

Machine Learning/artificial intelligence and quantum technologies at the university of Oslo; research, education and exciting possibilities in the future job market

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What is this talk about?

The main emphasis is to give you a short and pedestrian introduction to the whys and hows we can use (with several examples) machine learning methods and quantum technologies in science and perhaps in general. And why this could (or should) be of interest. I will also try to link to potential job possibilities and educational activities.

AI/ML and some statements you may have heard (and what do they mean?)

1. Fei-Fei Li on ImageNet: **map out the entire world of objects** ([The data that transformed AI research](#))
2. Russell and Norvig in their popular textbook: **relevant to any intellectual task; it is truly a universal field** ([Artificial Intelligence, A modern approach](#))
3. Woody Bledsoe puts it more bluntly: **in the long run, AI is the only science** (quoted in Pamilla McCorduck, [Machines who think](#))

If you wish to have a critical read on AI/ML from a societal point of view, see [Kate Crawford's recent text Atlas of AI](#). And [Inga Strumke, Machines which think](#)

Here: with AI/ML we intend a collection of machine learning methods with an emphasis on statistical learning and data analysis

Types of machine learning

The approaches to machine learning are many, but are often split into two main categories. In *supervised learning* we know the answer to a problem, and let the computer deduce the logic behind it. On the other hand, *unsupervised learning* is a method for finding patterns and relationship in data sets without any prior knowledge of the system.

An important third category is *reinforcement learning*. This is a paradigm of learning inspired by behavioural psychology, where learning is achieved by trial-and-error, solely from rewards and punishment.

Main categories

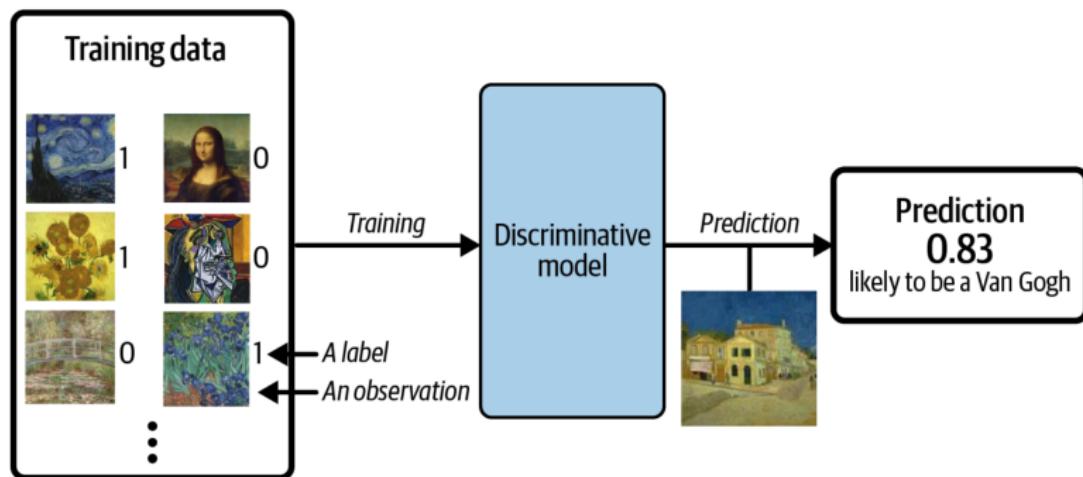
Another way to categorize machine learning tasks is to consider the desired output of a system. Some of the most common tasks are:

- ▶ Classification: Outputs are divided into two or more classes. The goal is to produce a model that assigns inputs into one of these classes. An example is to identify digits based on pictures of hand-written ones. Classification is typically supervised learning.
- ▶ Regression: Finding a functional relationship between an input data set and a reference data set. The goal is to construct a function that maps input data to continuous output values.
- ▶ Clustering: Data are divided into groups with certain common traits, without knowing the different groups beforehand. It is thus a form of unsupervised learning.

The plethora of machine learning algorithms/methods

1. Deep learning: Neural Networks (NN), Convolutional NN, Recurrent NN, Boltzmann machines, autoencoders and variational autoencoders and generative adversarial networks, stable diffusion and many more generative models
2. Bayesian statistics and Bayesian Machine Learning, Bayesian experimental design, Bayesian Regression models, Bayesian neural networks, Gaussian processes and much more
3. Dimensionality reduction (Principal component analysis), Clustering Methods and more
4. Ensemble Methods, Random forests, bagging and voting methods, gradient boosting approaches
5. Linear and logistic regression, Kernel methods, support vector machines and more
6. Reinforcement Learning; Transfer Learning and more

Example of discriminative modeling, taken from Generative Deep Learning by David Foster



Discriminative Modeling

When performing discriminative modeling, each observation in the training data has a label. For a binary classification problem such as our data could be labeled as ones and zeros. Our model then learns how to discriminate between these two groups and outputs the probability that a new observation has label 1 or 0

In contrast, generative modeling doesn't require the dataset to be labeled because it concerns itself with generating entirely new data (for example an image), rather than trying to predict a label for say a given image.

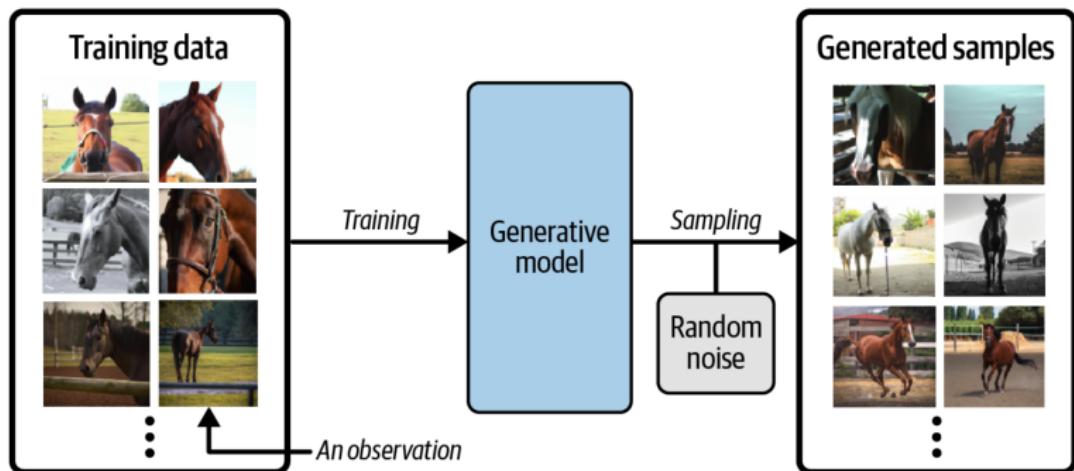
What Is Generative Modeling?

Generative modeling can be broadly defined as follows:

Generative modeling is a branch of machine learning that involves training a model to produce new data that is similar to a given dataset.

What does this mean in practice? Suppose we have a dataset containing photos of horses. We can train a generative model on this dataset to capture the rules that govern the complex relationships between pixels in images of horses. Then we can sample from this model to create novel, realistic images of horses that did not exist in the original dataset.

Example of generative modeling, taken from Generative Deep Learning by David Foster



Good books with hands-on material and codes

- ▶ Sebastian Raschka et al, Machine learning with Scikit-Learn and PyTorch
- ▶ David Foster, Generative Deep Learning with TensorFlow
- ▶ Bali and Gavras, Generative AI with Python and TensorFlow 2

All three books have GitHub addresses from where one can download all codes. We will borrow most of the material from these three texts as well as from Goodfellow, Bengio and Courville's text [Deep Learning](#)

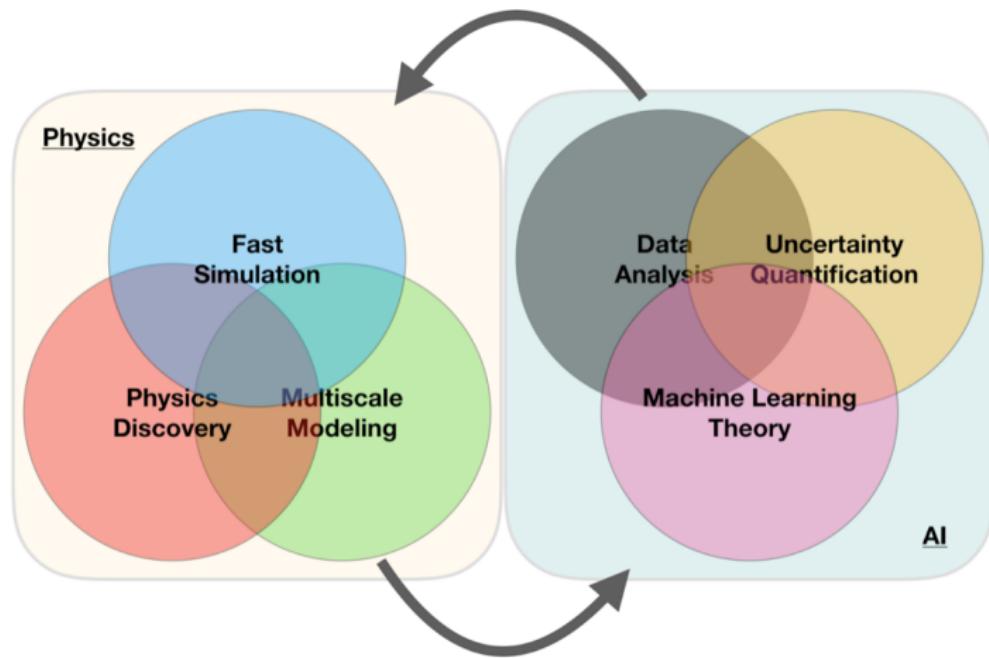
What are the basic Machine Learning ingredients?

Almost every problem in ML and data science starts with the same ingredients:

- ▶ The dataset \mathbf{x} (could be some observable quantity of the system we are studying)
- ▶ A model which is a function of a set of parameters $\boldsymbol{\alpha}$ that relates to the dataset, say a likelihood function $p(\mathbf{x}|\boldsymbol{\alpha})$ or just a simple model $f(\boldsymbol{\alpha})$
- ▶ A so-called **loss/cost/risk** function $\mathcal{C}(\mathbf{x}, f(\boldsymbol{\alpha}))$ which allows us to decide how well our model represents the dataset.

