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Agent-based Modeling Simulation of Social Adaptation and Long-Term Change in Inner Asia*

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Summary. We present a new international project to develop temporally and spatially calibrated agent-based models of the rise and fall of polities in Inner Asia (Central Eurasia) in the past 5,000 years. Gaps in theory, data, and computational models for explaining long-term sociopolitical change—both growth and decay—motivate this project. We expect three contributions: (1) new theoretically-grounded simulation models validated and calibrated by the best available data; (2) a new long-term cross-cultural database with several data sets; and (3) new conceptual, theoretical, and methodological contributions for understanding social complexity and long-term change and adaptation in real and artificial societies. Our theoretical framework is based on explaining sociopolitical evolution by the process of "canonical variation".

Keywords: computational social science, agent-based modeling, environmental adaptation, political development, social complexity, Inner Asia, MASON toolkit

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1. Motivation and Purpose

Inner Asia is the heartland of the Old World, a "bridge" and large-scale social network linking Asia and Europe across the steppe, and a laboratory for understanding long-term social and political adaptations in the face of great challenges—domestic and foreign, human and physical. Depending on the epoch, Inner Asia has fluctuated from being a core with influence on neighboring regions (China, Russia, South Asia, Eastern Europe, and the Middle East), to a passive-reactive periphery of such regions. The nomads, long-distance contacts and exchange, rapid transport technologies, and complex polities of Inner Asia offer opportunities to develop and test new theories on the emergence of horizontal and vertical polities (Ferguson & Mansbach 1996) as dynamic adaptive responses to social and environmental changes. We use *diachronic data*, from texts and from three archaeological projects located on a north-south transect in the Mongolian steppe, and develop *agent-based simulation models* that build upon and extend extant computational social science models to generate the emergence of multi-scale networks over space and time. Our project aims to contribute towards a better understanding of social dynamic responses and collective behavior.

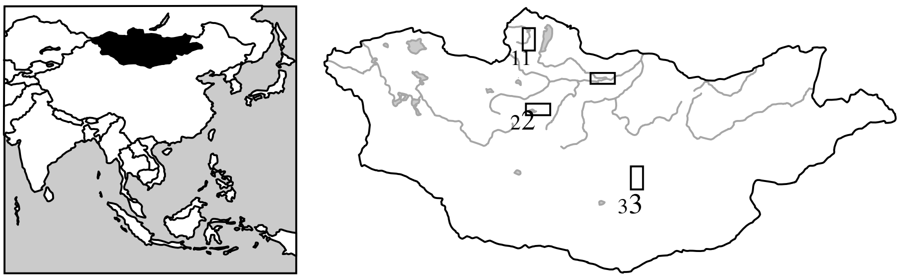

Figure 1. Inner Asia and Mongolia showing active survey sites. (1) Darkhat-Muron, (2) the Khanui and Terhiyn Valleys, and (3) Baga Gazaryn Chuluu. Unnumbered area represents a prior survey dataset at Egiin Gol (1996-2000).

1.1 Research Goals

We build on extant efforts in *computational* historical dynamics (or agent-based "cliodynamics"; paraphrasing Turchin 2003: 2004; Parisi 1998) by pursuing three synergistic goals:

(1) to develop, test, and analyze a new interdisciplinary theory of long-term societal change and adaptation to complex and evolving social and physical environments, a generative theory formalized by a spatial multi-agent computational model;

(2) to contribute to the shared understanding of social complexity in the social sciences, by integrating concepts and principles within the proposed theoretical framework and research methodology; and

(3) to produce and disseminate new interdisciplinary data created by this project, such as a new long-term dataset and diachronic atlas of Inner Asian polities.

1.2 Observed Facts

The space-time universe of human and social dynamics—world system history (Cioffi-Revilla 2006)—is vast and heterogeneous in terms of origins and long-term evolution of social complexity and environmental diversity. Regions of social space-time with great dynamism and originality (e.g., Asia in recent millennia) mix with others where social complexity was less pronounced (e.g., North America 5000 years ago). The long-term fabric of social transformation is not all woven of the same material. Significant differences and regularities occur in human and social dynamics across space and time (Peregrine & Ember 2004; Flannery 1999; Marcus 1998), so comparative research is essential.

