Endogenizing geopolitical boundaries with agent-based modeling

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Agent-based modeling promises to overcome the reification of actors. Whereas this common, but limiting, assumption makes a lot of sense during periods characterized by stable actor boundaries, other historical junctures, such as the end of the Cold War, exhibit far-reaching and swift transformations of actors' spatial and organizational existence. Moreover, because actors cannot be assumed to remain constant in the long run, analysis of macrohistorical processes virtually always requires ''sociational'' endogenization. This paper presents a series of computational models, implemented with the software package REPAST, which trace complex macrohistorical transformations of actors be they hierarchically organized as relational networks or as collections of symbolic categories. With respect to the former, dynamic networks featuring emergent compound actors with agent compartments represented in a spatial grid capture organizational domination of the territorial state. In addition, models of ''tagged'' social processes allows the analyst to show how democratic states predicate their behavior on categorical traits. Finally, categorical schemata that select out politically relevant cultural traits in ethnic landscapes formalize a constructivist notion of national identity in conformance with the qualitative literature on nationalism. This ''finite-agent method'', representing both states and nations as higher-level structures superimposed on a lower-level grid of primitive agents or cultural traits, avoids reification of agency. Furthermore, it opens the door to explicit analysis of entity processes, such as the integration and disintegration of actors as well as boundary transformations.

A decade ago, the Soviet Union ceased to exist, Yugoslavia started to disintegrate, and Germany reunified. Marking the end of the Cold War, these epochal events illustrate vividly that change in world politics features not just policy shifts but also can affect states' boundaries and, sometimes, their very existence. Clearly, any theory aspiring to explain such transformations or, more generally, the *longue durée* of history, must endogenize the actors themselves.

The current paper describes how agent-based modeling can be used to capture transformations of this boundary-transforming kind. This is a different argument from that advanced by most agent-based modelers, who resort to computational methods because they lend themselves to exploring heterogeneous and boundedly rational, but otherwise fixed, actors in complex social environments (1, 2). Without discounting the importance of this research, I will use illustrations from my own modeling framework to illustrate how it is possible to go beyond this mostly behavioral agenda. The main emphasis will be on the contribution of specific computational techniques to conceptualization of difficult-to-grasp notions such as agency, culture, and identity. Although a complete specification of the models goes beyond the current scope, the paper closes with a discussion of some of their key findings.

Because historians and historical sociologists relying on qualitative methods have pioneered the study of boundary change, the power of formal modeling remains almost entirely untapped. The crux is that conventional formal methods are not very helpful in these contexts because they treat actors as either reified or implicit. Rational-choice theorists build stable and fixed actors into their assumptions (3) and are even reluctant to let preferences vary (4, 5). In quantitative models, actors' identities figure only indirectly as ''cases'', although a somewhat stronger sense of agency can be restored through a merger with the rational-choice modeling. At any rate, both approaches converge on an ''essentialist'' and ''variable-oriented'' position that postulates ''that the social world consists of fixed entities (the units of analysis) that have attributes (the variables)'' and thus ''ignores entity change through birth, death, amalgamation, and division'' (6).

As illustrated by the process after the Cold War, however, it is precisely these ''entity processes'' that call for explanation. We cannot explain what is explicitly held constant or treated as an implicit assumption. Therefore, a ''sociational'' perspective seems more promising. Pioneered by Georg Simmel (7, 8), such a sociational (*vergeselleschaftung*) approach has had many followers who use similar concepts including ''figuration'' (9), ''structuration'' (10), and ''relationalism'' (11). This family of views claims that ''relations between terms or units as preeminently dynamic in nature, as unfolding, ongoing processes rather than as static ties among inert substances'' (10). Processes of this kind exhibit path-dependence and sensitivity to initial conditions. Moreover, rather than always following time-invariant laws, social action and boundary processes take place specifically in relational and/or geographic space. Whereas the essentialist perspective subscribes to a one-way explanation according to the formula ''actions produce interactions'', sociational theory insists on processes in which ''actions produce interactions that in turn transform the actors.''

Toward Sociational Modeling of Geopolitics

Although the sociational alternative offers ontological flexibility, it also complicates theory-building by relying on more moving parts. Paradoxically, the high degree of endogeneity makes formal tools, which help guarantee internal consistency and conceptual clarity, even more needed than in the simpler settings studied by essentialist theories. With few exceptions (12), however, scholars relying on sociational principles have refrained from formalizing their theories.

Given the inherent level of complexity of macrohistorical processes, it would seem natural that computers could help fill this analytical void (13). Yet, traditionally, computational methods have centered on variable-oriented simulation, such as global

This paper results from the Arthur M. Sackler Colloquium of the National Academy of Sciences, ''Adaptive Agents, Intelligence, and Emergent Human Organization: Capturing Complexity through Agent-Based Modeling,'' held October 4–6, 2001, at the Arnold and Mabel Beckman Center of the National Academies of Science and Engineering in Irvine, CA.

