

Mastermind: A Computational Framework for Studying Physical Crime

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Abstract. Criminal events are understood in the context of complex interactions between the most important elements of crime, namely: the *law*, the *offender*, the *target* and the *place*. We outline here an abstract formal framework for describing these elements and their relationships in computational terms. The framework is based on the Abstract State Machine (ASM) method and provides typical elements required for analyzing the multi-dimensional aspects of crime patterns by means of computational methods and tools. In particular, we formally define the mutual dependencies between social networks and offender activity patterns and the corresponding impacts on the target selection process. The Mastermind project aims at providing the fundamental building blocks for the computational study of crime in a new multidisciplinary research effort broadly classified as Computational Criminology.

1 Introduction

Crimes are complex, multi-faceted events. They are comprised of at least four necessary dimensions — the law, the offender, the target and the place [1]. For several decades, criminologists have contended that there is definite patterning in the temporal and spatial characteristics of physical crime [2]. In particular, Environmental Criminology focuses on studying crime in the context of people’s movements in the course of everyday routines. Three major theories of the field, namely, Crime Pattern theory [3], Routine Activities theory [4], and Rational Choice theory [5] contend that crime locations are not random, but rather are determined through a combination of normal movement and activity patterns, each of which is at least partly determined by the perceptions of the physical and social environment. Offenders choose good opportunities over bad risks through rational decisions considering cues from the environment. Within this setting, one can identify the importance of several elements in analysis of criminal events, including offender’s movement, routine activity patterns, the perception of the underlying environment, and the role of different cues in offenders’ decision making.

Although theories of crime are well established, the lack of a unifying framework for integrating the four dimensions of crime in a coherent and consistent way inhibits their applicability to real-life scenarios. Novel research directions [6, 7], however, suggest the use of mathematical modeling techniques combined with computational methods and tools to deal with the complex dynamics of social systems. Computer models can serve as a practical instrument for studying crime patterns and for reasoning about likely scenarios, facilitating the understanding of and experimenting with crime patterns [8].

In our previous work [9, 8, 10], we have addressed the challenge of systematically building a unifying computational model that captures the diversity of a wide range of theories and corresponding views involved in studying crime. In our experience, the success of any such endeavor critically depends on a well defined semantic foundation for modeling in abstract computational terms the key elements of the underlying social system consisting of offenders, victims and targets interacting with one another and also with their environment.

Mastermind is an ongoing interdisciplinary research project in Computational Criminology jointly managed by ICURS and the Software Technology Lab at Simon Fraser University.¹ The Mastermind framework facilitates crime modeling endeavors by providing the building blocks for *computational thinking* [11] of crime. Mastermind introduces an abstract computational framework for modeling, simulation and machine-assisted evaluation of discrete event models used in crime analysis and prevention. Within this framework different elements of crime are specified in a multi-dimensional model and the dynamics of their interactions is formalized. As such, it provides a sandbox for testing theories of crime and analyzing ‘what if’-scenarios.

Mastermind has been devised based on the Abstract State Machine (ASM) formalism and abstraction principles [12], offering considerable flexibility for integrating a multitude of diverse system views. Given the experimental subject nature and the evolutionary system development context, robustness and scalability are key aspects in the design of such a computational framework. This requirement calls for an abstract and mathematically well-defined semantic foundation, one that allows for the separation of high-level semantic concepts from low-level coding which predominantly focuses on syntactic aspects. As such, we believe that the ASM formalism is a natural fit for modeling systems in Computational Criminology. At the same time, this gives us an interesting exploratory opportunity posing new challenges by applying the ASM method beyond its natural habitat of hardware/software systems to social systems — a truly discrete, dynamic type of system, one that the very original definition of ASMs [13] intended to capture as well.

The body of this paper is structured as follows. The Mastermind framework is described in Section 2. Section 3 presents a concrete model of target selection and Section 4 concludes the paper.

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2 Mastermind Framework

We describe here the main structural elements of the Mastermind framework in terms of abstract data structures for modeling spatiotemporal aspects of crime.

2.1 Multi-dimensional Modeling

Our focus in the Mastermind framework is on the four major elements of crime — the law, the offender, the target and the place. In order to study the behavior (or impact) of each of these elements and capture the complexity of their interdependencies, we introduce several dimensions in which the same phenomena (i.e., criminal events) can be analyzed.

