Exploring geopolitics with agent-based modeling*

Lars-Erik Cederman and Luc Girardin
Swiss Federal Institute of Technology, Zurich
Seilergraben 49
8092 Zurich Switzerland
http://www.icr.ethz.ch

October 17, 2005

Introduction

Agent-based modeling has been applied successfully to a variety of areas in the social sciences (Johnson 1999; Macy and Willer 2002; Cederman 2005; Pepinsky 2005; Tesfatsion 2006). In this paper, we report on our efforts to explore geopolitics with computational simulation of this type. Pioneered by Bremer and Mihalka (1977), the use of agent-based modeling to study macro-processes of warfare and conquest goes back a quarter of a century. Here we focus on a GeoSim, which is a model family that was introduced by Cederman (1997; 2002). This framework allows the analyst to grasp geopolitical phenomena that are difficult to study with quasi-experimental methods.

Theoretical background: Schelling's segregation model

Why is it that computational modeling offers powerful tools to analyze geopolitics? To answer this question, we will use a classical model as our point of departure. The American economist Thomas Schelling, who also contributed prominently to the literature on game theory, belongs to the "founding fathers" of agent-based modeling in the social sciences. In his classical book, *Micromotives and Macrobehavior*, Schelling (1978) lays out the case for a generative approach that aims at uncovering micro-level mechanisms as an explanation of social macro phenomena.

Clearly, such a research agenda calls for a holistic approach. Without attention to the social context, it would be impossible to link systemic macro properties to the systems' micro foundations. For this reason, Schelling (1978, p. 19) insists that "that the entire aggregate outcome is what has to be evaluated, not merely how a person does within the constraints of his own environment." It is clearly not enough to study causal effects *ceteris paribus*. In complex systems, other things simply are not equal. In such situations, Schelling (1978, p. 14) points out,

> we usually have to look at the *system of interaction* between individuals and their environment, that is, between individuals and other individuals or between individuals and the collectivity. And sometimes the results are surprising. Sometimes they are not easily guessed. Sometimes the analysis is difficult. Sometimes it is inconclusive. But even inconclusive analysis can warn against

* Prepared for presentation at University of Tokyo, September 24-25, 2005.

jumping to conclusions about individual intentions from observations of aggregates, or jumping to conclusions about the behavior of aggregates from what one knows or can guess about individual intentions.

In order to illustrate the need for a holistic perspective, Schelling (1978) introduced a famous model of segregation that has become iconic in the computational literature. The logic of this model is so well known that it hardly bears repeating in detail. Here a brief introduction will have to suffice. Schelling was puzzled by the sharply delineated ethnic neighborhoods in American cities. As a way to explain this pattern, he decided to build a model to show how neighborhood segregation could emerge through unplanned interactions of micro-level actions.

Of course, segregation would not be so hard to explain if it stemmed from truly racist individuals. However, Schelling suspected that the explanation is much more subtle than that. Writing in the late 1970s at the dawn of the age of personal computers, Schelling set out to solve this problem equipped with a table of random numbers, a checker board, a bunch of coins, as well as equal measures of patience and curiosity.

Having placed his pennies and dimes randomly on the board, leaving a few vacancies, the famous economist now gave the coins the opportunity to move according to very simple rules. If a penny found that at least a third of the inhabitants in the immediate neighborhood were also pennies, there would be no reason to move. With less than the critical third, however, the penny would decide to move to another randomly selected site where it would be surrounded by enough pennies. The corresponding rule would also apply to the dimes.

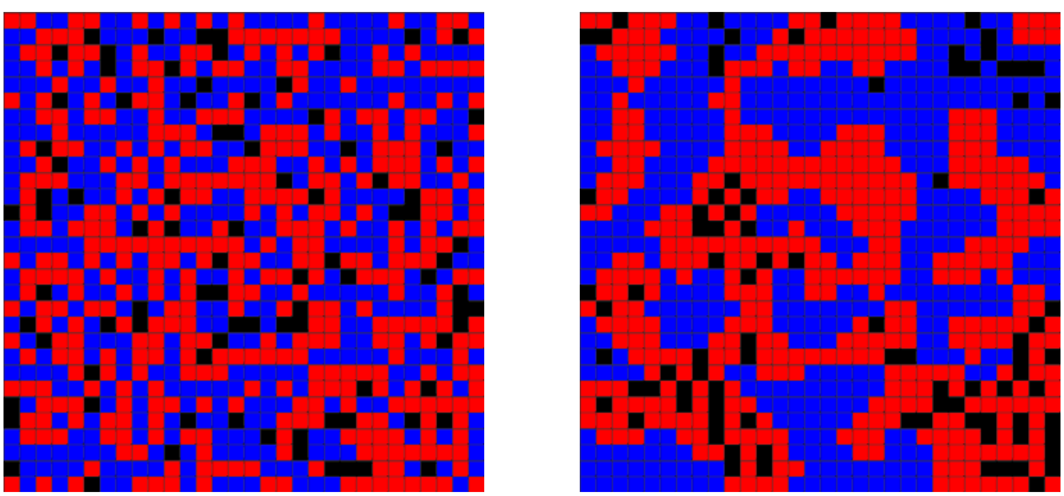

Figure 1. Schelling's segregation model at the beginning and end of the simulation

Based on these weak assumptions, will neighborhood segregation ever emerge? Instead of using coins, let us instead represent the two communities as light and dark grey people in a computer model. All in all, there are 30 by 30 sites, out of which 90% are occupied and divided into half of each type. In addition, there are 10% vacant sites, here shown in black. Note that all these sites are randomly mixed (see the left panel of Figure 1). Despite this initial randomness, will segregation result? As suggested by the right-hand panel of Figure 1, what emerges is a stunning segregation pattern. Schelling's intuition was right. Segregation emerges through self-organization even among relatively tolerant individuals.