We seek to minimize the function $\mathcal{C}(\mathbf{x}, f(\boldsymbol{\alpha}))$ by finding the parameter values which minimize \mathcal{C} . This leads to various minimization algorithms. It may surprise many, but at the heart of all machine learning algorithms there is an optimization problem.

Machine learning. A simple perspective on the interface between ML and Physics



High performance computing demands (and immense power consumption)

In June 2023, just a few months after GPT-4 was released, the developers publicly explained that GPT-4 was comprised of roughly 1.8 trillion (trillion=1000 billions= one million millions) parameters. More specifically, the architecture consisted of eight models, with each internal model made up of 220 billion parameters.

Observations

- ▶ Need for AI/Machine Learning in science, lots of ongoing activities
- ▶ To solve many complex problems and facilitate discoveries, multidisciplinary efforts efforts are required involving scientists in physics, statistics, computational science, applied math and many many other fields.
- ▶ There is a need for focused AI/ML learning for specific disciplines

Possible start to raise awareness about ML in your own field

- ▶ Make an ML challenge in your own field a la Learning to discover: the Higgs boson machine learning challenge.
Alternatively go to kaggle.com at
<https://www.kaggle.com/c/higgs-boson>
- ▶ HEP@CERN and HEP in general have made significant impacts in the field of machine learning and AI. Something to learn from

Important questions

1. How do we incorporate these topics in our education?
2. More difficult: what are the consequences for universities and our educational mission?

Education

1. Incorporate elements of statistical data analysis and Machine Learning in undergraduate programs
2. Develop courses on Machine Learning and statistical data analysis
3. Build up a series of courses in Quantum Information Technologies (QIT)
4. Modifying contents of present Physics programs or new programs on Computational Physics and Quantum Technologies
 - 4.1 study direction/option in **quantum technologies**
 - 4.2 study direction/option in **Artificial Intelligence and Machine Learning**
 - 4.3 and more
5. Master of Science/PhD programs in Computational and Data Science
 - 5.1 UiO has already MSc programs in CS and DS
 - 5.2 Many other universities are developing or have similar programs

Important Issues to think of

1. Lots of conceptual learning: superposition, entanglement, QIT applications, etc.
2. Coding is indispensable.
3. Teamwork, project management, and communication are important and highly valued
4. Engagement with industry: guest lectures, virtual tours, co-ops, and/or internships.

Observations

1. People do not really know what QIT is.
2. ML/AI seen as black boxes/magic!

Future Needs/Problems

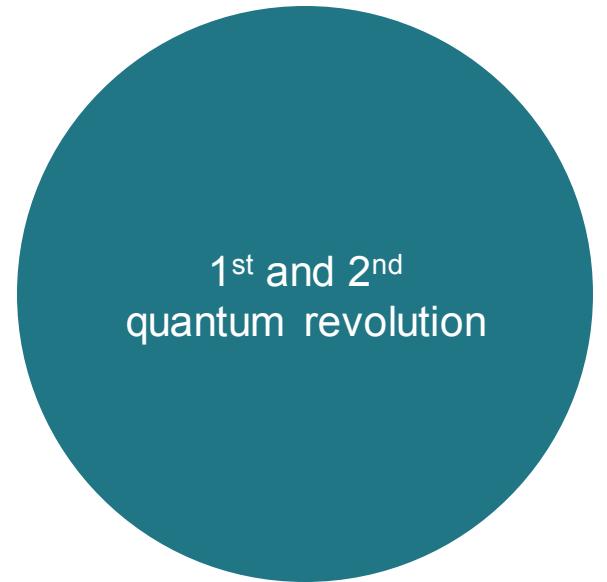
1. There are already great needs for specialized people (Ph. D. s, postdocs), but also needs of people with a broad overview of what is possible in ML/AI and/or QIT.
2. There are not enough potential employees in AI/ML and QIT . It is a supply gap, not a skills gap.
3. A BSc with specialization is a good place to start
4. It is tremendously important to get everyone speaking the same language. Facility with the vernacular of quantum mechanics is a big plus.



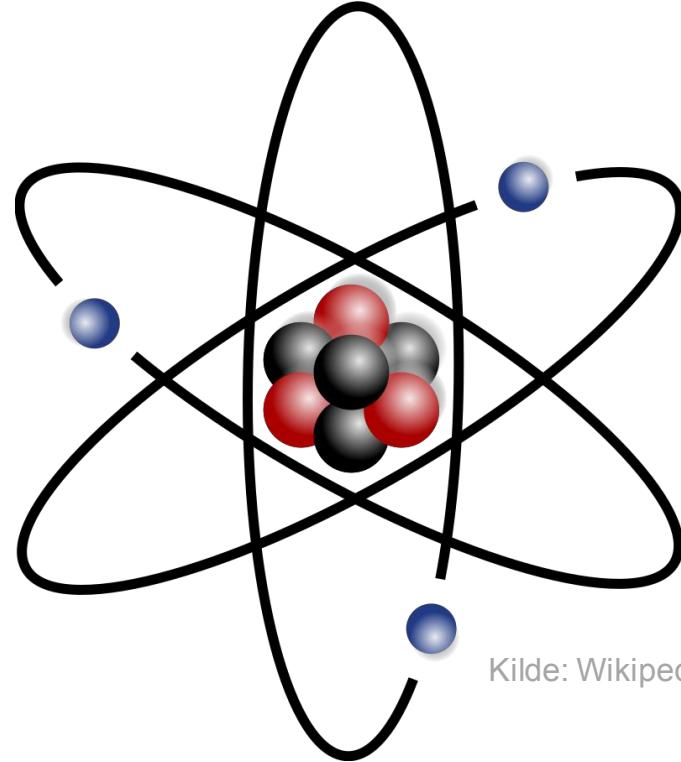
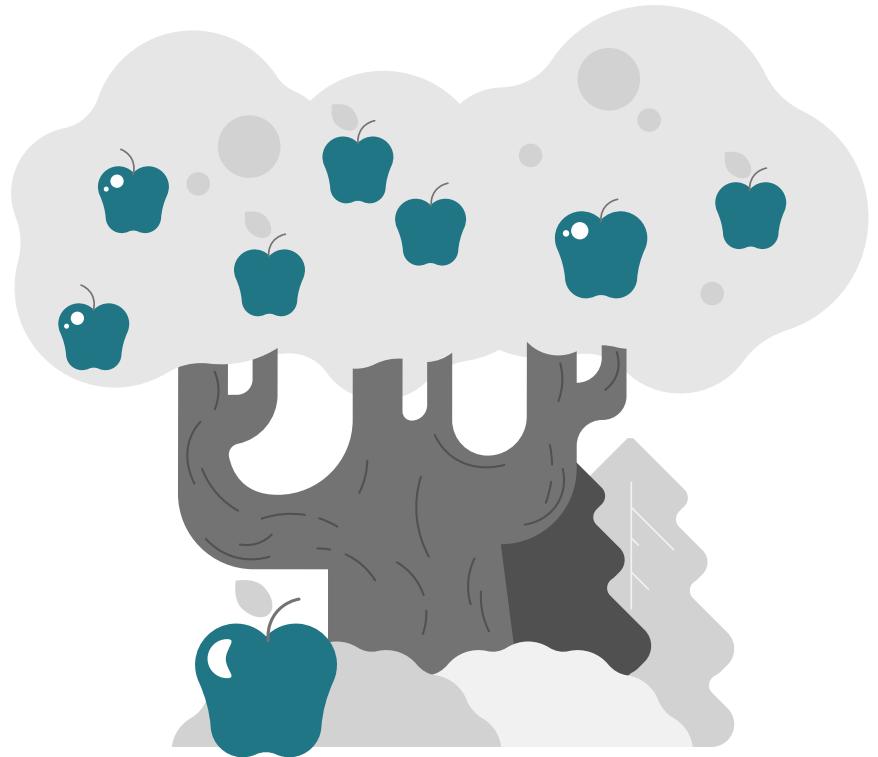
1st and 2nd
quantum revolution

Overview of
quantum
technologies

Status and
opportunities



From classical to quantum physics



Kilde: Wikipedia

The 1st quantum revolution: Quantum physics experiments

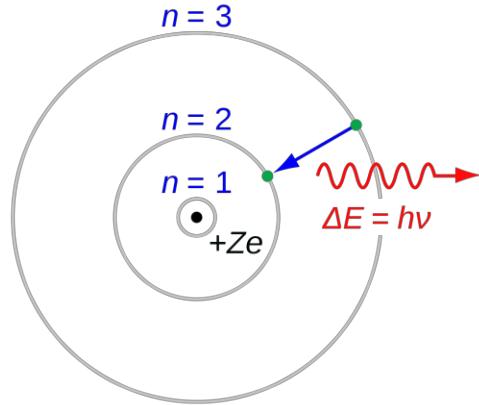
Max Planck, Albert Einstein, Arthur Compton



