Higher-order interactions accelerate cultural recombination

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Extended Abstract

Understanding how complex innovations emerge in human societies remains an open challenge in cultural evolution research. Unlike biological evolution, cultural advancement operates through recombination processes, where existing knowledge components combine into novel configurations [1]. This framework posits that cumulative culture arises not from *de-novo* inventions but from systematic integration of existing traits, a process accelerated by social connectivity and knowledge exchange. Experimental and theoretical work has shown that group structure critically shapes these dynamics, with intermediate levels of connectivity and collaboration fostering breakthrough innovations. Seminal studies by Derex and Boyd demonstrated that isolated subpopulations could only achieve major innovations through cross-group recombination, establishing that transmission pathways determine innovation rates [2]. However, most models still focus on dyadic interactions [3], even though empirical evidence shows that higher-order collaborations are decisive for scientific and technological breakthroughs as well as in traditional societies. This raises the unresolved question of how group-level interactions beyond dyads accelerate cultural recombination.

We address this gap by developing a hypergraph-based model that formalizes higher-order interactions in cultural transmission. In our framework, individuals interact not only through pairwise connections but also through triadic hyperedges, allowing simultaneous knowledge exchange among three agents. Using a hunter–gatherer–inspired camp structure, we explore how varying the fraction of higher-order interactions and the modularity of social organization affects innovation dynamics. We distinguish between lineage-specific recombinations, which extend a single technological trajectory, and crossover innovations, which integrate elements from multiple lineages (Fig. (1) (A)). Our simulations show that higher-order interactions do not accelerate lineage-specific recombinations but substantially reduce the time needed for crossovers, yielding a 30% improvement in innovation speed (Fig. (1) (B)). Statistical analyses confirm that this acceleration is driven primarily by triadic interactions between camps, which, though rare, account for nearly 80% of crossover events (Fig. (1) (C)). These findings highlight the disproportionate role of multi-agent, cross-group encounters in producing breakthrough innovations.

We further uncover an intrinsic trade-off between speed and spread. Higher-order interactions accelerate crossovers but simultaneously limit the diffusion of other high-fitness tools, leading to lower overall cultural complexity at the moment of breakthrough compared to dyadic systems (Fig. (1) (D)). This tension suggests that societies face a structural optimization problem: increasing group-level collaboration enhances the speed of innovation but reduces the breadth of cultural dissemination. We quantify this trade-off across interaction regimes and identify conditions under which the balance between innovation speed and knowledge spread may be optimized.

To validate the model, we implement it on empirical hypergraphs derived from two real-world datasets: a French high school and a Philippine hunter–gatherer community. In the high school dataset, strong modular structure and cross-class interactions enable higher-order interactions to accelerate innovation. By contrast, in the hunter–gatherer dataset, weak modularity reduces the advantage of hypergraph structures, and projected dyadic networks even produce faster diffusion. These contrasting results demonstrate that the effects of higher-order interactions depend critically on underlying community organization.

Our findings extend the cultural recombination paradigm by showing that higher-order group interactions are essential for understanding how complex innovations arise. While triadic interactions are sufficient to accelerate crossovers among three lineages, the results suggest a general principle: k-order interactions among k distinct cultural lineages may be required for rapid breakthrough innovations. This work highlights an intrinsic tension between innovation speed and cultural diffusion and underscores the importance of incorporating higher-order structures into models of cultural evolution.

References

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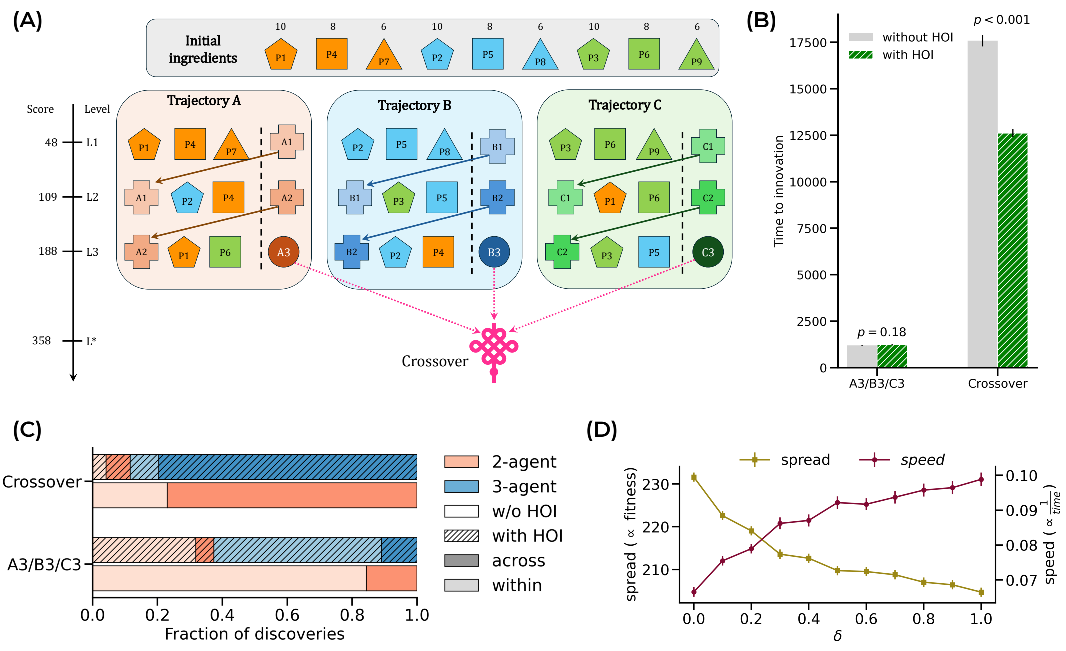

Figure 1: **(A)** Recombination trajectories for 3 lineages which ultimately lead to a high-fitness crossover innovation. **(B)** Acceleration of complex crossover in presence of HOI. **(C)** Fraction of interactions leading to simple and complex recombinations. **(D)** Trade-off between speed and spread of complex recombinations.