# SAMPLE

## Quantum Computing

Computing Beyond Bits

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# Chapter 1: The Bit and the Qubit

Every computer ever sold rests on a single, humble convention: information cut into pieces with exactly two values. A bit is one such piece, and its two values go by many names, one and zero, true and false, on and off, but the naming does not matter, only the two-ness does. The convention works because two-valued pieces are easy to make physical, a switch open or closed, a magnetization pointing one way or the other, a patch of charge present or absent, and because any message, number, picture, or sound can be translated into a long enough string of such pieces. Classical information theory, built in the middle of the twentieth century, rests entirely on this convention, and it is worth pausing on how total the convention is: the bit is the atom of the information age, indivisible, obedient, and identical everywhere.

A qubit is also a two-valued thing, but a two-valued thing with a strange middle. Physically it is any quantum system with two usable states, the spin of an electron or a nucleus, two energy levels of an atom, two orientations of a current in a superconducting loop, and by tradition the two states are called zero and one, the names of the classical values. The difference appears the moment the system is left alone. A classical bit is always in one of its states. A qubit, unmeasured, can be in a blend of both, a condition written with the word superposition, and the blend is not a matter of ignorance, a hidden fact we happen not to know, but a genuine indeterminacy in the world itself, one of the founding surprises of quantum mechanics.

A superposition has weights, and the weights are the heart of the subject. When a physicist prepares a qubit in a blend, the recipe specifies two numbers, called amplitudes, one attached to the zero condition and one to the one condition, and these amplitudes can be positive, negative, or even more exotic quantities that point in an abstract direction. The amplitudes themselves are never seen. What is seen, when the qubit is finally measured, is one of the two plain outcomes, zero or one, and the chance of each is fixed by a simple rule from the theory's early days: the probability is the size of the amplitude multiplied by itself, a rule associated with Max Born and now called the Born rule in his honor. After the measurement, the blend is gone, the qubit sits plainly in the outcome that was read, and any further measurement just reads the same thing again. This collapse, as it is often called, is not a footnote; it is the hinge on which every quantum computation turns, because it means a machine of superpositions still has to answer questions in ordinary bits at the end.

There is a useful picture, not the whole truth but a good servant, in which the state of a single qubit is drawn as an arrow of unit length pointing somewhere on a sphere. The north pole is the plain zero state, the south pole is the plain one state, and every other point on the sphere is some blend of the two. The picture is called the Bloch sphere, after Felix Bloch, and it earns its keep whenever one wants to reason about what a quantum operation does: most operations on a single qubit amount to turning the arrow, tipping it toward this pole or that, spinning it around the axis it currently

points along, and a computation on one qubit looks like a carefully choreographed sequence of such turns. A classical bit, in this picture, is a marble frozen at one of two poles; a qubit is a compass needle free to point anywhere, and a skilled programmer can use that freedom.

One more piece of vocabulary completes the starter kit: entanglement. Two qubits can be prepared in a way that has no description in terms of the parts, a joint superposition in which neither qubit has a state of its own and only the pair does. Measuring one member of such a pair instantly constrains what will be found when the other is measured, regardless of the distance between them, and though this connection cannot be used to send a message faster than light, a fact the later chapters return to, it is a resource with no classical equivalent. Superposition gives the quantum computer its breadth, entanglement gives it a way to make its parts answer to one another, and interference, the subject of the next chapter, gives it the means to turn a huge span of possibilities into a useful answer.

The qubit deserves one closing caution, because the popular telling oversells it. It is often said that a quantum computer tries every answer at once, and in a loose sense an algorithm's early steps do place the machine in a superposition spanning an enormous number of candidate inputs. But the machine does not report every answer; measurement yields exactly one outcome, and all that preparation is wasted unless the algorithm arranges for the wanted outcome to be likely. The craft of quantum computing is not in spreading wide, which is easy, but in folding the spread back down to something worth reading, which is hard, and the whole history of the field, from its first algorithm to its newest chip, is the history of people learning to fold.

## Chapter 2: The Founding Decade

The idea of a quantum computer did not arrive because anyone wanted a faster machine. It arrived because the machines of the day were choking on the physics. In the late nineteen seventies and early eighties, physicists trying to simulate quantum systems, molecules, materials, particle collisions, ran into a wall of arithmetic: describing even a few dozen quantum particles exactly requires keeping track of numbers that multiply with every particle added, a quantity that swells exponentially, and the computers of the era, and of every era since, simply cannot hold such descriptions for any but the tiniest systems. The mismatch was not an engineering problem, waiting on better transistors. It was structural. The natural language of quantum mechanics has a vocabulary too large for any machine that speaks only in bits.