Abbreviations: EP, Emergent Polarity; DP, Democratic Peace.

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 www.pnas.org/cgi/doi/10.1073/pnas.082081099

Table 1. Four types of social contexts

	Relational boundaries	Categorical boundaries
Interaction processes	*i*	*iii*
Entity processes	*ii*	*iv*

modeling with predictive aims (14). Although its structural approach differs from the individualism of rational-choice theory, such research relies on similar essentialist assumptions as does statistical modeling (15). By contrast, agent-based modeling is a computational methodology that allows the analyst to create, analyze, and experiment with artificial worlds populated by agents that interact in nontrivial ways and that constitute their own environment. Instead of studying variables that measure the actors' attributes, these models can (but do not have to) represent social actors as inherently changeable processes.

In fact, most agent-based models are used to tackle essentialist research puzzles. Indeed, the overwhelming majority of social-science applications capture the behavior of human individuals, such as consumers (16) and voters (17). Although evolutionary game theory (18) and ecological organization theory (19) have made some progress toward analyzing existential entity processes, endogenous boundary formation remains mostly beyond the reach of deductive techniques. Other agent-based frameworks analyze boundary change explicitly: computational organization theory is, perhaps, the best example (20). Here, I will focus on boundary change (merger and division) as it applies to geopolitics, although existential entity processes (creation and destruction) will also receive some attention.

Boundary processes express themselves both physically in spatio-temporal terms and organizationally. Because of the positivist quest for general laws expressed in terms of context-free variables, the spatio-temporal context of actors remains notoriously understudied in the social sciences, although there are exceptions, e.g., (21, 22). The endogenization of organizational boundaries leaves even more to be desired. Drawing on Simmel's work (7, 8) and more recent research by the sociologist Harrison White (23), I classify organizational boundaries as either relational or categorical. Relational boundaries demarcate organizations in terms of direct interpersonal or interorganizational contacts such as friendship networks. By contrast, categorical membership criteria operate indirectly through identification with cultural symbols (24). As will become clear below, agent-based modeling lets us express this fundamental difference explicitly.

Table 1 summarizes four types of social contexts in which actors can be embedded. The rows separate social processes, which do not affect actors' boundaries, from sociational ones that do affect actors' boundaries. The columns distinguish between actors with relational and categorical boundaries. This taxonomy creates four quadrants, with the upper left one (*i*) representing the standard mode of analysis in the vast majority of social-scientific models.

The remaining three possibilities are the ones that are relevant to this paper. Contexts of type *ii* transform actor boundaries that are relationally defined. As the next section shows, state formation before the era of nationalism approximates this context together with *i*. Quadrant *iii* captures actors constellations with categorical but fixed boundaries where the interaction processes are influenced by boundary categorization. A second example, drawn from the international relations literature, illustrates this mode of analysis. The phenomenon of evolving clusters of cooperative democracies combines quadrants *i*, *ii*, and *iii*. Finally, a third nested model of nationalism in a dynamic-state system brings together all four contexts.

Power Politics as a Relational Entity Process: The EP Model

Although the sociational perspective rejects the notion of presocial actors, it needs to start somewhere. Rather than privileging either the micro or macro level, as essentialist theories do, the solution is to postulate a "soup of preexisting actors" (25) that will serve as the "raw material" for the construction of higher-level actors. Although some of these primitive agents may assume a particularly pivotal role, most of them are no more interesting than single pixels on a computer screen. Because it is the macrolevel patterns that are of interest, this "finite-agent method" of sociational analysis treats the primitive agents as constant and presocial "atomic units" throughout the analysis without running the risk of reifying agency at higher levels of aggregation.

Fortunately, these ideas can be translated readily into computational language. In an experimental model of ecological morphogenesis called ECHO, John Holland lets "primitive agents" amalgamate into "multiagents" through a process of boundary formation where one agent becomes the head of the new composite entity, and others are relegated to the status of "agent-compartments" (26). This particular way of forming collective actors strongly resembles state formation.

In fact, already in 1977, Bremer and Mihalka (27) introduced a model of this type featuring conquest in a hexagonal grid, which was later extended and further explored by Cusack and Stoll (28). While drawing inspiration from this line of research, my own framework was implemented from scratch. After a first implementation in PASCAL (29), I ported it to the software package SWARM, and shortly thereafter to REPAST (available at http://repast.sourceforge.net.). Modeled on SWARM, REPAST is an object-oriented software library for agent-based simulations. Like its predecessor, it facilitates model representation and offers infrastructural routines for running simulations, the display of graphics and charts, and data collection. Because REPAST is entirely based on Java, it provides a number of advantages that make it particularly well suited for the modeling of entity processes. First, Java's object orientation allows for convenient representation of actors in memory with a unique identity (30). Unlike variables, actors modeled as object instances reside dynamically in memory and, thus, can both be born and die. Second, Java's standardized collection library and REPAST's powerful support for two-dimensional grids facilitate the modeling of both territorial and organizational boundaries of higher-level actors as hierarchical or flat networks. Geopolitical change affects the relational portfolio of states constantly, thus requiring a flexible representation. Third, in terms of programming, garbage collection makes life easier in modeling very complex frameworks. Fourth, the powerful visualization techniques of Repast help researchers discover patterns that then can be further explored in systematic replications, which are also well supported by the software package.

