

Editorial

From reductionism to integration: The evolving landscape of biological research

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For more than a century Biology has been progressing in the light of reductionism. We have broken down complex living systems into genes, proteins, cells and pathways, creating an amazing body of knowledge that is the basis of modern life sciences. There are few scientific strategies as fruitful, or as revolutionary. Reductionism has given clarity, precision, and mechanistic insight, and is essential to experimental rigor (Rosenberg, [2007](#); Treberg et al., [2020](#)).

But, the success of reductionist biology has created a turning point. The study of parts has become less of a way to help solve biological problems and more of a way to study parts that are tied to real-world problems, making it clearer than ever that knowledge of parts alone does not enable one to understand life as it exists in the real world. What we face is the problem of how to incorporate reductionism into a wider conceptual framework that accounts for interaction, dynamics and emergence (Kesić, [2024](#)).

This piece contends that biology is not just expanding its method but evolving, from a purely 'parts' science to a 'systems', 'relationships' and 'contexts' science.

The Reductionist Legacy—and Its Blind Spots

Biological research, its design, interpretation and rewards, have been affected by reductionism (Rocca and Anjum, [2020](#)). They are adept at working in a controlled environment where factors can be isolated and cause and effect understood in linear sequences. This paradigm is particularly useful in molecular biology, biochemistry and pharmacology, where individual mechanisms are now easily dissociable from each other (Van Regenmortel, [2004](#); Treberg et al. [2020](#)).

Many of today's most pressing biological issues are not so easily reduced though. Complex diseases are not caused by any single molecular defect, but by complex network interactions that are affected by genetic polymorphisms, environmental exposures, developmental history, and temporal changes (Craig, [2008](#)). On a similar note, biological response to environmental stressors such as chemical mixtures, engineered nanomaterials or chronic low dose exposure can be non-linear and context dependent, thus defying the traditional toxicological model (Wu et al., [2023](#)).

The constraint, thus, is not technical in nature, but conceptual. Reductionism has difficulty when the biological meaning comes out of the interaction of elements, when the action is not strictly linear and when results are scale and context dependent (Rosenberg, [2007](#)). It is not that these are unique, but rather they are

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characteristic properties of living things. Biological understanding is increasingly shaped by interactions across scales rather than isolated components (Figure 1).

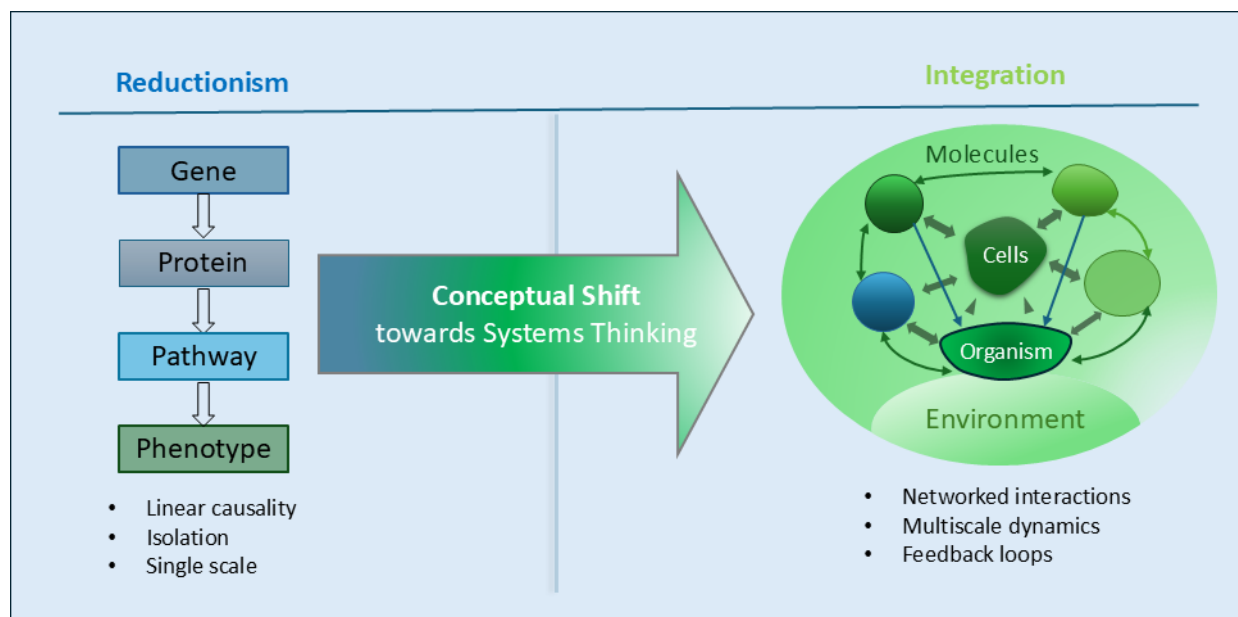


Figure 1. Conceptual evolution of biological research from reductionist, linear models toward integrative, multiscale frameworks emphasizing interactions, feedback, and context-dependent behavior.

