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The Graduate School
College of Information Sciences and Technology

**URBAN COMPUTING WITH MOBILITY DATA: A UNIFIED
APPROACH**

A Comprehensive Document in
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by
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Abstract

With the advent of information age, various types of data are collected in the context of urban spaces , including taxi pickups/drop-offs, tweets from users, air quality measure, noise complaints, POIs, and many more. It is crucial to use these data to solve urban issues, such as traffic congestion, crime prediction, and pollution. Two immediate questions are “Are those different data correlated?”, “How do we employ their correlation to infer one from the other?”

Urban computing has gained increasing popularity as an active research topic. These studies include profile city functions, detect traffic anomalies, predict air qualities, and location recommendation. The common challenges we face include 1) dealing with sparse and noisy data sources, and 2) handle implicit and complicated correlations. While various approaches are proposed, they still have the following drawbacks. 1) The partition of spatial-temporal space is over-simplified. Partition space into regions with road network or administrative division is widely used. However, these partitions does not always align with the data distribution. 2) Most models assume uniform correlation among different spatial regions. As a matter of fact, in my preliminary study I have observed that when training separate models on Chicago south and north, two models are different and the estimation results will be better. 3) The feature construction from different data sources is ad-hoc.

The goal of this thesis will be to develop a unified framework to capture the correlations of heterogeneous data in the urban context. Starting from a preliminary study on estimating the Chicago community level crime with POI and taxi flow. The intuition is that the POI complements the demographics features, and the taxi flow acts as a hyperlink to connect non-adjacent community areas. The results suggest that both newer type of features correlates with the crime and improves the estimation significantly. Next, I am trying to model spatial variations. Namely, the same features in different regions correlate differently. Meanwhile, a smart partition based on observed urban data is also a key component in this framework. Finally, the urban data are classified as nodal feature and dyadic feature, which belong to a spatial unit and a pair of units respectively. In my future work, I plan

to build a consistent approach to model different features.

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Acknowledgments

Dedication

Chapter 1 | Introduction – Urban Computing

1.1 The Challenges and Opportunities from Urban Data

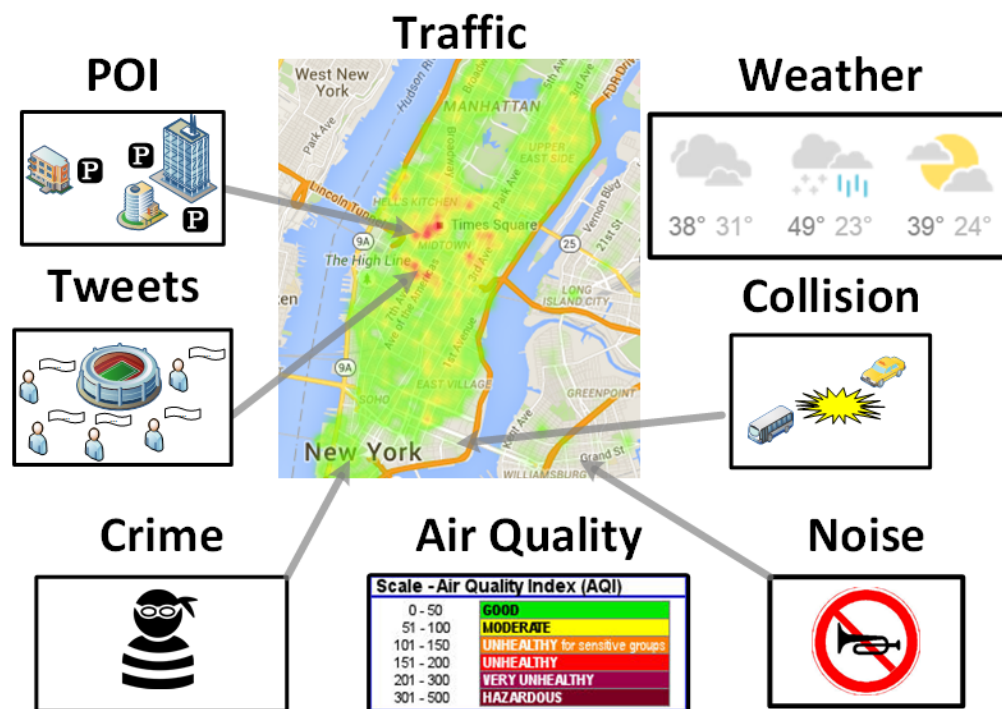


Figure 1.1. Use data collected in the urban space to address real urban problems.

