# Quantum Computing: from Science to Technology

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# *Is quantum physics so mysterious?*

An atom simultaneously in two places ==> **Linear superposition of quantum states**

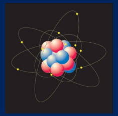
Spooky action at a distance ==> **Entanglement of two quantum systems**

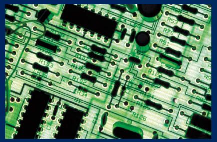
Quantum teleportation ==> **Quantum channel plus classical communication**

Quantum parallelism ==> **Massive entanglement of many quantum systems**

Quantum computing ==> **new paradigm of computing with quantum information**

Quantum technologies ==> ……………………………



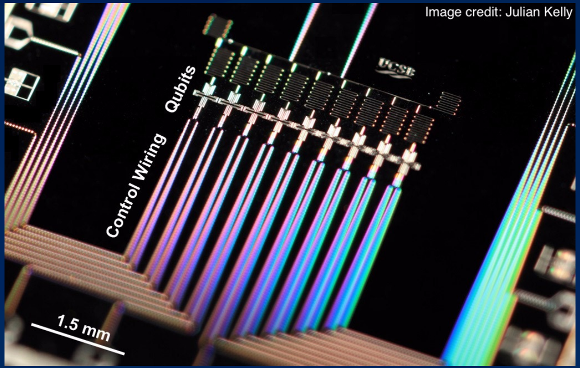


***Sorry guys, there is no mystery in quantum physics, only models and experimental verifications!***

# *Quantum computers use quantum parallelism*

$$00 \rightarrow 00$$
$$01 \rightarrow 01$$
$$10 \rightarrow 11$$
$$11 \rightarrow 10$$

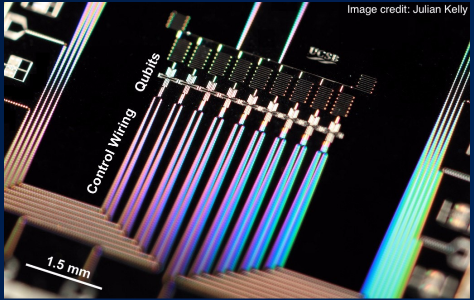
Classical controlled-NOT gate

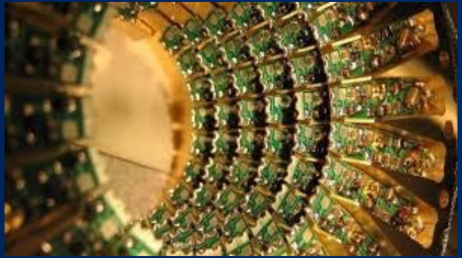


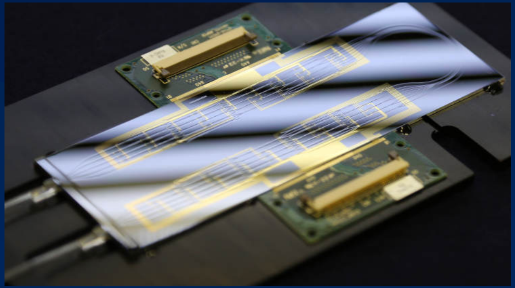

$$U_{CNOT}\left(c_{00}|00\rangle + c_{01}|01\rangle + c_{10}|10\rangle + c_{11}|11\rangle\right) =$$
$$= c_{00}|00\rangle + c_{01}|01\rangle + c_{10}|11\rangle + c_{11}|10\rangle$$

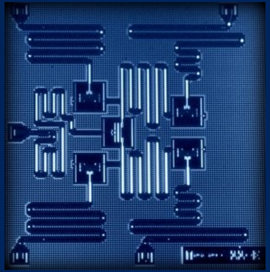
Quantum controlled-NOT gate

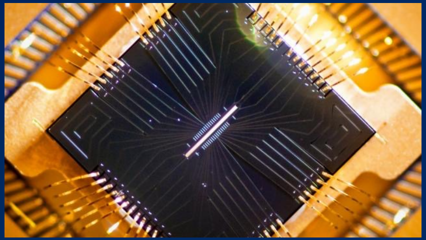
# *Quantum computers & Quantum supremacy*









***Will we ever have a quantum computer that outperforms classical computers?***

***Done by Google in US last year 2019, and  by USTC in China in years 2020-21***

# *STATEMENT OF PRINCIPLES*

I think digital quantum computers with error correction protocols will never scale up
to the many millions of physical qubits and operations needed for useful applications.