The *physical environment*, as described in [8], is the platform where all four elements come together and physical crime takes place. We introduce here, the *social environment* where the social interactions and associations between the offenders occur. While physical and social environments are more tangible and natural contexts, we also introduce a *target correlation space* where the interdependencies of different types of targets, such as cars, properties, or people, is defined. So far, each of these platforms is mainly dedicated to one element of crime: the focus of the physical environment is on the place; the social environment focuses on offenders; and the target correlation space focuses on targets. In principle, we also consider the law, encompassing different crime deterrents, as a separate dimension. Here, we do not focus on dynamic aspects of this dimension and the interactions between different entities of law. Instead, we study the impact of crime deterrents on criminal activity in the context of the physical environment. In the following, we mainly focus on the physical and social environments, due to their important impact on offender activity pattern and crime location.

2.2 Physical Environment

Mastermind abstractly represents the physical environment of a given urban landscape in terms of a *colored attributed directed graph*. Intuitively, the model of the physical environment includes everything from road and rail traffic networks to walkways and hiking trails in city parks. In principle, it also includes the layout of other public spaces such as shopping malls, underground stations and airports for instance. This model provides a stage for all four elements of crime to interact, mainly focusing on spatial and temporal aspects of crime, potentially involving multiple offenders, multiple targets, and multiple deterrents.

The model of the physical environment is formally defined as a graph G_{Phys} , $G_{Phys} = (V_P, E_P, \Theta_P, \Lambda_P)$, where

- V_P is the set of vertices where each vertex represents an intersection on the map, or any other location or point of interest;
- E_P is the set of directed edges with $E_P \subseteq V_P \times V_P$ representing roads, pathways, transit routes, et cetera;

- Θ_P , with $\Theta_P = (\Theta_{P_v}, \Theta_{P_e})$, denotes the attribute sets for vertices and edges respectively;
- Λ_P , with $\Lambda_P = (\lambda_{P_v}, \lambda_{P_e})$, abstractly represents the *agent* specific attribution of vertices and edges (e.g. frequency of visits to a vertex or an edge). Agents represent human actors of the system, including offenders, victims, and even police officers, who have a specific perception of the environment.

G_{Phys} can be seen as an attributed directed graph with colored attributes, where each color determines the specific perception of an individual agent. The operations defined on G_{Phys} serve for accessing and manipulating the graph structure and related attribute values to capture certain aspects of criminal behavior. For instance, the activity space of each agent, in any given system state, is defined as the subset of edges with an associated frequency of visits above a certain threshold. A notion of *proximity* in the physical environment is defined for each different element of crime using the attributes of the graph. In [8], the weighted sum of a subset of edge attributes is used as a measure of proximity for locations. This measure is then used in the *navigation* process, where an agent tries to find a suitable path between two locations. Likewise, one can define a proximity function for offenders which measures the similarity of their activity patterns based on their shared activity spaces.

2.3 Social Environment

Similar to the physical environment, we model the social environment as an attributed directed graph² G_{Soc} , $G_{Soc} = (V_S, E_S, \Theta_S)$, where

- V_S represents *identities* of an agents. Identities are extracted from offender or victim profiles at different levels of granularity. For instance, a vertex may represent a group of victims sharing an interesting property with respect to the problem under study, such as attending the same school.
- $E_S \subseteq V_S \times V_S$ represents immediate social links (or relationships) between the vertices. Defining what constitutes a social link is left abstract and is further refined by the designer of each specific system.
- Θ_S , with $\Theta_S = (\Theta_{S_v}, \Theta_{S_e})$, assigns attributes to vertices and edges respectively. Edge attributes, for instance, include the strength of a link depending on the type of the relationship (e.g. relative, friend, co-worker, etc.). Vertex attributes provide additional information about the person including the information extracted from the profile.

Following the discussion in Sect. 2.2, the notion of *proximity* between two individuals in the social environment is defined using the attributes of the graph. Likewise, different operations can be defined on G_{Soc} . For instance, a criminal organization can be defined as a subset of connected vertices sharing certain attributes with the proximity above a certain threshold.

² The direction of an edge is important in certain types of social relationships such as leader-follower.

