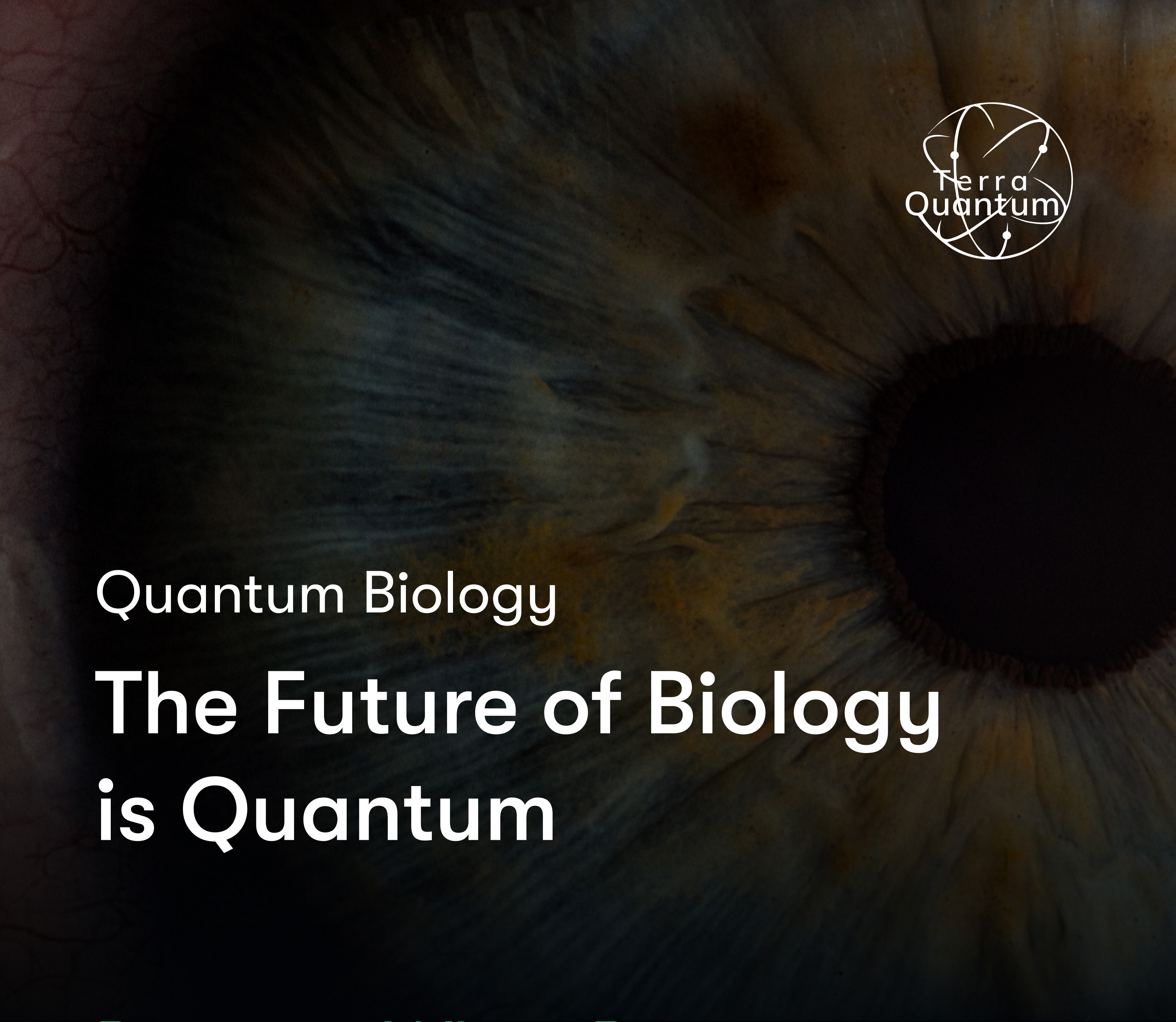


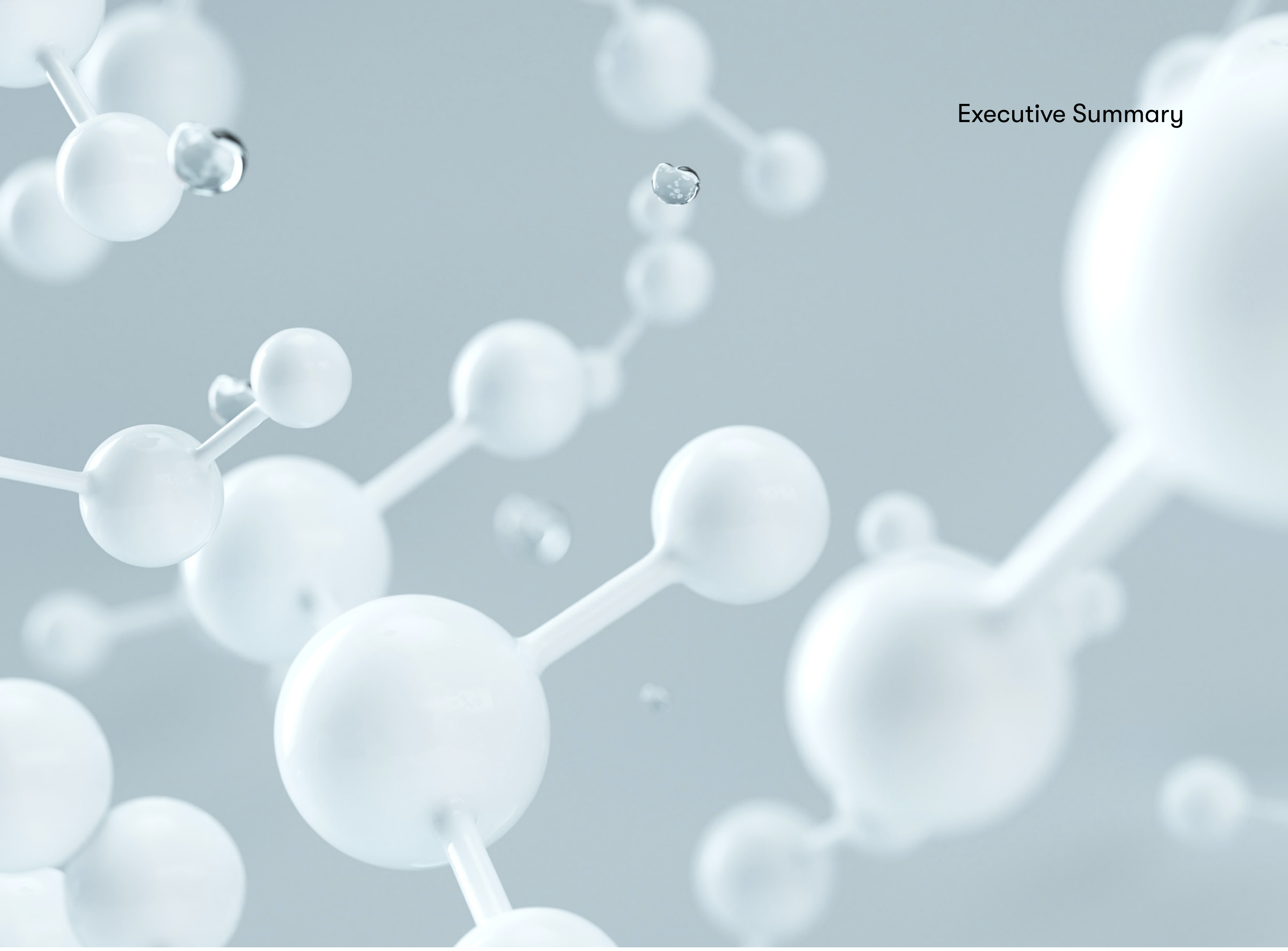
Quantum Biology

The Future of Biology is Quantum

Business White Paper

By Terra Quantum AG
terraquantum.swiss

December 2022



Quantum for Life Sciences & Health Care

Terra Quantum pioneers a range of quantum technologies with the mission of leading the quantum revolution from meaningful solutions today to a more prosperous future tomorrow. This business whitepaper focuses on our comprehensive approach to quantum biology.

