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# ALICE'S ADVENTURES IN COMPUTATIONAL MODELLING OF THE SUB-NEOLITHIC BOUNDARY: CURIOUSER AND CURIOUSER DYNAMICS GOVERNING THE ADAPTIVE MORPHOGENESIS OF CULTURE

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*„Well, in our country," said Alice, still panting a little, „you'd generally get to somewhere else – if you run very fast for a long time, as we've been doing."*

*„A slow sort of country!" said the Queen. „Now, here, you see, it takes all the running you can do, to keep in the same place."*

*– Lewis Carrol 1899 (excerpt from Through the Looking Glass and What Alice Found There)*

*The Sub-Neolithic hunter-gatherer-fisher (HGF) groups and Corded Ware (CW) agro-pastoral group interactions within the Lithuanian portion of the Neman Basin around ~3000 BC did not follow the same patterns of agriculturalisation seen elsewhere in Europe during Neolithization. The variation of interaction in this agricultural frontier zone provides valuable insight into the way information exchange between groups drives the exchange of intercultural information and how information exchange between groups ultimately the adaptive morphogenesis of culture. This article's primary author has already studied this outlier behaviour and the Unified Agricultural Frontier Model (UAFM) was proposed in volume 45 of this journal (Troskosky et al. 2019). The article presented in this volume is a companion piece to the 2019 publication which further explains and tests the mechanics underlying the UAFM. The UAFM applies self-organised criticality (SOC) to the hypothesis that marked cultural shifts are most likely to occur in response to increased levels of stress affect within a society. Stress affect is defined as the dissonance between encultured expectations of reality and phenomenologically lived reality within a population. To test this hypothesis, The Arithmetic Logarithm Illustrating Cultural Exchange (ALICE) model was developed; it provides confirmation that information exchange drives the behaviour of the UAFM across frontier zones. This model provides strong computational confirmation that information drives the behaviour of the UAFM across frontier zones. Theoretically, ALICE supports a general model for information flow between different cultures, facilitating corresponding cultural changes across any frontier. It models how increased levels of stress affect within interacting groups can lead to shifts of societal behaviour marked by a pattern of periods of equilibrium alternating with periods of disequilibrium. The results from the ALICE model and logical extrapolation of their effects in the UAFM demonstrate support for the eight new archaeological testable governing dynamics for information-driven adaptive morphogenesis of culture.*

***Keywords:*** Archaeology, Eastern Baltic, Neolithisation, Information Science, Computational Modeling, Self Organized Criticality, Frontier Zone Dynamics, Sub-Neolithic, Corded Ware, Cultural Morphogenesis

*Subneolito laikotarpio medžiotojų-rinkėjų-žvejų (angl. hunter-gatherer-fisher, HGF) ir virvelinės keramikos (Corded Ware, CW) agropastoralinių grupių sąveika Nemuno baseino Lietuvos dalyje apie 3000 m. pr. Kr. nesutampa su agrikultūrizacijos modeliu, būdingu kitoms Europos vietoms, kurios buvo veikiamos neolito revoliucijos. Sąveikos variacijos šioje žemdirbystės pasienio zonoje suteikia vertingų įžvalgų apie tai, kaip žinių keitimasis tarp grupių skatina tarpkultūrinės informacijos mainus ir kaip šie mainai tarp grupių galiausiai lemia adaptacinę kultūros morfogenezę.*

*Šio straipsnio pagrindinis autorius jau yra tyrinėjęs šią atsiliekančią elgseną ir šio žurnalo 45 tome pristatė Bendrąjį agrikultūrinio pasienio modelį (BAPM) (angl. Unified Agricultural Frontier Model, UAFM) (Troskosky et al. 2019). Šiame tome pateikiamas straipsnis yra 2019 m. publikacijos priedas, kuriame toliau aiškinama ir tikrinama BAPM pagrindą sudarantys mechanizmai. BAPM taiko savireguliuojamą kritiškumo modelį (SKM) (angl. Self Organized Criticality, SOC) hipotezei, teigiančiai, jog ryškūs kultūriniai pokyčiai labiausiai tikėtini kaip atsakas į padidėjusį streso poveikio lygį visuomenėje. Streso poveikis apibrėžiamas kaip disonansas tarp išugdytų tikrovės lūkesčių ir fenomenologiškai išgyventos tikrovės visuomenėje. Šiai hipotezei patikrinti buvo sukurtas aritmetinio logaritmo, iliustruojančio kultūrinius mainus, modelis (The Arithmetic Logarithm Illustrating Cultural Exchange, ALICE); juo patvirtinama, kad informacijos mainai lemia UAFM elgseną pasienio zonose. Teoriškai ALICE palaiko bendrą informacijos srauto tarp skirtingų kultūrų modelį, palengvinantį atitinkamus kultūrinius pokyčius bet kurioje agrikultūros pasienio zonoje. Parodoma, kaip padidėjęs streso poveikis sąveikaujančiose grupėse gali lemti visuomenės elgsenos pokyčius, dėl kurių visuomenė išgyvena ir pusiausvyros, ir neramumo laikotarpius. ALICE modelio rezultatai ir loginė jų poveikio ekstrapoliacija patvirtina aštuonias naujas archeologines dinamikas, susijusias su informacijos dalijimusi nulemta adaptyvia kultūros morfogeneze.*

***Reikšminiai žodžiai:*** archeologija, Rytų Pabaltijys, neolitizacija, informacijos mokslas, kompiuterinis modeliavimas, save reguliuojantis kritiškumas, pasienio zonos dinamika, subneolitas, Virvelinės keramikos kultūra, kultūrinė morfogenezė.

## INTRODUCTION

Agriculturalisation occurred in the Neman Basin region more than 1,000 years after it was fully adopted in neighbouring regions. There are no obvious contemporary geographic or cultural barriers to explain why it did not follow the pattern displayed across Western Asia, Turkey or Continental Europe. The Neman Basin case demonstrates that access to agriculture in neighbouring groups was not a sufficient incentive to adopt agriculture themselves in and of itself. The Unified Model for the Governing Dynamics of Agricultural Frontier Zones, published in 2019 The Edition 45 of *Archeologija Lietuvos* (Troskosky *et al.* 2019), proposed a model to explain the irregular agricultural availability and delayed adoption of agriculture (Zvelebil 2015) in the Neman Basin in comparison to the rest of continental Europe. In 2019, the UAFM created a model framework for two cultures in contact, based on the theory of structuration (Giddens 1984) as modified by Zvelebil (2005) and further modified by Troskosky *et al.* (2019).

In order to describe the process of agriculturalisation in the Neman Basin, Troskosky the UAFM hypothesised an SOC model of micro-level information exchange underlying the operation of a higher-level structuration model (ibid.). This UAFM model simulates the behaviour patterns of punctuated equilibrium displayed by cultural systems. These systems displaying punctuated equilibrium are characterised by long periods of material culture stability broken by short temporal bursts of high intensity material cultural change. As an underlying governing dynamic of human culture generally, SOC was convincingly presented by Brunk (2001; 2002) on both societal collapse and, more importantly, unpredictability in human societies, demonstrating how properties of large-scale human systems are constantly developed in an emergent and non-linear manner. Simply said, in SOC, cause is not directly related to effect in human systems and the totality of behaviour can not be reduced to the sum interactions of their various subsystems.

