Disruptive Computing Paradigms for Earth Observation

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A brief introduction of me

- **Name**: Gabriele Meoni, PhD

- **Role**: Innovation Officer at European Space Agency
  - Bringing transformational innovation to Earth Observation applications
  - **Sections**:
    - Advanced Concepts and Studies Office
    - Φ-lab
  - IEEE GRSS Earth Science Informatics (ESI): technical committee co-chair

- **Topic of interests**:
  - Edge computing for space
  - Artificial Intelligence for Earth Observations
  - Quantum Computing

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Learning objectives

- At the end of this lesson, you will be able to:
  - Explain the concept of disruptive computing paradigms and their significance in complementing conventional computational models.
  - Analyse the foundational principles of quantum and neuromorphic computing, including basic knowledge on hardware technologies, technical challenges, and their integration with Artificial Intelligence algorithms.
  - Describe the main EO use cases for quantum and neuromorphic computing and current related research trends

Outline

- What are Disruptive Computing paradigms?
- Quantum Computing
- Neuromorphic Computing
- Conclusion

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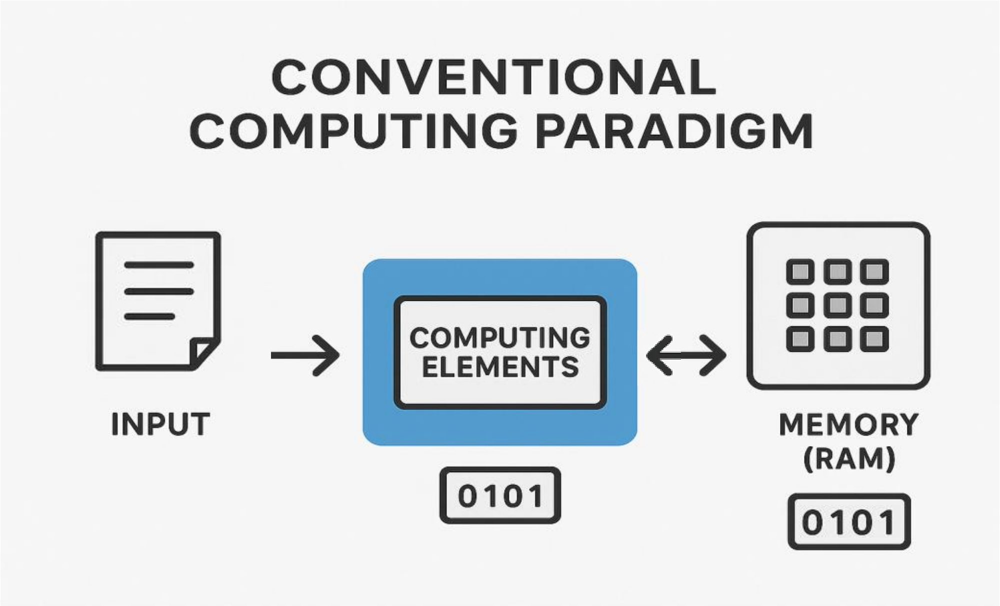
Conventional Computing (1/2)

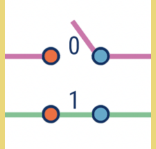


Information encoding & processing

- Using binary digits (1/0) to encode information
  - Binary representation of numbers (floating point)
  - ASCII code to represent characters and NAN
- **Mathematical operations**: computing using base 2 operations
- **Logical operations**: regulated by Boolean algebra (1 conventionally represents “True”, 0 represents “False”)

Hardware for conventional computing

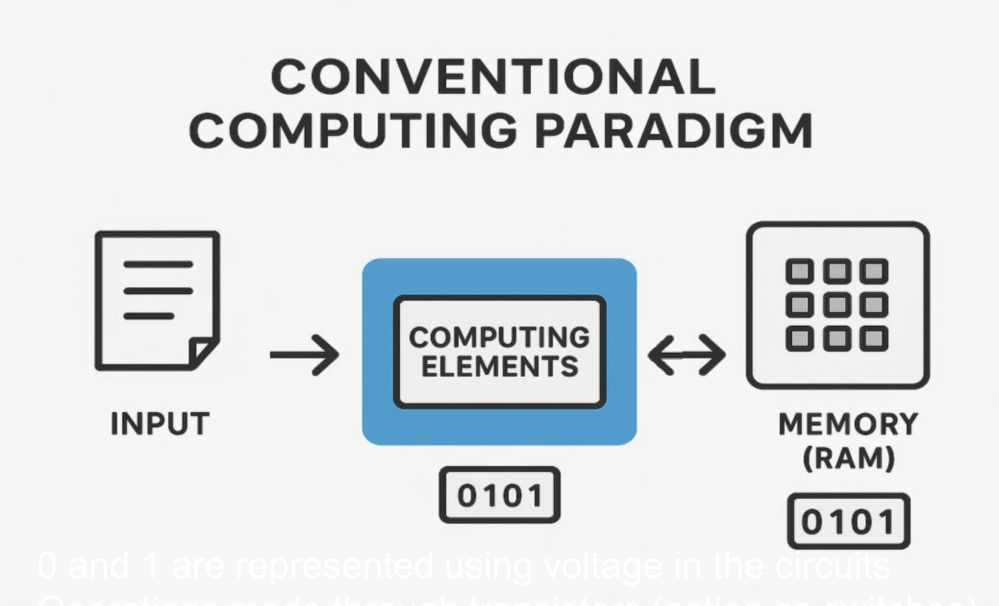
- 0 and 1 are represented using voltage in the circuits
- Operations made through transistors (acting as switches)
- Efficiently implemented in CMOS technology



Architecture of computing systems

- Many different architectures (e.g., CPUs, GPUs, …)
- All the architectures have common elements:
  - One or multiple computing elements to process information
  - Volatile memories (e.g., RAM) to contain intermediate results

Conventional Computing: Pros & Cons



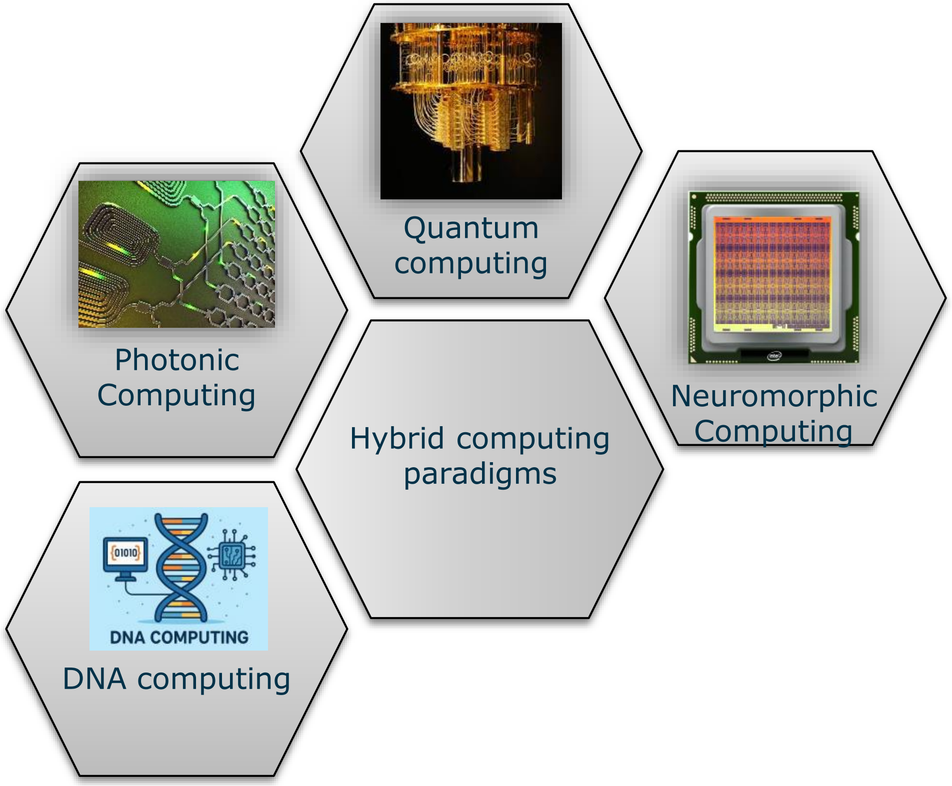
Pros

- **Based on CMOS technology**
  - Stable and reliable
  - Long heritage
  - High scalability
- It is a universal computing paradigm (Turing-complete)

Cons

- **Intrinsically limited parallelism**
  - Many modern algorithms (e.g., Dee Learning) make modern computing systems **memory-bounded** (computing performances are limited by the need of moving data out of RAM)
- For some problems (e.g., prime number factorisation), existing algorithms offer a solution whose **execution time scales exponentially the number of inputs**

What are Disruptive Computing paradigms?

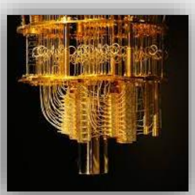


- Computing paradigms whose **underlaying principles** and/or **hardware implementation** differ from conventional computing

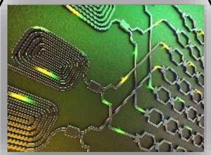
- We can consider mainly two categories:
  - **Same underlaying principles** but **different hardware implementation** from conventional computing (e.g., photonic computing encodes/processes information through light properties)
  - **Different underlaying principles** and **different hardware implementation** (e.g., quantum computing, neuromorphic computing, etc)

- Possible hybrid models exist
  - Neuromorphic quantum computing (using both principles)
  - Photonic quantum computing (quantum principles on photonic hardware)
  - …

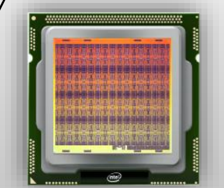
Disruptive Computing paradigms: Pros vs Cons



