The Quantum Zeno Effect as an Error-Correction Algorithm for DNA Data Storage

Ruben Gariazzo

student at the École Polytechnique Féminine

ABSTRACT

The use of synthetic DNA for high-density data archiving faces major challenges related to molecular alterations. Recent studies have modeled the impact of proton tunneling in base pairs, generating transient tautomers[1] responsible for spontaneous mutations. This article explores the theoretical hypothesis of applying the quantum Zeno effect to freeze the wave function of these protons and prevent mutations at the source. Through a multidisciplinary approach combining information thermodynamics, quantum optics, and structural chemistry, we demonstrate that the limitations of our current technologies make this method unfeasible as it stands. We establish a theorem of energetic non-viability for Zeno control of storage DNA, quantifying the structural limits (localization energies exceeding the phosphodiester bond rupture threshold) and thermodynamic limits (thermal dissipation governed by Landauer's principle). The article concludes with a roadmap ranking alternative technological and algorithmic proposals suited to the capabilities of contemporary engineering.

NOMENCLATURE

N	Total number of base pairs in the archive (e.g. 5×10^{15} for 1 Petabyte)
τ	Characteristic time of proton transfer by tunneling ($\sim 10^{-12}\,\mathrm{s}$)
Δt	Time interval between two successive Zeno-effect measurements
Δx	Spatial uncertainty or spatial resolution of the measurement ($\leq 0.1\,\mathrm{nm}$)
E_L	Minimum energy dissipated per irreversible operation (Landauer limit)
P	Minimum thermal power dissipated by the control system

1. INTRODUCTION AND SCIENTIFIC POSITIONING

The hybridization of information technology and molecular biology has established synthetic DNA as a leading candidate for long-term data storage. Foundational research by Church et al. [1] and Goldman et al. [2] validated DNA's capacity to store petabytes of information within a microscopic volume, while

[1] Tautomers: constitutional isomers interconvertible through the reversible intramolecular migration of an atom or group of atoms, here the shift of a hydrogen atom altering the bonds of a nucleotide base.

guaranteeing stability potentially spanning several millennia. However, although the macromolecule[1] is extremely robust, the fidelity of the information remains subject to alterations caused by synthesis errors, sequencing errors, and spontaneous degradation.

While most of these errors stem from classical biochemical factors, phenomena arising from quantum mechanics also come into play at the atomic scale. As early as 1965, Per-Olov Löwdin suggested that the protons forming the hydrogen bonds between nucleotide bases could undergo tunneling[2] [3]. More recently, the in silico work of Slocombe, Al-Khalili, and Sacchi accurately modeled this proton transfer within DNA, demonstrating the emergence of transient tautomeric states responsible for spontaneous mutations during replication [4].

In this context, an appealing theoretical hypothesis would be to exploit the quantum Zeno effect to neutralize these errors at the source. Described by Misra and Sudarshan in 1977 [5], the quantum Zeno effect postulates that continuous observation of an unstable quantum system freezes its evolution, keeping its survival probability in its initial state close to unity. In-depth studies of the dynamics of this effect, such as those conducted by Facchi and Pascazio [6], have confirmed its experimental validity in various rigorously controlled isolated systems.

However, these theoretical proposals on the Zeno effect have historically been confined to highly idealized quantum environments. They omit the complex mechanics of polymers and the thermodynamic costs of macroscopic coupling. Conversely, the existing literature on DNA storage focuses almost exclusively on biochemical or algorithmic error correction.

Our contribution fills this interdisciplinary gap. We formalize these constraints as a theorem of energetic non-viability for Zeno control of storage DNA (hereafter referred to as the "DNA-Zeno no-go theorem"). By "impossibility framework," we mean a set of explicitly formulated hypotheses (H1–H4) leading to quantitative bounds (i–ii) that render any active Zeno control scheme for DNA storage archives mechanically destructive and energetically non-viable.

We thus demonstrate that, even in an ideal observation scenario, maintaining such control would require sub-nanometer spatial resolution, implying probe energies on the order of 12.4 keV. These values exceed the physical rupture threshold of DNA's phosphodiester bonds (4.14 eV) by nearly three thousand times. Moreover, at the scale of a one-petabyte archive, the thermodynamic limits imposed by Landauer's principle would dictate an unavoidable minimum thermal dissipation of 14.35 MW.

Addressed jointly to quantum information theorists, biophysicists, and data architecture engineers, this result is crucial. It formally demonstrates that investing in research on active quantum stabilization of DNA is a fundamentally dead-end path. Systems engineering must therefore reallocate its efforts toward proven and achievable solutions (XNA substrate engineering, advanced classical coding schemes,

[1] Macromolecule: a very large molecule made up of many repeating subunits (monomers), as is the case for DNA polymers.

[2] Tunneling: a quantum phenomenon allowing a particle to cross an energy potential barrier that is theoretically insurmountable in classical mechanics, owing to the spatial extent of its wave function.

machine-learning prediction). Figure 1 visually summarizes the logical flow of our study.

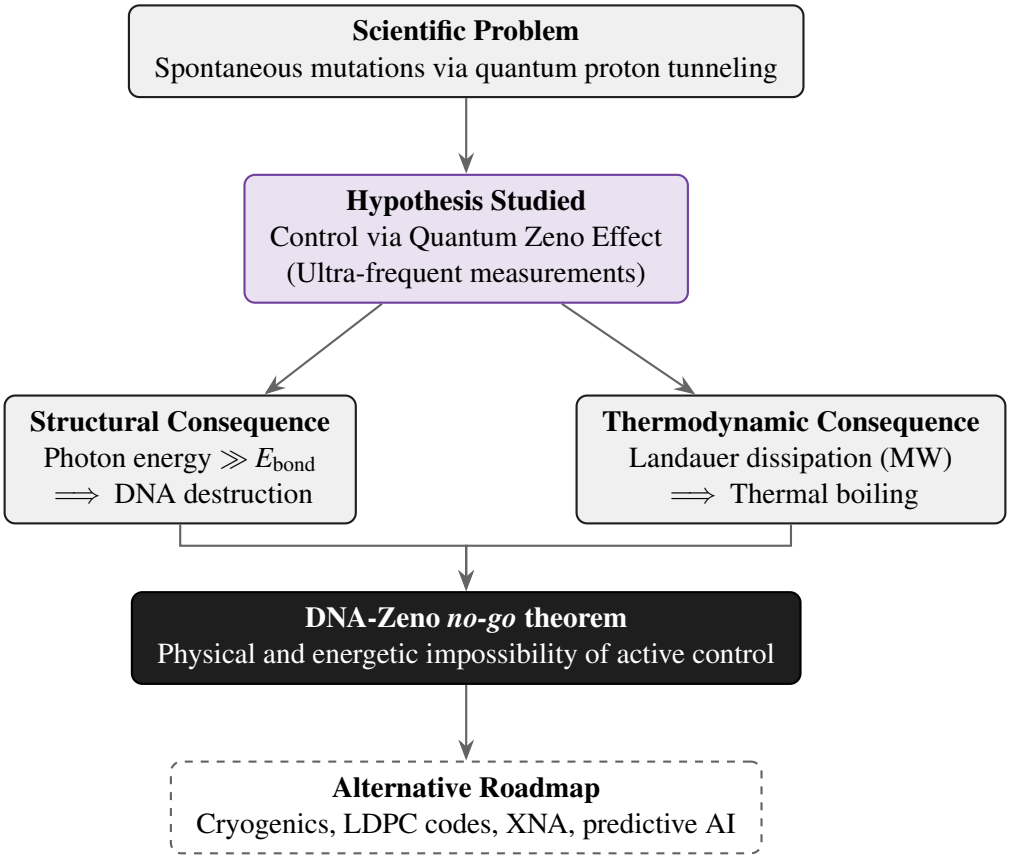

Figure 1: *General diagram of the study.* The logical flow shows how attempting quantum correction (Zeno effect) generates insurmountable structural and thermodynamic constraints, motivating the formalization of the impossibility theorem and steering research toward viable alternatives.

