Computer-Aided Simulation Framework: Natural Selection and Species Extinction Dynamics

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Abstract—**This research aims to structure a discrete event simulator that replicates the intricate interactions and evolutionary trajectories of various species coexisting within the same environment. Focusing on the Holocene epoch, approximately 11,650 years ago, the study investigates the different outcomes resulting from the interspecific interactions among distinct species of the genus Homo: Homo sapiens, Homo neanderthalensis, and Homo erectus. Through the simulation of historical scenarios, this project explores the dynamics of natural selection and species extinction. By employing an high-performance modeling framework, the research examines the implications of social structures, cognitive abilities, and resource competition on species survival and extinction rates. The simulator provides critical insights into evolutionary mechanisms and significant factors that led to the decline of non-contemporaneous species. Results from extensive simulations underscore the essential role of social cooperation and strategic alliances in shaping evolutionary outcomes. Ultimately, this investigation not only enriches the understanding of ancient human dynamics but also lays the groundwork for future explorations of evolutionary biology within complex ecological contexts.**

GitHub: https://github.com/305909/cascade

I. Introduction

In order to establish a reliable regime of historical events, the study revolves around the following assumptions:

- **Historical Assumption**: The Holocene period encompasses the coexistence of three distinct species of the genus Homo: sapiens, neanderthalensis, and erectus. According to recent anthropological studies [3] [4] [5], this period witnesses the massive extinction of minor species, leading as a consequence to the global supremacy of the sapiens species. The timeline of this evolutionary shift highlights significant developments in human history.
- **Evolutionary Assumption**: Among the various evolutionary theories attempting to explain the reasons behind the mass extinction of the minor species and the consequent supremacy of the sapiens species, this research supports the theory of the Israeli historian, philosopher and essayist Yuval Noah Harari. According to Harari's writing, Sapiens [1], the extinction of the neanderthalensis and erectus species occurs as a consequence of a mass genocide at the hands of the sapiens. Despite the more massive physical structure of neanderthalensis and the prolific reproduction rates of erectus, only sapiens possesses the cognitive ability to imagine and create complex social structures.

This unique trait enables sapiens to recognize and cooperate with individuals beyond immediate family groups, leading to alliances between clans and the development of sophisticated social networks. In compliance with these historical and evolutionary premises, the study simulates different scenarios within this historical period and provides outputs on the probabilities of extinction for each species. The approach enhances understanding of how these factors influenced the evolutionary trajectory of Homo sapiens.

II. Methodology

This section details the step-by-step approach to solving the problem, addressing key aspects such as environment structuring, species modeling, stochastic evolution, mobility and combat modeling, simulator architecture, and input parameter selection.

A. Environment Structuring

This research structures the geographic environment as a two-dimensional grid, on a scale of 1 to 10,000. Each node in the abstract grid represents a 10 square kilometer colony within the environment, while each edge symbolizes an interconnection between neighboring colonies. The basic unit within the abstract grid corresponds to a distance of 10,000 kilometers in the real geographic environment. This structuring of the environment enables for a comprehensive simulation of species interactions across different regions.

B. Species Modelling

This research models the species coexisting within the geographic environment according to a hierarchical scale of belonging. The individual serves as the basic unit, which, together with other individuals from the same family group, forms a clan. Different clans of individuals belonging to the same species combine to represent the species. This hierarchical modeling reflects the social structures in ancient human societies, i.e. clan-based organizations established by species membership and settlement area [3] [4] [5].

C. Stochastic Evolution

This research models the stochastic evolution of species within the geographical environment taking into account the Harari's evolutionary assumptions, according to which the genus Homo belongs to a class of continuously migrating hunters and gatherers [1].

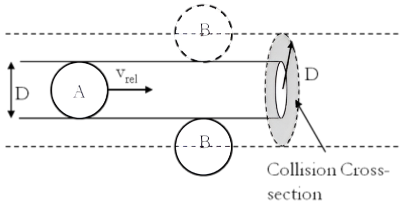

Fig. 1: The cross-section model.

In compliance, the study structures an ideal initial settlement phase, in which each clan within the geographic environment settles into an independent colony and progresses over time according to a cycle of natural births and deaths. Subsequently, the study revolves the simulation around migration phases, war phases and colonization phases. The simulator provides a dynamic view of how these factors interplay, influencing the survival and extinction of different species.

D. Mobility Modelling

The migration phase attempts to simulate the resource-dependent migration process of clans within the geographic environment [3]. Each clan, after a random interval of time, engages a migration process to reach a colony in the neighborhood, in search of resources. Migration time varies depending on the geographical distance between the departure and arrival colonies. The simulation halts the birth cycle for migrating clans due to resource constraints and the demands of relocation.

After the migration phase, in the case of arrival towards a colony without enemy settlements, the simulator triggers the colonization phase, which brings the clan back to a cycle of natural births and deaths and to an increase in the reproduction rate, due to the availability of resources and the monopoly of the colony. However, in the case of arrival towards a colony with enemy settlements, the simulator triggers the war phase, which instead leads the clan to engage a cycle of clashes against the enemy clans.