Light can behave like particles

Photons have momentum

Niels Bohr



Quantum systems have discrete (quantized) energy levels

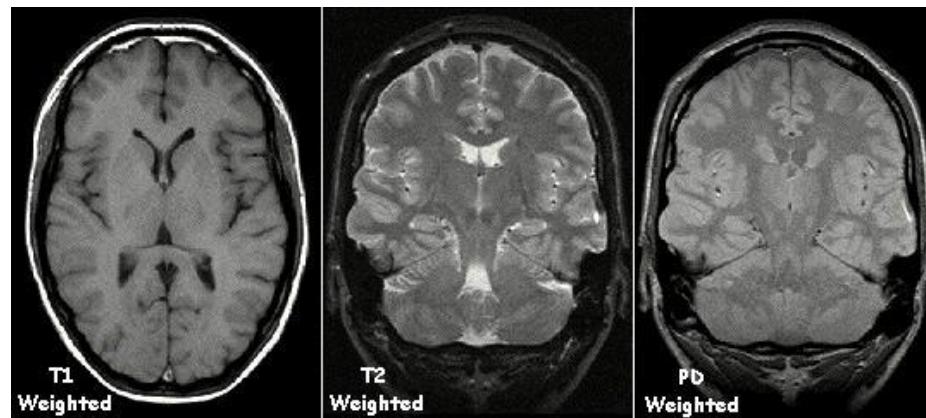
Louis de Broglie



Particle-wave duality

Particles can exhibit wave-like properties

Quantum revolution 1.5: Macroscopic quantum properties



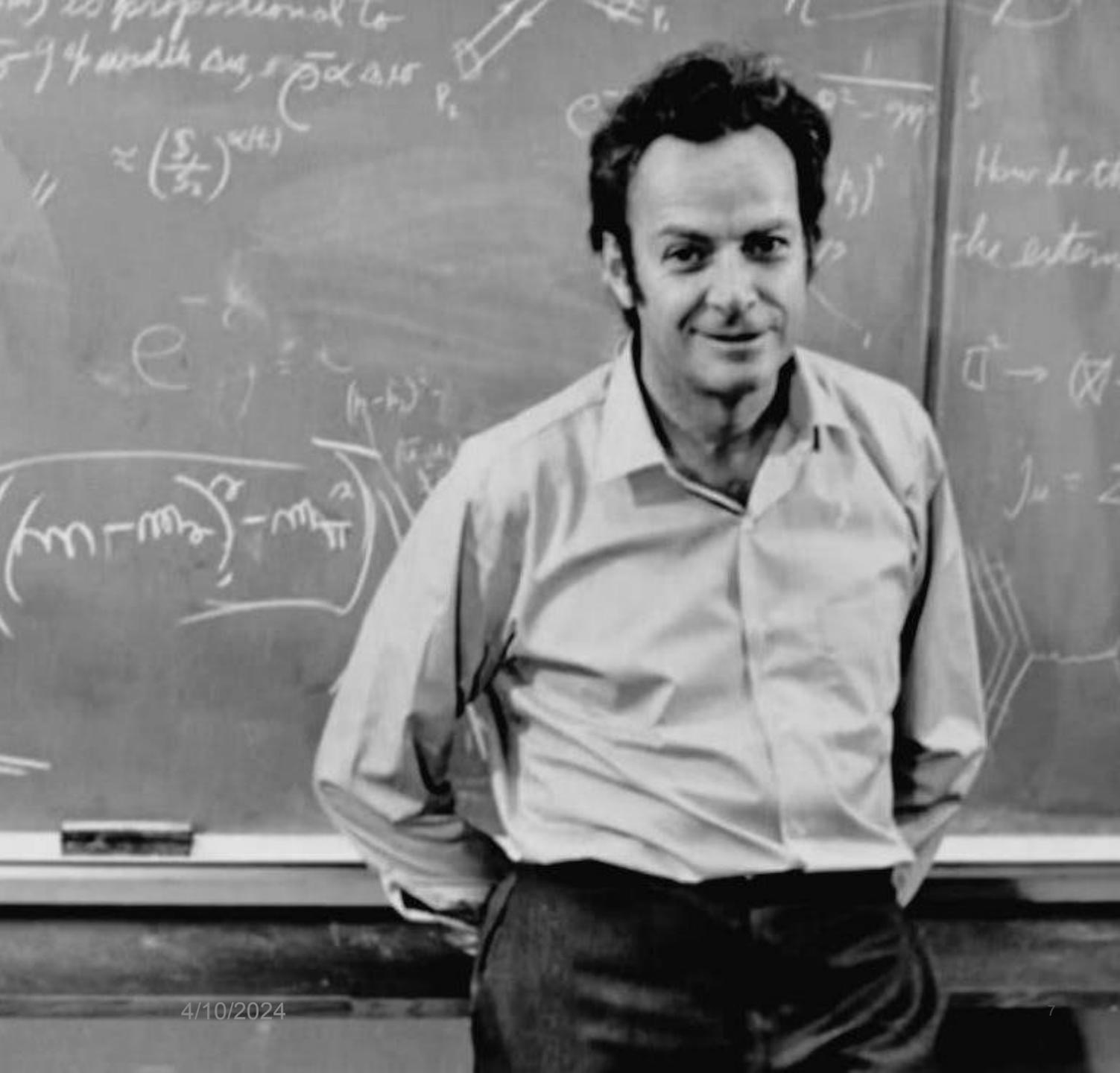
https://en.wikipedia.org/wiki/Magnetoresistive_RAM#/media/File:200mm_1_Mb_MRAM_-_D60_Symposium_-_Defense_Advanced_Research_Projects_Agency_-_DSC05568.jpg

“nature isn't classical,
dammit, and if you want
to make a simulation of
nature, you'd better make
it quantum mechanical.”

Richard Feynman

Quantum technology exploits the unique and exotic properties of quantum mechanics

- Superposition
- Quantum entanglement
- Tunneling



The 2nd quantum revolution: Direct control over quantum systems

1. Computing

- Information processing
- Solve tasks not possible with classical computing

2. Sensing

- Nanoscale spatial resolution
- Fast response

3. Communication

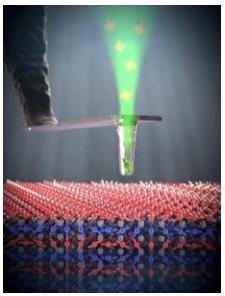
- Transmit information
- Quantum security

Quantum technology promises new opportunities

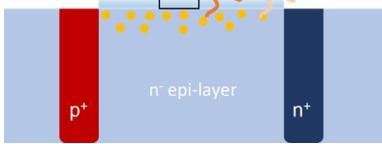
Extreme conditions



Nanoscale



Better control systems



Signals in cells



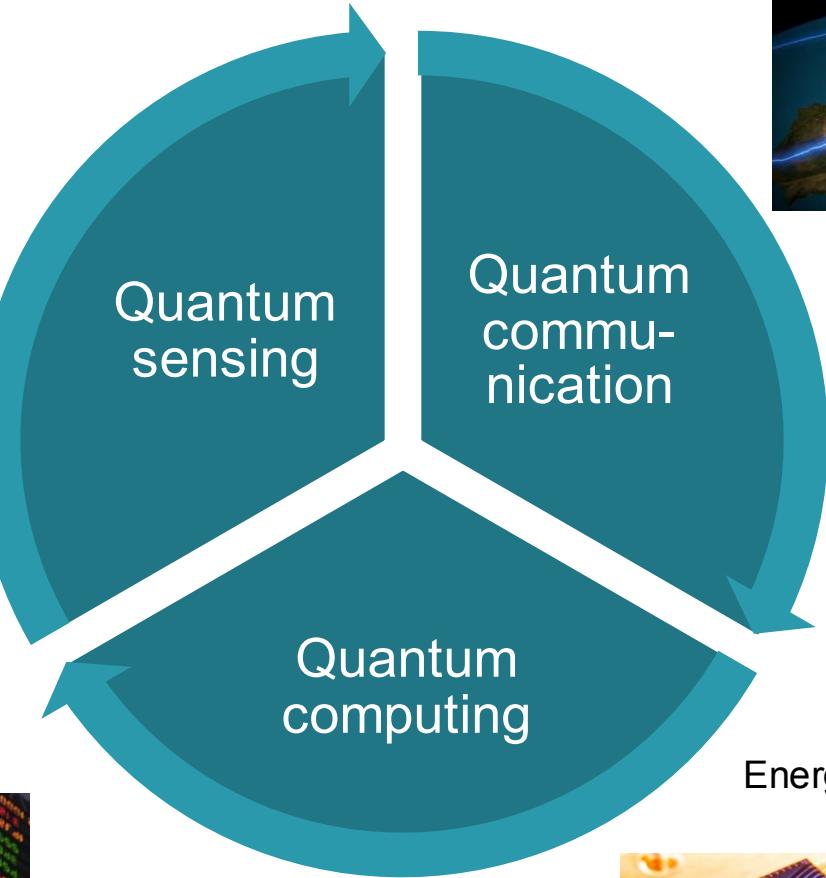
Model weather,
climate

Model finance market



Better logistics

Optimized energy consumption



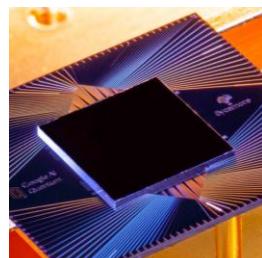
Quantum internet



Quantum cryptography



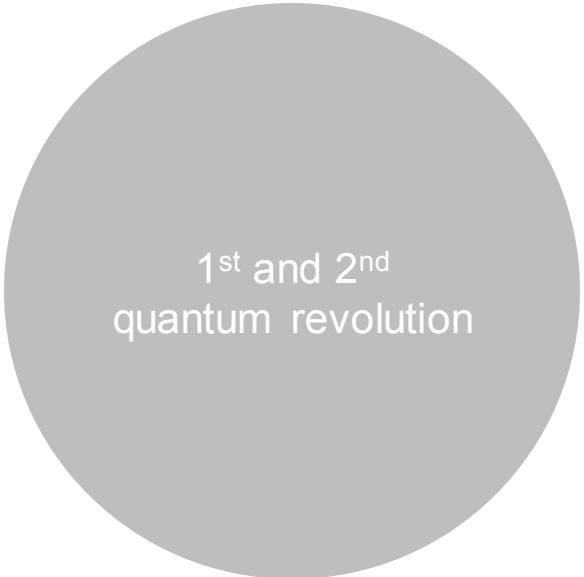
Secure communication based on
laws of quantum physics



