Chapter 29

COMPUTATIONAL METHODS AND MODELS OF POLITICS

KEN KOLLMAN*

Department of Political Science, University of Michigan, USA
e-mail: kkollman@umick.edu

SCOTT E. PAGE

Departments of Political Science and Economics, University of Michigan, USA
e-mail: spage@umich.edu

Contents

* The authors would like to thank Bob Axelrod, Jenna Bednar, Joe Harrington, and Leigh Tesfatsion for helpful comments on earlier drafts of this chapter.

Handbook of Computational Economics, Volume 2. Edited by Leigh Tesfatsion and Kenneth L. Judd

DOI: 10.1016/S1574-0021(05)02029-0

Abstract

In this chapter, we assess recent contributions of computational models to the study of politics. We focus primarily on agent-based models developed by economists and political scientists. These models address collective action problems, questions related to institutional design and performance, issues in international relations, and electoral competition. In our view, complex systems and computational techniques will have a large and growing impact on research on politics in the near future. This optimism follows from the observation that the concepts used in computational methodology in general and agent-based models in particular resonate deeply within political science because of the domains of study in the discipline and because early findings from agent-based models align with widely known empirical regularities in the political world. In the process of making our arguments, we survey a portion of the growing literature within political science.

Keywords

agent based models, political economy, spatial voting, collective action, complexity

JEL classification: D72, D74, H72

1. Introduction

In this chapter, we assess recent contributions of computational models to the study of politics. We focus primarily on agent-based models developed by economists and political scientists. These models address collective action problems, questions related to institutional design and performance, issues in international relations, and the study of competition in elections.

In order to place in context the research contributions discussed in this chapter, it is important to begin with a description of political science as an academic and scientific discipline. Modern political science is very broad, much broader than economics, both in terms of methodological approaches and in terms of the questions addressed. Despite this breadth, the set of methodologies used in political science does not contain the set used in economics. There are marked differences. As this is a volume on economics, these differences may not be apparent to all readers, and thus, we begin by describing the key subjects, approaches, and methods that animate contemporary political science.

As we discuss below, political scientists address three fundamental problems: collective action, the allocation of finite resources, and the determination of boundaries and secure spaces. These problems (especially the first two) have direct analogues to problems regularly studied in economics. Indeed, there is considerable overlap and cross-fertilization between the disciplines, especially in the field of political economy.

We discuss the implications of the fact that political scientists as a whole place much more emphasis on description and less emphasis on optimal design. Relative to economics, political science devotes more attention to history, case studies, and cross-national differences. And finally, political scientists show a greater willingness to engage the question of whether people are fundamentally self-interested or act in the interest of groups or collectivities.

We also discuss the methodological diversity of the discipline. Political science is open to far more methodologies than economics. In principle, this should make it easier for researchers attempting to integrate computational techniques into the discipline. However, at the same time computational techniques were being introduced into mainstream political science, there was a backlash of sorts against formal modeling, which has likely slowed the growth in use of these methods.

As will become evident, we are optimistic that complex systems and computational techniques will have a large and growing impact on research on politics in the near future. This optimism follows from the observation that the concepts used in computational methodology in general and agent-based models in particular resonate deeply within political science because of the domains of study in the discipline and because early findings from agent-based models align with widely known empirical regularities in the political world. In the process of making our arguments, we survey a portion of the growing literature within the discipline. We conclude with a discussion of fruitful research agendas that are already under way, and suggest some prospects for further progress.

2. Core questions motivating political scientists

The topics covered in political science research journals include the study of constitutions, public decision-making institutions, philosophical issues on the relationship between governments and individuals, courts and legal systems, race and ethnicity, economic growth and institutional structure, urban politics, public opinion, mass participation, lobbying, elections and voting, and cultural difference. Amidst this topical diversity, three major sets of questions cut across these topics and form the substantive bases of modern political science:

(i) How, when, and if individuals work together to accomplish common tasks, otherwise referred to as collective action for the purposes of, among other things, the production of public goods, the selection of leaders, and the determination of rules of behavior.

(ii) How governments, organizations, or societies divide up resources and who benefits from the division. Let us call this "pie-splitting."

(iii) How and when do groups and political units form, creating new identities or new legal entities. This includes both the origins of conflicts of interest and the study of how and when countries or sub-national groups decide to exit from the everyday, legal institutions of conflict resolution to threaten or engage in violent action. Let us call this "security and communal stability."

For any given domain of politics, all three questions can be important. For instance, electoral campaigns for national office concern who gets what (pie splitting), what public goods the government should provide (collective action), and how to define and then defend a country's interests (security and communal stability).

The disciplinary emphasis on collective as opposed to decentralized pie-splitting links the first two questions within political science. Political (i.e. non-market) institutions almost by definition require coordinated collective action to function. For example, federal systems, like the United States, involve collective participation by the subunits to decide on policies (as in the U.S. Senate) as well as dividing up of resources to states and regions. The pie is not always split fairly across geographic areas as electoral incentives of national leaders may lead them to provide benefits to different populations.

The discipline of economics places some emphasis on both of these two questions as well. Market allocations are of course of fundamental concern to economists, but as a general rule, political scientists focus more on non-market institutions that split pies–organizations, governments, courts, legislatures, electoral systems. They put less emphasis on market-based mechanisms than do economists. A major reason for the difference is the simple fact that governments tend to intervene when markets fail. While economics can be thought of as the study of how and when markets work, part of politics is the study of how to allocate resources when either markets fail to work or they result in distributions that people find unpalatable.

The third set of questions is central to political science. Defining the boundaries between political units, between organized groups, and between electoral, legislative, or judicial coalitions is fundamental to political processes. The international system of

nation-states at any moment in time is a consequence of wars, diplomatic agreements, and declarations of both independence and subservience by national and ethnic groups. Political scientists devote much attention to how the various boundaries are determined and potentially change over time, and whether some kinds of political pressures lead to instability and violence.

Moreover, the option for persons, groups, or countries to "exit" from legitimate institutions makes it difficult for researchers to contain all that happens in politics into simple models of specific institutional settings. In political settings, nations or groups can opt out of a structured institutional environment (a well defined "game", if you will).

An act of war, rebellion, or terrorism can be thought of as abandoning current institutional arrangements. There are two ways to characterize these actions within models. One can consider war as a type of punishment in an institution-free repeated game setting, or one can consider violence as destroying the game itself, not something typically allowed in most game theoretic models of institutions. At the end of the war, it is not necessarily the case that the countries or groups go back to playing the same game. In some political settings, the option exists to eliminate your opponent. One country may take over another country and impose a new set of laws and institutions, or interactions among groups or regions can cease altogether after violence ends.

3. Different practices in comparison with economics

The many overlapping interests across the two disciplines, economics and political science, have resulted in substantial cross-fertilization of ideas and tools. Researchers in both disciplines model, estimate, and compare levels of efficiency, equity, growth and robustness across places and eras. Political economy, a field blending insights from both disciplines, has flourished in recent years. These similarities notwithstanding, on the whole the two disciplines are quite different. To paint in very broad strokes, economics is more technical and probes deeper empirically and theoretically into topics, while political science is richer and broader.

In comparison with economists, political scientists tend to devote less attention to the study of idealized mechanisms for the distribution of resources and more attention describing how existing mechanisms perform. A consequence of this different emphasis is that relatively less effort is spent in political science proposing mechanisms for improving the efficiency of social institutions. Put differently, political science devotes less attention to the "engineering" part of social science than does economics. Rather, the practice of political science places more attention on what has been and what is.

Political science also emphasizes more than economics cross-cultural and cross-national differences. While it is true that economics departments include scholars who focus on particular regions and countries, regional economics does not occupy as central a place in its discipline as does comparative political science. Moreover, the type of analysis done in political science is more nuanced and certainly broader in scope. While development and growth economists typically focus on variations in performance

measures—rates of growth, inequality, and education levels—political scientists more often immerse themselves in understanding broader sets of concepts, including the culture of the countries they study. They consider, among other things, the lifestyles, beliefs, family structures, political participation, levels of trust, and religious practices.

An important reason for this emphasis on cross-cultural and cross-country variation is that the data demand it. Countries can have similar formal social, political and economic institutions, and yet the operation of those institutions can vary dramatically. For instance, Canada and India have the same electoral systems and systems of government, yet the nature of political competition, the relationships between levels of government, and the types of polices adopted by both countries have been vastly different. Argentina copied the United States constitution almost exactly. How political institutions have operated within those rules varies substantially across the two countries. Survey courses of comparative politics which cover many countries, the kind of courses taught at the undergraduate level, emphasize that, even though countries exhibit similarities in formal institutions, variation over time and across countries is the norm. Thus, as political scientists seek to discover and explain the empirical patterns in pie-splitting and collective action that emerge across countries or regions they incorporate not only institutional factors in their explanations. They also pay close attention to historical trajectories and cultural differences.

It is also the case that political scientists more openly grapple with the assumption of self interest. Granted, the rebirth of behavioralism has led economists to examine not only biases in behavior but also to question the self interest assumption (Camerer, 2003). And granted, some of that research demonstrates that in some contexts people act altruistically. But those experiments have not led economists to abandon the assumption of self interest. And for good reason. Economists mostly study situations for which an assumption of self interest makes sense. When a person buys a house or groceries, they create few externalities, other than pecuniary ones, so they might as well act in their self interest.