The broad and emerging field of quantum biology is centered on recent research into the subtle, non-trivial role that quantum effects play in the biological processes of living organisms. This document covers hybrid quantum-classical algorithms for simulating complex molecules, power-efficient transistors for use in neuromorphic computing, methods for keeping sensitive medical information secure from cyber threats and quantum enhancements to nuclear magnetic resonance metabolomics studies for advanced diagnostics.

Quantum mechanics — the founding principles of our universe and of life itself

Quantum mechanics is the physics of the very small, the very cold or the very isolated. The principles of quantum mechanics describe the behavior of sub-atomic particles such as electrons, protons and neutrons, which form the foundation of the world around us. The core of our existence is built upon so called "quantum effects" — empirically proven patterns that seemingly contradict the rules of the classical physics world (as described by Newton, Galileo and others).

For example, the sun wouldn't shine without quantum tunneling — a phenomenon whereby a particle is able to "jump" through a potential barrier — something that is deemed impossible in the classical, Newtonian description of the world. Quantum tunneling enables nuclear fusion — the conversion of matter into energy — which creates the electromagnetic radiation (sunshine) we so crave during our summer vacations.

But these effects don't just happen in objects that are many millions of miles away from us. The idea that quantum effects play a fundamental role in macroscopic living systems was put forth by Niels Bohr in his seminal lecture 'Light and Life' in 1932. In 1944, Schrödinger's book 'What is Life' picked up the cause. Today, we know that as all living systems are made up of atoms and molecules, a variety of processes necessary for the function of the living system depend on a delicate interplay between quantum and classical physical effects. Virtually every biological transport process (the movement of ions and particles through a membrane in a living organism) utilizes some form of quantum effect — from photosynthesis in plants to even respiration and vision in humans. In each of these, the transport of electrons and protons — governed by the laws of quantum mechanics — are required to make these processes work.

Take the human brain, for example. Comprised of an enormous network for excitable neurons, we can observe their activity through studying the electrical signals. This alone does not tell us, however, where the feelings, sensations, or conscious experiences emerge in these networks. In fact, the re-creation of consciousness in inanimate objects is one of the greatest challenges of our times. In the 1990s, long before winning the 2020 Nobel Prize in Physics for his prediction of black holes, Roger Penrose teamed up with anesthesiologist Stuart Hameroff to propose that the brain's neuronal network acquires consciousness according to the rules of quantum mechanics. They proposed that consciousness is based on non-computable quantum processing performed by qubits formed collectively on cellular microtubules, a process significantly amplified in the neurons [1]. If this holds, then quantum effects are a central component of enabling consciousness — probably the defining feature of being a human!

Quantum mechanics has already been the cornerstone of progress in life sciences

The impact of quantum mechanics in life sciences has been extensive. It has helped us observe and understand ourselves better, as well as design better treatments and develop complex logistical systems that enable these treatments to be deployed at scale.

One of the core principles of quantum mechanics is that of wave-particle duality. This unique and strange principle states that sub-atomic particles can exhibit both particle and wave-like properties in specific contexts. It is by leveraging this principle that German scientists Max Knoll and Ernst Ruska designed the electron microscope [2]. This remarkable invention has enabled us to directly observe and study viruses and other tiny aspects of life, which, in turn, has led to the discovery of a plethora of new medicines used every day.

Another remarkable invention that has been developed through the application of quantum mechanics is Magnetic Resonance Imaging (MRI), a non-invasive technique using the physical phenomenon of nuclear magnetic resonance to obtain structural and compositional information about the human body. MRI uses the properties of hydrogen nuclei exposed to high magnetic fields and radio-frequency fields to achieve nuclear magnetic resonance (NMR). When a nucleus is placed in a magnetic field, an interaction between the magnetic moment of the nucleus and the field leads to an energy splitting. Transitions between these energy states occur through the absorption and emission of photons with the right frequency. Any changes to these processes are detected by an antenna that sends a signal to a computer for decoding and image generation.

Through this technique, MRI machines have helped us observe and understand the human body at a level of detail beyond what was previously possible. In particular, the ability of MRIs to accurately identify tumors has given millions of people many more years of healthy living.

Life sciences has also benefitted from the advancements in classical computation brought about by quantum mechanics. The study of the movement of electrons through materials has been the basis for the development of semiconductors and transistors, which are the essential building blocks of all the classical computing that exists today. Advanced computation has enabled and accelerated study in the life sciences — from being able to study the human genome, to telemedicine and digitization of health records. The impact is almost too broad and profound to be quantifiable.

