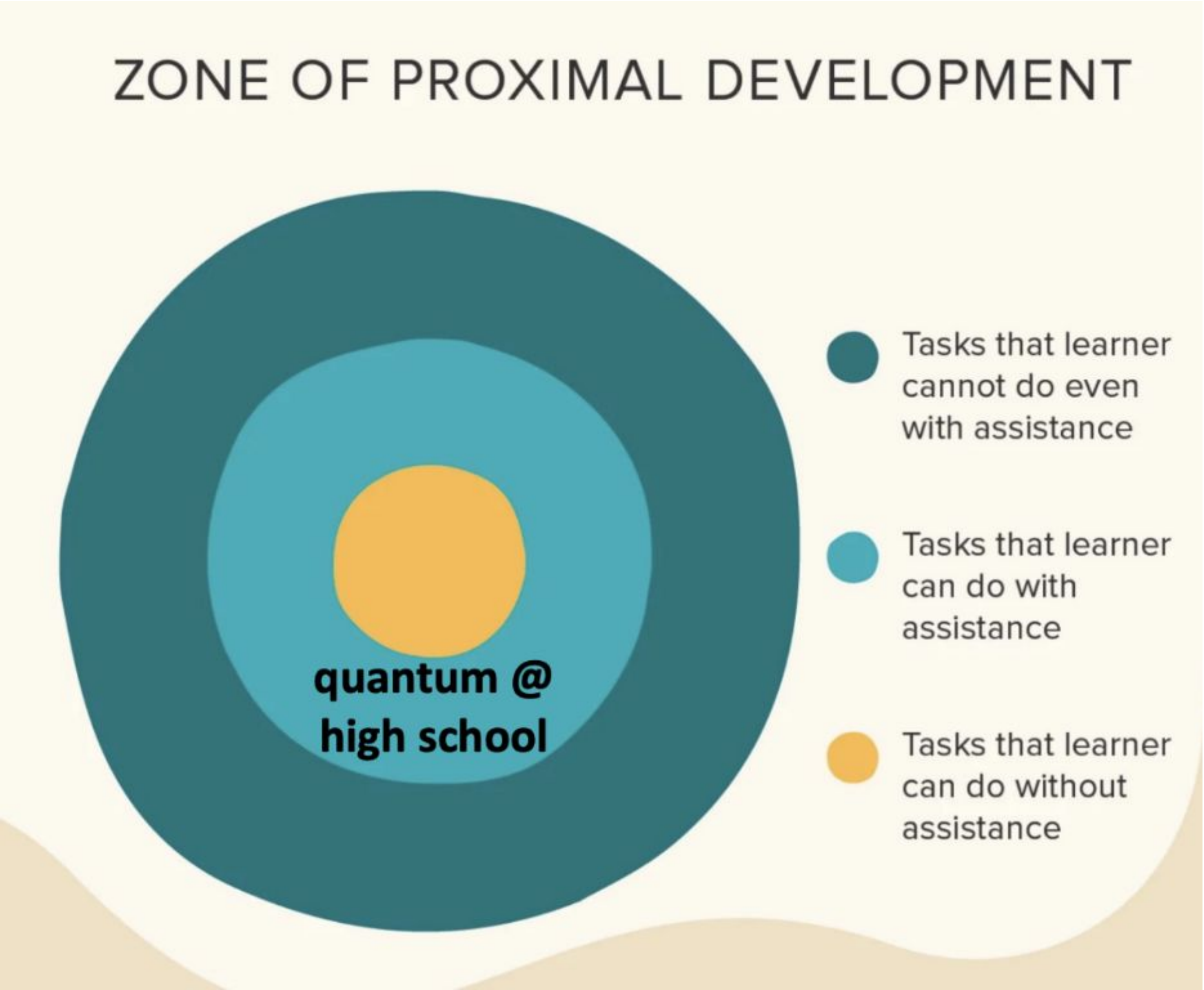
Exam Outcomes

- High retention: Over 50 students completed the course

- > 4 in 5 passed*
- ~1 in 2 distinction*

- >35% distinction✧
- Exceeds the fail✧ percentage

with* and without✧ filtering by a definition question



The participants pool

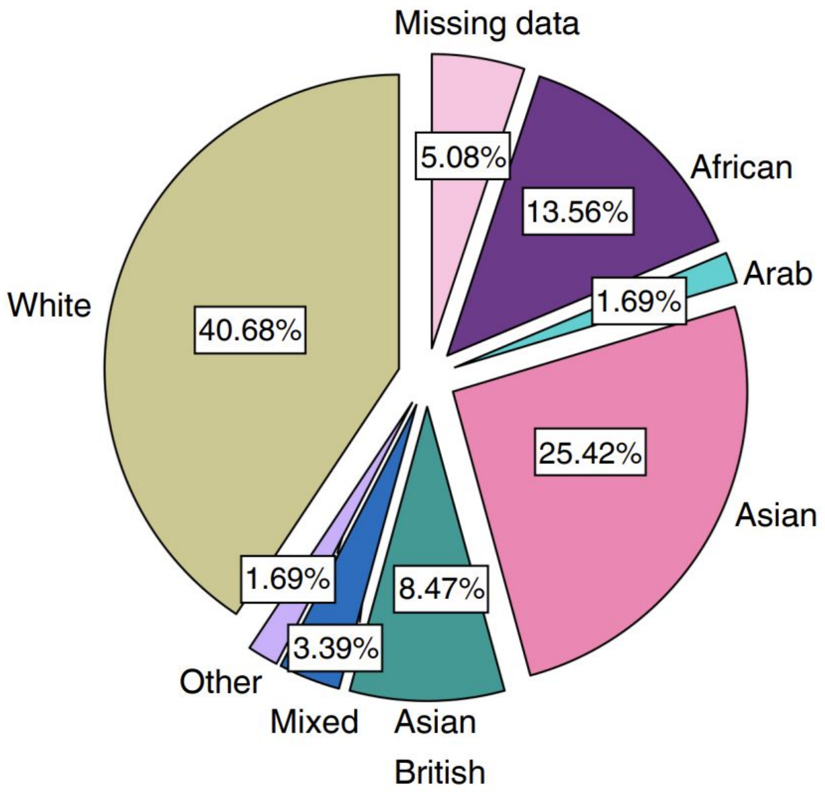


Fig. 2. The ethnic background composition of the participants.

Table 1

Frequency and percentage distribution of school types.

School type	*Frequencies*	*Percent*
State	30	55.6
Grammar	14	25.9
Private Boarding	2	3.7
State Boarding	3	5.6
Private independent	2	3.7
Missing data	3	5.5
Total	*54*	*100*

Diversity both in **ethnic** and **educational** background was observed.

An interesting observation

- Exam scores correlated poorly with max. study hours per week as well as school grades in Maths and Physics.
- Indicator that QPic can proceed in the absence of traditional competencies in science subjects.

Prior knowledge vs. learning effort

- While almost 80% of participants had limited to zero knowledge of quantum, almost 2/3 of them did not need more study hours than those required.
- All participants had other commitments during the course, including GCSE preparation.