The three questions at the heart of political science, however—collective action, pie-splitting, and security and communal stability—all involve decisions and outcomes that create externalities. And in each case, there may be reasons for individuals to act in the collective interest rather than in their narrow self interest. In fact, many of the experiments that reveal altruism involve variants of the divide the dollar games and collective action games, corresponding to two of the core problems for political science.

Not surprisingly, political scientists have long been interested in the degree to which people act in their self interest, in their group's interest, or in what they perceive to be the collective interest of some large polity. From studies of voting (do people vote with their pocketbooks?) to studies of family structure (do people take in elderly relatives?), to studies of trust among neighbors (are people willing to lend money to friends?), research demonstrates what appear to be systematic differences across countries in the extent to which people are individually and collectively motivated. Whether people act in their self interest or are willing to act in the collective interest influences how institutions perform. The invisible hand at the core of economics implies that self interest and

collective interest align. When providing for a public good, splitting a pie, or fighting wars, as everyone knows all too well, those interests may not align. In comparing the two disciplines, on balance political scientists are confronted more often with situations where the contrast between self-interest and group interest is evident.

4. Methodological diversity

Political science is a diverse and lively academic discipline. It is not uncommon for political science faculties to include scholars of ancient and modern political philosophy, area studies specialists who cover Russian and Chinese politics, students of the Supreme Court, experts on cultural change or diplomatic history, formal mathematical and statistical modelers using the latest techniques from econometrics or game theory to understand public opinion, elections, or legislative behavior, and researchers using the experimental techniques from psychology to understand mass political demonstrations. As we have mentioned several times, the discipline prizes empirical work and historical work, but it is decidedly not the case that the bulk of research is thick description. Many, if not most, political scientists are interested in discovering general understandings that translate across time and region. Nevertheless, there is a shared belief that such an understanding benefits from having solid accounts of what has happened and is happening across time and space so that such theories can be substantiated.

The upshot is that political scientists as a group will look at a single problem, process, or puzzle through many lenses. Voting behavior is analyzed with formal mathematical models, large N studies, small n in-depth surveys, controlled experiments, and historical analysis. Given this back-drop, computational models will never be seen as providing any definitive answers but as contributing to a general understanding formed through multiple methods. This is not a shortcoming of the approach—the same can be said of mathematical models—but a comment on the discipline (De Marchi, 2005).

Political scientists have made numerous methodological contributions to the social and behavioral sciences, including advances in survey research, spatial analysis of social processes, and models of collective decision-making, organizations and organizational decision-making. Yet the discipline also owes methodological debts to other disciplines, including, of course, economics. Researchers have borrowed theoretical concepts, statistical and experimental techniques, game-theoretic solution concepts, mathematical and behavioral axioms, and research design templates from across the social, natural, and even physical sciences. Given the broad scope of inquiry necessary to understand political systems and processes, perhaps this methodological diversity is inevitable and desirable.

In the best of scenarios, a diversity of approaches, methods, and areas of interest makes for interesting and productive seminars, faculty meetings, and professional conferences. The same diversity that can seed the cross fertilization of ideas, however, can lead to tension. In recent years, political science has delved into what have at times been heated controversies over the value of historical research, rational choice modeling

(what some have called economic hegemony), and psychological experiments. A focal moment in this discipline-wide debate was the circulation of an e-mail document by "Mr. Perestroika" in 2000, and then a follow-up letter signed by hundreds of professional political scientists that same year demanding an end to hegemonic economic-type methods and the opening of journals to a wider assortment of methodologies. Much more commonly than does economics, political science tolerates and even accommodates on a regular basis internal debates over methodology, the appropriate fundamental assumptions of human behavior and cognition, and the social value of abstract theorizing.

Within this context—methodological pluralism and a portion of the discipline resenting the accretion of dominant methodologies from economics—complex systems approaches have become more prominent and accepted in political science in the last ten years. By and large, the techniques and approaches used did not originate within political science, though clearly some political scientists have been at the forefront of some areas of computational modeling. The techniques were largely borrowed from other disciplines. In this case, the providers were physicists, computer scientists, economists, theoretical biologists, and even persons now called complexologists. At the same time the reactions to complex systems have been complicated.

The Perestroika letter and its resulting movement within the discipline were partly a backlash against abstract (particularly mathematical) modeling in recent years. The complaints about modeling are themselves varied. Some political scientists call for more direct empirical grounding in theoretical models, and wish for more realism in the concepts used. This complaint sometimes pairs with another one: that highly technical work focuses attention on trivial, technical problems at the expense of important political problems. Some object in particular to rational choice assumptions as unrealistic. Others complain about attempts to "scientize" what are highly contingent and time-dependent processes in the political world. Others question the validity of much of the data being collected and analyzed.

Of course, several of these complaints can extend to computational models as well. Complex systems research, while not necessarily based on rational choice assumptions, deals with abstract, technical models, often without direct empirical implications. The methodological debates within political science, while they signal a colorful and sometimes tolerant discipline, might have come at an unfortunate time for computational and complex systems approaches.

We think this would be unfortunate if true, because computational techniques can potentially build a bridge within political science between those who value the rigor of modeling and those who see the explanatory power of particular contextual details. Complex systems approaches in the social sciences typically allow for historical contingency, more complicated interactions of diverse agents, and adaptation of preferences and agent-types. Looking to the future, we see reasons to be optimistic that these approaches will gain increasing respect, prestige and usage, largely because many of the core concepts that define and characterize the computational agenda resonate among political scientists (Johnson, 1999).

5. Resonance within political science

As we have discussed, political scientists study collective action, pie-splitting, and security and communal stability. The political systems within which these activities occur also exhibit characteristics that are similar to those found in other systems of interest to researchers in complex systems.

Consider the following seven terms, referring to concepts fundamental to complex systems and agent based modeling: *adaptation, difference, externalities, path dependence, geography, networks*, and *emergence* (Page, 2000). These concepts all map to empirical features of political systems.

In other words, political systems and complex adaptive systems appear similar in many respects. This resonance between the methodology of complex adaptive systems and the reality of politics provides strong support for an increased mingling of computational techniques and approaches within mainstream political science.

5.1. Adaptation

By adaptation, we mean selective pressures and learning (Axelrod and Cohen, 2000). Both forms of adaptation occur in political systems. They often occur simultaneously and at different time scales. A politician who does not learn fast enough loses his or her job in the next election. Institutions also learn and get selected for and against based on their performance. The study of selection and learning holds a prominent place in political science. Lindbloom's (Lindbloom, 1959) seminal article on government agencies is entitled, "The Science of Muddling Through." His follow-up two decades later (Lindbloom, 1979) was entitled, "Still Muddling, Not Through Yet."

Political science PhD students tend to read a lot of history and case studies of particular events or institutions, in addition to receiving basic statistical and game theoretic training. Naturally, this differs from the training of economics PhD students, who devote much more time to mathematics and the intricacies of studying quantitative data. A reasonable defense of political science training is that the study of politics requires an appreciation of the complexity of particular circumstances, because contexts change rapidly, and decision-makers rarely face the same competitive situation more than once. Moreover, in many political settings, the range of tactics or strategies available to decision-makers can be immense, and the number of potential influences on the consequences of decisions can be far beyond what decision-makers can comprehend.

In combination, the relative lack of repeated, highly correlated decision-making environments and the vast strategy spaces confronting decision-makers makes politics a fertile ground for studying adaptive behavior. Game theoretic models of battlefield decisions on where to allocate troops (Colonel Blotto Games, for instance) and on which policy platforms to propose in electoral campaigns, typically do not have pure strategy equilibria even if it is assumed that there is complete information.

The idea that behavior adapts over time rather than being chosen by rational actors has implications for the study of social systems, including voting and elections

(Bendor et al., 2003a). Some have already used agent-based models to argue that fighting among agents, with some dying off, leads to selection towards altruists (Cederman, 1997; Bowles et al., 2003). The research identifies a fundamental tension present in many political situations, one that in the abstract is a basic collective action problem, but with a steep discount factor. Self interest can help an agent to survive in the short run, while relying on notions of collective interest helps the group of agents survive in the long run (Miller, 1996).

If there are frequent interactions that lead to extermination, such as wars or election results that wipe out competitors, group selection perhaps can lead to an increase in collectively-interested behavior. Thus, the collective-based incentives that we see in some societies may in fact have evolved over time given the propensity of dangerous conflict. As we discuss later in more detail, Harrington (1998) has shown that actors within organizations can adapt over time as hierarchical structures weed out certain types of potential leaders in ways that affect organizational performance.

5.2. Difference

At a descriptive level, political scientists often begin with the basic fact of difference. There are deep and consequential differences across population groups and across countries. Even within a country, groups differ by their levels and types of political participation. It is not enough to know different resource endowments, underlying preferences, or institutional rules. Cultural differences abound, and culture interacts in complicated ways with other differences that influence the success or failure of policies and reforms. As we discuss in more detail below, complex systems research, with its emphasis on interactions among agents, can help in understanding the emergence of cultural differences that are hard to explain with more traditional economic methods that focus on preferences and information.