Energy efficient computation



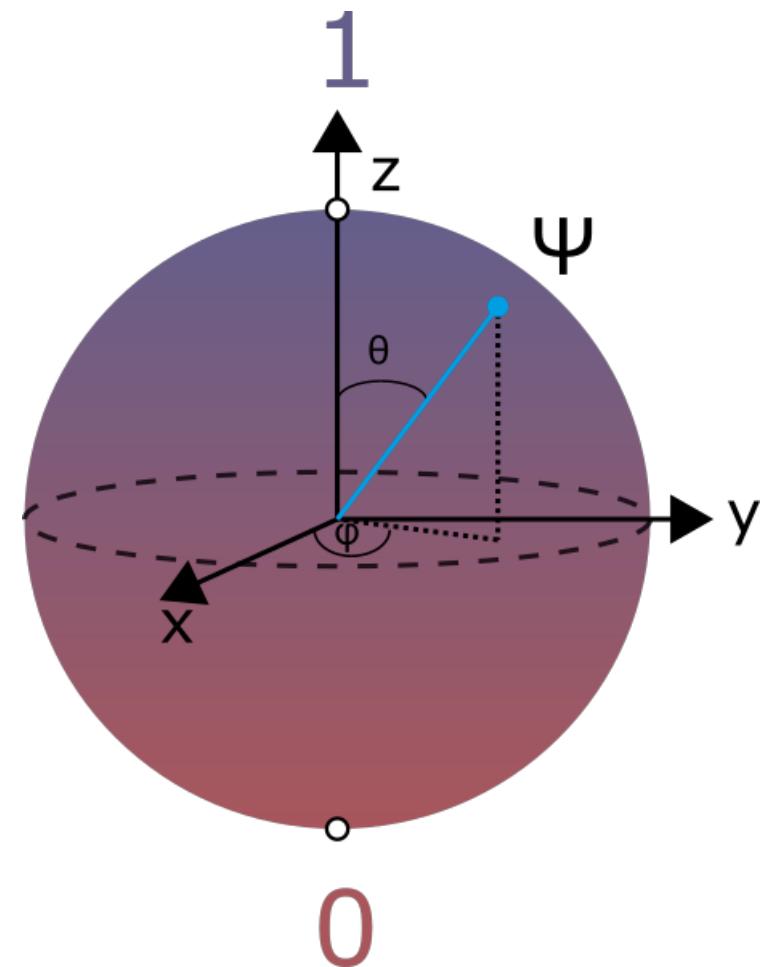
Find new drugs and materials for
green transition



Quantum bits: the building block of quantum technology

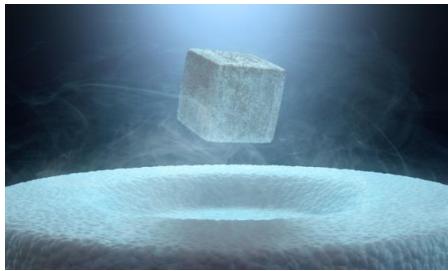
Qubit guidelines:

1. Stable, two-level quantum system
2. Communication path
3. Scalable
4. Energy efficient

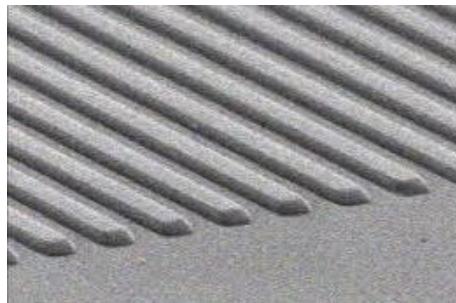


Choice of material platform depends on application

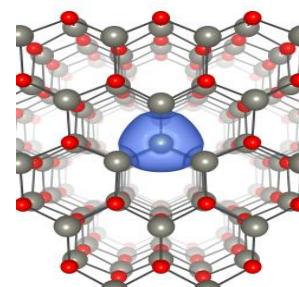
- Superconductors
- Trapped ions
- Optical gratings
- Quantum dots
- Defects in semiconductors
- ...



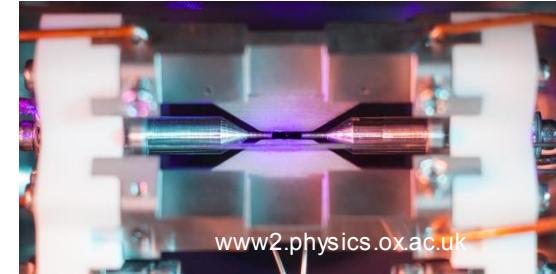
Superconductors



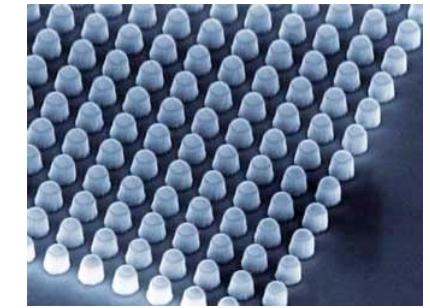
Optical gratings



Semiconductor
point defects



Trapped ions



Quantum dots

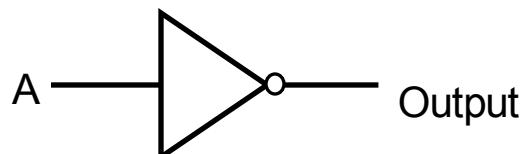
1. Gate model for quantum computing

Logic gates

- Classical circuits based on logic gates
- Gates perform logic operations
 - Rules for answering YES/NO questions
 - Input is 1 and 0 from transistors/bits

Example: NOT (inverter)

A	Output
0	1
1	0



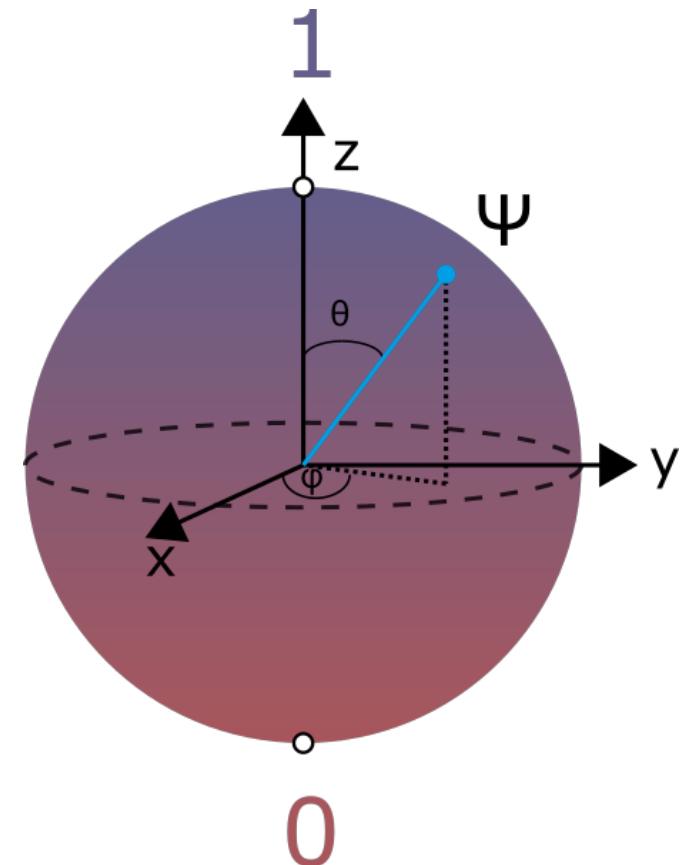
Quantum logic gates

- Most popular architecture for QC
- Inspired by classical logic gates
- Manipulate qubits by gate operations
- Quantum circuits are formed by qubits and quantum gates

Quantum gate operations

- Quantum gates can operate on one, two or more qubits
- We represent quantum gates by unitary matrices ($U^*U=I$)
 - 1-qubit gates are 2×2 matrices
 - 2-qubit gates have 16 matrix elements, etc.
- In practice; e.g. pulse of electromagnetic field

Represent qubits as a vector along a Bloch-sphere



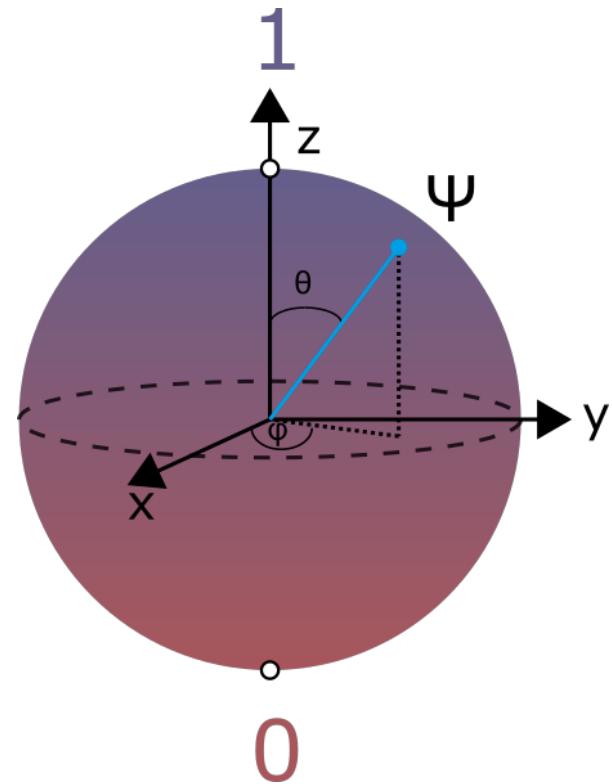
One-qubit quantum gates

X gate

- Quantum NOT
- Performs bit flip (0-to-1 and 1-to-0)

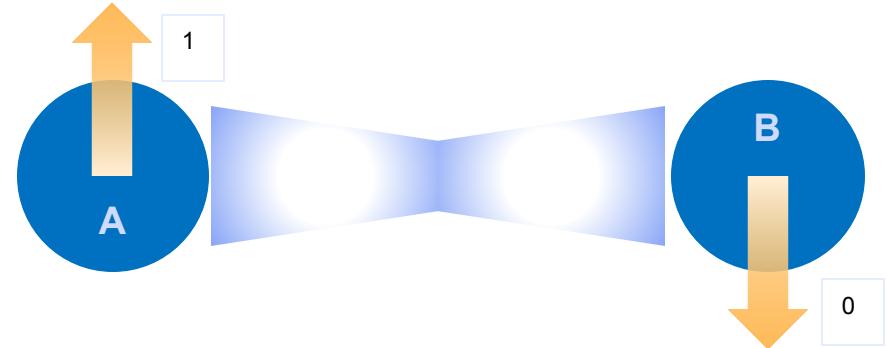
Hadamard gate

- Quantum analog to one-qubit Fourier transform
- Transforms a basis state (0 or 1) to a superposition of states