I am convinced that such universal quantum computers will never be even needed.

I think quantum advantage may be reached within 5-10 years with
Multiplatform Modular Co-Design Quantum Computers
coherent quantum annealers, digital-analog quantum computers,
digital-adiabatic quantum computers, neuromorphic quantum computers,
bio.-inspired quantum artificial life, and the playful creativity of humankind.

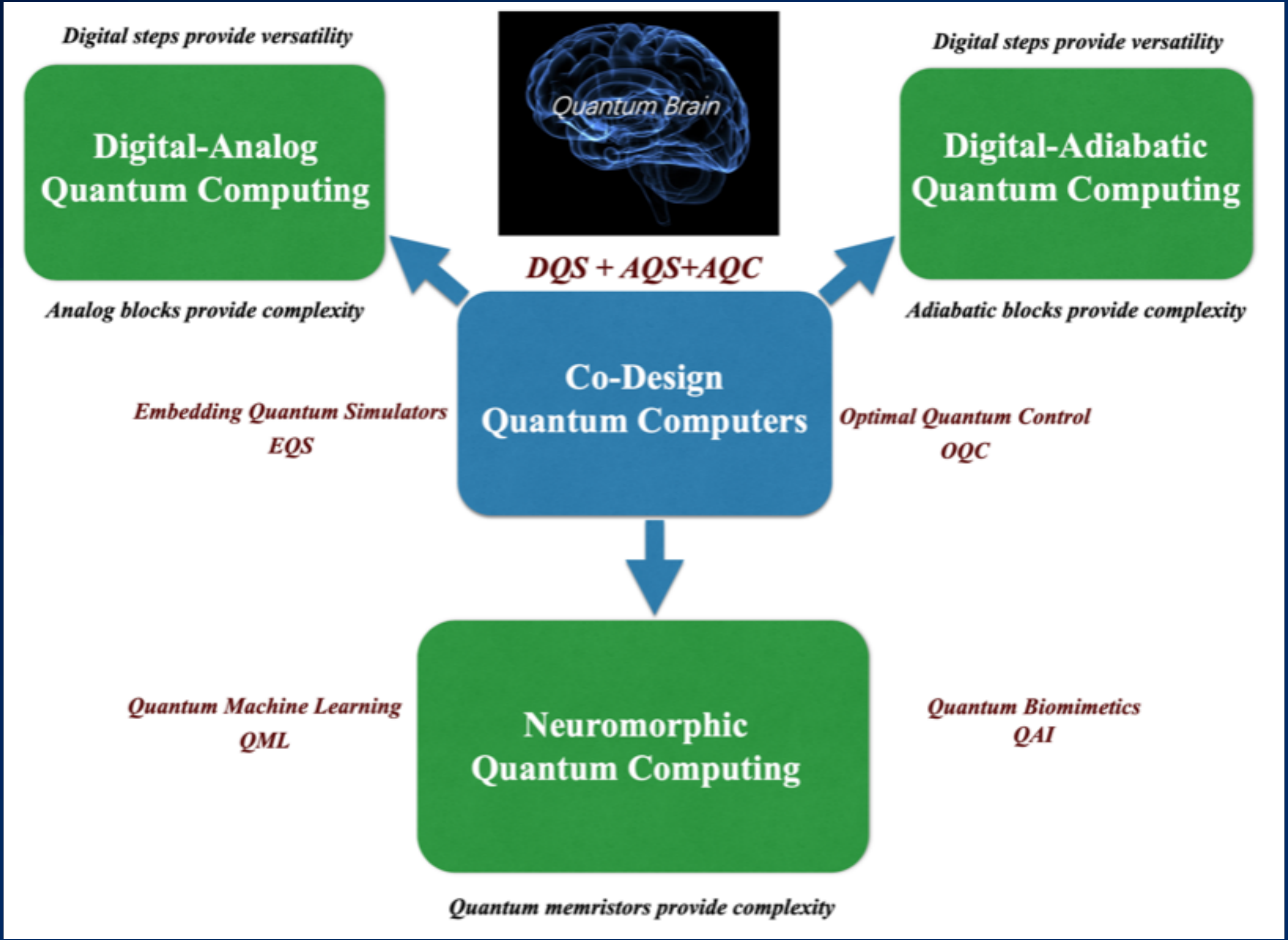
***Do I have futuristic ideas? Yes, but I work to bring them to the present.***
***You bet I do not work for posterity.***