The basic version of the formal framework is called the Emergent Polarity (EP) model, because it treats polarity, i.e., the number of sovereign states, as an emergent feature (29). As in Bremer and Mihalka's original setup, the EP model usually starts with a territorial grid of fixed and indivisible primitive agents that can be thought of as villages or counties. The states that survive grow and their boundaries expand endogenously through a repeated process of conquest. The resulting states become hierarchical organizations linking capitals to their respective provinces through direct, asymmetric relations of domination. Denoting state borders as lines and capitals as dots, Fig. 1 illustrates a system that evolves from an initial setup featuring 15 by 15 states to 9 states. Thus, as its name suggests, the very

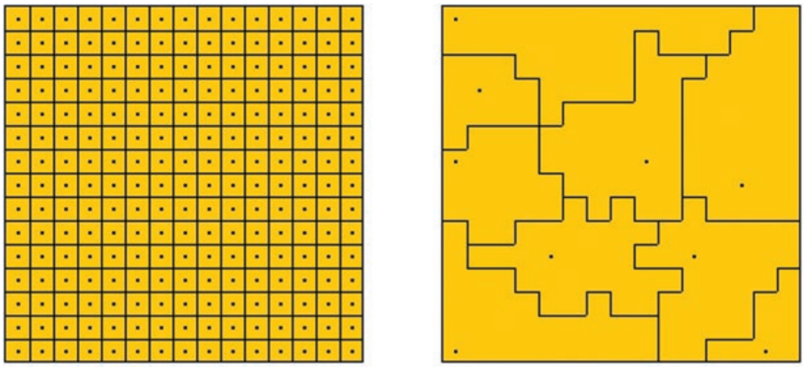

Fig. 1. The emergence of a multipolar balance-of-power system.

polarity of the state system emerges as a consequence of the state-formation process itself.

Thanks to the hierarchical design, the capitals retain full control of their foreign policy and decide on peace and war on behalf of their provinces. In the simplest version of the EP model, conquered provinces lose all of their agency rights. The capitals, by contrast, hold relational portfolios recording interactions with each sovereign territorial neighbor.[†] As opposed to Bremer and Mihalka's framework, all actions proceed in quasi-parallel as a Markovian process using the portfolios as a double buffer. This synchronous design allows for protracted and simultaneous conflicts that do not follow a preset protocol and that expose the states to geo-strategic problems of front allocation.

Because the focus in this paper is on how to endogenize actor boundaries, I will not provide a full description of the model's behavior. The interested reader is referred to ref. 31 for a detailed specification of the model. In brief, each simulation cycle comprises five stages: resource allocation, decisions, interactions, resource updating, and structural change. First, all states allocate resources to the local fronts partly in proportion to the overall resources possessed by their sovereign neighbors. Then, a phase of decision-making ensues. Each state plays a strategy of "grim trigger" with the neighbors, which means that they reciprocate any conflictual moves and pursue conflict until the battle is over. In addition, the states attempt to launch unprovoked attacks against their neighbors, provided that the local power balance exceeds a certain threshold in their favor and that they are not already engaged in combat. Typically, this probabilistic threshold is set to a value in the range of two to three. In the interaction phase, the consequences of the states' decisions are derived. If the local resource balance tips decisively in favor of one party, that state wins the battle and can advance a territorial claim. Otherwise, the battle continues, or it may end in stalemate. Normally, an aggressor can count on winning, but attacking states may weaken their other fronts, thus inviting attacks from other parties (32).[‡] Finally, structural change follows, the rules of which will be explained in greater detail.

To simplify the system's topology, it is assumed that territorial boundaries have to enclose a contiguous space. In contrast to single primitive agents, compound states can undergo all four entity processes: (re)emergence, disappearance, secession, and unification. While some states continue to exist since "primordial" times, most of them are eliminated when their capitals are occupied. However, such dominated territories can regain sovereignty as a consequence of the dominating state's collapse (or through secession, if two-level action is enabled). Whereas the political decisions leading to war between two states are made at the state level, conquest is a local process that always concerns the territory of a primitive agent rather than a whole state. This modeling choice eliminates the complicated division-of-spoils procedures in previous models (27, 28). The conquering state A randomly selects one of its own provinces as the attacking agent a from all units that border on the target state B. Then, it stochastically chooses a target province b that is adjacent to a. Together, the attacking and target agents constitute a battle path (a, b). Depending on the status and location of the target b, four types of outcomes are possible: if b is an "atomic" state, then b is absorbed in its entirety; if b is a capital of B, b is absorbed, whereas all other provinces regain sovereignty; if b is a province in B state and absorption b does not cut off access from the capital of B to any of its provinces, then the province is absorbed without any further changes; finally, if b is a province but absorption does cut off access between B and some of its provinces, then b is absorbed and the provinces that are cut off regain sovereignty.[§]