This article presents SOC more thoroughly as an integral concept when studying past and present human systems; ALICE is applied to simulate information exchange between cultural units while testing the UAFM hypothesis that scale-invariant behaviour would be present in relation to cultural change which is triggered by information exchange (Troskosky *et al.* 2019). In our studies presented here, ALICE demonstrates that scale-invariant behaviour in human information exchange is consistent both conceptually and at the population scale in the archaeological record.

These experimental results confirm that the UAFM is a viable working hypothesis for information-driven adaptive morphogenesis of culture over time in unranked societies on a changing geo-social landscape. It is important to note that additional factors of ranked societies, such as censorship, may affect the introduction of novel information into society that are not accounted for in this UAFM, and the UAFM also does not account for how information was delivered to a population. It requires only what can easily be confirmed by the material record in certainty, the fact that information was exchanged and that the information exchange gradient between groups changed over time.

The ALICE model operates under these six basic assumptions:

1. The endemic group has not closed the information frontier.
2. Affective stress on the endemic population is in direct proportion to the permeability of the information frontier zone to external information for the endemic group (Troskosky *et al.* 2019).
3. The specific means by which exotic information enters the endemic group is irrelevant to the operation of the model.
4. The iteration rate is defined by the frequency of interaction between the two populations rather than a standard period of time between iterations.
   a. This will be a function primarily of population density, the speed of information exchange over distance, and the amount of noise on the communication channel.
   b. For the purposes of this model, in relation to simple societies in the Neman Basin, perfect mutual intelligibility is assumed so channel noise is a constant.
5. The cultural units represented in the model are in contact.
6. The societies are not extensively socially stratified or ranked.

## CULTURAL HISTORY OF STUDY AREA AND CONTEMPORARY CONTEXT

With less than 200 kilometres of separation between the Northern European Plain and the Neman Basin, there is no specific identifiable cultural or environmental cause preserved in the archaeological and geologic records (Perrault 2019; Troskosky *et al.* 2019), to explain why HGF groups in the Neman Basin largely resisted the adoption of agriculture for approximately 1,000 years after agriculture widely developed in the region (Bogucki *et al.*, 1988).The western drainage divide of the Neman Basin shares borders with the Vistula Basin and is separated from the Vistula by the Pregolya Basin in other areas. While the Pregolya basin is much smaller than the Neman Basin, there are signs that cultural information exchange regarding agriculture within the Pregolya Basin between Zedmar and the Linin subgroup of the Neman-type culture groups and local Funnel Beaker Culture (TRB) agriculturalists of the Northern European Plain (Nowak 2007). These TRB influenced groups, though distinguished artifactually as material culture entities, likely formed a catena of HGF-agriculturalist hybrid adaptations within the Pregolya Basin at this time. It is important to note that the agricultural technology which was adapted by the TRB within both the Vistula and Pregolya Basins does not extend into the Neman Basin watershed, even among populations using similar technological assemblages and even though it is reasonable to assume they had sufficient mutually understandable ideologies and languages to accommodate this cultural information exchange. This argument is based on both geographic proximity and also a well-documented intraregional trade network (Nowak 2007; Rimantienė 1992; Szmyt 2010).

There are no reasonable environmental obstacles to the adoption of agriculture in the palynological record in the Neman Basin from ~4000 to ~3000 BC; nor were there any significant regional climatic macro-changes until well into the CW adoption period (~2900 BC to ~2800 BC) with a subsequent freshening of the Baltic Basin and the partial collapse of the marine ecosystem around the beginning of the Lithuanian Early Bronze Age ~2000 BC (Galatius *et al.* 2012; Mauri *et al.* 2015). The Neman Basin also displays an extremely quick, but ineffective advance of pastoralist agriculture into Sub-Neolithic HGF groups, with a subsequent disappearance from the archaeological record of the material culture of these HGF groups following the appearance of CW within the region (Piličiauskas 2018, Figure 104, p.177).

There is a sharp break at the natural topography point with groups to the east within the Neman watershed refusing to engage with agriculture while remaining in contact with groups to the west who were actively engaging with it. This indicates that the availability of agricultural and cultural information is not a sufficient impetus on its own to spread the knowledge and traditions required to establish enculturation of agriculture within a HGF group. The existence of this discrepancy without any causative geological or climatological factors, seems to indicate that neither the diffusion of information or the migration of individuals with novel information are strong enough factors to spread traditions of knowledgeability (e.g., information) between groups. The individuals who make up the HGF cultural unit must have sufficient cause for the selective rejection or acceptance of information that could potentially be applied to the HGF individual's cultural reality. Quite simply, the relevance of the information is not enough as it must also be deemed of value within the receiver's cultural reality in order to trigger potential cultural change.

For contemporary analysis of events in the Neman Basin in the 3rd Millennium BC, ALICE adds context and a driving mechanism behind the unusual cultural shift seen in the Neman Basin. With no geologic or climatic causes to explain the delayed uptake of agriculture, the concept of environment must be expanded to include all aspects of human life, both the aspects which are phenomenologically observable from a physical and material standpoint and those aspects which are intrinsically cultural and could only been observed by an inhabitant of that group. This concept is made clear in the UAFM where it is theorised that this could be simulated as the ability to make the frontier selectively permeable to various types of information by either party without changing its permeability to other types of information (Troskosky *et al.* 2019).

ALICE confirms the general dynamics outlined in the UAFM. Confirming the UAFM as an adequate presentation of frontier zone dynamics for the exchange of information between unranked societies in contact, along with the efficacy of stress affect as a universal driver for the permeability of information flow into a cultural unit; the punctuated equilibrium nature of the cultural change; and the impact of Van Valen's Law of constant extinction also known as the Red Queen's Race or Red Queen Hypothesis (Van Valen 1973) upon archaeological cultures (represented by the artefacts we find today which have been ascribed as 'being in common' to past cultural units at the population level.)

## MODELS

The UAFM must be assumed to be universally applicable in order to accommodate and encompass the individual ethnographic-facing drivers for agriculturalisation as cultures come into contact in frontier zones, replicate themselves, and evolve (Troskosky *et al.* 2019). It is also necessary to accommodate the polythetic nature of culture (Furholt 2014) in evaluating regional responses. The construction of the UAFM theorised the universality of SOC processes in human cultural reproduction, specifically information exchange. The UAFM is intrinsically a simple two-body statistical dynamic system which contains a sorting mechanism of information integration into a culture which functions mechanically like a functioning version of Maxwell's Demon while the cultural systems are unstressed and a malfunctioning Maxwell's Demon when under stress (Maxwell 1867; Troskosky *et al.* 2019).

The UAFM and its associated theories are supported by ALICE, an explicitly SOC computational model which illustrates how SOC behaviour drives the UAFM in a scale independent manner. An Abelian Sandpile model was chosen, (Bak *et al.* 1987) as opposed to other SOC models (e.g., stick-slip model of fault failure, Pruessner's forest fire model, etc. (Smalley & Turcotte 1985; Pruessner *et al.* 2002; 2004; Rhodes & Anderson 1996; Roy *et al.* 2014)) because the Abelian Sandpile provides the most easily understood application and best visual representation of SOC as it applies to human information exchange.. The ALICE model code download link is provided in Appendix A along with instructions on how to download and start the Python interpreter to run the model simulation.