Schelling's segregation model is a particularly simple instance of agent-based modeling. This modeling strategy allows researchers to create, analyze, and experiment with, artificial worlds populated by agents that interact in non-trivial ways and that constitute their own environment. Such models often produce emergent effects, i.e. outcomes that are truly systemic and that cannot be reduced to properties of the system's components, as for example the segregation pattern we just generated.

It's possible to measure such emergent effects. The segregation model produces two important results (see Figure 2). First of all there is a massive reduction of the number of neighborhoods, in this case, from 155 at the beginning down to a mere 16. Furthermore, the overall happiness in the system, measured as the proportion of content inhabitants, increases from about 80% to a state in which nobody has an incentive to move. This is a global equilibrium.

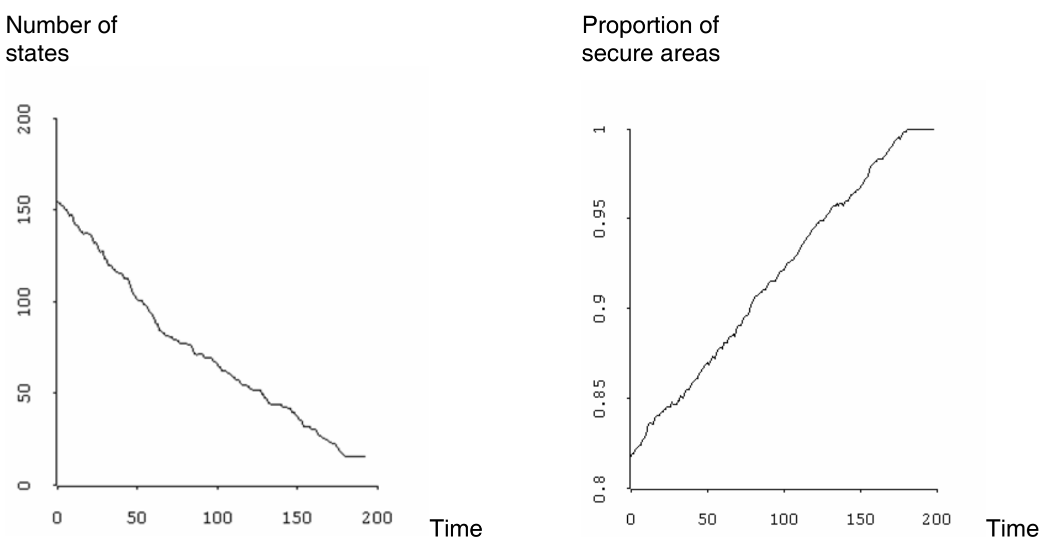

Figure 2. Two graphs that trace the emergence of segregation

Thus, through local, adaptive steps, the system as a whole manages to find an equilibrium. So far, however, we have not said much about war and peace. It is therefore time to return to the theme of geopolitics to see if there are useful analogies that can serve as a basis of theorizing.

Modeling geopolitics with agent-based simulation: Introducing GeoSim

We have already seen how the segregation process in Schelling's model reduces the number of neighborhoods drastically. By analogy a similar phenomenon actually happened in Europe with respect to the number of states. The same thing applied to other geopolitical systems, such as ancient China and India (Cusack and Stoll 1990). At the end of the Middle Ages, there were scores of independent or semi-independent geopolitical units in Europe. Depending on how one defines them, it is possible to count up to half a thousand such units in 1500 (Tilly 1975). Half a millennium later, however, the picture looks very different. The number of states has now gone down drastically to a couple of dozens.

What explains this extraordinary development? Although historians, sociologists and political scientists are still debating this issue intensively, most of them agree that this has something to do with warfare (Tilly 1990; though see Spruyt 1994). Impressed by this dynamic story, Cederman set out to create an artificial geopolitical system that mimics the process of competitive state formation. Rather than trying to capture international politics in terms of a set of laws operating in a timeless manner, his idea was to treat the topic as a geopolitical process unfolding at the macro level. More specifically, let us start with a large number of states and then let combat and conquest weed out the losers, thus creating a consolidated map like early 20th century Europe.

In a pioneering paper, Bremer and Mihalka (1977) introduced such a model of geopolitical competition. It features state-like organizations with dynamic borders that grow through conquest. This model became an important source of inspiration for the GeoSim project, which was constructed from scratch. GeoSim is a family of agent-based models that is based on a dynamic network of interstate relations superimposed on a square grid. All interactions are local, between adjacent states. Unlike Schelling's inhabitants, however, the main protagonists here are more complex, hierarchical states. Each state capital can absorb and dominate a number of provinces in a perfectly Hobbesian fashion (see the dots in Figure 3). Moreover, their borders are sharply defined (see the lines). Finally, they derive their power from the number of provinces they control -- thus, the larger a state is, the more powerful it is.

Initially, there are 200 sovereign states. What happens if we unleash these power-hungry organizations? Combat follows if the local power balance exceeds a preset threshold in favor of the attacker. In this simple case, a challenger has to be exactly twice as powerful as its opponent to launch an attack. The potential victims, who are vulnerable to invasion are here shown as shaded areas.