This set of simple rules allows us to endogenize sovereign states' boundaries in a parsimonious way. In addition, the EP model also can be extended to feature a simple mechanism for defensive alliance formation that allows states to balance against threatening states (29, 31). This extension has two behavioral consequences. First, they affect the potential challengers' force calculus by pooling their aligned, would-be victims' resources. Should deterrence fail all of the same, an alliance obliges all aligned states to come to the rescue of any attacked member by opening a front against the threatening state.

Note that whereas the EP model succeeds in endogenizing specific state boundaries, sovereignty itself is "hard-wired" into the specification. Thus, a deeper sense of emergence would require the institution of sovereignty to emerge from a Medieval backdrop of overlapping jurisdictions and fuzzy borders. For examples that outline ways to formalize a more radical sense of emergent actorhood, see Axelrod's "tribute model" (33) and Fontana and Buss (34).

[†]An extension featuring two-level action allows the provinces to enjoy the possibility of seceding on their own initiative and, in that case, they have relations only with their capital. In that scenario, the capitals have to deter attacks both externally and internally. See ref. 29.

[‡]Because of the quasi-parallel design of the model, victorious parties cannot be allowed to incorporate disputed territory directly. Instead, they raise "claims" that are processed once that all interactions are over. Structural change is then executed in random order, while skipping those campaigns that would lead to boundary inconsistencies.

[§]If two-level action is operational, secession proceeds along similar lines. Here, there are two topological situations similar to the two last cases just enumerated. If the province can leave B without compromising the access paths within B, then only the secessionist province becomes independent. If secession cuts other provinces off, then those provinces also are made sovereign.

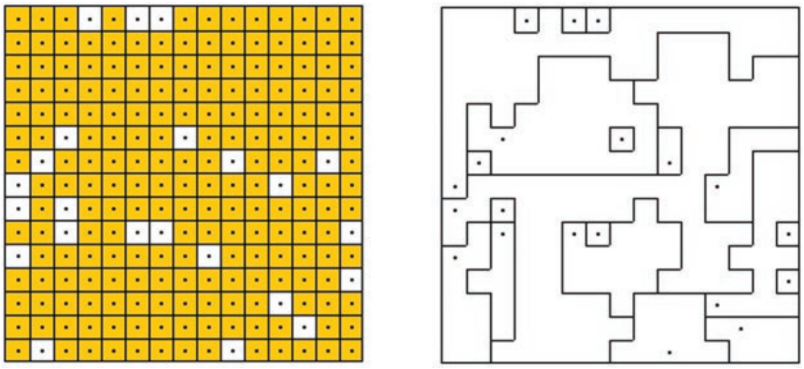

Fig. 2. The emergence of perpetual peace in a system with ideological alliances.

Democratic Cooperation as a Categorical Social Process: The DP Model

So far, we have only considered relational boundaries. The next modeling step introduces social processes including categorically defined coalitions of states (see category *iii* in Table 1). It is a well established fact that democracies do not fight each other (35). What is less obvious, however, is that this pattern has evolved as a macrohistorical process spreading democratic cooperation in time and space (36).

Fortunately, the literature on computational modeling provides conceptual solutions. In a pioneering contribution, Axelrod (37) suggests that spatial contexts and labels provide opportunities for mutual cooperation to take root. An inherent property of the international system, territoriality enables cooperative agents to cluster spatially, thus rendering predatory invasions harder and thus increasing the chances of stable and lasting cooperation. Suggestive findings indicate that localized interactions seem to facilitate the emergence of cooperative clusters. For example, Grim (38) employs two-dimensional cellular automata to demonstrate that once explicit spatial representation is introduced, even more generous strategies thrive (39). Although interactions within the international system are not exclusively local, logistical constraints on military operations remain considerable (40). Thus, the inherently territorial nature of world politics may in fact contribute to the emergence of democratic security communities.

The idea of label-induced collaboration conceives of democracies as conditional cooperators that make their behavior conditional on an abstract category, or a "tag" (41). Tags are reasonably stable actor-specific characteristics that are observed by other agents during interactions and on which their behavior can be predicated. Benign actors tend to profit from selection mechanisms that allow them to adjust their strategies to similarly peaceful partners while minimizing exposure to more aggressive players. Recent computational studies have confirmed that tags can have a considerable positive effect on cooperation. For example, Riolo (42) shows that under a broad range of conditions, agent populations that use tags attain a higher level of cooperation because of faster initial emergence of reciprocity and higher resistance to invasion by mutual defectors (43).