## ALICE MODEL PARAMETERS

ALICE is a modified Abelian Sandpile (Bak *et al.* 1987;1988) which generates and measures the movement of information over at least four scale independent orders of magnitude. This can be seen (if one ignores the faulty trend line - for which the authors apologise) along the main axis of the Log x Log plot in Figure 1. This demonstrates that an ALICE model could be produced to represent any unit size grouping of a human society without a general model failure. The ALICE model is functionally integrated across this spectrum while population behaviour is ultimately expressed as *Agency in Legion*, inspired by the Biblical reference "My name is Legion because we are many" (Mark 5:9) .

*Agency in Legion* is defined as the mathematically-integrated agency of all individuals under the curve within a defined geographical area over a period of time which resulted in the chain of events, their residues, and their spatio-temporal associations successfully preserved in the archaeological record. No claim is made about who is exercising what agency or who is acting in opposition to any particular action, merely that those actions and events which form the archaeological record did occur and they represent the combined agency of the entirety of past actors. The selective absence of certain types of material culture in certain places at certain times is viewed as a combination of preservation bias and the selective use of the landscape by these same actors

This is particularly important when attempting to interpret archaeological material from the 3rd Millennium BC in the Neman Basin. The regional nuances of the Baltic Basin in this time period include: radiocarbon anomaly; poor site preservation due to peat deposition and deglacial geology; and periglacial sites with both intense rains and boreal forest soils. These systematically fragmenting factors for preservation in the archaeological record make a working general model for the transmission of cultural information inherently more useful than any single-cause determinative one.

Since the archaeological record is underfit in most places for most times (Perrault 2019), it is of utmost importance to produce general statements which can be tested using traditional time transgressive archaeological research techniques in order to further develop the discipline and its scientific importance as a whole. A list of axioms derived from extrapolating model behaviour and model outputs illustrate governing dynamics derived from the ALICE model using the Neman Basin case study will be provided in the final section of the article. These statements are related to how information exchange drives cultural change and adaptive morphogenesis over time. Most importantly, these statements can be tested in the same manner of the hard sciences using existing archaeological techniques. The ALICE suite offers multiple variants to the base model. All results presented here are from the Red Queen Variant model.

## SELF-ORGANISED CRITICALITY

When heat is applied to a pot of water, the water comes to a boil – a chaotic phase change state – and creates steam. The amount of steam produced is directly proportional to the amount of water lost in the phase change to the next state. This is directly governed by the rate of drive flux from the heat reservoir (e.g., the range top setting temperature) until there is no more liquid to be converted into steam. This is analogous to traditional cultural phase change theories where change is directly proportional to the input of the change agent.

Using the boiling water analogy above for the case of this article, information is the system drive flux – the heat applied to the water – and a direct measure of system entropy – the temperature of the water itself. This is derived from statistical dynamics. Entropy in this sense is a measure of the possible number of microstates which define the macro-state of the system. Human systems generate this drive flux – information – through emergent system interactions and an external driver is secondary. The SOC state is governed by a critical threshold of information volume produced by the system and is directly related to the size or information capacity of the system (e.g., larger pots take longer to boil off than smaller ones).

While in SOC, the system generates a non-linear series of avalanche events of random magnitudes in which the system rearranges entropy within itself or dissipates entropy outside of the system (e.g., bubbles within the boiling water; releasing steam into the atmosphere). In SOC, the Second Law of Thermodynamics will be conserved on average over a sufficiently long time sequence of events although it will display short term characteristics which do not adhere to linear causation. For example, the magnitude of any given event is not directly proportional to the magnitude of the number of information bits currently in the system (system entropy), in contrast to the boiling water example in which more heat (entropy) added to the pot will reliably cause a chaotic phase change at an empirically observed temperature and atmospheric pressure. Due to the nature of the random movement of information through the system, different time-sensitive areas of the path-dependent potentiometric surface topography will be more critical, producing a larger cascade when affected by additional information (Bak *et al.*, 1987;1988). At any point in time (i.e., an iteration number in ALICE after a number of interactions have occurred) where the system is in the SOC state, an event of any magnitude may occur, up to and including a cascade beyond the size of the system.In the ALICE model, when the system drops out of SOC, it returns to SOC in a recovery cycle – the immediate post-avalanche state – will be equal in length to the number of iterations the system requires to retune (gain entropy) and drive itself back to SOC and is directly proportional to the magnitude of information dissipated from the system by the cascade event which dropped the system out of SOC; therefore, it will always take the system longer to recover from an event of large magnitude rather than one of small magnitude. In short, the normal operating state of mature SOC systems is a constant critical state with brief periods of sub-criticality after only the largest avalanches.

## METHOD

ALICE's base model simulates an endemic cultural unit through the use of a square grid cellular automaton. Each grid cell represents a member of the native cultural unit. During this simulation, grid cells randomly receive bits of information. If any individual cell contains more than three bits of information, the cell will distribute one bit of information to each neighbour to the north, south, east, and west, until they stabilise under their threshold of four bits. All ALICE models rely on a universal rule which removes any bit which is discarded to the side of the grid surface during an iteration.

The ALICE model simulations are driven to maturity (primed) by running the model with only native information until they exhibit SOC behaviour. This point can be roughly calculated by the total volume of information in the automata grid. ALICE enters SOC at between 2.1 to 2.3 times the area of the grid * with bits of information at iterations of approximately 2.1 to 2.3 times the area of the grid *. For the sake of completeness, all these native information seed topographies are run well beyond 2.3x area iterations to roughly 3x area so they are all simultaneously unique and randomly generated by the SOC behaviour of the system itself. This means that each ALICE simulation has a randomly generated information topography and potentiometric surface at the start of each model run.The most complex version of ALICE is the Red Queen (v4.0 see Appendix A) and is highlighted within this article. This model allows for a set permeability of the information frontier governing entry into the model's grid (See Figure 3). This would be governed by the relative effects of stress affect (Troskosky *et al.* 2019) on the native/endemic and novel/exotic populations participating in the information exchange as defined in the UAFM. The production of novel pieces of information at set differential rates of probability at each iteration allows for the number of iterations at various rates of permeability for the cellular automata to reach a critical volume. This simulates the sufficient exchange and retention of exotic information within the automaton to stabilise in relation to its socio-cultural environment necessary to be no longer strongly influenced by stress affect. It also lends strong evidence supporting the correctness of the Red Queen Hypothesis (Van Valer 1973, 1977) regarding the adaptive morphogenesis of culture over long periods of time (See Figures and Conclusion). The UAFM predicts that as a culture becomes more out of tune with its socio-cultural environment and therefore suffers from greater stress affect, it will become less resistant to novel information, as validated agency has a lesser role in cultural replication or no role at all (Troskosky *et al.* 2019). The Red Queen Variant of ALICE shows that as cultures become less resistant to novel information due to stress affect, there is an increased probability that novel information will be transmitted in large avalanches off the edges of the simulation automaton and into what would be neighbouring automata (Available from the _piles.npz file in model metadata in Appendix A). This would effectively cause a trickle back of information from the automata along the archaeological frontier to neighboring endemic groups causing a wave of advance type phenomenon very rapidly. Eventually the SOC nature of the model will produce enough cascades and filter enough information via avalanching off the edges of the automata, there is an increasing likelihood of overloading other nodes in the network and this overload will cause a distribution of information throughout the frontier in what, at archaeological time scales, is a nearly instantaneous event. In a real-time scale, this distribution likely occurred within several generations of the development of the original stress affect-driven disruption (Troskosky *et al.* 2019). It also indicates that the information required to return into equilibrium with the strongest affect being on socio-geologic environmental stress affect levels that are essentially viral within the population (See Figure 3 for model responses to various levels of simulated stress affect).