The quantum revolution we are experiencing will see a dramatic transformation in how we understand, measure, treat and enhance our human existence

The last 10 years or so have seen a very rapid acceleration and development of a broad range of quantum technologies. Terra Quantum aims to make a profound impact on the quantum biology field.

Deeper Understanding of Our Bodies and Their Interactions With The World Around Us

While we understand the chemical composition of many of the structures that make up our bodies and the substances we interact with in our daily lives, our understanding of how these behave at the molecular, atomic and sub-atomic level is still limited. This gives rise to the need to be able to virtually simulate the behavior of molecules (in-silico). This area has long been pursued by the most esteemed computational chemists and biologists among us, but their progress has been stunted by the extent of the available computational power. While there has been significant progress in this space through the application of machine learning techniques, we are still very far away from where we need to be.

The exponential improvement in computing power that is brought about by quantum computing will overcome the limitations we face today. Being able to simulate molecules of increasingly greater complexity will enable previously unforeseen insights into how our bodies function.

Eventually, we would be able to simulate entire organs deeply and accurately and one day, even create a truly digital twin of ourselves, identical down to the molecular level. This would revolutionize drug testing and all life sciences research.

At Terra Quantum, we utilize our techniques in hybrid quantum algorithms and the power of our hybrid quantum computing hardware to simulate the behavior of increasingly complex molecules today.

Using our techniques, we will significantly increase the speed of molecular simulation while also improving its accuracy, and these benefits will continue to improve significantly as we harness the improving quantum computing hardware.

Augmentation of Intelligence

The field of artificial intelligence has made enormous progress over the last 10 years, particularly driven by breakthroughs in artificial neural networks. These networks are software-based representations of neurons and synapses that simulate the functions of the human brain. They are typically executed on classical processing units, such as Central Processing Units (CPUs) or Graphics Processing Units (GPUs).

Further progress in the field of artificial intelligence is increasingly being limited by the underlying computing hardware available for training and executing the software representations.

The field of neuromorphic computing aims at re-creating physical representations of the brain through analogue circuits (i.e., hardware representations of neural networks). However, some challenges still remain in being able to scale this approach, classically.

Unlike classical computers, our brains do not function as binary registers. Additionally, to be able to efficiently re-create the human brain, we need processing units that have dramatically better power efficiency than the ones we use today (see Figure 2). For a sense of scale, the human brain has approximately 86 billion neurons and 500 trillion synapses, processing information in a non-binary method, whereas the most powerful classical computer today has approximately 2 to 3 billion (binary) transistors.

Terra Quantum's recent breakthrough work enables us to overcome these barriers. Our paper, recently published in a Nature group journal, "The ferroelectric field-effect transistor with negative capacitance," presents a path to overcome the limitations in power consumption that are present in other processing units [3]. Furthermore, the innovative ferroelectrics-based logical units [4] enable us to implement non-binary logic that is a break-away from the von Neumann architecture (see Figure 1).

The neurophysical principles of biological brains make it overwhelmingly clear that overcoming the von Neumann bottleneck is absolutely critical to the future development of computation. Terra Quantum's advanced hardware discoveries, in the form of ferroelectric logic units, are a major step forward in implementing of spiking neural networks on a yet unprecedented scale. Less heat generation allows for building far smaller transistors than previously thought possible, and thus for increased processing speed not only in neuromorphic computing.

In the human brain, these neural spikes spontaneously and efficiently synchronize with one another. Few computing systems reproduce this faithfully but synchronized temporal oscillations are well-studied by quantum physicists, allowing Terra Quantum to take a neuroscience-inspired path to creating a hybrid architecture of qubits and ferroelectric units.

Using these approaches, Terra Quantum will develop neuromorphic processing units capable of re-creating the functions of the human brain. Not only will we be able to have a larger number of physical neurons, but by overcoming the limitations in power consumption efficiency, we will also be able to re-create spiking neural networks, whereby we can re-create the systems of biological spiking neural networks.

At Terra Quantum, we see this as a critical step in the path to truly replicating and enhancing the most advanced information processing machine known to us — the human brain.

