

Evolution of Energy Metabolism

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Metabolism is a fundamental property of life, ensuring the transformation of matter and energy within biological systems. Despite the immense diversity of living organisms, core metabolic pathways, cofactors, and regulatory principles exhibit a remarkable degree of evolutionary conservation.

Among metabolic processes, energy metabolism — the integrated system of catabolic and anabolic reactions, occupies a central position. Life, as it exists on Earth and likely in any conceivable form, requires tightly regulated chemical reactions that are energetically constrained. Consequently, biological systems must not only acquire and utilize energy but also store it in chemically accessible forms. Key components of energy metabolism include carbon fixation pathways, carbohydrate metabolism, ATP synthesis, and associated redox processes.

In this paper, the evolution of metabolism is examined not as a series of contingent historical events, but as a process strongly constrained by fundamental biochemical laws. Drawing on comparative biochemistry, genomics, prebiotic chemistry, and systems biology, we analyze the origins and universality of glycolysis, the tricarboxylic acid cycle, the respiratory chain, and energy-transferring cofactors, primarily ATP. Particular emphasis is placed on regulation and compartmentalization as evolutionary strategies that enhance the stability and controllability of metabolic networks. We show that metabolism was not invented *de novo* by evolution, but rather optimized within a limited set of chemically permissible solutions. Thus, evolutionary innovation largely operated through modifications of regulatory architecture, including compartmentalization and functional specialization of nucleotide cofactors, rather than through the creation of fundamentally new biochemical reactions.