1.2 Take Crime Inference as an Example

Understanding how to control crime is important because exposures to violence and crime have been unusually high in the U.S. for several decades and, while declining, they remain high [1, 2]. Over half a million children and youth aged 10-24 years were treated in 2012 in emergency departments for nonfatal physical assault injuries related to gun shots, cuts and stabbings, among others [3]. Understanding the neighborhood context of crime is particularly important because victimization and other forms of crime exposures have many severe consequences. Beyond the high medical bills and violent death, consequences include behavioral and mental health problems, aggression, substance abuse, post-traumatic stress disorder, and suicide, lower academic achievement, and engaging in further violence [4].

In this paper, we study the problem of crime rate inference of communities. We select Chicago as the target of study for the following reason. Chicago has more homicides and non-negligent manslaughter rates (15.2) per 100,000 residents than New York (4.0) and Los Angeles (6.5) according to the FBI crime statistics for 2013 and has experienced no decline in the past decade compared to the other two large cities, which have been on a slow declining slope [5].

Traditionally, researchers have used demographic information (e.g., population poverty level, socioeconomic disadvantage, racial composition of population) to estimate the crime rate in a community [6]. However, such demographic information only contains partial information about the neighborhoods and does not dynamically reflect the changes in the community (demographic survey is conducted by census bureau every 10 years). Using only demographic information will result in a relative error of at least 30% for crime rate estimation in Chicago (refer to experiment section in the paper). Existing studies also use the geographical influence [7] to estimate the crime rate, i.e., the crime in the nearby communities can be propagated to the focal community. But this geographical influence is of little help in improving the crime inference on top of demographic feature, with at most 0.4% relative improvement in our experiments. This is probably because the nearby communities also share similar demographics, which limits the additional benefit of geographical influence.

Recently, big data reflecting city dynamics have become widely available [8], e.g., traffic flow, human mobility, social media, and crowd-generated Points-Of-Interest

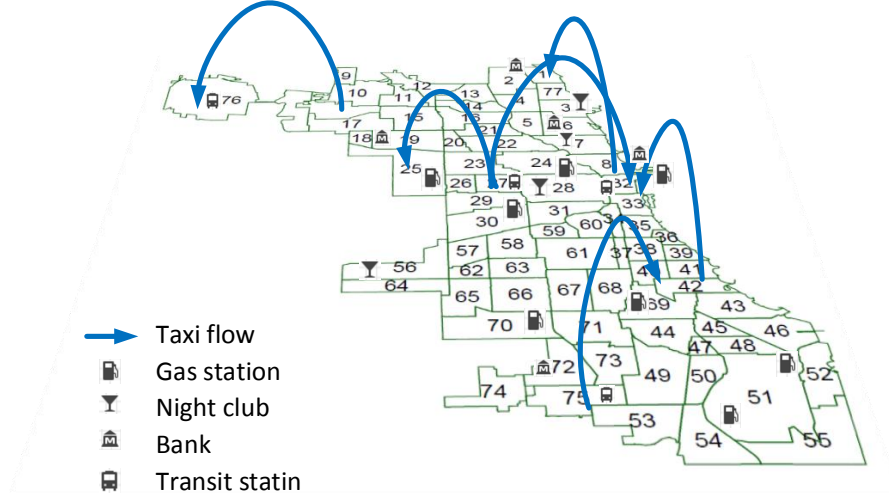


Figure 1.2. An illustration of various types of features we used in Chicago. The POI distribution across community areas reflects profiles of the region functionality. The taxi flow connects nonadjacent regions and act as a “hyperlink”.

