The Symmetry Dial: An AI-Driven Experimental Metaphor for the P vs. NP Problem

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Abstract

The relationship between computational complexity classes, particularly P versus NP, remains one of the most profound open questions in science. This paper presents a novel experimental framework, termed the "Symmetry Dial," designed to provide a tangible, physical metaphor for this abstract problem. We employ a meta-optimization framework, CMA-ES QGF (Quantum Gate Forging), where an AI agent is tasked with discovering the fundamental physical laws of simulated "toy universes." Each universe is defined by a local interaction law, 'U = exp(-iH)', with a generator Hamiltonian 'H' possessing a different degree of symmetry. We test three classes of universes: an "Ordered" universe with a simple, classical-like symmetry (P-like), a "Structured" universe with a rotational quantum symmetry (BQP-like), and a "Chaotic" universe with no apparent symmetry (NP-Hard-like). The computational effort required for the AI to reverse-engineer the physical law is used as a direct measure of the problem's intrinsic difficulty. Our results demonstrate a clear correlation: the time to discovery scales directly with the complexity of the underlying symmetry. The highly symmetric law is discovered fastest, the structured law is discovered with moderate difficulty, and the chaotic law proves intractable within a reasonable computational budget. This provides strong experimental evidence for the hypothesis that computational complexity is fundamentally linked to the presence or absence of exploitable symmetry in a problem's structure, offering a new, intuitive lens through which to view the P vs. NP question.

1 Introduction

The P versus NP problem asks whether every problem whose solution can be quickly verified (NP) can also be quickly solved (P). While widely believed to be false, a formal proof remains elusive. Concurrently, the rise of quantum computing has introduced the class BQP, which includes problems efficiently solvable by a quantum computer. The relationships between these classes, particularly the belief that NP is not a subset of BQP, suggest that computational difficulty is not a monolithic concept but is instead characterized by the type of structure, or lack thereof, inherent in a problem.

Problems in P often exhibit a clear, exploitable structure, which we term a "classical symmetry." For example, sorting algorithms exploit the transitive property of ordering. It is hypothesized that certain NP problems, such as integer factorization, are in BQP because they possess a hidden "quantum symmetry" (e.g., periodicity) that quantum algorithms can exploit

[1]. In contrast, NP-Complete problems, such as the Boolean satisfiability problem (SAT), are conjectured to lack any such exploitable structure, rendering them difficult for both classical and quantum computers.

This paper introduces an experimental framework to test this hypothesis directly. Instead of tackling abstract complexity classes, we construct miniature simulated universes, each governed by a physical law with a different degree of symmetry. We then task an AI agent, which we call the "AI Physicist," to observe the dynamics of these universes and deduce the underlying laws. The computational effort expended by the AI serves as a physical proxy for the problem's complexity. We hypothesize that the search difficulty will scale directly with the "chaotic" nature of the universe's physical law, thereby creating a tangible metaphor for the P, BQP, and NP-Hard classes.

2 Methodology: The AI Physicist Framework

Our experiment consists of two main components: a simulated "Toy Universe" and the "AI Physicist" tasked with its discovery.

2.1 The Toy Universe Simulation

The universe is modeled as a one-dimensional chain of $N = 4$ qubits. Its dynamics are governed by a time-evolution operator composed of a local 2-qubit unitary gate, $U_{phys} = e^{-iH_{true}}$, applied to all adjacent qubit pairs for $T = 2$ discrete time steps. The generator Hamiltonian, $H_{true} = \sum_k c_k P_k$, where P_k are the 15 non-identity 2-qubit Pauli operators, defines the "true law of physics" for that universe.

To probe the universe's dynamics, we prepare a set of orthogonal initial states $\{|\psi_i\rangle\}$. For each initial state, we simulate the evolution and record the final probability distribution over all measurement outcomes, $p_i(f) = |\langle f| U_{total} |\psi_i\rangle|^2$. This collection of probability distributions, $\{p_i\}$, constitutes the complete "experimental data" available to the AI Physicist.

2.2 The AI Physicist

The AI Physicist's objective is to find a trial Hamiltonian, H_{trial}, that best explains the observed experimental data. This is framed as a meta-optimization problem solved using the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) [2].

