QUANTUM COMPUTING FOR EARTH OBSERVATION

M2GARSS 2024 - Tutorial

April 15, 2024    Amer Delilbasic, Gabriele Cavallaro
Driving questions for the tutorial

- What is quantum computing?
- Why the quantum computing hype?
- How can Earth observation benefit from quantum computing?
- Which algorithms and resources are relevant for me?
Part 1: Introduction

- Quantum computing
- Quantum optimization
- Quantum machine learning

Part 2: Examples

- Acquisition planning for EO satellites
Evolution of computing architectures

IQM – LRZ, “Bringing quantum acceleration to Supercomputers”, whitepaper, May 2022
Quantum computing is defined according to the postulates and laws of quantum mechanics.

Underlying concepts:

**Superposition**
Quantum systems can be described as a superposition of quantum states

**Measurement**
Measuring the state of a quantum system affects the state of the system in a random way

**Entanglement**
In an entangled system, the states of the system particles are related to each other
Qubit as information unit

Classical bit
It can be either 0 or 1

<table>
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<tr>
<th>0</th>
<th>1</th>
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Quantum bit (qubit)
It can be $|0\rangle$, $|1\rangle$ or both at the same time!

$|0\rangle + |1\rangle / \sqrt{2}$

Bloch sphere representation
Measurement and qubit collapse

Measuring a qubit leads to a random result and affects the qubit irreversibly. The original state is lost, and no copies can be made (no-cloning theorem).
Quantum computational models

Quantum circuit model
Model where quantum gates and measurements are applied to qubits

Adiabatic quantum computation
Model where the time evolution of a quantum system under adiabatic conditions is described by the Hamiltonian $\mathcal{H}(t)$ and ruled by the Schrödinger’s equation

$$i\hbar \frac{d}{dt} |\Phi(t)\rangle = \mathcal{H}(t) |\Phi(t)\rangle$$

The quantum computing landscape

Investments in quantum technology reached their highest annual level.

Volume of raised investment in the indicated year, $ million

<table>
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<tr>
<th>Year</th>
<th>Investment</th>
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<tr>
<td>2022</td>
<td>$2.35 billion</td>
</tr>
<tr>
<td>2021</td>
<td>$3.33 billion</td>
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https://www.a quoi servent les ordinateurs quantiques 
Quantum computing can provide a substantial computational advantage

**Grover’s search algorithm**
Iterative algorithm that searches for an item in an unstructured database of $N$ objects
Time complexity: $O(\sqrt{N})$ instead of $O(N)$
Multiple applications and building block of many quantum algorithms

**Shor’s factoring algorithm**
Finds the prime factors of an integer $N$
Time complexity: polylogarithmic instead of sub-exponential
Applications in cryptography
Quantum computers present practical limitations

- Quantum information theory neglects physical implementation
- Current state: Noisy Intermediate-Scale Quantum (NISQ) devices
- Insufficient scale for a practical quantum advantage

Number of qubits
Dimension of quantum data that can be processed in a single QPU

Quantum volume
Dimension of the circuit that can be implemented with low error


Main applications of quantum computing

Quantum simulation

Quantum cryptography

Quantum optimization

Quantum machine learning

Which are the most relevant for Earth observation?
Examples of quantum optimization algorithms

Quantum Approximate Optimization Algorithm (QAOA)

Model: quantum circuits
Purpose: combinatorial optimization
Design: \(n\) qubits for \(2^n\) possible solutions, accuracy increases with repetitions

Quantum annealing

Model: adiabatic quantum computation
Purpose: combinatorial optimization (QUBO)
Design: \(n\) qubits for \(2^n\) possible solutions, a coupler for each non-zero coefficient

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Examples of quantum machine learning algorithms

Quantum neural networks

**Model:** quantum circuits

**Purpose:** learn the circuit parameters that generate the desired output, starting from a training set

**Design:** multiple architectures, usually $n$ qubits for $n$-dimensional data, subject to trainability requirements

Quantum kernels

**Model:** quantum circuits

**Purpose:** encoding data to a high-dimensional feature space and calculating the kernel matrix

**Design:** $n$ qubits for $n$-dimensional data, a run for every pair of training examples, circuit choice depending on data structure (can be trained), subject to trainability requirements

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Earth observation requires increasing computing capabilities
Where does quantum computing fit?