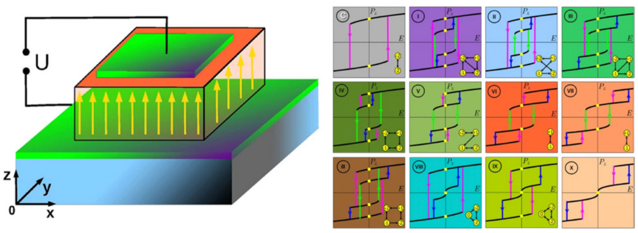


Figure 1. Implementing polarization multi-states switching in a ferro-electric transistor

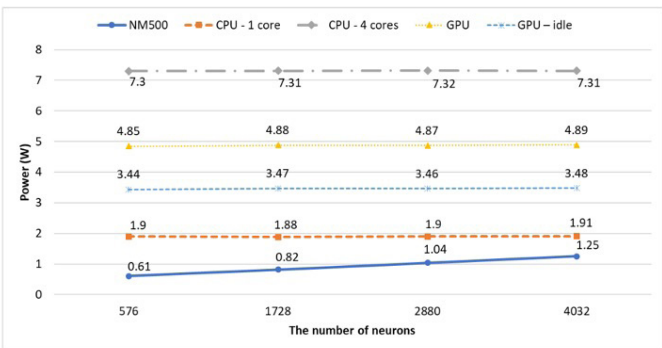


Figure 2. Power consumption remains a barrier for classical processing units [11].

Development of New Drugs

Quantum computing will have a transformative impact on the drug discovery lifecycle. As shown in Figure 3, there are significant failure rates all the way through the drug discovery process and reducing these failure rates can generate significant value.

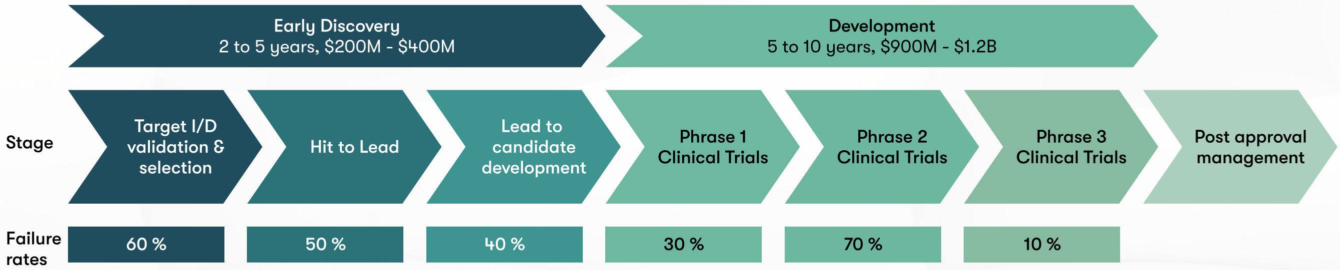


Figure 3. Failure rates in the current drug discovery process

An area of particular interest to Terra Quantum in the drug discovery lifecycle is in the “Hit to Lead” stage. Due to the limitations in computational capabilities, and in the data available, the only possible approach so far has relied on a tremendous amount of trial and error conducted by research scientists at this stage.

For example, the area of molecular docking requires examination of the structure of a protein target, while simultaneously requiring analysis of the structure of the drug candidate (or candidate antibody), shown in Figures 4 and 5, respectively. Based on this, one needs to assess the optimal docking position of the drug candidate (i.e., greatest binding affinity). Due to the complex structures of each of these molecules, there could be a large range of ways in which each molecule could be oriented to enable this docking. With thousands of drug candidates in molecular libraries at biotech companies, along with many millions of new potential drug and therapeutic molecules, this problem rapidly becomes intractable and cannot be addressed by classical computing.

