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Agent-Based Modelling

► Agent-Based Assessments of Criminological Theory

Agent-Based Models to Predict Crime at Places

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Overview

Crime occurrences are driven by a complicated mix of distinct influences, including those of the environment, the surrounding social context, and personal behavior/psychology of the people who could influence a crime event. Agent-based modelling is a methodology used in computer simulation that concentrates on individual-level behaviors and is ideally suited to modelling crime. This is particularly true of crimes such as burglary or street crime, which are heavily influenced by environmental factors and by the behavior of individual people. In an agent-based crime model, virtual "agents" are placed in an environment that allows them to travel through space and time, behaving as they would do in the real world. This entry will discuss why the crime system is such an ideal candidate for agent-based models and will review a number of crime models that have recently arisen.

Introduction

Individual crime occurrences are caused by a complicated mix of factors, including – but not limited to – the surrounding physical environment, the local social context, the presence or absence of crime reduction programs, and the behavior, psychology, and interactions between those people who might be able to influence a crime event (including victims, offenders, and guardians). Traditional mathematical models of crime can face difficulties with modelling systems which are inherently nonlinear (Eck and Liu 2008), and therefore, methods which are better suited to capturing the dynamics of complex, nonlinear systems are becoming popular.

Agent-based modelling (ABM) is a methodology used in computer simulation that concentrates on individual-level behaviors and is ideally suited to modelling crime. This is particularly true of crimes, such as burglary or street crime, which are heavily influenced by environmental factors and by the behavior of individual people. In an agent-based crime model, virtual "agents" are placed in an environment that allows them to travel through space and time, behaving as they would do in the real world. The environment can be as simple or detailed as the researcher chooses so the methodology can thus be used both to explore

criminology theory in the absence of confounding factors or to make realistic predictions in a real-world virtual environment.

This entry will review the technique of agent-based modelling and discuss what advantages it offers to the field of environmental criminology. It begins an overview of the "crime system" and discusses what makes it such an ideal candidate for agent-based modelling, followed in Section 3 by a discussion of the technique itself. Section 4 continues by reviewing a small number of the most recent and advanced agent-based crime models. Finally Sections 5 and 6 review some of the controversies in the literature and propose open questions for future research.

Background: Crime Is a Complex System

Social systems, including that of crime, belong to a class of system known as "complex systems." These are systems that consist of large numbers of diverse components, varied and complex interactions between components, and emergent properties – in this case city – or neighborhood-wide crime rates that cannot be attributed to any individual part of the system. Coupled with this inherent system complexity are "human" factors, such as a complex psychology, that further compound the rules that drive the individuals (Bonabeau 2002). In addition, the crime system is made even more complicated because as crime at places (Eck and Weisburd 1995) and situational crime prevention (Clarke 1995) research have demonstrated, the geography of the system itself introduces additional complexity. However, understanding the processes and drivers that characterize the crime system is the key to crime prevention and policy development.

Acquisitive crimes, such as burglary and street robbery, are important exemplars of the manner in which environmental, social, and individual drivers combine to create a set of complex processes. Because occurrences are dependent on a number of interacting factors (motivation, opportunity, recidivism, etc.), it is difficult to predict crime hotspots in advance, and therefore, many reduction schemes react to a crime hotspot once it has formed. Ultimately, acquisitive crimes are committed by individuals in a local environment and a particular time. Modern criminology highlights the importance of "micro-places" that act as the environment for a specific crime (Eck and Weisburd 1995), and research at scales larger than houses and streets hides key crime dynamics. The same scale issues apply to the individuals involved in a crime event (be they perpetrators, victims, or bystanders) whereby aggregate treatment of individual people is likely to miss the key dynamics associated with individuals and their daily lives. As Brantingham and Brantingham (1993) predicted:

> Potentially, the most productive model in environmental criminology is one that places both the actual criminal events at a specific site, situation and time and the individual committing the crime while in a specific motivational state on (or in) an environmental backcloth, that may itself be mostly stable, regular and predictable or may instead be irregular, rapidly changing and unpredictable.