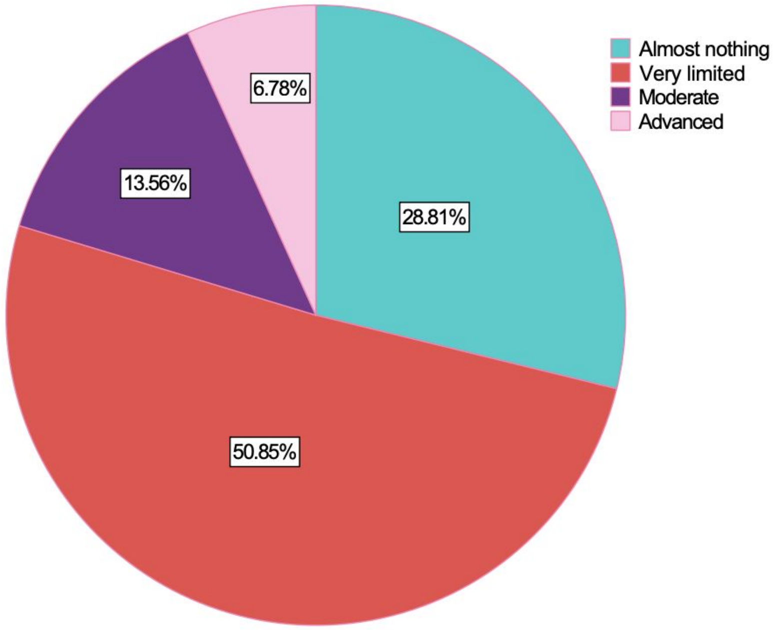


Fig. 5. Prior knowledge before attending training.

Table 2

Hours spent to study per week.

Hours/week	Percent
1-2	64.4
3-4	30.5
4-5	1.7
Total	96.6

Table 3

Other commitments over the course period.

	Exam preparation	Part-time job	Intership	Supportive activity	Camps/leisure
%	100	20.3	11.9	10.2	57.6

Impact of the course

- Almost 90% participants agreed that the course motivated them to pursue a STEM career and almost 70% agreed the course strengthened their motivation and confidence.
- The majority rated tutors' communication and teaching style as either good (40.7%) or very good (29.6%).
- Highly significant correlation between this evaluation and the item "the course motivated me to pursue a STEM career."