The first person to write the mismatch down as a prescription was Paul Benioff, a physicist at Argonne, in a paper of 1980. Benioff set out to describe a Turing machine, the abstract pencil-and-paper computer that underlies all of computer science, using the equations of quantum mechanics rather than classical logic, and he showed such a machine could exist: the tape, the head, the internal states, all rendered as quantum degrees of freedom, evolving coherently. His quantum Turing machine was a modest object, a demonstration that quantum theory and the theory of computation could be

made to share a page, and it is conventionally the first entry in the field's chronology. Around the same time, and entirely independently in Moscow, Yuri Manin reached a similar conclusion, noting that the exponential swelling of quantum descriptions pointed toward computers that were themselves quantum.

The person who turned the observation into a program was Richard Feynman. In a talk at a physics-of-computation conference in 1981, and in a widely read written version that followed in 1982, Feynman asked the question plainly: can a classical computer, any classical computer, ever simulate a quantum system efficiently? Nature, he pointed out, does not appear to do anything exponential when it juggles a molecule, so the unwieldiness must lie in our description, not in the world, and if nature juggles the pieces without effort, there should be a way of computing that juggling directly. His conclusion, offered with characteristic bluntness, was that a machine able to imitate nature would itself have to obey quantum mechanics. The name now attached to the idea, a quantum simulator, is exactly the machine he proposed, and simulation of quantum matter remains the most defensible application on the field's books four decades later.

David Deutsch, then a young physicist in Oxford, supplied the conceptual capstone in 1985. Deutsch asked a question with a philosopher's edge: the Turing machine had long been taken as the definition of what it means to compute, but the Turing picture is classical, and physics, as far as anyone knows, is quantum; which definition should we believe? His answer was to define computation physically, as anything a machine built out of quantum physics can do, and he constructed a universal quantum computer, a single quantum machine able to imitate any other quantum machine, the quantum analogue of Turing's universal machine. In the same paper he offered the first toy problem on which a quantum machine provably beats any classical one, a puzzle involving a function and a promise, ancestor of the first real algorithm. The 1985 paper is the field's founding document in the strict sense: it did not merely note that physics might speed things up, it asserted that the theory of computation is part of physics and should be rebuilt accordingly.

It is worth pausing on how quiet the following decade was, because the founding is often told as though applause followed immediately. It did not. Benioff, Feynman, and Deutsch had produced a beautiful idea with, at first, no workload: no tasks the machine could do better, no hardware, no obvious reason for anyone outside a handful of groups at Oxford, Argonne, and IBM to care. Quantum computing spent the years from 1985 to 1994 as a curiosity, cultivated by a small community of theorists who believed the physics deserved an exploration even without a payday, publishing in relative obscurity. The community also argued, as small communities do, about what a quantum computer would even mean: some saw it as a fantastical extrapolation of physics, some as a mere reformulation, and the question of whether the machine's powers could be accessed without breaking the theory itself was settled only gradually, in the mathematics of the late eighties, where the founding notions of quantum gates and circuits were laid down in their modern form.

The chapter's closing observation is about the shape of the whole history that follows.

Every major turn in this subject, the algorithms, the hardware, the money, arrived only after a physicist or a computer scientist reframed a question everyone thought was settled. Computation was settled, until Deutsch made it physical. Simulation was settled, until Feynman asked nature how it manages. Factoring was settled, until a Bell Labs mathematician took a quantum walk through it, and that story is the next chapter's.

## Chapter 3: The Grammar of Interference

A computation, classical or quantum, is a sequence of small transformations applied to stored information. In the classical world the vocabulary of those transformations is the logic gate: and, or, not, and their cousins, physical circuits that take bits in and push bits out. The quantum world has an exactly parallel vocabulary, with one deep difference of grammar. A classical gate is a fixed function: one input pattern, one output. A quantum gate is a rotation: it takes the whole arrangement of amplitudes it is given and turns it, smoothly and reversibly, into a new arrangement, and it can be undone, because the laws of quantum mechanics at bottom do not erase. This reversibility, odd as it looks to a programmer raised on destructive assignment, is not decoration; it is the grammar that makes interference possible.