Integration as a Scientific Necessity, not a Trend

Technology driven by multi-omics platform, single cell, advanced imaging, and artificial intelligence are often cited as the driver behind the growing focus on integration (Camps et al., 2025; Hsu et al., 2026). These tools have certainly helped to speed up the work of integrative research but they do not make it necessary. Instead, they have revealed that frameworks that hold complexity as the experimental noise and see it as a biological signal are inadequate (Lim et al., 2024).

Integrative biology aims to bridge the gap from molecular processes to cellular behavior, organismal physiology and environment. It includes systems-level thinking, network dynamics and multiscale analysis (Urbanski et al., 2019). Importantly, it recognizes that the properties of biological systems are emergent, that is, those properties that emerge from a collection of parts that can't be predicted from the parts alone (Cavigelli et al., 2021).

This transition is from an old notion that the deeper the resolution, the deeper the understanding. Often, the gaining of knowledge is not through the act of reduction, but synthesis.

A Conceptual Shift That Challenges Scientific Comfort Zones

Integration isn't just adding on, it's disrupting. It challenges scientific habits that are deeply entrenched, such as our tendency to simple causal explanations, hypotheses that are narrowly framed and to control experiments to sacrifice realism (Hoffmann and Vienni-Baptista, 2026). Integrative approaches sometimes provide probabilistic insight, sometimes models, sometimes patterns, instead of answers.

This is no ordinary pain. It involves basic questions of epistemology of biology, dealing with the validation of knowledge and the handling of uncertainty as well as the definition of scientific success. Interdisciplinary scientific research is often done in teams, and many scientists are required to be able to work with computers and deal with uncertainty—these aspects of research are not always valued in traditional academic environments (Durrive, [2012](#); Morrante and Rossi, [2016](#)).

These tensions need to be faced by the scientific community rather than being squeezed into reductionistic concepts if integration is to be more than just a rhetorical aim.

Implications for Environmental and Health-Related Research

Environmental and health sciences are probably most urgent fields for integration. Environmental context is not an independent variable in human biology, but is often ignored as if it were. The exposome, One Health and planetary health highlight the fact that health is the result of enduring, cumulative and synergistic effects (Wu et al., [2023](#)).

Reductionist toxicology has provided much needed mechanistic insights but has also failed to predict real-world settings involving low dose, chronic and mixed exposures (Ottinger and Geiselman, [2025](#)). Likewise, nano-toxicology has shown that the properties of the materials, their biological context and the time dimension are mutually dependent and cannot be easily categorized (Kumar et al., [2025](#)).

Integrative approaches provide a more realistic view of biological responses, but also require a new paradigm of thinking about causality, risk and uncertainty. These issues are not only methodological, but epistemological as well.

The Role of Journals in Shaping Integrative Science

Scientific journals play a unique role in the changing environment. The policies of the editor also affect the content that is published, and indeed the value of that content. For integrative research to flourish, structures for publishing should change to reflect that.

This involves understanding the need for interdisciplinary research, systems-level analysis, confirming research and methodological transparency (Casadevall et al., [2024](#)). It also means being able to resist the urge of trying to make the novel rather than the coherent or the mechanistic the most important point.

It is the responsibility not only of journals to be places of information, but also of synthesis, discussion, and conceptual progress for those that are committed to integrative science (Seeber, [2024](#)).

Training for a Complex Biological Future

One of the most significant consequences of this change is in terms of the education of future scientists. The depth of discipline is still important but not enough. The upcoming generation of biologists needs to learn how to deal with complex systems, understand multi-scale data, and be able to communicate among disciplines (Padilla and Grünbaum, [2024](#)).

This calls for a rethinking of education, mentoring and assessment, not to dilute but to broaden scientific vision. An intellectual flexibility is as essential to a science of life as it is to the technical aspects.

A Critical Moment for Reflection

The move from reductionism to integration does not mean that it is a linear movement or the substitution of one paradigm for another. Both are necessary and their fecund strain has been responsible for much of biology's achievement. It's not a problem with reductionism itself; it's the idea that reductionism is okay for everything.

Intangible inertia nurtures a cost, particularly as biological research becomes more involved with social, environmental and planetary issues. The issue at hand is not if integration is needed, it is whether the scientific creativity is ready to fully embrace the implications.

This brings us to an important question for the scientific community: can we adjust to a world of complexity, not one we need to simplify away, but one that we must embrace – perhaps even one that requires us to rethink the nature of scientific understanding, the way we design experiments and evaluate evidence?

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