Inner Asia consists of Mongolia, Inner Mongolia, Tibet, Manchuria, Eastern Turkestan [Xinjiang], and parts of eastern Central Asia and southern Siberia (Lattimore 1940) and we focus on the Mongolian steppe (fig. 1 above). The importance of this region for understanding socio-political development and international dynamics is well-known, as Inner Asia gave rise to some of the world's most expansive empires. From the 3rd millennium BC onward, the eastern steppe of Inner Asia showed significant variability in environment, productive resources, subsistence practices, and sociopolitical organization, as well as diverse networks of inter-cultural contact—including the famed Silk Road network (from ca. 200 BC; Malkov 2004, 2005). From the end of the 1st millennium BC several hierarchical, centrally integrated, and militarily powerful polities emerged in Inner Asia, including the Xiongnu, Turk, Uighur, and Khitan states (Rogers 2007). The 13th century AD/CE witnessed the Mongolian empire, from the Sea of Japan to the Mediterranean Sea. The immensity of Genghis Khan's imperial project and it's cultural, political, and economic effects have long challenged scholars to explain how a relatively obscure group of steppe nomads managed to conquer and rule such a substantial swathe of the Old World. According to anthropological models, *steppe conditions* (productive instability, low population density, high mobility) lower the potential for complex socio-political organization and favor more egalitarian polities (Barfield 2001; Salzman 1999; Johnson and Earle 2000). By contrast, there is compelling evidence that by the early 1st millennium BC, patterns of political complexity—and greater collective action capacity (*asabiya*; Turchin 2003, from Ibn Khaldun)—characterized small groups (later polities) in Inner Asia (Shelach 1999; Tsybiktarov 1998; Askorov et al. 1992; Hiebert 1992).

1.3 Theoretical Deficits

Social complexity is a measure of differentiation and integration in a society and is characterized by hereditary social hierarchy, occupational specialization, centralized decision-making, and governance capable of providing social viability in the face of emerging challenges. Complex societies range from small-scale groups with simple hierarchies to the highly specialized, multi-stratified, integrated polities of the modern world. Some of the most viable theories of sociopolitical development today are interdisciplinary (Epstein & Axtell 1996; Feinman & Marcus 1998; Flannery 1999; Turchin 2003) and they aim at integrating social and environmental dynamics using diverse scientific concepts and principles appropriate to the complex topic of long-term political development.

Needed is an interdisciplinary theory that builds on extant progress with diverse anthropological, economic, sociological, political, psychological and environmental dynamics. Such a theory should be constructed with concepts and principles appropriate for the ontology of social complexity and polity interactions, unobstructed by disciplinary boundaries. Formally, the new methodological paradigm of object-based modeling is ideal for modeling and understanding human and social dynamics, based on well-defined attributes and behaviors instantiated in computational models of evolutionary adaptive agents capable of self-generating and sustaining higher-order social complexity on multiple scales.

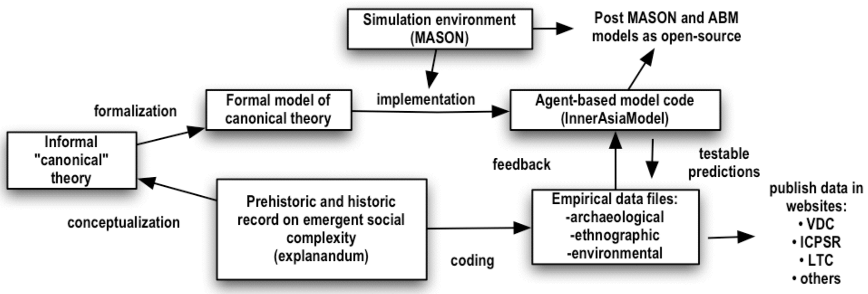

Figure 2. How data, theory, and computational models are integrated in our project.

The empirical record (observed facts or main *explanandum*) on social complexity in Inner Asian is our point of departure (fig. 2, bottom). This is used to inform our theory, build agent-based simulations (conceptualization → formalization → implementation), and for validating, calibrating, and testing the simulations (feedback from testing). Results from the simulation and empirical files are used to test and refine the computational model, as detailed in the next sections.

