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[Yehuda Roth](#) *

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Article

A Quantum-Inspired Model of Stem Cell Differentiation

Yehuda Roth

Science Department, Oranim College of Education, Tivon 3600600, Israel; yehuda_r@oranim.ac.il

Abstract

We propose a quantum-like model to describe stem cell differentiation, treating the undifferentiated stem cell as a superposition of its potential differentiated states. The process of differentiation is then modeled as a quantum-like collapse, analogous to measurement in quantum mechanics. This approach offers a novel conceptual framework for capturing the probabilistic and context-dependent nature of cell fate decisions. This formalism may also apply to other biological systems governed by probabilistic and context-sensitive transitions.

Keywords: quantum collapse; quantum model describing differentiation of stem cells

1. Introduction

Historically, the formalism of quantum mechanics was believed to apply only at scales shorter than the coherence length—such as subatomic dimensions or temperatures near absolute zero—while macroscopic systems beyond this scale were treated as classical [1–3]. However, increasing evidence suggests that certain biological systems may exploit quantum-like features, such as coherence and superposition, even under ambient physiological conditions. Notably, quantum coherence has been implicated in processes such as photosynthetic energy transfer, enzyme catalysis, and avian magnetoreception [4–6]. These findings challenge the traditional boundary between quantum and classical domains and motivate the exploration of quantum-like frameworks in modeling biological phenomena.

In this theoretical study, we extend this perspective by modeling stem cell differentiation using quantum-like tools, treating the undifferentiated stem cell as a coherent superposition of its potential differentiated states.

We focus on a simplified case—a two-dimensional conceptual space—representing pluripotent stem cells that possess the potential to develop into a wide variety of cell types. As a specific example, we consider bipotent stem cells, which can differentiate into two distinct lineages, such as hepatoblasts developing into either hepatocytes or cholangiocytes [7,8].

2. Conceptual Ideas and Analogy

Pluripotent stem cells can give rise to nearly any cell type, while bipotent stem cells differentiate into two specific lineages—for example, hepatoblasts that form either hepatocytes or cholangiocytes [7,8]. Bipotent differentiation is a process wherein a progenitor cell, such as a hepatoblast, is capable of differentiating into two distinct lineages, depending on specific signaling cues and environmental conditions [9].

A striking conceptual parallel exists between this biological phenomenon and quantum mechanics. Just as identical quantum particles remain indistinguishable until measured, stem cells are phenotypically similar prior to differentiation. Before commitment, the progeny of a stem cell are indistinguishable, aligning with the idea of a stem cell being in a superposition of potential fates. The act of differentiation resembles quantum collapse, wherein an external influence resolves the system into a specific outcome. In general, this probabilistic process mirrors the collapse of a quantum superposition, as seen in spontaneous measurements like nuclear decays.

Here, we introduce a quantum-inspired operator formalism to model stem cell fate decisions. In this framework, external biochemical or mechanical signals play a role analogous to quantum measurements, triggering a collapse from a coherent multipotent state into a committed lineage. We define a hypothetical operator $\hat{F}$, whose eigenvalues encode lineage biases and whose action maps the stem cell’s potential into discrete cell fates.

It is important to emphasize that this approach does not propose literal quantum processes within cells, but instead adopts the formal structure of quantum theory to represent the inherently probabilistic and context-dependent nature of biological decision-making. The analogy allows us to draw systematic parallels between quantum phenomena and stem cell behavior, as summarized in Table 1.

Table 1. Conceptual parallels between quantum mechanics and stem cell biology.

Feature	Quantum Mechanics	Stem Cell Biology
Object being observed	Identical particles (e.g., electrons)	Identical progenitor cells (e.g., hepatoblasts)
Non-collapse state	Superposition of entangled states	Coherent multipotency
Collapse trigger	Measurement interaction	Differentiation cue (e.g., Wnt/Notch signaling)
Post-collapse state	Defined eigenstate	Committed cell type
Context-dependence	Measurement basis influences outcome	Microenvironmental signals influence fate

To further develop this analogy, we integrate both structural and dynamical aspects of stem cell populations with key quantum concepts such as entanglement, decoherence, criticality, and measurement-induced collapse. While stem cells within a population may initially appear identical, their fate decisions are influenced by shared signaling environments, collective interactions, and noise-sensitive thresholds. These behaviors conceptually parallel the quantum dynamics of entangled particles, coherence loss, and probabilistic measurement outcomes. Moreover, both systems exhibit nuanced thermodynamic behavior: although quantum collapse can reduce the entropy of the observed subsystem, it typically increases global entropy and may involve heat exchange with the environment [10]. Similarly, cell differentiation reduces transcriptomic uncertainty but is accompanied by increased metabolic activity and entropy production [11,12]. Table 2 summarizes these extended analogies and their relevance to biological state transitions.