In understanding the mechanisms of politics, the two opposing forces, splitting and unifying, are always present. Individuals with different characteristics, preferences, and information have to conduct pie-splitting. At the same time, nothing of consequence can happen in most political settings without coalitions of diverse individuals, organizations, or countries, putting aside their differences to accomplish collective action.

Two important classes of traditional models in political science concern coalition formation among diverse individuals. Game theoretic bargaining models, such as those proposed by Baron and Ferejohn (1989) and by Harrington (1990)—both are variants of the Rubinstein bargaining model—help us to understand how coalitions might form within majority-rule legislatures to decide how to divide up a fixed pie. Agenda-setting agents make proposals and try to win majority support with a legislature. Variations in institutional rules can then be shown to affect how the pie is split. Being able to make the first proposal conveys an advantage. Allowing legislators to propose amendments can increase equality.

Spatial voting models, in a similar fashion, depict political parties or candidates as offering campaign platforms to try to win the votes of diverse citizens (Downs, 1957;

Enelow and Hinich, 1984). The parties or candidates that attract a coalition of voters around their platforms sufficient enough to win elections can choose how to divide the governmental pie.

Potential differences across individuals in these models are depicted as dimensions, where each political issue or each policy domain is its own dimension. For both classes of models, there exists the well-known problem of a lack of a core allocation in multiple dimensions. This means that if players are selfish, there typically is no collective decision or allocation of resources in multiple dimensions that cannot be blocked by some coalition of players. In bargaining models, tight agenda-control can avoid the problem of winning coalitions fragmenting with each new proposal. And in spatial voting models, with multiple dimensions, only by introducing uncertainty among agents or by fixing some party's or candidate's behavior artificially can we tie down pure strategy equilibria (Kollman et al., 1998; De Marchi, 1999).

Yet in real politics, coalitions and party ideologies are far more durable than these traditional models would generally predict. Agent-based models can help to understand this durability. The models help us pay careful attention to the limited cognition of political competitors and the consequences of repeated interactions with other people who live nearby and share similar cultures.

Difference can also lead to fighting. As we discuss later, Bhavnani and Backer (2000) model ethnic conflict using computational methods. Ethnic conflict naturally lends itself to dynamic, computational models because it is not a one-shot event, but a series of reactions and counter-reactions that result in patterns of activity over time.

Political scientists also care about difference as representation. When putting together a cabinet, a committee, or a court, a leader is often under tremendous pressure to choose members who represent various identity groups (by gender, race, ethnicity, and so on). Most arguments in favor of such diverse representation are based primarily on norms of fairness. Yet, as some complex systems research has shown (Hong and Page, 2001), diversity may also lead to better collective decisions.

5.3. Externalities

In economics, it is widely known that markets can fail because of unpriced externalities. Indeed, much of political science concerns the allocation of goods and services when markets do not work as intended, and specifically, how governments decide to manage externalities. Governments, at least in principle, ought to adopt policies to try to mitigate negative externalities and promote positive externalities. Government may also deliberately take actions intended to create positive externalities, such as building infrastructure and establishing the rule of law. Government actions have pronounced boundary effects: encouraging growth by protecting and encouraging industries; providing for schools, parks, roads, prisons, and welfare systems; and ensuring public peace by maintaining a military.

The scope of externalities can influence the performance of political institutions. Lacy and Niou (1998), for example, have shown how certain voting systems can perform

poorly when decisions have externalities, and Kollman et al. (2000) have shown that whether to decentralize or centralize decisions on policies in a federal system may depend upon the level of external effects among decisions. More externalities make for harder problems. Organizations, governments, or people facing harder problems may benefit from more sophisticated search techniques to find solutions (Page, 1996).

When the trading of goods only affects buyers and sellers, in principle any trade increases total happiness or utility: both sets of participants are better off and no one else is affected. Since total happiness probably has a maximum (due to resource or technological constraints), the trading system must stop and reach an equilibrium. In graduate economics textbooks, this process is often modeled with a Lyapunov function. With externalities, total happiness does not have to increase with each trade, so the trading process may not reach an equilibrium. If North Korea trades with a member of the former Soviet Union for nuclear fuel, both trading partners have improved their utility, but the rest of the world is worse off. Aggregate utility need not rise with some kinds of trading among nations. Furthermore, trades can beget further trades as total happiness flows up and down over time. The system can churn endlessly rather than settle.

Many political systems appear to be constantly churning and not settling into an equilibrium. (See Janssen and Ostrom, 2006 "Governing Social-Ecological Systems", this Handbook.) Admittedly, the alliance formation process that occurs in the international arena and the coalition formation process in electoral or legislative politics are more durable that one might predict in the absence of some kind of institutional structure, as discussed above, but it would be a stretch to say that participants in either domain attain a steady-state. Agent-based models can provide insight into both the dynamics of social interactions with externalities and the reasons some systems settle into equilibria and other systems do not (Jackson, 2003; Cederman, 1997).

Political scientists and economists both try to understand when it is better to use market solutions to solve problems of negative externalities and when it is better to centralize decision-making and solve those problems politically. Agent-based modeling techniques, by allowing for the exploration of different kinds of externalities affecting diverse agents interacting in space and in time, can help in making such decisions.

5.4. Path dependence

Path dependence refers to the idea that the particular way events unfold over time shapes future outcomes, and that systems exhibit feedback leading outcomes toward a strict subset of all possible steady-state or equilibrium outcomes. Political scientists have long acknowledged such path dependence in explaining specific institutional and cultural features of societies.

Sequential decisions can be path dependent. Consider, for example, how this matters for urban and regional development. In the splitting up of the pie in a federated system, giving a region a slice in the form of an airport, military base, or public works project can create positive and negative externalities. These externalities shape future decisions

on splitting the next pie, so that governments may want to continue to invest or cease such investments in a region, depending on the nature of the externalities. (See Arthur, 2006 "Out of Equilibrium Economics and Agent-Based Modeling", this Handbook.)

Institutional development can be path dependent. As Pierson (2000) has argued, the operations of political institutions lead to public attitudes and preferences among the population that in turn pressure government leaders to shape reforms of those institutions and to create new ones. Governmental programs, such as social security or educational loans, create constituencies among voters that severely limit the options available to public officials in budgeting and in administrative operations (Jackson, 2003). Over time, many governmental programs can outlive their usefulness but they survive because their histories have created constituencies that monitor closely government action.

Beliefs, values, and understandings support this path dependence. In international relations or in ethnic conflict, for instance, the past can shape present outcomes long after it seems rational for decision-makers to invoke the past in predicting the future behavior of adversaries. Tensions across national and ethnic boundaries often have their origins in events that transpired generations ago. In Ireland and in Serbia, for example, battles won or lost many centuries ago appear as focal events in generating collective action among ordinary Irish and Serbs. The collective actions then shape contemporary negotiations over splitting pies and establishing security and stability. History matters and lingers in ways that are hard to imagine in most systems that economists study, such as industrial or financial markets (Page, 2006).

5.5. *Geography*

Geography has become increasingly important in some fields of economics, such as in the study of city formation and location. It has long been important in political science, especially in the study of international relations, urban politics, and voting and elections. Besides the fact that wars and diplomatic disputes are often about the protection or acquisition of land, geography seems to have broader consequences in politics. People living near each other interact and influence each other on a regular basis, and differences can emerge among population groups based on little more than geographic proximity. Animosity can grow between groups that otherwise have similar political preferences simply because they live in different areas.

Geographic correlation of induced preferences over policies in democracies may be largely due to electoral districting rules. In all but a handful of countries, representatives are allocated by geographic districts or regions, and thus candidates or parties structure their campaigns around geography. They promise particular populations living in specific areas pieces of the pie to win their votes.

Geography has the effect of reducing the number of potential coalitions in a democracy or in an international dispute down to manageable numbers. Consider the potential number of coalitions of the members of the U.S. Senate or the U.S. House of Representatives. In the former case, the potential set of majority coalitions is 100 choose 51, or

over a million billion, while for the latter it is 435 choose 218, substantially bigger than a billion billion. Yet throughout American history, coalitions within the Congress have always had enduring geographic bases, over and above shared policy preferences that exist across widely spread population groups.

In international relations, the fact that wars are usually over land has the (hardly redeeming) characteristic of enabling coalitions to become manageable. The number of sides in wars has nearly always been two (Jervis, 1997). When Germany invaded its erstwhile ally the Soviet Union in 1941, it unified the Allies and the Soviets instead of creating a three-sided war, even though there were huge differences between the main Allied countries and the Soviets. It was not geographic proximity in this case, but the fact that the two new allied sides were poised to squeeze Germany from east and west. The aggregation of diverse preferences is central to the study of politics, and geography offers a convenient way for leaders to unify people, organizations, or countries, around common goals.

Agent-based models from political science have analyzed the dynamics of interactions and coalition formation not just in time but in space (Cederman, 1997; Lustick and Miodownik, 2000). Researchers can depict interactions of agents as occurring on a grid that has geographic features of proximity and the observable spread of something—agents, culture, characteristics, empires, political control—over space. (See Dibble, 2006 "Agent-Based Computational Laboratories", this Handbook.)