Controlled NOT (CNOT)

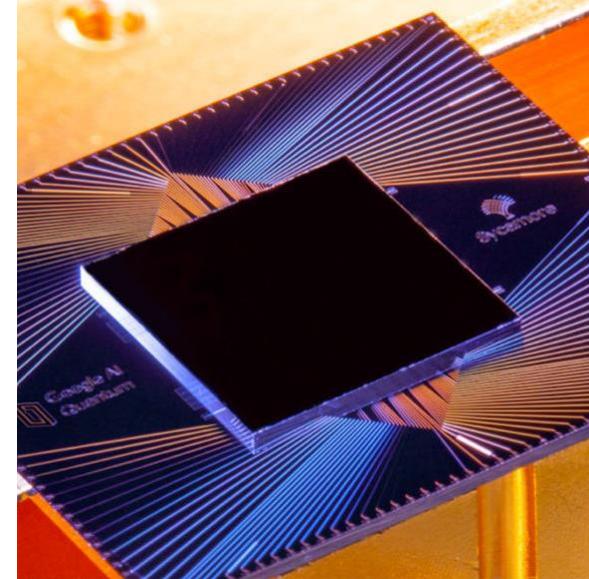
CNOT can generate a maximally entangled state between two qubits



Status for quantum computing

Where are we now?

- Noisy intermediate-scale quantum (NISQ)
- Superconducting qubits
- Quantum advantage is debatable
- Ideal time to learn!



<https://www.nature.com/articles/s41586-019-1666-5>



<https://www.ibm.com/quantum/roadmap>

2. Sensors are the foundation of the digital and green shifts



Kilde: Wikipedia



Input to AI



Better control systems

Improved safety



Optimized energy consumption



3 GOOD HEALTH
AND WELL-BEING



7 AFFORDABLE AND
CLEAN ENERGY



8 DECENT WORK AND
ECONOMIC GROWTH



9 INDUSTRY, INNOVATION
AND INFRASTRUCTURE



11 SUSTAINABLE CITIES
AND COMMUNITIES

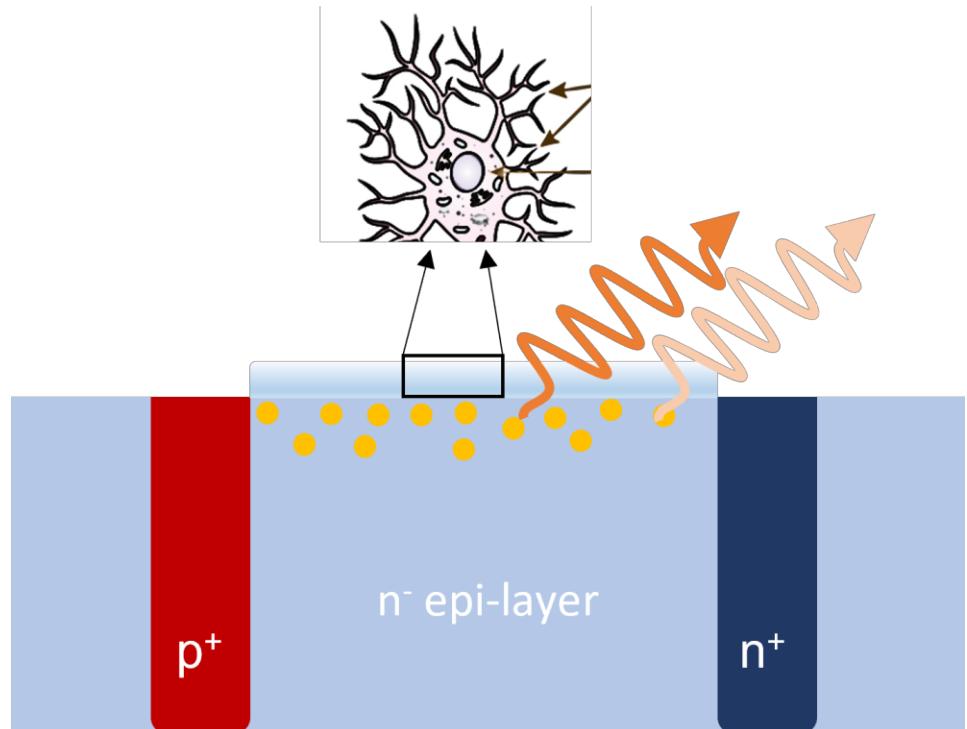
Need for quantum sensors

Limitations of today's technology

- Limitation in detection
 - Spatial resolution
 - Sensitivity
 - Extreme conditions
- Limitation in operation
 - Speed
 - Extreme conditions

Next generation: Quantum sensors

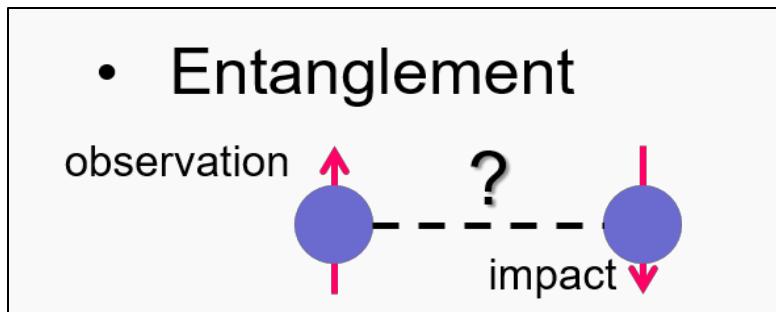
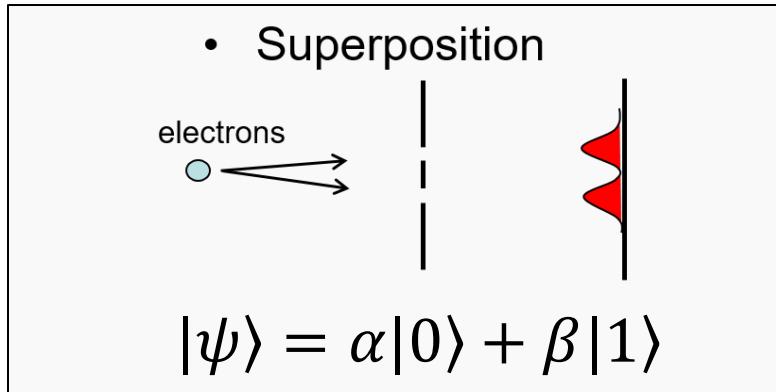
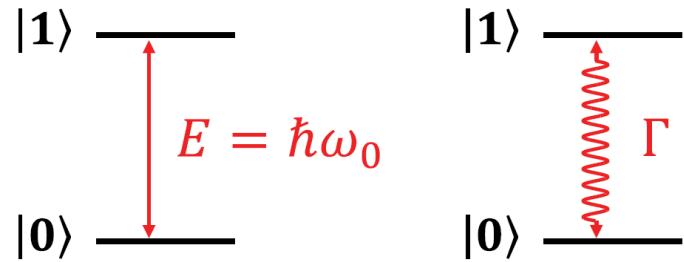
- Nanoscale spatial resolution, fast detection and extreme conditions possible
- Sensitivity beyond classical limit



What is quantum sensing ?

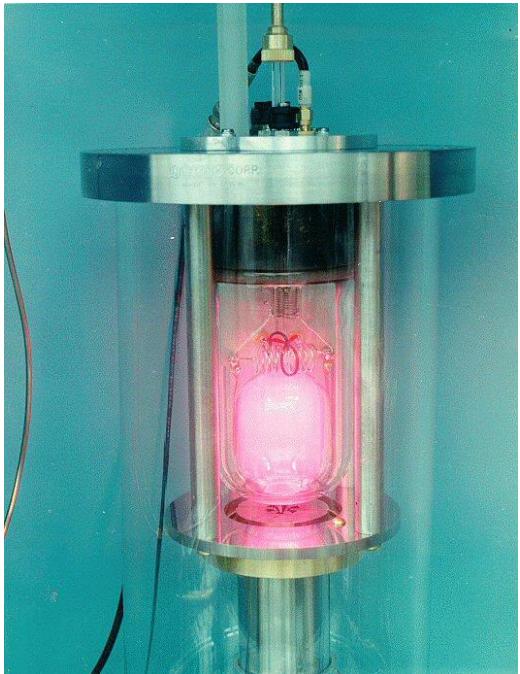
Definitions:

1. Use of quantum system with quantized energy levels to measure a physical quantity
2. Use of quantum coherence (i.e., wavelike spatial or temporal superposition states) to measure a physical quantity.
3. Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically



