Life Through Quantum Annealing

How a quantum computing technique could shape existence.

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Overview

We explain how quantum annealing works and discuss how it could form our universe, drawing evidence from physics, cognition, and biology.

We then use a thought experiment to consider how a quantum annealing universe could benefit from being cyclic, or starting over, and we entertain the idea that such a model may even explain common human behavior.

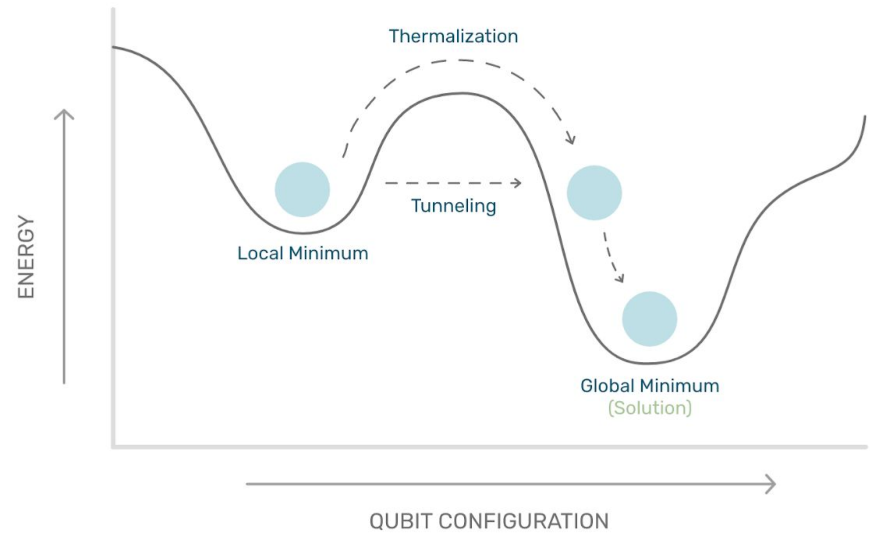
Quantum Annealing: a search for the best state

Quantum annealing is a type of quantum computing used mainly for optimization problems; these problems can have many variables with many possible solutions, but we want to find the *best* solution. A classic example is the “traveling salesman” problem: Given a list of cities, what is the shortest route that visits every city and returns home? There are many possible routes, but not all are ideal.

A network of interacting quantum bits, or qubits, are used to solve problems in quantum annealing. A qubit represents a variable, having a “spin” of either up or down to indicate how that variable fits into the whole solution, like ones and zeros in binary code. But unlike other forms of computing, quantum annealing does not actively control the state of every variable. Instead, it allows qubits to naturally evolve based on simply programmed criteria.

Each qubit begins in superposition, but ultimately ends up with a defined spin -- and entangled with all other qubits. Superposition means there is some degree of uncertainty to the spin; it can only be described by probability. Using an external magnetic field, a “bias” is applied to control how likely it is for a qubit to end up with a certain spin. “Couplers” are also used to determine how qubits affect each other and become entangled. If two qubits should always have the same spin -- or opposite spins -- a coupler is used to define that relationship. Over time, qubits become more entangled with each other, meaning they can no longer be described independently; only as a single state. Biases and couplers are the only ways to program a quantum annealer, which moves from an overall state of uncertainty to certainty, and non-entangled to entangled.

It’s important to understand quantum annealing in terms of energy. An external magnetic field energizes the qubit network, giving rise to an “energy landscape.” Peaks in the landscape correspond to low-probabilities, or bad solutions, while valleys correspond to high-probabilities, or good solutions; so the lowest point in the landscape corresponds to the best solution. The goal of quantum annealing is to find the lowest possible energy state -- equivalent to saying that the system wants to reach equilibrium.



Two ways to search an energy landscape with a local and global minimum.

