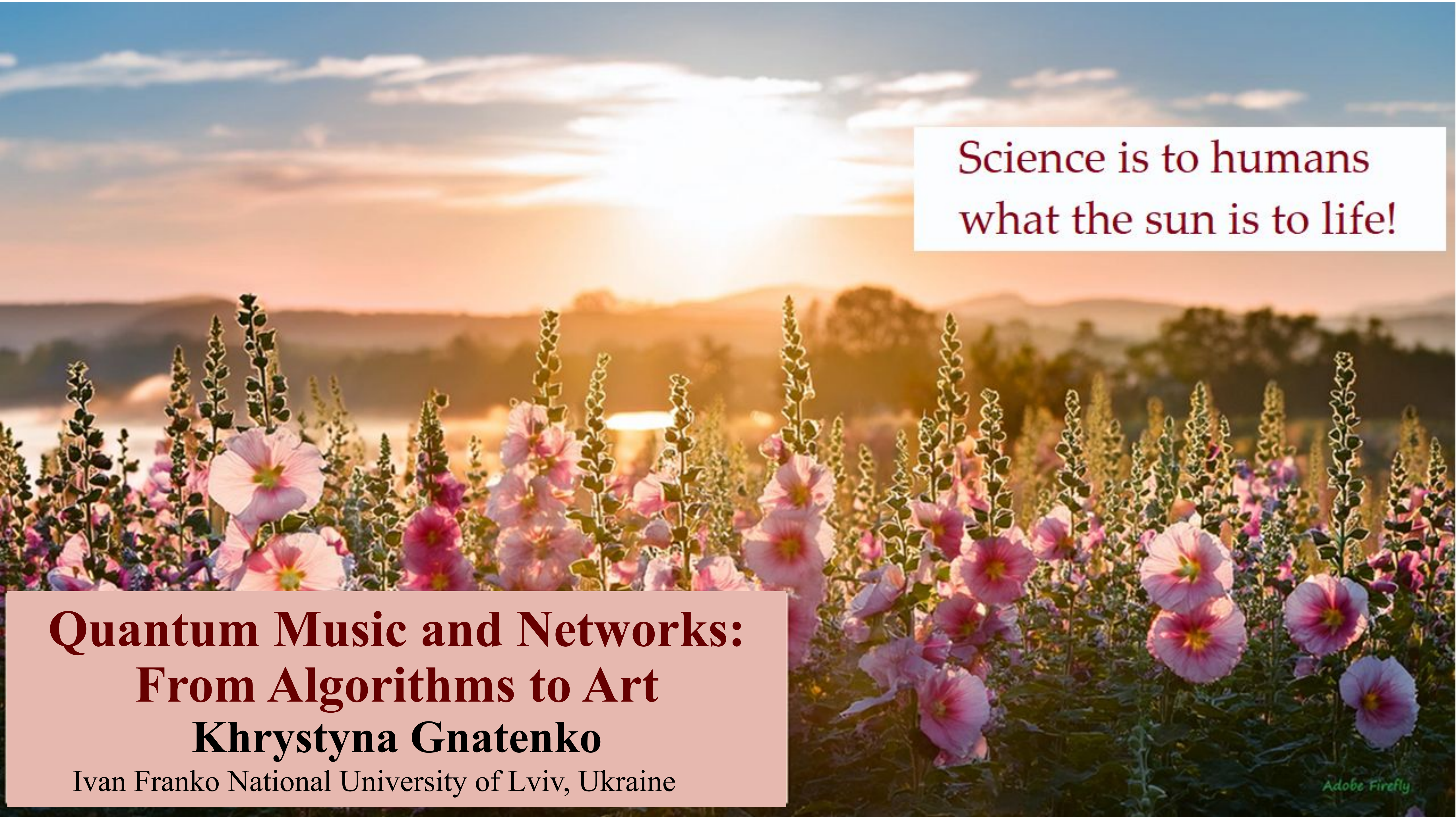


Science is to humans
what the sun is to life!

Quantum Music and Networks: From Algorithms to Art

Khrystyna Gnatenko
Ivan Franko National University of Lviv, Ukraine

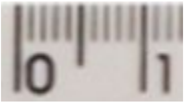
Outline

- Features of quantum programming
- Studies of graph properties with quantum programming
- Quantum music
- Graphs in music
- Educational Program “Quantum computers and Quantum programming”, Ivan Franko National University of Lviv

Quantum physics is the science of nature at very small scales (microscopic scales).

What does the term "microscopic scales" mean?

Micro (from the Greek *μικρός* — "small") means a reduction by a factor of one million!



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Microscopic scales are scales a **MILLION** times smaller than a meter!

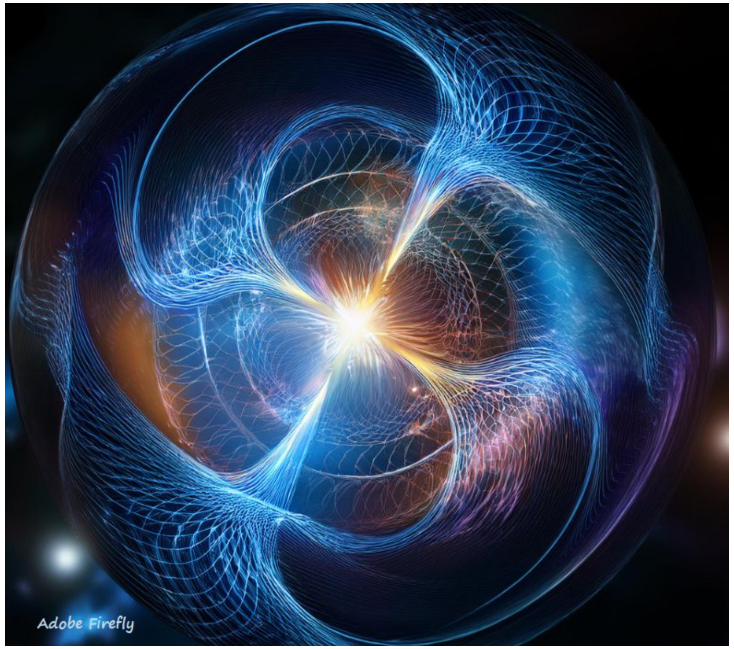
Classical World

We talk about

- coordinates
- velocities
- trajectory of motion

Quantum World

We talk about the wave function, the state of a quantum system, Ψ.