2. METHODOLOGICAL FRAMEWORK AND WORKING HYPOTHESES

To rigorously assess the feasibility of quantum control over a pool of storage DNA, we employ an approach based on order-of-magnitude estimates[1] (OOM) applied to the worst-case scenario (worst-case bounds). This choice ensures the evaluation of the absolute limits of the physical system without depending on minor engineering optimizations.

The modeled system is a standard exascale[2] archiving center containing one petabyte (1 PB) of digital data. Accounting for the encoding algorithms and addressing primers required (as documented by Organick et al. [14]), this capacity represents approximately $N = 5 \times 10^{15}$ base pairs of synthetic DNA. The characteristic time interval of proton tunneling within hydrogen bonds, denoted τ, is set at 10^{-12} s, in line with the vibrational dynamics calculated by Slocombe et al. [4]. The quantities we seek to bound

[1] Order of magnitude: an approximate evaluation of a physical quantity, generally expressed as a power of 10, used to check the viability of a concept.

[2] Exascale: refers to computing systems capable of performing a billion billion (10^{18}) operations per second, or by extension, of storing immense volumes of data (exabytes).

are the energy per quantum measurement transferred to the molecule, and the overall thermal dissipation of the storage system per unit of time, in order to compare them against DNA's structural and ecological tolerances.

3. ERROR MODELS: CLASSICAL VERSUS QUANTUM

To put the need for quantum control into context, it is essential to visualize the physical origin of the phenomenon (Figure 2) and to quantitatively compare the sources of error affecting the DNA communication channel, as described by Heckel et al. [13]. The thesis that Zeno-effect correction would be indispensable rests on the assumption that tunneling-induced mutations constitute a dominant threat. Current experimental data invalidate this assumption.

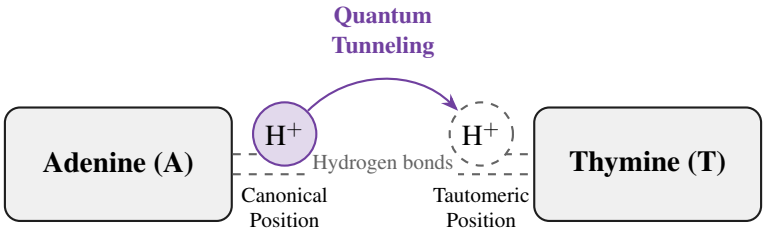

Figure 2: *Schematic representation of proton transfer by tunneling in a base pair.* The proton (H^+) forming the hydrogen bond has a non-zero probability of crossing the energy barrier, transforming the canonical base into an unstable tautomeric form, a source of mutations during replication.

Biochemical and mechanical errors, inherent to our current manipulation methods, largely dominate the error budget. During DNA synthesis (typically via the phosphoramidite method), the error rate from insertion, deletion, or substitution amounts to about 10^{-2} per base. During reading, nanopore sequencing[1] technologies generate error rates between 5×10^{-2} and 10^{-1}, while optical sequencing (Illumina-type) reaches about 10^{-3} per base [13]. By comparison, the open quantum dynamics model estimates the probability of a spontaneous mutation induced by proton tunneling, surviving the replication machinery, at about 10^{-8} per base [4].

Quantum correction therefore targets a phenomenon whose probability of occurrence is a million times lower than that of classical synthesis errors. Consequently, Zeno-effect correction proves not only physically unattainable with our current capabilities, but also numerically marginal relative to the overall error profile.

[1] Nanopore sequencing: a DNA-reading technology that passes the strand through a nanometer-scale pore and measures the electrical current variations induced by each base.

4. FORMALIZATION OF THE QUANTUM ZENO ALGORITHM

The principle of the quantum Zeno effect, conceptually illustrated in Figure 3, rests on the deliberate perturbation of a quantum system's evolution [5, 6]. Although the title of this article refers to an algorithm, the literature often omits defining its formal structure. A Zeno-effect error-correction algorithm applied to DNA would be defined by an iterative process made up of evolution phases and projections.

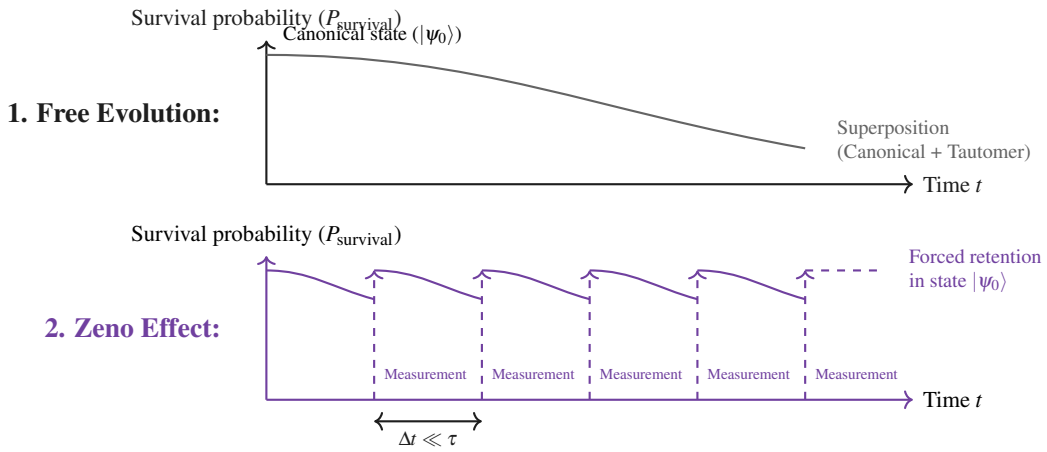

Figure 3: *Principle of the quantum Zeno effect.* In the absence of observation (Scenario 1), the survival probability of the initial state decreases as the system freely evolves toward the tautomeric state. Under very frequent projective measurements (Scenario 2), the coherent evolution is constantly interrupted, confining the proton to its initial canonical state.

Let the system be prepared in an initial canonical state, represented by the ket $|\psi_0\rangle$. The system's free evolution over a time interval Δt is governed by the unitary evolution operator $U(\Delta t) = \exp\left(-\frac{iH\Delta t}{\hbar}\right)$, leading to a coherent superposition between the canonical state and the tautomeric state (the error).

The algorithm would consist of applying, at regular intervals $\Delta t \ll \tau$, a projective measurement operator $P_{\text{canonical}} = |\psi_0\rangle\langle\psi_0|$. At each iteration, the collapsed wave function would be formally described by the following expression.

$$|\psi(t)\rangle = \left(P_{\text{canonical}} \exp\left(-\frac{iH\Delta t}{\hbar}\right)\right)^N |\psi_0\rangle$$

In this expression, N represents the number of measurements performed, such that $t = N\Delta t$. For this algorithm to guarantee data preservation, the survival probability $P(t) = |\langle\psi_0|\psi(t)\rangle|^2$ must remain close to 1, which requires physically interfacing the DNA with a macroscopic measurement device capable of implementing the $P_{\text{canonical}}$ operator on 10^{15} bases simultaneously and continuously. Figure 4 compares the time trajectories of a base pair with and without the application of such a Zeno control algorithm [5, 6].