Quantum computing



Photonic Computing



Neuromorphic Computing

Hybrid computing paradigms

DNA computing

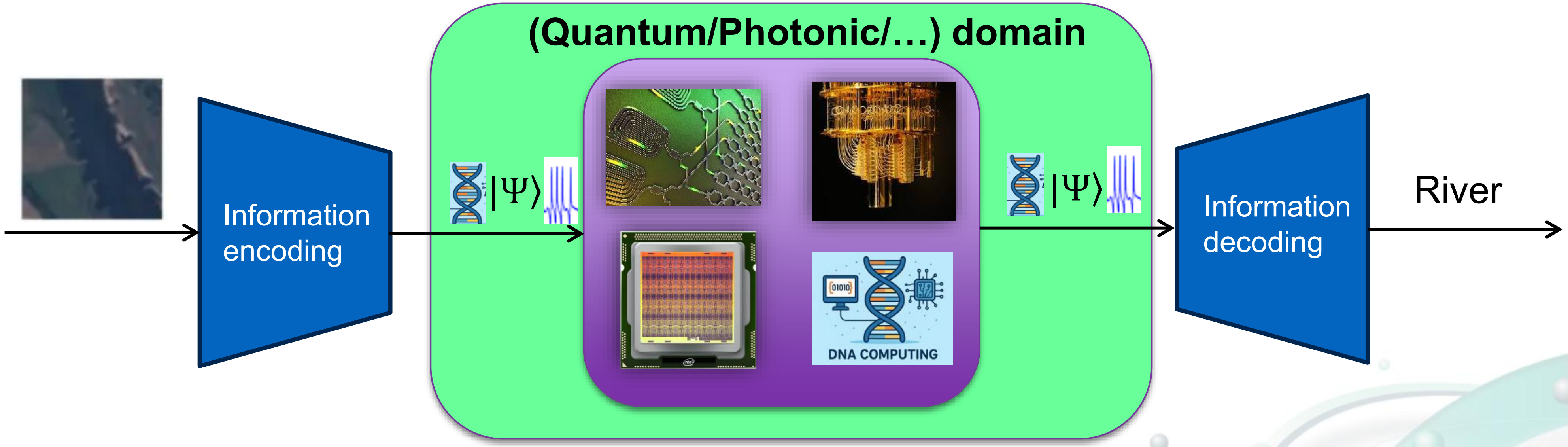
Pros

- Might feature **advantageous properties** (e.g., high power/energy efficiency, radiation tolerance, ..)
- Might be natively **highly parallel** (e.g., DNA computing, Neuromorphic computing, etc)
- They can unlock new capabilities due to novel underlaying principles
  - E.g., Some quantum computing algorithms feature **linear** time scale for problems for which conventional computing can solve with **exponential** time scale

Cons

- Most of these paradigms are **immature**
  - **Noisy** or **not scalable hardware**
    - Limited complexity of algorithms that can be tested
    - Lack of scalability often prevents operational uses
  - Limited algorithmic maturity compared to conventional counterparts

Disruptive Computing paradigms: typical chain



- **Encoding** and **decoding** are critical blocks
  - Might impact theoretical efficiency and achievable performance
  - Current open research problems for various computing paradigms

- For some of these computing paradigms, **dedicated sensors exist** (e.g., neuromorphic sensing)
  - Allow providing information directly in the encoded domain
  - Typically allowing for better efficiency/accuracy trade-offs

Outline

- What are Disruptive Computing paradigms?
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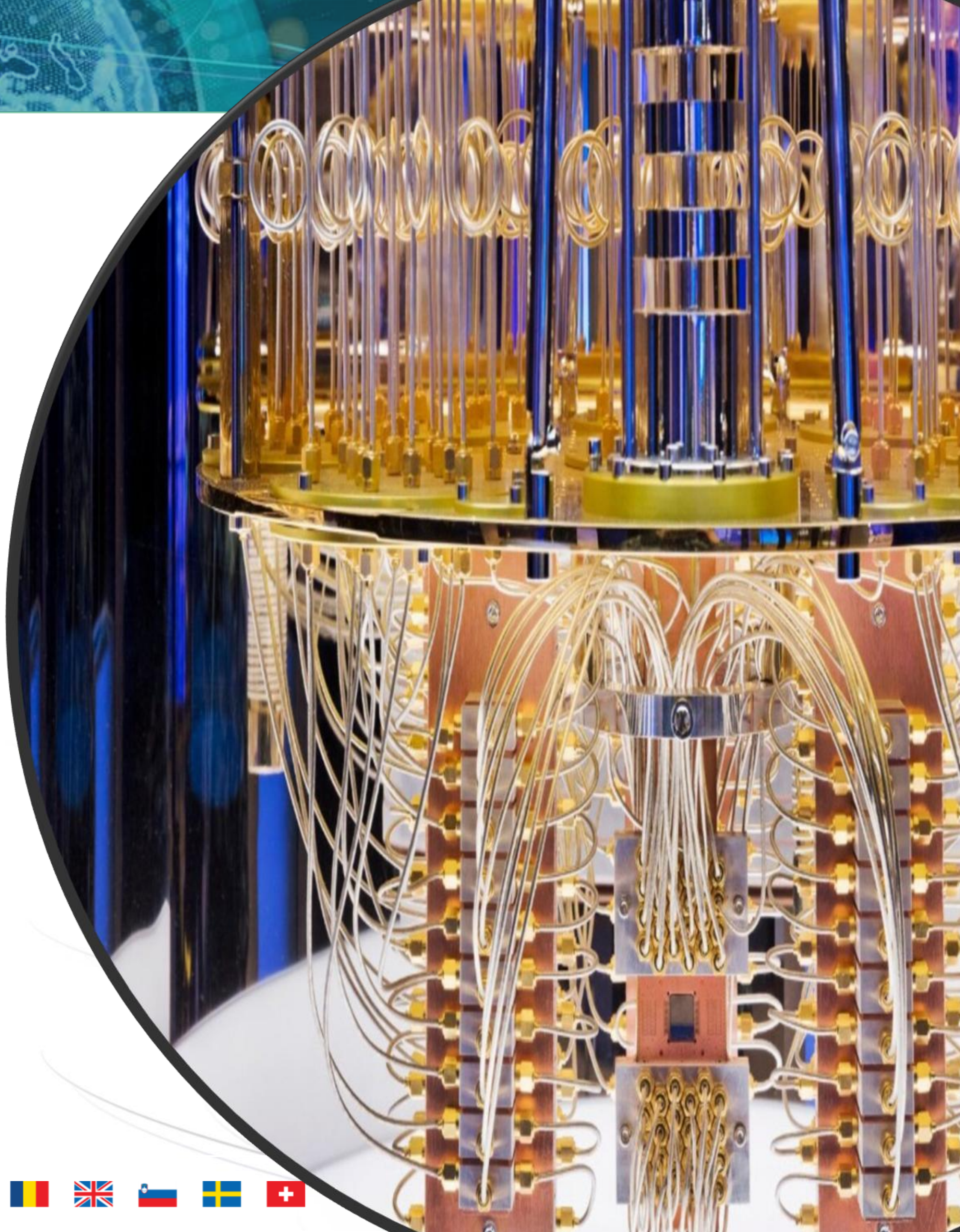
What is Quantum Computing?

Quantum Computing is a type of computations whose **operations** harness the laws of quantum **mechanics**, to **solve problems** too **complex** for classical computers.

For some problems, supercomputers are not that super. When classical computers fail, it is often due to complexity (problems with lots of variables interacting in complicated ways).

Any computational problem that can be solved by a classical computer can also be solved by a quantum computer (QC). Conversely, **any problem that can be solved by a QC can also be solved by a classical computer, at least in principle given enough time.**



Where Quantum Computing works?

According to IBM there are **four areas** where **quantum computing** would seem to be able to make **significant unique contribution**.

Mathemathical Models

Mathematical models and data structures. Particularly tied to **machine learning** (ML) constructs and efforts to factor, rank, or even classify symmetric groups at scale. **Quantum computers would seem to have a significant advantage in both speed and accuracy.**

Simulating Nature

Nature is complex with interdependent components in massive numbers that make accurate weather forecasting even hours in advance relatively impossible. But QC can digest huge amounts of data over short periods of time, potentially filling data gaps in ways that don't compromise the results. **This application will identify the best paths to addressing complex issues, like climate change and predicting when weather catastrophes are likely to hit.**

Complex problems where quantum computing could perform the role of accelerator for the parts of these complex problems that lend themselves to what only a quantum computer can do.

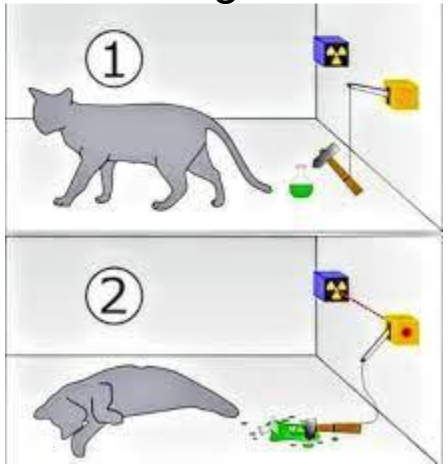
Sampling types of population analysis, analyse large samples more quickly, potentially increasing both the speed and accuracy of the related effort

Other

Population Analysis

Quantum bits and Superposition (1/2)

Schrödinger's cat



Credit: Wikipedia

- **Schrödinger's cat explanation**
  - A cat is placed inside a sealed box along with a radioactive atom, a Geiger counter, and a vial of poison.
  - If the atoms decades, the counter triggers a mechanism breaking the vial, releasing the poison and killing the cat
  - Opening the box also breaks the vial, killing the cat

- **Explanation**
  - Until the box is closed, the cat is in the "dead (0)" or "alive (1)" states at the same time (**superposition**)
  - **Measurement**: Opening the box constitutes a measurement, forcing the system to **collapse** into one of the two possible outcomes: the cat is either alive or dead

Quantum bits and Superposition (2/2)

Qubit

A classical bit can be in two states, it can be either zero or it can be one. A quantum bit or qubit, however, can be in a sort of zero state and in a one state at the same time. This situation is called a superposition of (quantum) states. Qubits have some very particular properties: for instance, it is not possible to make copies of qubits. This is sometimes very useful, such as when you want to keep information private, and in fact this property is used in quantum cryptography. But it is also sometimes very annoying, because if you can't copy a qubit, you can't use this copying mechanism as a way to fix errors.

Superposition

In quantum mechanics, superposition means a system can exist in multiple states simultaneously—like a wave combining amplitudes. Every quantum state is a linear combination of other valid states.

Why this is important: For qubits, this enables parallelism: a single qubit can represent both 0 and 1 at once, allowing quantum algorithms to evaluate multiple conditions simultaneously and exponentially expand computational reach.

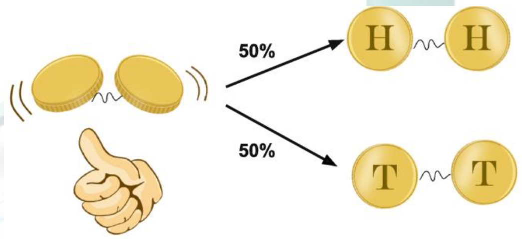
$$|\Psi\rangle = \alpha \cdot |0\rangle + \beta \cdot |1\rangle$$

Qubit

- When measured, $|\Psi\rangle$ collapses to $|0\rangle$ and $|1\rangle$ with probability $|\alpha|^2$ and $|\beta|^2$

Entanglement

Quantum entanglement is a special connection between two qubits. There are many ways of generating entanglement. One way is to bring two qubits close together, to perform an operation to entangle them and then move them apart again. When they are entangled, you can move them arbitrarily far away from each other and they will remain entangled. This entanglement will manifest itself in the outcomes of measurements on these qubits. When measured, these qubits will always yield zero or one randomly, but no matter how far away they are from each other, they will always yield the same outcome.