The simplest gates to picture are the single-qubit ones, and in the arrow-on-a-sphere picture from the first chapter they are literally turns. One gate, the quantum version of the classical not, tips the north pole to the south, turning zero into one and one into zero. A second, called the Hadamard gate after a nineteenth-century French mathematician whose name is also on a matrix family, takes a plain state and turns it to dead center, the blend with equal weight on zero and one, and running it again turns the blend back to plain. A third family, the phase gates, leaves the arrow's direction alone but spins the blend's phase, the abstract direction of its amplitudes, by a chosen amount. None of these operations are exotic science; on the hardware of the later chapters they are brief pulses of microwave radiation, and a modern chip runs them millions of times a second.

Single-qubit turns alone cannot make a computer, because they cannot make one qubit influence another, and influence is what computation is. The workhorse that supplies it is a two-qubit gate called the controlled not, in which one qubit, the control, decides whether the other, the target, gets flipped: if the control is in the plain one state, the target is turned over; if the control is plain zero, the target is left alone. The quantum novelty appears when the control is itself in a blend, in which case the target ends up entangled with it, flipped along some branches of the superposition and not along others, and the pair becomes a single four-part blend that no description of the qubits separately can capture. From this one gate and the single-qubit turns, everything can be built: it is a mathematical fact, not an engineering boast, that these operations together are universal, meaning any transformation quantum mechanics permits on any number of qubits can be assembled from them, the way any sentence can be assembled from a small alphabet.

The word for a program in this language is a circuit, a drawn diagram of wires and

boxes, read left to right like a musical score, and the discipline that studies efficient composition is, with slight irony, called circuit design just as in the classical trade. The composer's real problem is the one flagged in the first chapter: the machine ends in measurement, and measurement only yields one outcome. The whole art is interference. Amplitudes, the weights inside a superposition, are numbers that can add or cancel, and a well-designed circuit steers them so that the branches representing wrong answers gather negative or mismatched phases and cancel one another out, while the branches representing the wanted answer gather in phase and reinforce. Run the finished circuit and the measurement does not merely guess; it lands on the reinforced outcome with whatever probability the design achieved. An algorithm that does this well is a mathematical machine for constructive and destructive interference at scale, and this is why the popular phrase tries every answer at once is so misleading: trying is worthless, only the folding-back counts.

Two further pieces of grammar complete the basic toolkit, and both matter for everything that follows. First, measurement need not wait until the end; a program can measure some qubits midway and use the outcomes to choose later steps, a pattern called adaptive or measurement-driven computing, and one whole architecture, described in a later chapter, makes measurement the engine of the computation rather than its interruption. Second, the textbook gate set is an infinite family, since a phase turn can be by any angle, but finite sets suffice: a mathematical result called the Solovay-Kitaev theorem guarantees that any desired turn can be approximated to any accuracy using a modest chain of gates from a small fixed repertoire, at a cost that grows only gently. Chip designers live by this theorem, because it means a factory producing only a handful of primitive operations can, in principle, run anything.

The chapter closes with the sober arithmetic that gives the field its scale. One qubit is described by two amplitudes; each additional qubit doubles the count, so a machine of modest size carries a description with exponentially many moving parts, a few hundred good qubits requiring more numbers to specify than there are atoms in the observable universe. That swelling is the resource, the quantum computer's claim to attention, and it is also the trap: keeping hundreds of such numbers coordinated in a physical device, without the world's noise scrambling them, is the engineering problem that has consumed the field ever since the founding decade ended, and the chapters on decoherence and error correction tell that campaign in full.

## Chapter 4: Entanglement's Errands

Entanglement entered physics as an embarrassment and entered computing as a payroll. The quantum theory of the nineteen twenties predicted that two particles could be prepared with a joint state that no pair of separate descriptions could account for, and Einstein, who found this intolerable, publicized it in the nineteen thirties as evidence that something was missing from the theory: real physics, he argued, could not permit such ghostly connections at a distance. The argument sat as philosophy for three decades until John Bell, in 1964, converted it into a measurable

wager: certain statistical patterns in measurements on entangled pairs, Bell showed, are flatly impossible for any theory built on Einstein's assumptions, however cleverly patched. Experiments from the nineteen seventies onward, culminating in the celebrated tests of the eighties and nineties, found the impossible patterns, and entanglement stopped being an embarrassment and became a demonstrated fact, the most conclusively verified strangeness in all of physics.

