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Foreword

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Introduction

For most of computing history, the foundational hardware technology has been binary digital transistor logic. In such digital systems, data and programs represented as binary classical digits (bits) are encoded into physical transistors that have and can switch between two definite internal states: on and off. The field of quantum computing introduces a new approach to the underlying computing hardware by shifting from classical logic ("on" or "off") to a quantum logic where the "quantum bits" or "qubits" (the simplest units of quantum information) are encoded into physical registers that exhibit quantum-mechanical phenomena such as superposition and entanglement.

This shift from the classical digital representation found in today's conventional computers to a quantum digital representation in tomorrow's computers is expected to bring increases in computing power and new, innovative software applications, allowing us to tackle more complex computational problems and carry out powerful analysis of more complex data patterns that are already challenging or impossible for today's technology. Quantum computing holds the potential to revolutionize fields from chemistry and logistics to finance and physics.

However, the increase in power and capability that quantum computing will provide, will also pose an important security threat once quantum computers become large enough (or cryptographically relevant, as it is sometimes described). As strong as today's cryptographic mechanisms have been against conventional computers, almost all cryptographic protocols used are vulnerable to quantum-computing-based attacks with known algorithms. This widely known risk associated with the power of quantum computing is very concerning for governments, institutions and individuals whose encrypted data are safe today, but may become decryptable once quantum computers reach large enough size.

This document aims to assist in the understanding of quantum computing concepts and the exchange of information.

Information technology — Quantum computing — Vocabulary

1 Scope

This document defines terms commonly used in the field of quantum computing. This document is applicable to all types of organizations (e.g. commercial enterprises, government agencies, not-for-profit organizations) to exchange quantum computing concepts.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1 Background

3.1.1
model
physical, mathematical, or otherwise appropriate representation of a system, entity, phenomenon, process or data

[SOURCE: ISO/IEC 22989:2022, 3.1.23, logical has been changed to appropriate]

3.1.2
model parameter
internal variable of a *model* (3.1.1) that affects how it computes its outputs

[SOURCE: ISO/IEC 22989:2022, 3.3.8]

3.1.3
machine learning
process of optimizing *model parameters* (3.1.2) through computational techniques, such that the model's behaviour reflects the data or experience

[SOURCE: ISO/IEC 22989:2022, 3.3.5]

3.1.4
simulator
device, computer program, or system that behaves or operates like a given system when provided a set of controlled inputs

[SOURCE: ISO/IEC/IEEE 24765:2017, 3.3750]

3.1.5
program
computer program
syntactic unit that conforms to the rules of a particular *programming language* (3.1.6) and that is composed of declarations and statements or instructions needed to solve a certain function, task, or problem

[SOURCE: ISO/IEC 2382:2015, 2121374, modified — Notes to entry omitted]

3.1.6
programming language
artificial language for expressing *programs* (3.1.5)

[SOURCE: ISO/IEC 2382:2015, 2121374, modified — Notes to entry omitted]

3.1.7
programming
designing, writing, modifying, and testing of *programs* (3.1.5)

[SOURCE: ISO/IEC 2382:2015, 2121374, modified — Notes to entry and domain identifier <fundamental terms> omitted]

3.1.8
coding
<computer programming>process of expressing a *program* (3.1.5) in a *programming language* (3.1.6)

[SOURCE: ISO/IEC 2382:2015, 2121374, modified — Notes to entry omitted]

3.1.9
algorithm
process for computation, defined by a set of rules, that will yield a corresponding output

[SOURCE: ISO/IEC 18031:2011, 3.1, modified — Definition was modified]

3.2 Quantum physics background

3.2.1
Hilbert space
vector space equipped with an inner product operation which allows distances, angles and vector norms to be defined

Note 1 to entry: When used in the context of *quantum physics* (3.2.3), the space of *quantum states* (3.2.7) of a *quantum system* (3.2.6) is described by a complex Hilbert space, referred to as the state space.

Note 2 to entry: All possible quantum states can be represented as *operators* (3.2.2) on the quantum system's Hilbert space.

3.2.2
operator
mathematical entity that transforms the elements of an input space to the elements of an output space

Note 1 to entry: In *quantum physics* (3.2.3), simple operators can be mathematically represented by a matrix that acts via matrix multiplication on vectors in a *Hilbert space* (3.2.1).

