

# Quantum-Inspired Models for Cellular Signaling Networks and Energy Transfer Efficiency in Biological Systems

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**Abstract**—Understanding how living cells move information and energy so quickly and efficiently is a key question in modern biophysics. In this project, I use quantum-inspired computational models to study cellular signaling networks and energy transfer pathways. The main idea is to treat signaling molecules like “walkers” on a graph and compare how signals spread under classical rules versus quantum-inspired rules. Using Python, I built simple graph-based simulations of signaling and energy transfer. In the quantum-inspired version, nodes can be in superposed states and transitions are probabilistic, similar to quantum walks. I then compared how fast and how reliably signals reach target nodes in the two cases. The results suggest that quantum-inspired dynamics can support faster and more robust signal propagation, echoing coherence effects reported in photosynthetic complexes. I also reviewed recent work in quantum biology, biophotonics, and molecular computation to relate the simulations to real biological systems. Finally, I briefly reflect on ethical and societal questions that arise when quantum ideas are applied to biology and cognition. Overall, the project shows how quantum-inspired models can deepen our understanding of biological communication and open new directions in biomedical engineering and computational science.

■ Living systems show impressive efficiency in transmitting information and transferring energy at the molecular scale (Yuan et al., 2025). From photosynthetic complexes to neural signaling, these processes rely on large networks of interacting molecules. Classical biochemical models can explain many features,

but often struggle to capture the extremely high precision, low energy loss, and near-instant synchronization observed in real cells (Guan & Liu, 2025).

Recent work in quantum biology suggests that some biological processes may use quantum-like effects such as coherence, tunneling, or entanglement to improve efficiency (Kwon & Kim, 2025; Lorenzoni et al., 2025). This motivates the use of quantum-inspired models as a way of thinking about cellular signaling

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and energy transfer. Instead of proving that biology is “fully quantum,” the goal here is more modest: to see whether quantum-inspired rules in networks can reproduce some of the speed and robustness seen in nature.

In this project, I focus on quantum walk–style dynamics on graphs as analogs for signaling and energy transfer. By comparing classical and quantum-inspired simulations and connecting them to results from quantum biology and computational neuroscience (Chung, 2025; Youvan, 2025; Marengo & Santamato, 2025), the project explores how these models might help explain biological efficiency and inspire new computational approaches.

## Methods

### Quantum-Inspired Network Modeling

Cellular signaling and energy transfer were modeled as graph-based networks, where nodes represent molecular states or locations (e.g., proteins, complexes, or compartments), and edges represent possible transitions. Two types of dynamics were considered:

- Classical diffusion–like dynamics: signals move step by step according to fixed transition probabilities.
- Quantum-inspired dynamics: signals follow rules similar to discrete-time quantum walks, where nodes can be in superposed states and transitions are probabilistic and interference-like. The goal was not to implement a full quantum simulator, but to capture key features such as superposition and interference in a simplified way.

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### Python-Based Simulations

All simulations were implemented in Python. For each network:

- A graph structure was defined (adjacency matrix or edge list).
- Initial conditions were set by placing a “signal” at one or more source nodes.
- Time steps were simulated under both classical and quantum-inspired rules.
- At each step, the probability (or amplitude-derived probability) of finding the signal at each node was recorded.

Metrics such as time to reach a target node, distribution spread, and robustness to perturbations (e.g., removing edges) were compared between the classical and quantum-inspired versions.

### Literature Review and Conceptual Alignment

A focused literature review was performed on:

- Quantum biology and quantum effects in photosynthesis and living materials (Yuan et al., 2025; Lorenzoni et al., 2025),
- Quantum-inspired computation and its links to biology and healthcare (Kwon & Kim, 2025; Marengo & Santamato, 2025; Youvan, 2025),
- Neural and stochastic modeling of signaling and disease (Chung, 2025; Guan & Liu, 2025).

These sources were used to interpret the simulation results and to check whether the behavior seen in the models is at least qualitatively consistent with experimental and theoretical work in biological systems.

## Results

### Signal Propagation in Classical vs Quantum-Inspired Models

In the classical simulations, signals tended to spread gradually across the network, with clear diffusion-like patterns. Reaching distant target nodes typically required many steps, and blocking a key edge could strongly reduce performance.

In the quantum-inspired simulations, signals often reached target nodes in fewer steps. Because of superposed states and interference-like effects, multiple paths were explored effectively at once, similar to quantum walks. In some network structures, this led to:

- Shorter average hitting times to target nodes,
- More balanced distributions across parallel pathways, and
- Better recovery when certain edges were removed.

### Energy Transfer Analogies

When models were tuned to resemble energy transfer in systems like photosynthetic complexes, the quantum-inspired dynamics showed patterns that echo reported coherence effects in the Fenna–Matthews–Olson (FMO) complex (Lorenzoni et al., 2025). In particular, maintaining moderate levels of “decoherence” in the model sometimes improved transfer efficiency, matching the idea that a mix of

coherence and noise can be beneficial in biological environments.

## Discussion

### Implications for Biological Efficiency

The simulations suggest that quantum-inspired rules on networks can reproduce some of the speed and robustness seen in biological signaling and energy transfer. This supports the idea that quantum-like mechanisms might help explain why certain cellular processes are so efficient, even if real cells do not implement perfect quantum walks.

These findings are consistent with broader work in quantum biology and engineered living materials, which also point to structured networks and coherent-like dynamics as key ingredients in efficient energy and information flow (Yuan et al., 2025).

### Links to Neural and Computational Models

The project also highlights parallels between quantum networks and artificial neural networks or stochastic models used in neuroscience (Chung, 2025; Youvan, 2025). Quantum-inspired architectures could influence future designs of learning algorithms and brain-inspired computing, especially in tasks where fast, reliable propagation across complex graphs is needed.

### Ethical and Societal Considerations

Applying quantum paradigms to biology and cognition raises ethical and philosophical questions. Overinterpreting quantum models could lead to misleading claims about consciousness or “quantum brains.” It is important to be clear about what the models actually show, to respect data limits, and to consider how such ideas might be used in medicine, AI, or neurotechnology.

## Conclusion

This project uses quantum-inspired network models to study cellular signaling and energy transfer in biological systems. Python-based simulations show that quantum-like rules can support faster and more robust signal propagation than simple classical diffusion, while literature from quantum biology and computational science provides real-world context.

Although the work is conceptual and does not prove that cells use full quantum computing, it demonstrates how quantum-inspired thinking can deepen our

understanding of biological efficiency. It also points toward future research in quantum biology, biomedical engineering, and brain-inspired computation, where such models might guide new algorithms and technologies.

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