International Society of the Learning Sciences

From Molecules to Ecosystems: Scientists' Conceptualizations of Dynamic Equilibrium

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Abstract: The study investigates whether Dynamic Equilibrium (DE) can serve as a "powerful idea" (Papert, 1980) that bridges phenomena across STEM fields. Through semi-structured interviews with five scientists, we identified three themes: DE was rarely used explicitly but appeared across fields; reflection on DE prompted a more generalized framing; and DE spanned scales from molecules to human populations. These findings suggest DE's potential as a cross-cutting concept that connects otherwise fragmented content in STEM education.

Purpose

Integration across scientific disciplines is crucial for addressing complex issues in both scientific research (National Research Council, 2014) and science education (NGSS Lead States, 2013). For such integration, Papert (1980) coined the phrase "powerful ideas"— concepts that connect seemingly disparate phenomena and provide new ways of perceiving the world. Here, we revisit powerful ideas in the context of dynamic equilibrium (DE), a concept evident in various scientific domains.

Dynamic Equilibrium (DE) is defined as a state in which the inflows and outflows of a system vary over time, yet the levels of stocks remain stable (Meadows, 2008). Examples include homeostasis in biology and predator-prey interactions in ecology—phenomena common in K-12 curricula. However, learners often struggle to grasp that systems can be both dynamic and stable (Zion & Klein, 2015), and fragmented treatment of DE across domains may contribute to this difficulty. We interviewed scientists from various STEM fields to explore the potential of DE as a scientifically grounded cross-cutting concept. Our research was guided by the following questions:

RQ1. How do expert scientists define and conceptualize DE?
RQ2. What are the commonalities and distinctions among scientists and their respective STEM fields in their conceptualizations of DE?

Methods

This interview study is part of a larger research project aimed at developing a cross-disciplinary definition and computational representations of Dynamic Equilibrium (DE).

We invited 18 U.S.-based scientists from various STEM fields based on their prominence, determined by membership in honorary societies such as the American Academy of Arts and Sciences and the National Academy of Sciences. At the time of writing, six accepted the invitation, and interviews were completed with five: biology (n = 2), chemistry (n = 1), material science (n = 1), and epidemiology (n = 1) (2).

Semi-structured Zoom interviews focused on DE phenomena in the participants' work, definitions of DE, and its usage in their field. Interviews lasted 30–60 minutes and were video-recorded with consent.

Data were analyzed using thematic analysis (Braun & Clarke, 2021). Two researchers inductively coded the transcripts, and all members reviewed the final analyses. This paper focuses on scientists' verbal conceptualizations and examples of DE.

Findings

The findings revealed expert scientists' conceptualizations and articulation of DE across various STEM fields, including ecology, neuroscience, biology, chemistry, and engineering/material science.

Theme 1. Domain-specific discourse of the concept

The term dynamic equilibrium was typically not a prominent part of the scientists' professional discourse nor an explicitly defined topic within their pedagogical practices. Instead, when dynamic equilibrium appeared, it was closely tied to specific phenomena of interest within their areas of focus. This domain-specific framing was evident in response to general questions. For example, when asked, "Is there a clear and agreed-upon understanding of DE in your domain?” participants tended to ground their responses in specific phenomena without addressing the general concept they were asked about. A neuroscientist remarked, “Well, we don’t understand the details of *major depression* [as a case of disequilibrium] right,” focusing on the specific biological mechanisms rather than the broader DE concept. Overall, while scientists acknowledged DE’s relevance, their discourse remained tied to domain-specific content rather than explicitly articulating DE as a general concept.

Theme 2. Fluidity in conceptualizations: Toward generality

A notable question is whether scientists’ thinking about the relationship between Dynamic Equilibrium (DE) and their field was static or fluid. Could participating in this study have influenced scientists’ conceptualizations of DE toward greater generality? In one case, a biologist “Anne” (pseudonym) initially expressed skepticism about DE’s relevance to her work, but she was willing to provide several examples of DE phenomena based on what she described as her "superficial" understanding of the term. Later, when the interviewer echoed her doubt, Anne responded: “Well, I want to make a correction. The concept of dynamic equilibrium is part of everything we teach when we’re talking about behavior. Irrespective of whether the phrase 'dynamic equilibrium' crossed my lips, the concept of a system of interconnected loops with feedforward and feedback, excitation, inhibition, activation, suppression—that is biology. That is how biology works, and that's what we all teach.” By the end of the interview, Anne’s conceptualization of dynamic equilibrium had broadened to social systems, such as a teacher balancing social interactions in a class with students facing different challenges. This case suggests that reflective dialogue can prompt scientists to recognize DE as more broadly relevant than they initially assumed.

Theme 3. Implicit cross-disciplinary patterns

Across interviews, DE emerged as a concept relevant to phenomena at multiple scales—from molecular processes to population-level dynamics (see Table 1). DE was consistently described as stability maintained by opposing processes. Even without direct prompting, scientists emphasized the consequences of disrupted equilibrium. These included undesirable outcomes such as thermoregulatory failure (e.g., freezing), seizures from imbalances in neuronal excitation and inhibition, material failure under excessive stress, and ecological disruptions like climate change. In other cases, disruption was necessary for function, such as action potentials triggered by changes in membrane potential. These examples demonstrate that DE spans disciplines and scales, consistently involving opposing forces whose balance creates stability—while both maintenance and disruption serve as meaningful states across fields.

Table 1
Dynamic Equilibrium Across STEM Disciplines

Scale	Equilibrium State	Phenomena	Dynamic Processes
Molecular	fixed value of molecule concentration	chemical equilibrium	forward vs reverse reactions
Cellular	narrow range of voltage values	resting membrane potential in neurons	ion exchanges; diffusion vs electrostatic force
Organismal	narrow range of temperature values	homeostasis of body temperature	shivering vs sweating
Population of species	oscillatory infection rates	spread of diseases	infection vs vaccination and immunity
Engineering	optimization of material properties	material production	stress vs. resistance, optimization constraints

Discussion

The study explored how Dynamic Equilibrium (DE) was conceptualized by five scientists from different fields. Although the project began with a system dynamics definition of DE, the findings suggest no single definition captures all cases. “Equilibrium” ranged from fixed values to oscillations; “dynamic” included both discrete and continuous processes. DE seems to exhibit family resemblance (Wittgenstein, 1953)—connected by overlapping similarities rather than a single essential feature. Future work should identify whether this conceptual flexibility can support both domain-specific interpretation and cross-disciplinary understanding.

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Acknowledgments

This research was supported by NSF-BSF grant 2240216.