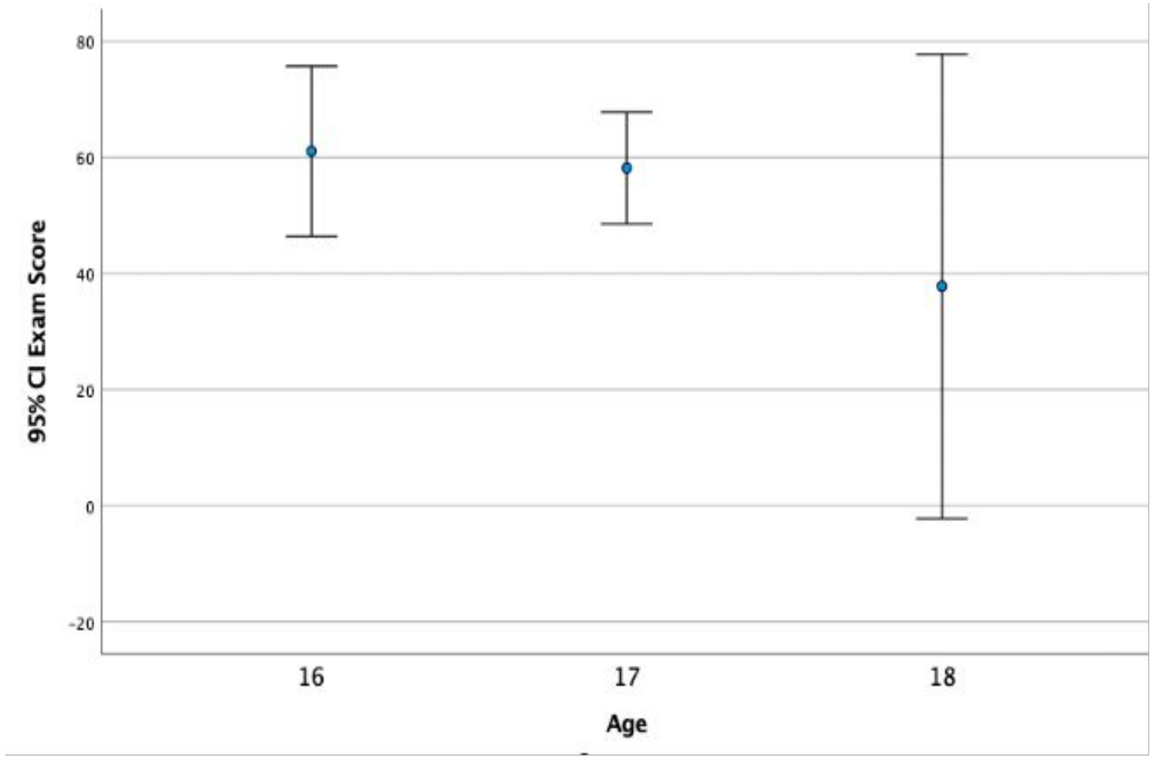
Table 9

Impact of course on participants.

	The course strengthened my motivation and confidence	The course motivated me to pursue a STEM career
Disagree	3.4	1.7
Not sure	28.8	11.9
Agree	37.3	32.2
Strongly agree	30.5	54.2

The age factor

- No significant age-related differences in comprehension.
- Presence of trend, although not statistically significant, indicating higher exam scores in 16 and 17-year-olds.
- We hypothesize the absence of developmental trends might reflect the effectiveness of teaching methods.
- Future work: lower the age barrier, with the hypothesis that trends may become evident below age 13.



Challenges and Limitations

- The study was completely online.
- Ethics approval and requirements – by the University of Oxford – caused many delays and limited interaction between the students.
- Most students would not turn on their cameras and not actively participate in the tutorials.
- The study was limited to students in the UK – since we could obtain ethics approval for UK students only.

Making the quantum world accessible to young learners through Quantum Picturalism: An experimental study

Selma Dündar-Coecke, Caterina Puca, Lia Yeh, Muhammad Hamza Waseem, Emmanuel M. Pothos, Thomas Cervoni, Sieglinde M.-L. Pfaendler, Vincent Wang-Maścianica, Peter Sigrist, Ferdi Tomassini, Vincent Anandraj, Ilyas Khan, Stefano Gogioso, Aleks Kissinger, Bob Coecke

The educational value of a fully diagrammatic approach in a scientific field has never been explored. We present Quantum Picturalism (QPic), an entirely diagrammatic formalism for all of qubit quantum mechanics. This framework is particularly advantageous for young learners as a novel way to teach key concepts such as entanglement, measurement, and mixed-state quantum mechanics in a math-intensive subject. This eliminates traditional obstacles without compromising mathematical correctness - removing the need for matrices, vectors, tensors, complex numbers, and trigonometry as prerequisites to learning. Its significance lies in that a field as complex as Quantum Information Science and Technology (QIST), for which educational opportunities are typically exclusive to the university level and higher, can be introduced at high school level. In this study, we tested this hypothesis, examining whether QPic reduces cognitive load by lowering complex mathematical barriers while enhancing mental computation and conceptual understanding. The data was collected from an experiment conducted in 2023, whereby 54 high school students (aged 16-18) underwent 16 hours of training spread over eight weeks. The post-assessments illustrated promising outcomes in all three specific areas of focus: (1) whether QPic can alleviate technical barriers in learning QIST, (2) ensures that the content and teaching method are age appropriate, (3) increases confidence and motivation in science and STEM fields. There was a notable success rate in terms of teaching outcomes, with 82% of participants successfully passing an end-of-training exam and 48% achieving a distinction, indicating a high level of performance. The unique testing and training regime effectively reduced the technical barriers typically associated with traditional approaches, as hypothesized.