With this in mind, agent-based modelling is a technique that is being shown to hold considerable promise as it represents a shift away from aggregate models towards those that work at the level of the individual. An agent-based computer model is comprised of autonomous entities called "agents," who have the ability to make decisions and interact with each other and their environment. As the model iterates, each agent has the ability to assess its circumstances and, based on a set of probabilistic rules or more advanced decision-making algorithm, make an informed/educated decision about its future course of action. Through this mechanism, it is possible to incorporate realistic human behavior into computational models. With respect to modelling crime, an agent-based model can be built to directly simulate the behavior of offenders/victims/guardians as they travel around their environment on typical routine activities and predict, as a result of these individual behavior patterns, when a crime occurrence is likely to occur. Building a model in this manner – *from the bottom up* – is a much more natural way of describing a complex system than by formulating rules to drive the system from an aggregate level

(Bonabeau 2002). Section 3 will now discuss the technique of agent-based modelling in more detail.

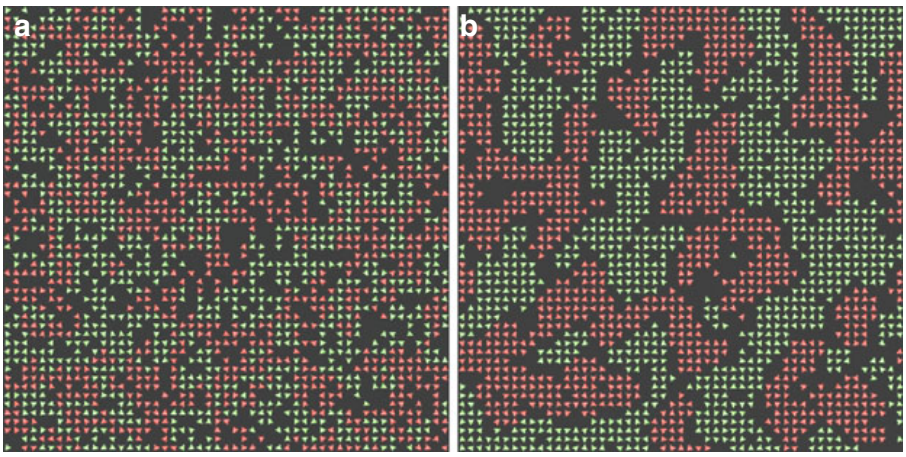
A Description of Agent-Based Modelling

The range of general agent-based theory is extensive, and so this entry will not attempt to provide a full account of all concepts, practices, and applications. For this, the reader is directed to Wooldridge (2009). Instead, it will provide a brief introduction to the methodology and focus on its application to crime. Described as a "breakthrough in computational modelling in the social sciences" (Gilbert and Terna 2000, p. 60) and "one of the most exciting practical developments in modelling since the invention of the relational database" (Macal and North 2005, p. 2), ABM is a reasonably new method of modelling systems. An agent-based model is comprised of virtual "agents" who are able to behave autonomously (i.e., without a central controller). They exist in a virtual environment which is often spatial, they can navigate around their environment, and they are able to make decisions about what they would like to do in a given situation. This approach is particularly relevant to criminology because using ABM, it becomes possible to use models to carry out experiments that would be impossible or unethical to perform otherwise.

There are many definitions of the term "agent" but, from a crime modelling perspective, the following are consistently applied:

- Autonomy: an agent should be free to control its own state, interact with other agents and its environment, and make decisions without direct control from some central source. This seems to be an ideal mechanism for modelling people, including offenders, victims, or other necessary individuals (guardians, managers, passersby, etc.).
- Heterogeneity: agents need not be identical. Offender agents can thus be created to reflect the variety of different offending behaviors that have been exhibited, allowing for the incorporation of qualitatively obtained data and theories.
- Reactivity: agents should be able to respond to changes in their environment, and the response should be proactive, indicating goal-directed behavior (Wooldridge 2009). This is particularly useful for a crime model because the environment will change as a result of crime which will in turn influence the future behavior of the agents.
- Bounded rationality: particularly with modelling in the social sciences, it is important that agents do not always act perfectly rationally. Agents can be programmed with "bounded" rationality by limiting their knowledge of the world so that choices are not always perfectly optimal (Castle and Crooks 2006).