These theoretical ideas are highly relevant to the democratic peace. It is conceivable that democracy could serve as a tag reinforcing the development of a pacific norm regulating interdemocratic relations. Without specifying the specific internal mechanisms of democratic decision-making, the Democratic Peace (DP) model extends the EP model by introducing a second type of actor: democracies (31). These actors are able to recognize each others' regime type so that they never attack each other. The tagging is implemented in such a way that it prohibits democratic states from selecting out other democracies as victims of unprovoked attacks. In addition, thanks to their mutual trust, such states do not have to allocate resources to their interdemocratic fronts.

In accordance with Kant's theory, the DP model also assumes that these states would band together in a liberal coalition, thus defending themselves collectively against nondemocratic incursions. As briefly mentioned in the previous section, the basic EP model can be extended to include alliances as well. In the DP model, a modified democracy-sensitive alliance mechanism introduces behavioral differentiation according to regime type. Whereas purely expansionist states behave according to power-related principles, democracies let ideology influence their alignment decisions. Both types of states align against threatening states, although democracies never feel threatened by other democracies and thus never balance against them. As in the EP model, it is assumed that alliances have both a deterrent and a combat effect.

Marking democracies as white actors and nondemocracies as yellow ones, Fig. 2 displays two snapshots of a sample run that starts with a mere 10% conditional cooperators. By time period 1,000, the entire system has reached a state "perpetual peace", to use Kant's terminology, which is entirely dominated by mutually cooperating democracies. Note that several small enclaves have managed to survive because there are no predatory actors that could absorb them. Although this is merely a sample run, it illustrates that together, tagged clusters with tag-sensitive alliances can produce perfectly peaceful worlds despite intense geopolitical competition.

To some extent, ideological alliances anticipate categorical entity processes of type *iv* (see Fig. 1). At least partially, their boundaries are determined by democratic tags in that democracies only align themselves against nondemocratic states, but the main threat-driven logic remains relational and short term. In this sense, the DP model exemplifies categorical social, rather than sociational, processes. To find a true example of the latter we need to turn to a qualitatively different actor type, namely, the nation.

Nationalism as a Categorical Entity Process: The NSC Model

Nations are stable actor configurations entirely based on categorical membership criteria rather than relational calculations. Distinct from states in the classical Weberian sense, nations already enjoy, or strive for, the possession of their own state (44). When states and nations coincide, the result becomes a nation-state. Nevertheless, this is a contingent outcome, for sometimes states span over more than one nation, and vice versa (29, 45). It is precisely in these complicated situations that the principles of territorial and popular sovereignty clash, thus generating tensions that drive conflict.

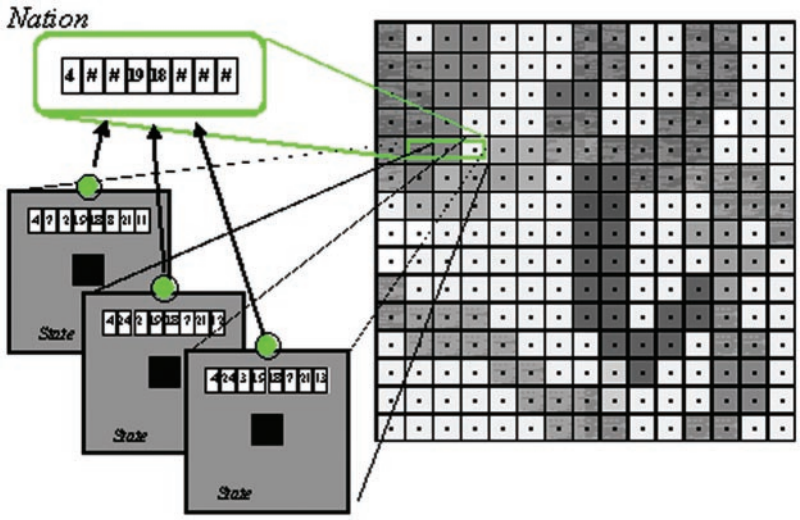

Fig. 3. A cultural landscape with three highlighted states and a nation.

As opposed to reified perspectives that resort to "groupism" (46), the sociational focus on the very existence of national collective identities forces the analyst to consider the puzzle of how nationalism ties together large numbers of people and spans over long time periods and vast territories. In contrast to premodern society which was based on direct interpersonal relationships, the large scale of the nation requires abstract categorization (47).

Thus, modern national identities should not be confused with premodern, ethnic cores: "Nationalism is not the awakening of nations to self-consciousness: it invents nations where they do not exist—but it does need some preexisting differentiating marks to work on, even if . . . these are purely negative" (48). Note that this constructivist perspective draws on the same "finite-agent" solution as Abbott's conception of boundaries, although here the soup of primitive elements is not the actors themselves but a set of cultural differences.