After the enemy's defeat, the victorious clan begins colonization. This cycle of migration, war, and colonization repeats for each clan within the geographic environment, reflecting the harsh realities of survival in the prehistoric world.

E. Combat Modelling

The simulator structures the war as a succession of clashes between individuals of different clans coexisting in a colony. This research leverages statistical thermodynamic models on the random walk of gas particles inside a box [6] to model the war as a thermodynamic system. Take into account a particle moving randomly inside a box at a velocity v. The average number of collisions with other particles, also in random motion, in the time unit ∇t results:

$$n = \frac{N}{V}\pi d^2 v \nabla t \tag{1}$$

Here, N represents the number of particles within the box, V the volume of the box and d the size of the particle's cross section radius. Dividing by ∇t, the equation leads to the average number of collisions per unit time:

$$\lambda = \frac{N}{V}\pi d^2 v \tag{2}$$

The model leverages the thermodynamic equation to compute the average number of clashes per unit time ∇t for an individual, such as particles, moving randomly at a velocity v within a battlefield of volume V against a number of enemies N. The radius of the cross section d comes out from the geometric dimensions of the human species. Each clash leads to a breathless individual. The other, however, returns to move randomly, according to the same thermodynamic model, but with an update on the number of enemies $N-1$, which consequently changes the average free path and the average time for the subsequent clash.

The coexistence of clans belonging to the sapiens species triggers the exception to the the war phase execution. In detail, upon interaction, sapiens clans form alliances instead of engaging in conflict. Such alliance process triggers when a sapiens clan migrates toward a colony with an existing sapiens settlement. Upon arrival, the clans immediately ally, forming a single social group. The simulator also triggers alliance procedures in war situations. For instance, if a war between an erectus clan and a sapiens clan occurs, the arrival of an external sapiens clan leads to an instant alliance, with the sapiens clans joining forces against the erectus clan.

III. Experiments

A. Simulator Architecture

The simulator manages the entire simulation by initializing and updating over time the various dictionary-type data structures archiving clans and individuals, i.e. the units, at different levels of aggregation, of the hierarchical scale of belonging, and the colonies, i.e. the basic units of the geographical environment. The architecture of the logical processing flow appears natural: the simulator proceeds forward in time through discrete events of births, deaths, departures, arrivals, and clashes.

The natural processing flow requires a complex structuring of control conditions to manage future events within the future events set according to the most critical phases, i.e. the migration and war phases. In particular, for each individual of a clan close to a migration phase or a war phase, the simulator removes birth events from the future events set and then triggers the birth of individuals again, with an increase in the reproduction rate, at the subsequent colonization phase.

B. Input Parameters Selection

This research selects some standard simulation parameters, such as the reproduction rate, the probability of improvement and the alpha improvement factor, the average lifetime of the initial generation individuals and the number of colonies/nodes within the geographical environment. In addition, the study structures a dictionary-type input parameter archiving each clan in the scenario with the respective number of initial individuals and the belonging species.

To study the influence of evolutionary assumptions regarding the superior alliance-building ability of sapiens, this research proposes a comprehensive simulation plan consisting of multiple scenarios by setting, for each clan, the value on the reproduction rate at 0.15, the alpha improvement factor at 0.25, the probability of improvement at 0.5, the average lifetime of the initial generation individuals at 15 years and the number of colonies/nodes at 25. Furthermore, the study triggers the event of a subsequent clan migration after a random time interval, according to a uniform distribution, between 0 and 5 years from the colonization phase, and an increase in the reproduction rate of 0.85 at colonization time.

C. Experimental Setup

This research simulates different scenarios, each with the same initial configuration, to evaluate the probability of extinction of the different Homo species within the environment. The simulator initializes five clans for each species, with each clan comprising 25 individuals, and then establishes an event loop tracking births, deaths, migrations, arrivals, and conflicts, until either the simulation reaches the time limit or one of the species faces extinction within the environment. Due to the high computation complexity of the simulation, the study sets the simulation time limit at 45 years, i.e. approximately after the elapse of three generations of individuals per clan. Furthermore, to obtain significant results in the simulation time frame, this research sets an initial reproduction rate of 0.15, which, even with the increase in the colonization phase, leads to the extinction of the species in the long term. After processing 10,000 simulations of different scenarios, for approximately 72 hours of simulation, the study reaches significant results with an accuracy level of 0.95 over a confidence level of 0.95, as shown in Table I.

Species	Extinction Rate
Homo Sapiens	**0.2187**
Homo Erectus	0.6575
Homo Neanderthalensis	0.7269

TABLE I: The extinction rate for each species.

Table I provides, for each species, the extinction rate as the ratio between the number of simulations in which the extinction of the *i*-th species occurs and the overall number of simulations.