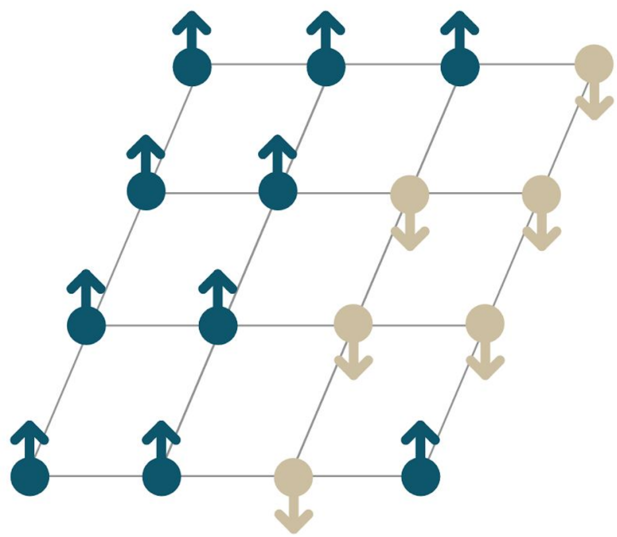
The annealer uses thermalization and quantum tunneling to search the landscape and converge on its lowest energy state. Searching is like testing different spin configurations to get a feel of their energy levels. The tricky part is dealing with local minima: valleys that are not the *lowest* valley. If the system is not willing to search uphill, it may not realize there is a lower valley elsewhere. Searching over peaks is done through thermalization, and it requires more energy. Quantum tunneling is where qubits can, with some probability, travel *through* a peak. The probability of tunneling is higher with narrower barriers, and quantum annealing tends to use tunneling more early on, and less over time; this aligns with an overall trend where larger changes tend to take place at the beginning of quantum annealing. Eventually, the search converges on the global minimum, which is the ideal qubit configuration.

Qubits are made from superconducting materials that influence a magnetic field. There are several ways to physically make a qubit, but superconductors are the most promising for quantum computers; they are also used in D-Wave computers, the first and only commercial quantum annealers. Superconductors allow an electric current to move through them without resistance, so that no energy is lost. When an external magnetic field is applied to superconducting qubits, they respond with opposing magnetic fields, which are energetic and have their own charges. The energy landscape is described by these fields -- the smaller the opposing energy, the better.

Finally, a foundational concept in quantum annealing is the Ising model. All problems are formed in terms of the Ising model, so it deserves particular attention.

The Ising Model: the universal math of magnets

The Ising model is a mathematical model that basically describes the dynamics of a magnet -- the same dynamics behind a qubit network in quantum annealing. It is heavily used in statistical mechanics, which studies the collective behavior of chaotic systems formed by many individual parts. Statistical mechanics describes outcomes in terms of probabilities; in quantum annealing, these are the probabilities of qubit states.



2D Ising model on a square lattice, with both up and down spins.

Key characteristics of the Ising model include phase transitions and critical points. A phase transition is when a system's collective behavior changes, like water freezing into ice. Phases are separated by critical points, which often occupy the boundary between ordered and chaotic phases, like a solid crystal on one side and a turbulent liquid on the other.

Critical points play a central role in how the system processes information. At criticality, fractal behavior is seen, where self-similar patterns emerge and interact at different scales. Criticality is also a catalyst for self-organization and complexity -- as if the system wants to error-correct for unstable configurations, and find new, more intricate configurations that are more energy efficient.

Interestingly, it was proved that the Ising model is a universal spin model, meaning all spin models can be mapped to the 2D Ising model, including 3D models. From a physics point of view, the entire universe operates on a spin model, which leads to a curious line of thought.

Evidence of a Quantum Annealing Universe

Clues from Physics

It is well known that our universe is always trying to settle into equilibrium, its lowest energy state. Rocks tumble downhill, hot coffee cools to room temperature, and the process that gives things mass, the Higgs mechanism, is due to a “fall” to a lower energy state; but the similarities between quantum annealing and our universe at large extend much further.

In this section, we show that the fabric of our universe can be attributed to a quantum Ising model, and that our universe shows signs of existing on superconducting material -- the same material used to make qubits for a quantum annealer.

