

Self-organized tower of Babel: Diversification through competition

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We introduce a minimal evolutionary model to show how local cooperation and global competition can create a transition to the diversity of communities such as linguistic groups. By using a lattice model with high-dimensional state agents and evolution under a fitness that depends on an agent's local neighborhood and global dissimilarity, clusters of diverse communities with different fitness are organized by equalizing the fitnesses on the boundaries, where their numbers and sizes are robust to parameters. We observe successive transitions over quasistationary states, as triggered by the emergence of new communities on the boundaries. Our abstract framework provides a simple mechanism for the diversification of culture.

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I. INTRODUCTION

It is generally taken for granted that “language has evolved as a means of communication,” which sounds intuitive and true, as the primary purpose of language is known to be a means of transferring information [1,2]. However, if only this aspect of language is taken into account, it is difficult to understand why there are so many languages that cannot communicate with each other. In terms of communication optimization, language diversity should decrease and homogenize. This question has been notably raised by Axelrod [3], and despite several studies on his model and variants of it [4–7], the primary focus is on how diversity is sustained, while studies on how diversification arises remain scarce.

Along with the problem of diversity, languages also have several complexities [8] that naively would seem to hamper information transfer. We hypothesize that there also exists a “discommunication” aspect in language, so that information is kept confidential within a group, to prevent exploitation by others. In other words, people wish to speak a language unintelligible to foreigners. While there exist theories that diversity of language can arise in order to distinguish “us” versus “them” [9–12], as well as several models [13–20], the communicative aspect has typically been emphasized. However, considering the existence of diverse languages in the world and the frequent emergence of dialects by region, it is essential to also investigate the nature of differentiation based on the latter aspect, rather than simple mutations.

This paper introduces a simple model that examines an antagonistic nature in agent interactions. Here, we use the term “language,” even though the model abstracts all details in the language by focusing only on cooperative interactions

by sharing similar aspects at short ranges and inhibitory ones to differentiate oneself from others at long ranges. With this abstraction, the model may also capture the dynamics of diversified communities with different cultures or institutions, as seen in the dynamics of nations [21], although we retain the term “language” throughout. After introducing an evolutionary model with agents, we will show how communities diversify, where clusters with different fitness can coexist, with successive changes caused by the emergence of new communities from the boundaries.

II. TWO-DIMENSIONAL MODEL

We define a total population size of $L \times L$ agents, placed on a two-dimensional (2D) grid with periodic boundary conditions [22]. Each agent speaks a language $\vec{c}$, defined by a bitstring of length B [23], for example,

$$\vec{c} = [0, 0, 1, 0, 1, 1, 0, 0, 1]. \quad (1)$$

Every bit in the bitstring can be thought of as a “feature” of a language, for example, the presence of tense, gender for inanimate objects, and so on. As our model is abstract, one could also consider a bit to represent a “word,” a minimal unit that allows for communication. With the above definition, we could consider the mutual “understandability” of two languages as the number of times both the bitstrings have a 1 in a particular position: If agent x has a word for a concept while y lacks it, communication is hindered. As such, it can be represented as a simple vector dot product of the two languages. We assume that each agent wishes to communicate with their neighbors (at short ranges), and wishes to withhold information from distant agents (long-range interactions). We study the limit of this behavior, i.e., local alignment and global differentiation [24].

Each lattice site contains one agent, with their own language. Every timestep, each agent x has two types of interactions:

(1) Local interactions: For the four nearest neighbors (up, down, left, and right), fitness is gained from understanding