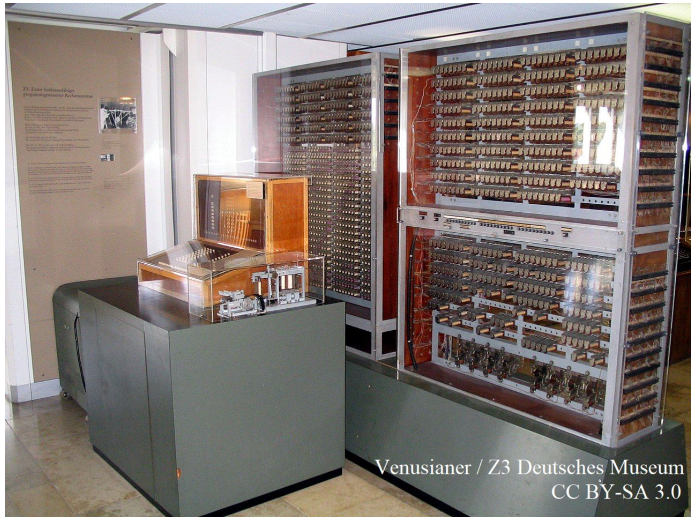
Classical

Quantum

Option 1

Option 2

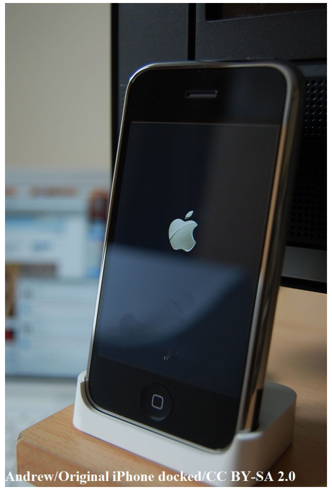
Superposition



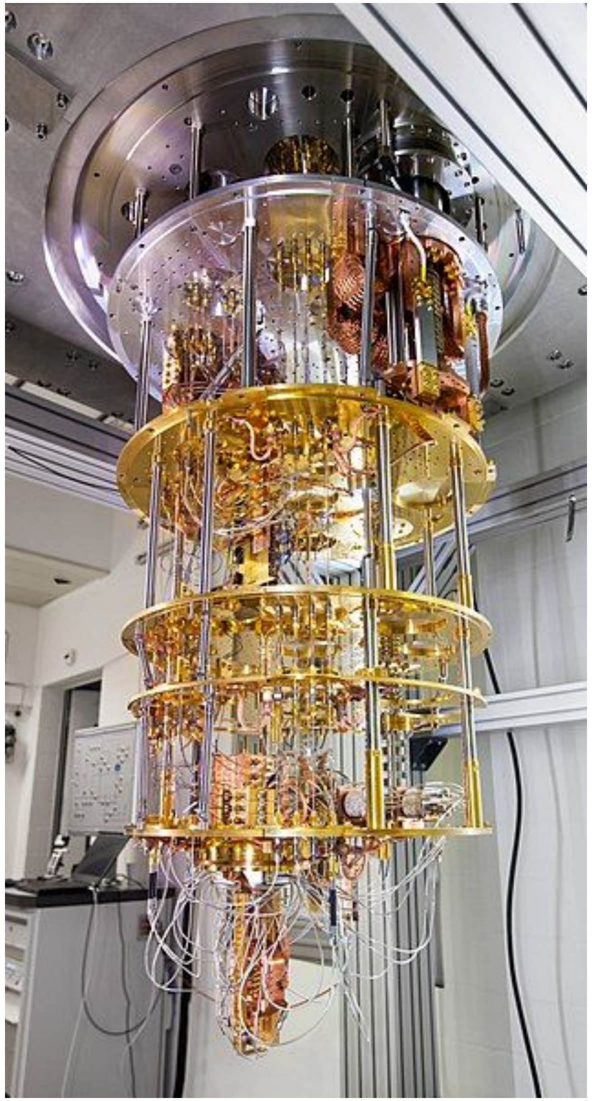
Venusianer / Z3 Deutsches Museum CC BY-SA 3.0

IBM Personal Computer XT front CC BY-SA 3.0

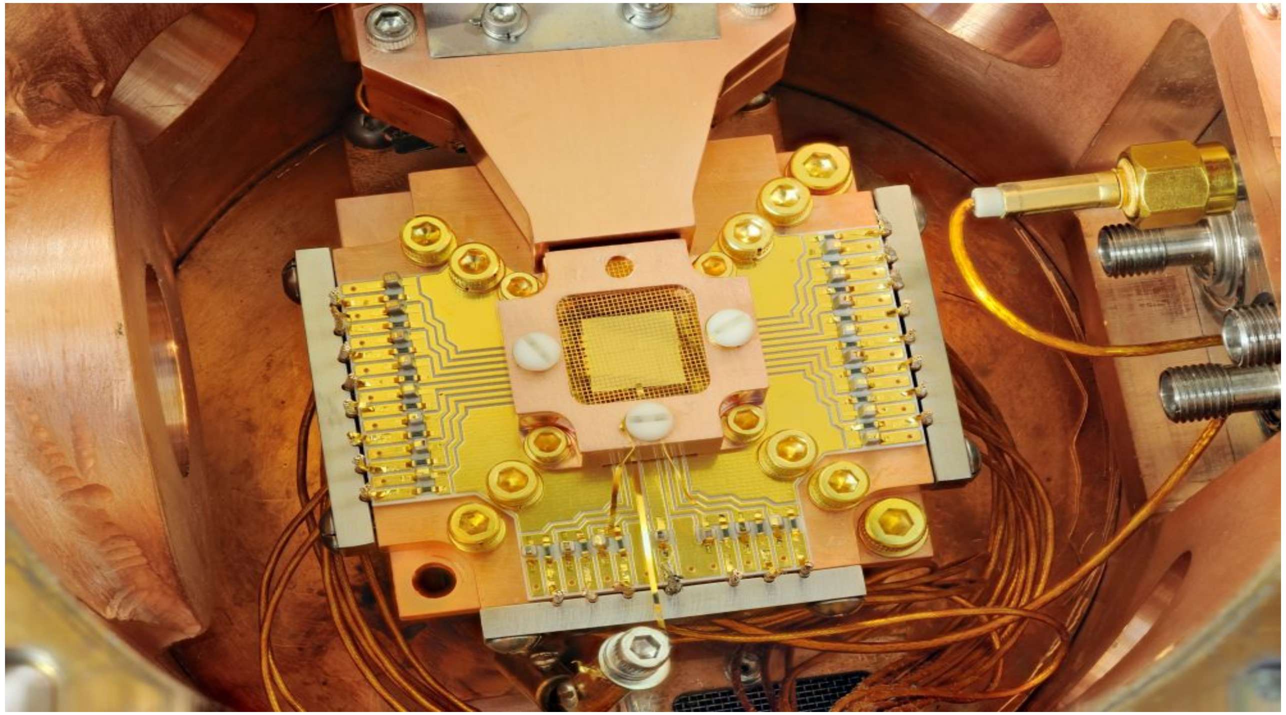
Georgy90/ Acer Aspire 8920 Gemstone/ CC BY-SA

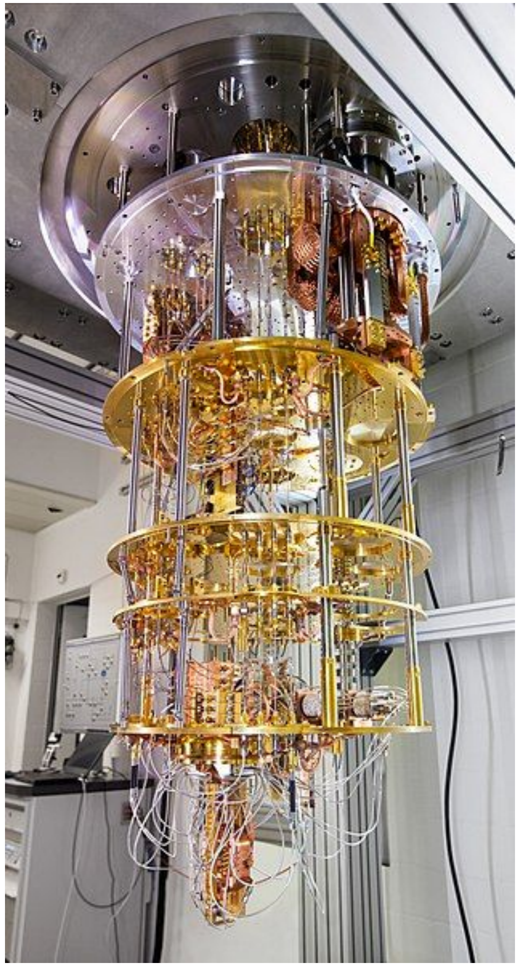


Andrew/Original iPhone docked/CC BY-SA 2.0



Quantum computers – computers that exploits quantum mechanical phenomena for calculations.