Table 2. Structural and dynamical analogies between quantum and stem cell systems.

Conceptual Feature	Quantum Mechanics	Stem Cell Systems
Object being observed	Identical particles	Identical stem cells
Non-coherent objects	Act independently, not entangled	Bacteria act independently
Entanglement / Coherence	Particles in collective quantum state	Collective oscillations, shared signaling
Collapse trigger	Measurement collapse	Signal-triggered lineage commitment
Decoherence and pointer states	Environment selects outcomes	Microenvironment/niche cues
Superposition/collapse	Probabilistic resolution	Multipotency collapses into identity
Bifurcation/criticality	Critical slowing, coherence loss	Differentiation at thresholds
Stochastic collapse	Noise and interactions	Biochemical noise drives fate choice
Measurement reversibility	Partial “un-collapse”	iPSC reprogramming reverses commitment
Basis dependence	Measurement basis determines outcome	Spatial/temporal cues bias fates
Entropy/thermodynamic cost	Heat, increased entropy [10]	Metabolic/entropy increase [11,12]

In summary, the quantum-inspired formalism offers a structured framework for modeling differentiation as a transition from a coherent, multipotent state to a committed lineage identity.

3. Biological Rationale for Coherence and Collapse in Stem Cell Fate

While the quantum analogy provides a compelling lens through which to view stem cell dynamics, it is essential to assess whether quantum concepts—superposition, coherence, collapse—have biologically meaningful counterparts. This section addresses that challenge by articulating mechanistic parallels that justify the use of coherence-like behavior in undifferentiated stem cells and collapse-like transitions during fate determination.

- 1. *Indistinguishability*: Pre-commitment, stem cells are nearly identical—mirroring pre-measurement quantum systems.
- 2. *Predictability*: Differentiation is probabilistic, not deterministic, for individual cells [13,14].
- 3. *Absence of environmental measurement*: Coherence is maintained in the absence of fate-defining cues.
- 4. *Collective dynamics*: Oscillatory gene expression in undifferentiated populations reflects coherence [15].
- 5. *Signal-induced collapse*: Differentiation occurs only when instructive cues project the cell into a definite fate.

Table 3. Quantum-inspired justification for coherence in undifferentiated stem cells.

Quantum Concept	Stem Cell Analog	Justification
Superposition	Multipotency	Multiple fate potential
Indistinguishability	Genetic/phenotypic similarity	Pre-committed cells indistinguishable
Coherence	No lineage cues	Maintains undecided state
Collapse	Fate cue as measurement	Commits to a specific lineage

In summary, this quantum-inspired framework provides a conceptual scaffold for the probabilistic and context-sensitive nature of stem cell fate decisions.

4. The Model

Each stem cell is represented by a quantum-like state $|S\rangle$, corresponding to its undifferentiated, multipotent condition. The potential differentiated outcomes are denoted by a set of orthonormal basis states $|L\rangle_i$, where i indexes distinct lineages. We consider a two-dimensional (bipotent) case:

$$|S\rangle = A_1|L\rangle_1 + A_2|L\rangle_2,$$
(1)

with $|A_1|^2 + |A_2|^2 = 1$. The amplitudes A_1 and A_2 depend on the cell’s identity and its signaling microenvironment. Fate commitment is modeled as a measurement-like operator:

$$\mathbb{M} = \lambda_1|L\rangle_1\langle L|_1 + \lambda_2|L\rangle_2\langle L|_2,$$
(2)

where λ_1, λ_2 are observable values associated with each fate (e.g., differentiation efficiency).

This operator framework enables modeling context sensitivity, reversibility, and quantitative transitions.

5. Discussion

This quantum-inspired formalism provides a new lens for interpreting the probabilistic nature of stem cell differentiation. Unlike decision tree models that assume deterministic progression, our model describes each cell as a superposition, with commitment as projection by environmental cues.

This abstraction allows for encoding context sensitivity (via amplitudes A_1, A_2), intrinsic process stochasticity, and the possibility of reversibility (e.g., reprogramming to iPSC state).

For experimental biologists, relative frequencies of differentiation outcomes can be used to estimate the amplitudes A_i . If the distribution remains stable under identical conditions, the amplitudes are considered constant. Assigning observables λ_i to eigenstates $|L\rangle_i$ connects mathematical models to biological measurements.

This approach does not claim that quantum physics operates in stem cells, but uses quantum mathematics to model biological processes classical in nature.

6. Methods

No experimental methods were employed. All results derive from theoretical modeling and conceptual analysis.

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Conflicts of Interest: The author declares no conflicts of interest.

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