Perhaps the most significant advantage of ABM is the "natural description" of a system which it provides. Complex systems, whose behavior is characterized by the behavior/interactions of its individual components, cannot usually be described by mathematical equations. Although mathematics provides a good basis for describing unexplained phenomena in the natural sciences, this experience is not echoed in the social sciences (Moss and Edmonds 2005). Often simplified assumptions are required if mathematical models become too complicated and these assumptions are often implausible or reduce the realism of nonlinear systems (Evans 2011). To understand geographical human systems, it is necessary to understand the reasoning behind individual decisions and modelling individuals directly is more natural than trying to build aggregate equations to control them (Bonabeau 2002). For example, with acquisitive types of crime, an individual's cognitive understanding of a local area can be as important as the physical characteristics of the area, as offenders commonly commit crimes within their routine activity spaces. These cognitive representations would be very difficult to incorporate into models which do not characterize individuals directly, whereas in an agent-based model they can be built directly up as the virtual agents navigate around their environment. The same can be said of environment: it has been shown that spatial aggregation hides important patterns in crime (Andresen and Malleson 2011) and ABM is



Agent-Based Models to Predict Crime at Places, Fig. 1 An example of an agent-based model of segregation, based on Schelling (1969). Figures show the percentage of similar racial type that each household unit wants to live next to

ideally suited to modelling at resolutions of the individual street or household.

Arguably the first published agent-based model in the social sciences was Schelling's hand-developed model of residential stability (Schelling 1969). Although extremely simple, the model goes a long way to illustrate how useful ABM can be for modelling social systems. The model consists of a one-dimensional environment (a line of spaces, some empty) populated by households that belong to one of two types of racial group. A global parameter dictates the percentage of the same group that each household wants to live next to. Households are able to move to an empty cell if they are unsatisfied (i.e., they live near to too many of the opposite racial type). The novel research finding was that, even with a relatively low preference for the same racial type, the environment can become highly segregated. It is relatively simple to develop a two-dimensional version of this now, and such a model, which is included as a demonstrator in the agent-based modelling software "NetLogo," is illustrated in Fig. 1. Here a preference to live next to only 50 % of the same racial group leads to clear segregation. Methodologically the Schelling results are interesting because they would not have been predicted by examining the rules of the individual in isolation, and from a practical position, it provides an insight into the dynamics of human residential segregation, suggesting that extreme segregation can emerge from individuals who actually have low preferences for segregation.

The finding that segregation arises even though no individual wants to live in a completely homogeneous area relates to the concept of *emergence*, exploring which is a key advantage of ABM. An emergent phenomenon is one that comes about as a natural (and often unintended) consequence of the behaviors and interactions of a system's constituent components. A city-wide crime rate is an example of an emergent phenomena and one which cannot be attributed to any part of the system itself – there is no single person who is responsible for, or even attempts to generate, the observed crime patterns. Rather than attempting to find global rules that determine aggregate crime rates, the agent-based crime modeller describes the individual components of the system and then tries to "grow" the observed crime patterns from the "bottom up." This also has the advantage of being a much more naturalistic way of describing a system. Social networks, human psychology, and detailed physical environments are essential parts of the crime system, and these are relatively simple to incorporate by using ABM. A related advantage, which is particularly relevant in environmental criminology, is that with ABM it is possible to treat offenders in a similar manner to non-offenders and explore the effects that noncriminal activities will have on crime. In this manner, the "natural variety" of cities becomes part of the model, rather than being smoothed out by aggregate methods (Brantingham and Brantingham 2004).

There are, of course, certain drawbacks to ABM which must be addressed. The advantage of being able to describe the behavior of individual people directly is tempered by the difficulty in modelling the "soft factors" exhibited by humans – such as seemingly irrational behaviors and complex psychology (Bonabeau 2002) – which can be very difficult to actually implement in a computer model. These factors must be defined explicitly in models which work at the microlevel, leading to a strong commitment to minimal behavioral complexity (O'Sullivan and Haklay 2000). This is compounded in crime modelling research by problems with the availability and accuracy of crime data to build up an accurate picture of offending behavior. Although there is considerable qualitative information available, quantitative data is sparse, and even when data are available, it is unclear whether or not they are an accurate reflection of true offending patterns because of potential reporting biases. For more information the interested reader could refer to Chainey and Ratcliffe (2005) for a comprehensive assessment of the issues surrounding the use of crime data.