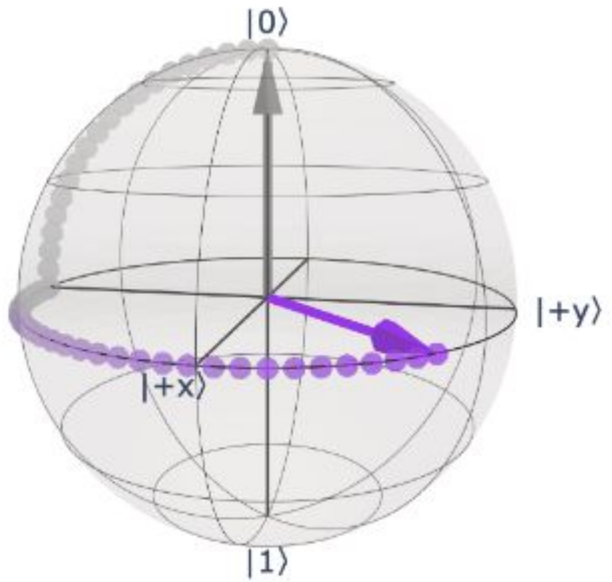


Quantum Computer Zurich,
IBM Zurich Lab,

Quantum bit - qubit

- States of one qubit:

$$\begin{pmatrix}1\\0\end{pmatrix} = |0\rangle \qquad \begin{pmatrix}0\\1\end{pmatrix} = |1\rangle$$



$$|\psi_1\rangle = C_1\,|0\rangle + C_2\,|1\rangle$$

Multiqubit quantum states. Quantum parallelism

Two-qubit state

$$|\Psi_2>= C_1|00> +C_2|01> +C_3|10> +C_4|11>$$

Superposition of 4 states.

n-qubit state

$$|\Psi_n>= C_1|000 \dots 0> +C_2|000 \dots 1> + \dots + C_n|111 \dots 1>$$

Superposition of 2^n states.

Entanglement of quantum states

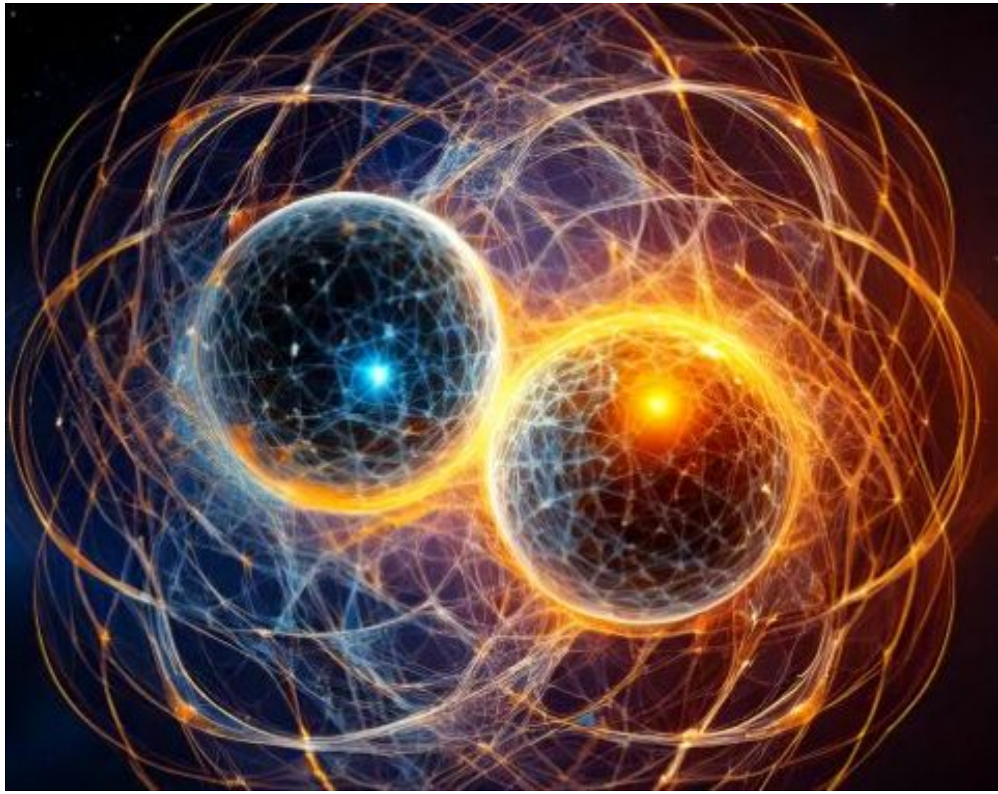
Let us consider two quantum systems A and B in state $|\psi\rangle$. If the state $|\psi\rangle$ can be represented as

$$|\psi\rangle = |\psi\rangle_A \otimes |\psi\rangle_B,$$

where $|\psi\rangle_A$, $|\psi\rangle_B$ are states of the systems A and B, the state $|\psi\rangle$ is not entangled. In other case

$$|\psi\rangle \neq |\psi\rangle_A \otimes |\psi\rangle_B,$$

the state is entangled.



Examples

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |1\rangle_B + |0\rangle_A \otimes |0\rangle_B) =$$
$$\frac{1}{\sqrt{2}}|0\rangle_A \otimes (|1\rangle_B + |0\rangle_B)$$

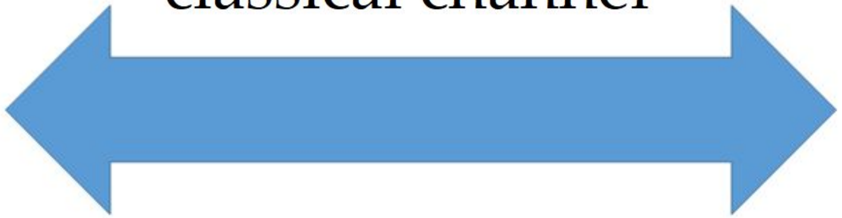
The state is not entangled.

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |1\rangle_B + |1\rangle_A \otimes |0\rangle_B)$$

The state is entangled.