3.2.3
quantum physics
quantum mechanics
fundamental theory of physics, in which physical properties of systems are completely determined by vectors in a complex *Hilbert space* (3.2.1) whose dynamics are determined by specific types of linear transformations on that space

Note 1 to entry: There are many different formulations of quantum physics, but the specific linear transformations allowed must all correctly describe stronger correlations than can arise in classical physics, such as those that are probed by Bell and Kochen-Specker tests.

Note 2 to entry: Measurement outcome probabilities are determined from the complex vectors, typically via the Born rule.

Note 3 to entry: Importantly, quantum physics is able to successfully describe the behaviour of light and matter in operating regimes where classical theories of physics can break down, like ultrasmall sizes or energies or at low temperatures.

Note 4 to entry: In the context of *quantum computing* (3.4.3), it is normally sufficient to consider *quantum state* (3.2.7) evolution as being governed by the non-relativistic Schrödinger equation through the *Hamiltonian* (3.2.12), for particles with mass, or the quantum electrodynamics formulation of Maxwell's equations, for light. However, quantum dynamics also includes broader contexts, such as the dynamics of relativistic systems, which are governed by the Dirac equation.

3.2.4
quantum, adjective
making use of or arising from the laws of *quantum physics* (3.2.3) in an essential way

3.2.5
quantum, noun
discrete, finite, indivisible, and measurable unit of a physical property such as energy

3.2.6
quantum system
system whose properties are determined by the laws of *quantum physics* (3.2.3), and cannot be completely described by just the laws of classical physics

3.2.7
quantum state
description of the state of a *quantum system* (3.2.6) defining the probability distribution of possible outcomes of any measurement upon it

Note 1 to entry: A quantum state can be mathematically represented by a vector or, more generally, a *density operator* (3.2.2) in the complex *Hilbert space* (3.2.1). (See Note 1 to entry in *quantum operator* (3.2.11) for discussion of density operators.)

Note 2 to entry: A *quantum* (3.2.4) wave-function is the mathematical representation of a quantum state in a particular basis of the Hilbert space. Wave-functions are often defined over continuous parameters, such as position, momentum and phase.

3.2.8
quantum superposition
complex linear combination of two or more different *quantum states* (3.2.7)

3.2.9
basis states
members of a set of *quantum states* (3.2.7) which span the *Hilbert space* (3.2.1) of a *quantum system* (3.2.6)

Note 1 to entry: Any quantum state in the Hilbert space can be written as a linear combination, or *quantum superposition* (3.2.8), of basis states.

Note 2 to entry: A set of basis states is often chosen to be complete and orthonormal. That is, the set spans the entire Hilbert space, and individual elements are orthogonal and normalised to length 1.

3.2.10
quantum entanglement
property of a *quantum state* (3.2.7) within a joint *quantum system* (3.2.6), consisting of at least two subsystems, for which the quantum state cannot be described in terms of independent characteristics of its individual constituents

3.2.11
quantum operator
operator (3.2.2) that acts on *quantum states* (3.2.7) in *Hilbert space* (3.2.1)

Note 1 to entry: In *quantum physics* (3.2.3), non-pure (or mixed) states, which are classical statistical mixtures of distinct pure quantum states, are represented by Hermitian density operators instead of complex vectors. Density operators contain information about both coherences between the *basis states* (3.2.9) used to represent the quantum state, and about the statistical distribution of those states.

3.2.12
Hamiltonian
<quantum physics>*quantum operator* (3.2.11) which determines the coherent evolution of a *quantum system* (3.2.6)

Note 1 to entry: The Hamiltonian operator usually corresponds to the total energy of a quantum system.

Note 2 to entry: The expectation value of the Hamiltonian gives the total energy for a particular quantum state.

3.2.13
eigenstate
<quantum physics>*quantum state* (3.2.7) left unchanged by the action of a *quantum operator* (3.2.11), except for a complex scaling factor

3.2.14
eigenvalue
<quantum physics>complex scaling factor corresponding to the *eigenstate* (3.2.13) of a *quantum operator* (3.2.11)

Note 1 to entry: Eigenvalues are real for Hermitian *operators* (3.2.2) and complex roots of unity for unitary operators.