There are also major difficulties that relate to the implementation of the model. Firstly, although there are numerous ABM tools that can assist with the development of models (NetLogo is a good starting point for those new to the technique), it is likely that a researcher will need a relatively high level of computer programming experience. Agent-based models are also extremely processor and storage heavy, not least because most are run multiple times with varying parameters to give probabilistic results. This means that the most advanced models often need to be distributed across large collections of computers to obtain the required processing and storage power. Such models present considerable debugging issues, not least because small pieces of computer code can form integral parts of hundreds of agents, with small errors in the logic of the code having huge effects on the outcome of the model.

Nevertheless, ABM is becoming an increasingly popular tool to aid crime analysis. The following section summarizes some of the more recent and advanced approaches.

State of the Art

The last decade has seen a gradual rise in agent-based crime simulation work. The earliest models are generally abstract and take place either in geographical social spaces or on abstract plains (much like the segregation model outlined in section "A Description of Agent-Based Modelling"), whereas more recent models include realistic representations of the physical environment and comprehensive agent decision-making. Most models consider some subset of the core elements of the crime system, such as the physical environment, the social context, victims, offender motives, and offender behaviors. However, the system is clearly extremely complicated, and it should come as no surprise to find out that most models concentrate on one particular aspect of the system. To provide an overview of the current research, this entry will briefly summarize a small number of applications which have very different foci. For a much more comprehensive review, the reader is directed to the book entitled *Artificial Crime Analysis Systems* (Liu and Eck 2008), a special issue of the *Journal of Experimental Criminology* entitled "Simulated experiments in criminology and criminal justice" (Groff and Mazerolle 2008) or the review paper by Malleson et al. (2011).

Offender Behavior

One of the obstacles with agent-based crime modelling is that it becomes necessary to explicitly define how agents in the model will behave. However, modelling human behavior is an extremely challenging endeavor. Fortunately there are numerous cognitive architectures that have been designed to model human behavior, and these can be used in crime models. Malleson et al. (2010) provide an example of such a model applied to residential burglary. The authors use the PECS (physical conditions, emotional states, cognitive capabilities, and social status) model of human behavior which controls agents by comparing the sizes of different *motives*. At any given time, the motive which is the strongest determines what the agent's current behavior will be such that the agent tries to satisfy that motive. Some

motives can be very simple to satisfy (such as travelling home to sleep), but others might require considerable planning and reevaluation before they can be accomplished (such as making money through the commission of burglary). By varying the ways that different motives affect the agents' behavior, it is possible to create different types of offender agents to reflect current criminological thinking (e.g., the difference between a "professional" burglar and an "opportunist"). By placing the virtual offenders in an environment that closely reflects that of the real world, the authors are able to explore the potential real-world crime patterns that might emerge under different scenario conditions.

Street Networks

An example of research which takes advantage of ABM's ability to incorporate a highly detailed physical environment is that of Groff (2007). Due to the lack of dynamic, individual-level interactions, the authors note that previous studies had failed to effectively test routine activity theory. The model by Groff addresses this through the incorporation of accurate street-level data in order to test the applicability of routine activity theory to street robbery. The model contains two types of agent: citizens (offenders, victims, and guardians) and police. The citizen agents are randomly assigned a particular home location, and in the model's most advanced form, they spend time away from home by visiting randomly assigned work and activity nodes following predefined routes. The offenders' decision to offend is stochastic and based on levels of guardianship and the wealth of the potential target at their current location. The model found that the number of street robberies increased with the amount of time spent away from home because citizens had the chance to meet more potential offenders. Interestingly, some street intersections exhibited significant clusters of events even though the travel patterns of the agents were random. This provides an insight into how the urban configuration of streets can influence locations of street crime with direct reference to the roads in a real city.

Social Networks and Cohesion

Plainly the social structure of areas and criminals will play a big part in developing larger patterns of offending. Hayslett-McCall et al. (2008) include a number of social-cohesion and guardianship indicators in their household burglary model. Homes are given attractiveness values based on variables including the socioeconomic status of the area and the degree of guardianship, as well as the ethnicity and income levels of the inhabitants – with agents preferring areas that are similar to their own. In terms of social interaction, Dray et al. (2008) include the relationships between local actors, including law enforcement agencies, social services, and drug users and dealers in an ABM of the Melbourne drug market. The model also includes larger-scale variables such as the strength of the national drug supply chains. Using this model, they showed that small-scale interventions were generally more successful at disrupting drug markets than national initiatives.