The modelling process continues until the groups(s) under stress affect return to equilibrium with their combined environmental and cultural residence. This will be caused by two factors: the acquisition and replication of traditions of knowledgeability from across the information frontier (Troskosky *et al.* 2019) and the degradation of the surprise value and redundancy of information being transferred (Shannon 1948). The receiving culture experiences less societal stress created from redundant or duplicative information crossing an information frontier than surprising or completely novel information. This creates a consolidation phase where the culture incorporates new traditions of knowledgeability which are in equilibrium with the socio-cultural environment and stress affect has effectively been lowered (See Figure 2 for a graphical representation of normalisation behaviour).

We can only include limited examples of the size of the model automata, as they were designed to operate within the processing capacity of an average laptop computer. There is no reason why the model should not be geometrically scale-invariant for cellular automata of significantly larger orders of magnitude given access to sufficient processing power.

## METHOD 2: DATA COLLECTION PROTOCOL

The data collection protocol for the ALICE Red Queen Variant model is two-fold. First, all endemic (Black) information (probability of exotic =0) was run on 20x20, 30x30, and 50x50 cell cellular automata for enough iterations to prime the automaton to SOC. This generates completely random starting grid topographies for the purely black phase of the model in each case. During the Red-Black Phase, the model produces a random bit of information, based on preferential permeability to represent information exchange in the UAFM, with the colour and location drop of the bit selected with several random number generators, simulating exotic or endemic information added at each iteration. This percent chance was set at the beginning of each run cycle to represent and increased for following run cycles. All random number generators used in ALICE use the current computer time stamp code protocol in python, which means a different random number generator seed was selected for every random number calculation.

Running lengthy iteration sequences relative to grid size ensured that the automata classification threshold trigger was tripped on each simulation during the Red-Black Phase. The artificial threshold(s) were met and maintained by the model itself very quickly following a clear exponential growth function and then stabilised (See Figures 2 and 3). This represents a state where the endemic system has acquired both information and context about that information but has been saturated enough that new exotic (red) information would lose most of its surprise value following Shannon's Formulation (1948).

This results in the generation of several pieces of information for each run:

- A Log (magnitude) X Log (frequency) plot of all cascades
- A unique path-dependent time series of cascades and their magnitude by iteration throughout the simulation presented alongside their unique path-dependent time series
- Quantified dissipation of the total number of red bits run off each of the three edges of note (available in metadata Appendix A)
- Full documentation of the movement of every grain for each iteration which can be dredged for individual dissipation event particulars (available in metadata Appendix A)
- The ability to compare full iteration runs plotted against each other (available in metadata Appendix A)
- When approached holistically, a graph showing information frontier permeability plotted against the time in iterations it takes for enough exotic information to reach a critical threshold in the grid by area and by proxy volume (Figure 3).

## RESULTS:

All model results are presented in the form of figures illustrating the mathematics underlying the described model behaviour. This is done for the sake of brevity.

**Note:* Slope should be closer to 1 due to issues with fat tailing effects outweighing the best fit method used. A visual aid only manual best fit is provided by the blue line which partially compensates for the skew. (See Brunk 2000; 2001 for a more in-depth discussion on the statistical properties of SOC results)

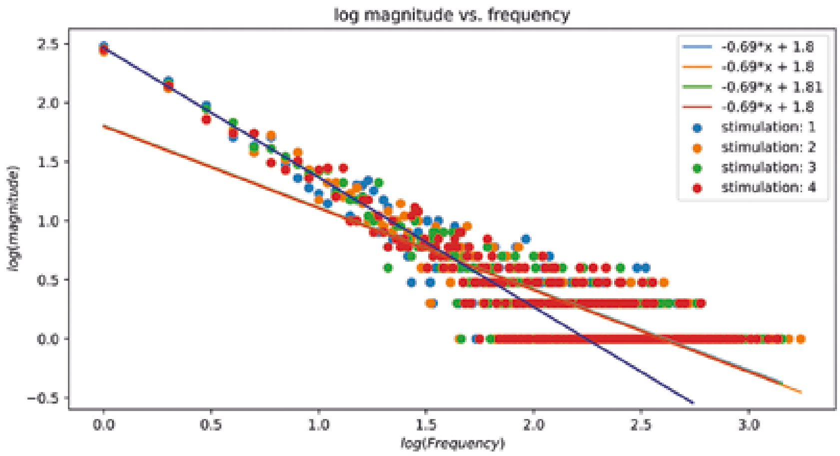


Figure 1*. Log(Magnitude) Plotted against Log(Frequency of magnitude) for four consecutive SOC model runs of the ALICE Red Queen model showing uniformity of the model dynamics despite the random time series created by the model. *Fig. by Tianyu Chen.*

1 pav. *. Log(dydis) nubrėžtas pagal log(dydžio dažnumas) keturiems iš eilės „ALICE Red Queen“ modelio atliktiems SOK modelio bandymams, rodantiems modelio dinamikos vienodumą, nepaisant modelio sukurtų atsitiktinių laiko sekų. *Tianyu Chen piešė.*

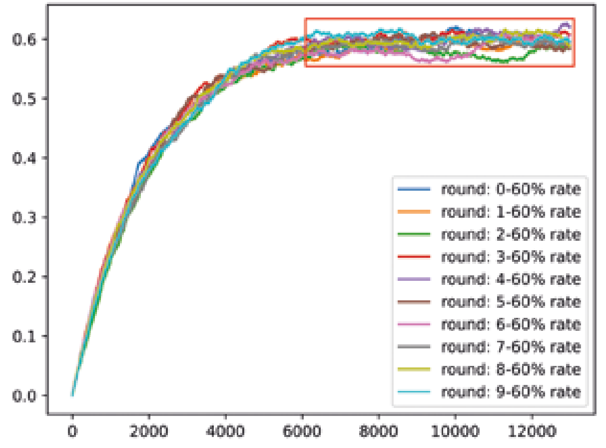


Figure 2. Plot of ten primed ALICE Red Queen model runs showing variability of time series following new equilibrium (Red Box) for ten consecutive 60,000 iteration runs at a 60% stress affect-driven permeability rate. Percentage of exotic information is plotted on the Y axis. Iteration count is plotted on the X axis. *Fig. by Tianyu Chen.*

2 pav. Dešimties paruoštų „ALICE Red Queen“ modelio bandymų grafikas, rodantis laiko sekų kintamumą po naujos pusiausvyros („Red Box“) dešimčiai iš eilės atliktų 60 000 pakartojimų bandymų esant 60 % streso įtakos poveikio laidumo lygiui. Egzotiškos informacijos procentinė dalis pateikiama Y ašyje. Pakartojimų skaičius pateikiamas X ašyje. *Tianyu Chen piešė.*