3.2.15
eigenspace
<quantum physics>*Hilbert space* (3.2.1) spanned by a set of *eigenstates* (3.2.13) that share the same *eigenvalue* (3.2.14)

3.2.16
quantum measurement
process that outputs a physical property of a *quantum state* (3.2.7)

Note 1 to entry: Quantum measurement usually involves interaction with a meter system which encodes the output of the physical property.

Note 2 to entry: In quantum computing, quantum measurement is often modelled as a *projective measurement* (3.2.17).

3.2.17
projective measurement
quantum measurement (3.2.16) for which instantaneously repeated measurements do not change the *quantum state* (3.2.7) achieved after an initial measurement

3.2.18
quantum coherence
existence or extent of unambiguous phase relationships between possible states of a *quantum system* (3.2.6)

Note 1 to entry: Quantum coherence in a quantum system is often defined between populations of different *basis states* (3.2.9) in an individual *quantum state* (3.2.7) of that quantum system.

3.2.19
decoherence
loss or degradation of *quantum coherence* (3.2.18)

Note 1 to entry: Decoherence requires interaction between a *quantum system* (3.2.6) and environmental degrees of freedom.

3.2.20
coherence time
characteristic time scale for *decoherence* (3.2.19)

Note 1 to entry: Different measurement protocols can be designed to probe different types of *decoherence* (3.2.19), and give rise to different complementary coherence times. Important examples of commonly used protocols are Ramsey, Hahn echo and CMPG.

3.2.21
relaxation time
<quantum physics>characteristic time scale for decay from a non-equilibrium state to the steady state of a *quantum system* (3.2.6)

Note 1 to entry: Relaxation commonly refers to decay from an excited state to a lower energy state as a result of energy decay.

Note 2 to entry: The relaxation time constant is usually denoted by T_1.

3.3 Quantum information

3.3.1
quantum information
information contained or encoded in a *quantum state* (3.2.7).

Note 1 to entry: Quantum information may be transformed via *quantum* (3.2.4) operations and processes.

3.3.2
quantum encoding
representation of information in states of a *quantum system* (3.2.6)

3.3.3
qubit
quantum system (3.2.6) with two *basis states* (3.2.9)

Note 1 to entry: Qubit stands for *quantum* (3.2.4) bit.

Note 2 to entry: Qubit is the smallest unit of *quantum information* (3.3.1).

Note 3 to entry: The *Hilbert space* (3.2.1) of a qubit is the space spanned by its two basis states. The *quantum state* (3.2.7) of a qubit can therefore be any *quantum superposition* (3.2.8) of these states.

Note 4 to entry: In practice, qubits are often realised as *physical qubits* (3.3.5) in many-state quantum systems where the computational information is stored in only two *basis states* (3.2.9).

Note 5 to entry: See also *logical qubit* (3.3.7) and *qudit* (3.3.4).

Note 6 to entry: By default, this document generally defines terms in relation to qubits, but these definitions can usually also be straightforwardly applied or generalised to the case of *qudits* (3.3.4).

3.3.4
qudit
quantum system (3.2.6) with *basis states* (3.2.9) where is an integer greater than or equal to two

Note 1 to entry: Qudit stands for *quantum* (3.2.4) dit or quantum -level system.

Note 2 to entry: Qudit is a -fold unit of *quantum information* (3.3.1).

Note 3 to entry: The *Hilbert space* (3.2.1) of a qudit is the space spanned by its *basis states* (3.2.9). The *quantum state* (3.2.7) of a qudit can therefore be any *quantum superposition* (3.2.8) of these states.

Note 4 to entry: In practice, qudits are often realised as *physical qudits* (3.3.6) in many-state quantum systems where the computational information is stored in only basis states.

Note 5 to entry: *Qubit* (3.3.3) is a special case of qudit in which “d” is equal to 2.

Note 6 to entry: *Qutrit* is a special case of qudit in which "d" is equal to 3.

Note 7 to entry: See also logical *qudit* (3.3.4) and *qubit* (3.3.3).