The computing chapters of this story began when people noticed the strange fact could be spent. The first errand is called teleportation, a name chosen with a wink. The setup: Alice holds a qubit in some unknown state and wants Bob, somewhere else, to hold an identical qubit. There is no way to measure the state and send a description, because measurement destroys the blend and no finite list of numbers can be read out of one copy; the information in an unknown qubit is, in this precise sense, untransmittable by classical means. But if Alice and Bob share an entangled pair, prepared in advance and split between them, two classical bits sent from Alice to Bob suffice: Alice performs a joint measurement on her unknown qubit and her half of the pair, sends the two-bit outcome over any ordinary channel, and Bob, applying one of four corrections chosen by those bits, ends up holding the original state exactly. The word teleportation is honest about the outcome and honest about the cost: the original is destroyed at Alice's end, nothing travels faster than light, and two classical bits must cross the gap at light speed or slower, a fact the popularizations routinely mangle and this book will not.

The second errand runs the errand backward, with a result that sounds like a violation of accounting. In superdense coding, Alice again sends two classical bits' worth of information, but the transmission itself consists of conveying a single qubit: the pair's shared entanglement, banked earlier, lets one quantum particle carry what classically would need two. The two protocols, teleportation and superdense coding, are twin faces of one theorem about entanglement, one bit of prior entanglement being exactly the currency that lets a qubit and two classical bits trade places, and the pair of them together demonstrate that entanglement is a quantifiable resource, spendable and bankable, a conclusion formalized in the nineties by theorists who defined it much as engineers define kilowatt-hours.

Between those errands sits a caution worth its own paragraph, because it draws the line between quantum magic and science fiction. Entanglement correlates; it does not communicate. When Alice measures her half of a pair, Bob's half acquires a definite character at once in the formalism, however far apart they are, but Bob, looking only at his own laboratory, sees pure chance, indistinguishable from noise; the correlation becomes visible only when the two compare notes over a classical channel, at light speed or slower. This is not a technical limitation that cleverness might lift. It is the content of a theorem from the field's early years, the no-signaling result, and every claimed faster-than-light scheme in the popular literature fails against it. Quantum computing's errands all obey the postal speed limit; what they buy is not speed of communication but a new kind of content.

One more errand belongs in the kit, because it powers the great algorithms of the

next chapter. Beyond carrying messages, entanglement can be woven inside a single machine's register, binding dozens or hundreds of qubits into states no subset can be described without, and it is exactly such weaving, amplified to scales no laboratory could inspect branch by branch, that lets Shor's factoring algorithm and its relatives hold their exponential hay. Entanglement inside the machine also has a shadow: it is delicate, hard to create on demand across many qubits, and the first thing to dissolve when noise intrudes, so the resource and the vulnerability are the same substance. The field's entire hardware story, told in later chapters, is the story of weaving entanglement that stays woven.

The chapter closes with the phrase that entanglement earned in the wider culture. Einstein's ghostly action at a distance, Bell's wager, and the laboratory verdicts that followed gave the world a permanent piece of vocabulary, quantum weirdness, now attached to everything from cryptic pronouncements in films to marketing copy for cosmetics. The reader is entitled to know that the phrase points at something real, experimentally established beyond reasonable dispute, and simultaneously that the real thing is narrower than the folklore: a precise, quantifiable, spendable correlation with sharp mathematical limits, no faster-than-light post, no consciousness involved, nothing mystical. In the chapters that follow, entanglement appears whenever it is doing work, which is nearly everywhere: in the algorithms, in the security of quantum key distribution, and in the error-correcting codes that the machines of the coming decade will stand on.

# Chapter 5: The Algorithmic Harvest

For its first decade, quantum computing was a machine in search of a job. The founding decade built the physics and the grammar, but no one had produced a task the machine could perform usefully better than its classical rivals, and the field's standing outside its own seminars rested on faith in the idea's beauty. The harvest changed that in two years, in the mid-nineties, when a small burst of algorithms turned the quantum computer from a philosophical proposal into a threat, a tool, and a research economy, and this chapter walks the burst in order, because the order itself teaches how quantum speedups are actually found.