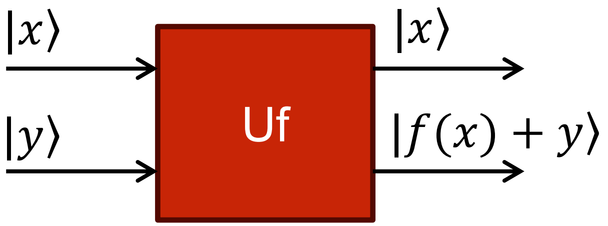


Quantum Gates

- **Quantum Gate:**
  - Modelled as **linear**, **invertible** operator with unitary **eigenvalues**, ensuring the preservation of quantum state norms
  - There exist well-known gates acting on **single qubits** (e.g., Hadamard, Phase, T) and **multiple qubits** (e.g., CNOT, Toffoli), each performing specific transformations.
  - A **universal set of quantum gates**—such as {H, T, CNOT}—can be composed to approximate **any unitary operation** on qubits
    - If a quantum computing hardware can implement a universal set of quantum gates, it is said **universal quantum computer**

The power of Quantum Computing(1/3)

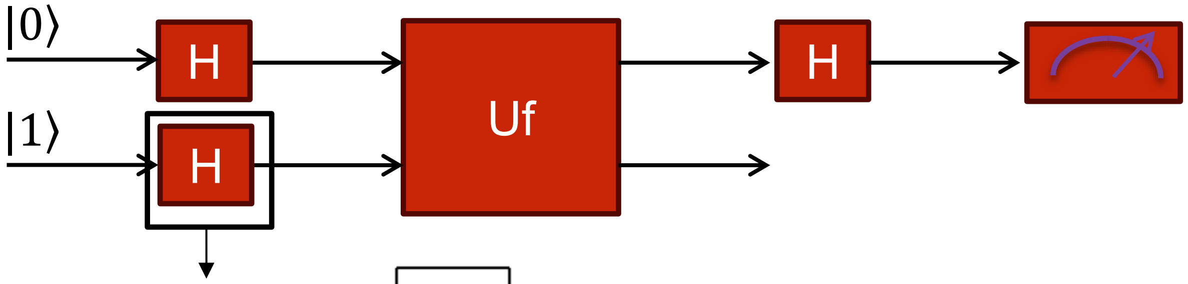
- Let's take a binary function $f(x)$. **Problem**: $f(0) = f(1)$?
- Conventional computing requires to test $f(0)$ and $f(1)$
- What about quantum computing?
- **Quantum Oracle**



Invertible blocks such as: $U_f(|x\rangle|y\rangle) = |x\rangle|y + f(x)\rangle$

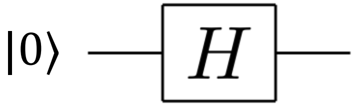
The power of Quantum Computing (2/3)

Deustch’s algorithm



Hadamard Gate

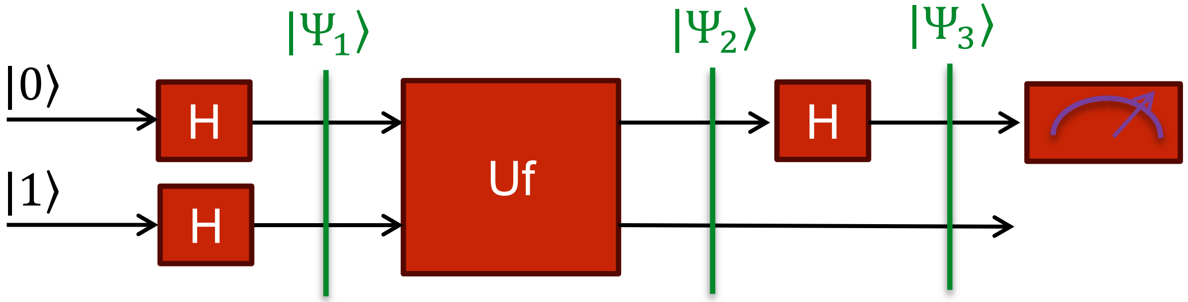
Single qubit gate described by the matrix $\mathrm{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$



Starting from the single state qubit $|0\rangle$, the Hadamard gate returns the superposition of two states, namely the so-called *plus* state $|+\rangle$, i.e.

$$H|0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 0 \end{pmatrix} + \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle = |+\rangle$$

Deustch’s algorithm



- $|\Psi_1\rangle = H|0\rangle \otimes H|1\rangle = |+\rangle|-\rangle$
- $|\Psi_2\rangle = U_f(|+\rangle|-\rangle) = \frac{1}{\sqrt{2}} \cdot (U_f(|1\rangle\,|-\rangle + |0\rangle\,|-\rangle)$=$\frac{1}{\sqrt{2}} \cdot (\,|1\rangle\,(|-\rangle + f(|1\rangle)) + |0\rangle\,(|-\rangle + f(|0\rangle)))$ =

  = $\frac{1}{\sqrt{2}} \cdot ((-1)^{f(0)}\,|0\rangle$+$(-1)^{f(1)}\,|1\rangle)$.
  - If $f(|1\rangle) = f(|0\rangle)$, $|\Psi_2\rangle$=$\pm|+\rangle|-\rangle$
  - If $f(|1\rangle) \neq f(|0\rangle)$, $|\Psi_2\rangle$=$\pm|-\rangle|-\rangle$

- $|\Psi_3\rangle = (H \otimes \mathbf{I})|\Psi_2\rangle =$
  - $|0\rangle|-\rangle$, If $f(|1\rangle) = f(|0\rangle)$
  - $|1\rangle|-\rangle$, If $f(|1\rangle) \neq f(|0\rangle)$

In a single step, you can identify whether $f(|1\rangle) = f(|0\rangle)$ by looking at the output of the circuit (0, f is constant, 1 f is not constant)

Expected Advantages of Quantum Computing

Most relevant Quantum Advantages that will impact EO.

Speed — Quantum computers can perform **specific calculations** much **faster** than classical computers

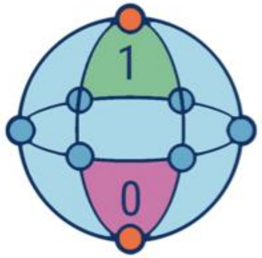
Accuracy — QCs can **perform simulations of complex systems with a much higher degree of accuracy** (e.g. they can compute the interactions between individual **particles**)

Efficiency — Quantum computers can perform certain calculations using **fewer resources than classical computers** (Energy Efficiency)

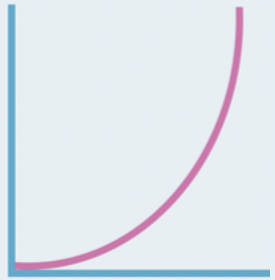
New opportunities — Quantum computing can solve a class of **problems that are not possible with classical computing** (e.g. factoring large numbers, Optimization in Complex, High-Dimensional Spaces)

Differences between Quantum and Conventional Computing

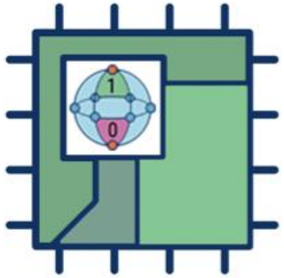
Quantum Computing



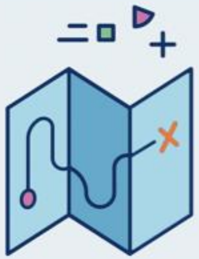
Calculates with qubits, which can represent 0 and 1 at the same time



Power increases exponentially in proportion to the number of qubits



Quantum Computers have high error rates and need to be kept ultracold



Well suited for tasks like optimization problems, data analysis and simulations

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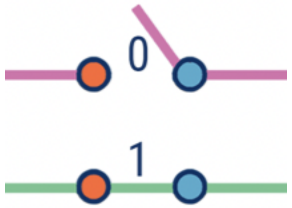
Calculates with transistors, which can represent either 0 or 1



Power increases in a 1:1 relationship with the number of transistors

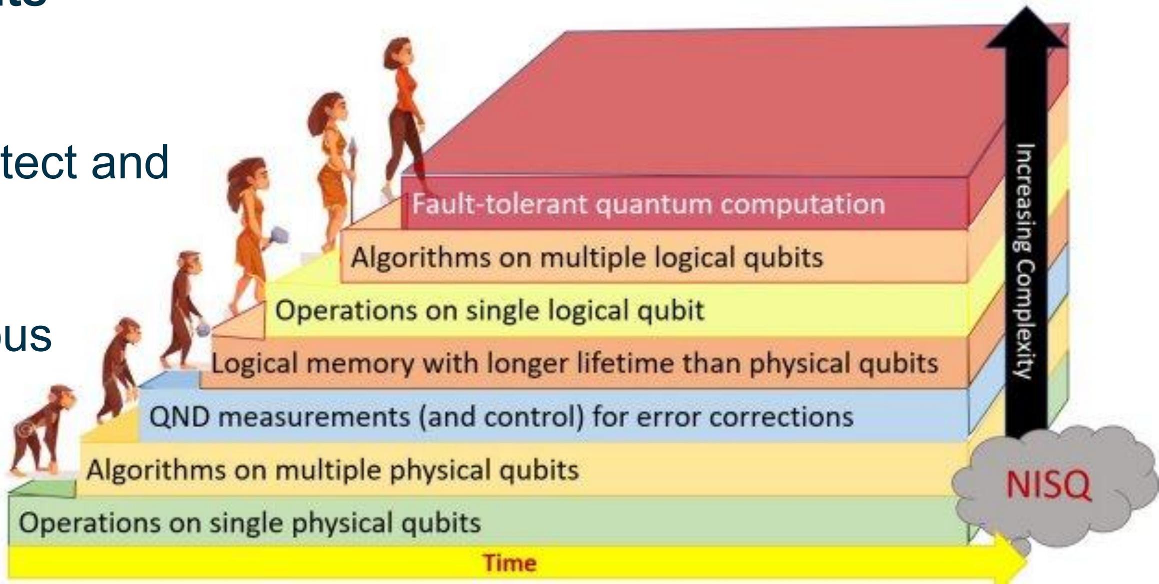
Conventional Computers have low error rates and can operate at room temperature

Most everyday processing is best handled by conventional computers

Conventional Computing

Quantum Computing hardware

- QC is in the **Near-Intermediate-Scale Quantum (NISQ)** era**:**
  - The number of qubits in a quantum computer is limited depending on technology
  - Qubits are **sensitive to noise** that:
    - Limits the coherence time (time for which phase of qubit is conserved)
    - Limits the relaxation time (time for which the qubit goes from $|1\rangle$ to $|0\rangle$.
    - Such noise sensitive qubits are called **physical qubits**
  - Noise correction techniques exist (e.g., surface codes):
    - They encode the information on multiple qubits to detect and correct errors without measuring the quantum state
    - The result is a **logical qubit**
    - A surface code capable to correct up to 2 simultaneous errors requires **25 physical qubits**!
  - There is no an established technology for quantum hardware. Many solutions exist with different trade-offs between noise resistance, scalability, etc.