3.3.5
physical qubit
individual tangible *quantum system* (3.2.6) that is used to encode the two *basis states* (3.2.9) of a *qubit* (3.3.3), or one qubit of *quantum information* (3.3.1)

Note 1 to entry: Unlike a logical qubit (3.3.13), a physical qubit is usually "irreducible" in that it cannot be broken down into multiple independent information-carrying components.

Note 2 to entry: A physical qubit is often realized (brought about in practice) by storing computational information in a two-state subspace of a larger full *Hilbert space* (3.2.1), engineered to minimize interactions between the qubit computational quantum states and other non-computational quantum states.

Note 3 to entry: In the scientific literature, a physical qubit is often just called a qubit, even though its state space may not be strictly two-dimensional.

3.3.6
physical qudit
individual tangible *quantum system* (3.2.6) that is used to encode the multiple (d) *basis states* (3.2.9) of a *qudit* (3.3.4) or one qudit of *quantum information* (3.3.1)

Note 1 to entry: Unlike a *logical qudit* (3.3.4), a physical qudit is usually "irreducible" in that it cannot be broken down into multiple independent information-carrying components.

Note 2 to entry: A physical qudit is sometimes realised (brought about in practice) by storing computational information in a -state subspace of a larger full *Hilbert space* (3.2.1), engineered to minimize interactions between the qudit computational quantum states and other non-computational quantum states.

Note 3 to entry: In the scientific literature, a physical qudit is often just called a qudit, even though its state space may not be strictly -dimensional.

3.3.7
logical qubit
qubit (3.3.3) encoded in a joint two-dimensional *eigenspace* (3.2.15) of one or more symmetry *operators* (3.2.2) defined with a larger physical *Hilbert space* (3.2.1)

Note 1 to entry: The two *basis states* (3.2.9) of the logical qubit Hilbert space are used to specify its logical, or canonical, *quantum operators* (3.2.11).

Note 2 to entry: Symmetry operators must have support across the entire *Hilbert space* (3.2.1). Mathematically, this requires that the symmetry operators do not have a zero-*eigenvalue* (3.2.14) *eigenspace* (3.2.15).

3.3.8
logical qudit
qudit (3.3.4) encoded in a joint d-dimensional *eigenspace* (3.2.15) of one or more symmetry *operators* (3.2.2) defined within a larger physical *Hilbert space* (3.2.1)

Note 1 to entry: The d *basis states* (3.2.9) of the logical qudit *Hilbert space* (3.2.1) are used to specify its logical, or canonical, *quantum operators* (3.2.11).

Note 2 to entry: Symmetry operators must have support across the entire *Hilbert space* (3.2.1). Mathematically, this requires that the symmetry operators do not have a *zero-eigenvalue* (3.2.14) *eigenspace* (3.2.15).

3.3.9
logical operator
<quantum computing>canonical *quantum operator* (3.2.11) defined relative to *logical qubit* (3.3.7) or *logical qudit* (3.3.8) *basis states* (3.2.9)

Note 1 to entry: For example, standard logical operators for a single *qubit* (3.3.3) are the logical X (bit-flip) and logical Z (phase-flip) *quantum gates* (3.4.2).

Note 2 to entry: In a classical computing context, a logical operator can refer to a logical gate, like a NAND or XOR.

3.3.10
state fidelity
measure of the similarity of two *quantum states* (3.2.7) that expresses the probability that one state will pass a test to identify as the other

Note 1 to entry: In quantum computing, state fidelities are often described in reference to an ideal or target state.

Note 2 to entry: Other mathematical definitions of state fidelity have been used over time, so care is required when comparing reported fidelities.

3.3.11
fidelity
measure of similarity between mathematical objects, defined via the *state fidelity* (3.3.10) for their appropriate state-like representations

3.3.12
process fidelity
fidelity (3.3.11) between two quantum processes

3.4 Quantum processing

3.4.1
quantum information processing
quantum processing
process, algorithm or computation that stores and processes *quantum information* (3.3.1) using, in an essential way, properties such as *quantum superposition* (3.2.8) and *quantum entanglement* (3.2.10)

Note 1 to entry: Examples of common quantum processes where fidelities are reported include *quantum gates* (3.4.2) and *quantum measurements* (3.2.16).