5.6. Networks

The idea that information can spread through networks in unexpected but consequential ways has long been understood by social scientists, including political scientists. Just as people tend to get jobs through weak ties, they also obtain political information through friends of friends. Moreover, there has been a long-standing interest in how these networks are connected and who has power within those networks. This includes research on the topology of networks, such as the research by Padgett and Ansell (1993) on the Medici family in Italy. (See Vriend, 2006 "ACE Models of Endogenous Interactions", and Wilhite, 2006 "Economic Activity on Fixed Networks", both in this Handbook.)

Within political science, there has been a great deal of research on social capital. Putnam's research (Putnam, 2000) concludes that social capital in the United States is declining, with negative consequences. Tilly (1998) provides data indicating that a systematic lack of social capital for one group can lead to long term inequality relative to other groups with higher social capital. For Putnam, a lack of social capital can lead to less pie to split; for Tilly, network connections may explain how the pie is split.

In our times, the link of networks to security and stability seems obvious, though it was not twenty years ago. Terrorist networks are now one of the greatest threats to domestic and international security and stability. Threats are no longer restricted to state-sponsored militaries. Naturally, there is growing interest in network structures that cross national boundaries and that rely on religious motivations to work.

Research on networks in political science is still primarily empirical and descriptive. At present, efforts are more toward documenting the operations of the networks rather than trying to understand theoretically the structural implications of those networks. There are reasons to be optimistic that computational techniques can help researchers lead the way in understanding both beneficial and insidious networks in the politics. The recent work by Huckfeldt et al. (2004) discussed below on political participation demonstrates the power of computational techniques to study social networks.

5.7. Emergence

Emergence refers to surprising aggregate phenomena that result from the micro level actions of agents (Axelrod et al., 1995). Gliders can emerge in the "game of life", and prices can emerge in complex markets. Segregation can emerge in Schelling's (Schelling, 1978) tipping model, and criticality emerges in sand pile models. Emergence can even be formally defined as a logical or statistical property that occurs at a higher level than the component units.

Since political scientists observe cultural differences across space and time, the notion of emergence resonates in the discipline. (See Axelrod (2006), "Agent-based Modeling as a Bridge Between Disciplines", this Handbook.) As an indication, the studies by Axelrod on the emergence of cooperation (Axelrod, 1984) and the emergence of norms (Axelrod, 1986) have been very influential. Empirically, macro-level characteristics of societies can change over time, sometimes gradually and sometimes dramatically. For example, societies vary substantially in their levels of trust and individualism displayed in surveys and in experiments (Inglehart, 1997). If asked if they trust other people, over two-thirds of Scandinavians will reply that they do. Fewer than a fifth of Turkish people do. Some countries have seen increases in measures of trust, something often attributed to economic growth. Economic growth itself has an emergent quality that is hard to predict in advance, and can occur in a relatively short period of time, as observed in several East Asian economies, and in Ireland in the 1980s and 1990s. (See Howitt, 2006 "Coordination Issues in Long-Run Growth", this Handbook.)

Most political scientists agree that cultural differences exist and are meaningful, but there is less agreement on where these cultural differences come from, and the role of institutions in forming and transforming culture. Putnam et al. (1993) attributes the profound differences between the trusting, economically well-off Northern Italians and the less trusting, less well-off Southern Italians to the "mists of the dark ages", or the historical legacies of centuries-old practices.

We have reasons to believe that complex systems and agent-based modeling are well suited to construct valuable models of culture. There has already been computational research on where and how cultural differences emerge (Axelrod, 1997; Bowles et al., 2003, and Bednar and Page, 2006). This research examines three different aspects of culture: within group homogeneity, altruism, and behavioral consistency; all three programs hint at the enormous potential for future work. Some political scientists, especially from the area studies tradition, believe that each region or country is exceptional,

and that because people of different regions interpret the world differently and act differently, comparative work across cultural contexts obscures the uniqueness of each setting and leads to false inferences about the causes of varying outcomes. Computational models can help us understand how unique kinds of behavior emerge in specific contexts (Epstein, 2003).

For political scientists, fieldwork to study the local context will continue to be valuable. In fact, they may be even more so as it becomes possible to link more tightly the results of models on the emergence of those cultural contexts with data collected in the field.

6. The state of research

In reviewing current research on computational methods in political science and political economy, not surprisingly we observe diverse approaches and purposes. If we cast our net broadly, to capture all computational modeling, including numerical estimations of equilibria from game theory (see, for example, Baron and Herron, 2003), calculations of all possible coalitions in large groups (see, for example, Laver and Benoit, 2003), or Monte Carlo simulations of social processes using empirically-derived estimators, then the amount of published work is quite large. For purposes of this handbook, however, it is most useful to cast our net somewhat narrower, to focus on agent-based computational models.

Political scientists have used computer simulation and computational modeling in various guises for many decades. Guetzkow (1963) simulated the international system using complicated computer models in the 1960s. Computational versions of Axelrod's prisoner's dilemma tournament (Axelrod, 1984) were summarized in publications more than 20 years ago. The use of computation to explore domains of interest to political scientists has grown tremendously. A list of the computational versions of the repeated prisoner's dilemma would alone fill a chapter of this handbook.

In this brief summary of the research, we focus on those papers or books that address what we previously identified as the core concerns of political scientists: collective choices and production of public goods; pie splitting; and cohesion and conflict. However, as will be seen below, many of the models we summarize address more than one of these concerns, and thus it is difficult to categorize the models cleanly. Nevertheless, to generalize over the following summary, the models of electoral competition and institutional comparisons tend to focus on issues of collective choice, the models of adaptive agents within organizations and complex environments tend to focus on issues of pie-splitting, and the models of identity tend to focus on issues of cohesion and conflict.

6.1. Models of electoral competition

The study of elections is central to political science. A great deal of research is devoted to the analysis of party position-taking and voter behavior. By some depictions, in U.S. presidential elections, the candidates compete within vast multi-dimensional issue

spaces and voters are bombarded with diverse and often conflicting information from a variety of sources. The resulting system of positioning, advertising, and voting among diverse kinds of actors lends itself to agent-based modeling.

We consider electoral models in some detail to provide a vivid example of how computational models can add value to the study of politics. The model that is most widely used to study candidate behavior is called the spatial model, as policies and voter ideal points are represented as vectors. Voters vote for the party or candidate closest to them in the space of possible positions. This was first proposed by Hotelling (1929) as a model of economic spatial competition in one dimension. Downs (1957) applied this model to candidate positioning with the result that in two-candidate competition, the candidates converge to the median voter's position.

For nearly fifty years spatial models of electoral competition have been prominent fixtures in political science journals or on bookshelves. Subsequent to Downs, Plott (1967) proved that in higher dimensions, unless voter ideal points satisfied radial symmetry (an extremely strong condition), any policy position could be defeated. This ruled out pure strategy equilibria in predicting candidate behavior. The lack of a pure strategy equilibrium can be overcome by introducing uncertainty by candidates, but the informational assumptions in such models are still quite strong. Candidates have to know the distribution over votes for all pairs of positions. Building upon the logic in Plott's result, McKelvey (1976) then showed that the top cycle set, the set of positions that defeat any other position, equals the entire set. This is typically taken to mean that there is no equilibrium policy position in a multidimensional voting model where majority rule is the means of deciding among policies.

Yet the McKelvey result is often interpreted incorrectly. Some have concluded that the result means electoral democracy in general leads to chaos (Riker, 1982). In fact, the McKelvey result is a theorem about what kind of preference aggregation is possible under majority rule. It does not tell us what happens under specific institutions (other than majority rule) or given a specific set of behavioral assumptions about rational actors. The latter consideration was considered by Kramer (1977) who showed that if an incumbent party remains fixed while the challenger party seeks a position to defeat the incumbent, and parties want to maximize their vote total, over a sequence of elections policies would converge to the min max set, the set of policies that lose by a minimal amount. This would seem to lend some stability to electoral outcomes. Unfortunately, once the min max set is reached, the winning policy can then jump back out of the set in a future period. Kramer's result does not, therefore, imply stability.

Viewed in summary, the Plott, McKelvey, and Kramer results made some scholars question whether democratic procedures could aggregate preference information in a coherent way. The multidimensional results have also led theorists and empiricists to rely on more manageable one-dimensional models. A single-dimensional model of competition, while useful for some purposes, is by some considered too simplistic to capture many aspects of electoral competition, such as the trade-offs voters make across issue dimensions in evaluating candidates or parties.

To draw an analogy to economics, suppose that economists discovered in mathematical models with rational consumers and firms that supply equaled demand if there were a single market but not if there were more than one market attracting the dollars of consumers. If economists then collectively decided that there was really only one market and that this was the only kind of model worth studying, we would be disappointed that constraints on modeling were leading us away from studying more complex aspects of the real economy. In fact, in standard economic models, two markets work as efficiently as one. (To be fair, economists are not faultless either. They assume that a million markets also behave like a single market, a conjecture that certainly cannot be true.)

The contribution of computational models to the elections literature takes three forms. First, scholars have asked the basic computational question: how hard would it be to find a sequence of policies that led through a series of votes from one policy to a second arbitrary policy? More formally, given a policy x and a policy y, how difficult is finding policies $x_1, x_2, \ldots x_n$ such that $x_1 = x$, $x_n = y$, and x_{i-1} loses in a democratic election to x_i for each $i = 1 \ldots n$? Bartholdi et al. (1989) show that manipulating a plurality voting system is computationally hard. They show that if there are C candidates and V voters, then the difficulty of manipulating a voting system by adding or deleting candidates is NP hard in $C * V$, the number of candidates times the number of voters. This result points toward a more nuanced interpretation of McKelvey's result. Even if the top cycle set is the entire set, the ability of someone to manipulate outcomes may well be limited by computational constraints. We might think of McKelvey as showing what is possible and the later results of Bartholdi, Tovey, and Trick as describing what is plausible.