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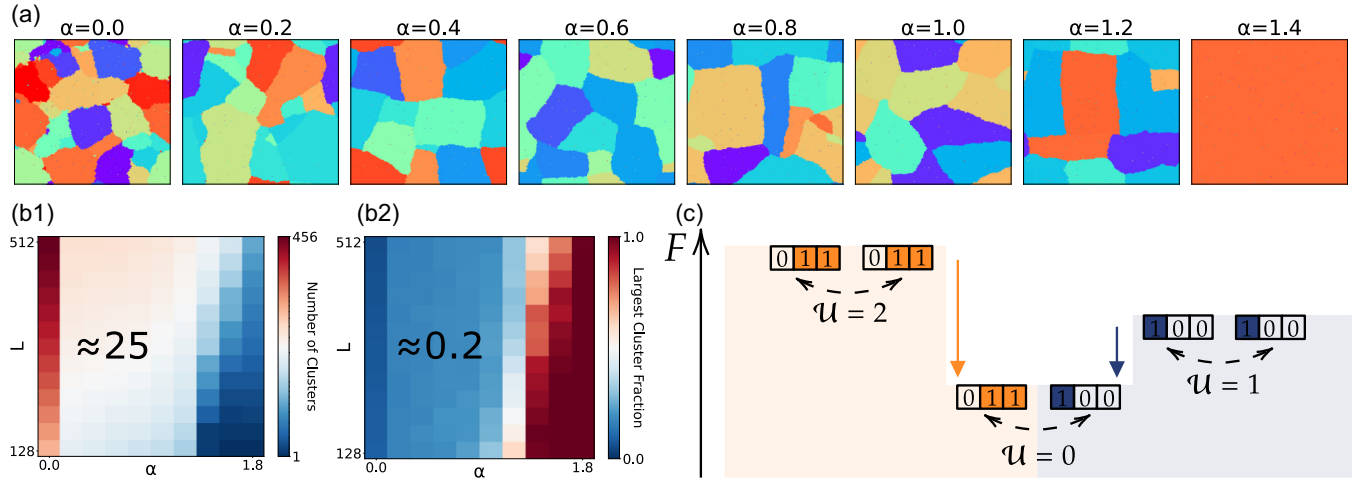


FIG. 1. (a) Snapshots showing the state of the 2D lattice for varying alignment strength α , for $\gamma = 1$, $L = 256$, $B = 16$, and $\mu = 0.001$. Agents are colored randomly by their language [25]. (b) Phase diagrams for the mean number of clusters [26] [panel (b1)] and the largest cluster size divided by L^2 [panel (b2)] over α and L . We observe ≈ 20 – 30 clusters, with the largest around 25% of the system size robust to changing parameters, as long as $\alpha > 0$ and is before the transition. (c) A schematic diagram of the boundary between two languages. The small rows represent the languages (011 and 100) and their heights represent their fitnesses. The α term of the fitness can be seen to drop, from 4 to 2 for the left language, and from 2 to 1 for the right language. This asymmetric dropoff allows languages with different bulk fitnesses to coexist, as long as their boundary fitnesses are equalized.

each other:

$$F_{x,y}^{\text{local}} = \frac{\alpha}{4} \cdot \mathcal{U}(\vec{c}_x, \vec{c}_y). \quad (2)$$

(2) Global interactions: For every agent in the lattice, fitness is gained by having a different language from one another:

$$F_{x,y}^{\text{global}} = \frac{\gamma}{L^2} \cdot d_{\mathcal{H}}(\vec{c}_x, \vec{c}_y), \quad (3)$$

where $\mathcal{U}(\vec{c}_x, \vec{c}_y) = \vec{c}_x \cdot \vec{c}_y = \sum \text{AND}(\vec{c}_x, \vec{c}_y)$ represents the “understandability” and $d_{\mathcal{H}}(\vec{c}_x, \vec{c}_y) = \sum \text{XOR}(\vec{c}_x, \vec{c}_y)$ represents the Hamming distance between the two languages.