(POI). As shown in Figure 1.2, such newer types of big data could provide us new insights to understand some traditional socioeconomic urban problems, such as crime rate inference problem we focus on in this paper. In particular, we propose to study two newer types of urban data: POI and taxi flow.

POI data. POI data provide venue information such as GPS coordinates, category, popularity, and reviews. These POIs mostly belong to categories such as food, shop, transit, education, and etc. Recent studies have shown that using such categorical information of POIs are useful to profile neighborhood functions [9]. And such neighborhood functions could further help us predict crime rate (e.g., communities with less education or entertainment facilities may have a higher rate of crime). Our experiments show that incorporating POI features significantly improve the crime rate inference. Adding POI features in addition to demographics features reduces the relative error by at least 5% in our experiments. This demonstrates that POI data provide additional information about the communities that is not covered by the demographics.

Taxi flow data. A huge amount of taxi flow data reflect how people commute

in the city. In previous studies, when using geographical influence [7], people assume that a community is affected by the spatially nearby communities. However, communities are not only affected by spatially-close communities. Even if two communities are distant in geographical space, they could have a strong correlation if there are many people frequently travel between these two communities [10]. We hypothesize that taxi flows may be considered as “hyperlinks” in the city that connect the locations and we use such data to estimate crime rates. Our experiments show very promising results – adding taxi flow data on top of all other features can further decrease the error by 5%.

We conduct extensive experiments including a systematic comparison between linear regression model and negative binomial model, tests of different combinations of features, detailed discussions of how to construct features and why, analysis of features’ relative importance, and theoretical interpretation of the results with a social scientist (a co-author in the paper). The experiments are conducted on the crime data over multiple years and using the modern big data show significant improvements.

Chapter 2 |

Related Work

2.1 Crime Inference In the Literature

In the criminology literature researchers have studied the relationship between crime and various features. Examples are historical crime records [11, 12], education [13], ethnicity [14], income level [15], unemployment [16], and spatial proximity [7]. In data mining field, newer type of data are used in the study. For example, there are works using twitter to predict crime [17, 18], and works using cellphone data [19, 20] to evaluate crime and social theories at scale.

Overall, the existing work on crime prediction can be categorized into three paradigms.

Time-centric paradigm. This line of work focuses on the temporal dimension of crime incidents. For example, in a study [11], the authors propose to use a self-exciting point process to model the crime and gain insights into the temporal trends in the rate of burglary. In another study [21], the authors investigate the temporal constraints on crime, and propose an offender travel and opportunity model. This paper validates the claim that a proportion of offending is driven by the availability of opportunities presented in the offender's routine lives.

Place-centric paradigm. Most existing work adopt a place-centric paradigm, where the research question is to predict the location of crime incidents. The predicated crime location is usually refereed by the term *hotspot*, which has various geographical size. There are plenty of works on exploration of the crime hotspots. For example, in a study [22] the authors use criminal offense records to identify spatio-temporal patterns at multiple scales. They employ various quantitative tools

from mathematics and physics and identify significant correlation in both space and time in the crime behavioral data. Short *et al.* [23] use a simple model to study the dynamics of crime hotspots and identify stable hotspots, where criminals are modeled as random walkers. Bogomolov *et al.* [20] use human behavioral data derived from mobile network and demographic sources, together with open crime data to predict crime hotspots. They compare various classifiers and find random forest has the best prediction performance. The paper [17] bases on automatic semantic analysis to understand natural language Twitter posts, from which the crime incidents are reported. Some other work [24, 25] employ the kernel density estimation (KDE) to identify and analyze crime hot spots. Those works form another form of crime prediction, which relies on the retrospective crime data to identify areas of high concentrations of crime. In [26], the authors extend the crime cluster analysis with a temporal dimension. They employ the space-time variants of KDE to simultaneously visualize geographical extent and duration of crime clusters.