2.4 System Dynamics

One of the goals of formalizing different dimensions of crime is to provide a clearer representation of the relations and interdependencies between these dimensions. For instance, criminology literature suggest that the large majority of offenders will commit most of their offences near places they spend most of their time. According to this principle, there often is a connection between offenders who are *close* in the physical environment (defined by the proximity measure as described in Sect. 2.2) and whose preferred targets are *close*³ in the target correlation space. This connection can be realized by adding a *weak* edge between the two corresponding nodes in the social environment. The dynamics of such a dependency can be formalized using the following ASM rule.

choose $(v, u) \in V_S \times V_S$ **with**
 $close_{Phys}(v, u) \wedge close_{TrgtCor}(trgtPref(v), trgtPref(u)) \wedge satisfyOtherReq(v, u)$
new $l : SocialLink$
 add l **to** E_S
 $head(l) := u$
 $tail(l) := v$
 $weight(l) := calcWeight(v, u)$

The *satisfyOtherReq* predicate abstractly checks for any other requirement that one might want to enforce before the new link is created.

Formalizing the dynamics between key elements of crime at a high level of abstraction is an important step towards thinking computationally about crime. Due to the complex nature of social systems, most of the research in crime analysis is restricted by simplifying assumptions on the system. Whereas, in the structured framework that Mastermind offers, one can formulate all the *known* connections between different elements, and also use the framework to infer *unknown* dynamics. For instance, similar to the above rule, one may define a rule that suggests that if two offenders share their activity space ($close_{Phys}(u, v)$) and are associated in the social environment ($close_{Soc}(u, v)$), then there might exist a *weak* link between their preferred targets in the target correlation space. Understanding the dynamics of the system is crucial for building more concrete models of criminal activity. The next section provides an example of such usage.

3 Methodology and Application

The Mastermind framework is designed to facilitate computational studying of crime by capturing different aspects of the complex underlying social system. Using the ASM formalism, our goal is to cope with the intricate nature of criminal behavior by providing suitable abstractions and expressive means that facilitate the accurate formalization of relevant interactions of the various conceptual entities at different levels. Beyond the need for managing complexity and for

³ The stronger the correlation between two targets, the closer they are.

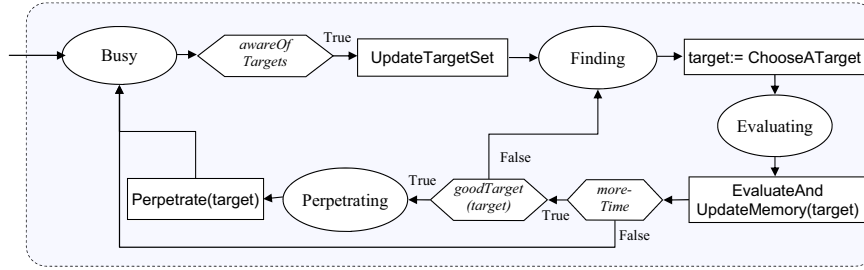


Fig. 1. Control-State ASM of the Target Selection Module

gaining clarity of representations of complicated concepts and relations, it is the interdisciplinary nature of the system that calls for an intelligible formalization as a reliable basis for communication with experts from truly different fields. Hence, we utilize the ASM ground model method to cope with the language and communication problem [14]. ASM ground models are used to integrate different views of the system, and to provide well-defined semantics for the key elements of the system. Moreover, we further benefit from the operational character of ground model ASMs [14] and use CoreASM [15] to validate the model by running test experiments. This step proved to be very important, specially because of the multi-dimensional nature of the model. Many problems with respect to integration of different dimension showed up in this phase, even when only the very basic elements of the system were modeled. In the last step, we refine the ASM model into a simulation model to accommodate real-world experiments and validation with real-world data. The next section outlines how one such simulation model is constructed starting from the basic framework.

3.1 Target Selection

The behavior of an offender in a physical environment is influenced by a number of social, spatial and temporal factors. In [8, 10], we presented an ASM ground model focusing on movement patterns of a person, modeled as an agent, in an urban environment. While the activity pattern of an agent is a major element in crime analysis, offence occurrence behavior, called *target selection* behavior, is of equal importance in understanding crime patterns. Here, we briefly describe how this behavior is defined in terms of an ASM ground model. The model presented here is a refinement of the *Target Selection Module (TSM)* presented in [8].