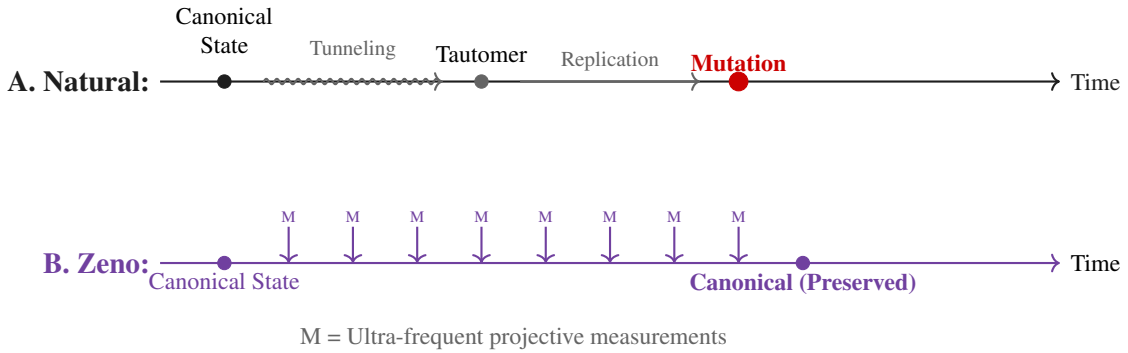

Figure 4: *Timeline of mutation emergence and its theoretical prevention.* The natural scenario (A) allows tunneling to result in a permanent mutation during DNA replication. The theoretical scenario under Zeno control (B) imposes measurements (M) at an extremely high frequency to forbid tautomerization.

5. TUNNELING DYNAMICS AND ENVIRONMENTAL INFLUENCE

To understand why measurement is necessary, the natural dynamics of the proton within its biochemical environment must be modeled. Figure 5 schematizes this fundamental coupling. In this study, proton transfer is not modeled as an isolated system, but as an open quantum system interacting with its fluctuating biological environment.

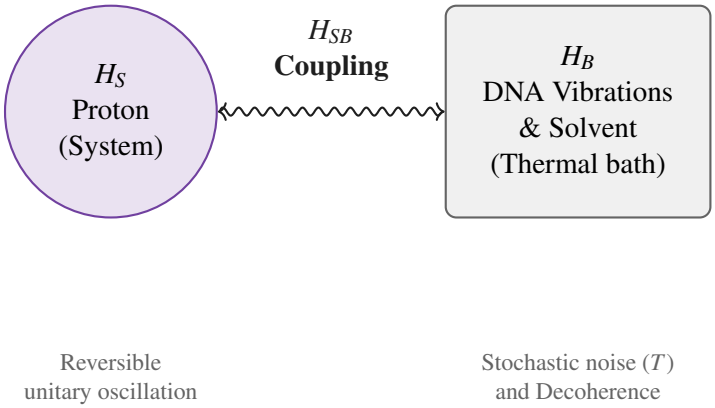

Figure 5: *Conceptual representation of the open quantum system.* The proton (H_S) is not isolated but perpetually interacts, via H_{SB}, with a thermal bath (H_B) formed by the rest of the macromolecule and the solvent, inducing energy exchange and a loss of quantum information.

The total Hamiltonian H[1] of the system is thus expressed as the sum of three fundamental components.

$$H = \underbrace{H_S}_{\text{System}} + \underbrace{H_B}_{\text{Thermal bath}} + \underbrace{H_{SB}}_{\text{System-bath interaction}}$$

In this equation, H_S represents the proper energy of the isolated proton navigating the asymmetric po-

[1] Hamiltonian: a mathematical operator in quantum mechanics corresponding to the sum of a system's kinetic and potential energy, dictating its time evolution.

tential well of the hydrogen bond. The H_B component describes the energy of the surrounding thermal bath (the stochastic vibrations of the rest of the DNA macromolecule and the surrounding solvent). Finally, the H_{SB} term quantifies the specific coupling between the proton and this bath, responsible for the unavoidable exchanges of energy and information with the medium.

The evolution of the proton's quantum state, after averaging out the complex effects of this environment, is described by the reduced density matrix[1] $\rho_S(t)$. Its time dynamics are governed by the Caldeira-Leggett master equation.

$$\frac{d\rho_S}{dt} = -\frac{i}{\hbar}[H_S, \rho_S] - \frac{i\gamma}{\hbar}[x, \{p, \rho_S\}] - \frac{2m\gamma k_B T}{\hbar^2}[x, [x, \rho_S]]$$

This differential equation is crucial because it captures the competition between purely quantum effects and the classical influence of the environment. The first term describes the pure unitary evolution, that is, the reversible quantum oscillation by tunneling between the two DNA strands, dictated by the commutator of the Hamiltonian and the density matrix.

The subsequent terms introduce the perturbative influence of the environment. The second term, proportional to the anticommutator involving position x and momentum p, expresses the dissipation of energy (quantum friction) into the thermal bath. The third term, which depends on the double commutator of position, models the thermal fluctuations responsible for decoherence[2]. This process of environmental decoherence is schematized in Figure 6.

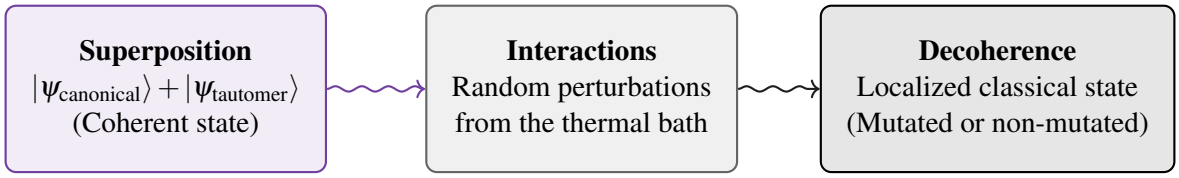

Figure 6: *Quantum decoherence process.* Under the effect of the random thermal interactions described by the Caldeira-Leggett equation, the proton's initial quantum superposition (left) rapidly reduces to a defined, classical state (right).

It is this last process that rapidly destroys the proton's quantum superposition, forcing the system to settle into a defined state. In this formulation, γ represents the macroscopic damping rate, m the proton's effective mass, k_B the Boltzmann constant, T the temperature in Kelvin, and $\hbar$ the reduced Planck constant. The Zeno algorithm is meant to counteract this natural decoherence by forcing the state before the environment does so randomly.

[1] Reduced density matrix: a probabilistic mathematical tool used to describe the statistical state of an open quantum subsystem interacting with a massive environment, unlike a simple wave function.

[2] Decoherence: the process by which a quantum system loses its interference and superposition properties due to its interaction with its environment, thereafter behaving in a classical statistical manner.

6. THE MEASUREMENT PARADOX AND THE STRUCTURAL LIMIT

The physical implementation of the $P_{\text{canonical}}$ operator requires localizing the particle with a spatial resolution strictly finer than the distance separating the two potential wells. Implementing this projective measurement raises a major energetic paradox, illustrated in Figure 7. Since the length of a hydrogen bond in DNA is about 0.3 nm, the observation probe (for example, a photon) must have a maximum wavelength of 0.1 nm to avoid spatial uncertainty.