Population-centric paradigm. In the last paradigm, research focuses on the criminal profiling at individual level and community level. At the individual level, [12] aim to automatically identify crimes committed by same individual from the historical crime database. The proposed system called *Series Finder*, is designed to find and classify modus operandi (M.O.) of criminals. At the community level, Buczak *et al.* [27] use fuzzy association rule mining to find crime pattern. The rules they found are consistently held across all regions. The paper constructs association rules from population demographics in community. In another paper [19], the authors use computation method to validate various social theories at a large scale. The data they used is mobile phone data in London, from which they mine the people dynamics as features to correlate with crime.

Our problem is different from the first two categories of work, mainly because our innovation mostly lies in using newer type of data to enhance the commonly used traditional counterpart. More specifically, we use POI to enhance the demographics information, and use taxi flow as hyper link to enhance the geographical proximity correlation. Although our problem does not consider the temporal dimension of crime in depth, it could be a promising supplement to better profile crime. Our problem dose not predict the location of any particular crime incident. Therefore the methods proposed in place-centric method are not applicable in our problem. However, the features we proposed may be incorporated in those crime prediction

model. Our problem falls into the third paradigm, because we are trying to profile the crime rate for Chicago community areas. In our problem, the community areas are well-defined and stable geographical regions. The newly proposed POI feature and taxi hyper link provide a unique perspective in profiling the crime rate across community areas.

Chapter 3 |

Base Model For Crime Inference

3.1 Problem Formulation

The crime dataset in Chicago has detailed information about the time and location (i.e., latitude and longitude) of crime and the types of crime. In our problem, when we use term crime count, we often refer to crime count in a region (i.e., community area) in a year. The *community area* is used as our geographical unit of study, since it is well-defined, historically recognized and stable over time [28]. In total, there are 77 community areas in Chicago. Crime rate is the crime count normalized by the population in a region. We use vector $\vec{y} = [y_1, y_2, \dots, y_n]$ to denote the crime rate in region i . The crime rate inference problem is to estimate the crime rate in one region using the crime rate of other regions in the same year by considering the features of regions and correlations between regions.

The crime data of Chicago are obtained from City of Chicago data portal [29]. Chicago is the city with most complete crime data that are made public online. The crime dataset contains the incident date, location (street name and GPS coordinates), and primary type from year 2001 to 2015. In total there are 5,856,414 recorded crime incidents over 15 years, which is an average 390,417 crimes incidents per year. We visualize the crime normalized by population in Figure 3.1, from which we can see that the downtown area has the highest crime rate.

In this paper we study the crime rate inference problem. More specifically, we estimate the crime rate of some regions given the information of all the other regions. Without loss of generality, we assume there is one community area t with crime rate y_t missing, and we use the crime rate of all the other regions $\{y_i\} \setminus y_t$ to

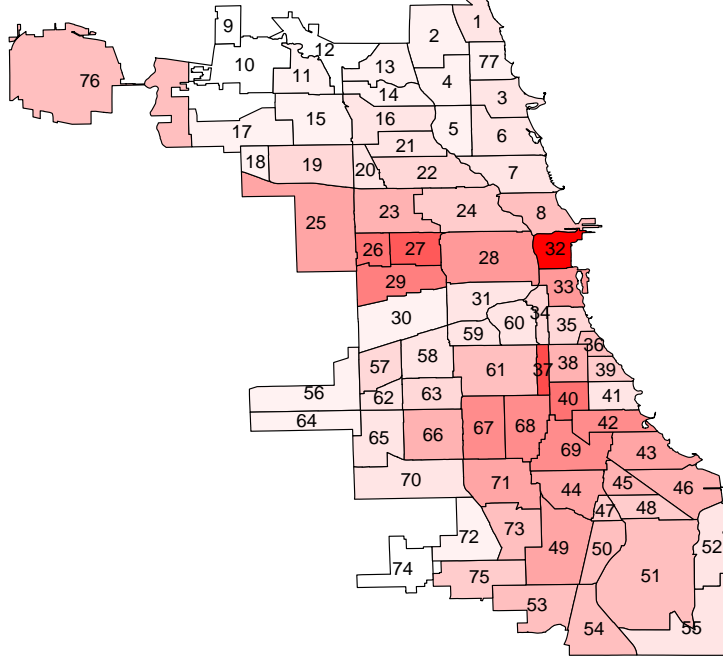


Figure 3.1. Crime rate of Chicago by community areas. The community area #32 is Chicago downtown, which has the highest crime rate.

infer this missing value. Our problem is mathematically formalized as follows

$$\hat{y}_t = f(\{y_i\} \setminus y_t, X), \quad (3.1)$$

where X refers to observed extra information of all those community areas.