One of the challenges of building target selection into Mastermind is abstraction of the crime process such that it is applicable to a wide range of crime types. For our purposes, we are interested in crime that takes place in the course of daily activities; i.e. we consider the opportunistic side of criminal activity. This can either be the entire offence if an agent acts immediately upon noticing a target, or simply the moment of awareness that leads to a more complex plan.

Figure 1 shows the high level control-state ASM of the TSM, where the key aspects of the behaviour is captured while technical implementation details are left abstract. For instance, following their daily routines, the agents navigate through the physical environment and develop an awareness of the environment. For criminal agents, the *awareness space* provides knowledge about potential targets. The *awareOfTargets* predicate captures the interplay between the target selection and the navigation process. Movement patterns also affect how much time offenders have to consider potential targets, which is abstractly represented by the *moreTime* predicate. Hence, the model of target selection includes interactions between the physical environment and the target correlation space. The *evaluation* process is also left abstract at this level, which allows for capturing different evaluation methods in separate refinements. For instance, in the operational CoreASM model, the evaluation process has been refined using probabilistic methods, while in the simulation model Fuzzy Logic is used as well for determining the viability of a potential target. Classical logic could also be used to implement this component. However, at a higher level of abstraction these divergent decision-making technologies are equivalent from a practical point of view. Each of them is able to take the information given to them and make an evaluation about the target considered. Hence, different technical approaches can be attempted as solutions without requiring the design to change.

The TSM exemplifies one of the key advantages of using ASMs: separation of design and implementation. The ASM model provides a clear specification of the target selection behaviour which is comprehensible without any specific technical knowledge to be verified by the experts of the field.

The TSM can also utilize other relations between different layers of the multi-dimensional model of Sect. 2. One such relation is the effect of social interaction on crime. Options for criminal targets are not only developed through direct personal experience, but also by knowledge gained through social communication [16]. Therefore, we can extend the system dynamics rules of Sect. 2.4 by considering the dynamics at a more concrete level. At this level, one agent's knowledge of potential targets is updated considering the knowledge of its social associates and their activity patterns.

The main purpose of the Mastermind project is to provide a well-defined abstract computational framework for developing computer models and analytical tools to be used by criminologists, policing agencies and policy makers. Therefore, a simulation model is being developed that refines the operational CoreASM model. The simulation model imports real-world road network data from a geographic information system (GIS) to create a simulated urban area. It is then populated with computer agents, who represent individuals, such as criminals, police or victims. The simulation model has been used to run experiments using the downtown core of the city of Vancouver (including 416 intersections; 710 street sections) as the underlying environment. The results of one such experiment, focusing on motor vehicle theft, is presented in [10]. The results of the experiments so far are of preliminary nature; they do not provide sufficient evidence to allow any final conclusions, but they are promising, raise interesting

questions and are well-received by the domain experts. One valuable aspect of using Mastermind as a platform for experimentation is that it helps the domain experts develop new ideas and gain a better understanding of what is feasible. Furthermore, the evolutionary nature of the Mastermind modeling framework and simulation environment is most valuable in its ability to spur its users on to further research and new developments allowing for increasingly complex and meaningful experiments.

4 Conclusion

The inherent complexity, the intricate nature and the high dynamics of social systems pose considerable challenges for studying of social phenomena, including criminal events. Due to these difficulties and practical limitations of real-world experiments in this field, a consistent and coherent integration of well established theories of crime within a unifying computational framework based on abstract mathematical concepts provides a promising alternative to overcome limitations imposed by the simplifying assumptions made by conventional methods. The Mastermind framework formalizes the key elements of crime and their respective dynamics in a high level multi-dimensional model, based on the ASM method.

Although unconventional, the application of the ASM modeling paradigm to social systems turns out to be a reasonable choice. The goal is to facilitate computational modeling of crime by providing the essential building blocks and setting the stage for *thinking* about crime in computational terms. To this end, the ASM ground model method allows for a systematic approach to overcome the inherent complexity of the social system aspects, and offers a practical solution to the well-known communication problem, something that is invaluable for effective collaboration in a project where the domain experts usually do not have a technical background. ASM models are refined into executable CoreASM models for validation and testing purposes. Furthermore, the simulation model that is developed based on the operational ASM ground model focuses on the criminal behavior of offenders in a given urban surrounding and is supposed to serve as a practical tool for criminologists, policing agencies and policy makers.

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