Comments: 82 pages, 14 figures. This paper is on the outcomes of the study proposed in this https URL (arXiv:2312.03653)
Subjects: **Physics Education (physics.ed-ph)**; Quantum Physics (quant-ph)
Cite as: arXiv:2504.01013 **[physics.ed-ph]**
(or arXiv:2504.01013v1 **[physics.ed-ph]** for this version)

Impact and Prospects

July 2, 2024

Elevate Quantum Awarded $127 Million to Secure US Leadership in Quantum Technology

Elevate Quantum

Federal and State Funding to Support Elevate Quantum's Efforts to Create 10,000+ New Quantum Jobs, Educate 30,000 Workers Over the Next Decade

DENVER, Colo. July 2, 2024 – Today, Elevate Quantum announced that it has received a Tech Hub Phase 2 Implementation award from the Department of Commerce, unlocking more than $127m in new federal and state funding. The award is expected to drive more than $2bn in additional private capital and cement the Mountain West as a global leader for quantum innovation.

March 26, 2024

Quantum in Pictures: Quantinuum Publishes New Book to Introduce Quantum to the Masses

QUANTINUUM

A core member of Elevate Quantum and a global leader in the space, Quantinuum has published *Quantum in Pictures: A New Way to Understand the Quantum World*, a new book that promises to make the fields of quantum physics and quantum computing fun, more inclusive and open to anyone, regardless of their mathematical or scientific background.

By introducing readers of all levels of expertise – from school children, parents and general science enthusiasts to businesspeople and educators – to the central concepts of quantum theory, *Quantum in Pictures* helps to grow public understanding of quantum computing, and the scientific theory that lies behind it.

To learn more or to purchase *Quantum in Pictures*, click the link here.

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Zeeya Merali

Sat 16 Dec 2023 14.00 GMT

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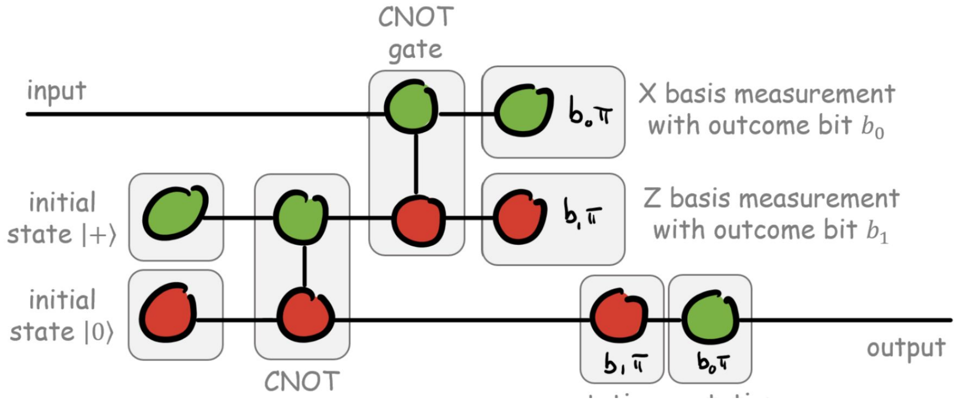
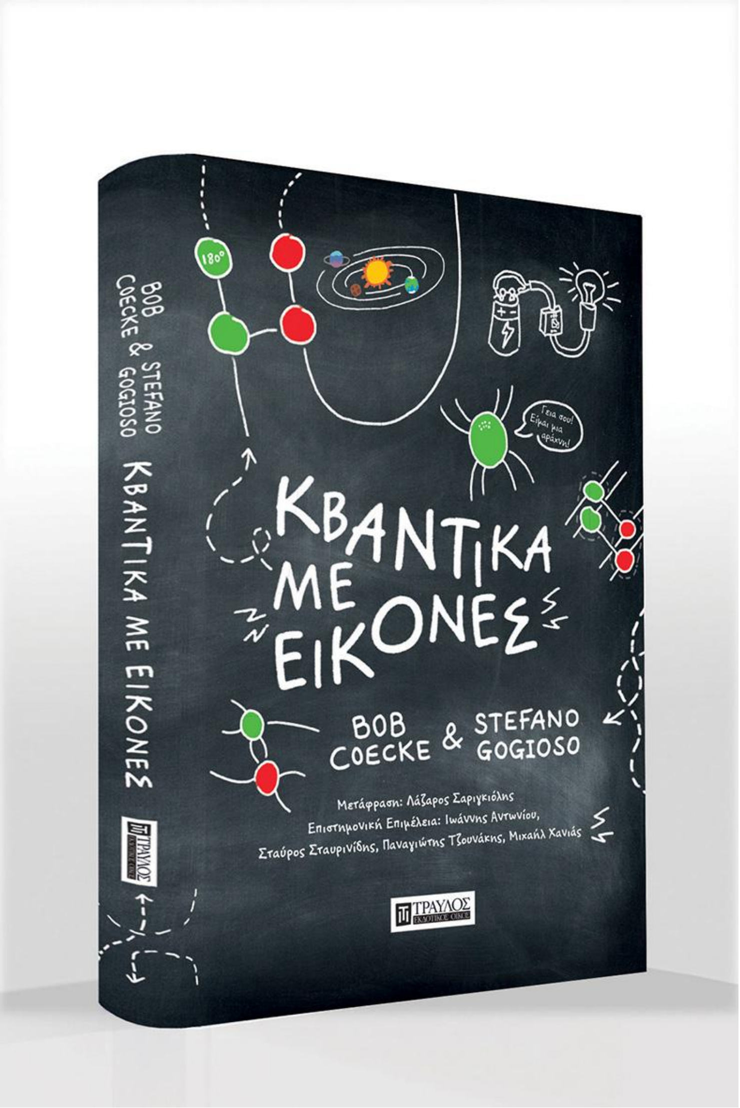
Picturing The Future Quantum Workforce: Visual Thinking May Help Break Quantum Education Barrier