Quantum teleportation

classical channel

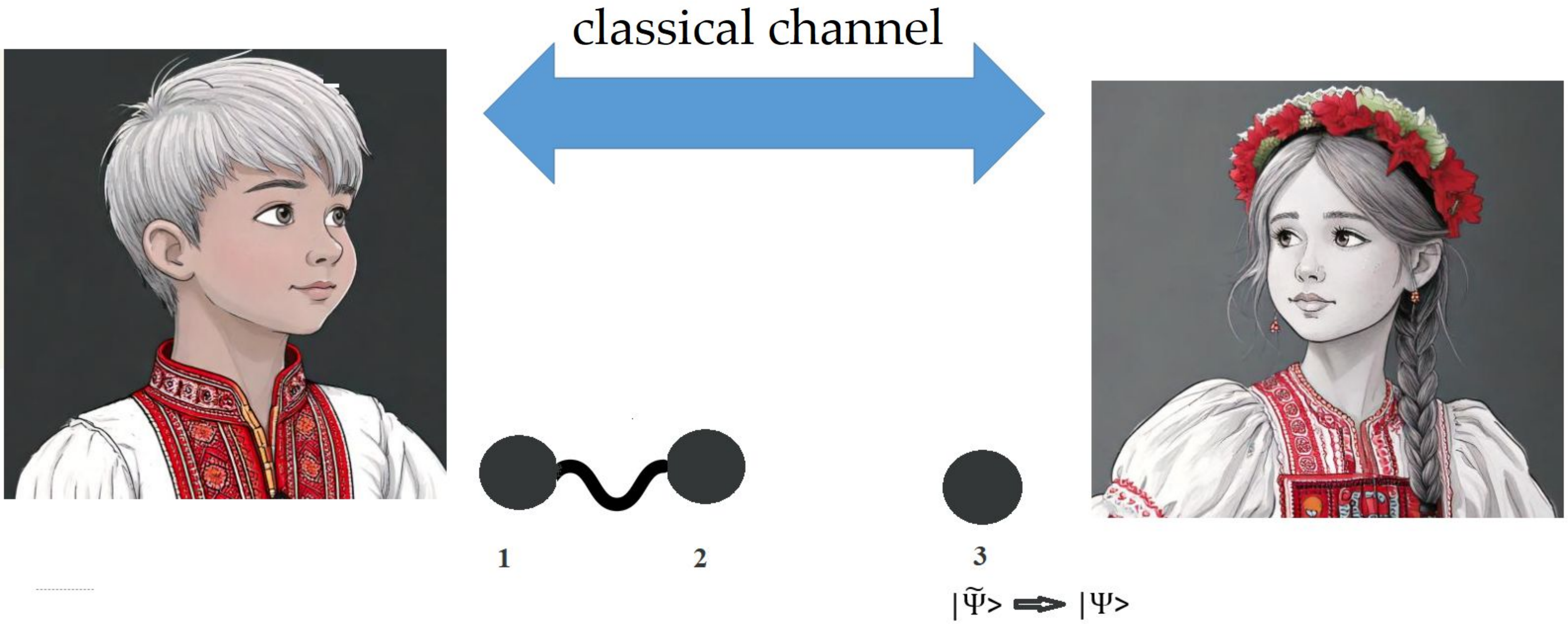


quantum channel

1 2 3

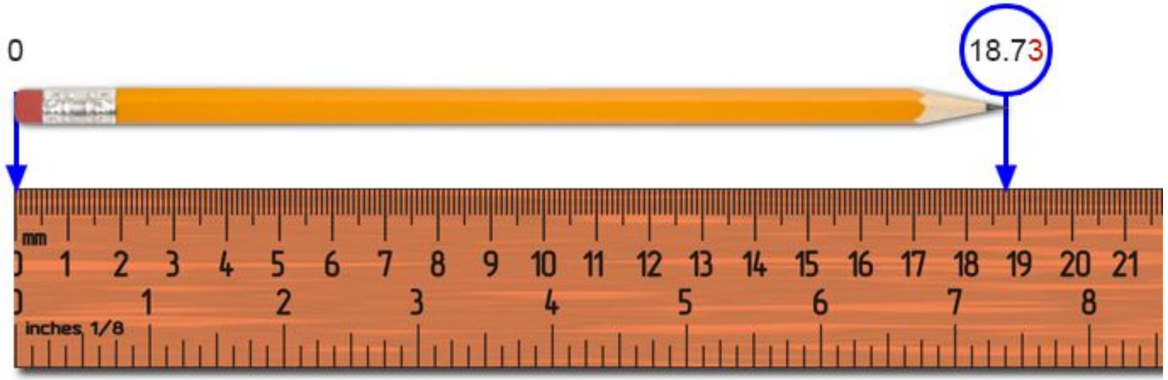
$|\Psi>$ $|\Psi^->=\frac{1}{\sqrt{2}}(|0>_2 \otimes |1>_3 - |1>_2 \otimes |0>_3)$

Quantum teleportation



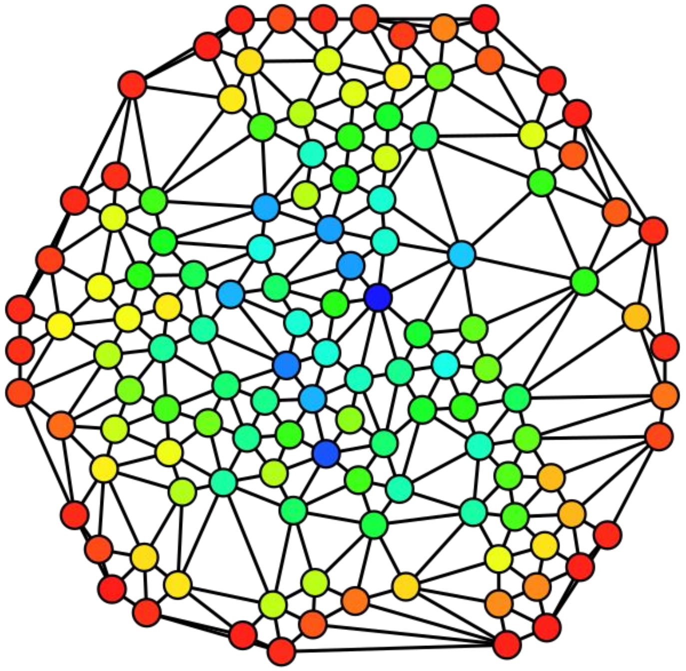
Classical measurement vs. Quantum measurement

Measurement in quantum mechanics is described by the postulate of measurement and has a probabilistic nature.



Graph –

a structure made of vertices and edges.



Quantum states

$$|\psi\rangle = e^{-\frac{it}{2\hbar}\sum_{ij} J_{ij}\sigma_i^x\sigma_j^x}|\psi_0\rangle, \quad |\psi_0\rangle = |00...0\rangle$$

$$|G\rangle = \prod_{(a,b)\in E} RXX_{ab}(\phi)\prod_i RZ_i(\alpha)RY_i(\theta)\,|0\rangle^{\otimes n}$$

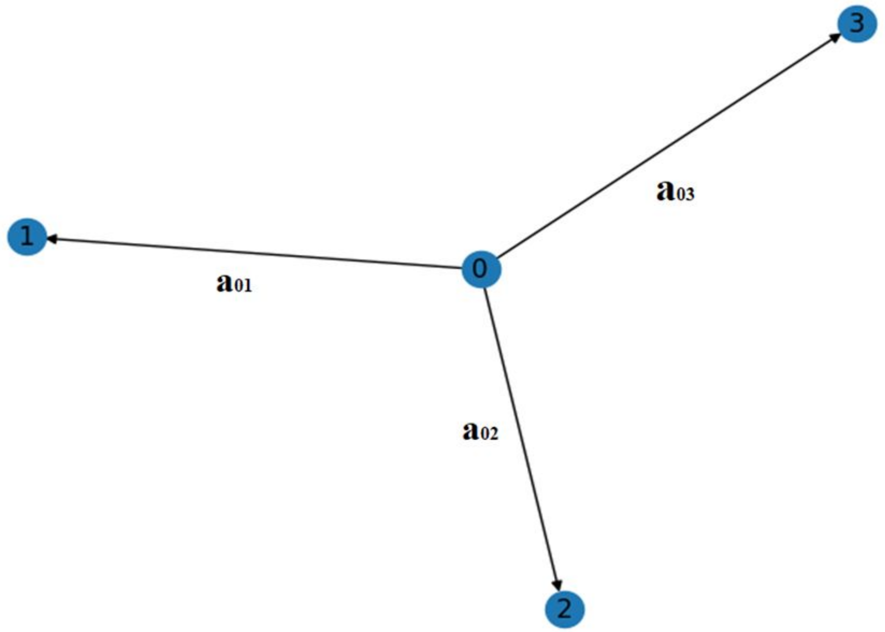
Quantum graph state – *quantum state that can be represented by a graph.*

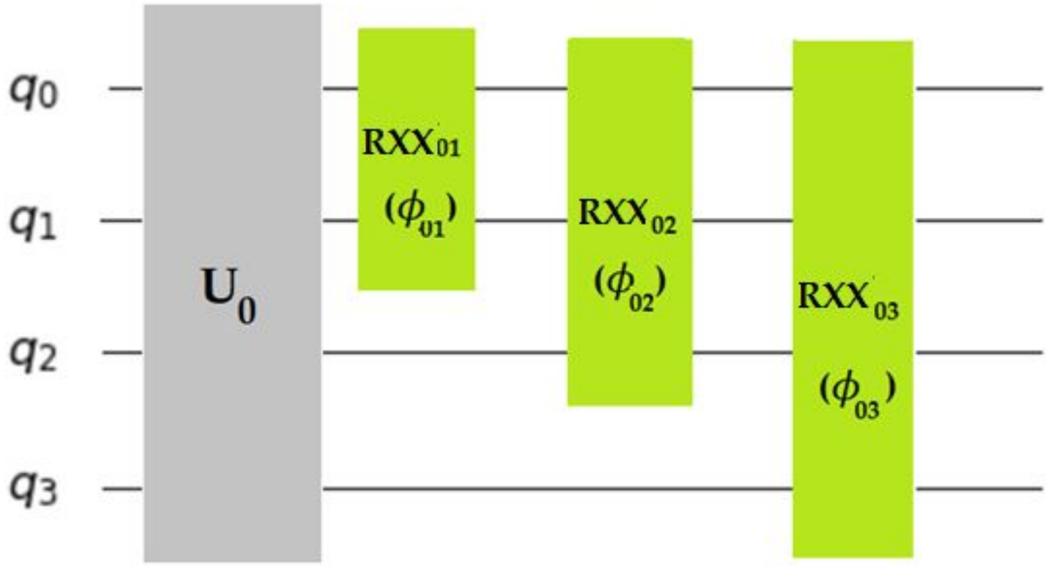
Weighted and directed quantum graph states