In other words, the total fitness gained by an agent can be written as

$$F_x = \underbrace{\frac{\alpha}{4} \sum_{y \in \text{nbrs}} \mathcal{U}(\vec{c}_x, \vec{c}_y)}_{\text{understandability}} + \underbrace{\frac{\gamma}{L^2} \sum_{y=0}^{L^2} d_{\mathcal{H}}(\vec{c}_x, \vec{c}_y)}_{\text{discommunication}}. \quad (4)$$

According to the fitness, agents are replicated: We randomly select a site on the lattice, and check if its fitness is greater than any one of its four neighbors. If it is, it invades the weakest neighbor, replacing it with a clone of the “winner”. The newly created clone is immune to any successive invasion attempts this phase, and cannot be selected as a proposed replicator. We then continue this process until we have made $L^2/2$ trials for replication. Finally, after the reproduction is complete, we mutate each agent by modifying their bitstring, with each bit being flipped with an independent probability μ . This makes up the next generation, and the evolutionary algorithm continues [27]. As the selection depends only on relative fitnesses, we ensure that only the ratio of α/γ is a parameter, and as such γ is set to unity. The system can be thought of as one with local activation (speaking easily understood languages) and global inhibition (speaking different

languages) [28,29], similar to several pattern-forming models [30,31].

We start all agents speaking the same “unevolved” language consisting of a bitstring of 0s, and perform the evolutionary simulation. Looking at the evolved state, we notice that agents form communities that speak the same language [25]. We observe a transition into diversity of communities. While α/γ is large, speaking the same language is beneficial as all agents wish to speak a language that is easily understood. As such, we observe coarsening, and finally the entire system of agents speaks one common language (a bit string of only 1s), with fluctuations corresponding to the mutation rate μ . However, as α/γ is decreased, agents prefer to communicate in different languages, and the number of distinct languages increases.

Snapshots of the lattice for increasing α can be seen in Fig. 1(a). We obtain diverse languages if $\alpha/\gamma \lesssim 1.4$ [32]. The clusters commonly have vertical or horizontal boundaries as a consequence of using a square lattice: Straight lines are more robust to invasions than corners or diagonal lines. Clusters are also formed for $\alpha = 0$, due to the local reproduction in the system. Interestingly, while different values of α/γ do not appear to significantly change the cluster size distribution [26], $\alpha = 0$ is a special case, and appears to have a larger number of clusters, along with the presence of smaller clusters, than cases where $\alpha > 0$ [Fig. 1(b)]. The lattice size L only weakly affects the number of clusters ($L = 128$ leads to 20 clusters, while $L = 512$ leads to 30: see Fig. 5 in the Supplemental Material [33] for L, B scaling) without changing the largest cluster size, due to the global inhibition (γ) term: “Winning” languages are penalized not when they reach a certain absolute size, but rather, when they reach a certain fraction of the system size.

One might expect that the coexisting clusters have the same fitness, but that is not the case. A peculiarity of the model

is that the fitness on the boundaries are (nearly) all equally balanced. Fitness in this case can be considered analogous to pressure in bubble dynamics: If the fitness on a boundary is not equal, the stronger language can invade the weaker one. This, in turn, affects the γ term of the fitness equation for the agent on boundary, causing the invader's fitness to drop, and the invaded's fitness to rise. This happens incrementally until all boundaries simultaneously equalize their fitnesses. It is important to note, however, that the *bulk fitnesses* of languages are different: We can observe coexistence of strong species with weak ones, due to asymmetric fitness dropoffs at the boundaries [Fig. 1(c)].

Under the presence of mutations (which allow the system to escape unstable configurations), the system never reaches a constant steady state, but appears to keep switching between “metastable” states, even at long time [Fig. 2(a)]. This is due to the global inhibition introducing a context-dependent winner: While a language might do well in a certain environment, as it gets larger, it affects the global dynamics and promotes other languages based on the γ term [38]. As such, there is no clear “fittest” language in the system, and we cannot assign a potential to discuss a fitness landscape. At high mutation rate μ , the frequency of switching increases to the point that we lose the metastable-switching behavior, and the dynamics resemble oscillatory fluctuations. Several communities appear to converge to similar sizes, a phenomenon we investigate in the 1D case (Section III).

Agents in the center of a cluster have a higher α fitness term than agents on the boundary, which disalign with some neighbors. This leads to the boundaries being less fit than the bulk. Snapshots of the lattice during one such “switching” event can be seen in Fig. 2(b). While mutations happen everywhere in the system, mutants in the center of a cluster are likely to be removed due to the presence of several highly fit neighbors. However, mutations on the boundary have a chance of having higher fitness than their neighbors and have a chance to grow, destabilizing the “steady state” of the system and pushing it to a new one.