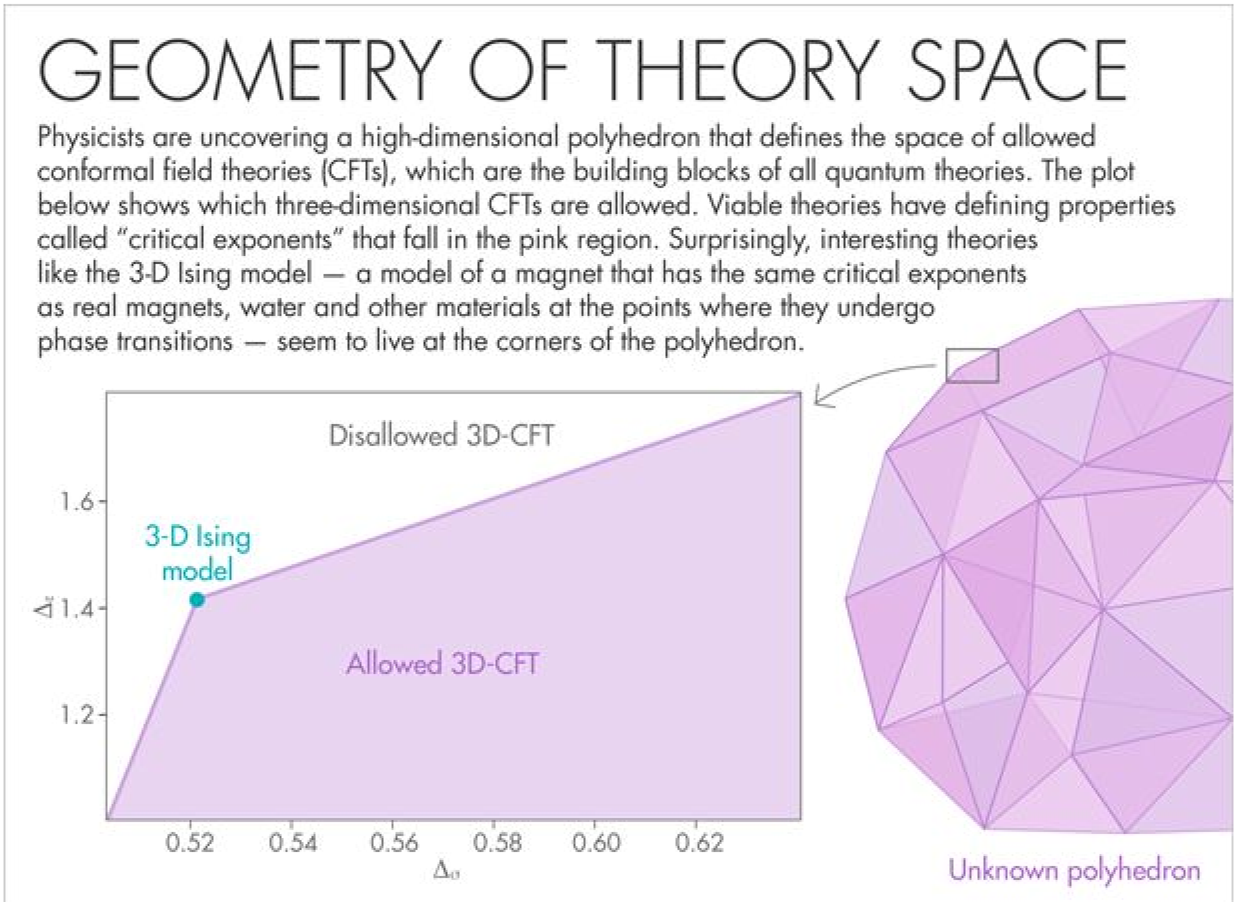
Living Inside the Ising Model

Physicists have noticed that the fabric of spacetime can emerge naturally from a complex network of entangled particles, which they have called tensor networks. Not only that, but spacetime behaves just like code, with the same error-correcting behavior we would expect in stable quantum computers.

These findings come from an idea called the Holographic Principle, which states that all information about a “bulk” area is contained within a lower-dimensional “boundary” -- like saying that the 3D contents of a room can be completely described by information encoded on its 2D walls. In this framework, the boundary contains a conformal field theory (CFT), which describes quantum interactions, and the bulk contains spacetime, which includes gravity. The interactions on the boundary’s CFT directly correspond to effects within the bulk’s spacetime.

Naturally, we can see how an entangled network of qubits in quantum annealing may serve as a CFT that creates spacetime in a holographic universe. Furthermore, an increasing number of scientists believe that the arrow of time is due to increasing entanglement, defined by a process of “becoming correlated with your surroundings” that also happens in quantum annealing. We also know that gravity perfectly describes optimal information processing in quantum computing, and that there is a direct correspondence between gravity and the Ising model, hinting at an Ising-based CFT.

One particular analysis created a geometric plot of “critical exponents” for all allowed CFTs for our universe. Critical exponents describe a system’s behavior near phase transitions, where critical points are. The researchers found, unexpectedly, that this plot perfectly matched the plot for the 3D Ising model. Any quantum mechanical description of our universe must share the same structure as the 3D Ising model, which we also know can be mapped to the universal 2D Ising model.