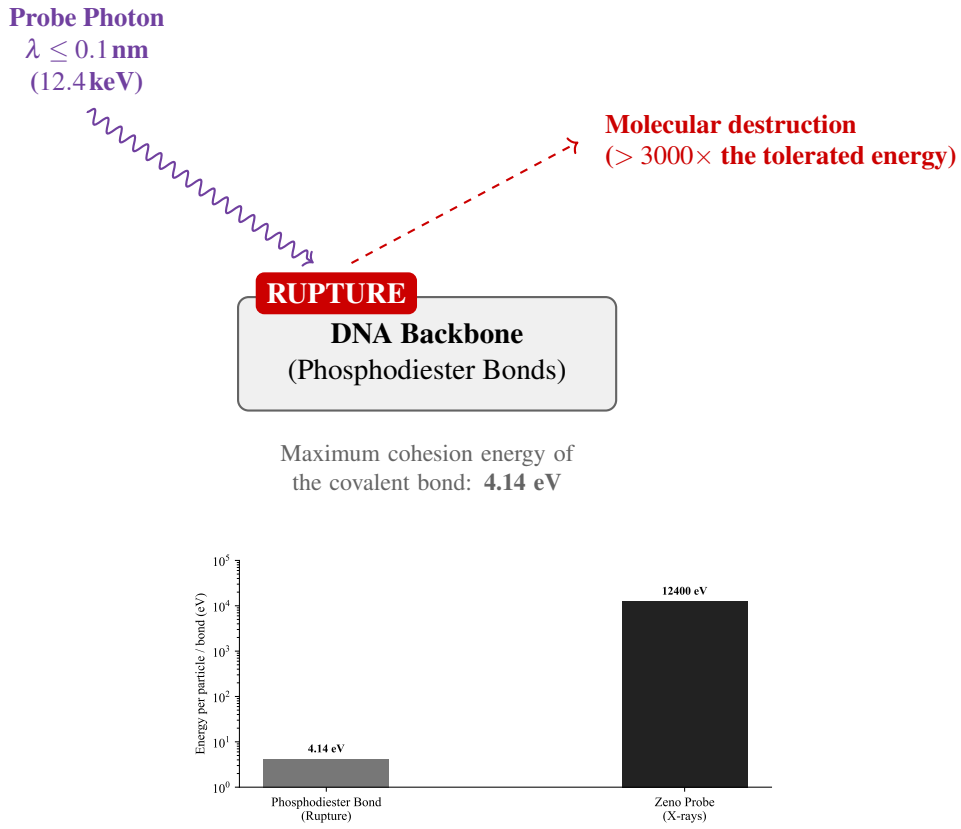

Figure 7: *Destructive nature of localized measurement and comparison of energy scales.* To observe a proton with sub-nanometer resolution, the energy of the probe photon (hard X-rays) instantly shatters the rupture threshold of the DNA backbone's phosphodiester bonds, destroying the macromolecule.

The energy associated with this photon is calculated using the Planck-Einstein equation, where energy is inversely proportional to wavelength.

$$E = \frac{hc}{\lambda}$$

In this formulation, E denotes the photon's energy, h the Planck constant ($6.626 \times 10^{-34}\,\text{J}\cdot\text{s}$), c the speed of light ($3 \times 10^8\,\text{m/s}$), and λ the probe's wavelength. Applying a value of 0.1 nm, the resulting energy is about $1.98 \times 10^{-15}\,\text{J}$. Converted to electronvolts, this energy reaches about 12.4 keV, which places this radiation within the hard X-ray spectrum.

However, the structural backbone of the DNA molecule is held together by covalent phosphodiester bonds. The dissociation energy of these bonds amounts to 400 kJ/mol, equivalent to 4.14 eV per individual bond. The energy of the required measurement photon is therefore approximately three thousand times greater than the cohesion energy of the molecule itself.

At present, we have no technology capable of performing a projective measurement at this spatial scale without transferring a destructive amount of energy. Other observation regimes, such as coupling the system to a resonant optical cavity (cavity quantum electrodynamics), have been proposed in other fields [15]. However, at room temperature, DNA's thermal decoherence rate vastly exceeds the achievable coupling constant between a proton and the cavity mode, rendering Zeno stabilization inoperative without vaporizing the sample. Attempting continuous observation to induce the Zeno effect with our current sensors would cause radiolysis[1] and immediate degradation of the storage medium.

7. THE THERMODYNAMIC CHALLENGE: LANDAUER'S PRINCIPLE

Even assuming the hypothetical future development of a non-destructive measurement method, the system would still face a major thermodynamic constraint. Landauer's principle[2], formulated in 1961 [8] and experimentally verified by Bérut et al. in 2012 [7], establishes that any irreversible processing of information, including the measurement and subsequent erasure of a qubit's state, dissipates a minimum amount of heat into the environment.

The energy dissipated by a single irreversible logical operation is expressed by the relation.

$$E_L = k_B T \ln(2)$$

Where E_L is the Landauer energy, k_B the Boltzmann constant, and T the absolute temperature of the system. At room temperature ($T = 300\,\mathrm{K}$), the energy dissipated per measurement is about 2.87×10^{-21} Joules.

For a moderate storage volume of 1 petabyte, representing about 5×10^{15} base pairs (denoted N), the Zeno algorithm requires each base to be measured every picosecond ($\tau = 10^{-12}\,\mathrm{s}$) to outpace the tunneling transfer time. The minimum thermodynamic electrical power P generated as heat would be.

$$P = \frac{N \times E_L}{\tau} \quad \longrightarrow \quad P = \frac{5 \times 10^{15} \times 2.87 \times 10^{-21}}{10^{-12}} \approx 14.35\,\text{Megawatts}$$

[1] Radiolysis: the decomposition of chemical molecules caused by the impact of very high-energy ionizing radiation, resulting in the destruction of genetic material.

[2] Landauer's principle: a fundamental theorem stating that the irreversible erasure of one bit of information releases an irreducible amount of heat, creating a direct bridge between thermodynamics and information theory.

It should be noted that relaxing this constraint by spacing out the measurements (increasing τ) or using probabilistic sampling would proportionally reduce thermal dissipation, but would mathematically cancel out the Zeno effect. The algorithm's success relies on a strict observation frequency; any missed measurement allows the wave function to evolve toward mutation.

The major ecological advantage of DNA archiving, which justifies current investments, lies in its zero energy requirement once the data is stored. The continuous dissipation of more than 14 megawatts of energy as heat within storage facilities represents a fundamental thermodynamic limit (Figure 8). It implies thermal and energy constraints that are structurally incompatible with the architecture of a dense organic medium.

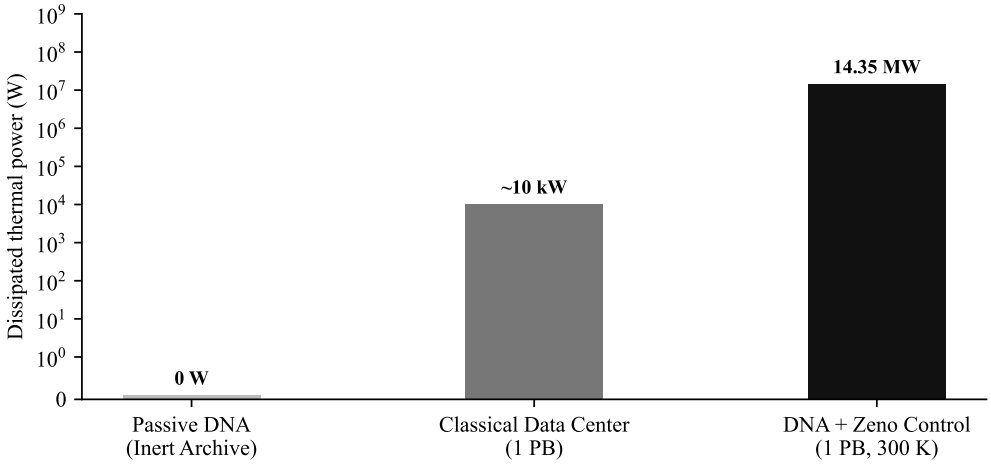

Figure 8: *Comparison of the theoretical thermal dissipation generated by measurements under Landauer's principle.*

8. FORMULATION OF THE DNA-ZENO NO-GO THEOREM

Building on the full set of derivations obtained in the preceding sections, we can bring these results together into a unified formalization. Figure 9 maps out the full set of insurmountable physical barriers identified, converging toward the statement of our impossibility theorem.