# Multiplatform Modular Co-Design Quantum Computers

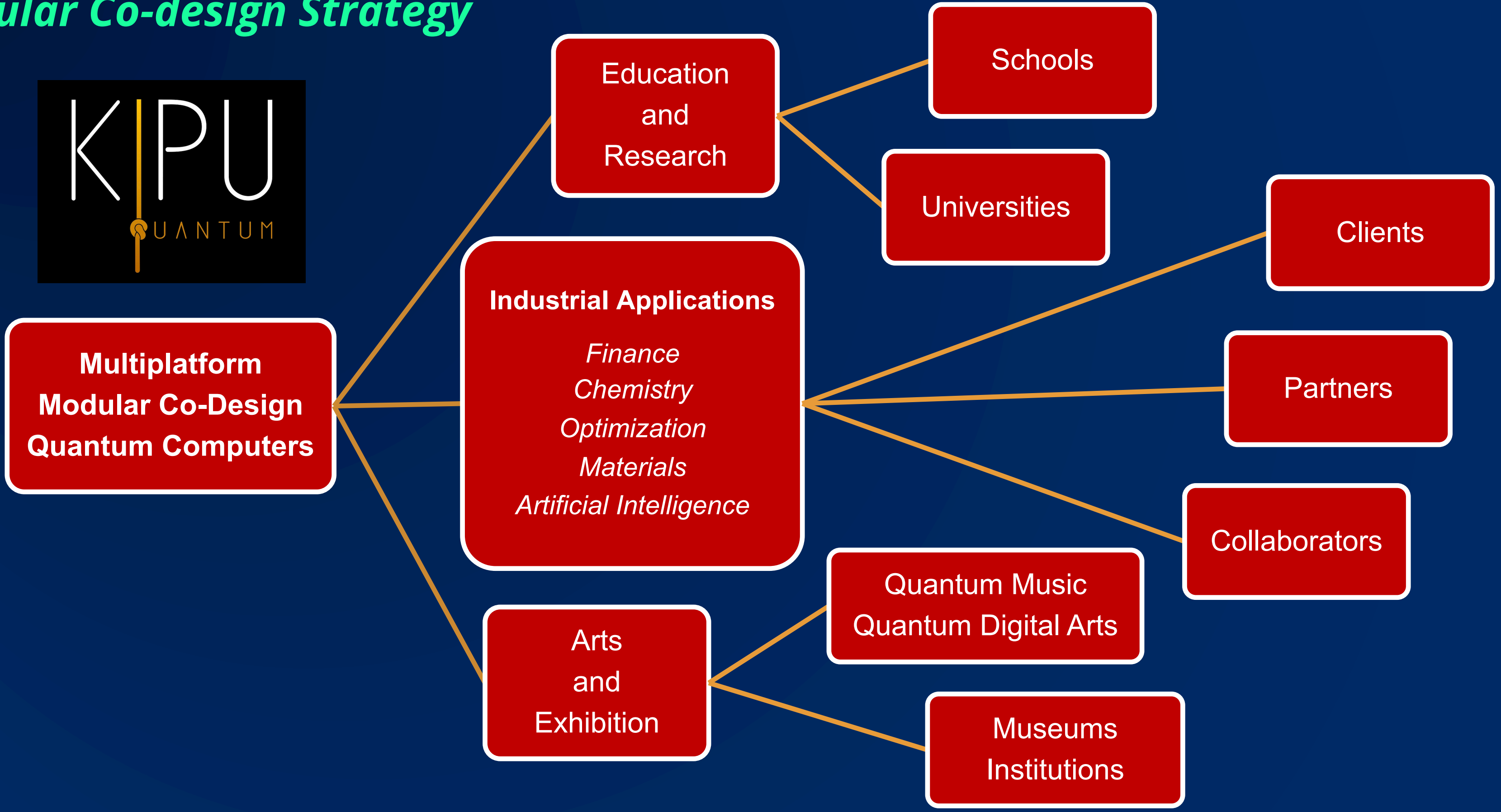
**Co-Design QC** is a quantum processor built with state-of-the-art quantum hardware and designed to perform with application-oriented quantum software.

Known **NISQ architectures** are a subset of state-of-the-art quantum computers, while **digital quantum algorithms** are arguably the worst matching to them.