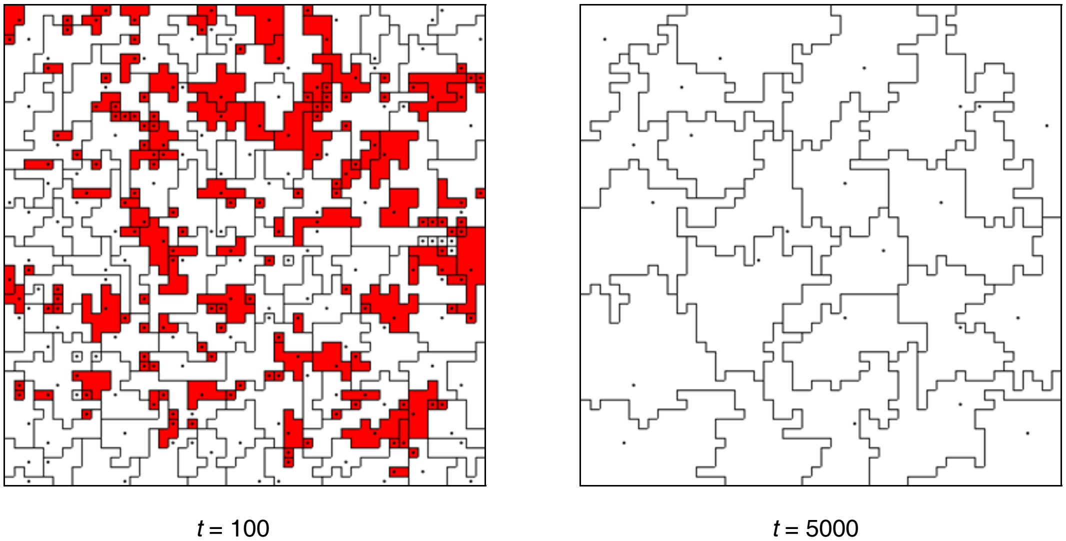

Figure 3. A simple state system undergoes geopolitical consolidation in GeoSim

What can be said about the process?

- First of all, the number of states declines drastically.
- Moreover, conquest happens frequently, which leads to complete and partial state disintegration when the capital loses control over its territories.
- Perhaps most surprisingly, in this run, a stable equilibrium results with as many as 15 states results rather than one state taking over the entire system.

As with Schelling's model, it is possible to measure the development of the system over time. Instead of neighborhoods, we trace the decline in the number of states over time. A declining, irregular pattern appears, as illustrated by the left panel of Figure 4. The increase in security is not a regular one either. Indeed, the proportion of secure areas, measured in terms of the number of unthreatened sites, exhibits an even more jagged curve pointing upwards. Clearly the states become more secure over time.[1]

Despite this variety, the analogies to Schelling's model should be clear: First, the processes reach equilibrium through self-organization. Second, there is a reduction of collective units, in Schelling's case neighborhoods, and in Geosim, states. Third, the system adapts by making the individual units more satisfied or secure. Of course there are important differences too. Whereas Schelling's model features moving individuals, in the simple GeoSim model adjustment happens through moving borders as a result of conquest. Furthermore, convergence in the geopolitical case is less even and includes reversals. Despite the differences, however, it seems useful to conceive of international politics as a decentralized system inhabited by state-like agents, where outcomes emerge as self-organized, aggregated effects.

[1] It should be noted that security in this Hobbesian sense may be less than normatively appealing, because we are counting conquered provinces inside unthreatened states as secure. This amounts to the same security as prey feel inside the belly of the predator.

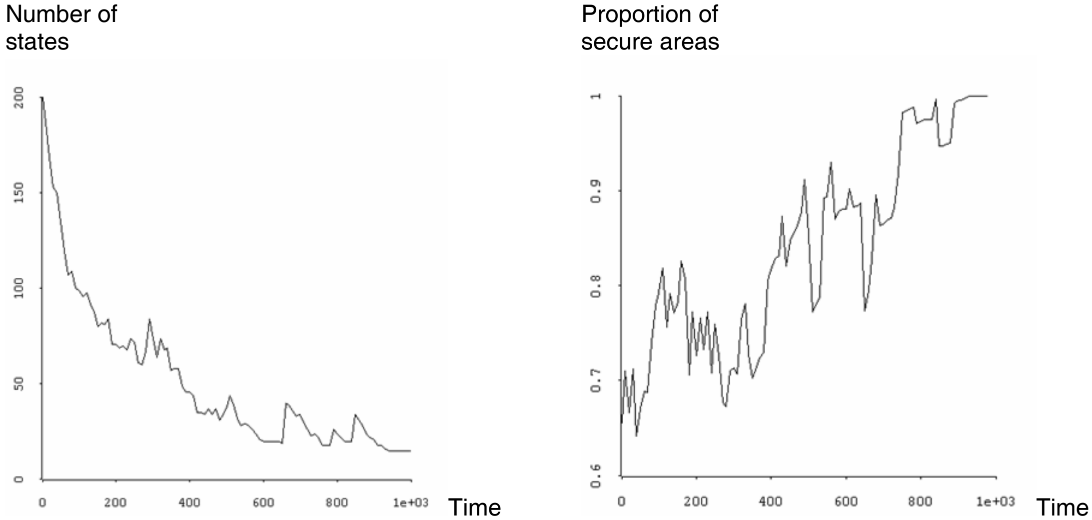

Figure 4. Two graphs that trace the consolidation of the state system

Applications of the GeoSim framework to geopolitical research problems

Now that we have familiarized ourselves with the core logic of the GeoSim framework, it is time to introduce a bit more realism. It goes without saying that the exceedingly simple model of the previous section was designed mostly for illustrative purposes. So far we have focused on processes that end in a stable equilibrium, but in world history, there is no end in sight. Thus we should be at least as interested in studying on-going processes as exploring specific configurations. Moreover, it is possible to ask for a closer fit with the phenomenon in question, whether it is a configuration or a process. We may want to reproduce entire probability distributions of properties rather than merely qualitative characteristics.