As new languages appear through mutations, a phylogenetic tree of the evolutionary sequence can be depicted (Fig. 7 in the Supplemental Material [33]). In our model, however, a mutation of language c_x on the border with c_y is unlikely to grow unless it aligns with c_y [due to Eq. (2)] and thus mutants that “borrow” from their neighbors are often selected [Fig. 2(c)]. This is not represented in a phylogenetic tree, and is an aspect shared with real languages, which are reported to not solely be derived from a parent language, but also contain several “borrowed” features and words [39,40].

Next, we investigate the effect that the mutation rate μ has on the system. We can construct a similar phase diagram to the one in Fig. 1, except over α and μ , for a fixed value of L (Figs. 3(a) and 3(b)). We observe that large mutation rate shrinks the cluster sizes, and is also able to destabilize a fully aligned cluster for the same ratio of α/γ . We did not observe a strong dependence on the bitstring length B , as long as the mutation rate per bit μ is scaled inversely to preserve the probability of a mutation across the entire bitstring.

Increasing the mutation rate μ leads to an inability to effectively transfer information to the next generation, similar to the error catastrophe first discussed by Eigen [41,42].

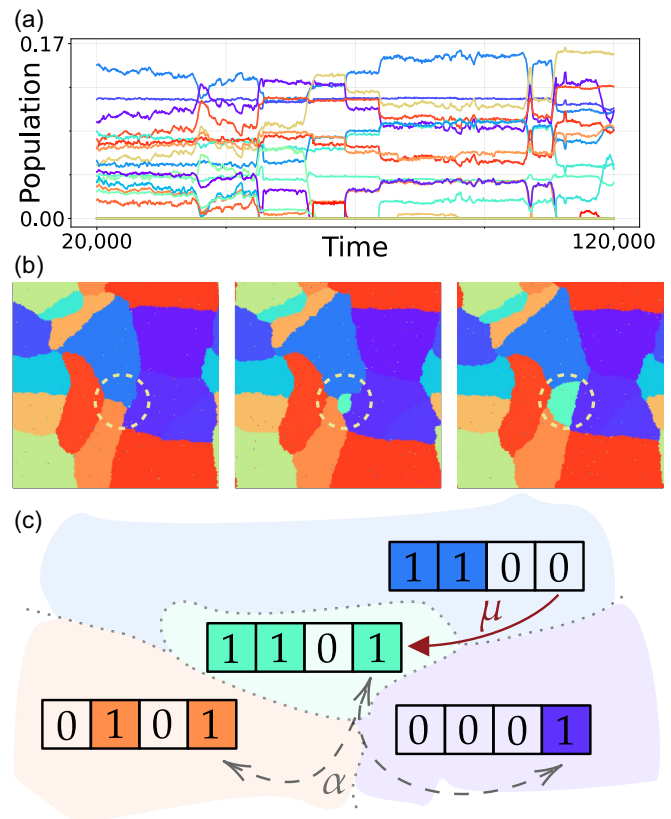


FIG. 2. (a) The number of agents speaking a given language in the 2D lattice model, over time. For low μ ($= 10^{-5}$ in the figure), the system appears to stay in mostly “metastable” states, which can be destabilized in a quick transition. This transition moves the system to a different steady state, where populations remain roughly constant (reminiscent of punctuated equilibria [43,44]). (b) Snapshots of the time evolution, showing the emergence of a new cluster. A mutation (cyan) forms on the boundary of three clusters, which proceeds to expand and “invade” its neighbors. Mutations in the bulk of a cluster are often unfit due to nonalignment with the neighbors, but cluster boundaries have lower fitness from alignment and thus are more vulnerable. (c) A schematic diagram for new community creation. Although the cyan language (1101) is created as a mutation from the blue (1100) in the top right, it contains “borrowed” features from the other languages, as that would “increase the mutant’s fitness” over one which lacks them (e.g., if 1110 was mutated instead, it would have a lower fitness and promptly be eliminated).