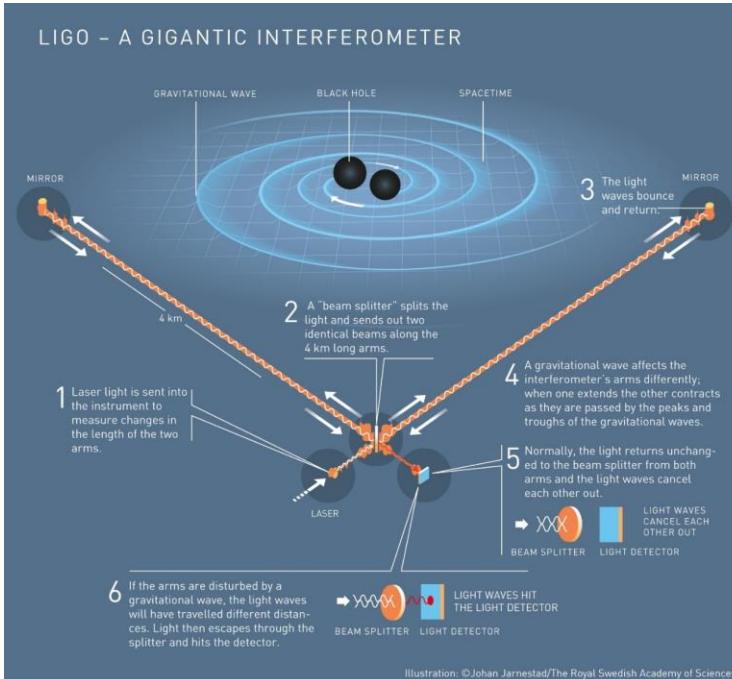
Early examples of quantum sensors

Atomic clock

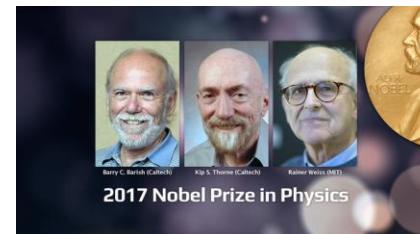


Kilde: Wikipedia

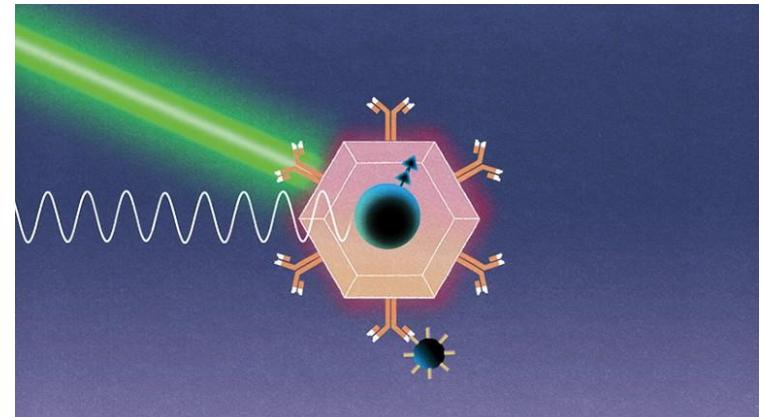
LIGO: Gravitational wafer



LIGO collab.,
Nature Photonics,
7, 613 (2013)



NV-centres in diamond
(semiconductor-based) for
biological sensing



Nature 591, S37 (2021)

3. Quantum communication

Transferring a quantum state from one place to another

Application areas

- Provably secure communication
- Quantum networks
 - Optical fiber network
 - Free space network
 - Part of quantum computers
- Secure quantum internet



<https://www.wired.com/sponsored/story/with-quantum-computings-rise-cybersecurity-takes-center-stage/>

<https://physicsworld.com/a/a-roadmap-for-the-quantum-internet/>

Transmitting information

Flying qubits

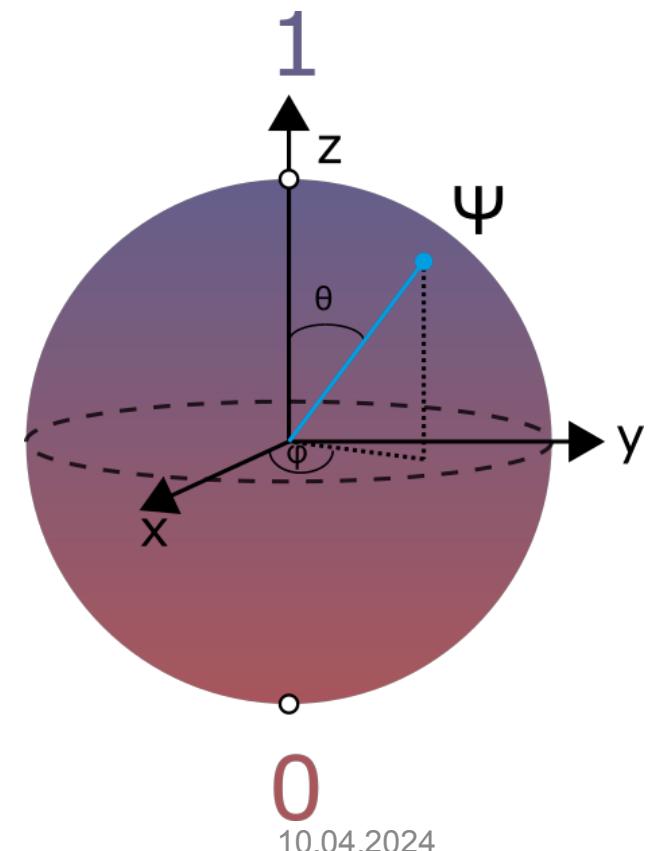
Individual or entangled photons are used to transmit data in a provably secure way

Degree of freedom to encode information in

- Spatially encoded qubits
- Temporal structure
- **State of polarization**

Advantage of photonic polarization qubits

- Easily generated and manipulated
- Photons interact little with the environment



Why quantum communication? Security in the quantum age



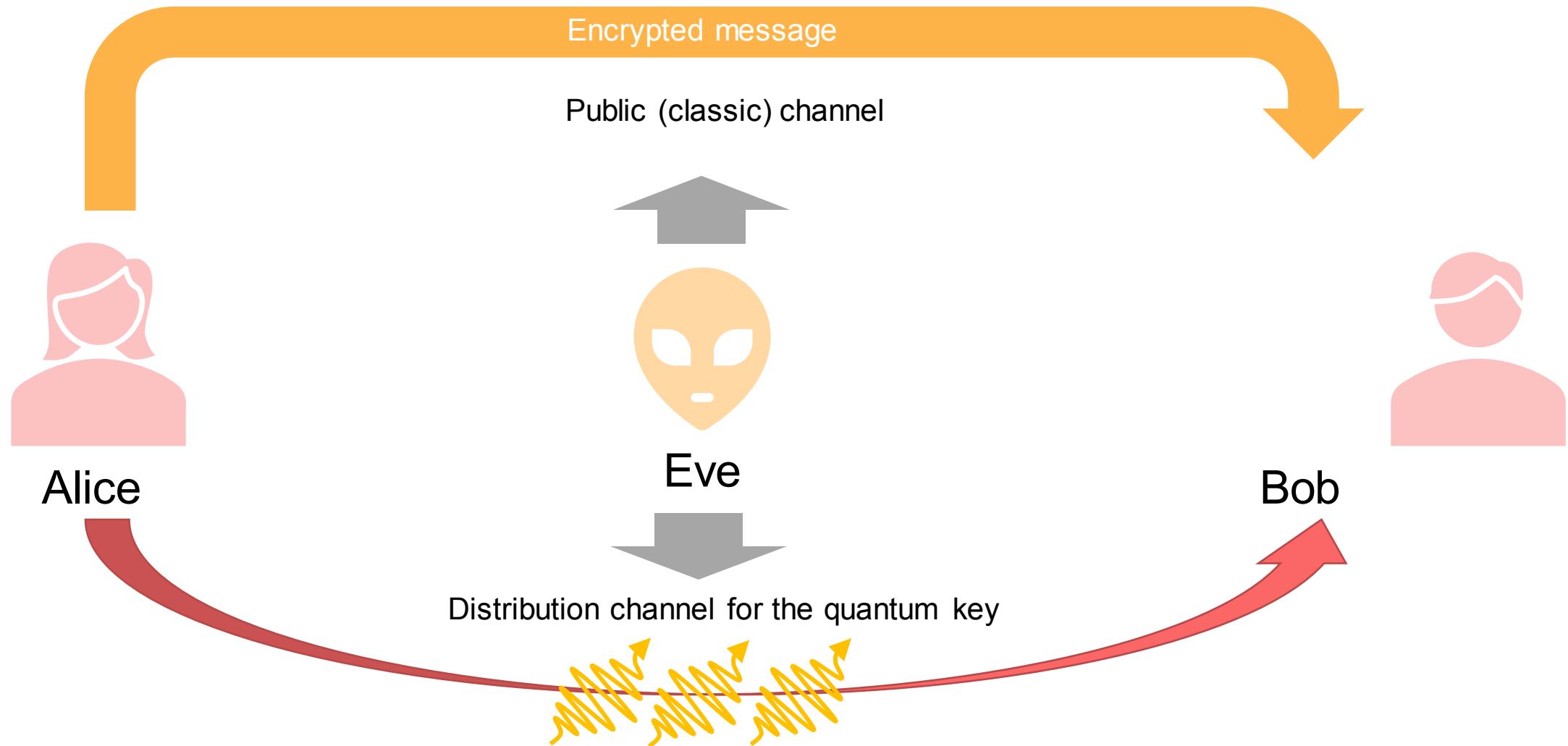
<https://www.healthcarecompliancepros.com/blog/usa-leads-the-way-with-the-most-expensive-healthcare-data-breaches>

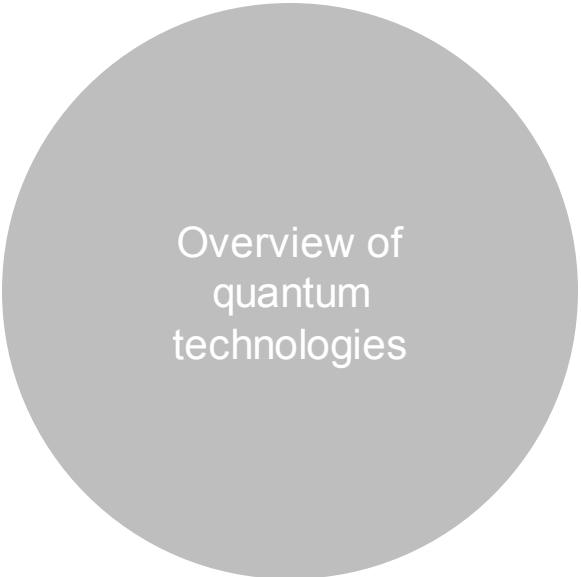
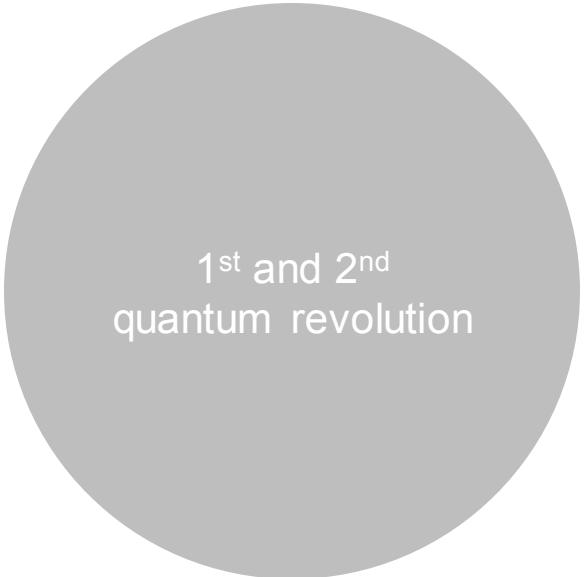