We consider two types of features X for inference:

- Nodal feature. Nodal features describe the characteristics of the focal region. Such features include demographic information and Point-of-Interest (POI) distribution. Demographics are frequently used in literature, but POI is a newer type of big data, which we find significantly improve the crime inference accuracy.
- Edge feature: (1) Geographical influence. Geographical influence considers the crime rate of the nearby locations. This feature has been extensively used in literature as well. To estimate the focal region, the crime rate of nearby

regions are weighted according to spatial distances. (2) Hyperlink by taxi flow. Locations are connected through the frequent trips made by humans, which can be considered as the hyperlinks in space. This type of feature has never been studied in literature. We propose to use taxi trips to construct the social flow. Our hypothesis is that similarity in the crime rate of two regions should correlate with the social flow strength between these two regions.

3.2 Base Inference Model

3.2.1 Linear Regression

The most straightforward prediction is linear regression model. This model assumes the error terms follow a Gaussian distribution $\epsilon \sim \mathcal{N}(0, \sigma^2)$. As a result the parameter distribution also follows a Gaussian distribution. This assumption makes the model less generative, since in real applications, there is no way to ensure the dependent variable has a Gaussian error term.

Equation 3.2 gives the linear regression formulation of our problem.

$$\vec{y} = \vec{\alpha}^T \vec{x} + \beta^f W^f \vec{y} + \beta^g W^g \vec{y} + \vec{\epsilon}, \quad (3.2)$$

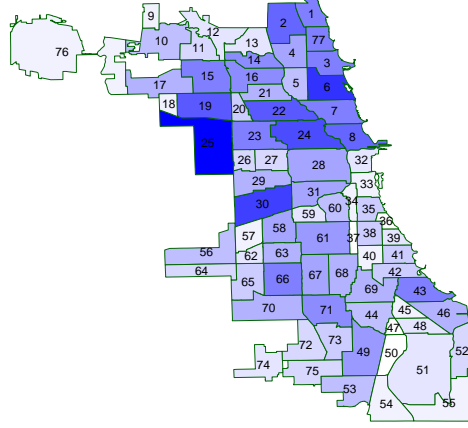
where \vec{x} represents the nodal features including demographics and POI distribution, W^f is the flow matrix of taxi flow, and W^g is the spatial matrix representing the geographical adjacency. On the right-hand side, ϵ is the only stochastic variables, and all other terms are fixed observation values. Therefore, we incorporate all the fixed observations into one term X , and we get the standard regression problem

$$E(y) = Xw + \epsilon.$$

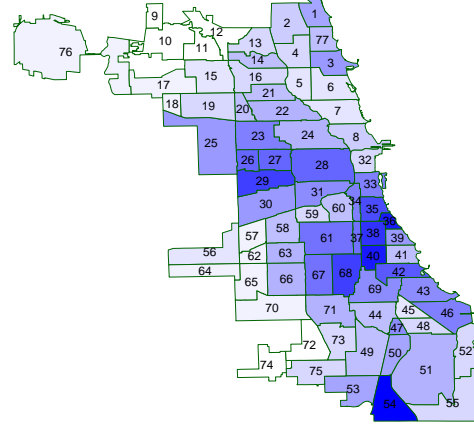
In order to learn the regression parameter w , we can use a maximum likelihood estimator. Since $\epsilon = y - Xw$, the joint probability of error term is

$$P(\epsilon|w) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(y-Xw)^2}{2\sigma^2}}. \quad (3.3)$$