If we combine these possibilities, we get four types of emergent phenomena that fit into a 2 x 2 table. The first of these dimensions determines if the macro pattern in question is an configuration or an on-going process. Comparing two different levels of isomorphism, the second dimension questions whether a distributional match can be expected or whether mere qualitative fit is aimed for.[2]

Moving clock-wise from the more ambitious to the less advanced research tasks, we start by considering Example 1, which is exemplified by war-size distributions. This case requires the researcher to reconstruct the stochastic profile of an on-going process.

---

[2] Likewise, Axelrod (1997, p. 32) introduces three levels of replication. The two least ambitious ones, relational and distributional equivalence, correspond to the qualitative and distributional criteria used here. The most demanding level of equivalence, “numeric identity,” is rarely a realistic goal in empirical applications.

Example 2 shifts the focus to the reconstruction of frequency distributions of territorial state sizes. Here the main interest is in configurations rather than in process. Also targeting configurations while lowering the ambition to qualitative validation, Example 3 asks the question of how roughly half of the world's states could become democratic from a starting point featuring virtually no democracies. Finally, Example 4 illustrates how agent-based modeling can be used to reconstruct qualitative processes featuring novelty, in this case the emergence of the territorial state in early modern Europe.

Table 1. Four types of macro-level patterns to be explained.

	Configurations	Process
Qualitative	Example 3. Democratic peace as process outcome	Example 4. Emergence of the territorial state
Distributional	Example 2. State-size distributions	Example1. War-size distributions

Example 1. Growing war-size distributions

Since Richardson's (1948) pioneering efforts to collect quantitative data about conflict processes in the 1940s, we know that war sizes are power-law distributed. Using logarithmic axes, Figure 5 plots cumulative war frequencies as a function of war size. A straight line in a log-log plot suggests the presence of a power law (e.g. Jensen 1998).

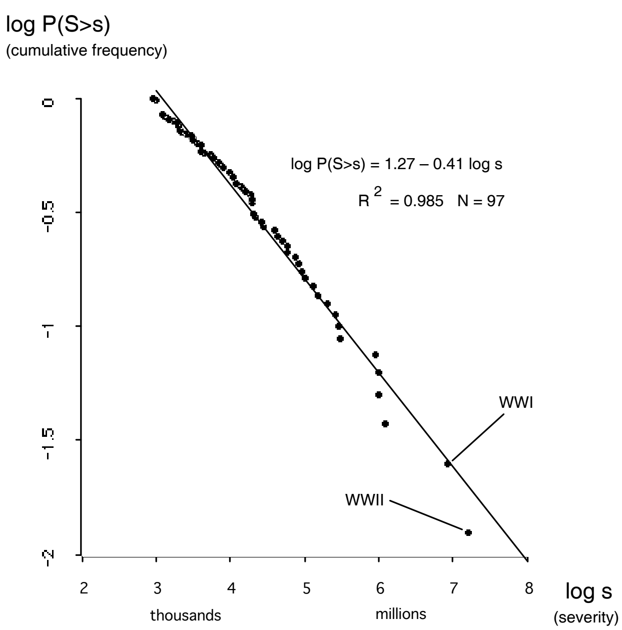

Figure 5. Cumulative frequency distribution of severity of interstate wars, 1820-1997

While such distributions could emerge in many different ways, the notion of self-organized criticality provides clues about a plausible set of mechanisms.
In general, outcomes of this type are typically generated by non-equilibrium processes building up tension within slowly driven non-linear systems. When the tension is released, the outbursts conform with power-law distributions, not unlike earthquakes. The late Danish physicist Per Bak (1996) used a sandpile as a paradigmatic example of this type of systems.

What are the geopolitical mechanisms that generate this pattern? To find out, GeoSim was modified to produce realistically distributed war sizes (Cederman 2003a). The idea is to let technological change play the role of the steady trickle of sand. The repeated introduction of technical innovations creates strategic opportunities that states will exploit to expand their territories. Warfare in different sizes emerges as a side-effect of this process.

In order to measure the size of wars, Cederman (2003a) introduces an algorithm that identifies wars as spatiotemporal clusters of dyadic conflict that can merge and split. The left-hand panel of Figure 7 shows three such examples shown as shaded areas. If this particular simulation is allowed to progress, the outcome in the rightmost panel is arrived at.

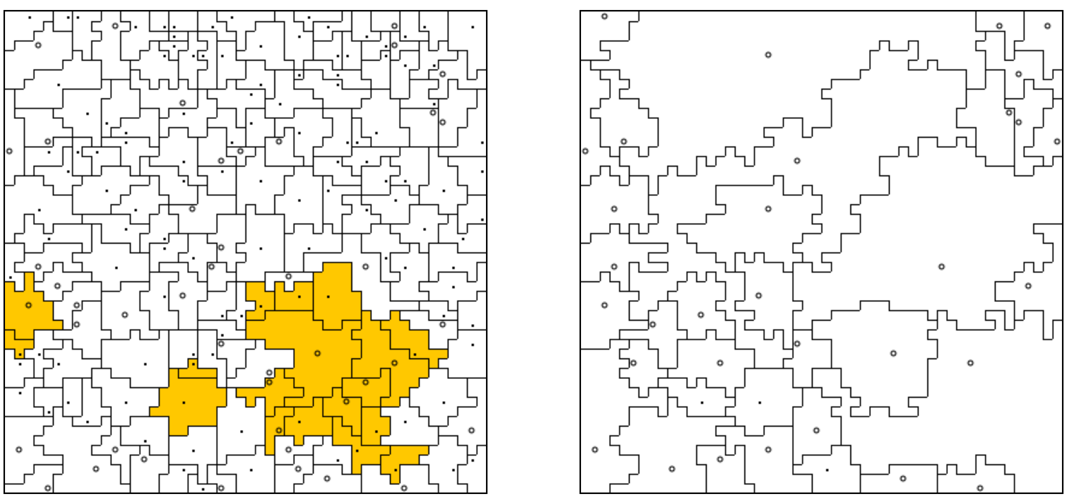

Figure 6: Two snapshots from a simulation of GeoSim with war clusters.