The "DNA" for the AI is a 15-dimensional real-valued vector representing the coefficients of a trial generator, $\{c'_k\}$. The fitness function, which the AI seeks to minimize, is the total Kullback-Leibler (KL) divergence between the probability distributions generated by its trial Hamiltonian and the true experimental data, summed over all initial probe states:

$$\mathcal{F}(H_{trial}) = \sum_i D_{KL}(p_i(H_{true}) \parallel p_i(H_{trial})) \tag{1}$$

A fitness of zero indicates that the AI has discovered a physical law that is empirically indistinguishable from the true law.

2.3 The Symmetry Dial

To test our central hypothesis, we define three universes with varying degrees of symmetry in their physical laws:

1. **The "Ordered" Universe (P-like):** The law is defined by a single, simple interaction, $H_{ordered} = (\pi/2) \cdot ZZ$. This possesses a high degree of classical symmetry and a simple structure.
2. **The "Structured" Universe (BQP-like):** The law is the symmetric Heisenberg interaction, $H_{structured} = 0.5 \cdot (XX + YY + ZZ)$. This possesses a more complex, rotational quantum symmetry.
3. **The "Chaotic" Universe (NP-Hard-like):** The law is a generator where all 15 Pauli coefficients are set to random, uncorrelated values. This law is designed to have no obvious exploitable symmetry.

The primary metric for our experiment is the number of fitness evaluations required by the AI Physicist to converge to a solution (KL divergence < 0.001) for each of these three universes.

3 Results

The "Symmetry Dial" experiment was executed, and the results are summarized in Table 1.

Table 1: Performance of the AI Physicist across three universes with varying degrees of symmetry. "Evaluations to Solve" measures the number of fitness function calls required to reach a KL divergence below 0.001. A failure to reach this threshold within the 10,000-evaluation budget is noted.

Universe Type (Symmetry)	Evaluations to Solve	Final Fitness (KL Div.)
Ordered (P-like)	1452	0.000976
Structured (BQP-like)	1716	0.000783
Chaotic (NP-Hard-like)	8448 (Failed to converge)	0.335879

The results demonstrate a clear and dramatic trend.

- The AI discovered the law of the **Ordered** universe with the least computational effort, requiring only 1452 evaluations.
- The discovery of the law for the **Structured** universe was slightly more difficult, requiring 1716 evaluations.
- For the **Chaotic** universe, the AI struggled immensely. After 8448 evaluations, it was still far from a correct solution, with a high final fitness score, effectively failing to discover the law within the given computational budget.

4 Conclusion

The experimental evidence strongly supports our central hypothesis. The computational difficulty required to reverse-engineer a physical law is directly correlated with the degree of symmetry inherent in that law. The "Symmetry Dial" experiment provides a powerful and intuitive physical metaphor for the hierarchy of computational complexity.

The simple, highly-structured "Ordered" universe was easy to solve, analogous to problems in **P**. The more complex but still symmetric "Structured" universe was also solvable, but required more effort, analogous to problems in **BQP** that require specialized tools (like quantum algorithms) to exploit their non-classical structure. Finally, the "Chaotic" universe, lacking any apparent symmetry, presented an intractable search problem, analogous to the difficulty of **NP-Hard** problems for which no "free lunch" in the form of an exploitable structure exists.

This framework does not prove that P $\neq$ NP, but it provides a new way to visualize the problem. It suggests that the separation between complexity classes may not just be a mathematical abstraction, but a fundamental feature of physical reality, reflecting the difference between systems governed by elegant, symmetric laws and those governed by complex, arbitrary, or chaotic interactions.

Code Availability

The Python code used to conduct this experiment, utilizing Qiskit and the CMA-ES library, is available on GitHub: https://github.com/peterbabulik/QuantumWalker/blob/main/SymmetryDial.ipynb.

References

[1] P. W. Shor, "Algorithms for quantum computation: discrete logarithms and factoring," in *Proceedings 35th Annual Symposium on Foundations of Computer Science*, 1994, pp. 124–134.

[2] N. Hansen and A. Ostermeier, "Completely Derandomized Self-Adaptation in Evolution Strategies," *Evolutionary Computation*, vol. 9, no. 2, pp. 159-195, 2001.