Quantum states of spin systems with Ising model are considered

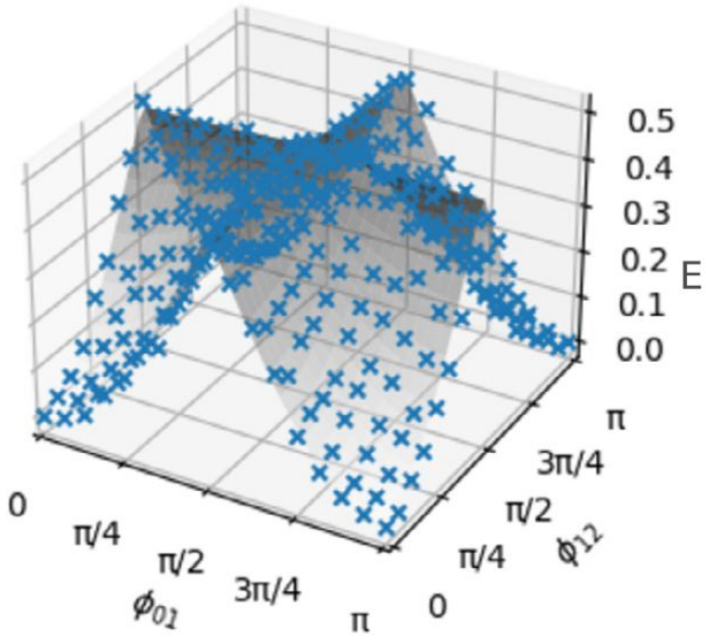
$$|\psi_G\rangle = \prod_{(i,j)\in A} RXX_{ij}(\phi_{ij})\,|\psi_0\rangle \,. \quad |\psi_0\rangle = \prod_{k\in V} |\psi(\alpha_k,\theta_k)\rangle_k \,,$$

$$|\psi(\alpha_k,\theta_k)\rangle_k = \cos\frac{\theta_k}{2}\,|0\rangle_k + e^{i\alpha_k}\sin\frac{\theta_k}{2}\,|1\rangle_k = e^{i\frac{\alpha_k}{2}} RZ(\alpha_k)RY(\theta_k)\,|0\rangle_k \,.$$

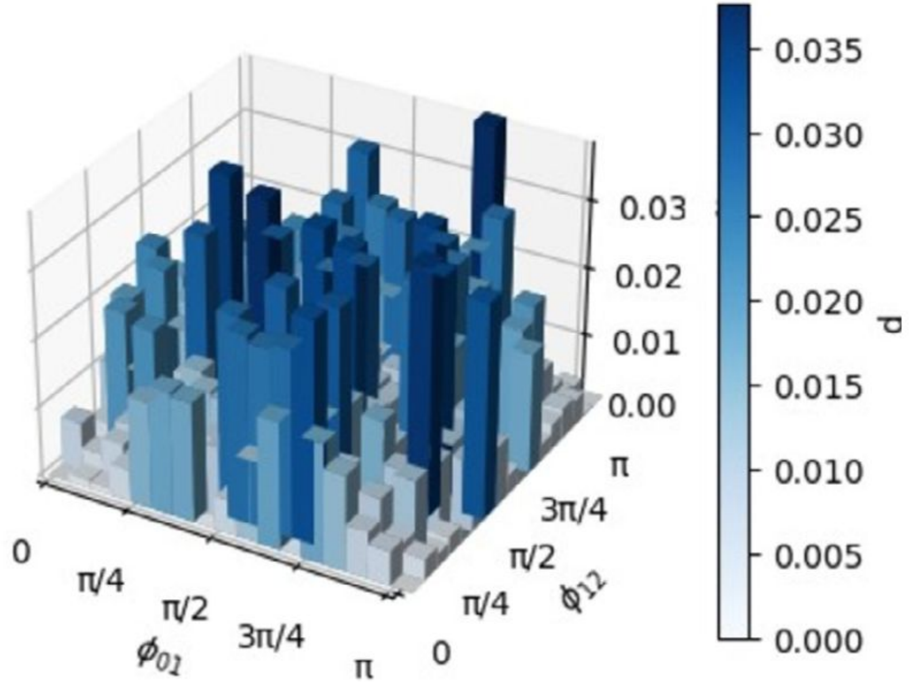




Results of quantum calculations



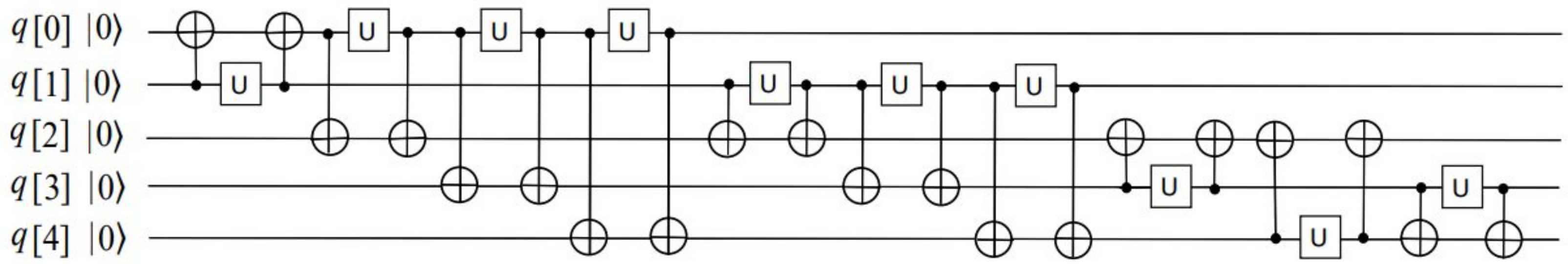
(a)



(b)

Entanglement of qubit $q[1]$ with other qubits in quantum graph state (a) for $\alpha_i = \theta_i = 0$ and different values of ϕ_{01}, ϕ_{02}. (b) 3D histogram shows the differences between the simulated and theoretical results.