How could one formalize this conception of nationhood computationally? The following describes an extension of the EP model under the label of the Nationalist Systems Change (NSC) model.[¶] Cultural landscapes constitute a good starting point for such a modeling exercise (49), because they provide the cultural building blocks out of which communities can be constructed. Suppose that each primitive agent is equipped with a cultural string with, for example, eight traits, each of which can assume 1 of 25 values. Fig. 3 shows a grid where all of the unitary actors are endowed with cultural strings that form a landscape in aggregation. The darker shading represents cultural differences compared with the surrounding sites.

Inspired by Stuart Kaufmann's notion of tunable landscape, the initial cultural configuration can be made dependent on just two parameters (50). In this case, landscapes are defined by the number of distinct tribes that originally populated the map and by the cultural drift characterizing their settlement of the grid. A large number of tribes and great drift make the landscape more "rugged". This process guarantees that there will be both dialectal nuances as one moves from province to province as well as more abrupt ethnic cleavages.

Although the cultural map has an impact on identity formation, there is no one-to-one correspondence between culture and national identities, because only politically relevant traits count in national identity formation. Fortunately, there is a computational solution to this conceptual problem as well. In an attempt to formalize sets of symbol strings to be used in schemata representing rules, John Holland (51) introduces wildcards (#) for those traits that could be of any value. For example, the string {4, #, #, 19, 18, #, #, #} represents an identity template to which the cultural strings {4, 17, 18, 19, 18, 1, 2, 1} and {4, 17, 25, 19, 18, 7, 9, 11} could belong. It is convenient to represent national identities in a similar way. Let us assume that nations form as "imagined communities" in the public domain and that states could become members of them as long as their culture strings match them. To the left of the grid, Fig. 3 illustrates national affiliations of three states with arrows. Nations are denoted by green thick boundaries to distinguish them from states.

Nation formation could follow a number of plausible rules. In this particular model, any primitive agent, whether sovereign or not, can take the initiative of forming or joining a nation. Whereas both capitals and provinces are eligible members of nations, the probability of launching a nationalist movement depends crucially on the geopolitical status of the territory in question. Thanks to their resources, capitals have a much higher likelihood of founding their own nations, but provinces may sometimes create their own nationalist platforms in opposition to their respective capitals.

Like alliances, nations change profoundly the behavior of the lower-level actors: "Group behavior is the behavior of individuals acting on the basis of a categorization of self and others at a social, more 'inclusive' or 'higher order' level of abstraction than that involved in the categorization of people as distinct, individual persons" (52). Thus, the model introduces nationalist action as a distinct type of group behavior operating in tandem with power-seeking motivations. If nationalist behavior ensues, the state searches for a nationalist "other", i.e., a nation that is dominating the state's conational kin. If these conationals inhabit a neighboring state, the state in question will be motivated to trigger an "irredentist" invasion to incorporate the kin group. Nationalist mobilization also typically implies a higher level of societal research extraction, which can be easily implemented by making the logistic distance function depend on whether a province belongs to the same nation as the capital. Nonnationalist actions follow the same rules as in the previous models, with the important distinction that two-level action is

[¶]Cederman, L.-E. (2001) *Nationalist Systems Change and its Geopolitical Consequences*, (Annual Convention of the American Political Science Association, San Francisco; http://www.apsanet.org/mtgs/proceedings/).

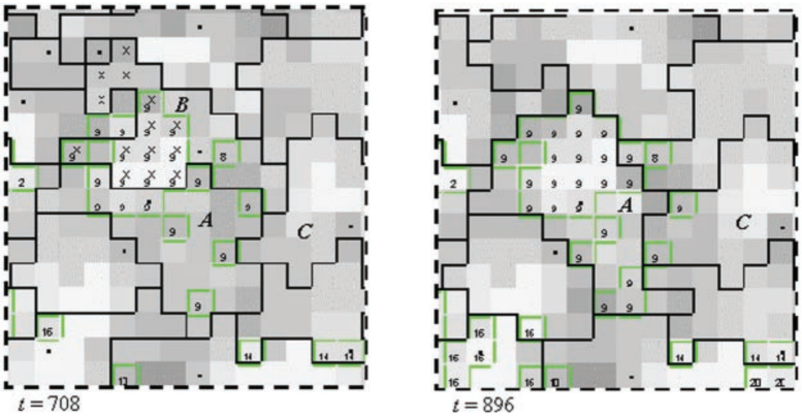

Fig. 4. An example of irredentism.

always enabled, for nationalism without the possibility of secession is hard to imagine.

