Universal Biology: A Physicist's Approach to 'What Is Life?' via Macro-Micro Consistency Principle

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Living systems are complex and hierarchical, with diverse components at different scales, yet they sustain themselves, grow, and evolve over time. Here we note that for a hierarchical biological system to be robust, it must achieve consistency between micro-scale (e.g., molecular) and macro-scale (e.g., cellular) phenomena, which allows for a universal theory of adaptive changes in biological systems. The talk will present a demonstration of how adaptive changes in high-dimensional phenotypes (biological states) are constrained to a low-dimensional manifold as a consequence of macroscopic robustness and plasticity acquired through evolution. This dimensional reduction leads to a macroscopic law for cellular states, as confirmed by bacterial adaptation experiments. The theory is then extended to evolution and development, leading to the evolutionary fluctuation-response relationship, akin to thermodynamics, and proportionality between phenotypic variations due to environmental adaptation and genetic changes, as are also verified experimentally. Finally, we extend this argument to learning in neural systems, resulting in a learning-fluctuation relationship. Overall, this talk highlights the potential of physics for the study of biology through a universal perspective based on macro-micro consistency in hierarchical living systems.

References:

Kaneko, K. (2024) "Constructing universal Phenomenology for biological cellular systems: An idiosyncratic review on evolutionary dimensional reduction", Journal of Statistical Mechanics: (JSTAT) 024002

Furusawa, C., Kaneko, K. (2018) "Formation of Dominant Mode by

Evolution in Biological Systems", Physical Review E 97, 042410

Kaneko, K., Furusawa, C. (2018) "Macroscopic Theory for Evolving Biological Systems Akin to Thermodynamics", Annual Review of Biophysics 47, 273-290.

Sakata, A., Kaneko, K. (2020) "Dimensional Reduction in Evolving Spin-Glass Model: Correlation of Phenotypic Responses to Environmental and Mutational Changes", Physical Review Letter 124, 218101.

Tang Q-Y., Kaneko, K. (2021) "Dynamics-evolution correspondence in protein structures", Physical Review Letter 127, 098103

Kaneko, K. (2024). "Dimensional reduction and adaptation-development-evolution relation in evolved biological systems", Biophysical Reviews 16(5), 639-649.

Kurikawa, T., Kaneko, K., (2025). "Fluctuation-learning relationship in recurrent neural networks". Nature Communications 16(1), 9663.

Kaneko, K. (2025) "Universal Biology", Cambridge University Press