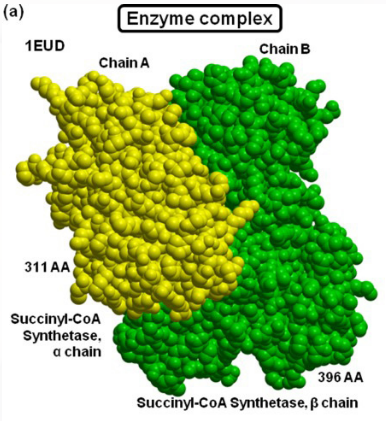


Figure 4. Example of a target protein structure

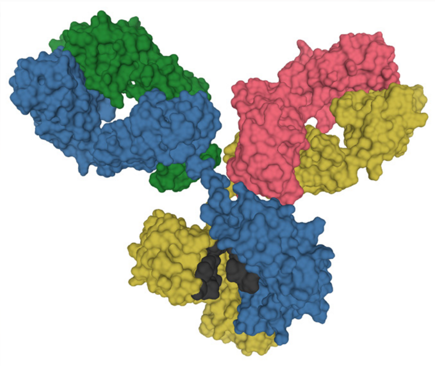


Figure 5. Example of an antibody

Terra Quantum offers a deep expertise in solving classically intractable optimization problems with our hybrid quantum algorithms. In the space of molecular docking, we are able to solve optimization problems with a potentially exponential speed-up. This paves the way for rapid acceleration and improved failure rates in the “Hit to Lead” stage, leading to significant value enhancement and ultimately better treatments for patients.

Personalization of Treatments

While modern medicine and the global pharmaceutical industry have been adopters of numerous breakthrough innovations throughout their evolution over the last century, there is still significant room for continued improvement.

For example, the statistics below illustrate the stark reality of the current situation:

- The top 10 highest-grossing drugs in the United States only help between 1 in 25 and 1 in 4 of the people who take them [5]
- Up to 9% of Emergency Department hospital admissions have been attributed to adverse medicine reactions [6]

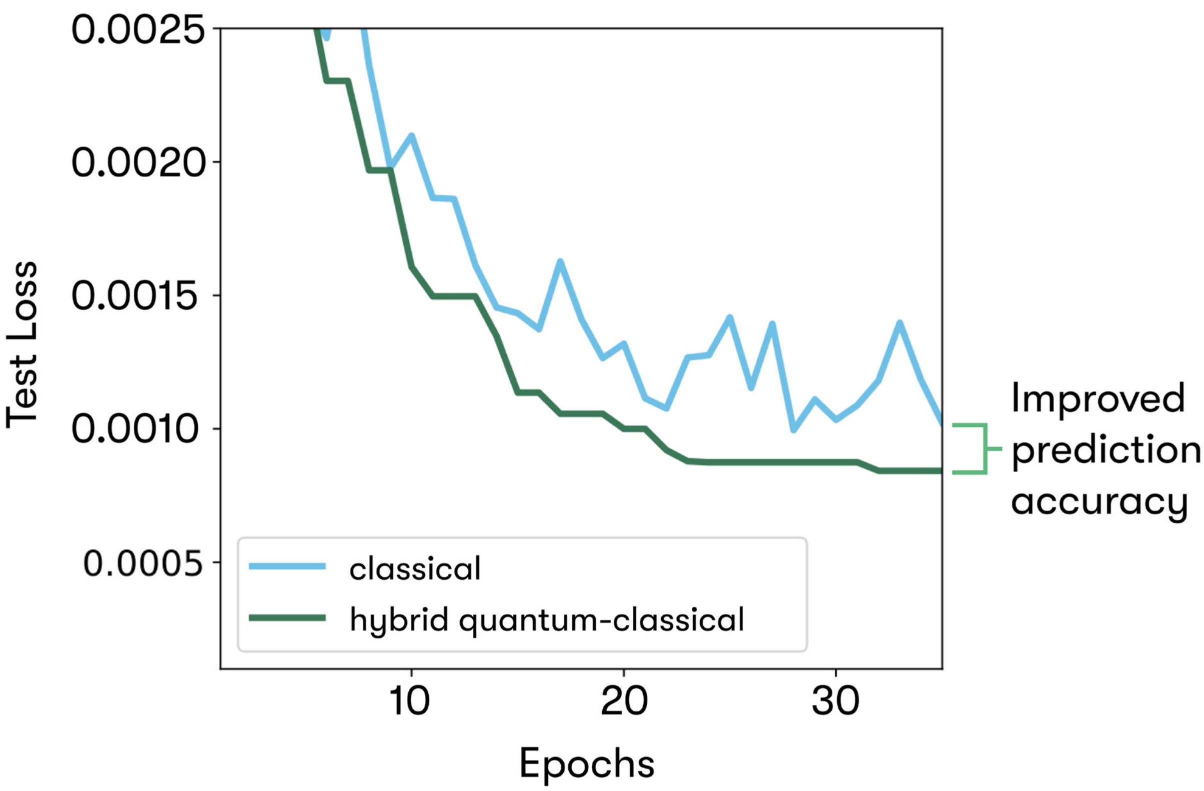
- The effectiveness of major drugs for addressing major illnesses are:
    - Cancer: 25% [7]
    - Alzheimer's: 30% [8]
    - Diabetes: 57% [9]