2. Theoretical framework

2.1 Conceptual framework: Change, response, and the social dynamics of complexity

The processes emphasized in recent anthropological models include prestige-biased cultural transmission, ambitious agents, social leadership dynamics and technological change, manipulation of ideological and material media, and strategic management of intra- and extra-group relations (Cioffi-Revilla et al. 2005). Collective action capacity (*asabyia*) is important in Turchin's "metaethnic frontier" model (2003)—arguably the most advanced formal *and* empirically tested theory today ("clearly the state of the art in formal modeling and computer simulation of long-term historical changes in territorial states"; Collins 2003). Korotayev et al. (2006) present a related project on long-term world macrodynamics.

Situational changes produce transfers of information between individuals and their environments, causing the former to sometimes coalesce into social relationships that span new networks. Such a system is "complex" in the sense of von Neumann (1951), because it is iteratively capable of generating increasingly more complex successors. Individual agency occurs in these processes, enabled by opportunity and willingness such as provided by extant relations, cultural precedent, and resource and environmental constraints (Cioffi-Revilla & Starr 1995). As with other networked phenomena, social networks grow opportunistically, preferentially, and through a nonlinear "punctuated" process with connectivity governed by power laws. When successful, collective action yields new bonds between individuals, forging new relationships based on shared knowledge and experience, and contributing to the emergence of norms, processes, and institutions that constitute social complexity. These, in turn, increase a group's or a polity's collective action capacity (*asabyia*) as a mission-critical sociopolitical resource.

2.2 Canonical theory: The process for emergent social complexity (fig. 2, left)

We use the "canonical theory of social complexity" developed by Cioffi-Revilla (2002; 2005), formally derived from the general theory of political uncertainty (Cioffi-Revilla 1998). As a *canonical* theory, the iterative and uncertain process of institutional emergence and political development (and occasional decay) is explained as resulting from a succession of non-deterministic phase transitions that occur in space-time, based on path-dependent *variations* on a *common theme* called the *"fast" branching process*. As each canonical variation of the same "fast" process occurs for a given society, social complexity may accrue, decrease, or remain the same, producing the "slow" accrual process based on emerging experience, statecraft, bonds of trust, norms, institutions and other collective goods. Negative externalities may also be produced, leading to decay in sociopolitical complexity, as explained below. The canonical theory explains sociopolitical evolution by the process of canonical variation.

2.2.1 The "fast"(micro) process at the agent level. Figure 3 shows the main events in the "fast" canonical process, denoted by **G**, **C**, **N**, **U** and **S**, and their failure modes ~ **C**, …, ~ **S**. The process as a whole generates a political sample space Ω (outcomes on the right). Social complexity emerges (event **S**, the top outcome in Ω) as a path-dependent phase transition produced by a process of several different albeit specific outcomes. The full model (not shown here) has five other detailed sub-trees (triggering or production rules) for generating each of the five main events in the "fast" branching process (Cioffi-Revilla 2005).

The *first stage* begins when an existing group lacks a system of government (i.e., the community is not yet a polity, event **G** in fig. 3, left) and *may* end in a different situation (politically complex phase) when such a community has formed a system of government (the community is a polity after iterations of the event **P** in fig. 3, top right). In Inner Asian this occurred up to the early Neolithic period, during which time not even chiefdoms are archaeologically observable. The process had begun by 2500 BC (*terminus ante quem*).

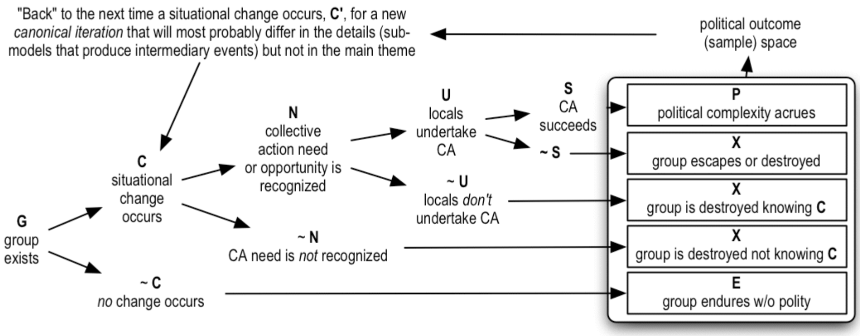

Figure 3. Canonical theory of social complexity: the "fast" iterative branching process. In turn, each main event (G, C, N, U, S, and complimentary failure modes) has an associated causal model in conditional logic, such that the composite causal structure (branching process with all component sub-models) constitutes a sequential-conditional model (Cioffi-Revilla 1998:239-41; 2002; 2005).