Unlike Eigen’s original example, we lack an “optimal” (fittest) language, as the best language to speak depends on your environment. However, the collapse of the structured state into an unstructured one allows us to draw parallels to the original idea. In addition, Fig. 3(c) shows how the number of clusters and the largest cluster size scale with μ . The behaviors for different α/γ appear to collapse on common scaling functions.

III. ONE-DIMENSIONAL MODEL

Finally, we investigate the behavior of our model on a 1D lattice. Again, clusters of different languages evolve, whose number increases with μ (Fig. 4). We observe that several clusters typically consist of the same number of agents. This

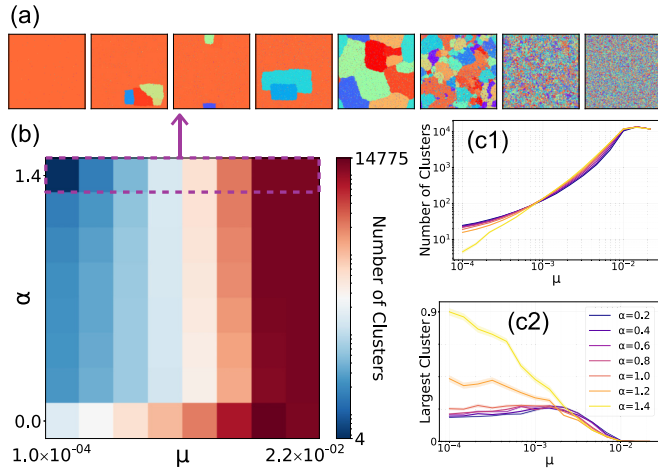


FIG. 3. (a) Snapshots of a $L = 256$ lattice with $B = 16$ at $\alpha = 1.4$ ($\gamma = 1$), just above the transition point, showing the behavior for increasing mutation rate μ . The homogeneous cluster can be destabilized by increasing μ (on a log scale for μ), forming clusters that collapse into uncorrelated languages on further increasing μ . (b) A phase diagram for the same parameters over alignment term α and mutation rate μ showing the number of clusters [26] observed. While α does not appear to significantly change the number of clusters (similar to Fig. 1) increasing μ appears to increase the cluster number. (c) Plots of the number of clusters [26] [panel (c1)] and the size of the largest cluster [panel (c2)] as a function of μ . The scaling seems similar, robust to changes in α/γ , and only weakly dependent on L and B (for B , assuming μ is scaled inversely: see Figs. 8 and 9 in the Supplemental Material [33]).

can be explained in a simple case: Consider that we have three different species, c_0 , c_1 , and c_2 , with populations N_0 , N_1 , and N_2 respectively. At the boundary between c_1 and c_2 , the total fitness must be equal, and thus we can derive (see Sec. II in the Supplemental Material [33])

$$\left[\frac{\alpha}{\gamma} - N_0 \right] (f_1 - f_2) = [d_{\mathcal{H}}(c_1, c_2)](N_1 - N_2). \quad (5)$$

While there are several values of f_1 , f_2 , N_1 , and N_2 that solve this equation, we typically observe that languages contain the same number of bits ($f_1 = f_2$), set by α/γ . In that case, the only way to solve the equation is for N_1 to be equal to N_2 , which can explain the alignment of species populations.

At low μ , the switching behavior seen in Fig. 2 is not observed. Instead, random mutations can cause shifts in the boundaries (Fig. 4 in the Supplemental Material [33]). This can appear to behave as a traveling wave; however, over very

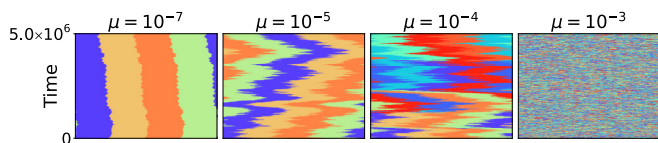


FIG. 4. A plot of the 1D lattice over time, from the same initial condition, for different values of mutation rate μ , for $L = 512$, $B = 16$. $\mu = 0$ has stable boundaries that remain in place. Increasing μ leads to faster-moving boundaries, the emergence of new languages, and finally a collapse into an unstructured state.

long time intervals it can be seen to be simply Brownian motion with inertia, where the source of the inertia comes from the global carrying capacity [47].