To address these shortcomings, there is a drive from the pharmaceutical industry to shift away from a 'one-size-fits-all' policy to precision medicine.

In the world of precision medicine, one looks at the specific characteristics of the patient and the specific sub-type of the conditions they are looking to treat, and accordingly generates a personalized treatment plan, covering drug type and dosage, etc.

Often, one of the big challenges in this space is in determining the expected effectiveness of a particular drug, based on the specific cell line being treated (for example in cancer treatment) as well as the patient's genetic and biological characteristics. Making accurate predictions in this space is a computationally challenging task, as there are many varied factors to consider. This is a space where hybrid quantum algorithms promise a very meaningful impact.

At Terra Quantum, we have developed an algorithm that can predict the effectiveness of drugs on specific cancer cell lines. Using our hybrid quantum machine learning models, we made predictions of IC50 values (a measure of drug responsiveness) across thousands of cancer cell lines against hundreds of drug compounds. Our solution was compared against a benchmark of machine learning models in this space and demonstrated improved prediction accuracy, as shown in Figure 6 (arXiv:2211.05777 [quant-ph]).



Databases used: wellcome sanger institute; MASSACHUSETTS GENERAL HOSPITAL CANCER CENTER

Figure 6. Performance of Terra Quantum's hybrid machine learning model against the benchmark

Security of information in healthcare systems

In recent years, we have seen an explosion of personal health data being generated and collected through the emergence of personal health tracking devices, telehealth, digital therapeutics, etc. In addition, huge amounts of data are generated through increasingly digitized pharmaceutical supply chains and we have also seen an increasing use of blockchain technology in tracking pharmaceutical products from the factory to the patient.

One of the unintended consequences of the emergence of quantum computing technology is that it puts all this information at risk. Quantum computing hardware and software pose a threat to contemporary encryption standards. As a result, the security threat to personal health data can lead to severe consequences, if realized. This includes:

- Exploitation of the data by malicious actors for their own economic gain
- Incorrect medications being administered — leading to catastrophic patient outcomes
- Fraudulent prescriptions and insurance claims
- Counterfeit transactions and sales

Terra Quantum offers a broad range of quantum security solutions to protect against the quantum threat (or any potential cyber threat).

Our Quantum Random Number Generator (QRNG) creates random keys by harnessing the random properties of photons. This enables secure encryption that cannot be compromised through solving complex mathematical problems, such as prime number factorization.

Our novel Quantum Key Distribution (QKD) solution also secures the transmission of information by applying the principles of quantum physics. Here, we apply our deep expertise in quantum thermodynamics to detect any intruder or non-natural losses in transmission lines (see Figure 7). As a result, information security is guaranteed by the laws of physics.

Through applying these technologies and other products in our Quantum Security business unit, we are ready to protect the life sciences industry from all current and future cyber-security threats. For more details about our security solutions, download our Quantum Security whitepaper on https://terraquantum.swiss.