Research · Matt Swayne • April 4, 2025



What’s happening and what’s next?

- Next experiment: comparative study of the effectiveness of QPic and the traditional approach, involving both high school and university students.
- Release of all course materials.
- Online course in Ghana (2024).
- Greek translation out. More translations in the works.
- Teacher training for Denver Public Schools, Colorado, USA.
- Pedagogical study in Sweden
- Workshops and courses planned in USA, Dubai, Morocco, and Pakistan.



For more details

- arXiv

Quantum Picturalism: Learning Quantum Theory in High School

Selma Dündar-Coecke, Lia Yeh, Caterina Puca, Sieglinde M.-L. Pfaendler, Muhammad Hamza Waseem, Thomas Cervoni, Aleks Kissinger, Stefano Gogioso, Bob Coecke

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- Medium

Everyone can learn quantum now, even at a cutting-edge level…and we have the test scores to prove it!

Bob Coecke · Follow

Published in Quantinuum · 10 min read · Dec 21, 2023

Thank you for your attention.

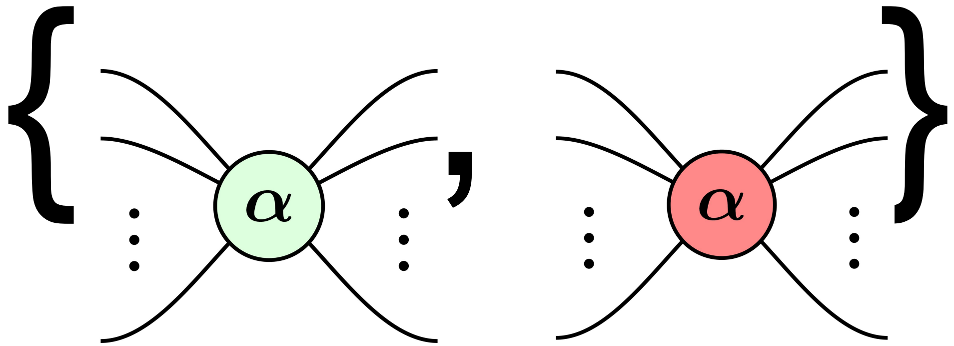
Hamza Waseem

Compositional Intelligence Team, Quantinuum

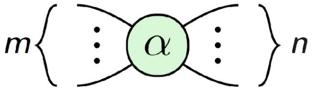
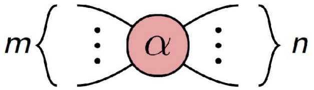
hamza.waseem@quantinuum.com