3.4.2
quantum gate
applied quantum (3.2.4) operation that transforms input *quantum states* (3.2.7) into output quantum states

Note 1 to entry: Individual quantum gates are defined or characterised by the specific mathematical transformation between input and output quantum states.

Note 2 to entry: The processing of *quantum information* (3.3.1) via a nontrivial sequence of quantum gates is the defining feature of circuit-based *quantum computing* (3.4.11). In the context of *quantum circuits* (3.4.5), individual quantum gates usually act on a limited number of *qubits* (3.3.3).

Note 3 to entry: In *quantum processors* (3.4.8), quantum gates are often implemented via finite-duration *quantum system* (3.2.6) evolution or operations that are activated by external controls, signals or components.

3.4.3
unitary gate
quantum gate (3.4.2) that preserves inner products between *quantum states* (3.2.7)

Note 1 to entry: Unitary gates do not cause *decoherence* (3.2.19) of the *quantum system* (3.2.6).

3.4.4
gate fidelity
process fidelity (3.3.12) defined in relation to an ideal target *quantum gate* (3.4.2)

Note 1 to entry: In quantum computing, the ideal target quantum gate is usually a *unitary gate* (3.4.3).

3.4.5
quantum circuit
combination or sequence of *quantum gates* (3.4.2) and other operations

Note 1 to entry: Quantum circuits are usually designed to perform a more complex function than individual gates.

Note 2 to entry: Examples of other operations in this context include *quantum state* (3.2.7) preparation and *quantum measurement* (3.2.16).

3.4.6
quantum error correction
procedure to diagnose and correct errors in the constituent parts of a *logical qubit* (3.3.7) without measuring any logically encoded *quantum information* (3.3.1), by exploiting the logical qubit's symmetries

Note 1 to entry: Typically, errors are caused by interactions with the environment or by inaccurate implementation of *quantum gates* (3.4.2).

Note 2 to entry: Quantum error correction protocols can also be designed to work for -dimensional *logical qudits* (3.3.8).

Note 3 to entry: The aim of quantum error correction is to reduce the sensitivity of *quantum information* (3.3.1) encoded in a logical qubit or logical qudit to errors and imperfections in its constituent parts.

3.4.7
quantum error mitigation
procedure designed to ameliorate or partially compensate for errors, noise or their effects in a *quantum processor* (3.4.8) to reduce errors in its output or results

Note 1 to entry: Quantum error mitigation can be implemented either during quantum processor run-time or data post-processing.

Note 2 to entry: Quantum error mitigation techniques are not always compatible with *quantum error correction* (3.4.6) or fault-tolerant *quantum computing* (3.4.11), but when they are, may form part of a suite of measures designed to reduce *quantum circuit* (3.4.5) error rates to a level where they surpass the threshold for full fault tolerance.

3.4.8
quantum processor
tangible device that performs *quantum information processing* (3.4.1)

3.4.9
quantum algorithm
algorithm (3.1.9) for use on a *quantum processor* (3.4.8)

Note 1 to entry: Quantum algorithms often incorporate aspects from both classical information processing and *quantum information processing* (3.4.1).

Note 2 to entry: The output of a quantum algorithm as used in this definition is intended to be a very flexible concept. For example, it could be the outcome of a *quantum measurement* (3.2.16) of a *quantum state* (3.2.7), the state itself to be used directly as a resource for further computation, or it could even just be the current state of the quantum processor, as might be the case during ongoing *quantum error-correction* (3.4.6) of a *logical quantum memory* (3.4.29).

Note 3 to entry: Quantum algorithms can be designed so that they need to be run multiple times to extract the required result, for example, to overcome noise or as a means to implement a target algorithm efficiently using approximate *quantum circuits* (3.4.5).

3.4.10
quantum computer
fully programmable *quantum processor* (3.4.8) that can implement or approximate any unitary dynamics defined within its full *Hilbert space* (3.2.1)

Note 1 to entry: In *circuit-based quantum computing* (3.4.13), a quantum computer has access to a universal set of *quantum gates* (3.4.2).

Note 2 to entry: Quantum computers most commonly use *quantum information* (3.3.1) encoded in *qubits* (3.3.3).