IBM Research,
https://www.flickr.com/photos/ibm_research_zurich/51248690716/, CC BY 2.0

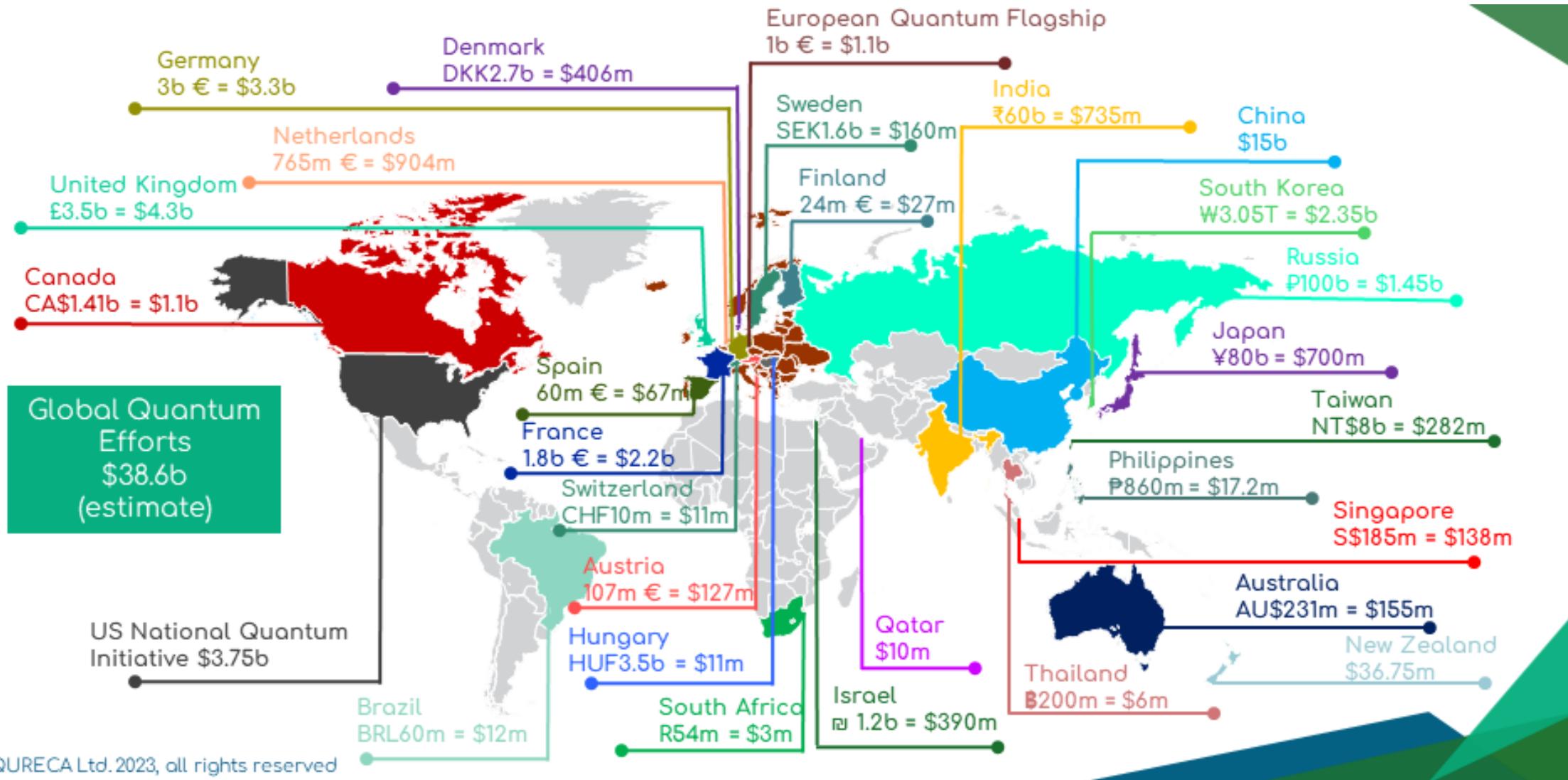
Security through quantum mechanics

Quantum key distribution (QKD)

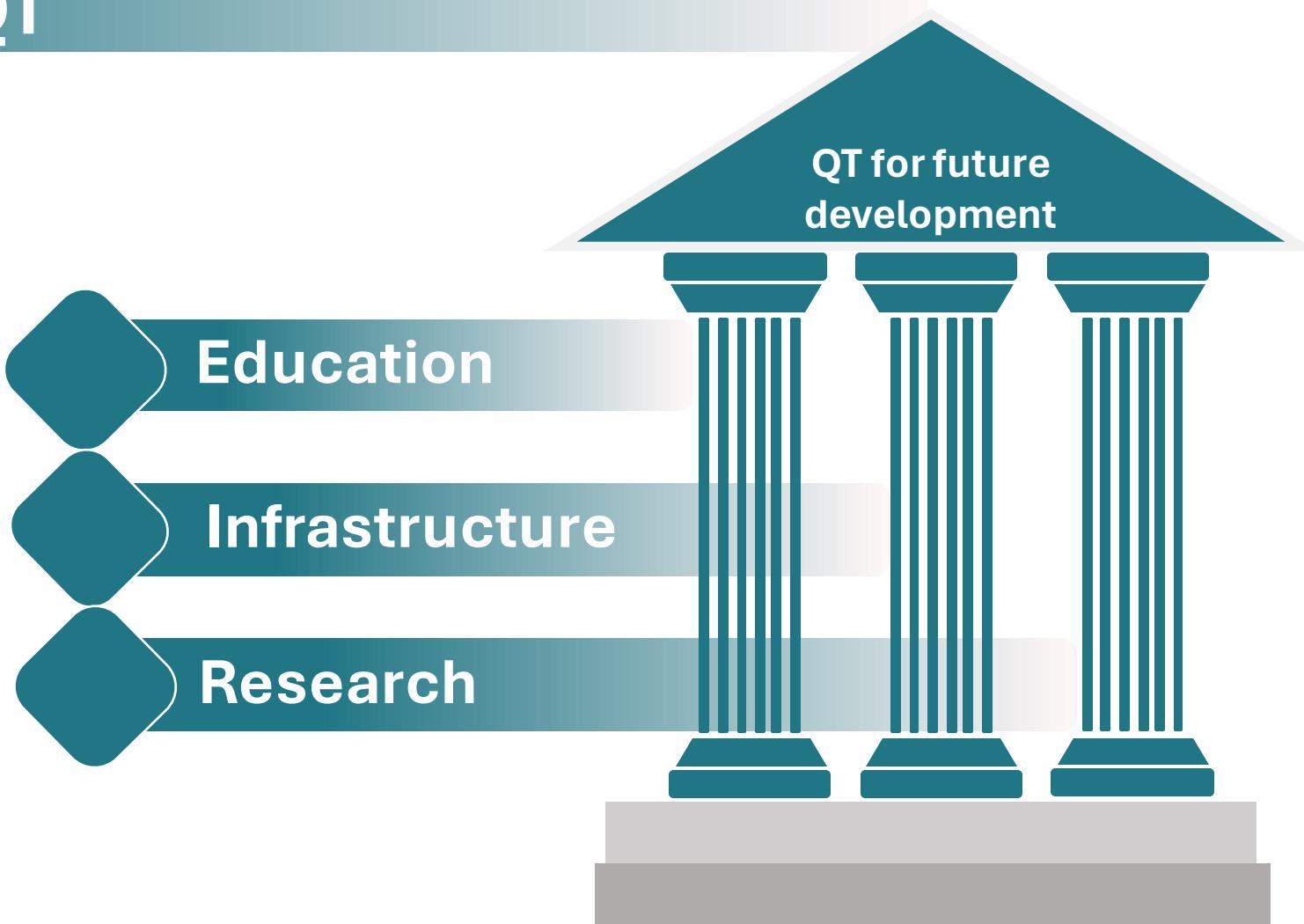
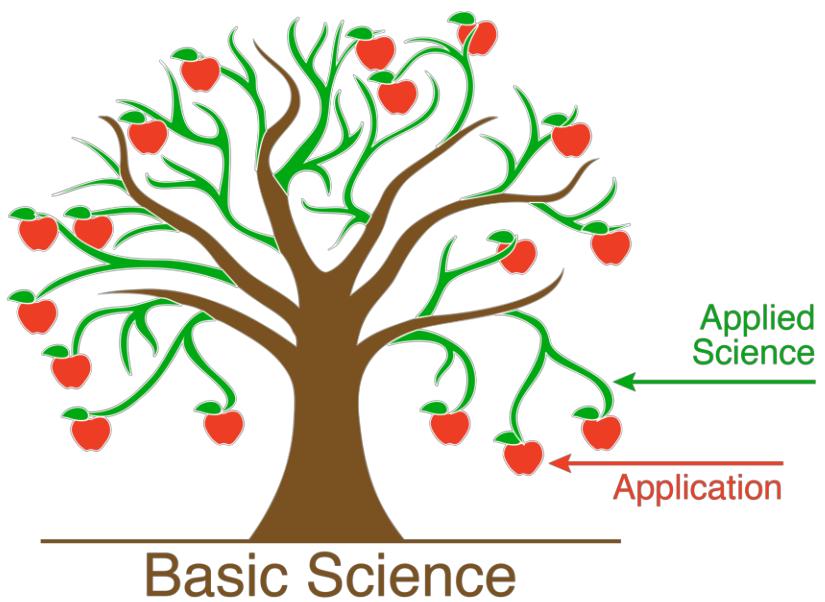