Credit: au, J.W.Z., Lim, K.H., Shrotriya, H. et al. NISQ computing: where are we and where do we go?. AAPPS Bull. ***32****, 27 (2022). https://doi.org/10.1007/s43673-022-00058-z*
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Quantum Computing hardware technologies

Superconducting Qubits
Mature fabrication, fast gates
Challenges: cooling, scaling coherence

Trapped Ions
High fidelity, long coherence
Challenges: slow gate speeds, scaling

Neutral Atoms
Scalable arrays, flexible connectivity
Challenges: control precision

Photonic Qubits
Room-temperature operation, telecom-ready
Challenges: photon loss, error correction

Spin Qubits (Semiconductor)
Silicon compatibility, small footprint
Challenges: uniformity, noise

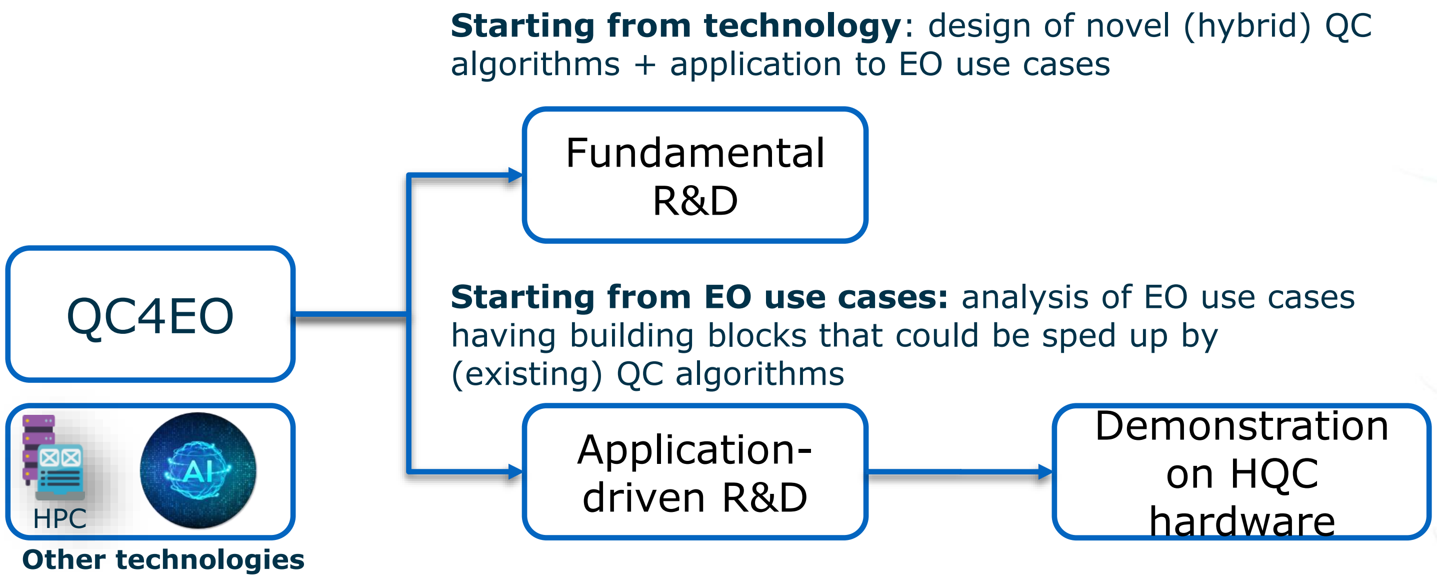
Topological quantum computers
Intrinsically noise resistant, potentially scalable
Challenges: first prototyping under experimentation

QC4EO: the Φ-lab's approach

- Earth Observation (EO) imagery is typically complex (large imagery, with complex features)

- Research on QC4EO is still at its infancy:
  - Limited QC algorithms availability
  - Existing algorithms cannot be deployed on QC hardware due to its limitation

- Because of that, the Φ-lab's approach is as follows:



Fundamental algorithms: quantum diffusion models, noise filtering, ...

Use cases: rapid fluid dynamics computation for DTE, SAR Raw data processing, Multiple View Geometry, Mission Planning

Outline

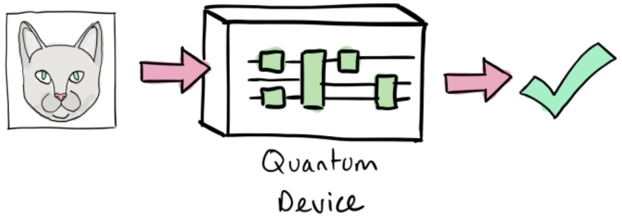
- What are Disruptive Computing paradigms?
- Quantum Computing
  - Quantum Computing: fundamental R&D
  - Quantum Computing: application-driven R&D
- Neuromorphic Computing
- Conclusion

Quantum Machine Learning

Quantum machine learning is a research area that **explores the interplay of ideas from quantum computing and machine learning.**

Why Quantum Machine Learning

- Aiming to enhance AI algorithms leveraging quantum properties (e.g., superposition, entanglement)
- As shown before, such properties might lead to quantum speed up compared to conventional ML algorithms

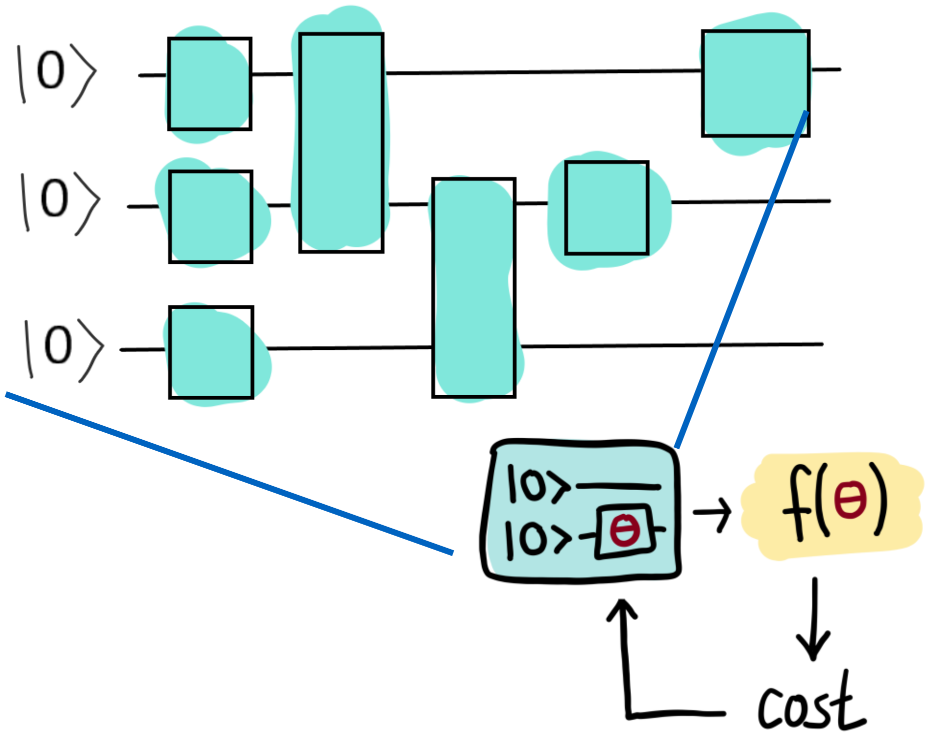


Using QC like neural networks

In the modern viewpoint, quantum computers can be used and trained like neural networks. We can systematically adapt the physical control parameters, such as an electromagnetic field strength or a laser pulse frequency, to solve a problem.

For example, a trained circuit can be used to classify the content of images, by encoding the image into the physical state of the device and taking measurements.

Variational Quantum Circuits

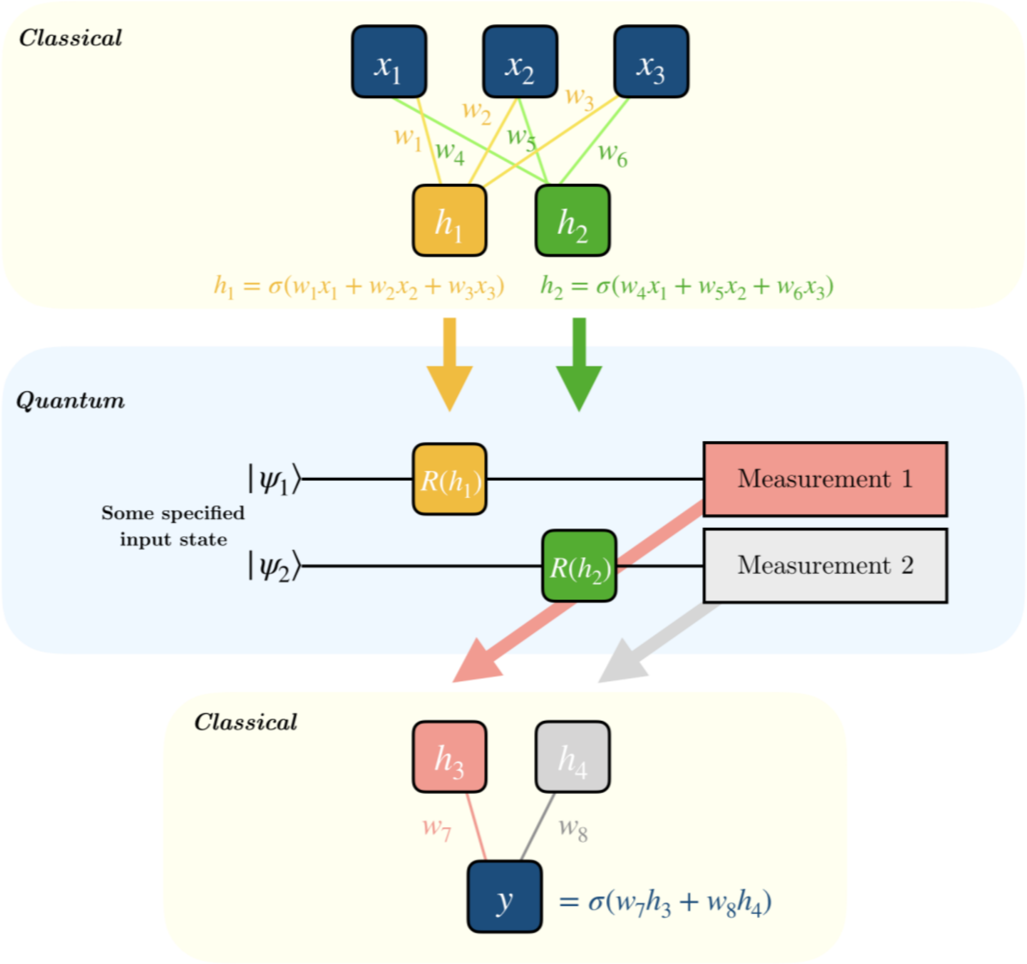


Variational or parametrized quantum circuits are quantum algorithms that depend on free parameters. Like standard quantum circuits, they consist of three ingredients:

1. Preparation of a fixed initial state (e.g., the vacuum state or the zero state).
2. A quantum circuit $U(\theta)$, parameterized by a set of free parameters θ.
3. Measurement of an observable the output.