Moreover, if anything, these findings understate the difficulty of the task because these researchers assume sincere voting (voting for the most preferred outcome in the choice set) by everyone. With sophisticated voting (voting for the option that maximizes one's utility given one's knowledge of others' behavior) or a blend of sophisticated and sincere voting, predicting the outcomes of various configurations of candidates might itself be even more difficult computationally than even Bartholdi, Tovey, and Trick describe.

The second computational contribution to this literature relies on agent-based models of elections. These papers relax the assumption that parties choose their platforms optimally. Instead, the parties adapt platforms using search strategies that range from quite simple to rather sophisticated. In an early paper, Kollman, Miller, and Page (Kollman et al., 1992) show that adaptive parties in a multidimensional environment tend to converge to central regions of the policy space.

In the basic KMP model, voters have ideal points in an N-dimensional policy space. Candidates or parties choose policies in that space. A voter chooses to vote for whichever party's platform is closer to her ideal point. Unlike in the standard spatial model, parties are constrained in their movements and in the information they have. In the KMP model, parties can only move locally, in the neighborhood of their current policy platform.

In one version of the KMP model, a party's decision about where to move is dictated by polling results. A party with a policy $(y_1, y_2, \ldots y_n)$ tests a neighboring policy $(\hat{y}_1, \hat{y}_2, \ldots \hat{y}_n)$. If that new policy gets more votes against the opponent in a poll than does the old policy, then the party moves to $(\hat{y}_1, \hat{y}_2, \ldots \hat{y}_n)$. In another version of the model, parties toss out an initial set of policies in the neighborhood of their current policies and choose the best among those. In yet another, the parties use a genetic algorithm to evolve policies. (See Brenner, 2006 "Agent Learning Representation: Advice on Modeling Agent-based Learning", and Duffy, 2006 "Agent-based Models and Human Subjects Experiments", both in this Handbook, for detailed discussion of genetic algorithms.)

Regardless of the policy formation rule, the qualitative results remain unchanged: parties tend to choose policies near the center of the policy space. Once both parties locate there, they make small changes hoping to build winning coalitions of voters. One result that depends upon the learning rule was the time it took the parties to locate the center of the policy space. This depended on the relationship between the sophistication of the policy search algorithm and the size of the policy space.

The convergence of the parties' platforms depended on other parts of the model. In later work KMP (Kollman et al., 1998) reveal a relationship between the nature of voter preferences and policy convergence. They use the metaphor of an "electoral landscape" as a way to describe the adaptive environment that a political party faces. In their use of the concept, higher points on the landscape mean more voter support. They find that voter preferences help determine whether electoral landscapes are relatively flat or relatively rugged. This matters because with flat landscapes, parties have difficulty finding more popular, winning policies through adaptation. With more pointed landscapes and steep slopes, parties can easily find pathways to high ground. In contrast, if modelers assume optimizing parties, as is standard in traditional spatial models, the notion of landscapes is irrelevant. The slope of the payoff function does not matter with optimizing parties because the parties can find the optima immediately and do not need to find pathways there. Thus, the computational approach with adaptive parties can highlight a linkage between voters' preferences and rates of party convergence by focusing on *how* parties adapt toward more popular policy positions.

The near-convergence result from the computational model suggests a reconsideration of the importance of a lack of a formal equilibrium in the multiple-issue domain. Does the equilibrium really matter that much if it is just a benchmark? Given optimizing agents and certain additional regularity conditions, a market has an equilibrium that is efficient. But agent-based models of markets do not necessarily go right to that equilibrium. Instead, they often bounce around in the neighborhood of the efficient allocation. Two-party competition in multiple dimensions does not have a pure strategy equilibrium in the absence of institutional or information constraints, but in agent-based, adaptive models candidates tend to bounce around in the neighborhood of the policies that give the highest utility. If modern social science relied on agent-based models with adaptive, purposeful, but not hyper-rational agents, and not on equilibrium notions, then perhaps social scientists would not be led to think that markets work and electoral democracy

does not. Instead, perhaps the two kinds of systems for aggregating preferences would look about equally effective at carrying out their respective tasks.

In addition to convergence results, KMP also find that incumbents, who are assumed to be fixed in the policy space, often win elections. This occurs because challengers may not adapt well enough to locate winning policy positions. These challengers were not stupid. The difficulty in beating an incumbent results from the fact that the challenging candidate who has just been defeated often has many possible policy changes that improve its vote total but there is no-clear direction on which changes will lead to winning. Moreover, the elections are depicted are zero sum games. If one candidate is at a multi-dimensional peak, then the other is stuck in a multi-dimensional hole. Positioned in this hole, any path leads upward, toward more votes, but only a few of these paths may lead to a platform that wins the election (Tovey, 1991).

These computational models of elections not only generate intuitively appealing results, they display a kind of realism lacking in some game theoretic models that assume perfect optimizing behavior. In the adaptive models, parties take polls and respond to the polling information by moving locally in policy space. Parties attain office with moderate platforms. And the parties occasionally, but only occasionally, re-aligne themselves, changing the blocks of voters to whom they appeal. This is similar to real politics, such as when most African-Americans switched their allegiances from the Republican Party to the Democratic Party over the latter half of the 20th Century because of the changes in party position-taking.

The initial KMP models were somewhat primitive. There have been extensions and variations by other authors that include interest groups and adaptive voters. De Marchi (2003), for instance, considers a two-dimensional issue space. As before, the parties respond to polls of voters on issues. His models depart from the more basic KMP model in their assumptions about voter information and sophistication. In the KMP model, voters know the parties' policy positions exactly. De Marchi's assumptions incorporate widely accepted research findings on the distribution of information among mass electorates. Including empirically supportable assumptions of informational diversity among voters lends realism to his computational models and offers the potential for empirical testing as well as calibration.

In the first of De Marchi's models, some voters have sophisticated ideologies and therefore are consistent in their survey responses to pollsters. Other voters are not ideologically "constrained", and their poll responses across issue dimensions are highly variable. He finds that the responsiveness of the adaptive parties to the voters is sensitive to the instability of voters' answers to pollsters about their favorite policy positions, and not so much to the levels of ideological sophistication.

In the second model, voters vary in the amount of information they have. He finds that less voter information leads to an even greater incumbency advantage compared with the case of more voter information. Incumbents' platforms are better known so incumbents do better. De Marchi also explores competition over which issues candidates choose to highlight. Candidates can emphasize certain issues at the expense of others. Here again,

we get an incumbency advantage. Incumbents tend to have more money, and therefore can highlight issues upon which they have an electoral advantage.

In light of the fact that adaptive parties tend to converge in more than one dimension, there are single-dimensional political models with adaptive agents. In one such model, Jackson (2003) proposes a single-dimensional dynamic model of two-party electoral competition where both parties and voters adapt. The parties adapt to the position of the median voter in trying to win elections, while simultaneously the position of the median voter adapts to the positions of the parties. Voters change policy positions because they develop partisan attachments to the parties and are influenced by the policy positions of the parties. The computer in this case solves a system of five equations that depicts the changing policy positions of the parties, the changing position of the median voter, and the changing levels of party loyalty present among the voters. Jackson finds that for reasonable ranges of parameter values, the model does settle into equilibrium party positions, but only after a lengthy time period. Under various conditions, the fortunes of the parties, and their policy positions, fluctuate over time, with alternating stretches of one party dominance followed by collapse and the emergence of the other party as the dominant force. This again is similar to real election results in American history, where there have been long stretches of one-party dominance, followed by abrupt change.

In a recent paper, Laver (2005) proposes an innovative computational model of party competition and then tests its implications using electoral data from Ireland. The model includes parties with different kinds of strategies and different motivations. Some parties in the model, for example, change their policy positions to mimic the largest party, and then move in the direction of the maximal gradient. Other parties retain their founding policy positions and move incrementally in search of more votes. Laver studies competition with diverse kinds of parties with different motivations, and suggests that his model captures the essence of many multi-party systems, such as those in many European countries. Some parties seek to maximize votes while others seek to retain their ideological identities. He calibrates his simulations using real data from Irish elections, making assumptions about the strategies of the various Irish parties. He is able to create simulated results that resemble historical changes in parties' support in Ireland.

6.2. Institutional comparisons

Institutions enable groups to decide over public goods, but they also enable collective decisions over pie-splitting—who gets what, where and when, and how, to paraphrase the definition of politics given by Harold Lasswell (1958), a famous political scientist from the 1950s. (See Janssen and Ostrom, 2006 "Governing Social-Ecological Systems", this Handbook.)

A small but growing literature is devoted to comparisons of political institutions using computational models. We think this area of research is particularly promising. For example, McGann et al. (2002) study voting behavior under three different electoral rules using a computational model. In the model, candidates are randomly selected from the population to run for office and their policy platforms are depicted as falling on a one-

dimensional scale. Citizens vote sincerely for the candidate closest to them. McGann et al. evaluate results from many simulations of voting behavior under plurality, run-off, and sequential elimination voting rules, and measure how closely the winner in each election approximates the median voter or is the Condorcet winner among the candidates.