A situational change makes a group *metastable*, because a *potential* for increased (decreased) sociopolitical complexity is created, but not immediately realized. The realization of a potential for complexity depends on how the rest of the fast process evolves and on how people and environments interact. Xiongnu and Mongol societies succeeded; many others failed.

Given a situational change (**C**), the group may or may not *understand the need for collective action* caused by the change (event **N** in fig. 3, after **C**). Causally, **N** is an information-processing event, involving signal detection, cognition, and other causal events, and is modeled accordingly. If the group does *not* understand the situational change, it may be destroyed or dispersed without further political development (outcome $\mathbf{X^*} \in \Omega$); hence the critical role of intelligence.

If the group grasps the situational change, it may or not be willing and able to *undertake collective action* (**U**), depending on its capacity (*asabiya*). Collective action occurs in several modes (Lichbach 1996), detailed in Cioffi-Revilla (2005). Sometimes society fails to undertake collective action (~**U**), even when it understands a situational change **C**, by incapacity. If collective action occurs with persistent situational change, then *it may succeed* (**S**) *or fail* (~**S**), depending on the situation and action. If it fails, society may be destroyed (outcome $\mathbf{Z} \in \Omega$). The

Mongol federation succeeded; others failed and were absorbed or destroyed as the Mongol imperial polity expanded. Several outcomes in the outcome space (events denoted by **X**) can all eventually lead to state failure, for example by long-term loss of collective action capacity.

Finally, if the society succeeds at time t, then the consequences or societal effects will augment its political complexity (outcome $\mathbf{A} \in \Omega$) at time $t + 1$, because—even if only on a small scale and temporarily—mobilization of resources, lessons about who to trust, hierarchies of leaders and followers, specialized assignments, division of labor, information sharing, coordination experience, and other elements of governance will have been realized through the experience. Significantly, collective action capacity (CAC) for dealing with the next situational change (threat or opportunity) will increase. The phase transition in the quantum increase in CAC is observable by the formation of multiplex networks on several scales: cognitive, individual, group, and institutional. Such a phase transition has enduring organizational effects on the group, and the next time their situation changes and demands collective action they will draw on more CAC and cope better; they will have more governance experience than before. The phase transition also means the *realization* of the *potential* that had been created by the earlier situational change, when the group had become *metastable* after the initial phase.

2.2.2 The "slow"(macro) process at the societal level. A single passage through the "fast" canonical process was just described. Over time, a group will experience many such processes, each as a variation on the common theme of challenge-response. Failure paths lead to political decay or even destruction (events beneath **P**), so gains in political complexity are not preordained (*asabyia* is not produced automatically).

In Inner Asia the slow process at the societal level eventually generated state-level polities (Xiongnu, Türk, Uighur, Khitan, Mongol empire, and others) and some failures. The Xiongnu polity formed ca. 200 BC *because* the Xiongnu society at that time was able to overcome, through collective action, a situational change given by Chinese attacks from the south, which took place while the Xiongnu had a pre-state system of government. Had Xiongnu society failed in their collective action it would have transitioned into one of the other forms of social complexity in the outcome-space Ω. For example, it may have been destroyed, conquered, or dispersed (event **X**). The latter were failure instances in dealing with invasions, economic, demographic, or environmental changes. For example, power struggles after the 15^{th} century produced political decline and Mongolia was eventually conquered by the Manchus in the 17^{th} and 18^{th} centuries.

3. Towards computational implementation

3.1 Model instantiation and analysis with MASON

The canonical theory is being instantiated with an agent-based model in the new MASON simulation environment (http://cs.gmu.edu/~eclab/projects/mason/).

MASON is a fast, easily extendable multiagent simulation library with visualization tools and other modules, and is a joint effort of Sean Luke (original creator of MASON) and Cioffi-Revilla. MASON has been co-funded by George Mason University's Evolutionary Computation Laboratory and GMU's Center for Social Complexity. MASON was explicitly designed to foster cross-fertilization between computer science and the social sciences, and so supports the interdisciplinary goals of NSF's Human and Social Dynamics Priority Area.