What is the result of this specification? Figure 7 shows a simulated war-size distribution produced by Geosim. It is evident that the fit with a power law is quite accurate. Thus, it can be concluded that technological change together with strategic interdependence among the states were sufficient to generate the result, but there may well be other mechanisms that come closer to the truth.

In general, self-organized criticality has important consequences for theorizing about world politics. If it is true that warfare follows such a process, then the conventional focus on equilibria is misplaced, because warfare happens when the system is in transit from one equilibrium to another (cf. Gilpin 1981).

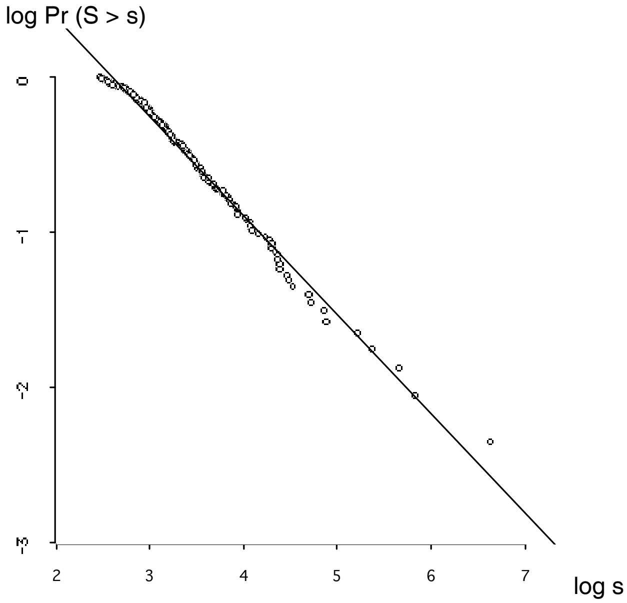

Figure 7. Simulated cumulative frequency distribution in the sample run

Example 2. Growing state-size distributions

Having confirmed that war sizes are indeed power-law distributed, it is natural to investigate the distribution of territorial state sizes. Do they also exhibit patterns of the same type? Thanks to a new data set developed by colleagues in San Diego (Lake and O'Mahony 2004), it can be established that the answer to this question is no. In fact, state sizes are log-normally distributed.

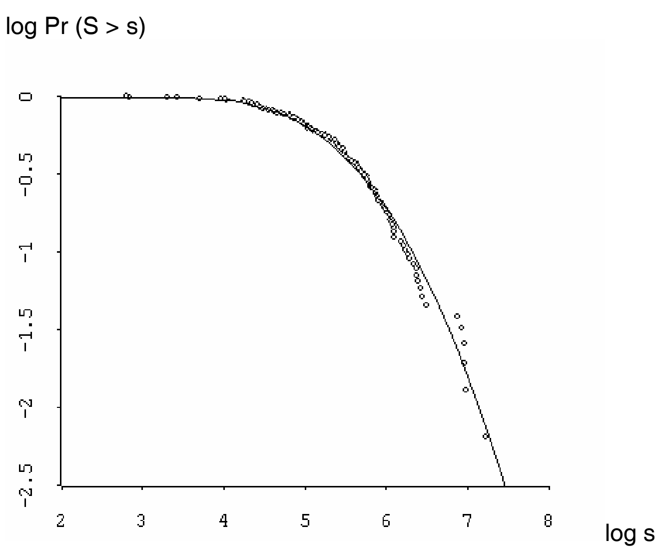

Figure 8. Empirical state sizes in 1998.

Figure 8 provides a snapshot from 1998 that speaks a clear language. Had this configuration been power-law distributed, it should have appeared as a straight line in this doubly logarithmic diagram. In contrast, it is easy to fit a log-normal curve.

Again, we have to ask what mechanisms are responsible for this type of patterns. Cederman (2003b) uses the GeoSim model with exactly the same configuration as the one used to produce war sizes (i.e. Cederman 2003a) with a very poor fit. The simulated state sizes were simply too similar. It was not until mountainous terrain was introduced that realistic distributions started to appear (see Figure 9).

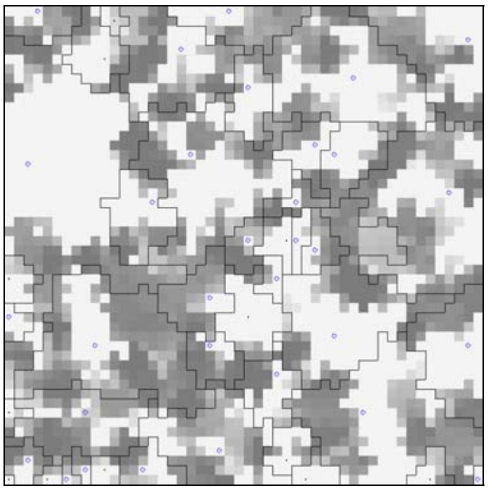

Figure 9. Simulating state size with terrain

Here is the system with rugged terrain marked in darker shades. In these areas, the capitals' power extraction and projection are reduced. As in European history, the largest states are located in the plains, whereas the smaller ones are mostly protected by the mountains. Does the model manage to generate log-normally distributed state sizes? Figure 10 displays a representative example of a simulated state-size distribution from this system. Though there are some deviations, the fit is not bad.

Of course, this does not mean that I have found the set of empirically accurate mechanisms. It merely says that this is a plausible set. Further experiments will be necessary to find robust answers to the question.