QC4EO Study technical reports: https://eo4society.esa.int/projects/qc4eo-study/
Contributions to quantum computing for Earth observation

Acquisition planning for EO satellites
Operational planning of satellite acquisition processes


Contributions to quantum computing for Earth observation

**Mission analysis**

**Data acquisition**

**Raw data processing**

**Data analysis**

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**InSAR phase unwrapping**

Generation of 3D topography maps from modulo $2\pi$ phase maps

**Bundle adjustment**

Keypoint extraction and feature matching for data fusion of images taken from different points of view

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Contributions to quantum computing for Earth observation

**Event detection**
Supervised training of hybrid quantum convolutional neural networks on multispectral image datasets

**Semantic segmentation**
Supervised pixel-based or region-based kernel methods (quantum kernels, quantum SVM)

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Practical examples

Acquisition planning for EO satellites

Use case for quantum optimization algorithms (QAOA, QA)

Semantic segmentation of satellite images

Use case for quantum machine learning algorithms

Session “Quantum Approaches in Remote Sensing”
Tools for testing quantum algorithms

**Qiskit**
Creating and running *quantum circuits* on multiple backends
Example: IBM Torino: 133 qubits
Free access to QPUs (queue time may vary)

Qubit structure of IBM Torino

https://quantum.ibm.com/

**D-Wave Ocean**
Creating and solving *QUBO optimization problems* on multiple backends
Example: D-Wave Advantage quantum annealer: 5000+ qubits

1-min free computing time

JUPSI, a D-Wave Advantage quantum annealer hosted at FZJ

Acquisition planning for EO satellites

**mqt-problemsolver**: great library for testing QAOA for acquisition planning


```python
def init_random_acquisition_requests(n: int) -> list[LocationRequest]:
    """Returns list of n random acquisition requests""
    np.random.seed(10)
    acquisition_requests = []
    for _ in range(n):
        acquisition_requests.append(
            LocationRequest(position=create_acquisition_position(), imaging_attempt_score=np.random.randint(1, 3))
        )
    return acquisition_requests(acquisition_requests)

def solve_using_qaoa(qubo: QuadraticProgram, noisy_flag: bool = False) -> Any:
    if noisy_flag:
        qaoa = QAOA(
            QAOA_params={"reps": 3, "optimizer": COBYLA(maxiter=100), "sampler": BackendSampler(FakeMontreal())}
        )
    else:
        qaoa = QAOA(
            QAOA_params={
                "reps": 3,
                "optimizer": COBYLA(maxiter=100),
                "sampler": Sampler(),
            }
        )
        qc_qaoa, res_qaoa = qaoa.get_solution(qubo)
    return res_qaoa
```

Example problem instance
Acquisition planning for EO satellites

Solving QUBO with quantum annealing:

```python
def solve_using_qa(qubo, qa_setup: dict[str, Any]):
    # Create a client instance
    client = Client.from_config()

    # Get the list of available solvers
    solvers = client.get_solvers()

    # Print the name of the used solvers
    print("Using solver", solvers[0].id)

    # Create a sampler
    sampler = DWaveSampler(solver=solvers[0].id)

    # Solve the QUBO using the D-Wave sampler
    sampleset = sampler.sample_qubo(qubo, num_reads=qa_setup["num_reads"], label="Acquisition Planning")
    return sampleset
```
Conclusions

- Multiple tools are available and multiple applications are possible
- Testing today: insights on the behavior of quantum algorithms > actual advantage
- Fast development of quantum hardware can change the game

Session “Quantum Approaches in Remote Sensing” (tomorrow, 9.30-10.30, in this room)

- Quantum neural network for semantic segmentation of radar sounder data: 9.45-10.00
- Quantum annealing for semantic segmentation of optical images: 10.15-10.30
Join us!

Earth Science Informatics (ESI) Technical Committee

Advance application of informatics to geoscience and remote sensing

https://www.grss-ieee.org/technical-committees/earth-science-informatics/

Manil Maskey
Peter Baumann
Gabriele Cavallaro

High-performance and Disruptive Computing in Remote Sensing (HDCRS) Working Group

Connect and support the community of interdisciplinary researchers in remote sensing who are specialized in emerging computing paradigms


Dora Blanco Heras
Iksha Gurung
Rocco Sedona
Sudan Jha


Upcoming event: School on High Performance and Disruptive Computing in Remote Sensing 4-7 June 2024, Santiago de Compostela, Spain (https://www.hdc-rs.com/)
Questions?

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