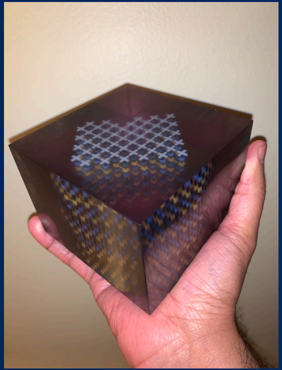
**Digital-Analog Quantum Computing** is only the tip of the iceberg of what will be Co-Design Quantum Computers, aiming at vanishing the quantum winter.

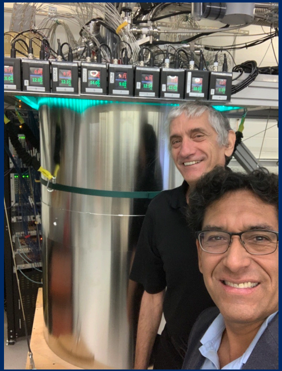

Digital steps provide versatility
Digital-Analog Quantum Computing
Analog blocks provide complexity
Quantum Brain
DQS + AQS+AQC
Digital steps provide versatility
Digital-Adiabatic Quantum Computing
Adiabatic blocks provide complexity
Embedding Quantum Simulators
EQS
Co-Design Quantum Computers
Optimal Quantum Control
OQC
Quantum Machine Learning
QML
Neuromorphic Quantum Computing
Quantum Biomimetics
QAI
Quantum memristors provide complexity

# *Modular Co-design Strategy*



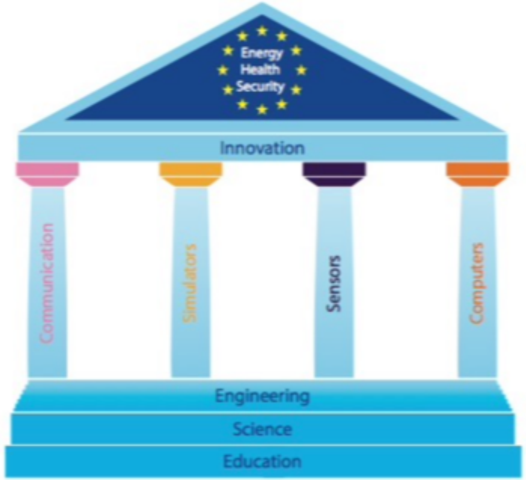
# *Influencer on Google, IonQ, Huawei, and all continents*




# *Quantum technologies*

Quantum Computing, Quantum Simulation, Quantum Communication, Quantum Sensing




*Elements of a European programme in quantum technologies.*

In quantum technologies there is room for arts, science, business, and societal interest

## *Where are we now worldwide:*
## *hype, bubble, or promising emerging technology?*


Elements of a European programme in quantum technologies.

Geopolitical present

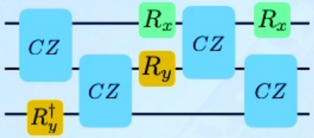
Real present

Desired future

# Digital-Analog Paradigm for Quantum Simulation & Quantum Computing

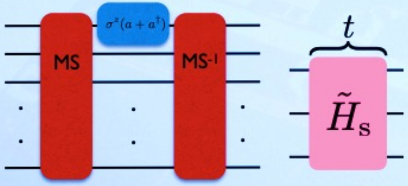
## Digital Steps

- Single-qubit rotations
- Fixed-phase multiqubit gates



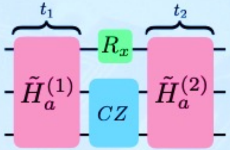

## Analog Blocks

- Discrete and continuous harmonic oscillators
- Multiqubit evolution with a continuous parameter ***t***




## DAQS and DAQC

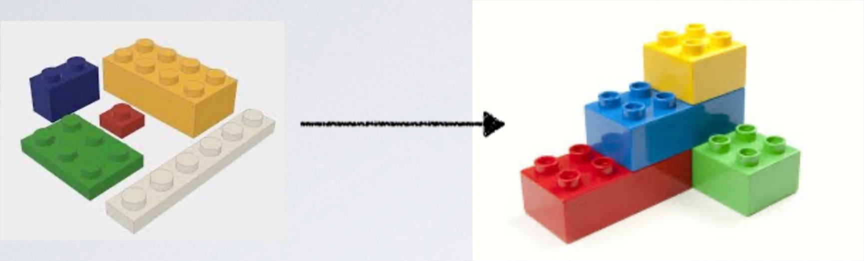
Combination of digital steps and analog blocks for quantum simulations and quantum computing