Variational circuits are trained by a classical optimization algorithm that makes queries to the quantum device. The optimization is usually an iterative scheme that searches out better candidates for the parameters θ with every step.

Hybrid quantum-classical Neural Networks



https://qiskit.org/textbook/ch-machine-learning/machine-learning-qiskit-pytorch.html

To create a quantum-classical neural network, one can implement a hidden layer for our neural network using a parameterized quantum circuit or variational circuit.

The outputs from our neural network's previous layer will be collected and used as the inputs for our parameterized circuit. The measurement statistics of our quantum circuit can then be collected and used as inputs for the following layer.

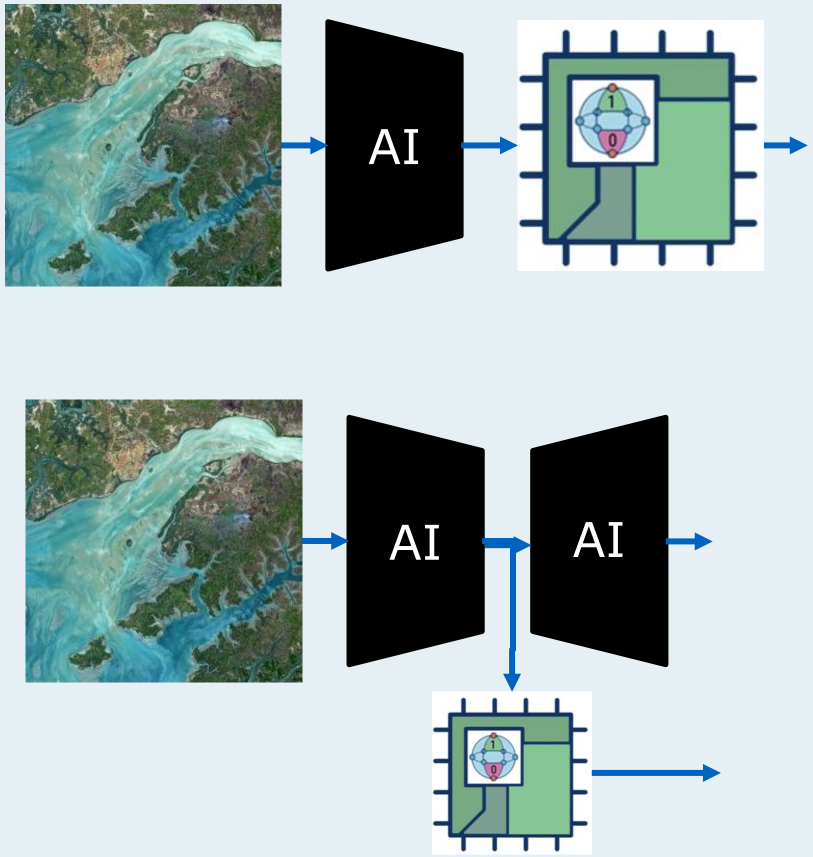
This approach allows to overpass some limitations of QC and allows also to work with complex and heavy data, that at the moment are difficult to feed into a QC.

Moreover, all the classical training algorithm can be applied without any particular modification.

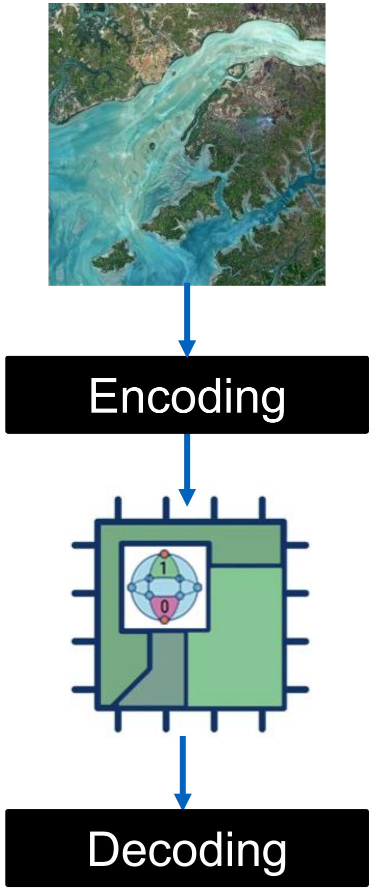
Quantum Machine Learning for EO

Quantum machine learning is a research area that **explores the interplay of ideas from quantum computing and machine learning. We adopted this vision and applied it to Earth Observation.**