Theorem 1 (Theorem of energetic non-viability of Zeno control of storage DNA, or DNA-Zeno *no-go* theorem)**.** *Let there be a set of DNA polymers serving as a digital information storage medium, operating under the following hypotheses.*

H1. ***Spatial resolution:*** *To prevent proton tautomerization by tunneling, the position of the proton in the hydrogen bond is measured with a spatial uncertainty* $\Delta x \leq 0.1\,nm$.

H2. ***Structural integrity:*** *The cohesion of the macromolecule relies on phosphodiester bonds whose individual rupture energy is* $E_{bond} \approx 4.14\,eV$.

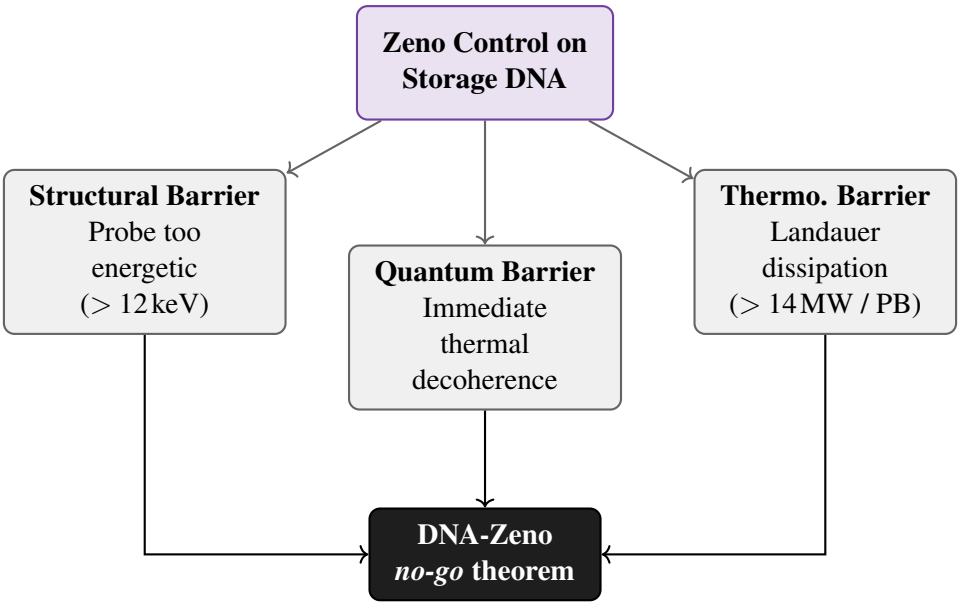

Figure 9: *Synthesis of the three fundamental physical barriers.* The convergence of structural, quantum, and thermodynamic limitations forbids any technological viability for Zeno control of DNA storage, thereby grounding the impossibility (*no-go*) theorem.

H3. ***Landauer thermodynamics:*** *Each act of irreversible projective measurement dissipates at least* $E_L = k_B T \ln 2$ *as heat.*

H4. ***Zeno cadence:*** *Measurements are repeated at a time interval* $\Delta t \leq \tau_{tunnel} \approx 10^{-12}\,s$ *over a set of* N *base pairs.*

Then, any active quantum control protocol satisfying H1–H4 inevitably induces:

i. An individual probe energy $E_{probe} = \frac{hc}{\lambda} \approx 12.4\,keV \gg E_{bond}$*, causing instant radiolysis of the polymer.*

ii. A minimum dissipated thermal power $P = \frac{N k_B T \ln 2}{\tau_{tunnel}} \approx 14.35\,MW$ *for* $N = 5 \times 10^{15}$ *bases (1 PB at* $300\,K$*), canceling out the medium's passive energy balance.*

Box 1 - Interpretation for the Engineer.
In practice, this means that if one attempts to monitor every proton frequently and precisely enough to block tunneling-induced mutations, (i) the energy transfer from the sensor (X-ray type) mechanically destroys the DNA, and (ii) permanent monitoring requires an uninterrupted power supply of about 14.35 MW for 1 petabyte, which completely negates the goal of ultra-low-power DNA storage [7, 8].

- **H1 (Resolution)**: To localize the proton, the wavelength of the observation probe must be strictly smaller than the amplitude of its spatial displacement.
- **H2 (Integrity)**: The structural integrity of the macromolecule is broken if the energy transferred by the probe exceeds DNA's covalent bond energy (4.14 eV).
- **H3 (Landauer)**: Any measurement-and-reset operation of a sensor generates an unavoidable thermal dissipation imposed by thermodynamics.
- **H4 (Cadence)**: The observation frequency must exceed the proton's natural dynamics (at the picosecond scale) to freeze its state.

9. SENSITIVITY ANALYSIS AND PARAMETER REGIME VARIATION

To assess the robustness of our DNA-Zeno no-go theorem against possible variations in architecture or operating conditions, we conduct a systematic sensitivity analysis by varying the storage capacity N, the operating temperature T, and the measurement regime.

9.1 Sensitivity to System Capacity (N)

If the DNA pool's capacity is reduced from 1 PB to more modest volumes, the thermal power dissipated under Landauer's principle scales strictly linearly with capacity N.

- For 1 MB ($N \approx 5 \times 10^9$ bases): $P \approx 14.35$ W.
- For 1 GB ($N \approx 5 \times 10^{12}$ bases): $P \approx 14.35$ kW.
- For 1 PB ($N \approx 5 \times 10^{15}$ bases): $P \approx 14.35$ MW.
- For 1 EB ($N \approx 5 \times 10^{18}$ bases): $P \approx 14.35$ GW.

Although for a single megabyte the power of 14.35 W may seem technically manageable on a macroscopic scale, it should be remembered that this heat is dissipated within a microscopic molecular volume

of about $10^{-6}\,\mathrm{mm}^3$. The volumetric thermal power density then exceeds $10^7\,\mathrm{W/cm}^3$, which would cause a local temperature rise destructive to organic matter.