Results of calculations on IBM's quantum computer



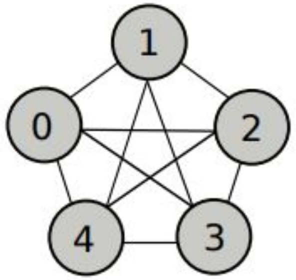
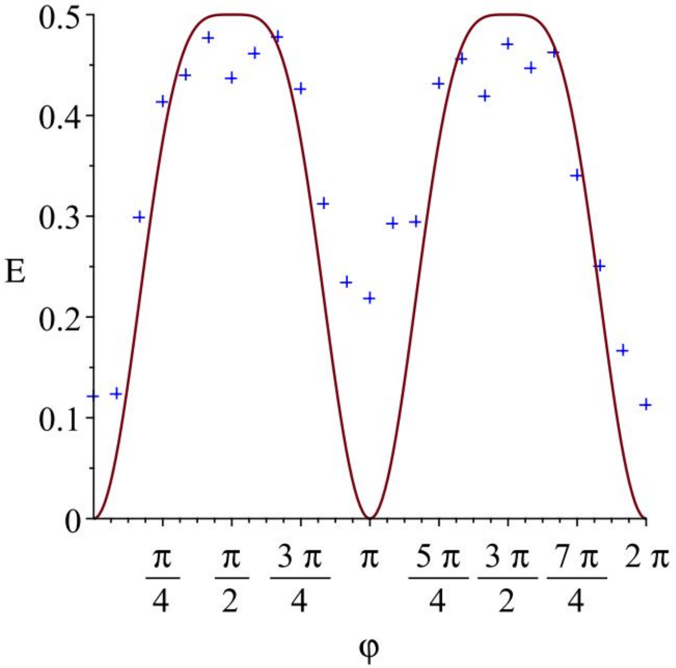


Figure : Quantum protocol for preparing graph state. Here U represents gates $HP(\varphi)H$. $\varphi = \dfrac{2Jt}{\hbar}$,

$$|\psi\rangle = e^{-\frac{it}{2\hbar}\sum_{ij} J_{ij}\sigma_i^x\sigma_j^x}|\psi_0\rangle,$$

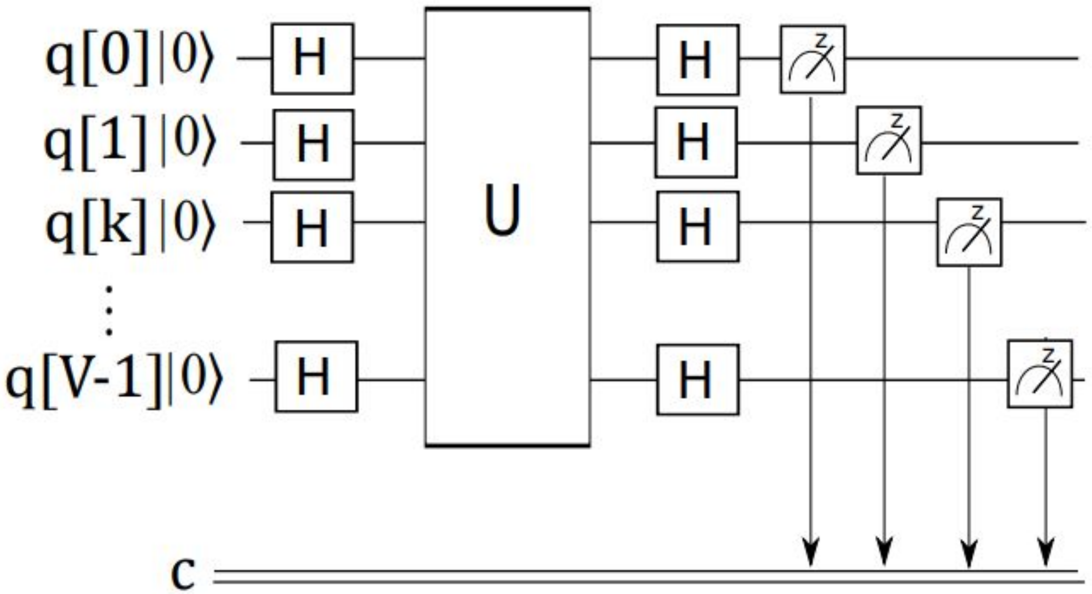
$$|\psi_0\rangle = |00...0\rangle$$



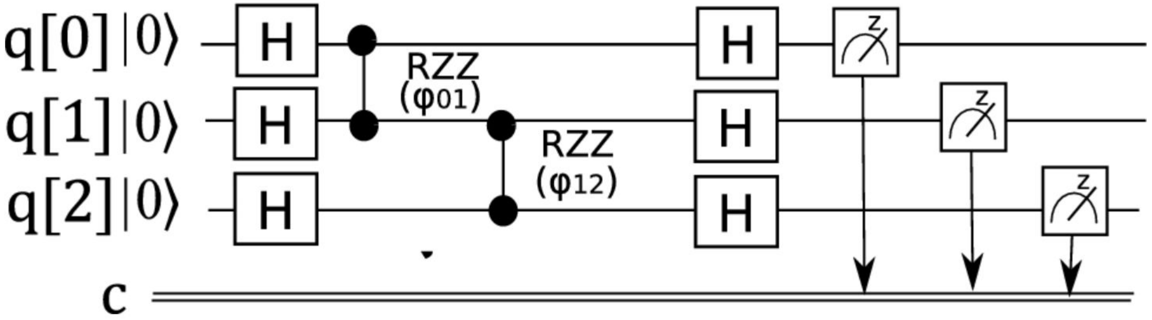
Quantum calculations of the geometric properties of graph states on IBM's quantum computer

As an example we examine a spin chain

$$H_I = J_{01}\sigma_0^z\sigma_1^z + J_{12}\sigma_1^z\sigma_2^z,$$



Quantum protocol for quantifying $|\langle U \rangle|^2$ with quantum programming.



Quantum calculations on IBM's quantum computer

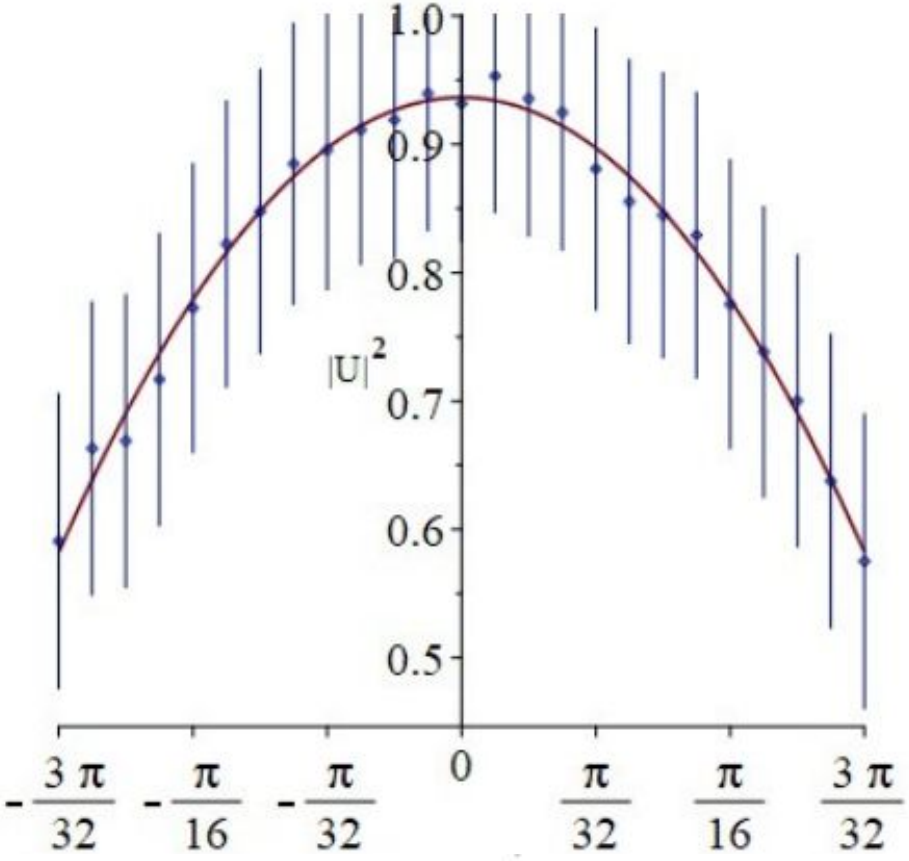
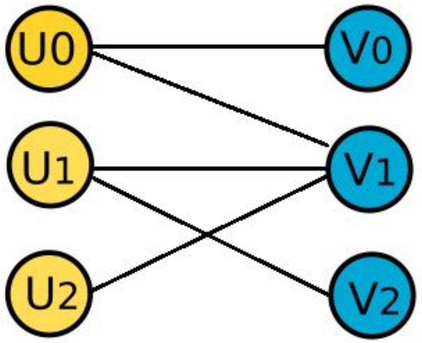


Figure: Results of quantum calculations of $|U|^2$ for spin chain (marked by crosses) and fitting curve $-4.08\phi^2 + 0.94$ (represented with a line).