In this model, candidates or citizens are not adapting in a complex environment, in contrast to most agent-based models. Instead the computer is able to replicate various instantiations of specific kinds of voting behavior under different institutional rules. The researchers find that winners are more often than not representative of modes in the distribution of voters instead of medians, and that the run-off and sequential elimination rules reward the Condorcet winner more often than plurality rules.

Hayes and Richards (2003) rely on computational methods to analyze economic behavior in the context of different kinds of exchange rate regimes by governments. In their model, buyers and sellers of foreign currencies who can profit by predicting future exchange rates attempt to learn the true nature of the monetary regime by observing changes in the money supply. The currency traders use Bayesian reasoning to learn whether the regime is contractionary or expansionist, although the agents receive noisy information generated by the stochastic environment. The model indicates, surprisingly, that politically-dependent central banks may benefit traders because learning the nature of the regime becomes easier. A dependent central bank produces politically motivated policies, and therefore traders can ascribe less of the variance in the money supply to stochastic variables than they can in the case of an independent central bank. They compare the results of their computational model to real data from Britain and Germany. The trajectories of excess returns from both countries differ in ways predicted by the model.

As these papers suggest, computational models allow scholars to capture explicit differences in institutions and to consider the implications of those differences. Another advantage of computational models is that they allow for multiple institutions to be considered simultaneously. As an example, Kollman et al. (1997) embed their spatial voting model with adaptive parties in a Tiebout framework. In the model, citizens are free to move between locations based upon the locations' offerings of public goods. Those public goods are decided by voting among the citizens at the locations.

The results of this model were surprising. Poorly performing rules for voting—those that produced the least stable policies within locations—did the best in the Tiebout setting. Thus, the instability of majority rule voting, the lack of equilibrium that everyone considers a weakness, turns out to be a strength when Tiebout effects are included. After analyzing the results of the computational model, the reason becomes apparent. Stability of electoral outcomes is correlated with the homogeneity of preferences. If people in a location all want the same thing, the parties offer that. If people have diverse preferences, the parties wander in policy space. This policy instability leads to more sorting. If people have not yet sorted into homogeneous preference groups, then the policies continue to cycle. If the people have sorted into groups with homogeneous preferences, then the system stabilizes.

The key insight is that, if instability of the entire system decreases as utility increases, then the system stabilizes at good outcomes. Bad outcomes get disturbed by the local instability, leading the system to search for better policies in locations and better distributions of citizens across locations. This results in a search that is even better than simulated annealing. In simulated annealing, the amount of instability decreases with time. In the Tiebout model, the amount of instability decreases with total utility.

There is a further point related to the future of the spatial modeling literature. In political institutions, voters cast ballots for candidates who then comprise a legislature. Within that legislature, there are rules for how votes get aggregated. The candidates, when making appeals to voters, propose policies. These policies generate outcomes over which the voters have preferences. Voters, candidates, parties, legislatures—political systems are linked at several levels that ultimately result in policy outcomes of great importance. Many game theoretic models of politics tend to focus on a single level, such as the relationship between voters and election outcomes, the relationship between legislative composition and coalition formation, or the relationship between coalitions and policy choices. Some game theoretic models include voters who take into account the composition of the legislature, but it is very difficult to model the full linkage that includes whether policies lead to good outcomes and learning about the policy space among the various actors. Agent-based models and computational equilibrium models may allow richer institutional analyses of linked levels of conflict and organized behavior among people deciding over public goods. (See Chang and Harrington, 2006 "Agent-based Models of Organizations", this Handbook.)

6.3. Individuals or agents adapting in complex political environments

The computational literatures on electoral competition and on institutional analysis complement a relatively large literature that considers adaptive individuals and organizations in political systems. We discuss four general classes of research here: general models of political organizations; models of information transmission in political networks; models of violence (non-lattice based); and models of electoral settings. Within each, we highlight a handful of prominent papers.

The Tiebout model by Kollman et al. (1997) analyzes multiple institutional forces occurring simultaneously. Several organizational models consider structural features of an environment or organization and ask how those features influence behavior of agents. Harrington (2003), for example, examines a series of models of competition within hierarchies. In one paper, he proposes a model of agents competing for promotion in a hierarchical society or organization. We can think of these as politicians rising to positions of prominence. In the political story told to motivate the model, candidates pair off against each other at each level of the hierarchy. The winner goes on to compete again, while the loser leaves the population of competitors.

There are two types of candidates in the Harrington model, those who adapt to their environment and those who are rigid and do not adapt. The policies that the agents

propose correspond to unidimensional issue positions. The rigid types are ideologues. They will not switch their positions to match current public opinion. Given the assumptions of the model, the number of survivors gets smaller as competitors ascend up the hierarchy of political offices. Harrington analyzes which kinds of agents (or candidates) survive to higher office when the exogenous environment changes over time. In particular, he traces the proportion of rigid (as opposed to flexible) agents in the top level of the hierarchy as competition unfolds and the population of surviving politicians evolves. Thus, the Harrington model can be thought of as a model of pie-splitting in two senses. First, the agents are proposing a particular way to split the pie. Second, there are only a limited number of positions at the top of the hierarchy.

Intuitively, we might expect the rigid agents to lose more often. However, in his model, voters have lexicographic preferences. They prefer someone who takes their preferred position; but if both candidates propose the same policy, the voter prefers a candidate who has consistently favored the policy. Thus, as they move up the hierarchy, the flexible agents get exposed and will lose to a rigid agent provided the rigid agent advocates the policy currently in fashion. Under some conditions, Harrington shows that the rigid agents, and not the flexible agents, win out.

The Harrington paper considers politicians who evolve in a complex system. A natural question to ask is what attributes of voters might emerge. In a series of papers, Bendor et al. (2003a, 2003b) explore how the aspiration levels of agents evolve over time. They find surprising emergent outcomes in the aggregate. In one paper (Bendor et al., 2003a), they propose a model of citizens deciding whether to vote when it is costly to do so. Voters have aspiration levels that respond to whether they voted and the election outcome, and they decide whether to vote based on how their expected utility compares to aspiration levels. Instead of focusing on free-riding, as with most voter turnout models, this research examines the dynamics of voter turnout as aspiration levels evolve over time, and whether that turnout settles into an equilibrium level. The computational experiments allow for different scenarios, such as specifying the cost of voting and the number of voters. They find that turnout does equilibrate at empirically observable levels—ranging from 30% to 70% in two-party systems—and those levels are lower as the number of voters increases and the cost of voting increases.

In another paper (Bendor et al., 2003b), agents pair off and play one of a number of well-known games, such as stag hunt, chicken, or prisoner's dilemma. However, instead of assuming optimization by agents, they assume that agents "satisfice" according to an aspiration level. An agent's aspiration level adjusts in response to payoffs from previous games. Thus, the agents adapt their decision rules according to their experience. With this simple model, the authors can examine a large number of questions, such as the amount of cooperation induced by agents with adaptive aspirations and the sensitivity of players' strategies to initial conditions (e.g., the initial aspiration levels). Among the many results in their paper, they find that cooperation in games like prisoner's dilemma can occur even in one-shot settings. They also show by including trembles that the games have unique limiting distributions, a valuable "existence" result that allows for empirical applications of the model.

In a recent book, Huckfeldt et al. (2004) summarize a study of how individuals talk politics within social networks. The authors begin with the following stylized facts that might seem contradictory. People are easily influenced by their friends and acquaintances on politics. People interact with many others over the course of a relevant period prior to an election. Diversity of political attitudes exists within electorates, even among people who interact with each other on a regular basis and who even talk about politics with each other. Given how easily people are influenced, how does the diversity happen? Why do societies fail to converge on uniform opinions?

The authors demonstrate empirically, first, that individuals talk about politics within social networks, and that diversity exists even among loose social networks. The authors suggest that the social networks are the key mechanisms that lead to diversity of opinions within an electorate. To understand these social networks, the authors describe a simple agent-based model, based on the culture model by Axelrod (1997) discussed below. In brief, agents with political attitudes interact and can influence each other, and one can trace the spread of attitudes across the social system. In the first version of this model, all agents eventually agree on the same political attitudes. In contradiction to their empirical findings, there is no diversity of opinion after a relatively short period of time within the model. They test several simple solutions, such as introducing rigid agents who do not change, and various parameter changes that make sense.

Eventually, they introduce different, more realistic changes to the model. Most importantly, they give agents different layers of friends and acquaintances, where the probability of being influenced depends on how close the other agent is to you. As they examine the runs of this model, they see that social networks begin to emerge, and over time diversity exists in the societies. The social networks cling to opinions that differ from other social networks, and the entire population exhibits both an intra-group homogeneity but an across-group heterogeneity. It looks a lot like the empirical data. The basic insight, which is similar to others from the research summarized below, is that social systems can exhibit a balance of influence and social cohesion that leads to clumping of people into like-minded social groupings. Moving the parameters of choice, interaction, or influence too much in one direction or the other in the model can lead to complete homogeneity.