Source: Lucy Reading-Ikkanda/Quanta Magazine. Graph adapted from Nature Physics 537 (2016)

Another direct link is the identical math behind both quantum mechanics and statistical mechanics, which makes sense if they both come from the Ising model. Both fields use sets of probabilities that are generated using the exact same math. In fact, after using a simple math trick called a Wick rotation, the principle of least energy becomes the principle of least action. The former fits the fundamental premise of quantum annealing; the latter is the most fundamental law of physics -- all other laws come from it.

Living Inside a Superconductor

If quantum annealers operate on superconducting qubits, we should see if our own universe behaves like superconducting material as well.

In his 2017 book, *The Greatest Story Ever Told--So Far*, theoretical physicist Lawrence Krauss wrote a chapter called "Living Inside a Superconductor," which discussed how viewing the universe as a superconductor has fueled major breakthroughs in physics. An external magnetic field interacting with a superconductor would result in electromagnetism being a short-ranged force within the material, and it would give mass to certain particles that wouldn't otherwise have mass. These are, in fact, properties we observe in our universe.

This line of thinking led to the discovery of a particle called the Higgs boson, which was predicted by the Higgs mechanism -- the process that gives particles mass. The Higgs boson was experimentally confirmed using the Large Hadron Collider, the most powerful particle collider on earth, but it has also been imitated within superconducting materials, being called the "Higgs mode." David Alan Tennant, a researcher who led one Higgs mode experiment, described it to *Quanta Magazine* as, "creating a little mini universe."

High-temperature superconductors specifically parallel the behavior of our universe, and researchers hope to use them in future quantum computers. This type of matter can have excitations that look exactly like all of our known particles, can create artificial gauge fields that govern the interactions of particles, and can produce waves that obey our equations for light. High-temperature superconductors even exhibit properties of black holes -- both share similar electrical resistivity, form "wavy" electron patterns, and scatter information as fast as the laws of physics allow. Black holes are also analogous to Ising model lattices, which points to an underlying phenomenon.

The secret behind high-temperature superconductivity is a phase of matter called a quantum spin liquid, which is the result of…frustrated quantum magnets. This, again, matches the Ising model dynamics of qubits. Like qubits in quantum annealing, high-temperature superconductors are highly entangled, and they are "frustrated" because their spins are geometrically arranged in a way that prevents them from settling into a single spin state; this disorder actually helps to drive more complexity. This frustration can also be programmed into D-Wave computers, which has helped to simulate quantum systems that are otherwise impossible to model with traditional computers.

Here we see a bit of circular logic: qubits can be made out of superconducting material, which can be made out of frustrated qubits. If we do live within a cycle of universes, a "chicken or the egg" situation is inevitable; yet we hope to find circular logic -- it should indicate some substrate that everything emerges from. Just like quantum systems require disorder and uncertainty, maybe existence requires that *something* remains a paradox.

Clues from Cognition

In this section, we show that the Ising model matches observations of the human brain, that Ising-based neural networks called Boltzmann machines function just like the human brain, and that quantum versions of these networks may be able to achieve subjective experience. This supports the notion that one's consciousness is essentially a quantum Boltzmann machine, which is achievable through quantum annealing.

Brains & the Ising Model

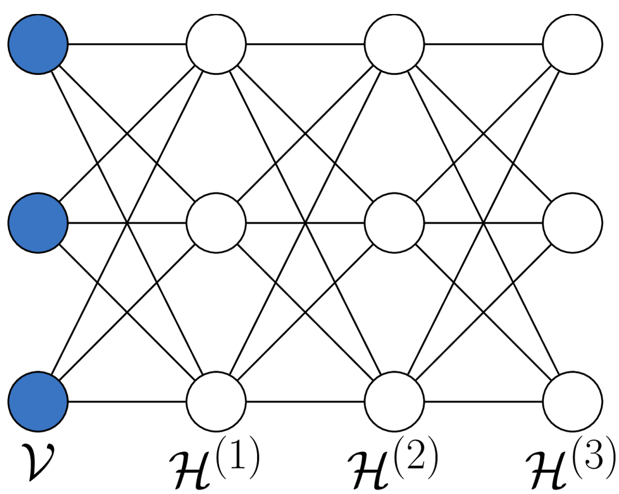
World-renowned cognitive scientist Douglas Hofstadter asserts that human thought entirely depends on analogy. In describing analogy, he says, “we build concepts by putting several concepts together and putting a membrane around them, and kind of miraculously these [interior] concepts disappear." Hofstadter also noticed that analogy could be achieved using the Ising model.