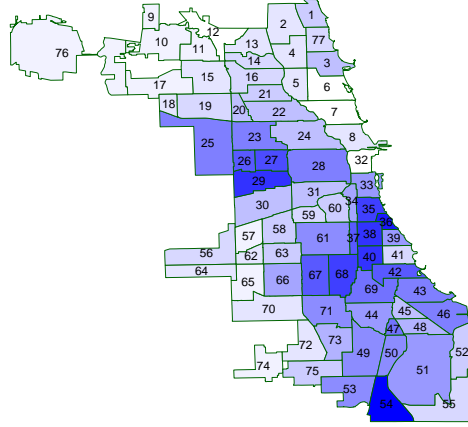
Maximizing the joint probability gives us the optimal solution.



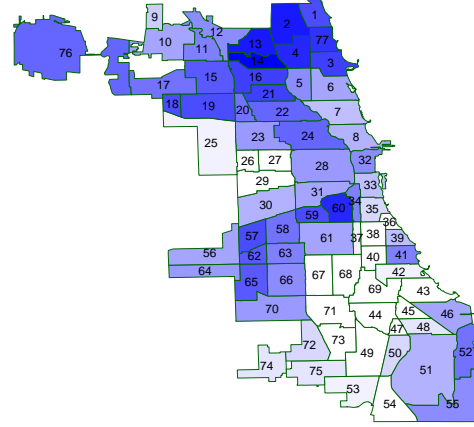
(a) Total population



(b) Poverty index



(c) Disadvantage index



(d) Ethnic diversity

Figure 3.2. (a)-(d) Demographics in Chicago by community areas. Darker colors indicate higher values.

3.3 Feature Extraction

In this section, we will discuss the details of features used in our method. The two types of new features we will use are extracted from Point-Of-Interest data and taxi flow data. Below we will describe the datasets used to construct features and the characteristics of these features.

3.3.1 Nodal Feature: Demographics

Socioeconomic and demographic features of neighborhoods have been widely used to predict crime [20, 30–32]. Previous studies have shown that crime rate correlates with certain demographics. For example, [6, 33] suggests that population diversity leads to less crime in certain neighborhoods. In our study, we include demographic information from the US Census Bureau’s Decennial Census of 2010 [34] and American Community Survey’s five-year average estimates between 2007 and 2011. We use year 2010 data because we are evaluating crime rates in 2010-2013. The demographics include the following features:

total population, population density, poverty, disadvantage index, residential stability, ethnic diversity, race distribution.

The poverty index measures the proportion of community area residents with income below the poverty level. The disadvantage index is a composite scale based on prior work [35], a function of poverty, unemployment rate, proportions of families with public assistance income, and proportion of female headed households. The residential stability measures home ownership and proportion of residents who lived in the neighborhood for more than one year. Racial and ethnic diversity is an index of heterogeneity [6] based on six population groups, including: Hispanics, non-Hispanic Blacks, Whites, Asians, Pacific Islanders and others.

Figure 3.2 visualizes the crime rate and demographics features in Chicago by community areas. Comparing with Figure 3.1, it is clear that the crime rate and poverty index and disadvantage index are consistent, the ethnic diversity shows an inverse correlation, and the total population has little correlation with crime.

Table 3.1 shows the Pearson correlation coefficient between various demographics features and the crime rate at community area level. The corresponding p-value is also calculated and shown in the table to indicate the significance of the correlation coefficient. There are in total 77 community areas in Chicago. Table 3.1 shows such correlation with several most correlated features. We can see that the poverty index and disadvantage index positively and strongly correlate with crime, while the ethnic diversity negatively correlates with crime. Other features such as total population, population density, and residential stability have weaker correlations. One counter-intuitive observation is that the total population has a weak and negative correlation with crime. The reason is that we use crime rate in each

community area, which is already normalized by the population, and therefore the total population and population density have less impact.

Table 3.1. Pearson correlation between demographic features and crime rate (* indicates significant correlations with p-value less than 5%).