Quantum Picturalism

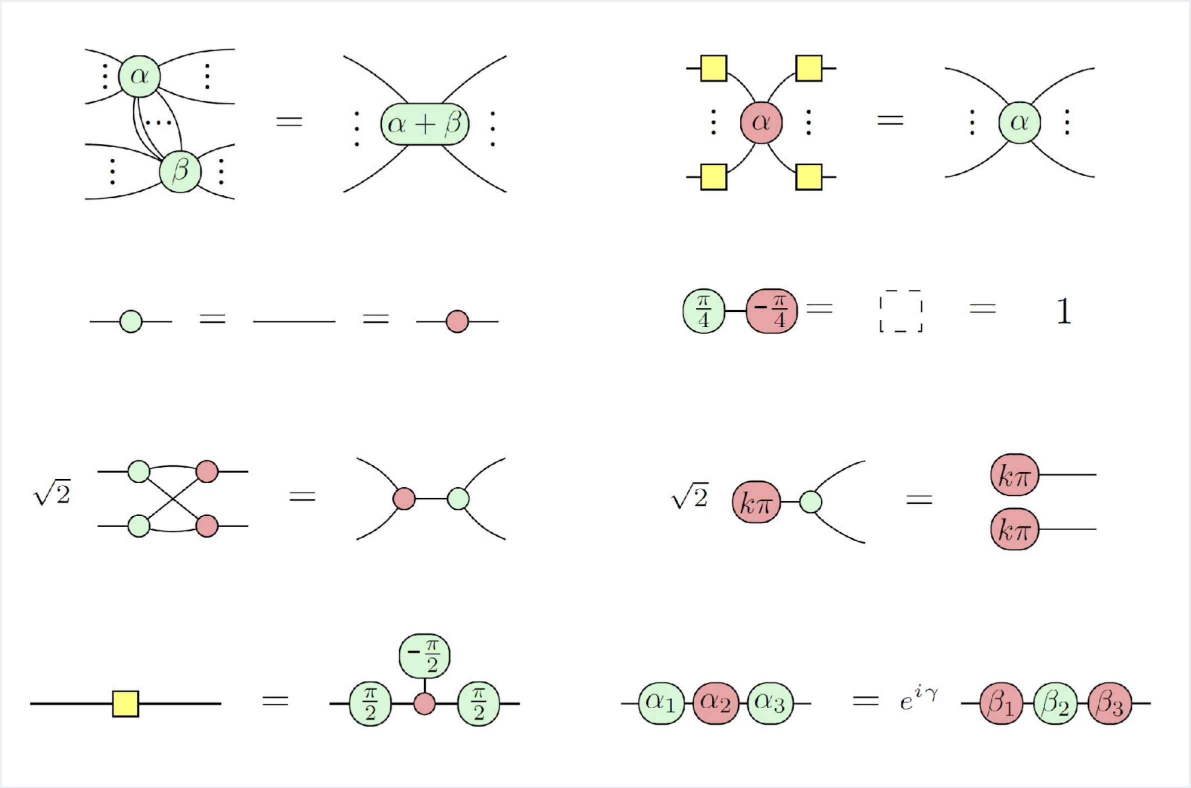
ZX-calculus
Ingredients: Spiders!



You can draw any quantum circuit using just these two types of spiders.