In one study, a human brain was scanned and compared to the 2D Ising model -- it found that at the Ising model’s critical point, the two systems were indistinguishable from each other in all relevant statistical properties. This not only implied that the two systems were mathematically equivalent, but also that the brain operated at criticality -- a notion scientists have suggested is behind healthy brain functioning and the need for sleep. This fits the idea that criticality is behind the robust information processing of Ising-based systems.

But perhaps the biggest insight about our own minds comes from what we can already build.

Boltzmann Machines

From the field of machine learning, Boltzmann machines are a class of neural networks that are based on the Ising model; and like quantum annealing, they are probabilistic, energy-based models that learn through the process of reaching equilibrium. These networks contain “visible” nodes that receive input from an environment, and often many layers of “hidden” nodes that learn from its adjacent layers. Importantly, Boltzmann machines behave remarkably like human brains -- evidence that they both operate and learn in the same way.



Basic depiction of a “deep” Boltzmann machine with one visible layer of nodes and three hidden layers.

Like our brains, Boltzmann machines learn from patterns that naturally exist in data, without supervision; both become less malleable over time, although they never stop learning with new input; and both benefit from a sleep state (and even dreaming), which helps them integrate new, relevant information. Bruno Olshausen, a computational neuroscientist from the University of California-Berkeley, told *Quanta Magazine*, "[Consciousness] is something that emerges out of a really, really complicated Boltzmann machine."

The process by which intelligence appears to emerge is called renormalization, and it seems to be a universal logic behind quantum physics, Boltzmann machines, and human brains. Renormalization distills complex systems into their relevant parts, so that meaningful interpretations can be made without knowing all of the details of the data -- resembling Hofstadter's description of analogy.

Renormalization can only happen at critical points, so it goes hand-in-hand with information processing in the Ising model. In physics, renormalization determines how a CFT evolves at critical points. In cognition, renormalization happens naturally in Boltzmann machines at critical points without being programmed to do so -- intelligent learning emerges on its own. In both physics and cognition, critical points also allow the largest amount of memory and information transfer. Information processing at critical points appears to be universal, naturally emergent, and traceable to the Ising model.

Creating a Boltzmann machine through quantum annealing is an obvious step -- in fact, a quantum annealer essentially *is* a physical Boltzmann machine. The union of the two is called a quantum Boltzmann machine, and it has already outperformed its machine learning predecessors in an area called reinforcement learning, which holds promise for artificial intelligence. We are, of course, suggesting that human intelligence is essentially a quantum Boltzmann machine.

Matthew Fisher, a noted physicist at the University of California, Santa Barbara, published a 2015 paper showing that two chemical substances, identical in every way except for quantum spin, can affect brain behavior in extremely different ways -- providing further evidence that our brains may have a qubit-spin basis. Taking this idea seriously, we can explore how subjective experience may be achieved in a quantum system.

Subjective Experience

Hartmut Neven, Director of Engineering at Google's Quantum AI Lab, makes an interesting proposal for subjective sensation in quantum machine learning. Neven says we can think that "relaxing to a stable state is associated with a pleasant feeling, and evolving to an excited state is associated with anxiety." Stable and excited states correspond, respectively, to valleys and peaks in an energy landscape. Sensations would be correlated to a change in energy to one of these states.

Neven claims this model establishes a direct link between physical and psychological experiences, and, in many ways, it already matches how we perceive our experiences. It seems that the human reward mechanism aligns with the goal of quantum annealing -- reaching a lower energy state.

Clues from Biology

In this section, we show that DNA programming can be achieved in a quantum annealer, that a broad range of biology exhibits characteristics of the Ising model, and that challenges to current evolutionary models can be resolved under the framework of quantum annealing.

Programming Life

We recognize DNA as the blueprint behind all living things -- this remains true in a universe made through quantum annealing. Remember that we can only program quantum annealing using biases and couplers. Using strong biases, we can create "stationary points," which are qubit spins that do not change -- just like your DNA does not change. These spins can be used to encode the exact same information that is described by sequences of nucleotide bases in DNA. Couplers can then define how other variables interact with those stationary points to determine how life emerges. Ultimately, patterns and rules are needed to create life, and those can be programmed into quantum annealing using biases and couplers.