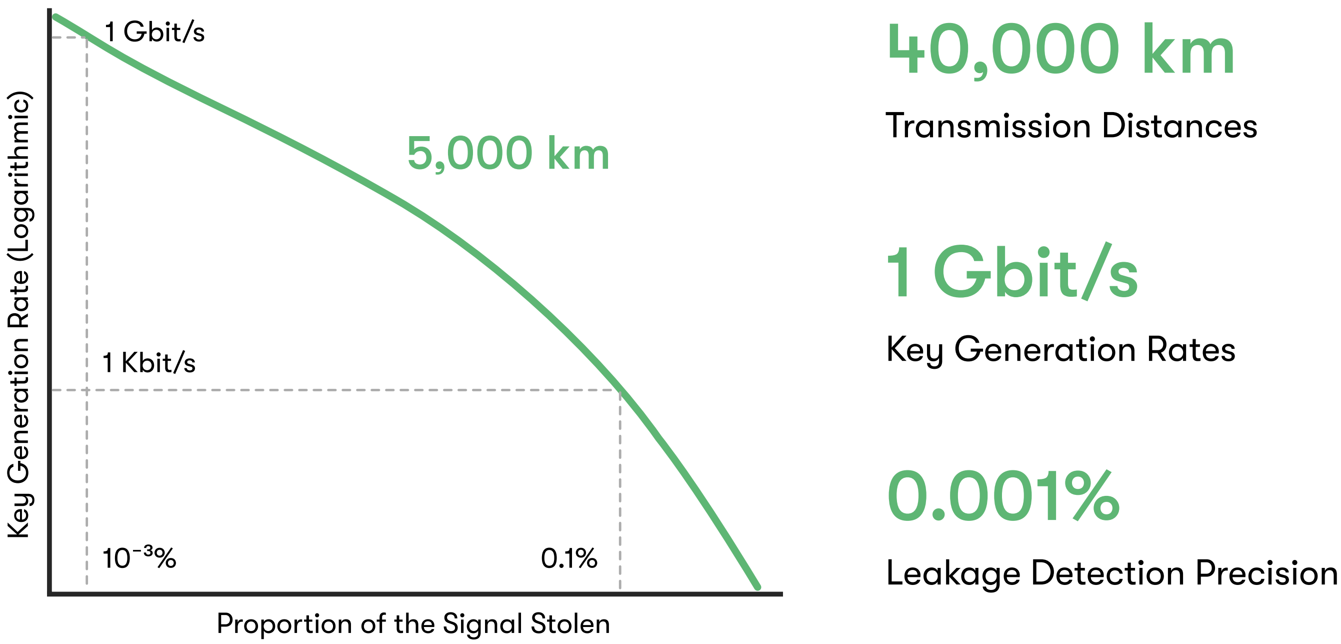


Figure 7. Proven Performance

Nuclear magnetic resonance for metabolomics

Metabolomics is the scientific study of the molecules involved in an organism's metabolism. It provides a fast, reliable and non-invasive method of diagnosing diseases and has further applications in drug discovery, precision medicine, personalized nutrition and agricultural research. The global metabolomics market was valued at $1.84 billion in 2020 and is projected to reach $4.95 billion by 2028 [10].

Currently, out of all the metabolites that are relevant to human health, the fraction that has been subjected to quantitative analysis is tiny. The remaining, uncharted metabolites are known as 'metabolic dark matter' and their characterization is an important and outstanding challenge in the pharmaceutical industry.

The phenomenon of nuclear magnetic resonance (NMR) was first observed over 80 years ago. It has played a prominent role in the development of quantum theory and, more recently, quantum computing. It is a method of interacting with atomic nuclei using magnetic fields and electromagnetic pulses and has been used in biology and chemistry for decades.

NMR spectroscopy of a typical biological sample leads to data with a highly complex structure. Fortunately, Terra Quantum has been developing techniques, such as polarization transfer, quantum tomography and peak detection algorithms, to speed up both the data acquisition and the data analysis. Additionally, these tools are being incorporated into a complete software suite that will enable the metabolomics pipeline to be automated, so that expensive NMR equipment gets used as efficiently as possible. Our work on the metabolomics of prostate cancer is already underway, providing us with both a realistic testing ground for our new methods and an opportunity to have a positive effect on patient outcomes.

Quantum Will Transform Life Sciences

While quantum technologies will have a profound impact across many sectors, their impact will probably be most transformative in the life sciences industry. The coming years will see a paradigm shift in how we understand the human body and our true uniqueness. Not only will we see revolutions in the drug design process and the personalization of treatment, but we will also harness this knowledge to develop computing devices that truly rival the creativity, complexity and efficiency of the human brain.

We see it as only fitting that we draw on the fundamental laws of the universe — quantum mechanics — to understand and enhance our health and well-being. The possibilities are endless, perhaps limited only by our imaginations.

At Terra Quantum, we will continue to be at the forefront of this field.

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