Bipartite graphs

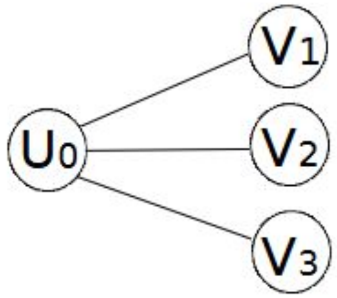
A bipartite graph G(U,V,E) is a type of graph in which the set of vertices can be separated into two distinct and non-overlapping groups, U and V, such that every edge connects a vertex from U to a vertex from V.



$$|\psi_{K_{1,3}}\rangle = CNOT_{01}CNOT_{02}CNOT_{03}\,|\psi^{(U)}_{init}\rangle\,|\psi^{(V)}_{init}\rangle\,,$$

$$|\psi^{(U)}_{init}\rangle = \cos\frac{\theta_0^{(U)}}{2}\,|0\rangle_0 + e^{i\alpha_0^{(U)}}\sin\frac{\theta_0^{(U)}}{2}\,|1\rangle_0\,,$$

$$|\psi^{(V)}_{init}\rangle = \prod_{v=1}^{3}\left(\cos\frac{\theta_v^{(V)}}{2}\,|0\rangle_v + e^{i\alpha_v^{(V)}}\sin\frac{\theta_v^{(V)}}{2}\,|1\rangle_v\right).$$

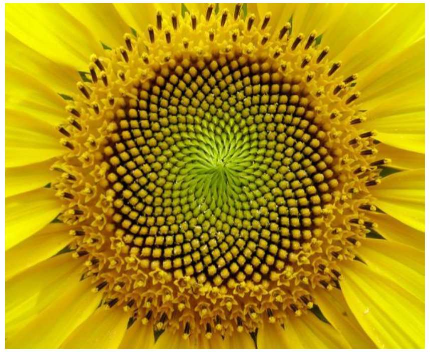


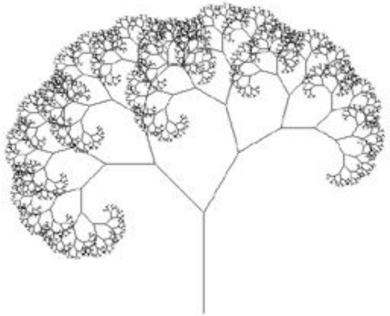
More details can be found here

- Gnatenko Kh. P. Studies of properties of bipartite graphs with quantum programming Phys. Lett. A 566, 131191 (2026).
- Gnatenko Kh. P. Relation of curvature and torsion of weighted graph states with graph properties and its studies on a quantum computer Eur. Phys. J. Plus 140(3), 241 (2025).
- Gnatenko Kh. P. Entanglement of multi-qubit states representing directed networks and its detection with quantum computing //Phys. Lett. A 521, 129815 (2024).

Harmony of science and music

From Greek, harmony (αρμονία) — connection, order, coherence, agreement.



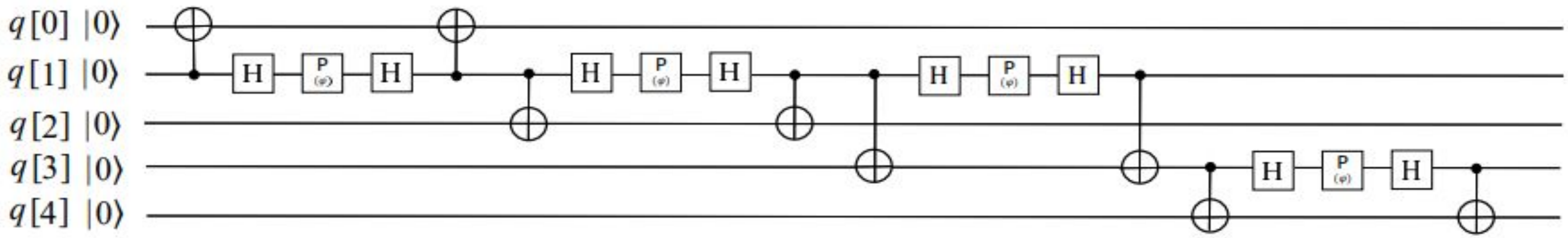


Music is the mediator between the life of the mind and the life of the emotions.