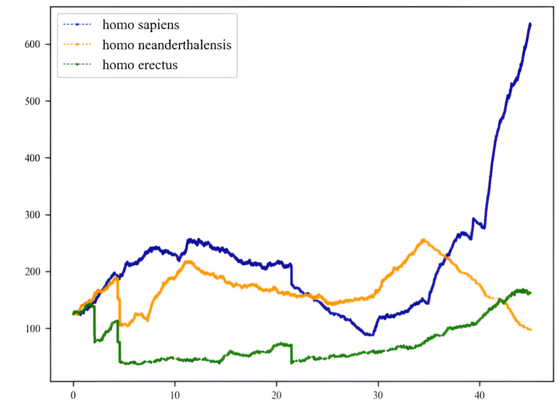

Fig. 2: The evolution of species over time.

Figure 2 shows the evolution of species over time within the environment, in terms of number of individuals. The figure represents a single scenario, randomly drawn from the ten thousand simulations. Noticeable collapses in the number of individuals occur at specific points, such as around year 5 and year 20 of the simulation. The phenomena appear as the natural consequence of war phases, where, within short periods, massive clashes lead to the extermination of some clans. For example, a clear conflict between erectus clans emerges around year 2.5, followed by a more significant clash between neanderthalensis and erectus clans at year 5, and another between sapiens and erectus clans around year 20. Furthermore, Figure 2 captures increases in the number of individuals of the species at certain points in time. The phenomenona appear as the natural consequence of colonization phases, where the availability of resources and control over a colony boost the clan's reproduction rate by 0.85.

On the other hand, decreases in the number of individuals over medium to long intervals stem from random model events, such as the selection of subsequent births or migration phases, which interrupt the birth cycle for migrating clans. Figure 3, in contrast, presents the geographical environment as a two-dimensional abstract grid, where each node signifies a colony and the edges indicate connections between neighboring colonies. This figure also traces the colonization history of the species within the same scenario of Figure 2.

IV. Conclusion

This research reveals significant insights into the evolutionary dynamics among species of the genus Homo over the Holocene epoch. Simulating interactions between Homo sapiens, Homo neanderthalensis, and Homo erectus highlights the factors driving species extinction and the dominance of sapiens. Simulation outcomes show Homo sapiens demonstrating a higher survival rate with respect to Homo erectus and Homo neanderthalensis.

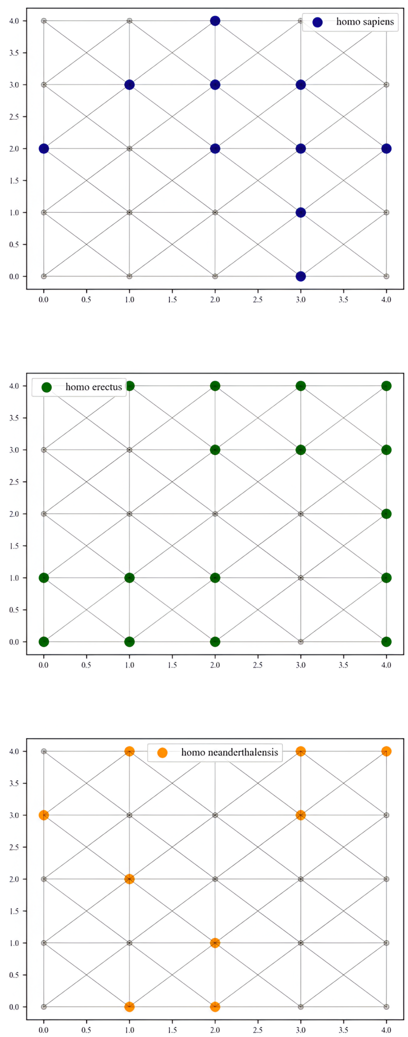

Fig. 3: The colonization history.

This result supports Harari's hypothesis [1], indicating that cognitive and social advantages significantly influence survival and expansion. The capacity of sapiens to forge alliances beyond immediate family groups proves crucial. The strategic alliances enhance collective defense and resource access, improving the chances of thriving and contributing to the decline of competing species. In contrast, Homo neanderthalensis and Homo erectus face challenges adapting to dynamic interactions. Despite physical strength and reproductive advantages, these species lack the complex social structures and cooperative strategies of sapiens. Increased vulnerability to threats and conflicts accelerates extinction rates among these species. The results underline the importance of social and cognitive factors in evolutionary success, reinforcing the notion that sapiens' superior social abilities play a critical role in their survival. Limitations of the simulation include assumptions of random combat strategies and uniform resource distribution, which might oversimplify real-world complexities.

The abstract geographical layout and environmental conditions might miss nuances such as terrain and climate variations impacting migration and conflict. The model's exclusion of non-random combat strategies and external ecological pressures may affect the generalizability of findings. Future research may improve the model by incorporating realistic environmental and strategic elements, as well as interactions with other species. While focusing on interactions within the genus Homo, this research does not negate other external factors like climate change, disease, and competition with other species, which may also influence extinction. This study complements alternative hypotheses by emphasizing the impact of social cooperation and alliance-building as key evolutionary factors.

In conclusion, this research contributes to understanding how migration, colonization, and warfare shape evolutionary histories. Highlighting the advantages of social cooperation and strategic alliances supports Harari's hypothesis [1] and provides a foundation for future exploration into the complex dynamics of human evolution. Further refinements and expansions of the simulation model may offer additional insights into the intricate factors influencing survival and extinction in prehistoric environments.

References

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