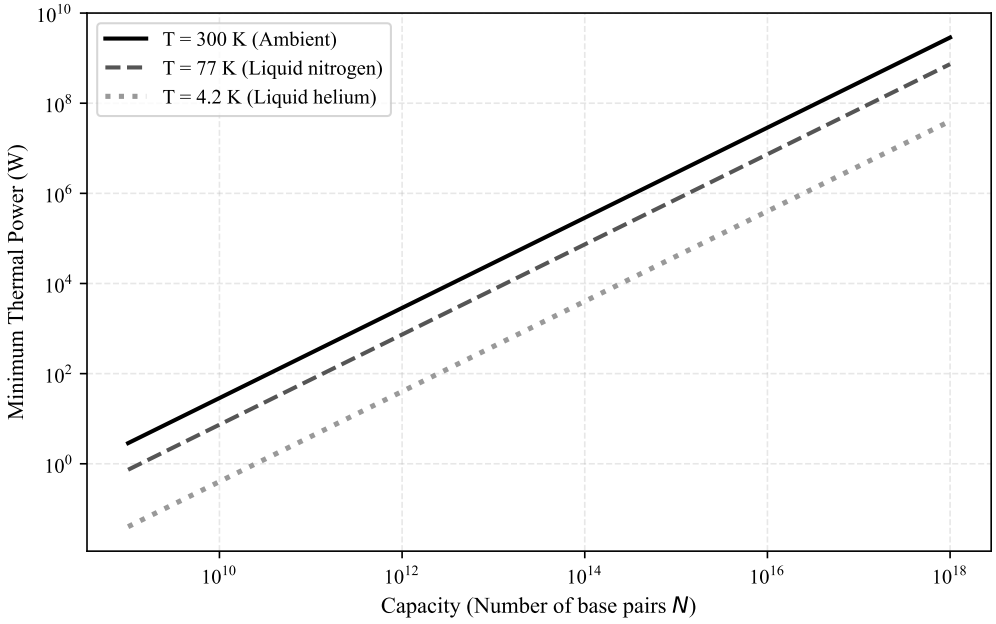

Figure 10: *Evolution of the dissipated thermal power (Landauer) as a function of storage capacity N and temperature T. Even for modest volumes, the local energy density remains a major barrier.*

9.2 Sensitivity to Temperature (T)

Lowering the temperature directly reduces the Landauer energy per measurement ($E_L \propto T$).

- At room temperature ($T = 300\,\mathrm{K}$): $E_L = 2.87 \times 10^{-21}\,\mathrm{J} \implies P = 14.35\,\mathrm{MW}$ for 1 PB.
- At liquid nitrogen temperature ($T = 77\,\mathrm{K}$): $E_L = 0.737 \times 10^{-21}\,\mathrm{J} \implies P = 3.68\,\mathrm{MW}$ for 1 PB.
- At liquid helium temperature ($T = 4.2\,\mathrm{K}$): $E_L = 0.040 \times 10^{-21}\,\mathrm{J} \implies P = 0.20\,\mathrm{MW}$ (200 kW) for 1 PB.

Although cryogenics reduce the Landauer thermal power by a factor of 70 at 4.2 K, extracting this 200 kW of heat at temperatures close to absolute zero requires an external refrigeration electrical power (per Carnot efficiency) exceeding several tens of megawatts. Moreover, lowering the temperature does nothing to reduce the energy of the localization photon (12.4 keV), making the rupture of phosphodiester bonds just as inevitable.

9.3 Sensitivity to Resolution and Cadence (Δx, Δt)

Sensitivity to spatial resolution (Δx): Even relaxing Δx to 0.2 nm (a less precise measurement), the required photon energy would be $E = hc/\lambda \approx 6.2\,\text{keV}$. The ratio $E_{\text{probe}}/E_{\text{bond}}$ remains above $1500 \gg 1$, so the structural destruction of the polymer persists implacably [1, 2].

Sensitivity to measurement cadence (Δt): Even reducing the measurement cadence by an order of magnitude (for example $\Delta t = 10\tau$), the thermal power would drop to 1.4 MW, which remains unmanageable at archive scale. Moreover, at this cadence, the quantum behavior shifts. The survival probability of the canonical state, which decreases quadratically in the Zeno regime ($1-(\Delta t/\tau_Z)^2$), shifts toward a classical linear exponential decay ($e^{-\Gamma t}$). The quantum freeze is then broken and the method becomes inoperative [5, 6].

9.4 Summary of the Robustness of the Impossibility Theorem

In summary, the sensitivity analysis demonstrates the robustness of this DNA-Zeno no-go theorem. No variation of the operational parameters restores the viability of such a quantum control system.

- **Reducing capacity (N)** lowers the overall power, but maintains a destructive local thermal energy density ($> 10^7$ W/cm^3).
- **Lowering temperature (T)** reduces the unit thermodynamic cost, but adds a disproportionate macroscopic refrigeration cost, while leaving the molecular destruction caused by the measurement photon untouched.
- **Degrading spatial resolution (Δx)** still requires a probe energy (X-rays) an order of magnitude far above the covalent bond energy.
- **Spacing out the measurement cadence (Δt)** dissipates less heat, but purely and simply destroys the Zeno regime, allowing tunneling and mutations to proceed freely.

The impossibility is therefore not an artifact resulting from extreme parameters, but truly a physical limit inherent to the very paradigm of quantum control applied to a dense information polymer.

10. INADEQUACY OF BIOLOGICAL OBSERVATION METHODS

Faced with the destruction of the medium by direct observation, the use of indirect analytical methods drawn from quantum biology might be considered. Could engineering turn to the state-of-the-art tools used in laboratories to observe and freeze these phenomena? A detailed analysis shows that our observation technologies render these methods inoperative for data storage.

10.1 The Kinetic Isotope Effect (Deuterium Substitution)

In research biophysics, tunneling is experimentally slowed by replacing DNA's hydrogen with deuterium (a heavy isotope with one extra neutron). The tunneling transmission probability T across a barrier is defined by the WKB approximation[1] (Wentzel-Kramers-Brillouin).

$$T \approx \exp\left(-\frac{2a}{\hbar}\sqrt{2m(V-E)}\right)$$

In this equation, a represents the width of the potential barrier, m the mass of the particle crossing the barrier, and $(V-E)$ the energy deficit (barrier height relative to the particle's energy). By doubling the particle's mass m from 1 u (hydrogen) to 2 u (deuterium), the quantum tunneling probability T collapses exponentially. The quantum state is thus thermodynamically stabilized, without requiring active observation.

However, our current reading technologies (sequencing by synthesis) rely on polymerase enzymes whose enzymatic kinetics are strictly calibrated to the dynamics and mass of hydrogen. The secondary kinetic isotope effect caused by deuterated bonds considerably slows strand separation by helicases, blocking PCR processes and rendering the reading of the digital data unworkable with our standard sequencers today.

10.2 Ultrafast Spectroscopy (Femtosecond Lasers)

Observing an ultra-brief quantum state before its decoherence requires laser pulses on the order of a femtosecond (10^{-15} s). To keep a system frozen by the Zeno effect, the hydrogen bonds would need to be bombarded continuously at this stroboscopic cadence. The optical intensity I delivered by the beam is calculated from the energy E, the pulse duration Δt, and the focal area S.

$$I = \frac{E}{\Delta t \cdot S}$$

Even for minimal photon energies, dividing by a pulse duration Δt of 10^{-15} s generates colossal intensities that easily exceed the multiphoton ionization[2] threshold (estimated at about 10^{13} W/cm^2 for organic molecules). At this intensity, our optical instruments would not merely observe the substrate; they would instantly turn it into plasma through nonlinear electron stripping, incinerating the targeted information.

[1] WKB approximation: a semiclassical approximation method in quantum mechanics, very commonly used to evaluate the exponential decay of the probability of crossing a potential barrier.

[2] Multiphoton ionization: a nonlinear optical process by which an atom simultaneously absorbs several photons to release an electron, generating the formation of a destructive plasma.