The first fruits were deliberately small. Deutsch's founding puzzle of 1985 had shown a quantum machine answering a certain one-question-about-a-black-box problem with fewer queries than any classical machine, but the margin was one call versus two, a demonstration rather than a promise. In 1992 Deutsch and Richard Jozsa generalized it, and around the same period a sequence of results, including work by Ethan Bernstein and Umesh Vazirani in 1993 and Daniel Simon's in 1994, enlarged the pattern into a family: black-box problems, where the goal is to extract a hidden global property of a function by feeding it inputs and reading outputs, where quantum superposition and interference could cut the number of trials dramatically, sometimes exponentially. Simon's problem in particular, finding a hidden pattern in a function's behavior, contained the essential trick of the period: load many inputs into a superposition, run the function once across the whole blend, and let interference

condense the global property into measurable form. None of these tasks was useful to anyone outside the seminar room. What they were was evidence, an existence proof that the folding problem of the third chapter had real solutions, and the theorists hunting speedups knew a wider door had been opened.

The door led to Bell Labs and to Peter Shor, and the year was 1994. Shor, a number theorist by training, had attended a talk on Simon's problem and gone home with the observation that Simon's hidden-pattern machinery might attach to a pattern anyone could care about: the periodicity hiding inside modular arithmetic, the mathematical engine room of the public-key cryptosystems that secured, by the mid-nineties, most of the world's commerce and mail. Factoring a large number, the hard direction on which the security of those systems rested, could be reframed, through classical mathematics Shor assembled from number theory's standard toolkit, as the problem of finding a period, and finding periods is exactly what interference in a superposition of inputs is born to do. The algorithm that carries his name runs a quantum subroutine related to the discrete mathematics tool called the Fourier transform, which takes a spread-out pattern and concentrates it onto its frequencies, the same mathematical servant that turns a blurred signal into a spectrum. The result: a quantum machine factors an integer of a given size in a running time that grows gently, polynomially, while every known classical method grows explosively. The claims of the next decade and the alarm of the intelligence agencies both trace to that one paper, and the chapter on cryptography returns to its consequences with the seriousness they deserve.

Two years later came the second great harvest, from a Bell Labs theorist of a different temperament. Lov Grover, in 1996, asked the plainest question possible: what does quantum mechanics buy for the humblest task of all, finding a marked item in an unsorted list? Classically nothing helps; the average search takes half the list. Grover's answer was an iterative, beautifully symmetrical circuit that rotates the state of the whole register a little toward the marked item with every repetition, amplitude flowing from the unmarked to the marked in small increments, like water tilted gently toward one basin. The repetition count needed grows as the square root of the list size, a quadratic improvement, modest next to Shor's exponential win but prized because search is everywhere, the unsorted haystack being the shape of a great many real problems, including the brute-force breaking of secret-key codes. Grover also gave the result its bookend: an accompanying argument that the square-root improvement is the best quantum mechanics permits for this task, an optimality proof, so the algorithm is not merely clever but optimal, a rare instance in this subject of a known and proven limit.

The harvest's remaining rows were stranger, and worth listing because they became the trade's standard stock. Algorithms drawing on Shor's period-finding skeleton attacked related algebraic problems, including the discrete logarithm, the second pillar of public-key cryptography. A 1996 result by Seth Lloyd, and parallel work by others, showed that simulating physical systems, Feynman's original errand, could be done efficiently after all, confirming that the founding application was no mirage: a quantum machine can track quantum dynamics with effort growing roughly linearly in

the system's size, where classical machines drown. And the search-for-a-solution pattern of Grover generalized to a host of satisfiability-style problems, quadratically faster, never exponentially, a ceiling the later complexity chapter explains. Quantum walks, adiabatic methods, and amplitude amplification joined the toolkit in the following years, each a variation on the single theme: superpositions carrying parallel exploration, interference folding the exploration back to answers.

The chapter closes with the harvest's honest ledger. Every algorithm of note, from the toy problems to Shor and Grover, shares one architecture: spread across many possibilities, compute on all of them, then interfere so that the measurement is likely to deliver the answer. None of them violates the folding constraint of the first chapter; all of them are the folding constraint, mastered. And the ledger's other column: for the overwhelming majority of computational tasks, no quantum speedup is known, and for many there are reasons to believe none exists. The harvest was real, reaped from a specific and narrow family of mathematical structure, periodicity, search structure, simulation, and the machines of the later chapters are built to serve exactly this family while the rest of computing continues, unmolested, in classical silicon.