Late Hybrid Schemes



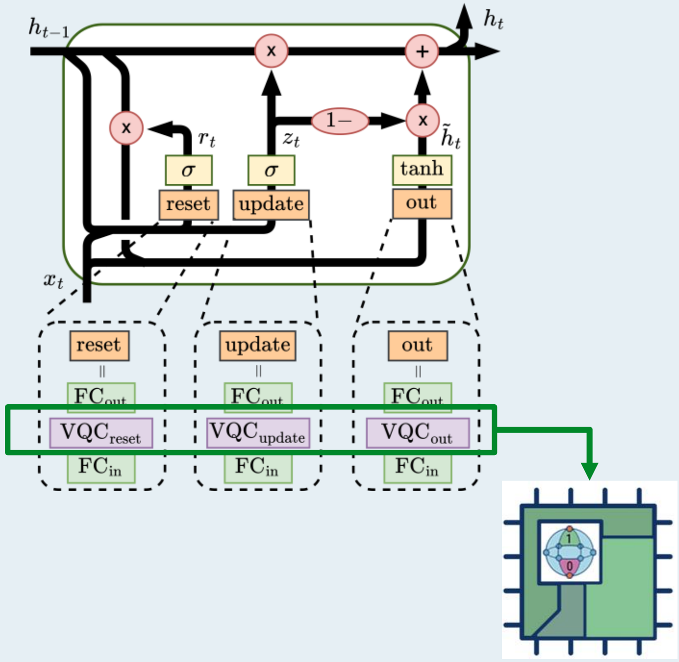
Fully Quantum Scheme



Early Hybrid Schemes

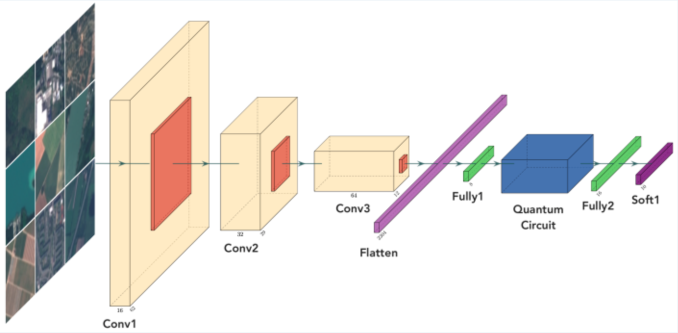
Nodes of AI model are empowered by QC

LSTM Model

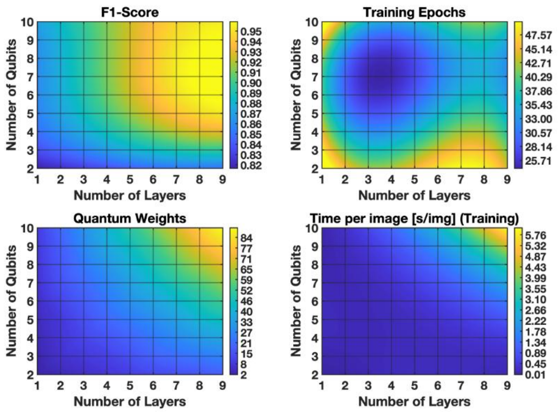


Some fundamental algorithms under study

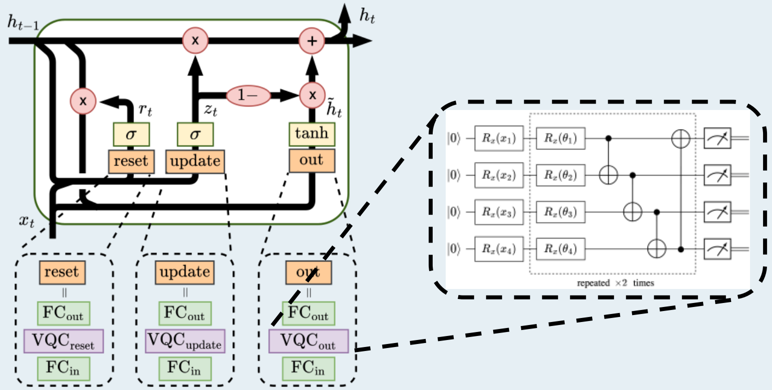
Hybrid Quantum Classifiers



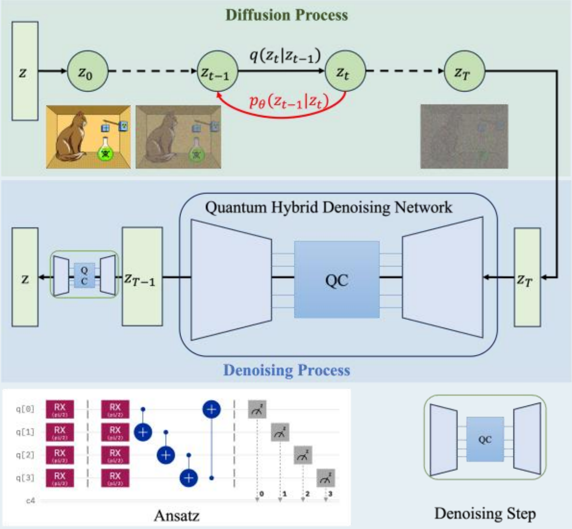
Quantum Hyperparameters Optimization



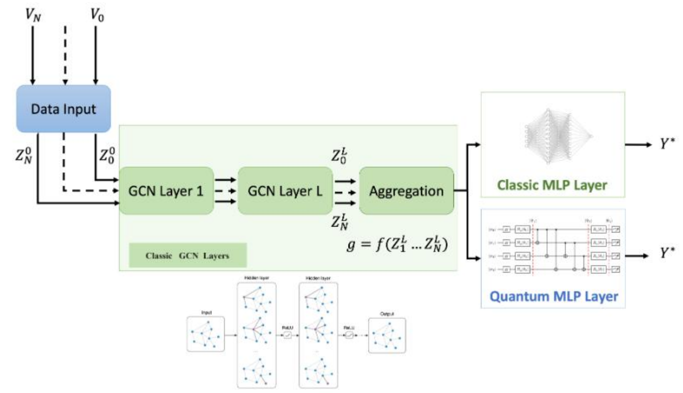
Quantum Recurrent Neural Networks



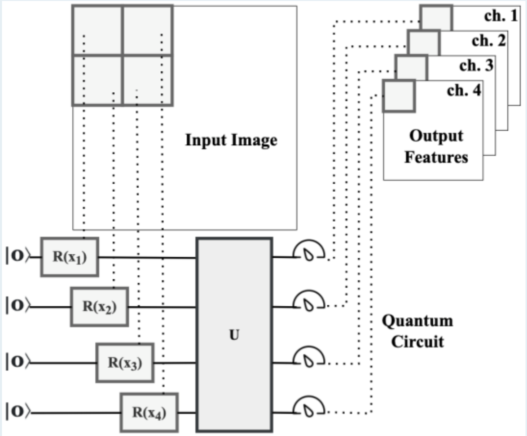
Quantum Generative AI



Quanvolutional Neural Network



Quantum Graph Neural Network



Current research trends

- The number of papers on Quantum Machine Learning for Earth Observation is growing exponentially (up to 32 papers in 2024)
- Multiple sensors and EO Task are currently investigated
- **Main findings**:
  - the vast majority of current papers simulate quantum computing on conventional computers (noise free) overestimating performances
  - The vast majority works on simplified tasks (e.g., subsampled datasets) making difficult to support the fact there is a *quantum advantage* for AI

Source: A. Sebastianelli et al. “Quantum Machine Learning for Earth Observation: A Review and Future Prospects” (under review)

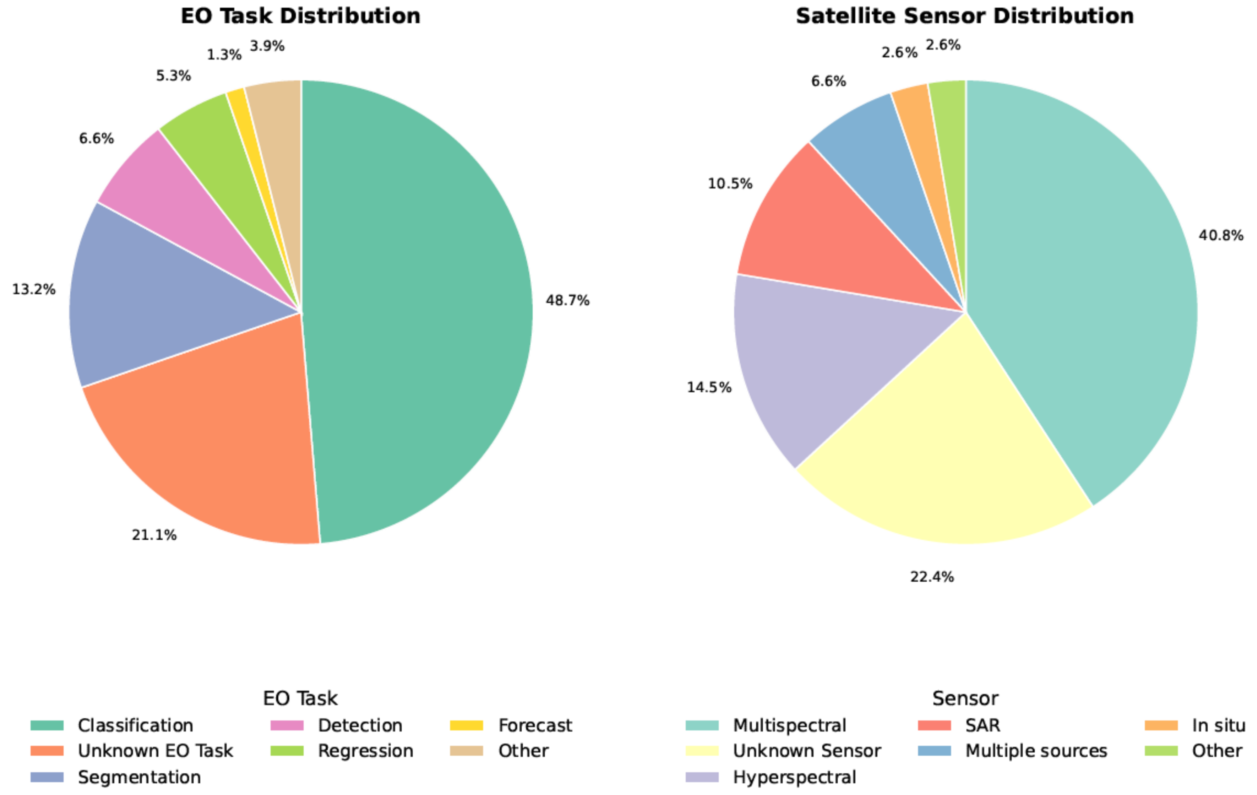
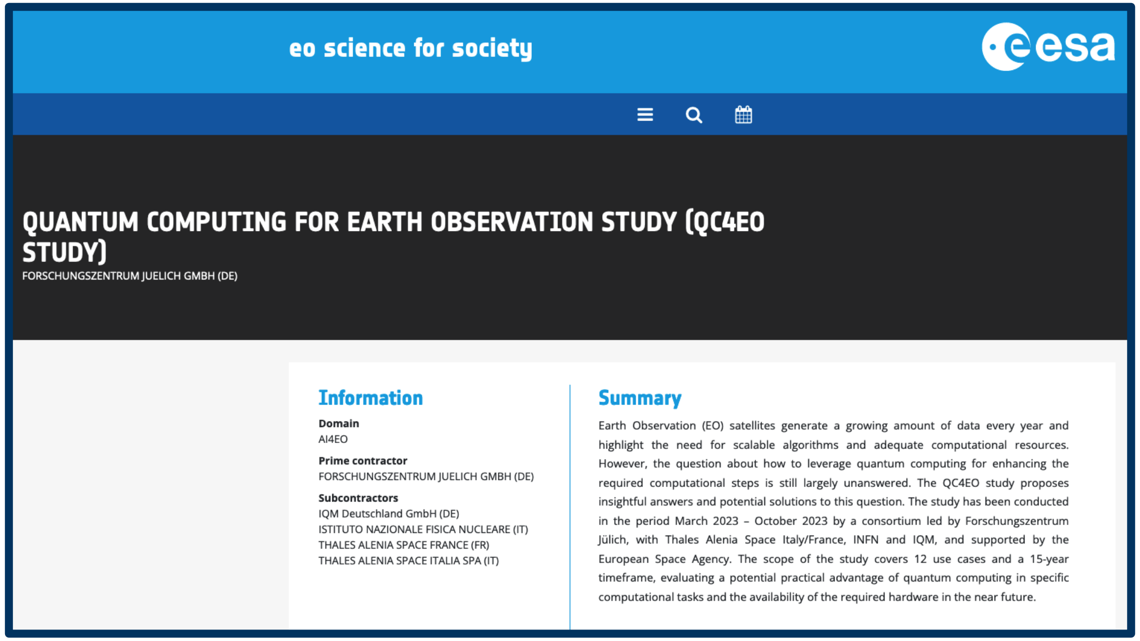


Figure 6. Distribution of QML applications across EO sensor modalities (left) and task types (right).

Outline

- What are Disruptive Computing paradigms?
- Quantum Computing
  - Quantum Computing: fundamental R&D
  - Quantum Computing: application-driven R&D
- Neuromorphic Computing
- Conclusion

Quantum computing studies



eo science for society

QUANTUM COMPUTING FOR EARTH OBSERVATION STUDY (QC4EO STUDY)

FORSCHUNGSZENTRUM JUELICH GMBH (DE)

Information

Domain
AI4EO

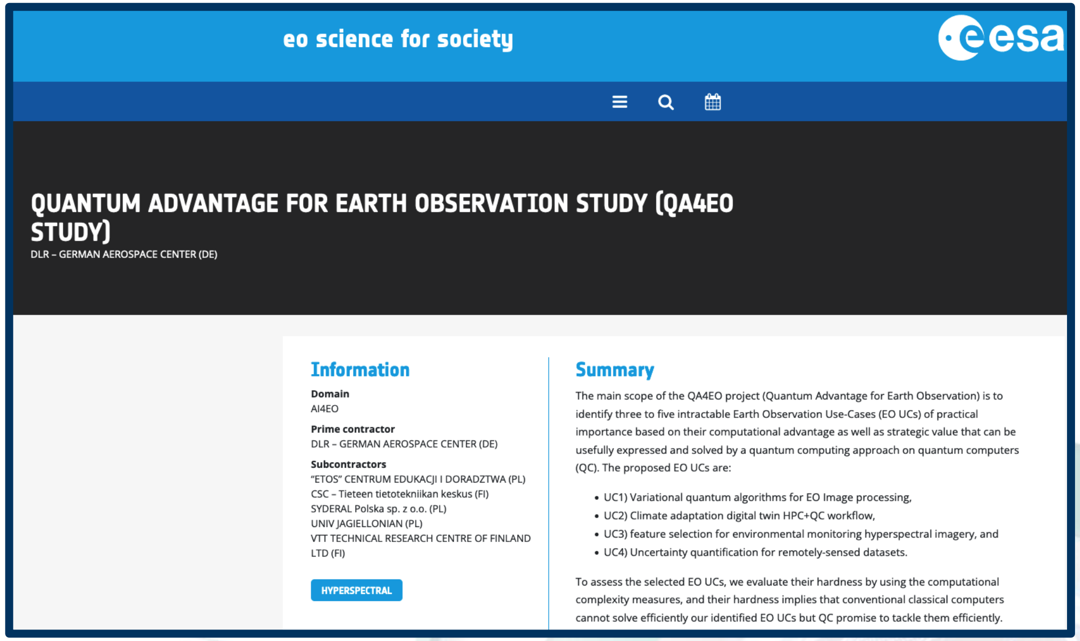
Prime contractor
FORSCHUNGSZENTRUM JUELICH GMBH (DE)