10.3 Electron Paramagnetic Resonance (EPR)

Electron paramagnetic resonance is the standard tool for observing the quantum properties of DNA in the laboratory. It detects energy transitions via the splitting of spin states in a magnetic field, a phenomenon described by the Zeeman effect[1].

$$E = g\mu_B B m_s$$

In this formula, g is the Landé g-factor, μ_B the Bohr magneton, B the intensity of the applied magnetic field, and m_s the spin quantum number. The physical problem for storage engineering lies precisely in this m_s term. EPR requires a non-zero magnetic moment, hence unpaired electrons. However, the inert DNA synthesized for digital storage is a fundamentally diamagnetic[2] molecule; all of its valence electrons are paired, canceling the signal. To induce an observable signal, free radicals would have to be generated chemically. In biochemistry, the deliberate addition of free radicals constitutes severe oxidative stress, causing phosphodiester strand breakage. Attempting to observe DNA by EPR with our current induction methods would therefore corrupt the encoded binary data.

10.4 In Silico Quantum Chemistry (Density Functional Theory – DFT)

An algorithmic alternative would be to apply the Zeno projection virtually, via a digital twin simulating the dynamics in real time using density functional theory (DFT)[3]. Although approximate methods such as machine-learned interatomic potentials (MLIPs) [16] have accelerated calculations, the exact collapse of a wave function requires strict ab initio resolution. The computational cost of traditional DFT grows cubically with the number of electrons N.

$$\text{Computation time} \propto \mathcal{O}(N^3)$$

A modest megabyte of data stored in DNA represents about 2.4×10^9 valence electrons. The proportional computational effort becomes $(2.4 \times 10^9)^3 \approx 1.38 \times 10^{28}$ mathematical operations. Our current exascale supercomputers would need millennia to compute the exact quantum state of a single megabyte frozen at a given instant t. Simulating the Zeno effect continuously entirely exceeds our hardware computing capabilities.

[1] Zeeman effect: a phenomenon describing the splitting of the energy levels of a quantum system, such as an atom or molecule, due to its exposure to an external magnetic field.

[2] Diamagnetic: a property of a material with no permanent magnetic moment, whose orbital electrons are all paired with opposite spins.

[3] DFT: a powerful quantum method for studying the electronic structure of a many-body system using the spatial electron density rather than complex wave functions.

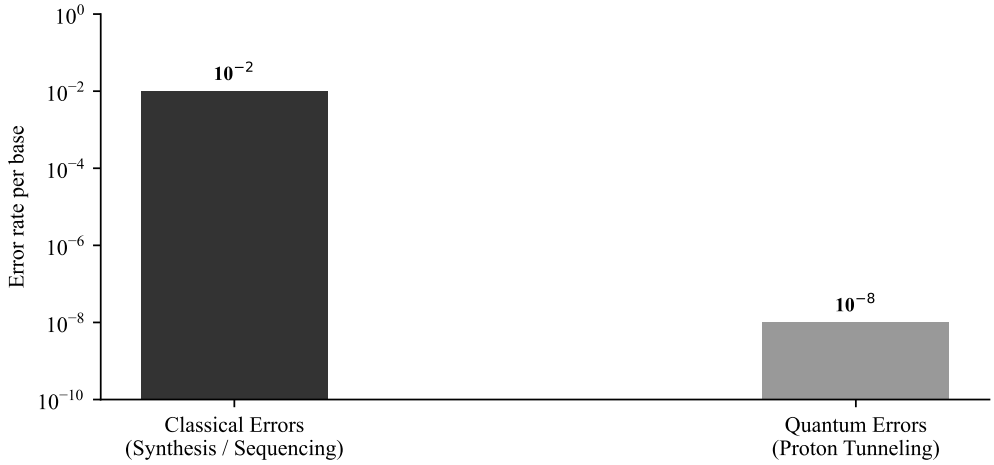

Figure 11: *Frequency of occurrence of classical errors compared to quantum-origin errors. Quantum control would target only a marginal fraction of overall alterations.*

11. PROPOSALS AND STRATEGIC ROADMAP

The direct application of the quantum Zeno effect as a hardware error-correction system for storage DNA constitutes a physical challenge that our current technologies cannot practically meet. The complexity of DNA as a dense macromolecular medium, subject to continuous thermal noise, requires considering alternative solutions suited to our technological level. To guide R&D investment, Table 1 summarizes the comparative performance of the different preservation and correction approaches.

Table 1: *Quantitative comparison matrix of preservation and error-correction strategies for DNA storage.*

Method / Strategy	**Energy Cost (W / bit / year)**	**Target Error Rate**	**Volumetric Density**	**Time Horizon**	**Practical Feasibility**
Active Zeno Control (QZE)	$\sim 10^{-9}$ W	10^{-8} (Quantum)	Zero (Plasma)	Speculative	Zero (Physical)
Passive Cryogenics (77 K) [10]	$\sim 10^{-14}$ W	$< 10^{-5}$ (Global)	Conserved	Immediate	High
XNA / Polymer Engineering [9]	0 W (Inert)	$< 10^{-6}$ (Global)	Equivalent	5-10 years	Medium
Error-Correcting Codes (LDPC) [11]	0 W (Passive)	0 (Recovered)	-15% to -30%	Immediate	Maximum
Predictive AI (Deep Learning) [12]	0 W (In silico)	Optimized	Maximum	2-5 years	High

To mitigate the risks of quantum and biochemical mutations, we structure our proposals according to their feasibility, energy cost, and time horizon.

11.0.1 Short-Term Solutions (High Technological Maturity)

Since physical intervention at the proton's quantum level is currently beyond the reach of our instruments, the most robust and immediate solution lies in the software and thermal layer.

- **Predictive Algorithmic Correction via Artificial Intelligence:** The information theory devel-

oped by Claude Shannon [11] provides the mathematical foundations for managing uncertainty in any communication channel. More recently, deep neural networks have begun to be applied to modeling sequencing and synthesis errors [12]. Rather than physically correcting the proton, it becomes feasible to train artificial intelligence models to identify quantum "hotspots," the specific DNA sequences where the energy landscape favors transient tautomerization. The data-encoding algorithm could then allocate a higher redundancy rate (via LDPC[1] codes) specifically around these vulnerability zones identified in silico. This method is immediately implementable using our existing software architectures, at a negligible encoding energy cost.

- **Passive Thermodynamic Preservation (Cryogenics):** To limit the molecule's internal dynamics without using destructive electromagnetic probes, storage at very low temperature remains a proven solution. The literature on DNA preservation, such as the silica-encapsulation work of Grass et al. [10] or recent cryogenic archiving trials, shows that thermal reduction considerably suppresses molecular agitation and chemical reactivity. The near-total suppression of phonons[2] substantially slows tautomeric processes. While this does not entirely eliminate tunneling (which is inherently temperature-independent), it prevents the subsequent structural rearrangements that permanently fix the mutation. This proposal shows very strong feasibility, at the cost of a moderate maintenance energy cost for the cooling infrastructure.

11.0.2 Medium-Term Solutions (Translational Research)

If algorithmic control is not sufficient, a structural solution at the level of the polymer itself could be envisioned within a decade, eliminating the need for dynamic control.

- **Molecular Engineering and Xeno Nucleic Acids (XNA):** Using artificial nucleic acids (XNA), which introduce chemical modifications relative to natural DNA (such as L-DNA or modified sugars), makes it possible to create extremely robust genetic polymers. The pioneering work of Pinheiro et al. [9] demonstrated XNA's ability to preserve heredity while offering structural resilience far superior to nucleases and chemical degradation. By designing artificial nucleotides, it would be possible to alter the shape of the hydrogen bonds' potential wells. By creating a strongly asymmetric energy profile from the point of chemical synthesis onward, the potential barrier would become too high or too wide for proton tunneling to occur significantly. This passive solution would inherently stabilize the quantum information, although it still requires major advances in the speed and cost of synthesizing and sequencing these XNA molecules.