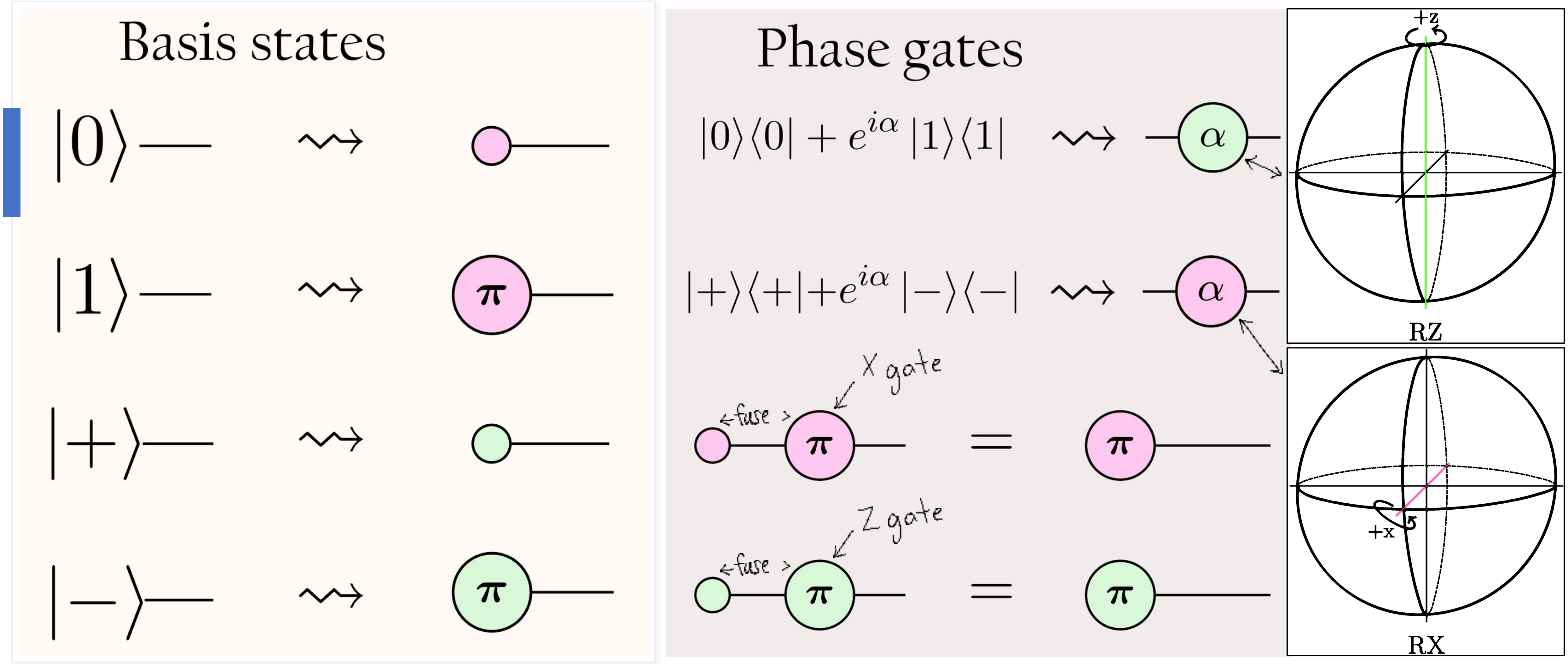
 $:= |0\rangle^{\otimes n}\langle 0|^{\otimes m} + e^{i\alpha}|1\rangle^{\otimes n}\langle 1|^{\otimes m}$ and  $:= |+\rangle^{\otimes n}\langle +|^{\otimes m} + e^{i\alpha}|-\rangle^{\otimes n}\langle -|^{\otimes m}$

Since 2018: The ZX-calculus is finally complete!



Completeness:

These **8** rules suffice to prove all equalities of linear maps on any number of qubits.



Basis states
|0⟩ ⇝
|1⟩ ⇝ π
|+⟩ ⇝
|−⟩ ⇝ π
Phase gates
|0⟩⟨0| + e^{iα} |1⟩⟨1| ⇝ α
|+⟩⟨+| + e^{iα} |−⟩⟨−| ⇝ α
X gate
<fuse>
π = π
Z gate
<fuse>
π = π
+z
RZ
+x
RX