Other discrete-event multi-agent simulators exist, but MASON meets our design criteria better than other systems because it is faster, portable, completely separable (visualization-modeling), with checkpointing and guaranteed replicability (Luke et al. 2005). These MASON features are essential for our goals, including the special needs of evolutionary computation.

3.2 Inner Asia Agent-Based Model

"ModelofInnerAsia" (MIA; fig. 4) will be a simulation that instantiates the canonical theory (fig. 3)—a model for understanding polity fluctuations produced by societal responses to challenging changes, in the tradition of earlier territorial competition models (Cioffi-Revilla & Gotts 2003). The objective is to *generate pristine social complexity over a territory*, not evolve pre-existing polities. The design principle is to build the ABM using the "fast" and "slow" dynamics of the canonical theory, which endogenizes the process of collective responses (or failures).

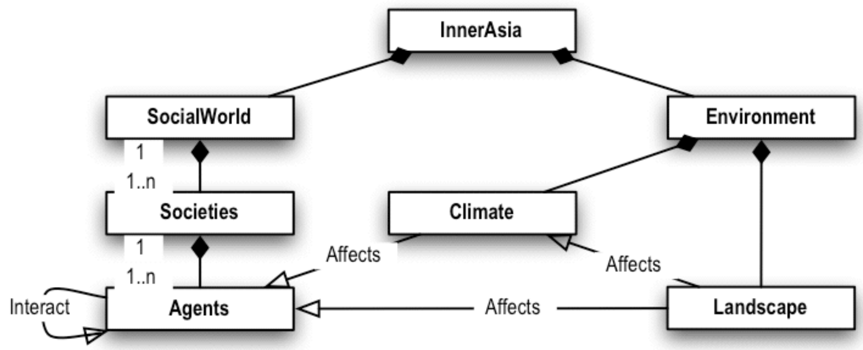

Fig. 4 Computational objects (social agents, groups, environments) that compose the InnerAsia model

The planned simulation will have individual-agent granularity during the initial process when collective action capacity (*asabyia*) is relatively low and limited to group hunting skills: elements of leadership, intelligence, coordination, some logistics. MIA will be developed as a "research programme" (Lakatos 1970) through a sequence of models with progressive problemshifts. The models will form a hierarchy from local to global, each model aggregating and abstracting results of the previous model.

Model I will consist of a single group of human agents in a simple environment, to understand the fundamental human and social dynamics of the "fast" branching process (fig. 3 earlier). This model will explore the complete outcome space, particularly the relative frequency for the "top *explanandum* event" (accrual of social complexity by successful collective action). We will draw on the Wetlands model in MASON (Cioffi-Revilla et al. 2004; see Fig. 5 below), given its focus on hunter-gatherer groups or households that exchange information in a changing environment where minimal sociality emerges. Basic land-use patterns are already present in the Wetlands version of Model I, since groups make differential use of the landscape (feeding, transit, shelter, etc.).

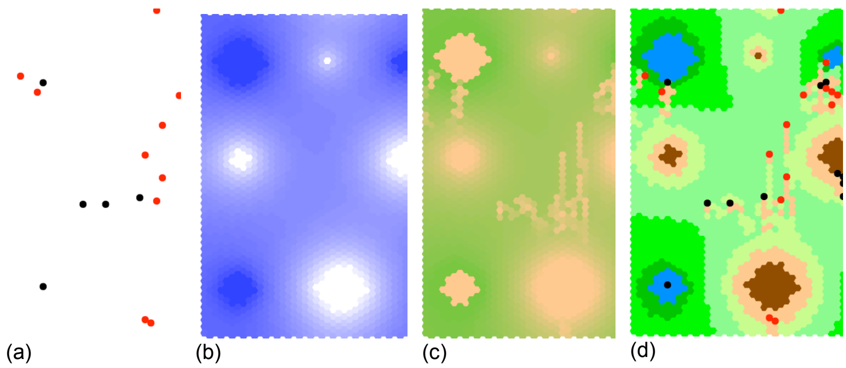

Figure 5. The MASON Wetlands simulation (Cioffi-Revilla et al. 2004) separates computation from visualization to increase speed and computational power. The visualization layers portray the spatial distribution of (a) ethnic groups, (b) climate (dark blue is very rainy, white is dry and offers shelter), (c) food sources (green), and (d) the composite Wetlands world with nomadic groups searching food, seeking shelter and adapting to climate.