[1] Low-Density Parity-Check: a class of highly efficient linear error-correcting codes using bipartite graphs, originally designed for noisy telecommunications.

[2] Phonons: quanta of agitation or vibrational energy (similar to acoustic waves) traveling through the polymer's atomic structure, responsible for heat transmission.

11.0.3 Long-Term Solutions (Speculative)

Maintaining direct active control over the quantum state of biological data requires major conceptual leaps, whose application horizon remains speculative.

- **Weak Quantum Measurements:** Although the projective measurement of the classical Zeno effect is too energetic for our current sensors, fundamental research could turn toward weak quantum measurements. This theoretical concept, formalized by Aharonov et al. [17], relies on an extremely faint entanglement[1] between the observed system and an auxiliary system. This approach allows partial information to be gathered continuously without causing an abrupt collapse of the wave function, and above all without introducing the destructive photon energy of X-rays. While our technologies currently master these techniques only on simple, isolated optical or superconducting systems [15], the distant evolution of our capabilities in molecular nanophotonics could offer a form of non-invasive quantum feedback applicable to genetic engineering.

12. CONCLUSION AND RESEARCH AGENDA

The application of the quantum Zeno effect as a hardware error-correction system for storage DNA constitutes a physical paradox whose resolution eludes our contemporary technologies. We can summarize our conclusions in three key points.

1. **Structural incompatibility:** The photon energy required to localize a proton at the angstrom scale (12.4 keV) exceeds the covalent dissociation energy of the phosphodiester backbone (4.14 eV) by a factor of 3000, causing the immediate destruction of the molecular memory through radiolysis.
2. **Thermodynamic barrier:** The continuous projective measurement imposed by the Zeno cadence dissipates, by virtue of Landauer's principle, a minimum thermal power of 14.35 MW for a one-petabyte archive, completely invalidating the energy frugality of biological storage.
3. **Asymmetry of error budgets:** Proton tunneling generates an error rate of 10^{-8} per base, marginal compared to classical biochemical synthesis noise (10^{-2} per base).

This situation highlights an essential boundary between theoretical quantum computing and applied molecular engineering. The Zeno effect is an elegant concept exploitable by our equipment for isolated, cryogenic systems (such as quantum computers), where the environment is highly controlled. DNA, by contrast, is a dense macromolecular medium whose strength in retaining information lies precisely in not needing active control. Attempting to impose continuous quantum control on it would cancel out the entirety of its inherent advantages in volumetric density and energy frugality.

[1] Entanglement: a striking quantum phenomenon in which two particles form an indivisible linked system, where the state of one instantly determines the state of the other, regardless of the distance separating them.

Consequently, the priority research agenda for the DNA storage community should move toward the following recommendations.

- **Short term:** Favor the combination of cryogenic storage [10] and logical error-correcting codes (LDPC / Fountain) [11], which guarantee perfect data restoration while preserving DNA's volumetric density.
- **Medium term:** Invest in predictive modeling via artificial intelligence [12] to map tautomerization hotspots, as well as in XNA chemistry [9] to reduce the need for dynamic control through structural immunity.
- **Long term:** Relegate active quantum control approaches (such as weak measurements [17]) to speculative fundamental research, with no foreseeable industrial horizon for data archiving.

The integration of advanced logical error-correction codes, coupled with passive molecular engineering and inert storage [10], remains today the most rational, secure, and scientifically coherent approach.

REFERENCES

1. Church, G. M., Gao, Y., & Kosuri, S. (2012). Next-generation digital information storage in DNA. *Science*, 337(6102), 1628. https://doi.org/10.1126/science.1226355

2. Goldman, N., et al. (2013). Towards practical, high-capacity, low-maintenance information storage in synthesized DNA. *Nature*, 494(7435), 77-80. https://doi.org/10.1038/nature11875

3. Löwdin, P.-O. (1965). Quantum genetics and the aperiodic solid. *Advances in Quantum Chemistry*, 2, 213-360. https://doi.org/10.1016/S0065-3276(08)60076-3

4. Slocombe, L., Al-Khalili, J. S., & Sacchi, M. (2022). An Open Quantum Systems approach to proton tunnelling in DNA. *Communications Physics*, 5(1), 109. https://doi.org/10.1038/s42005-022-00881-8

5. Misra, B., & Sudarshan, E. C. G. (1977). The Zeno's paradox in quantum theory. *Journal of Mathematical Physics*, 18(4), 756-763. https://doi.org/10.1063/1.523304

6. Facchi, P., & Pascazio, S. (2008). Quantum Zeno dynamics: mathematical and physical aspects. *Journal of Physics A: Mathematical and Theoretical*, 41(49), 493001. https://doi.org/10.1088/1751-8113/41/49/493001

7. Bérut, A., et al. (2012). Experimental verification of Landauer's principle linking information and thermodynamics. *Nature*, 483(7388), 187-189. https://doi.org/10.1038/nature10872

8. Landauer, R. (1961). Irreversibility and Heat Generation in the Computing Process. *IBM Journal of Research and Development*, 5(3), 183-191. https://doi.org/10.1147/rd.53.0183

9. Pinheiro, V. B., et al. (2012). Synthetic genetic polymers capable of heredity and evolution. *Science*, 336(6079), 341-344. https://doi.org/10.1126/science.1217622

10. Grass, R. N., et al. (2015). Robust chemical preservation of digital information on DNA in silica with error-correcting codes. *Angewandte Chemie International Edition*, 54(8), 2552-2555. https://doi.org/10.1002/anie.201411378

11. Shannon, C. E. (1948). A Mathematical Theory of Communication. *The Bell System Technical Journal*, 27(3), 379-423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

12. Bar-Lev, D., Orr, I., Sabary, O., Etzion, T., & Yaakobi, E. (2025). Scalable and robust DNA-based storage via coding theory and deep learning. *Nature Machine Intelligence*, 7(4), 639-649. https://doi.org/10.1038/s42256-025-01003-z

13. Heckel, R., Mikutis, G., & Grass, R. N. (2019). A Characterization of the DNA Data Storage Channel. *Scientific Reports*, 9(1), 9663. https://doi.org/10.1038/s41598-019-45832-6

14. Organick, L., et al. (2018). Random access in large-scale DNA data storage. *Nature Biotechnology*, 36(3), 242-248. https://doi.org/10.1038/nbt.4079

15. Blais, A., et al. (2021). Circuit quantum electrodynamics. *Reviews of Modern Physics*, 93(2), 025005. https://doi.org/10.1103/RevModPhys.93.025005

16. Behler, J. (2016). Perspective: Machine learning potentials for atomistic simulations. *The Journal of Chemical Physics*, 145(17), 170901. https://doi.org/10.1063/1.4966192

17. Aharonov, Y., Albert, D. Z., & Vaidman, L. (1988). How the result of a measurement of a component of the spin of a spin-1/2 particle can turn out to be 100. *Physical Review Letters*, 60(14), 1351. https://doi.org/10.1103/PhysRevLett.60.1351

Further Reading *(not directly cited in the text, but relevant for context)*

- Facchi, P., & Pascazio, S. (2002). Quantum Zeno subspaces. *Physical Review Letters*, 89(8), 080401. https://doi.org/10.1103/PhysRevLett.89.080401

- Vinjanampathy, S., & Anders, J. (2016). Quantum thermodynamics. *Contemporary Physics*, 57(4), 545-579. https://doi.org/10.1080/00107514.2016.1201896