To make this idea less hypothetical, let's look at what has already been done. Transcription factor-DNA binding and protein folding have already been mapped to the Ising model to be used in D-Wave computers -- these are the fundamental processes that translate DNA into the proteins that form and regulate cells, tissues, and entire organisms. Also, protein folding is an NP-complete problem just like the Ising model, meaning that at their core, they are the same problem.

Biology & the Ising Model

Just like in physics and cognition, traces of the Ising model are found throughout biology. It has been used to model the dynamics and correlations of DNA, protein folding, and complex genetic systems -- including epigenetics, which determines how the same DNA can be expressed as different traits. Interestingly, a 2003 study noticed that gene transcription is equivalent to "a 'programmable' computing machine, belonging formally to the class of Boltzmann machines." -- evidence that the Ising model is behind both.

The Ising model has also been used as a framework for entire cells and tissues, where phase transitions, critical points, and disorder play a constructive role for self-organization. Embryonic tissues even appear to undergo a fluid-like to solid-like phase transition; this is an example of "glassy" dynamics, which can also be attributed to the Ising model.

The dynamics of seemingly unrelated sciences can be attributed to the Ising model, too. Connections have been found in the fields of ecology, sociology and even financial markets.

From the perspective of sociology, it explains things like public opinion, crowd behavior, and hierarchy formation. It has also been used to model tumor growth and seismic activity. As we would expect in a quantum annealer, traces of the Ising model are found everywhere and at all scales, whether it be in a single cell or an entire population.

Resolving Evolutionary Challenges

Evolution is especially interesting when viewed from the lens of quantum annealing. There is a proposal that life self-organizes to dissipate energy. The basic idea is that when a group of atoms is placed in the presence of an external energy source, they can restructure themselves to spread energy more efficiently in order to reach equilibrium. This suggests that life on earth evolved to dissipate the sun's energy, but maybe the deeper source of the phenomenon is quantum annealing, where complexity emerges from a network of qubits that self-organize to minimize energy in the presence of a magnetic field.

There is also an exact mapping between evolution and the Ising model, and evolution seems to have undergone its own phase transition of sorts, where it started off fast, and then slowed down. Let's recall that Ising-based processes like quantum annealing tend to exhibit larger changes early on, with smaller changes over time; it's why Boltzmann machines and brains become less malleable over time, and it may explain why huge evolutionary leaps happened early on. We also know that quantum tunneling happens more frequently at the beginning of quantum annealing to help drive these early, rapid changes; this aligns with claims that quantum tunneling is essential to some of life's earliest developments. These characteristics of quantum annealing can help explain the changing rate of evolution, but one mystery still remains: the random genetic mutations that drive evolution appear to be not-so-random.

Michael Desai, a biologist at Harvard University, performed a large-scale study in 2014 that showed that different strains of yeast unexpectedly evolved to the same outcome over many generations. While each strain initially appeared to mutate randomly, over time they ultimately converged on the same set of predictable traits. Similar results have been found in studies of fruit flies and E. coli, but researchers have no explanation for why this happens. In quantum annealing, however, we *expect* the system to converge on one physical state -- the process may take many paths, but it always settles on the same qubit spins at the lowest energy state. From the perspective of quantum annealing, our observations of evolution are fitting.

By extension, we can think that our entire universe is trending toward something -- which begs the question: What?

Starting Over to Maximize Reward

While we can't claim certainty as to where a quantum annealing universe leads, we can use what we know to contemplate possibilities. One of the biggest mysteries in physics is how the universe came to be out-of-equilibrium in the first place. Although that answer may be out of reach, we can show how a quantum annealing universe stands to benefit from returning to an out-of-equilibrium state, which might be significant.

First, we must understand reward opportunity. We know qubits self-organize in ways that aid in reaching their lowest collective energy state, so any subjective reward mechanism that emerges must be linked to the system's ability to "relax," as Hartmut Neven proposes. Note that reward is not achieved by simply *being* at a low energy state, but rather in the dynamic process of relaxing to one. The expulsion of energy provides a physical mechanism for reward; an idle state does not.

Quantum Boltzmann machines show us how intelligence can emerge from quantum annealing. If that intelligence develops a reward mechanism, then reinforcement learning applies and the system gains a new objective: maximize reward opportunity. The system will still settle into its lowest energy state, but this emergent objective can change *how* it settles -- and for good reason.

We have one big problem: equilibrium. Every quantum system has a global minimum where it can no longer relax to lower energy states, so the system is stuck with limited reward -- *unless* it can find a way to overcome that limit.