The operation of the nationalist microlevel mechanisms depends on the specific geopolitical settings. In cases where political and cultural borders do not coincide, national self-determination expresses itself through integration and disintegration. In some irredentist situations, as explained by Myron Wiener (53), both processes are at work at the same time. As a way to capture the dynamics, Fig. 4 displays two subsequent snapshots cut out from a larger system. Graphically, national communities are marked with gray boundaries and an index number. At time 708, state *A* has already acquired the national identity 9 (hence the index 9 in the capital province). There are another few national communities visible in this figure (i.e., 2, 8, 14, and 16). Despite several communities of 9-nationals inside the territory of state *B* (and one small community of 8 nationals), the capital remains unmobilized. This configuration violates the self-determination of the members of nation 9 inside state *B*, which is why they are rebelling (see the crosses). At the same time, irredentist warfare is underway, because *A* wants to incorporate its nationalist kin currently residing within *B*'s territory. In addition, a few communities in the north west of state *B* have taken the opportunity to rebel as well, but their secessionist attempt is not motivated by any particular nationalist claim, because these provinces have not yet acquired their own national identities.

Many iterations later, at time step 896, *A*'s borders coincide much more closely with nation 9. But the correspondence is not perfect, for a few 9-nationals were, in fact, incorporated by foreign states in the east (see especially state *C*). The reason for *A*'s having lost control of these territories relates to its having spread its own forces thin while redeeming its kin in *B*. Although this process did entail some voluntary unification events of recently liberated territories, most of this incorporation required costly irredentist warfare with *B*.

In general, nationalist capitals seek to liberate their nationalist kin in other states if these populations do not enjoy "home rule." Provinces that belong to a nation modify their strategy such that they try to jointly break out of "foreign rule". This calculation implies that the national communities' decision making can be coordinated and that their resources can be pooled within the national community *across state borders*. On the whole, these rules are more prone to drag nationalist actors into armed struggle than the purely geopolitical strategy, as the near collapse of *A* illustrates. Other irredentist projects may lead to a "Kurdish" situation, as the "homeland" state loses its sovereignty.

Sociational Modeling: Rationales and Results

The main purpose of this paper has been to illustrate how agent-based modeling does a better job at representing complex actor transformations than do conventional approaches of the essentialist type. Still, the critical reader may retort: why bother? Ultimately, sociational analysis would be of marginal interest were all important social outcomes ultimately reducible to patterns resulting from the interactions among fixed sets of actors. However, there are good reasons to suspect that this is not the case.

To identify "value added" of sociational modeling beyond heuristic representation, it is useful to revisit the basic rationale for computational modeling. In Schelling's classical rendering, social scientists should seek to explain "macrobehavior" in terms of "micromotives" (54). By drawing attention to sociational processes, I have tried to show that individual motivations may be too narrow a category of causal mechanisms. Indeed, there are many similarities between the present formalizations of geopolitical boundary change and Schelling's segregation model. The latter illustrates how relatively tolerant individual households "voting with their feet" may produce a powerful segregation pattern at the macrolevel. In such a setting, the outcome derives from local attempts to reduce the "frustration" of being surrounded by unlike neighbors. Similarly, the geopolitical models feature interactions that serve to reduce imbalances in the local balance of power, and, in the NSC model, also serve to reduce violations of national self-determination. Yet, these sociational models differ from Schelling's segregation scenario in that the adjustment mechanisms involve boundary adjustments, such as conquest, secession, and unification, rather than migration. Seen from this perspective, international politics resembles a repeated search process that selects out border configurations that satisfy specific organizational principles.

In addition, the sociational models presented here go beyond traditional approaches to computational modeling in terms of the macrobehavior explored. Most commonly, analysts validate the macrobehavior of their models in terms of end points. But, as Schelling stresses, it is also possible to treat the emergent properties of on-going processes as the main object of validation (see Table 2). Setting aside the (overly) ambitious goal of replicating real outcomes numerically, a second distinction separates qualitative from distributional modes of validation (55). Whereas the former is the least demanding because it establishes merely qualitative resemblance with the pattern to be explained, the latter requires empirical validation of the model's distributional properties.[‖]

[‖] As I use the term, validation, which can never be absolute and definitive, stands for a relative comparison of agreement with a semantic theory, another model, or real-world evidence (*cf.* ref. 64).

Table 2. Four types of macro-level validation

	Object of validation	
	End point	Process
Mode of validation		
Qualitative	*a*	*c*
Distributional	*b*	*d*

Viewed together, the two distinctions create four types of macrolevel validation. My geopolitical research program has shifted from a validation strategy focusing on qualitative properties of end points (*a*) to one that prioritizes distributional process evaluation (*d*). To start with *a*, the original EP model yields surprising insights relating to the effect of defensive behavioral orientation on equilibria. Many qualitative theorists expect defensive technology and alliances to stabilize the "pluralistic" nature of the international system. By contrast, the sociational setup indicates that precisely the opposite may be true: the more defensive the system is, the weaker the balance of power gets, thus increasing the likelihood of unipolar outcomes (29, 56). Examples of this effect could be seen in Renaissance Italy, where a well working system supported by defensive alliances prevented the Italian city states to grow enough to prevent foreign domination.