- Stepwise digital-analog approach
- Banged approach

***Let us allow complexity simulate and compute complexity***

*Can we fly with these building blocks?*



*There are times, even decades, where an airplane propeller…*

*… should be represented by an analogue version of a propeller*

# Digital-Analog Quantum Computing of QAOA

## Approximating the Quantum Approximate Optimisation Algorithm

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(Dated: February 28, 2020)

The Quantum Approximate Optimisation Algorithm was proposed as a heuristic method for solving combinatorial optimisation problems on near-term quantum computers and may be among the first algorithms to perform useful computations in the post-supremacy, noisy, intermediate scale era of quantum computing. In this work, we exploit the recently proposed digital-analog quantum computation paradigm, in which the versatility of programmable universal quantum computers and the error resilience of quantum simulators are combined to improve platforms for quantum computation. We show that the digital-analog paradigm is suited to the variational quantum approximate optimisation algorithm, due to its inherent resilience against coherent errors, by performing large-scale simulations and providing analytical bounds for its performance in devices with finite single-qubit operation times. We observe regimes of single-qubit operation speed in which the considered variational algorithm provides a significant improvement over non-variational counterparts.

**Enhanced quantum volume and save coherence time**

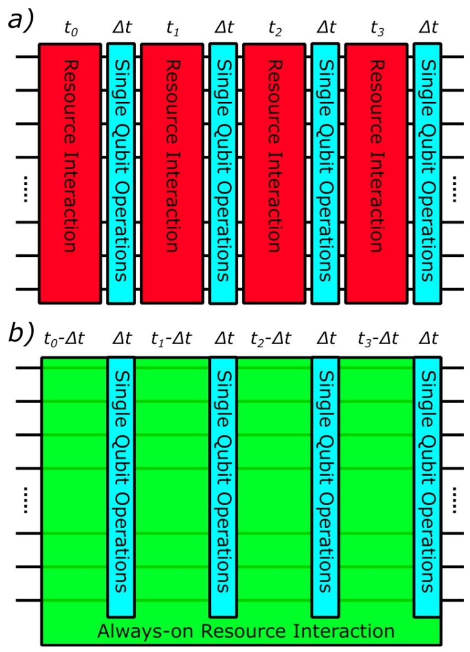


FIG. 1. The two schemes for digital analog computation. a) The stepwise or sDAQC scheme in which a series of programmable *digital* single qubit gates are applied in alternation with *analog* resource interactions. b) The always-on or bDAQC scheme in which the resource interaction is never turned off and single qubit operations are applied in parallel with the resource interactions. Performing the single qubit operations simultaneously with the resource interaction introduces coherent errors but reduces device control requirements. The first interaction block denoted with the time interval $t_0$ corresponds to the *idle* block.

# Digital-Analog Quantum Computing of QAOA

**Improving the Performance of Deep Quantum Optimization Algorithms with Continuous Gate Sets**

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[3] *Canadian Institute for Advanced Research, Toronto, ON, Canada*

(Dated: May 12, 2020)



Variational quantum algorithms are believed to be promising for solving computationally hard problems and are often comprised of repeated layers of quantum gates. An example thereof is the quantum approximate optimization algorithm (QAOA), an approach to solve combinatorial optimization problems on noisy intermediate-scale quantum (NISQ) systems. Gaining computational power from QAOA critically relies on the mitigation of errors during the execution of the algorithm, which for coherence-limited operations is achievable by reducing the gate count. Here, we demonstrate an improvement of up to a factor of 3 in algorithmic performance as measured by the success probability, by implementing a continuous hardware-efficient gate set using superconducting quantum circuits. This gate set allows us to perform the phase separation step in QAOA with a single physical gate for each pair of qubits instead of decomposing it into two *CZ*-gates and single-qubit gates. With this reduced number of physical gates, which scales with the number of layers employed in the algorithm, we experimentally investigate the circuit-depth-dependent performance of QAOA applied to exact-cover problem instances mapped onto three and seven qubits, using up to a total of 399 operations and up to 9 layers. Our results demonstrate that the use of continuous gate sets may be a key component in extending the impact of near-term quantum computers.