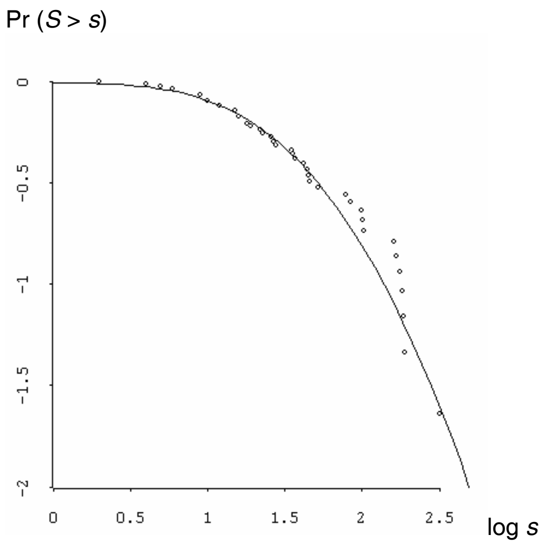

Figure 10. Representative size distribution for system with terrain at t = 7000

Example 3. Growing democracies

Let's now lower our ambitions to a qualitative, rather than a distributional fit. How could one account for the extraordinary spread of democracy throughout the state system, starting with virtually no democracy in the late 18th century?

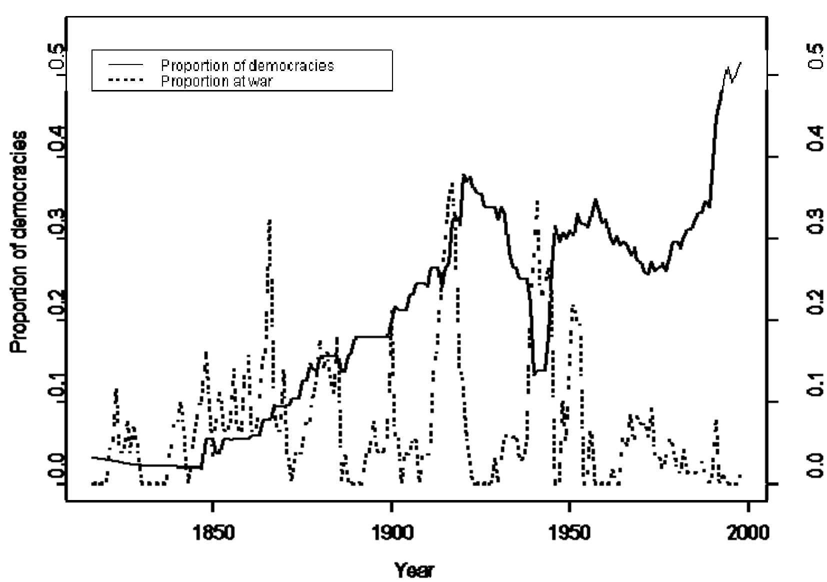

Figure 11. The evolution of democracy in the international system

Figure 11 traces the strength of democracy over time, measured by the proportion of democratic countries. The curve shows that the share of democratic states has increased from less than 5% at the starting point in 1816 to more than 50% at the present.

Despite being one of the most robust regularities to have been established in IR, the observation that democratic states rarely, if ever, go to war against one another remains a regularity in search of a theory. However, the so-called democratic peace has rarely been theorized as a macro process, as it was by Immanuel Kant. The famous philosopher argued that democracy has the potential of taking off even in a harsh geopolitical environment (Cederman 2001).

To test Kant's peace scenario, Cederman and Gleditsch (2004) introduce a new type of state. Shown in light shading are democracies as conditional cooperators, i.e. these states refrain from attacking each other, but otherwise have a healthy geopolitical appetite (see Figure 12). Based on a collective-security mechanisms, the democratic states come to each other's help if attacked by non-democratic aggressors (shown as dark areas).

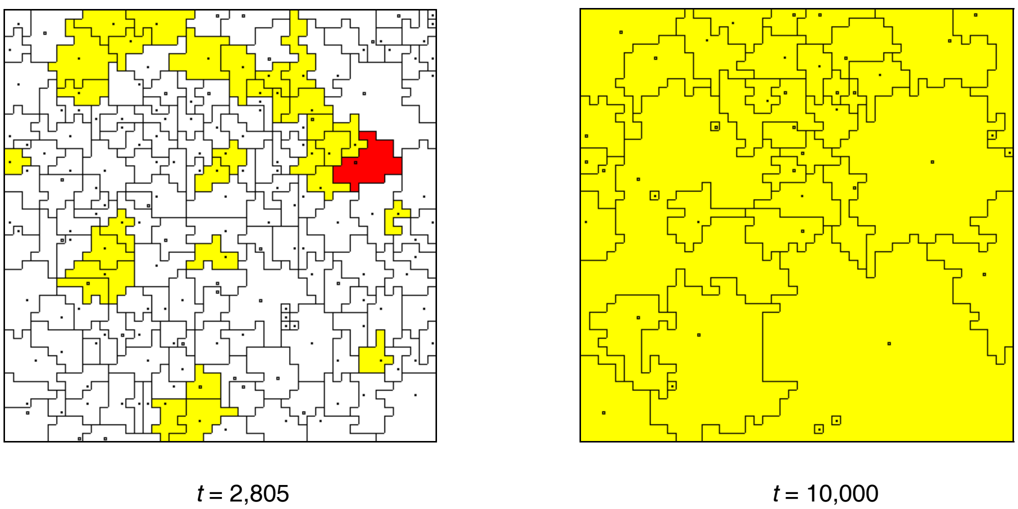

Figure 12. Growing the democratic peace with collective security

As shown by this sample run, local democratization together with the collective security mechanism is sufficient to democratize the entire system. Rerunning the system with random changes confirms that in most of the runs, the democracies dominate the final equilibrium.