Subcontractors
IQM Deutschland GmbH (DE)
ISTITUTO NAZIONALE FISICA NUCLEARE (IT)
THALES ALENIA SPACE FRANCE (FR)
THALES ALENIA SPACE ITALIA SPA (IT)

Summary

Earth Observation (EO) satellites generate a growing amount of data every year and highlight the need for scalable algorithms and adequate computational resources. However, the question about how to leverage quantum computing for enhancing the required computational steps is still largely unanswered. The QC4EO study proposes insightful answers and potential solutions to this question. The study has been conducted in the period March 2023 – October 2023 by a consortium led by Forschungszentrum Jülich, with Thales Alenia Space Italy/France, INFN and IQM, and supported by the European Space Agency. The scope of the study covers 12 use cases and a 15-year timeframe, evaluating a potential practical advantage of quantum computing in specific computational tasks and the availability of the required hardware in the near future.

https://eo4society.esa.int/projects/qc4eo-study/



eo science for society

QUANTUM ADVANTAGE FOR EARTH OBSERVATION STUDY (QA4EO STUDY)

DLR – GERMAN AEROSPACE CENTER (DE)

Information

Domain
AI4EO

Prime contractor
DLR – GERMAN AEROSPACE CENTER (DE)

Subcontractors
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UNIV JAGIELLONIAN (PL)
VTT TECHNICAL RESEARCH CENTRE OF FINLAND LTD (FI)

HYPERSPECTRAL

Summary

The main scope of the QA4EO project (Quantum Advantage for Earth Observation) is to identify three to five intractable Earth Observation Use-Cases (EO UCs) of practical importance based on their computational advantage as well as strategic value that can be usefully expressed and solved by a quantum computing approach on quantum computers (QC). The proposed EO UCs are:

- UC1) Variational quantum algorithms for EO Image processing,
- UC2) Climate adaptation digital twin HPC+QC workflow,
- UC3) feature selection for environmental monitoring hyperspectral imagery, and
- UC4) Uncertainty quantification for remotely-sensed datasets.

To assess the selected EO UCs, we evaluate their hardness by using the computational complexity measures, and their hardness implies that conventional classical computers cannot solve efficiently our identified EO UCs but QC promise to tackle them efficiently.

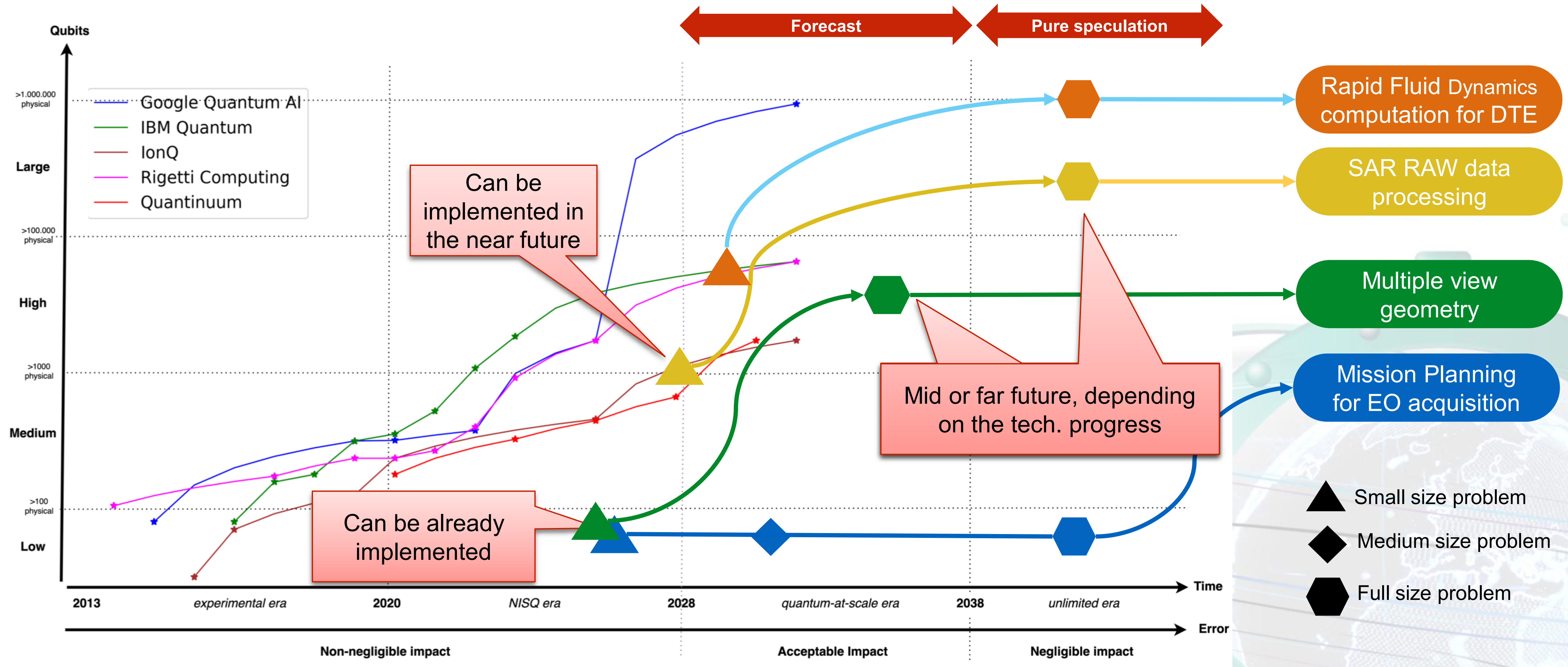
https://eo4society.esa.int/projects/qa4eo-study/

- Studies investigating use cases for Quantum Computing.
- Considering applications whose algorithms whose building blocks are computationally expensive and might be accelerated by Quantum Computing

Identified use cases

USE CASE	SHORT DESCRIPTION	BOTTLENECKS OF THE CONSIDERED CLASSICAL SOLUTION	PROPOSED QUANTUM SOLUTION
Multiple-view Geometry on Optical Images	Analyzing satellite images of a specific area captured from various perspectives	Keypoints extraction: combinatorial optimization problem of exponential complexity	Quantum clustering: quantum k-medoids, quantum kernel density
Mission Planning for EO applications	Finding an optimal acquisition plan of a satellite constellation given user requests	Acquisition planning is a combinatorial optimization problem of exponential complexity, currently solved with deterministic or heuristic methods	Two different approaches have been studied: quantum optimization and quantum machine learning
SAR Raw Data Processing	Image generation of an area of interest from the raw signal received by the SAR system	Frequency-based methods (Range Doppler): polylogarithmic complexity of Fourier transformation	Quantum Range Doppler Algorithm
Climate adaptation digital twin HPC+QC workflow	Rapid computation of fluid dynamics for Digital Twin Earth applications.	Large data requirements and short computation time steps make classical fluid dynamics simulations computationally expensive.	Utilizing quantum algorithms, such as HHL (Harrow-Hassidim-Lloyd) and Quantum Singular Value Transformation (QSVT), to improve computational efficiency in solving linear systems related to fluid dynamics.

Possible roadmap for QC4EO



Coherence times, operation fidelity, and qubits connectivity are at least as important

Outline

- What are Disruptive Computing paradigms?
- Quantum Computing
- Neuromorphic Computing
- Conclusion

Neuromorphic computing

- **Neuromorphic Computing** (NC) is a massively parallel and asynchronous computing paradigm.

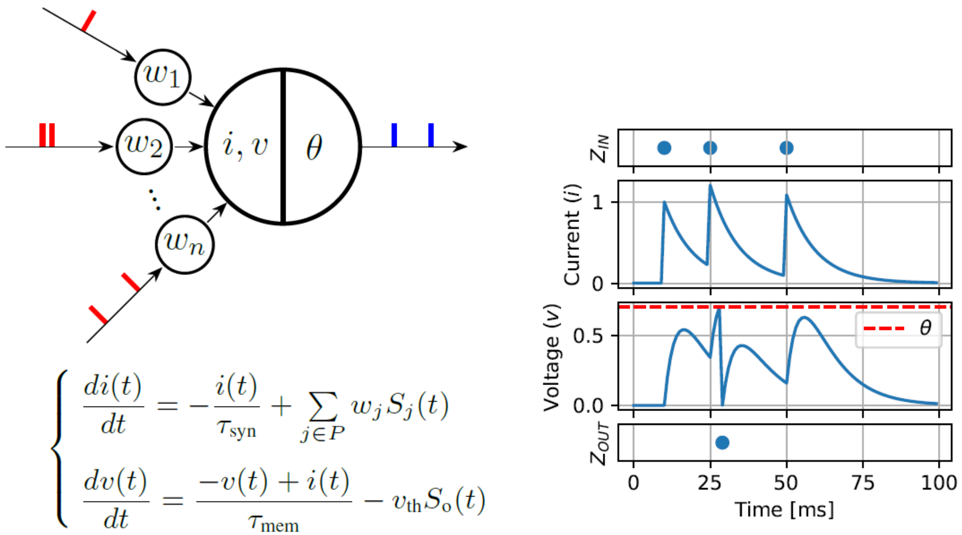
- In its more modern connotate, neuromorphic computing encodes and processes information through **spikes**, mimicking the brain's working principles.

  - Brain is really energy efficiency (about 20 W)
  - Spikes can be encoded and transmitted with very few memory (**reducing memory bottleneck problem**)

- NC can be combined with AI algorithms, implementing **Spiking Neural Networks (SNNs).**

- There are numerous **spiking neuron models** with different trade-offs between fidelity to nature emulation and computational complexity

- Nowadays, the most used model is the "**Leaky Integrated and Fire**" (LIF) model



$$\begin{cases} \frac{di(t)}{dt} = -\frac{i(t)}{\tau_{\text{syn}}} + \sum_{j \in P} w_j S_j(t) \\ \frac{dv(t)}{dt} = \frac{-v(t) + i(t)}{\tau_{\text{mem}}} - v_{\text{th}} S_o(t) \end{cases}$$

(a) LIF spiking neuron. **(b)** Neuron internal states.