Bhavnani and Backer (2000) analyze the spread of genocide using a computational model. In the model, there are two groups of agents, and each agent has a different propensity to violence based on the number of others participating, and a different level of hatred toward the other group. The agents interact and influence each other. The model begins with a signal sent to one or the other group, or both, that violence has broken out. Then agents react to the news and to the behavior of other agents. They discover two sets of findings. In some instances, violence between the groups can occur sporadically and intensely, with many killed. In other instances, violence occurs at a moderate level at a constant rate. Which outcome occurs depends on the initial conditions: the distribution of propensities, of inter-ethnic hatred, and of frequencies of interactions between the groups.

6.4. The spread of collective identities or authority structures

As in other fields, in political science agent-based models have been used to analyze the spread of characteristics across a lattice, when the agents on the lattice interact and influence each other. Sometimes those characteristics are the component descriptors of a location on the lattice. Other times, those characteristics are the boundaries of political units or social networks.

As for the former type of model, Axelrod (1997) models the spread of culture by creating a $N \times m$ lattice of sites—interpreted in one version as villages—where two sites interact with probability in proportion to their cultural similarity. If sites interact, then with a given probability one site takes on some of the cultural characteristics of the other. He finds that the social system usually settles into a relatively small number of cultural zones, defined as homogeneous groups of sites forming a contiguous set on the lattice. Moreover, the number of cultural zones that exist either in equilibrium or after a very large number of interactions varies with the size of the lattice, the number of cultural characteristics, and the number of possible types of culture.

In a similar vein, Lustick and Miodownik (2000), model a process of deliberation among citizens trying to decide on a common course of action. A prominent topic for research within political science and law has been on the value of having groups of people discussing current events or political issues before deciding how to answer opinion polls, vote, or choose a particular action for the collective. Some think that deliberation leads to wiser or more considered decision-making (Fishkin, 1997), while others are deeply skeptical (Lupia, 2002).

The Agent-Based Argument Repertoire (ABAR) model developed by Lustick is a two-dimensional lattice with agents in locations on the lattice interacting with neighbors and influencing them. Lustick and Miodownik (2000) use this model to simulate democratic deliberation. There are two types of agents on the lattice, ordinary citizens and opinion leaders. All agents in the model interact with only their neighbors, but opinion leaders have larger neighborhoods. A citizen is called upon to propose an argument (a way of interpreting the problem at hand), and others in the neighborhood are differentially influenced by that argument, depending on their types. Through interactions, neighbors with some probability reduce their levels of disagreement with each other, but may increase it with other groups on the lattice.

In one version of the model, Lustick and Miodownik vary the number of different arguments available in the population, the number of opinion leaders relative to ordinary citizens, and the size of the opinion leaders' neighborhoods. They then track the overall level of disagreement in the population on the lattice. They find a trade-off in the deliberative process between engendering less disagreement and more common stances on proposed solutions, and diversity in the population. That is, under certain conditions, the population comes to agreement but has little diversity and not much flexibility to adapt to new information, and under other conditions the population remains divided, but diverse and flexible.

In a paper using similar methodology but tackling a different set of questions, Lustick et al. (2004), simulate the changing identities of agents on a two-dimensional lattice and how the emergence of identity patterns might encourage secession. One possible identity, if agglomerated in sufficient weight in one geographic region, will encourage agents to push for secession from the entire group of agents. Lustick, et al. examine different parameter ranges to examine what can cause more or less sentiment for secession. For instance, one kind of identity that can emerge in the population is the propensity for agents to share power with minorities, and this is varied to understand how it interacts with other identities to mitigate or possibly encourage secession by those minorities. They find that increased power-sharing sentiments among the population as a whole leads to greater numbers of minorities arising, with fewer number of secessionist movements proportional to the number of minorities. However, secessionism can still arise even under tolerant regimes.

For the second kind of model, where characteristics that change on the lattice are political boundaries or networks of trusting agents, several studies deserve mention here. Macey and Skvoretz (1998) analyze the evolution of trust and cooperation among agents engaging in one-shot prisoner's dilemma games. As in the earlier Axelrod models of iterated prisoner's dilemma games and dynamic population changes, the authors depict agents as having strategies that can evolve over time as they interact with other agents, using a genetic algorithm to simulate the evolution of strategies. Payoffs to an agent in the Macey and Skvoretz model do not depend on prospects for repeated play with the same opponent, but rather on the standard cooperation and defect choices in a one-shot setting and also on the possibility of refusing to play at all. They track the propensity of agents to cooperate as one increases the payoff for refusing to play, and as one embeds agents into smaller and smaller communities. It turns out that, in this model, embeddedness in small communities is the key linchpin to increasing cooperation among strangers in one-shot PD games.

In several articles and a book, Cederman (1997, 2002, 2003) reports a series of results using a network model (projected onto a lattice) of political units that can choose to cooperate or fight each other. His basic interest is in understanding the emergence of new political boundaries, thus simulating the spread of empires or the enlargement of countries. Each political unit exists as a location on a two-dimensional lattice. With some probability, one location, following a fight if it takes place, can 'swallow" the other to integrate together into a larger political unit.

Cederman's core model has many facets. He varies parameters such as the propensity of units to attack each other, the costs of defending oneself, and the size of the grid. His main variables of interest are the number and size of the political units over time. In Cederman (2003), for example, he finds that territories expand and wars take place in distributions that correspond to empirical patterns discovered many decades ago in international relations. Empirically, the size of wars and the number of casualties in those wars approximate a power law distribution when plotted against their frequency. This relationship also emerges from Cederman's simulations, with the parameters of that power law determined by the initialized parameters in the computational experiments.

Cederman interprets many of his results that accord with data on inter-state conflicts as vindicating an agent-based modeling approach. He notes that agent-based modeling can provide distributions of outcomes in international relations, not simply point predictions about specific events.

Several researchers have analyzed models of civic violence using interacting agent-based models. Epstein (2002) proposes a model with two types of agents, ordinary persons and cops, who live on a lattice. Ordinary persons decide in each time period whether to rebel or not, and they can influence each other. Cops decide whether or not to arrest rebellious persons. There are various renditions of the model, including one where two different population groups might fight each other as a form of rebellion. Epstein examines the rebelliousness of persons as their grievance levels increase relative to the number of cops, and as the behavior of the cops change. He finds that over time rebelliousness comes in waves (like punctuated equilibria), with the size and frequency of the waves varying with parameters in some intuitive and some nonintuitive ways.

7. Conclusion

In taking stock of the contributions of agent-based modeling to the study of politics so far, we conclude that though small in number, the papers and models have been high in quality and growing in their impact. We also detect an increase in interest among political scientists of all disciplinary stripes from formal theorists to empiricists to historians. At our most optimistic, we might even claim, with others, that complex systems research might prove to be a glue that can hold some disparate parts of the discipline together. Computational methods may offer a bridge between the side of political science with scientific aspirations, including those researchers with preferences for, or openness to, rigorous theories, falsifiable propositions, and systematic data collection, and the side of political science that forces us to confront contextual details that provide vital information about cross-national and cross-cultural differences (Kollman et al., 2003).

Computational models can perform this role because of what they are well disposed to capture: systems with adaptive structures but not deterministic structure, and systems with diverse agents who interact over time on a geographic space. Political systems contain diverse actors who pass information among each other through complicated networks. Conflict within political systems is often highly dimensional, and outcomes appear to be path dependent. Some outcomes in political systems emerge into stable equilibria, but much of what emergences is complex and nonlinear.

The separate components of complex systems research resonate within political science—adaptation, difference, externalities, path dependence, geography, networks, and emergence—but so does the complete picture. One might argue, as Jervis (1997) has in reference to the importance of complexity studies in international relations, that most of the linear and equilibrium features of political systems are now understood, and that we should turn to these latest techniques to grapple with what is left, the complex. Major events in the political world are often unpredictable. By definition, terrorist acts

can only be predictable in a statistical sense. The implications of events are often impossible to foresee from simple models. As Neil Harrison (2004) writes: "The reality of world politics is more complex than dreamt of in most theories."

In addition to enabling political science to enlarge the domain of possible questions, agent-based models may allow the discipline to accommodate some of the conflicting claims made by rational choice modelers and scholars who advocate thick description. Rational choice theory allows us to capture important basic causal forces, but models based on game theory are limited in helping us understand how history, culture, information networks, and collective-interested behavior also matter. Agent-based-models may enable us to advance the discipline by bridging formal modeling and thick description given the dual capacity of these models to capture the richness of history and the theoretical sturdiness of logically consistent aggregation.

References

Arthur, W.B. (2006). "Out of equilibrium economics and agent-based modeling", this handbook.

Axelrod, R. (1984). The Evolution of Cooperation. Basic Books, New York.

Axelrod, R. (1986). "An evolutionary approach to norms". American Political Science Review 80, 1095–1111.

Axelrod, R. (1997). The Complexity of Cooperation. Princeton University Press, Princeton.

Axelrod, R. (2006). "Agent-based modeling as a bridge between disciplines", this handbook.

Axelrod, R., Cohen, M. (2000). Harnessing Complexity: Organizational Implications of a Scientific Frontier. Free Press.

Axelrod, R., Mitchell, W., Thomas, R., Bennett, D.S., Bruderer, E. (1995). "Coalition formation in standard-setting alliances". Management Science 41, 1493–1508.