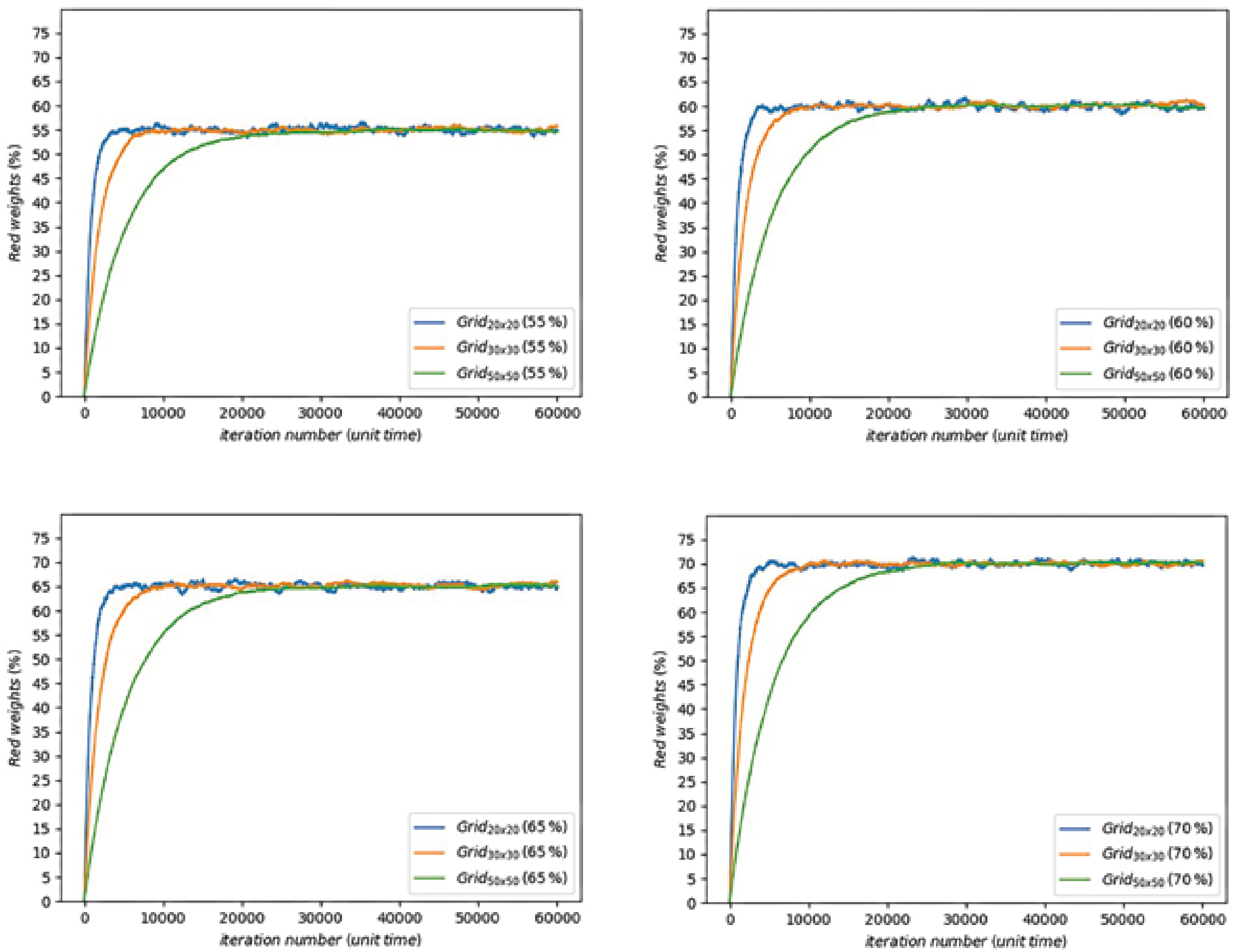


Figure 3. Graphs showing the effect of grid size on the total time period required to reach equilibrium at permeabilities on different sized grids. Note that it takes fewer iterations to drive a smaller grid to equilibrium regardless of permeability rate. *Fig. by Tianyu Chen.*

3 pav. Grafikai, rodantys tinklelio dydžio įtaką bendram laikotarpiui, kurio reikia pusiausvyrai pasiekti esant skirtingų dydžių tinklelių laidumui. Atkreipkite dėmesį, kad, nepaisant laidumo koeficiento, norint pasiekti pusiausvyrą mažesniems tinkleliams, reikia mažiau pakartojimų. *Tianyu Chen pieš.*

## DISCUSSION 2: THE NEMAN BASIN 3rd MILLENNIUM BC

In general, the Neman Basin and the Eastern Baltic likely contained the highest density of HGF people in Europe during Neolithization (Tallavaara *et al.* 2018). The edge effect, which is common to any endemic group within ALICE, partially explains the ~1000 year time lag between the availability of agricultural knowledge within TRB groups (and TRB influenced groups) adjacent to the region (Troskosky *et al.* 2019) and the actual adoption of agriculture, but it is antithetical when attempting to explain the massive disruption caused by the migration of CW agriculturalists ~2900 BC into the Neman Basin region (Piličiauskas 2018). For whatever intra-cultural reason, Baltic Basin HGF groups underwent staggering amounts of stress affect with the arrival of relatively small and sparse travelling CW groups as they migrated, likely in a series of shuttled trips (Piličiauskas 2020, personal communication, September 2021). Over time, these interactions at the information frontier became more frequent. The modelled results would suggest the likelihood of CW traditions of knowledgeability spreading northwards through and beyond the frontier zone within generations of first contact. Therefore, the bulk of the CW population would have been moving through territory well behind the information frontier advance of CW traditions of knowledgeability over the next 300–400 years.

Within the Neman Basin, there is a discrepancy between the location of CW axe finds and the location of dense CW settlements and land use areas which is closely associated with the tributaries of the Neman River Valley system (Piličiauskas 2018, Figure 1, p.25). Battle axes have been long theorised to have emblematic significance and are heavily associated with CW male identity and the beaker vessels of CW social structure (Bourgeois *et al.* 2017; Furholt 2014; Malmström *et al.* 2019; Kristiansen *et al.* 2017). Recent research (Olerud 2001) based on network analysis limits this relationship to biological gender rather than a binary male/female gender identity, although she strongly identifies axes, particularly battle axes, as associated with male individual material culture. Based on the distribution of stray axe finds, these items were primarily deposited largely within the HGF settlement system, in areas for which there is no high intensity CW use areas in the archaeological record. It is most likely that they were transported to these locations through the building of an artificial kinship network or with their owners.

This distribution does not fit the pattern of Indo-European migration described by Kristiansen *et al.* in their seminal 2017 article (Kristensen *et al.* 2017) which describes a pattern of forced female exogamy into migrating male CW groups. In stark contrast, the Lithuanian data supports an interpretation that the infiltration of CW males into HGF groups via male exogamy, well away from the areas of heaviest CW residential activity, as represented by pottery discard density in a much more peripheral manner from the sites of heaviest interaction. It is a reasonable assumption that these individuals quickly became influential within their adoptive groups and donor groups as they could interact in a more nuanced manner with their CW neighbours. If prestige is an indication of human breeding success, as it is commonly held to be (McGuire and Hidlebrandt 2005), then this would also account for the influx of aDNA from the Pontic Steppe around this time (Kristiansen *et al.* 2017; Juras *et al.* 2018; Malmström *et al.* 2019; Scorrano *et al.* 2021)

There are numerous of equally underfit ethnographic hypotheses that could explain the patterns empirically observed in the archaeological record, however at this point these theories are all speculative and will forever remain so. The modelled results clearly demonstrate that stress affect disrupted HGF society enough that most of their endemic cultural historical markers drop out of the archaeological record. However, based on the results of the model concerning the impossibility of complete replacement through information exchange, it is unlikely that they became extinct. Simulation results indicate more succinctly that HGF groups adapted very quickly to their new phenomenological reality brought on by the CW migration itself under extreme stress affect and became archaeologically indistinguishable from CW and post-CW groups. Some evidence exists for this line of reasoning in the form of hybrid CW vessels from some of the highest intensity CW occupation sites in the Neman Basin (Piličiauskas 2018).