Source: Lunghi. P. et all "Energy efficiency analysis of SpikingNeuralNetworks for space Applications", Astrodynamics (in press)

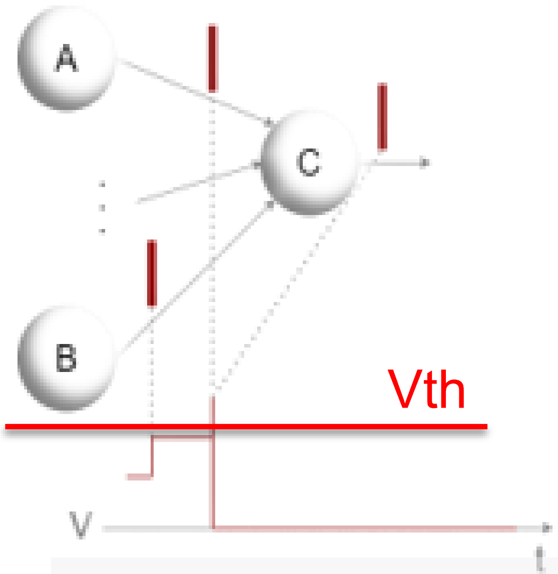
- Neurons are made of two parts (synapses and membrane).Synapses link a neuron to other neurons

- The **synaptic current** $\boldsymbol{i(t)}$ is obtained by integrating the weighted $(\boldsymbol{w_j})$ train of synaptic binary spikes $\boldsymbol{S_j(t)}$

- The **membrane voltage potential** $\boldsymbol{v(t)}$ is obtained as in a RC filter (integrating $\boldsymbol{i(t)}$)

- When $\boldsymbol{v(t) > v_{th}}$, $\boldsymbol{v(t)}$ is reset and a spike is emitted

Spiking Neural Networks (SNNs)



1. Neuron C accumulates spikes from neurons A and B
2. When a spike is detected, voltage (V) of neuron C grows
3. When V passes a threshold (Vth), neuron C emits a spike, and V is reset

Advantages

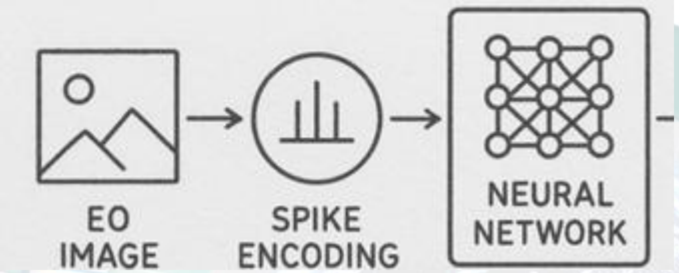
1. Computation is **sparse** and triggered locally by ***events***
2. **Neuromorphic hardware** can leverage these features and ensure **energy-efficiency** and **rapidity**

Limitations

1. Immature computing paradigm
2. SNNs are difficult to train due to non-differentiability of LIF neurons equations

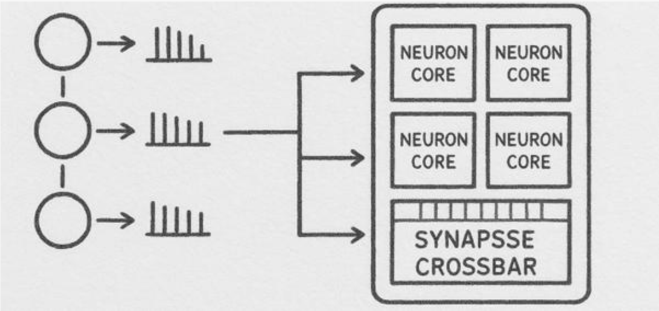
Spike encoding

- Spike encoding encodes information (e.g., EO images) into spikes
- Multiple spike encoding
  - **Frequency-based** (more active pixel =higher frequency rate) – more robust/less efficient
  - **Latency-based** (more active pixels fire before – technically, it is possible to have neurons firing only one) – less robust/more efficient
  - **Others…**



Neuromorphic hardware

Digital Chips



- Multiple digital cores working asynchronously
- Spikes are routed through cores via a synaptic crossbar
- Higher scalability but requires time discretization of SNNs

Analog/Mixed signals chip

- Synaptic operations are obtained through analog chips
- Do not require time discretization of SNNs and very energy efficient
- More complex design flows and limited scalability (limitations to SNN models size)

Why neuromorphic computing (1/5) ?

- Due to its potential energy-efficiency, NC looks promising for **onboard processing applications**

- Satellites (especially small satellites) have limited energy and power-budgets

- Yes, but… energy efficiency depends on **sparsity** that depends on the encoding used and the inputs

- EO optical images are a **static input** => sparsity depends on the encoding used.

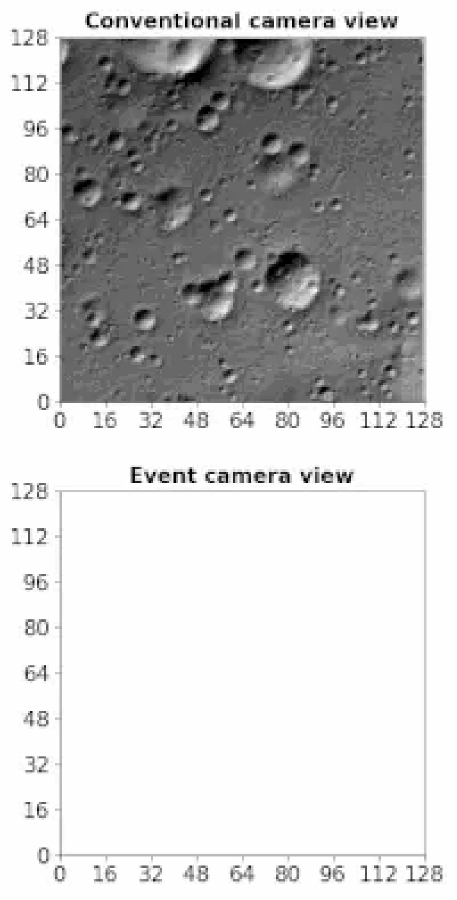
Why neuromorphic computing (2/5) ?

- Is there an advantage in using neuromorphic computing for onboard processing of EO static imagery?

Source: Lunghi. P. et all "Energy efficiency analysis of SpikingNeuralNetworks for space Applications", Astrodynamics (in press)

- Multiple SSNs were compared on EuroSat RGB (land use/land cover classification) in terms of **energy (estimated)** and **accuracy** with standard deep learning models
- SNNs **do NOT** exhibit advantageous trade-offs w.r.t. conventional deep learning models for land use/land cover classifications

Neuromorphic sensing



Credit: ESA ACT

- Each pixel produce a **spike** when it detects a significative variation of the corresponding input brightness

- Neuromorphic cameras are:
  - **Event-based, asynchronous**
  - **Sparse**
  - **Much faster than normal cameras**
  - **High dynamic/range**
- Their output is already encoded in the spike domain

Why neuromorphic computing (4/5) ?

Studying red-sprites

Credit: ESA

- Red sprites are specific thunderstorm events of 14km-26km size forming above clouds
- **THOR-DAVIS** project: using event-based cameras to monitor red sprites
  - Fast acquisitions
  - Producing data only when an event happens

Space situational-awareness

- **NEU4SST project**: preliminary concept study of neuromorphic sensing and computing to track near-Earth
objects (e.g., space debris)

- Preliminary results show that full neuromorphic systems can detect fast moving objects and easily tracking using SNNs

Outline

- What are Disruptive Computing paradigms?
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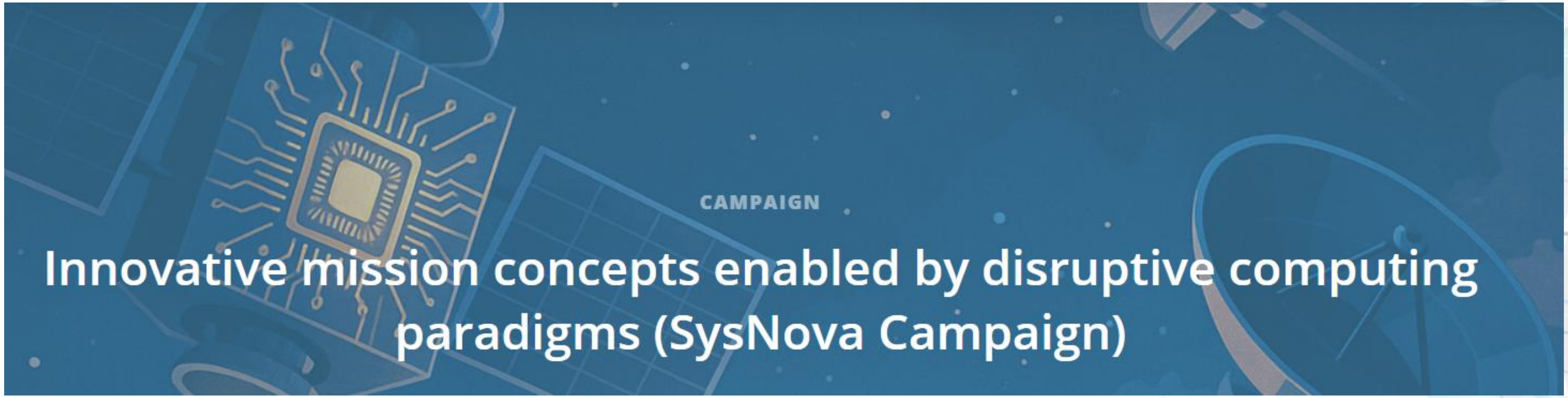
Conclusion

- There are numerous emerging computing paradigms
- Many of these paradigms are still in their infancy, showing immaturity both from the hardware and algorithmic points of view
- Despite that, these paradigms might be beneficial for specific EO applications, even if further research is needed to demonstrate clear advantages
- Further research is needed

Conclusion

- ESA launched a **SysNova campaign** focusing on the exploration of of Disruptive Computing paradigms for EO (and other) missions
- **Deadline**: 30° September



Working with us is very easy

- Visiting Professor
- Visiting Researchers (Industrial and Scientific)
- ESA Research Fellowships
- ESA Co-funded PhD
- ESA Early Graduate Traineeships (EGT), Internships, National trainee

Join ESA Φ-lab through CIN

The **Collaborative Innovation Network (CIN) by ESA Φ-lab**, provides to leading researchers and University Professors the **opportunity to** join ESA Φ-lab and be actively involved in **accelerating the future of Earth Observation with ESA**.

The ESA Φ-lab CIN aims to:

- Establish a global network through which researchers and innovators can **JOIN ESA Φ-LAB**
- **Promote knowledge** sharing and develop groundbreaking EO solutions

Check the open calls

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What to go deeper into Φ-lab disruptive innovation?

Don’t miss our spotlight session at Big Data from Space
(Day 2 – October 2nd at 17:50)