Also illustrating qualitative equilibrium validation (a), the DP model shows that the state perpetual peace is a possible outcome thanks to clustered democratic collaboration together with ideology-sensitive defensive alliances. By freezing state borders from the outset of the analysis, essentialist theories make things both too easy and too hard at the same time: too easy because they assume away the threat of conquest, and too hard because their lack of spatial representation overlooks the contribution of contextual cooperation (36).

So far, I have not subjected my models to validation of type *b*, although this is perfectly possible. For example, it would be possible to collect data on polarity structures and state sizes in the international system and compare those results to the computational findings. Epstein and Axtell's (1) analysis of skewed Pareto welfare distributions in their "sugarscape" model exemplifies this type of validation in another setting.

Going beyond the artificial endpoints imposed by equilibrium analysis, the frameworks also invite process validation at the qualitative level (see type *c*). With nationalism "switched on", the NSC model can be shown to generate warfare that is much more damaging than in the counterfactual case without national mobilization. Although this basic result confirms the intuition about nationalist warfare of von Clausewitz (57) and many historians (58), it has been lost on most contemporary analysts of international relations, who generally fail to distinguish between states and nations. Moreover, the model also suggests that national unification has a strongly destabilizing effect on the balance of power. Although many scholars have put the blame on Germany for the outbreak of the First World War, this finding opens a new line of inquiry linking the war to structural conditions relating to boundary change.

It is also instructive to explore distributional properties of model processes (type *d*). Within specific parameter regimes, the EP model generates power-law-distributed war sizes, which correspond closely to empirically observed patterns (L.-E. Cederman, unpublished work). As with earthquakes, there are many events with few casualties, fewer large ones, and a very small number of huge disasters. More precisely, power laws tell us that the size of an event is inversely proportional to its frequency. In other words, doubling the severity of wars leads to a decrease in frequency by a constant factor regardless of the size in question. This remarkable finding belongs to the most accurate and robust ones that one is likely to find in world politics (59).** This result resembles strongly a similar finding about firm-size distributions recorded in entity processes involving the creation, growth, and death of firms (60). Even more generally, if it can be shown that the international system obeys the principles of self-organized criticality (61), a number of interesting consequences would follow. First, in contradiction with attempts to link power-law regularities to simple social diffusion processes (62), the computational models indicate that power-law-distributed wars may be a side-effect of profound boundary-transforming processes. Second, these findings cast doubt on the focus on equilibria that is dominant in social-scientific theorizing because warfare ensues when the system moves *between* metastable equilibria. Third, tensions typically build up during potentially long periods in the system, which means that efforts to match causes with events based on conventional microlevel explanations, be they game-theoretic, statistical, or qualitative, fail to do justice to the different time scales involved in the sociational transformations. Although more research is needed to corroborate these initial findings, sociational agent-based models remain the only ones that have managed to reproduce statistical regularities of this sort.

Conclusion

In this paper, I have argued that, in addition to the advantages usually attributed to agent-based modeling, such as its ability to capture bounded rationality and heterogeneous agent populations, this technique also promises to overcome the reification of actors. Whereas this common, but limiting, assumption makes a lot of sense during periods characterized by stable actor boundaries, other historical junctures, such as the end of the Cold War, exhibit far-reaching and swift transformations of actors' spatial and organizational existence. Moreover, because actors cannot be assumed to remain constant in the long run, analysis of macrohistorical processes virtually always requires sociational endogenization.

Computational modeling provides a set of formal tools that assists the analyst in tracing complex macrohistorical transformations of actors, be they hierarchically organized as relational networks or as collections of symbolic categories. With respect to the former, dynamic networks featuring emergent compound actors with agent compartments represented in a spatial grid capture organizational domination, as in Weber's notion of the territorial state. In addition, models of tagged social processes allow the analyst to show how such actors predicate their behavior on categorical traits. Finally, categorical schemata that select out politically relevant cultural traits in ethnic landscapes formalize a profoundly constructivist notion of national identity in conformance with the qualitative literature on nationalism. The "finite-agent method" models both states and nations as higher-level structures superimposed on a lower-level grid of primitive agents or cultural traits and avoids reification of agency, thus opening the door to explicit analysis of entity processes. Although my examples have centered on international politics, it should be clear that this mode of analysis is by no means limited to such settings. More generally, history-dependent institutionalism (63) promises to capture entity processes in a variety of sociational contexts wherever actors' boundaries and existence are up for grabs, as in the case of the coevolution of firms, political parties, bureaucracies, interest groups, and churches.

**What is more, the NSC model also produces power laws with slopes that become steeper once nationalism enters the picture. Statistical analysis of partitioned data from before and after the French Revolution suggests that empirical power law distributions change in a similar way.

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