This scenario is borne out in ALICE model results which indicate that dissemination of information required to reach stress affect equilibrium would have been viral; spreading well ahead of the actual information frontier interaction interface and furthermore that it would be spread at precisely the levels necessary to alleviate stress affect (See Figure 2 and 3). This indicates that groups in the HGF network well north of the original information frontier zone likely would have had second hand CW information, may have attempted to assimilate a large amount of information about their new neighbours, and likely began to modify their cultural practices to match their HGF neighbours who had been in contact before they even met CW groups face to face. This would have significantly expedited the CW advance through thee Neman Basin and fits well with the apparently nearly instantaneous (max 200 years) nature of the event and the accompanying radical shift in material culture patterns within the Basin during this timeframe.

## CONCLUSION

In general, the archaeological record is underdetermined for the ethnographically facing applications to which it is currently being routinely applied (Perrault 2019). This means the archaeological record is not a complete volume of text in any sense of the word and cannot be read in its entirety without the researcher filling in large chunks of the story from other fallible or tangential sources, including the written record. Parallels can be drawn to the study of the nascent state of the universe and its development since the Big Bang extensively studied from deeply fragmentary raw data and considerable pure theory in cosmology within physics, and geological macro-evolutionary biology studies the history and evolution of life on earth through an even more fragmentary fossil record using data from virtually every hard science. Archaeology needs to do the same. There is nothing special about human systems except that we, as humans, falsely imbue them with the status being fundamentally different from other natural systems. The societies they represent are relative, but that relativity is not general to the point of mathematical inadequacy. They are relative only to the totality of known human societies and only within the range of human societies available for study. It is undoubtedly the case that past human societies operated differently in any number of ways from modern and premodern societies at the same levels of complexity so we must consider the fact that if we only look for patterns which can be suggested from ethnographic analogues we will be fitting models to past behaviour which are only fitting our preconceived notion as archaeologists that we *should* find patterns for which we have an existing empirically documented analog. This is bad science. However, human systems must share a common mechanism for reproducing themselves and adaptively metamorphosing into the various generally techno-typical population level groups we see in the archaeological record. An adaption necessitated by the switchover from pure biological evolution to cultural adaptive morphogenesis very early in the history of the genus *Homo sapiens sapiens*. As shown by the ALICE results below, that mechanism is the preferential exchange of information between groups on their geo-social landscapes under differing levels of stress affect being suffered by members of that group. If a group is interacting with its peer(s) under the stress affect threshold, it will not be forced to become more permeable to novel information. If it is interacting with its peer above the stress affect level, simulated by most of the ALICE experiments, it is forced to become more permeable to novel information.

The ALICE model data clearly shows the path-dependent series of simulated events is irrelevant to the result of the model. This strongly implies there is a deterministic path dependency for information exchange between human groups, a deterministic path dependency which can be more succinctly and comprehensively explained by stress affect-driven change (Troskosky *et al.* 2019) than by any single ethnographic-facing factor (Perrault 2019).

ALICE and the UAFM also strongly suggest there are specific governing dynamics of cultural adaptive morphogenesis and that, furthermore, these governing dynamics are universal. They may be more complex in ranked societies, but it is highly unlikely that the basic governing dynamics of how human beings actually exchange information when approached from an integrated population perspective, and how these governing dynamics shape the adaptive morphogenesis of culture. Modelled results show that changes in landscape socio-geological ecology (the Geo-Cultural fitness landscape) is a higher determinant of stress affect than any specific cultural adaptation is. Therefore, some version of the Red Queen Hypothesis (Van Valen 1973; 1977) appears to be active for *Homo sapiens* at the population level.

Furthermore, the fact that exotic information levels stabilise at the stress affect-driven permeability of the representative frontier zone indicates the combined geologic and cultural fitness landscape represented by stress affect (Troskosky *et al.* 2019) may be better served by a Lamarckian paradigm for the adaptive morphogenesis of culture (Gould 2002). The totality of the construct which makes up a culture must be learned during the lifetime of one generation if a modified form is to be passed on to the next generation of enculturated individuals. This can be tentatively extended to the orthogenesis of complexity (Lamarck 1873) as larger automata take longer to stabilise than smaller counterparts. A culture which runs out of room to expand geographically in the presence of larger more information buffered neighbours must complexify in order to buffer itself against losing its traditions of knowledgeability to a persistent input of massive amounts of external information flux. This may have some passing significance in relation to the question of how and why complexity develops as a modified function of existing governing dynamics of the adaptive morphogenesis of culture. This research also has direct bearing on how anthropology can be used to study the epidemiology of belief and enculturation which occurs in the context of high-speed information exchange across modern information frontiers, such as those encountered on the internet, specifically in the environment of social media where peer interacts in anonymous overtly egalitarian forums has resulted in the creation of radicalising echo chambers resulting in systemic misinformation, radicalization, and propagation of social norms which were a decade ago fringe, isolated, or non existent a decade ago. This will be addressed in a future study.

## GOVERNING DYNAMICS DERIVED FROM THE ALICE MODEL SUITE

The following governing dynamics for the adaptive morphogenesis of culture are derivable from the ALICE model suite:

- Selection for permeability across the information frontier will be determinate regardless of the series of micro events which take place. This indicates that Agency in Legion is determinate to the actual events preserved in the archaeological record. There is no scenario where CW fails to replace HGF groups in the Neman Basin.
- Iteration rate is governed by peer-to-peer interactions and therefore, is proportionate to the density of human beings on the landscape and available rates of information exchange over distance. Rates of change should be slower in the Palaeolithic than the Mesolithic, etc. and should be increasingly exponential as local communication speed approaches the fraction of the speed of light which renders communication clear and for all intents instantaneous through either demographic growth, technological innovation, or both.
- Redundant exotic information entering an endemic system will undergo a decrease in surprise value commensurate with Shannon's Formulation of Information Entropy (Shannon 1948) indicating that a 100% cultural replacement is not possible across any information frontier.
- Larger endemic groups will take relatively longer than smaller groups to be assimilated under the pressure of stress affect due to edge versus total area effects.
- Initial uptake of exotic information into endemic groups will be rapid and follow an exponential growth function which stabilises around the information frontier permeability.
- Information exchange will be relational to the intensity of the dissonance causing stress affect in a culture (Troskosky *et al.* 2019) until equilibrium with respect to frontier zone permeability is restored.
  - This dissonance will affect all cultures on the landscape but will be culturally relative with regards to intensity at any given point in time.
- The model results are consistent with the Red Queen Hypothesis in macro-evolutionary biology. In human societies however, stress affect acts as the environmental selector of fitness instead of biological niche fitness.
  - This means that no one adaption is intrinsically more fit to the geo-cultural landscape until a time dependent and essentially random (from a contemporary perspective) stressor is applied.
- Information as the driver of cultural adaptive morphogenesis under a Lamarckian paradigm may lead to the orthogenic emergence of complexity among populations in densely populated geo-social landscapes in order to buffer the combined effects of higher stress affect and iteration rate.

