Inferring trajectory-level information flow from time-series data

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Stochastic information flow (SIF) quantifies, at the trajectory level, the information a subsystem acquires about the rest of a system during its dynamical evolution. In contrast to conventional ensemble-averaged and often symmetric measures, SIF captures directional, fluctuating information exchange even between statistically identical components. Despite its conceptual appeal, empirical estimation of SIF from data remains challenging due to its dependence on path probabilities. Here, we introduce a scalable deep-learning framework that infers SIF directly from time-series data without requiring explicit knowledge of the underlying dynamics. We validate the method on model systems and experimental datasets, demonstrating that SIF reveals the information-flow structure underlying collective dynamics in a fully data-driven manner.