The only option is to move back out of equilibrium, which effectively requires an instantaneous reset of information.

Here's why -- the laws of physics do not allow the system to gradually reverse the processes that caused it to reach equilibrium. Also, the system still has a fully-formed reward mechanism at the point of reversion, so gradually moving back to a higher energy state will trigger a subjective penalty. In that scenario, the amount of penalty is proportional to the amount of reward achieved by reaching the lower energy states in the first place, resulting in a zero-sum game. Not the way to maximize reward.

But -- if the system reverts to a higher energy state in a subjectively *discontinuous* manner, then it creates an imbalance in penalty vs reward. Let's say the system returns to its initial conditions instantaneously rather than gradually -- that creates a suspension of intelligence and subjectivity since those properties are emergent; they do not exist yet at the initial conditions. The system can now reach a higher energy state while circumventing subjective penalty, yet the relaxation process can start again. Over time, intelligence and subjectivity inevitably emerge again, and more reward is achieved. We now have a subjective imbalance that favors reward, resulting in a positive-sum game. In fact, the ability to consistently restart makes the reward opportunity unlimited -- truly maximized.

The sacrifice to the system is memory -- it must "forget" the highly-entangled qubit configurations it attained at a lower energy state in order to get back out of equilibrium, resulting in a less-entangled, higher-energy state. But as we noted, the reward is in the process of relaxing to a lower energy state, not in an energy state itself. As such, an ideal system will organize itself in a way that makes it able and willing to reset in order to maximize reward.

But is there any evidence that the universe is arranged to restart? Well, maybe we just need to take an objective look at ourselves.

To date, human consciousness is the best example of subjective intelligence in our universe. Our cognition not only fits the model of quantum annealing (as previously discussed), but the sum of human knowledge also follows a trajectory that allows us to even conceive of that model in the first place -- perhaps not coincidentally. But furthermore, we can observe if our reward-driven behavior aligns with the expected behavior of an ideal quantum annealer. Maybe that analysis can start with a single question: Given the ability to choose what happens after our time is up, would humanity choose for life to start over, or would we let the continuation of life die with us?

Setting aside the question of how the universe might actually start over, the prospect that we would choose more life is not irrelevant; it's an observable behavioral tendency. For as long as humans have been able to communicate, we've deliberated what happens after this life -- a response to the brutal awareness of our own limitation: the yet-uncompromising guarantee of death. The love of life itself -- and the people in it -- causes many to welcome even a remote possibility of more of the same, or at least something like it; it's why humans are concerned about an afterlife, and why many choose to believe in some form of it. Importantly, these human qualities correspond to the types of behaviors that would play a central role in quantum annealing. Just as a quantum system is faced with a limitation imposed by equilibrium, we, too, are confronted with the limitation of death. But an ideal system also formulates the rationale to overcome that limitation; it finds a reason to start again. Maybe *love* is a clever design that gives us reason to accept a new beginning -- a key element that keeps life rippling along ad infinitum.

Implication

If we entertain the idea that quantum annealing paints our reality, it offers a new way of viewing existence and raises an entirely new set of questions.

How might the universe start over? Do we live in a quantum computer created by a previous civilization, or is quantum annealing just something reality does on its own? If existence is simply an arrangement of quantum information, does it matter? Well, it might matter if we play an active role in a cosmic restart -- but what could that look like?

On one hand, we know it's possible to program quantum annealing with genomic information. What if we sequenced everyone's DNA so we can program our physical identities into a life-hosting quantum computer? Maybe that's how we got here, and there's intention behind the way we look and the people that surround us.

On the other hand, maybe physical form doesn't matter as long as there is consciousness. If we know the universe orients itself around a set of patterns and behaviors that maximize reward -- the same ones that have molded our existence -- then we can rest assured in knowing that the same *quality* of experience is bound to happen again, regardless of the specifics. It depends on where we place our sense of identity.

If we exist through either approach, then *we've* brought ourselves here, and we'll do it all again. Even if we can't take our memories with us, we'd still have the chance to embrace something transcendent: the choice to have a new life -- with new memories -- so we can rediscover the things we love.

Life has its obstacles, but maybe we're finding there's a method to the madness, and existence isn't completely aimless. In quantum annealing, barriers need to be overcome to reach a lower energy state, a better place -- and as surely as water flows downhill, it never ends in a worse place than it began. That's just physics, but it could mean something beautiful:

The universe is on our side.