Note 3 to entry: A restricted or non-universal quantum computer belongs to the broader category of *quantum processors* (3.4.8), which includes both universal and non-universal quantum computers, including examples such as *quantum simulators* (3.4.22) and *quantum annealers* (3.4.31).

3.4.11
quantum computing
computation that can be carried out on a *quantum computer* (3.4.10)

3.4.12
fault-tolerant quantum computing
quantum computing (3.4.11) that uses fault-tolerant *quantum circuit* (3.4.5) design principles that inhibit individual errors from cascading through the computation in an unbounded manner

Note 1 to entry: When combined with *quantum error correction* (3.4.6), fault-tolerant quantum computing exhibits a finite error threshold, relative to an error model, that is independent of computation size, below which arbitrarily long computations can be carried out to arbitrarily good precision.

Note 2 to entry: Although the definition of fault-tolerant quantum computing does not necessarily need error correction, it is common usage that both fault-tolerant design principles and quantum error correction are required to achieve full fault tolerance.

3.4.13
circuit-based quantum computing
gate-based quantum computing
archetypal model of *quantum computing* (3.4.11) based on execution of *quantum circuits* (3.4.5)

3.4.14
one-way quantum computing
measurement-based quantum computing
measurement-based model of *quantum computing* (3.4.11) executed by performing, on a highly entangled resource state, a sequence of *single-qubit* (3.3.3) *quantum measurements* (3.2.16) and feedforward operations

Note 1 to entry: The resource state can be either prepared prior to commencement of the computation, or continually extended during computation from an initial resource state to keep ahead of the measurement and feed-forward operations.

3.4.15
adiabatic quantum computing
Hamiltonian-based model of *quantum computing* (3.4.11) involving continuous and gradual evolution of a *quantum state* (3.2.7) towards a desired solution state

3.4.16
topological quantum computing
model of *quantum computing* (3.4.11) using topologically ordered *quantum systems* (3.2.6) with non-Abelian excitations where *quantum gates* (3.4.2) are performed by braiding

Note 1 to entry: Topologically ordered quantum systems are usually associated with a gapped ground *quantum state* (3.2.7) with degeneracy dependent on the topological properties (typically, a Betti number) of the underlying spatial manifold, and gapless edge modes when boundaries are present. For example, in the case of two-dimensional spatial manifolds, excitations are particle-like with anyonic statistics (anyons).

Note 2 to entry: Examples of non-Abelian anyons include quasiparticles in Majorana edge modes in 1D nanowires and non-Abelian quantum double spin-lattice models. Defects in surface-code *qubit* (3.3.3) lattices provide an example of Abelian anyons.

3.4.17
quantum code
<quantum error>set of *basis states* (3.2.9) used to encode a *logical qubit* (3.3.7) or *logical qudit* (3.3.6) to enable *quantum error correction* (3.4.6), suppression, detection or fault-tolerant *quantum computing* (3.4.16)

Note 1 to entry: Illustrative examples include repetition codes, surface codes and GKP codes.

3.4.18
quantum coding
<quantum error>use of *quantum codes* (3.4.17) to protect *quantum information* (3.3.1)

Note 1 to entry: For use in *quantum error correction* (3.4.6), *quantum communication* (3.6.1) or quantum cryptography

3.4.19
quantum coding
<fundamental quantum information theory>*quantum encoding* (3.3.2)

3.4.20
quantum coding
<quantum programming>*coding* (3.4.19) for a *quantum processor* (3.4.1)

3.4.21
quantum programming
<quantum software>*programming* (3.1.6) for a *quantum processor* (3.4.8)

3.4.22
quantum simulator
quantum emulator
<classical software>*simulator* (3.1.4) of *quantum circuits* (3.4.5) or *quantum systems* (3.2.6) that uses a classical computer program

3.4.23
quantum simulator
simulator (3.1.4) of the dynamics of the *model* (3.1.1) for a complex target system using a *quantum processor* (3.4.8)

3.4.24
digital quantum simulator
quantum simulator (3.4.22) that uses discretised *quantum circuits* (3.4.5)

3.4.25
analogue quantum simulator
quantum emulator
quantum simulator (3.4.23) whose dynamics directly maps the full dynamics of a *model* (3.1.1) for a target *quantum system* (3.2.6)

Note 1 to entry: An analogue quantum simulator is normally designed to be tuned, controlled, and measured in a useful way that, for example, is not necessarily easily realizable in an underlying target quantum system.