IV. DISCUSSION

Our model is abstract, as the complexities of language cannot be simply mapped to a 16-dimensional Boolean vector. Furthermore, we assume that a single agent speaks only a single language, while bilingualism could be a powerful tool, allowing an agent to have a local “secret” language while still being able to communicate globally. Despite these issues, we feel that our toy model and its generality can explain the diversity of language in a different way from traditional arguments.

Our model is fairly distinct from Axelrod’s model: While several studies of it exist [4,5], the model relies on diverse initial conditions and coarsening, thus being unable to show how diversification can arise. Furthermore, the diversity is only sustained by having cultures that share no features with their neighbors, which is not entirely true for language, which are known to often borrow concepts from one another [39,40] and even form creoles [49] that encapsulate features of both languages at a boundary. Radillo-Diaz *et al.* study a modification with repulsive interactions [6], though it too lacks several of the dynamical aspects we expect from language [50], while also not exploring how diversification could arise from homogeneity. Klemm *et al.* introduce mutations [7], which can lead to dynamic behavior and sustained diversity, yet the diverse states remain unstable and diversity is sustained by constant random perturbations without letting the system relax.

In practice, γ and α , which represent the “competitiveness” and “cooperativity” of an environment, are not fixed, but vary with time. They could also vary by sector: “Languages” used in war are heavily encrypted and complex in order to prevent eavesdropping, while those used in trade are much more homogeneous.

If we consider an abstract definition of language, communication goes beyond just animals: Microbes, for instance, communicate via exchange of chemicals in a phenomenon called quorum sensing [51,52]. While there is plenty of evidence of an ever evolving “arms race” between microbes and phages (viruses that infect bacteria) [53], we believe that there could be a “cryptographical arms race” between microbial species, and perhaps even larger organisms like plants [54,55].

The model shows switching between quasistable states, reminiscent of punctuated equilibria, which are discussed in language and cultural evolution [56,57]. In addition, the appearance of new languages on the boundaries is similar to existing theories for creole formation [11,49], whereas the rise of new nations from the border is frequently observed in history [21,58]. A straightforward comparison of our model to linguistic data might be challenging due to the complicated socio-political processing and limitations in the data. Nevertheless, the model is able to explain, for instance, the remarkable diversity seen in the Formosan languages [59–61], with are of linguistic relevance as the proposed origin of the Austronesian language family (Sec. IV in the Supplemental Material [33]).

In conclusion, much of the complex behavior in the model stems from two primary aspects: the presence of a

high-dimensional state and the context-dependent fitness. Together, they allow for asymmetric fitness dropoffs at the boundaries and thus the coexistence of less-fit communities.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [62].

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 - [25] We run the simulations for a minimum of 40 000 generations before recording the snapshots. The same (statistically) evolved states are also obtained by starting from random initial conditions.
 - [26] Due to the presence of mutations causing single random agents to have a different language, we ignore clusters of size 1.
 - [27] We obtain similar results with a sequential algorithm: There is a shift in the transition boundary, and the sequential algorithm remains diverse for longer [the transition boundary moves from $\alpha/\gamma \approx 1.6$ to $\alpha/\gamma \approx 1.8$ for $L = 256$]; however, the main features of the model (the robustness of the clusters to the parameter α/γ (although the number itself is slightly modified, from ≈ 25 to ≈ 21), the nature of the transition, and its dependence on L and μ , etc.), remain unchanged.
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- Material [33]) reminiscent of classical nucleation theory [34,35], which implies that the transition also depends on initial conditions. However, the transition is observed to be shallower (easier to homogenize) in the mean-field model and steeper (easier to diversify) in 1D (Fig. 2 in the Supplemental Material [33]).
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