Ludwig van Beethoven

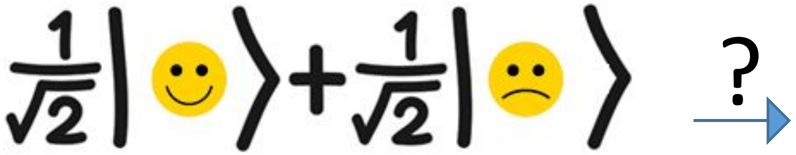
Quantum composer

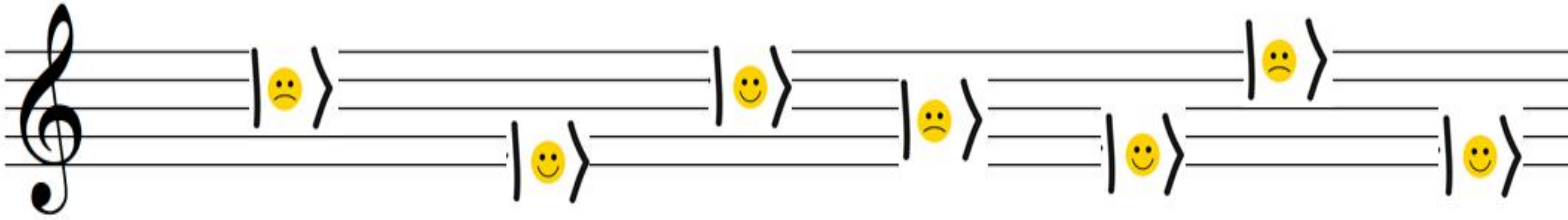
Quantum protocol



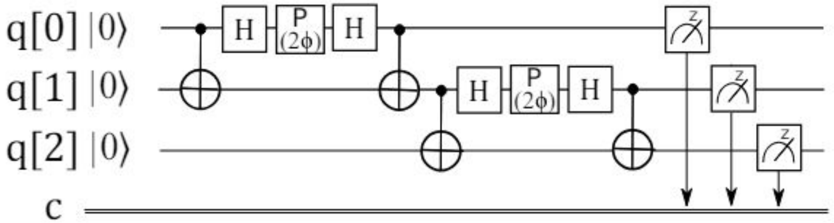
Music score

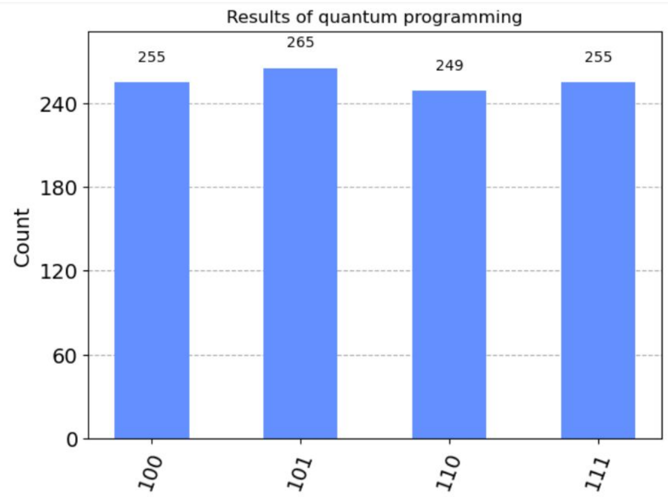
Developing quantum music

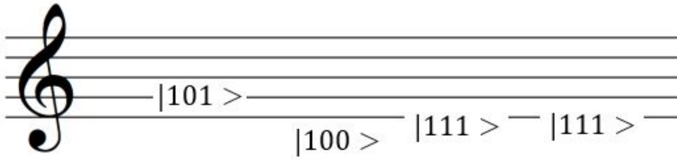




Method I: Each sound is assigned a corresponding quantum state

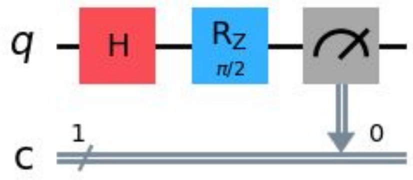






Developing quantum music

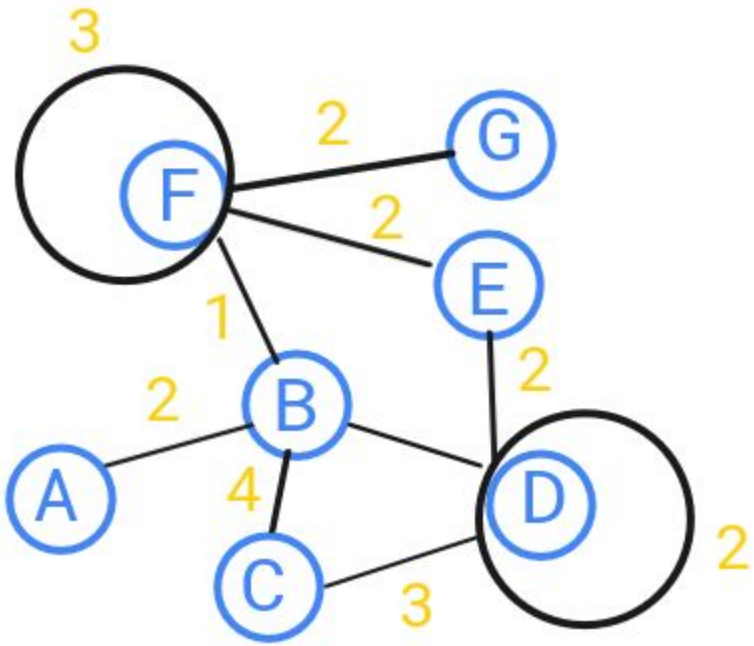
Method II Reduction of polyphony to monophony



BWV 1005 - Sonata No. 3 in C Major - Johann S. Bach

Graphs in music

N. Paganini



Educational Program

IVAN FRANKO NATIONAL UNIVERSITY OF LVIV

FACULTY OF PHYSICS
LVIV UNIVERSITY

Lv|Q><ℂ|
LVIV QUANTUM COMPUTING

EDUCATIONAL PROGRAM

The Bachelor's and the Master's educational programs "Quantum Computers and Quantum Programming" were launched at the Ivan Franko National University of Lviv in 2020 .

60 students –
future specialists in quantum computing

Expansion of the research group in more distant future

Summer-school “Quantum programming for school students” 2023

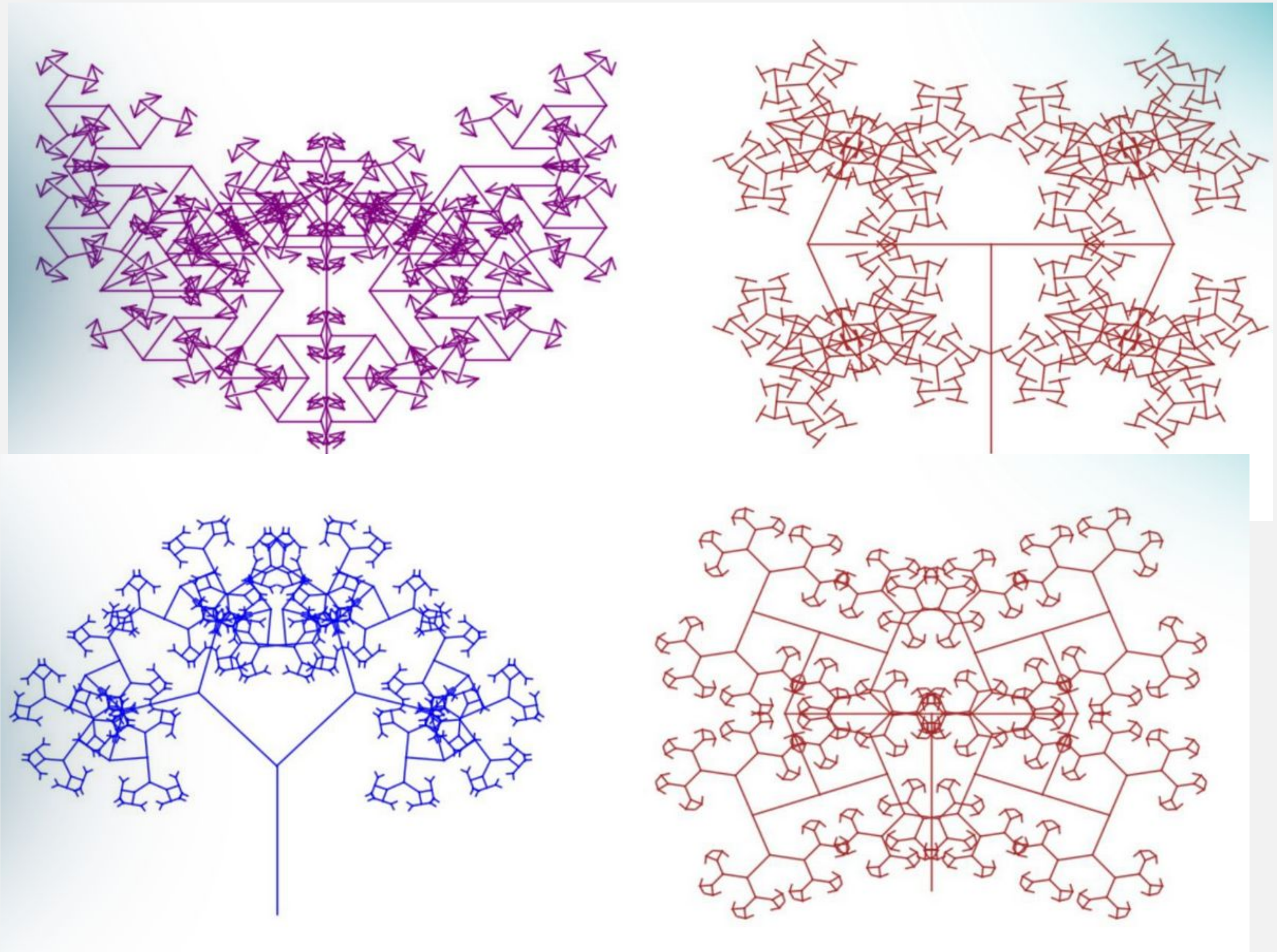
Participants: 25 school students, Lviv, Ukraine

“Quantum programming for school students” 2024

Traditional Ukrainian embroidery created using quantum programming

“Quantum programming for school students” 2023

Stochastic fractals created using quantum programming   (Girls STEM 2025)



Yulia Bartkiv


Scientific event in Lviv
dedicated to
the WORLD QUANTUM DAY
April 25-26, Lviv, Ukraine
FACULTY OF PHYSICS
LVIV UNIVERSITY
QUANTUM COMPUTERS AND QUANTUM PROGRAMMING
VIRTUAL
UKRAINE INSTITUTE FOR ADVANCED STUDY
UNESCO
МАН
WORLD QUANTUM DAY
APRIL 14


FEDERATED HIERARCHICAL SDN ARCHITECTURE


Thank you for your attention!
Knowledge is to a person what wings are to a bird.