## Chapter 6: What Quantum Computers Cannot Do

A book about quantum computing owes its reader the negative results with the same clarity as the positive ones, because the boundary between the two is where most of the public confusion lives. The fastest way to draw the boundary is through the language computer scientists use to sort problems by difficulty. A class of problems, called P in the trade's shorthand, collects everything a classical computer can solve with a running time that grows only as a modest power of the input's size, the problems that are practically solvable at scale. A much larger class, called NP, collects everything whose answers can be checked quickly once someone hands you one, a class that includes many famous puzzles, routing, scheduling, certain proofs and codebreaking games, whose answers are easy to verify and, as far as anyone knows, hard to find. The famous question of the trade, whether finding is as easy as checking, stands open after half a century and is the deepest unresolved question in mathematics' applied half.

Quantum mechanics gets its own class in this sorting scheme, called BQP, the problems a quantum computer can solve quickly with a small chance of error allowed, quantum mechanics being probabilistic at bottom. The class behaves like a slightly enlarged sibling of the classical tractable class: every classical quick problem is also quantum-quick, because a quantum computer can run classical programs without effort, while a handful of things outside the classical quick set, factoring the most famous, sit inside the quantum one. The known inclusions are settled mathematics: the quantum quick class contains the classical quick one, and is contained inside a class of problems solvable with modest memory. The interesting boundaries are dark. Nobody knows whether the quantum quick class contains the checking-easy class's hardest problems, the so-called NP-complete core, and the shared expectation of the theory community leans hard the other way: the evidence, though not proof, indicates

quantum machines cannot crack the hardest NP problems, so the scheduling nightmares of industry would survive the quantum era intact, and a traveling salesman has nothing to fear from a qubit.

The factoring exception deserves its own paragraph of boundary-drawing, because it is routinely over-read. Shor's algorithm breaks the specific algebraic systems underlying public-key cryptography as it was deployed in the nineties, and the cryptography chapter tells that story fully. But factoring is not a license for speedups generally; it is one narrow door, open because factoring hides a periodic structure that interference happens to expose. The popular imagination, fed on phrases like exponential speedup, assumes the door opens onto a corridor of doors, and the theory community's settled position is that it does not: no quantum algorithm is known for the broad NP-hard middle of industrial computation, and the strongest results available, search's square-root optimality among them, stand as walls. The honest summary, stated once and repeated throughout this book, is that quantum computers are not faster computers; they are differently-abled ones, gifted on a narrow family of structures and ordinary everywhere else.

Skepticism of the whole enterprise deserves its paragraph too, and not the dismissable kind. A minority of serious physicists, represented most colorfully by Mikhail Dyakonov, has argued since the two-thousands that the engineering is foredoomed: a quantum machine's state is steered by a host of continuous physical parameters, and the skeptic's point is that no physical apparatus will ever track so many continuous quantities with the perfection the theory seems to demand, a line of argument descended from the same intuition that made Einstein distrust entanglement. The error-correction chapter is the field's formal answer, and the machines of the present chapter are its experimental one, but the reader should know the debate is not purely rhetorical: it forced the community to state precisely what fidelity is needed, roughly one error per thousand operations for the known schemes, and to build the tools, benchmarked and measured, that answer the objection in the laboratory rather than in print. Science is healthiest when a serious objection forces a measurable reply, and this one did.

There is also a quieter failure mode, discussed mostly inside the field, that the reader meets before the machines do: the data-loading problem, sometimes called the input problem. A quantum speedup on paper assumes the data arrive already encoded in qubits, but loading a large classical dataset into a quantum register is itself a costly operation, and for many proposed applications, especially in machine learning, the loading cost quietly eats the advertised advantage. Related traps include algorithms whose speedup vanishes against the best classical competition once the classical side is tuned honestly, and proposals that assume oracular access to data no realistic system provides. A decade of quantum-machine-learning papers has passed through this filter, and the surviving consensus is that claimed advantages live or die on the details of encoding, a caution the applications chapter applies case by case.

The closing entry in the cannot-do ledger belongs to the theory's own kind of honesty. Nothing in quantum mechanics forbids a classical simulation of a quantum computer;

# ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

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