3.4.26
circuit-based quantum computer
gate-based quantum computer
tangible device that performs *circuit-based quantum computing* (3.4.13)

3.4.27
one-way quantum computer
tangible device that performs *one-way quantum computing* (3.4.14)

Note 1 to entry: In *quantum physics* (3.2.3), adiabatic evolution is defined as evolution that is continuous and gradual, compared with the instantaneous gap between energy *eigenstates* (3.2.13) of the time-dependent *Hamiltonian* (3.2.12).

3.4.28
adiabatic quantum computer
tangible device that performs *adiabatic quantum computing* (3.4.15)

3.4.29
quantum memory
component of a device or *quantum processor* (3.4.8) that can store a *quantum state* (3.2.7) or *quantum system* (3.2.6) for later retrieval

3.4.30
simulator
device, computer program, or system that behaves or operates like a given system when provided a set of controlled inputs

[SOURCE: ISO/IEC/IEEE 24765:2017, 3.3750]

3.4.31
quantum annealer
quantum processor (3.4.8) that exploits *quantum* (3.2.4) tunnelling induced as a result of slow, or adiabatic, variation of its *Hamiltonian* (3.2.12) to find a minimum energy *quantum state* (3.2.7) that encodes solutions to a discrete classical search or optimization problem

Note 1 to entry: The key principles of slow control-parameter evolution used in quantum annealing are similar to those used in adiabatic *quantum computing* (3.4.15).

3.4.32
coupler
<quantum hardware>hardware element, or part of a hardware element, designed to connect and enable interaction between two or more parts of a *quantum system* (3.2.6), *quantum* (3.2.4) device or *quantum processor* (3.4.8)

Note 1 to entry: In quantum hardware, coupler elements can be both classical or explicitly quantum in design, so long as the element operates to maintain *quantum coherence* (3.2.18). Examples include classical elements such as optical mode couplers in integrated photonics and capacitive couplers in superconducting microwave circuits, and quantum elements such as superconducting *qubits* (3.3.3) or resonators used as coupling buses.

3.5 Quantum technologies

3.5.1
quantum simulation
computational task that aims to calculate the static and dynamic physical properties of complex *quantum systems* (3.2.6)

Note 1 to entry: Quantum simulations only offer an advantage over classical computing if the quantum system is sufficiently complex, e.g. it has sufficiently many constituents or experiences complex dynamics in a sufficiently large *Hilbert space* (3.2.1).

Note 2 to entry: In the context of *quantum computing* (3.4.11), quantum simulation algorithms are typically digitised to enable scaleable, fault-tolerant simulations. Analogue quantum simulators engineer quantum systems to directly mimic a target system, but do not achieve fault tolerant operation.

Note 3 to entry: Example applications of quantum simulations include advanced materials manufacturing, quantum chemistry, and pharmaceutical design.

3.5.2
quantum machine learning
suite of computational tasks that combine concepts and tools from *machine learning* (3.1.3) and *quantum algorithms* (3.4.9)

Note 1 to entry: Within *quantum* (3.2.4) machine learning, four current distinct development directions are: (i) quantum-assisted machine learning which uses *quantum computers* (3.4.10) to accelerate training and development of *models* (3.1.1) for classical machine learning, (ii) quantum-enhanced machine learning, where quantum computers accelerate a particular subroutine of a classical machine learning application, (iii) machine-learning-assisted quantum, where classical machine learning is used to optimize compilation of quantum algorithms for hardware platforms, and (iv) quantum-intrinsic machine learning where machine learning is inherently quantum such as quantum neural networks and quantum support vector machines.

3.5.3
sampling algorithm
computational task that aims to produce output samples according to a given probability distribution

Note 1 to entry: Examples of *quantum* (3.2.4) sampling algorithms include quantum Gibbs sampling and quantum Metropolis sampling.

Note 2 to entry: Applications of sampling algorithms include material science, quantum chemistry and cryptography. Sampling algorithms are sometimes used to solve *optimization* (3.5.4) problems.