Quantum technology is a major theme in research and technology development



UiO is investing in QT



Education

- Ny studieretning i kvanteteknologi (BSc)
 - Starter høsten 2024
 - Gir bred bakgrunn over hele feltet
 - Dette er det første BSc-programmet i Norge, og andre i Norden, med en slik mulighet
- Nye studieretninger på MSc-nivå ved FI
 - Studieretning for kvanteteknologi og maskinlæring innen beregningsorientert vitenskap
 - Studieretning i kvanteteknologi innen fysikk
- PhD (forskerutdanning)

Quantum literate workforce

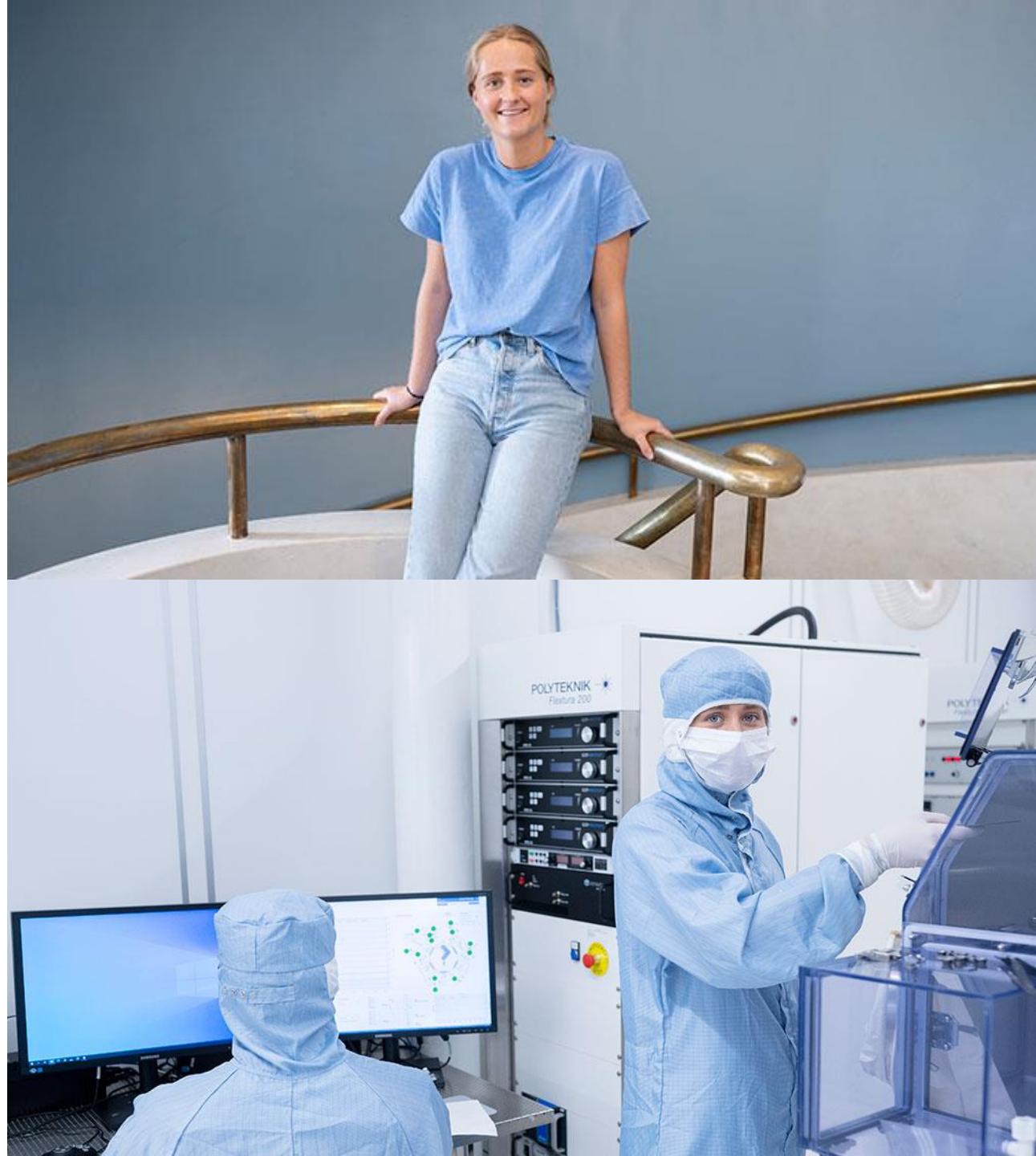


UNIVERSITETET
IOSLO

NORWEGIAN HIGH- AND NANOFABRICATION FACILITY
NorFab



Støttet av
Forskningsrådet



Infrastructure

- QT is an experimental field
- QT is a main strategic area in NorFab
- Norway needs competence building in practical QT

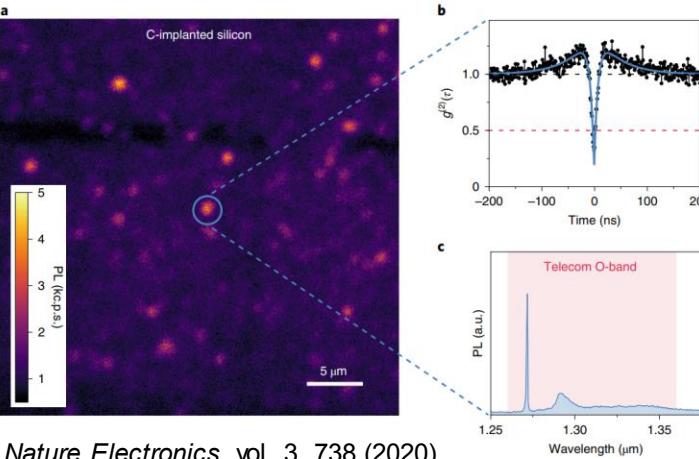
NorFab and UiO-MiNaLab provide open-access test arena for QT



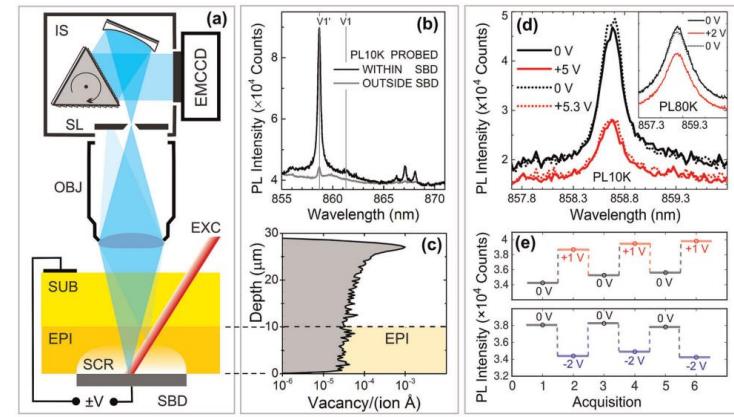
Research

- UiO has extensive theoretical, computational and experimental quantum science and technology
- Semiconductors for sustainable QT
- Quantum sensors will be strategically important for Norway

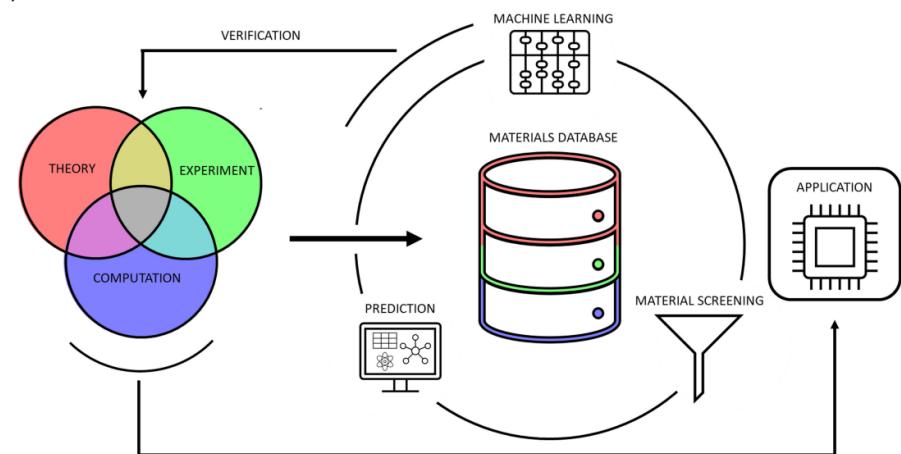
Collaboration between research, start-ups, industry and public sector is needed



Nature Electronics, vol. 3, 738 (2020).



npj Quantum Information, vol. 5, 111 (2019).



npj Comp Mat, vol. 8, 207 (2022).

White paper:
Quantum Technology in Norway –
Proposal for a National Funding Strategy
Self-published on
<https://www.quantumnorway.no/>

Quantum Technology in Norway Proposal for a National Funding Strategy

F. Massel (USN), J. Danon (NTNU), S. Ali (Simula), K. Børkje (USN),
F. G. Fuchs (SINTEF/Uo), N. Larsen (UiO), S. Selstø (OsloMet),
K. Tywoniuk (UiB), S. Viefers (UiO), J. W. Wells (UiO)

September 1st, 2023

Summary

Quantum technology holds the promise to revolutionize our technological future with applications in fields ranging from information and communication technology to medical imaging and drug design. In this document we provide a brief but broad overview of the field, including its potential impact in more general terms. We evaluate Norway's current position in the global, European and Nordic landscape of quantum technology, and based on this we suggest a funding strategy which, if followed, could keep Norway on track to partake of the upcoming technological revolution.

Our main suggestion is the implementation of two funding instruments, through the Research Council of Norway: (i) a thematic area within a call and (ii) a dedicated call for projects within quantum technology. In our opinion, these instruments would be very effective ways to allocate