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# APPENDIX A: ALICE MODEL INSTALLATION MANUAL, DOWNLOAD LINKS, ALGORITHM, META CODE, AND VERSION INFORMATION

## INSTALLATION MANUAL

ALICE model is a sandpile simulation software written in Python and requires all Python packages to be installed in order for it to be used.

## DOWNLOADING PYTHON

The version of Python used in this work is Python 3.10 and can be obtained from the following hyperlink: https://www.python.org/downloads/release/python-3100/

Select the download version which matches your computer's operating system. When the download is complete, install Python using the installation prompts. Make sure the "add python 3.10 to PATH" option is checked as in the installation settings (see image below) so the python interpreter can be accessed either through DOS command terminal or the IDE-provided interface.

## DOWNLOAD THE ALICE MODEL SOFTWARE

Current versions of the software files are hosted in both GitHub and Google Drive. The software at both locations is identical and only requires download from one location. For the GitHub download option, please use following link: https://github.com/Joechen9071/alice_sandpile

The download can be accessed on Google Drive through following link: https://drive.google.com/drive/u/1/folders/19pBtZXGXVF2BVWoT4Bxle_qHvmATXMtB

The download package will contain the following files:

1. setup.csv
2. sandpile_ver2.py
3. reading.py
4. cross_read.py
5. application.py
6. abliean_sandpile.py
7. sandpile_redblack.py
8. Requirements.txt

**Please Note:** If you download from the GitHub repository you will also acquire some GitHub services files. This is normal and will not harm your machine or corrupt the software.

## ALGORITHM

The ALICE algorithm is similar to the original three-dimensional Abelian sandpile code with modifications to allow for randomization in the placement of new information within the automata, user settings to control rates of information by type which enters the automata at each iteration in the multiple-type variants of the model, the tracking of every individual piece of information during its residence time within the automata, and locational information concerning where any bit of information leaves the automata during a model run.

The pseudo code of algorithms is defined as follows:

- The probabilities of the random number generator (RNG) used to generate information, which varies by and is identified by color, is pre-determined by the probability that red will be chosen as information "color" for all iterations prior to the running of the algorithm as a decimal value between zero and one
- The probability that the information generated at each iteration will be "colored" black is defined as one minus the red probability in the RNG.
- Threshold value is determined as the volume of information a single cell can hold without collapse as a constant integer value.
- Iteration number serves as both the number of times the model operation is to be repeated and a numerical identifier for each bit of information added to the system.
- Height and Width are set as initial conditions which form the size of the cell structure represented by the automata on an X-Y plane.

**Algorithm 1** Alice abelian sandpile model

**Require:**
$iteration \geq 0$
$height \geq 1$
$width \geq 1$
$threshold \geq 1$
$redProb \geq 0$
**Ensure:**
$i \leftarrow 0$
$grid \leftarrow eight\ *\ width$
**while** $i \neq iteration$ **do**
  $x \leftarrow random(0, width)$
  $y \leftarrow random(0, height)$
  $sand = random(0, 1) \leq redProb$
  $grid[x, y] += sand(red|black)$
  **while** $i, j\ in\ range(width, height),\ grid[i, j] > threshold$ **do**
    **for** $direction\ in\ ((-1, 0), (1, 0), (0, 1), (0, -1))$ **do**
      **if** $[i, j] + direction\ not\ in\ range(width, height)$ **then**
        $skip$
      **else**
        $grid[[i, j] + direction] += sand(red|black)$
      **end if**
    **end for**
  **end while**
**end while**

## RUNNING ALICE SOFTWARE

Several files are included in the ALICE model download package. Each file codes for different components of the work. In order to successfully execute the ALICE application, change current work directory to target folder, then in terminal type command "pip install -r requirements. txt" This will install all required packages. Once installation is completed in Python the files required for operating the ALICE model will be available as a component of the ALICE simulation and the various versions of ALICE can be executed.

There are four versions of ALICE available in the suite and generally represent stages in the development of the ALICE model which is discussed extensively in the paper which is the red queen model or ALICE 4.0.

1. **ALICE1.0:** abliean_sandpile.py – This model was designed to serve as proof of concept, a simple implementation version of abelian sandpile, algorithm simply records size of each cell after each iteration for graphical analysis.
2. **ALICE2.0:** sandpile_ver2.py – This file is advance implementation of sandpile algorithm, where cells were recoded as bins in order to provide volume capabilities in order to compute stored sand and a feature was installed allowing the tagging and tracking the identity of each sand grain dropped as it moves through the sandpile.
3. **ALICE3.0:** Application.py – This file is GUI version of ALICE sandpile program


For each simulation, four figures will be presented using the UI version:

- All cascades and their magnitudes occurring during the stimulation process in a time-series graph.
- Log/Log Fat-tail graph of the magnitude of cascades plotted against the frequency of a cascade of that magnitude
- Three-dimensional spatial density plot showing stimulated matrix size and final information topography
- A graph showing the total area of the grid involved in a given cascade presented as a time series

4. **ALICE 4.0:** sandpile_redblack.py and setup. csv work together as an integrated whole to extract the configuration from a number of csv files which were produced by very long monochromatic model runs so that novel (differently colored) information can be added to a mature information topography generated by ALICE independently of the Red/Black simulation. This model simulates the information flow between two cultures in contact in which stress affect has

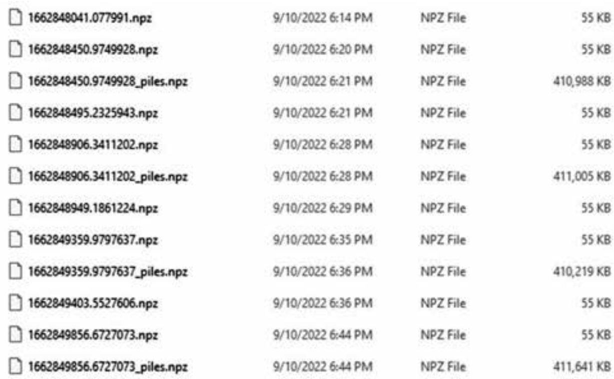
> forced a culture to become reactive and also of how reactive they become and the patterns they follow as they acquire novel information to alleviate their changing reality.

For setup.csv to operate properly you will need to manually create a file, where the format must be {[width,height,iteration,red_prob, after] * rows}, Number of rows determines how many models you wish to run. where height and width defines size of the cellular automata, iteration denotes number of iteration runs to prime the model, red_prob is the probability of dropping "red" information at each iteration after the model is primed, after denotes the number of iterations to be run with red_prob after the model is primed.

As a data type restriction, all parameters should be integers except red_prob where red_prob should be a fraction of 1 expressed as a decimal (.5 for example), black probability will be automatically determined by the ALICE software.