3.5.4
optimization
computational optimization task carried out via *quantum information processing* (3.4.1)

Note 1 to entry: Examples of *quantum* (3.2.4) optimization algorithms include quantum semidefinite programming, quantum combinatorial optimization and *quantum algorithms* (3.4.9) for satisfiability problems. In addition, variational quantum eigen solvers, quantum approximate optimization algorithms (QAOA), quantum annealing algorithms and quantum adiabatic optimization, are typically used for cost-function minimisation and pattern matching.

Note 2 to entry: Potential end-user applications of quantum optimization algorithms include financial portfolio optimization, supply-chain optimization and scheduling optimization.

3.5.5
linear systems solving
computational task that outputs the vector solution which satisfies a specified system of linear equations

Note 1 to entry: Linear systems solving finds many applications across science, mathematics, engineering, medicine, business and social science.

Note 2 to entry: The main *quantum algorithm* (3.4.9) for solving equations of linear systems is known as the HHL (Harrow, Hassidim and Lloyd) algorithm, and maps the solution onto the stored register state of a *quantum computer* (3.4.10).

3.5.6
search algorithm
computational task that aims to find the input to a function that produces a specified output, potentially with the assistance of an auxiliary probabilistic guessing algorithm

Note 1 to entry: Grover's *quantum* (3.2.4) search algorithm and the quantum amplitude amplification algorithm solve unstructured search and heuristic search problems (those which can access a probabilistic guessing algorithm – the heuristic), respectively, with a quadratic speed-up over classical algorithms.

Note 2 to entry: Grover's quantum search algorithm can be applied to any problem in the complexity class NP (nondeterministic polynomial time).

3.5.7
hidden subgroup problem
computational task that aims to find a subgroup which is hidden by a given function acting on a mathematical group

Note 1 to entry: In the case a group is Abelian, hidden subgroup problems have efficient, i.e. polynomial time, solutions by *quantum algorithms* (3.4.9).

Note 2 to entry: Efficient quantum algorithms to solve hidden subgroup problems provide an efficient way to break a range of cryptosystems using *quantum computers* (3.4.10). Important examples including the Shor's period finding quantum algorithm which can efficiently factor semi-prime integers thus compromising the RSA encryption protocol, and Shor's discrete logarithm quantum algorithm which can efficiently break elliptic-curve cryptography.

3.5.8
boson sampling
model of *quantum information processing* (3.4.1) implementing a *sampling algorithm* (3.5.3) which generates samples from a random unitary *quantum circuit* (3.4.5) operating on boson-like *quantum systems* (3.2.6)

Note 1 to entry: Boson sampling is not universal for *quantum computing* (3.4.11) and is not error correctable with existing schemes.

Note 2 to entry: Bosons are particles that are indistinguishable under particle exchange.

Note 3 to entry: In the context of quantum computing, the most commonly used bosons are harmonic oscillator mode excitations such as photons. Boson sampling is usually implemented with photons and linear optical circuits.

Note 4 to entry: Bosons are commonly used to encode *qudit* (3.3.4) *quantum information* (3.3.1).

Note 5 to entry: The random circuit sampling protocol implements a quantum random sampling algorithm for *qubit* (3.3.3) *quantum information processors*, and forms the basis of the first quantum supremacy experiments in quantum computing. Similarly, boson sampling has been used as the basis for demonstrating quantum supremacy in some non-universal quantum information processors.

3.6 Related quantum technologies

3.6.1
quantum communication
communication that utilizes for information exchange *quantum information processing* (3.4.1) in an essential way

Note 1 to entry: Protocols that use classical information processing and transmission at all stages of communication, like post-quantum cryptography, fit into the broader category of quantum-secure or quantum-safe communication, rather than quantum communication.

3.6.2
quantum cryptography
cryptography that utilizes *quantum communication* (3.6.1) in an essential way

3.6.3
quantum sensor
tangible device that performs *quantum sensing* (3.6.4)

Note 1 to entry: A useful quantum sensor would have the capacity to provide improved performance over what can be achieved with a conventional sensor, and this improvement would arise from the *quantum* (3.2.4) properties exploited by the sensor.

3.6.4
quantum sensing
process that uses *quantum information processing* (3.4.1) to measure a physical quantity of interest