Baron, D.P., Ferejohn, J.A. (1989). "Bargaining in Legislatures". American Political Science Review 89, 1181–1206.

Baron, D., Herron, M. (2003). "A dynamic model of multidimensional collective choices". In: Kollman, K., Miller, J., Page, S. (Eds.), Computational Models in Political Economy. MIT Press, Cambridge, MA.

Bartholdi, J., Tovey, C., Trick, M. (1989). "Voting schemes for which it can be difficult to tell who won the election". Social Choice and Welfare 6, 157–166.

Bhavnani, R., Backer, D. (2000). "Localized ethnic conflict and genocide: accounting for differences in Rwanda and Burundi". Journal of Conflict Resolution 44, 283–307.

Bednar, J. Page, S. (2006). "Can game(s) theory explain culture?", Rationality and Society, in preparation.

Bendor, J., Diermeier, D., Ting, M. (2003a). "A behavioral model of turnout". American Political Science Review 97, 261–280.

Bendor, J., Diermeier, D., Ting, M. (2003b). "Recovering behavioralism". In: Kollman, K., Miller, J., Page, S. (Eds.), Computational Models in Political Economy. MIT Press, Cambridge, MA.

Bowles, S., Gintis, H., Boyd, R., Fehr, E. (2003). "Explaining altruistic behavior in humans". Evolution and Human Behavior 24, 153–172.

Brenner, T. (2006). "Agent learning representation: advice on modeling agent-based learning", this handbook.

Camerer, C. (2003). Behavioral Game Theory: Experiments in Strategic Interaction. Princeton University Press, Princeton, NJ.

Cederman, L.-E. (1997). Emergent Actors: How States and Nations Develop and Dissolve. Princeton University Press, Princeton, NJ.

Cederman, L.-E. (2002). "Endogenizing geopolitical boundaries with agent-based modeling". Proceedings of the National Academy of Sciences 99, 7296–7303.

Cederman, L.-E. (2003). "Modeling the size of wars: from billiard balls to sandpiles". American Political Science Review 97, 135–150.

Chang, M.-H., Harrington, J.E. (2006). "Agent-based models of organizations", this handbook.
De Marchi, S. (1999). "Adaptive models and electoral instability". Journal of Theoretical Politics 11 (3), 393–419.
De Marchi, S. (2003). "A Computational Model of Voter Sophistication, Ideology and Candidate Position-taking". In: Kollman, K., Miller, J., Page, S. (Eds.), Computational Models in Political Economy. MIT Press, Cambridge, MA.
De Marchi, S. (2005). Lifting the Curse of Dimensionality: Computational Modeling in the Social Sciences. Cambridge University Press, New York.
Dibble, C. (2006). "Agent-based computational laboratories", this handbook.
Downs, A. (1957). Economic Theory of Democracy. Harper and Row, New York.
Duffy, J. (2006). "Agent-based models and human subjects experiments", this handbook.
Enelow, J., Hinich, M. (1984). Spatial Theory of Voting. Cambridge University Press, New York.
Epstein, J. (2002). "Modeling civil violence: an agent-based computational approach". Proceedings of the National Academy of Sciences 99 (5), 7243–7250.
Epstein, J. (2003). Generative Social Science. Princeton University Press, Princeton, NJ.
Fishkin, J. (1997). Voice of the People. Yale University Press, New Haven, CT.
Guetzkow, H. (1963). Simulation in International Relations. Prentice Hall, Englewood Cliffs, NJ.
Harrington, J. (1990). "Power of the proposal-maker in model of endogenous agenda formation". Public Choice 64, 1–20.
Harrington, J. (2003). "Rigidity and flexibility in social systems". In: Kollman, K., Miller, J., Page, S. (Eds.), Computational Models in Political Economy. MIT Press, Cambridge, MA.
Harrington, J. (1998). "The social selection of flexible and rigid agents". American Economic Review 88 (5), 63–82.
Harrison, N. (Ed.) (2004). Complexity in World Politics: Concepts, Methods, and Policy Effects. State University of New York Press, Albany, NY.
Hayes, J., Richards, D. (2003). "Learning, central bank independence, and the politics of excess foreign returns". In: Kollman, K., Miller, J., Page, S. (Eds.), Computational Models in Political Economy. MIT Press, Cambridge, MA.
Hong, L., Page, S. (2001). "Problem solving by teams of heterogeneous agents". Journal of Economic Theory 97, 123–163.
Hotelling, H. (1929). "Stability in competition". The Economic Journal 39, 41–57.
Howitt, P. (2006). "Coordination issues in long-run growth", this handbook.
Huckfeldt, R., Johnson, P., Sprague, J. (2004). Political Disagreement. Cambridge University Press, New York.
Inglehart, R. (1997). Modernization and Post Modernization. Princeton University Press, Princeton, NJ.
Jackson, J. (2003). "A computational theory of electoral competition". In: Kollman, K., Miller, J., Page, S. (Eds.), Computational Models in Political Economy. MIT Press, Cambridge, MA.
Janssen, M., Ostrom, E. (2006). "Governing social-ecological systems", this handbook.
Johnson, P. (1999). "Simulation modeling in political science". American Behavioral Scientist 42 (8), 1509–1530.
Jervis, R. (1997). System Effects: Complexity in Political and Social Life. Princeton University Press, Princeton, NJ.
Kollman, K., Miller, J., Page, S. (1992). "Adaptive parties in spatial elections". American Political Science Review 86, 929–937.
Kollman, K., Miller, J., Page, S. (1997). "Political institutions and sorting in a Tiebout model". American Economic Review 87, 977–992.
Kollman, K., Miller, J., Page, S. (1998). "Political parties and electoral landscapes". British Journal of Political Science 28, 139–158.
Kollman, K., Miller, J., Page, S. (2000). "Decentralization and the search for policy solutions". Journal of Law, Economics, and Organization 16, 102–128.
Kollman, K., Miller, J., Page, S. (Eds.) (2003). Computational Models of Political Economy. MIT Press, Cambridge, MA.

Kramer, G. (1977). "A dynamical model of political equilibrium". Journal of Economic Theory 12, 472–482.
Lacy, D., Niou, E. (1998). "Elections in double-member districts with nonseparable voter preferences". Journal of Theoretical Politics 10, 89–110.
Lasswell, H. (1958). Politics: Who Gets What, When, How. Meridian Books, New York.
Laver, M. (2005). "Policy and the dynamics of political competition". American Political Science Review 99, 263–281.
Laver, M., Benoit, K. (2003). The Evolution of Policy-Seeking Political Competition Between Elections. Trinity College, Dublin.
Lindbloom, C. (1959). "The science of muddling through". Public Administration Review 19, 79–88.
Lindbloom, C. (1979). "Still muddling, not yet through". Public Administration Review 39, 517–526.
Lupia, A. (2002). "Deliberation disconnected". Law and Contemporary Problems 65, 135–150.
Lustick, I., Miodownik, D. (2000). "Deliberative democracy and public discourse: the agent-based argument repertoire model". Complexity 5, 13–30.
Lustick, I.S., Miodownik, D., Eidelson, R.J. (2004). "Secessionism in multicultural states: does sharing power prevent or encourage it?". American Political Science Review 98, 209–230.
Macey, M., Skvoretz, J. (1998). "The evolution of trust and cooperation between strangers: a computational model". American Sociological Review 63, 638–660.
McGann, A., Koetzle, W., Grofman, B. (2002). "How an ideologically concentrated minority can trump a dispersed majority: non-median voter results plurality, run-off and sequential elimination elections". American Journal of Political Science 46, 134–148.
McKelvey, R.D. (1976). "Intransitivities in multidimensional voting models and some implications for agenda control". Journal of Economic Theory 12, 472–482.
Miller, J. (1996). "The coevolution of automata in the repeated prisoner's dilemma". Journal of Economic Behavior and Organizations 29, 87–113.
Padgett, J., Ansell, Ch. (1993). "Robust action and the rise of the Medici 1400–1434". American Journal of Sociology 98, 1259–1319.
Page, S. (1996). "Two measures of difficulty". Economic Theory 8, 321–346.
Page, S.X. (2000). "Computational economics from A to Z". Complexity 5, 35–40.
Page, S. (2006). "Essay: path dependence", Quarterly Journal of Political Science, in preparation.
Pierson, P. (2000). "Increasing returns, path dependency, and the study of politics". American Political Science Review 94, 251–267.
Plott, Ch. (1967). "A notion of equilibrium and its possibility under majority rule". American Economic Review 57, 787–806.
Putnam, R. (2000). Bowling Alone. Simon and Shuster, New York.
Putnam, R., Leonardi, R., Nanetti, R. (1993). Making Democracy Work. Princeton University Press, Princeton, NJ.
Riker, W. (1982). Liberalism Against Populism. Freeman, San Francisco.
Schelling, Th. (1978). Micromotives and Macrobehavior. Norton, New York.
Tilly, Ch. (1998). Durable Inequality. University of California Press, Berkeley.
Tovey, C. (1991). "The instability of instability", Technical Report NPSOR 91-15. Department of Operations Research, Naval Post Graduate School, Monterey, CA.
Wilhite, A.W. (2006). "Economic activity on fixed networks", this handbook.
Vriend, N.J. (2006). "ACE models of endogenous interactions", this handbook.