Once the stimulation has completed there will n*2 files ending with. npz format, which contains all matrices during stimulation. Filename will be a unix timestamp of when the file is created. _piles in particular records the entire simulation history of the movement of every piece of information within the system at each iteration. Of primary importance is when Novel information thresholds are reached, where information lost outside the primary model zone is propagated to, and that novel and native information levels maintain their relative levels once new equilibriums are reached.

An example of the output file structure produced is pictured below. This system allows for the automated collection of large amounts of data from very long model runs.



| | | | |
|---|---|---|---|
| 1662848041.077991.npz | 9/10/2022 6:14 PM | NPZ File | 55 KB |
| 1662848450.9749928.npz | 9/10/2022 6:20 PM | NPZ File | 55 KB |
| 1662848450.9749928_piles.npz | 9/10/2022 6:21 PM | NPZ File | 410,988 KB |
| 1662848495.2325943.npz | 9/10/2022 6:21 PM | NPZ File | 55 KB |
| 1662848906.3411202.npz | 9/10/2022 6:28 PM | NPZ File | 55 KB |
| 1662848906.3411202_piles.npz | 9/10/2022 6:28 PM | NPZ File | 411,005 KB |
| 1662848949.1861224.npz | 9/10/2022 6:29 PM | NPZ File | 55 KB |
| 1662849359.9797637.npz | 9/10/2022 6:35 PM | NPZ File | 55 KB |
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| 1662849856.6727073.npz | 9/10/2022 6:44 PM | NPZ File | 55 KB |
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## ABBREVIATIONS

ALICE – Arithmetic Logarithm Illustrating Cultural Exchange

CW – Corded Ware

HGF – Hunter-gatherer-fisher

SOC – Self-organised Criticality

SPQR – Several Population Query Research model

TRB – Funnel Beaker Culture

UAFM – Unified Agricultural Frontier Model

# ALICE NUOTYKIAI KOMPIUTERINIAME MODELIAVIME: SUBNEOLITO PARIBYS IR SMALSUMO DINAMIKOS VALDYMAS KULTŪROS EVOLIUCIJOJE

Christopher Barber Troskosky, Tianyu Chen, Katie Nicole Troskosky

## Santrauka

Subneolito medžiotojų-rinkėjų-žvejų (toliau – MRŽ) grupių ir virvelinės keramikos kultūros (toliau – VKK) agropastoralinių grupių sąveika Nemuno baseino lietuviškoje dalyje apie ~3000 m. pr. Kr. neatitinka agrarizacijos modelių, pastebėtų kitur Europoje neolitizacijos metu. Dėl to regionas yra nepaprastai svarbus norint suprasti, kaip keitimasis informacija tarp grupių skatina keitimąsi tarpkultūrine informacija ir, galiausiai, kultūros evoliuciją. Šį išskirtinį elgesį anksčiau tyrė šio straipsnio pagrindinis autorius, o bendrasis agrikultūrinio pasienio modelis (toliau - BAPM) pasiūlytas šio žurnalo 45 numeryje (Troskosky *et al.* 2019). Šiame numeryje pateiktas straipsnis yra 2019 m. straipsnio papildinys, kuriame išsamiau paaiškinama ir pritaikoma BAPM mechanika. BAPM taiko savireguliuojamą kritiškumo modelį (toliau – SKM) ir streso įtakos teoriją, teigiant, kad ryškūs kultūriniai poslinkiai labiau tikėtini, nes stiprėja streso poveikis visuomenei. Streso įtaka apibrėžiama kaip disonansas tarp populiacijos kultūrinių tikrovės lūkesčių ir jos fenomenologiškai išgyvenamos tikrovės. Norėdami patikrinti šią hipotezę, sukūrėme apskaičiavimo modelį, kurį vadiname *ALICE* (*aritmetinis logaritmas, iliustruojantis kultūrinius mainus*). ALICE suteikia tvirtą pagrindimą, kad informacija lemia BAPM elgseną ribų zonose. Teoriškai ALICE palaiko bendrą informacijos srauto modelį ir atitinkamus kultūrinius pokyčius per bet kurią besiribojančių kultūrų ribą. Jis taip pat modeliuoja visuomenės elgesį pusiausvyros ir pusiausvyros sutrikimo laikotarpiais, kuriuos sukelia sustiprėjęs streso poveikis. Išnagrinėjus ALICE modelio rezultatus ir logiškai ekstrapoliuojant jų poveikį BAPM, buvo sudarytos aštuonios naujos patikrinamos teorijos, reguliuojančios informacija pagrįstą kultūros evoliuciją.

# ALICE'S ADVENTURES IN COMPUTATIONAL MODELLING OF THE SUB-NEOLITHIC BOUNDARY: CURIOUSER AND CURIOUSER GOVERNING DYNAMICS OF THE ADAPTIVE MORPHOGENESIS OF CULTURE

Christopher Barber Troskosky, Tianyu Chen, Katie Nicole Troskosky

Summary

In this paper we explored the nature of information transmission both between and within unstratified societies which are in contact under various levels of stress affect forcing.

Using a computer simulation, the Arithmetic Logarithm Illustrating Cultural Exchange Model (ALICE) we verified the proposed causality mechanism of the theoretical Unified Agricultural Frontiers Model (UAFM) structuration model for cultural interaction across agricultural frontier zones. The 2019 paper concluded that the scale independence and non-linear dynamics inherent in self-organized criticality models were the correct lens to be used to study the micro level behaviour which allowed for punctuated equilibrium in the UAFM. This allowed for the large and very fast variances in material culture assemblages in the Neman Basin during the Corded Ware migration around 2900 BC. This migration followed an ~1000 year period in which agricultural information did not enter the Neman Basin even though it was widely available on the North Polish Plain; a result for which the model also accounts.

The micro level phenomenon of information driven change demonstrated (crudely but effectively) in this paper confirm that the ALICE model is a compatible driver for the UAFM model proposed in 2019. Thee ALICE models also suggests governing dynamics for how different cultures on the same landscape must adapt via the incorporation of new information derived from their neighbours or perish following Van Valen's Red Queen Hypothesis (Van Valen, 1973; 1977). This in turn has relevance on the type of adaptive morphogenesis which cultures must go through. We argue that as suggested by Gould (2002) there is mounting evidence that culture adapts in a manner more Lamarckian than Darwinian.

The UAFM and the ALICE model are important as a tool in their own right both theoretically and practically for the analysis of frontier zone dynamics. The governing dynamics for the exchange of information between contemporary cultures on the landscape may be used to practically to analyse and narrow the path dependent series of past events which most likely based on the confidence criteria of: relevance, adequacy, completeness, and parsimony. This is in contrast with ethnographic facing explanations using strictly simple statistical testing for only completeness which are almost uniformly underfit in archaeology (Perrault 2019). In combination with archaeological material data they can be used to greater effect tracking direct markers of information exchange over space and time. Examples of both were utilized in the text concerning claims about the nature of Corded Ware migration into the Neman Basin and the punctuated equilibrium nature of the processes inherent in the adoption of agriculture group to group. This should hold regardless of what landscape an early agricultural frontier is located on geographically or temporally as long as oth ocieties involved are non-ranked.

Further work will be undertaken constructing models of ranked societies using additional adaptions of the same basic methodology to see if the same governing dynamics hold for more complex societies. The Several Population Query Research model (SPQR) is currently under development to model the internal dynamics of information flow within a ranked society consisting of two units one elite one non-elite.

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