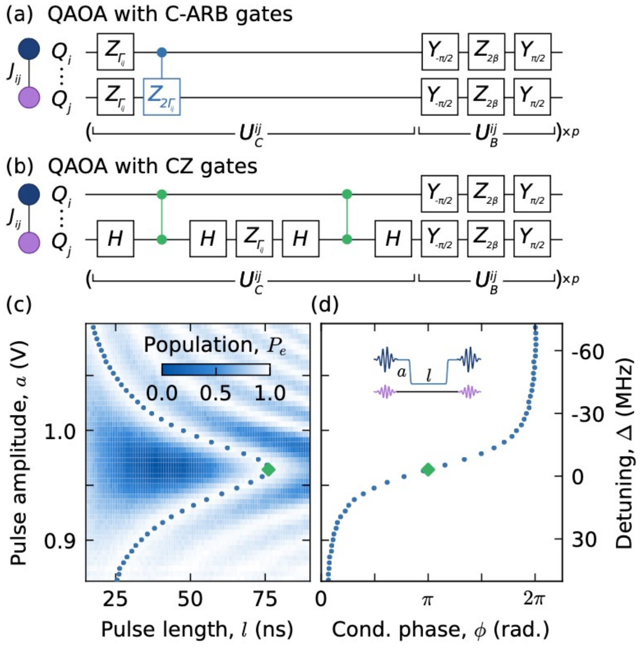
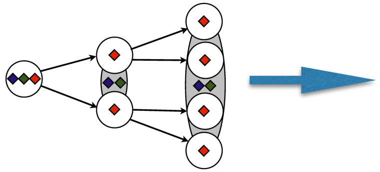


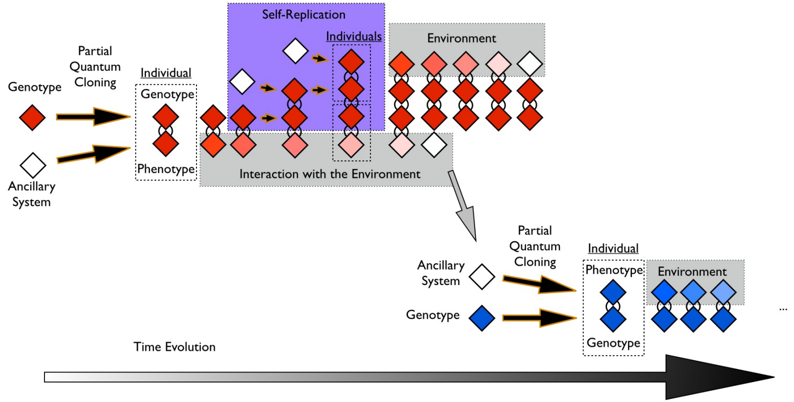

FIG. 1. (a) Quantum circuit of a layer $q$ of QAOA for the two-qubit subspace $|Q_iQ_j\rangle$, using the controlled arbitrary-phase gate (blue) to rotate the $|11\rangle$ state by an angle $2\Gamma_{ij}$ where $\Gamma_{ij} = 2\gamma_q J_{ij}$. (b) A QAOA layer with the phase-separation unitary $U_C^{ij}$ decomposed into $CZ$ gates (green) and additional Hadamard gates and single-qubit $Z$-gates. (c) Excited-state

**Interesting use of Arbitrary-Phase Gates**

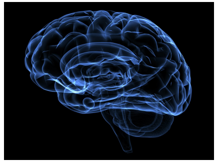
# *Partial quantum cloning* ==> *quantum artificial life (QAL)*

How to reproduce in the lab quantum cloning quantum artificial life if they are forbidden?



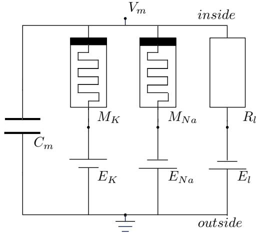


# *Quantum memristors for neuromorphic quantum technologies*

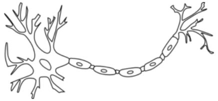


classical

Hodgkin-Huxley model
of neuron membrane

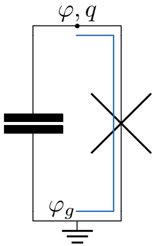



mimics

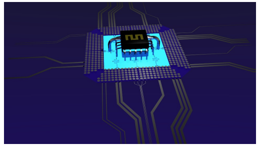


[1] Hodgkin, 1952

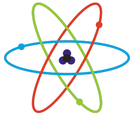
Cooper Pair Box



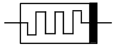

quantum



mimics



[2] Nakamura, 1999



**Classical memristors**

- history-dependent response/resistance
- processing and storage in the same device
- applications in neuromorphic computing, learning circuits, memcomputing

**Quantum memristors**

- memory feature in quantized circuits
- interplay of memory & quantum properties
- new paradigm and novel building block for quantum technologies

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