This model serves as a corrective to the gloom and doom scenario of power laws. Indeed, by building up communities of trust and cooperation, democratic states seem capable of emancipating themselves from the iron law of geopolitics.

Example 4. Growing sovereignty

Our final example illustrates how to regenerate a qualitative process. The emergence of the territorial state in early modern Europe belongs to the most difficult puzzles that IR theorists are confronted with. Conventional theories of political science assume not only that actors are fixed and given, but also that fundamental actor types remain constant (Cederman 1997). For example, international relations theory postulates the existence of a system of states, and then goes on to explore interactions among such actors. However, the world is not only made up of territorial states, and these entities have not always been, and will not necessarily always remain, the most important actors in world politics.

One of the most striking aspect of this complex macro process is the shift from indirect to direct rule (Tilly 1990). Whereas the main political units in the Middle Ages were governed indirectly through intermediaries, the onset of modernity brought about a revolution in terms of governance. Rather than having to rely on vassals and other underlings, the monarchs could now rule their territories directly, extracting taxes and resources through their own civil servants.

Based on a simple, one-dimensional model, Cederman and Girardin (2005) construct an extended version of GeoSim that they call OrgForms. This framework relaxes the assumption of GeoSim that limits the number of organizational levels to two. With the relaxed specification, it is possible to model states with an arbitrary hierarchical depth. Figure 13 illustrates a state system that features a considerable degree of indirect rule. While the large rings represent state capitals, black dots stand for intermediary power centers that are connected with the higher-order instances through shaded hierarchical links. In this figure, the white areas represent those provinces that are directly ruled by the capital (and for which the power dependencies are not shown).

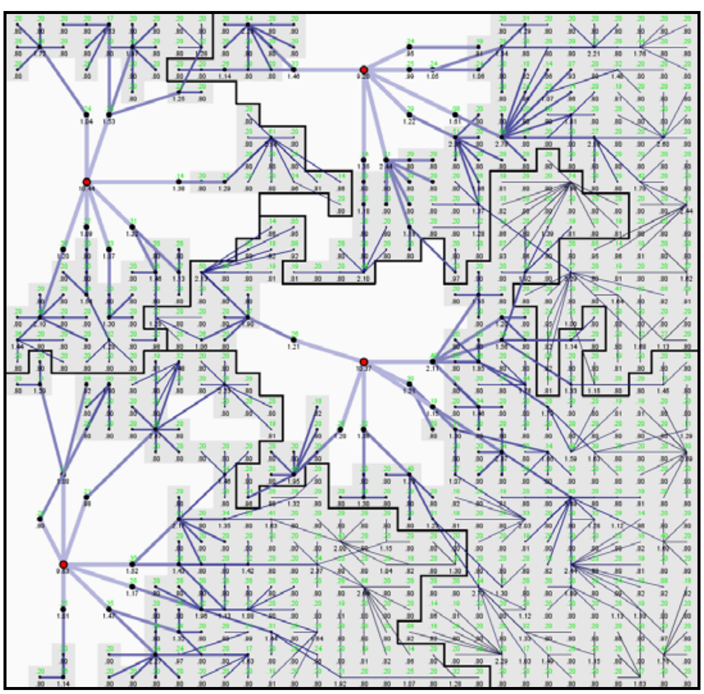

Figure 13. The evolution of deep hierarchies in the “Middle Ages” of OrgForms (t = 137)

The OrgForms model explicitly represents causal mechanisms of conquest and internal state-building through organizational bypass processes. The computational findings confirm our hypothesis that technological change is sufficient to trigger the emergence of modern, direct state hierarchies.

Figure 14 traces the shift from indirect to direct rule. The simulations start with a large number of directly ruled principalities. However, these soon give way to indirectly ruled empires. The graph shows that different measures of hierarchical depth increase before the actual phase of state formation sets in. The system converges on a situation in which direct rule dominates. One interesting finding is that the historically observed shift only occurs with loss-of-strength gradients of the threshold type rather than with exponential decay. This is an important theoretical result that can guide future theory-building in an area that suffers from a severe lack of precise empirical data.