Model II will expand the environments and groups, to grow the first chiefdoms or interaction network of simple autonomous polities. Model II will explore why some groups evolved politically complex societies in some ecotopes and others did not. An explanation based on the canonical theory would use *asabyia* as a key causal variable (group cultural attribute). Model III, will be calibrated to run for a "long" historical period, similar to the duration for the first state-level Xiongnu system to emerge (ca. 200 BC). Each model will increase the space-time scale of the simulation, from local to increasingly global, with several mesoscales.

The main simulation loop for each time step will be formalized from the canonical theory, starting from what triggers situational changes (event **C**, fig. 3) to the production of one of the political outcomes in the outcome space of the "fast" branching process (**P** or one of the **X** failure events in fig.3). The loop will include explicit situation-dependent information-processing (Devlin 1991; Simon 1996), multi-mode decision-making, collective action problem-solving processes (Lichbach 1996) including CA capacity dynamics (Turchin 2003), and opportunity-willingness conditioning (Cioffi-Revilla and Starr 1995; Starr 1978). The main loop always begins from situational change **C**. Sigmoid functions for modeling various "tipping point" triggers (called driven threshold systems in complexity theory; Rundle et al. 1996) will be developed, including modeling the probability of new object formations as complexity evolves.

3.3 Model Calibration and Verification

We aim at level 2 or 3 models (Axtell-Epstein scale) capable of replicating the evolution of political landscapes with sufficient detail for historical recognition. In addition to hand-calibration of the model based on empirical data, the model will also autocalibrate using global stochastic optimization techniques such as *Evolutionary Computation* (EC) (Fogel & Michelewicz 2000; Mitchell 1996; see Gilbert and Troitzsch 2005: ch. 10 for an overview of EC in social simulations*)*. EC iteratively makes small modifications to the model parameters and rules (i.e., it evolves the code), tests those modifications against a set of known data (the *training set*), and updates model parameters and rules based on feedback from testing, eventually producing a model that fits the data as closely as possible. EC and related methods have been successful at discovering or calibrating models in ant colony optimization, competitive game-playing, and robot team simulation. The techniques may also be used to increase model robustness by selecting a subset of parameters over which we wish the model to produce invariant results. The EC then tries to optimize the model in the face of changing settings from these parameters; such changes may also be co-adaptive to the optimization system.

The primary challenge for EC is model complexity (hence speed). If the model takes a long time to run, it will be challenging to use in an EC framework requiring large numbers of runs. But, while EC is not central to our project, we *will* be able to demonstrate the efficacy of these techniques on a model of this size. Co-PI Sean Luke has developed a popular stochastic optimization system called ECJ (EC in Java; www.cs.gmu.edu/~eclab; Luke 2000), specially designed to deal with large-scale models. ECJ dovetails well with MASON.

After calibrating the model through hand tuning and computer optimization, we will then validate the final model against a separate *validation set* of data to claim generality—by comparing distributions and stochastic functions, logit models, statistical moments, life tables of actors, settlement and land-use patterns, Markov processes, counting processes, and other features in the databases. Our virtual histories must match the real histories obtained from the archaeological, ethnographic, and environmental data.

5. Conclusions

Our project is motivated by gaps and deficits in theory, data, and computational models for explaining long-term sociopolitical change in terms of both development and decay. We anticipate three contributions to our understanding of human and social dynamics in response to change and long-term adaptation: (1) a new theoretically-grounded simulation model validated and calibrated by the best available data; (2) a new long-term cross-cultural database with several datasets; and (3) new conceptual, theoretical, and methodological contributions for understanding social complexity and long-term change and adaptation in real and artificial societies. Our theoretical framework is based on explaining sociopolitical evolution by a process called "canonical variation". We have provided an initial roadmap for these contributions in the sections of this paper. Besides their intrinsic value, each contribution can provide foundations for further scientific advances in theory, data, and methodology, as well as suggest new lines of scientific investigation.

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