Abstract Theory

The models introduced thus far both utilize realistic virtual environments in order to place crime in an accurate environmental context. However, accurately predicting spatiotemporal crime patterns does not need to be the aim of the research – indeed, as the following section will discuss, a realistic virtual environment is seen by some as a drawback. An advantage of ABM is that the model can act as a "virtual laboratory," allowing researchers to explore the individual-level dynamics that emerge as a result of different crime theories in an environment that is free from the usual complexity of the real world. Brantingham and Brantingham (2004) have developed a model of crime in which they utilize an abstract state machine to provide a precise logical/mathematical foundation to an agent-based model. In the model, agents can move through time and space, interacting with each other and the environment. They are also able to learn, and they have "preferences" which translate to forms of behavior. Along with experimenting with criminology theory, the resulting simulation

can be used as an interdisciplinary tool to assist criminologists in investigating the dynamics of urban crime.

Controversies in the Literature

In general, agent-based models tend to either be pessimistically abstract or optimistically realistic. The Schelling segregation model and the model by Brantingham and Brantingham (2004) both fall at the more abstract end of the scale. With these types of models, the difficulty of capturing the total behavior of such large, open, and nonlinear systems is accepted, and modellers concentrate on building simple models based on limited subsets of the rules and environmental conditions that may be operating. These models are then treated as thought experiments and can be manipulated to see what effect varying our broad ideas about the systems has on the patterns it generates. In the field of crime modelling, Elffers and van Baal (2008) advocate the notion that such simple models can be a powerful explanatory force, particularly when the aim of the research is to explore theory rather than make accurate predictions. One always has to be aware, however, that patterns may match models even though explanations differ (the identifiability problem), and it is often difficult to verify that human systems would respond as these simple models do.

The second point of view holds that it is possible to accurately model the world with a finite ruleset and list of environmental variables, but that the more realism the model encompasses, the more constrained to the real world the model will be. In some cases, such as the models by Groff (2007) and Malleson et al. (2010), geographical realism is added by combining the model with a geographical information system (GIS). The hope with more realistic models is that the multiple patterns and data streams used to constrain the model will resolve the identifiability problem and make comparisons with reality more reliable. However, it is usual to calibrate such models using real data, and the large numbers of variables involved may mean that the models are over-flexible, essentially fitting any data – again raising the issue of identifiability. Rigorous retesting with new data is often difficult for models that study crime; even though more accurate data is being made available to researchers all the time, it is still at a premium and it is usually unclear how well the data reflects real-world crime patterns in the first place. In general, models are best built up gradually, verifying that simple behaviors with simple elements of the system work as expected to start with and then, if needed, build up the complexity to something that more closely matches reality in order to make more reality-aiming predictions. However, as Edmonds and Moss (2005) note, a phrase such as "for the sake of simplicity" is not well founded, and simplicity should only be a target if this is justified by the underlying system. The crime system is not, usually, simple.

Open Questions

Two significant and related directions seem of immediate future significance in the ABM of crime (Malleson et al. 2011). The first is the more detailed simulation of social networks, particularly within criminal organizations. There has been some work in this area; however the potential for spatially enabled social network modelling is increasing as law enforcement agencies gain access to mobile phone and internet records. The second direction is more contentious – the modelling of specific individuals within ABM. To our knowledge there are not, as yet, individual-level models that predict the actions of real individuals. However, there is an increasing use of real crime data to seed models of abstract individuals, and increasing amounts of personal information about all citizens, potential victims, and potential offenders are stored electronically on a daily basis. It seems likely, therefore, that the modelling community will need to consider the ethical issues of the Minority Report option within the very near future: is it appropriate to model real individuals in a predictive sense, and what use should such predictions be put to once made?

Related Entries

- ▶ Agent-Based Modeling for Understanding Patterns of Crime
- ▶ Spatial Models and Network Analysis

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Aging Correctional Populations

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Overview

The American prison population is rapidly aging. Yet relatively little is known about the unique challenges facing older adults in the criminal justice system. This knowledge gap has significant implications for the understanding of the health and health-care needs of a growing, medically vulnerable population. This entry describes the demographics of aging in corrections, focusing on