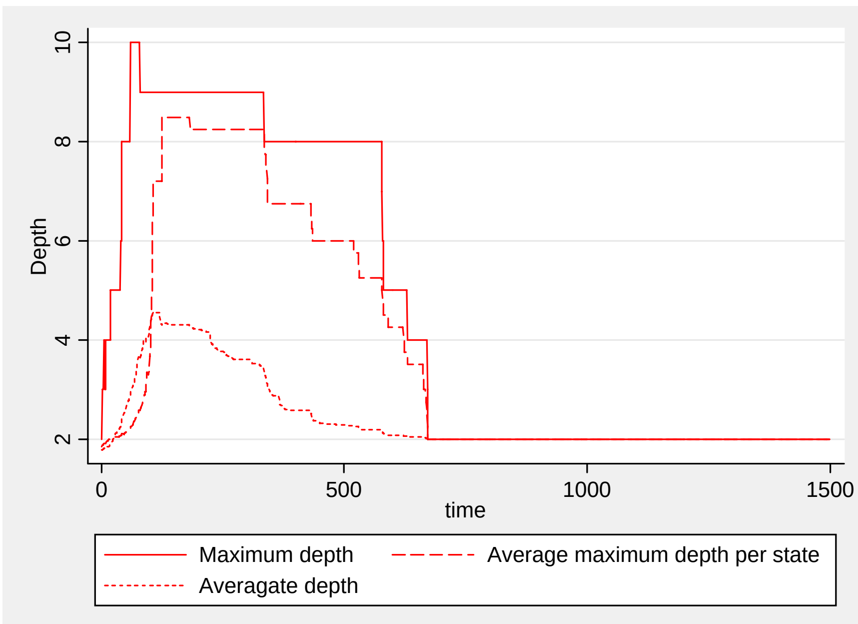

Figure 14. The shift from indirect to direct rule

Future research

The four sample models surveyed in this paper are all relatively simple. Our current research efforts revolve around the possibilities of creating more realistic models that can be applied to urgent security problems in the contemporary world, in particular civil wars and other types of internal conflicts. Building on GeoSim, Cederman (forthcoming) introduces a new version of the model that features several layers in addition to the standard state system, such as geography, a cultural landscape and national identities. Based on this complex specification, the study articulates causal mechanisms that are often alluded to in the quantitative literature on civil wars. Furthermore, Cederman (2004) endogenizes state boundaries of the previous model and uses the framework to study the impact of nationalism on state sizes, thus complementing the findings of Cederman (2003b). Future research will focus on ways to create a new generation of modular simulation tools, going well beyond the existing GeoSim framework. Such a project will include a strengthened link to real-world data based on Geographic Information Systems (GIS) in the area of civil war studies, where such tools have already seen some pioneering use. It is our hope that such research will elucidate the operation of causal mechanisms that have so far been insufficiently articulated and contextualized in the conventional literature.

References

Axelrod, Robert. 1997. "Advancing the Art of Simulation in the Social Sciences." In *Simulating Social Phenomena*, ed. Rosaria Conte, Rainer Hegselmann, and Pietro Terna. Berlin: Springer Verlag.

Bak, Per. 1996. *How Nature Works: The Science of Self-Organized Criticality*. New York: Copernicus.

Bremer, Stuart A., and Michael Mihalka. 1977. Machiavelli in Machina: Or Politics Among Hexagons. In *Problems of World Modeling*, edited by K. W. Deutsch. Boston: Ballinger.

Cederman, Lars-Erik. 1997. *Emergent Actors in World Politics: How States and Nations Develop and Dissolve*. Princeton: Princeton University Press.

Cederman, Lars-Erik. 2001. Back to Kant: Reinterpreting the Democratic Peace as a Macrohistorical Learning Process. *American Political Science Review* 95:15-31.

Cederman, Lars-Erik. 2002. Endogenizing Geopolitical Boundaries with Agent-Based Modeling. *Proceedings of the National Academy* 99 (suppl. 3):7796-7303.

Cederman, Lars-Erik. 2003a. Modeling the Size of Wars: From Billiard Balls to Sandpiles. *American Political Science Review* 1 (97):135-150.

Cederman, Lars-Erik. 2003b. Explaining State Sizes: A Geopolitical Model. In *Proceedings of Agent 2003: Challenges in Social Simulation*, edited by Macal, Charles, Michael North, and David Sallach. Argonne, IL: Argonne National Laboratory.

Cederman, Lars-Erik. 2004. "Nationalism and the Puzzle of Changing War Sizes." Paper presented at the Annual Convention of the American Political Science Association, Chicago, September 2-5, 2005.

Cederman, Lars-Erik. 2005. Computational Models of Social Forms: Advancing Process Theory. *American Journal of Sociology* 110 (4): 864-893.

Cederman, Lars-Erik. forthcoming. Articulating the Geo-Cultural Logic of Nationalist Insurgency. Forthcoming in *Order, Conflict, and Violence* edited by Stathis Kalyvas and Iain Shapiro. Cambridge: Cambridge University Press.

Cederman, Lars-Erik and Luc Girardin. 2005. Growing Sovereignty: Organizational Shifts in State Systems. Unpublished ms. Swiss Federal Institute of Technology, Zurich.

Cederman, Lars-Erik, and Kristian Skrede Gleditsch. 2004. Conquest and Regime Change: An Evolutionary Model of the Spread of Democracy and Peace. *International Studies Quarterly* 48 (3):603-629.

Cusack, Thomas R. and Richard Stoll. 1990. *Exploring Realpolitik: Probing International Relations Theory with Computer Simulation*. Boulder: Lynnie Rienner.
Gilpin, Robert. 1981. *War and Change in World Politics*. Cambridge: Cambridge University Press.
Jensen, Henrik Jeldtoft. 1998. *Self-Organized Criticality: Emergent Complex Behavior in Physical and Biological Systems*. Cambridge: Cambridge University Press.
Johnson, Paul E. 1999. Simulation Modeling in Political Science. *American Behavioral Scientist* 42 (10):1509-1530.
Lake, David A., and Angela O'Mahony. 2004. The Incredible Shrinking State: Explaining Change in the Territorial Size of Nations. *Journal of Conflict Resolution*.
Macy, Michael W. 2002. "From Factors to Actors: Computational Sociology and Agent-Based Modeling." *Annual Review of Sociology* 28: 143-166.
Pepensky, Thomas B. 2005. From Agents to Outcomes: Simulation in International Relations. *European Journal of International Relations* 11 (3):367-394.
Richardson, Lewis F. 1948. "Variation of the Frequency of Fatal Quarrels with Magnitude." *American Statistical Association* 43: 523-546.
Schelling, Thomas C. 1978. *Micromotives and Macrobehavior.* New York: W. W. Norton.
Spruyt, Hendrik. 1994. *The Sovereign State and Its Competitors: An Analysis of Systems Change.* Princeton: Princeton University Press.
Tesfatsion, Leigh and Kenneith L Judd. 2006 . forthcoming. *Handbook of Computational Economics. Vol. 2: Agent-Based Computational Economics.* Elsevier.
Tilly, Charles. 1975. Reflections on the History of European State-Making. In *The Formation of National States in Western Europe*, edited by C. Tilly. Princeton: Princeton University Press.
Tilly, Charles. 1990. *Coercion, Capital, and European States, AD 990-1990*. Oxford: Basil Blackwell.