Feature	Correlation	p-value
Total Population	-0.1269	0.2716
Population Density	-0.1972	0.0855
Poverty Index	0.5573*	1.403e-07
Disadvantage Index	0.5959*	1.082e-08
Residential Stability	-0.0453	0.6965
Ethnic Diversity	-0.5545*	1.678e-07
Percentage of Black	0.6696*	2.779e-11
Percentage of Hispanic	-0.3820*	0.0006

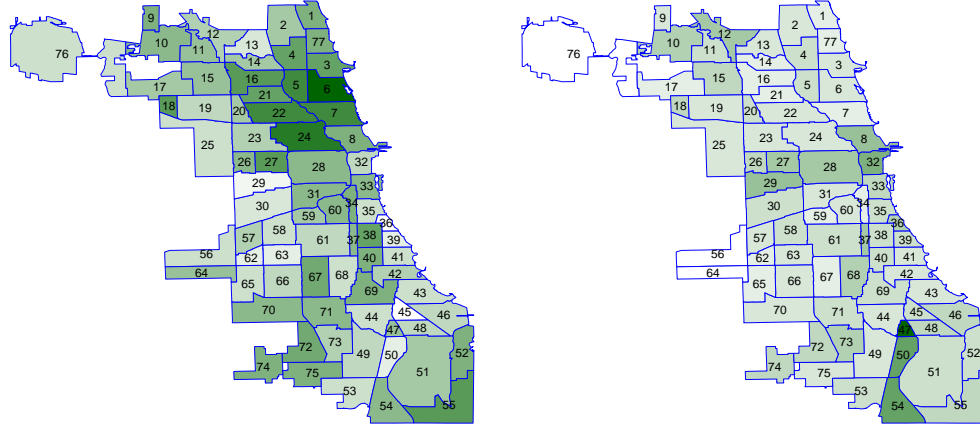
3.3.2 Nodal Feature: Point-of-Interest (POI)

While demographics are traditional census data, POI is a type of modern data that provide fine-grained information about locations. We collect POI from FourSquare [36]. POI data from FourSquare provide the venue information including venue name, category, number of check-ins, and number of unique visitors. We mainly use the major category information because categories can characterize the neighborhood functions. There are 10 major categories defined by FourSquare:

food, residence, travel, arts & entertainment, outdoors & recreation, college & education, nightlife, professional, shops, and event.

In total, we have crawled 112,000 POIs from FourSquare for Chicago. Most of these POIs are in downtown area of Chicago. We normalize the POIs count per category by the total POI count in a neighborhood and plot two selected category, i.e. nightlife and professional, in Figure 3.3. The darker colored neighborhoods in Figure 3.3 are the ones with a higher portion of residence POIs.

In Table 3.2 we show the Pearson correlation between POI category and crime rate. The category “professional” is most significantly correlated with the crime rate. Under the professional POI category, there are some venues with a large population concentration, such as transportation center, convention center, community center, and coworking space. In those venues, the population volume is high and residential



(a) Nightlife

(b) Professional

Figure 3.3. Plot the POI ratio per neighborhood. The saturation of color is proportional to the ratio value. The “professional” category distribution is more consistent with the crime distribution, and therefore it is the most correlated with crime. Meanwhile, the “nightlife” category is not positively correlated with Chicago crime.

Table 3.2. Pearson correlation between POI category and crime rate (* indicates significant correlations with p-value less than 5%).

POI category	Correlation	p-value
Food	-0.1543	0.1803
Residence	-0.0610	0.5984
Travel	-0.0017	0.9883
Arts & Entertainment	-0.0049	0.9661
Outdoors & Recreation	0.0668	0.5637
College & Education	-0.0078	0.9473
Nightlife	-0.1553	0.1775
Professional	0.3221*	0.0043
Shops	-0.1676	0.1450
Event	0.2196	0.0549

stability is low, therefore the professional POI counts positively correlates with crime rate. One counter-intuitive observation is that “nightlife” category is not positively correlated with crime (-0.1553). This can be explained through Figure 3.3(a). The majority of nightlife venues in Chicago locate in northern area, while most crime incidents occur in downtown area.

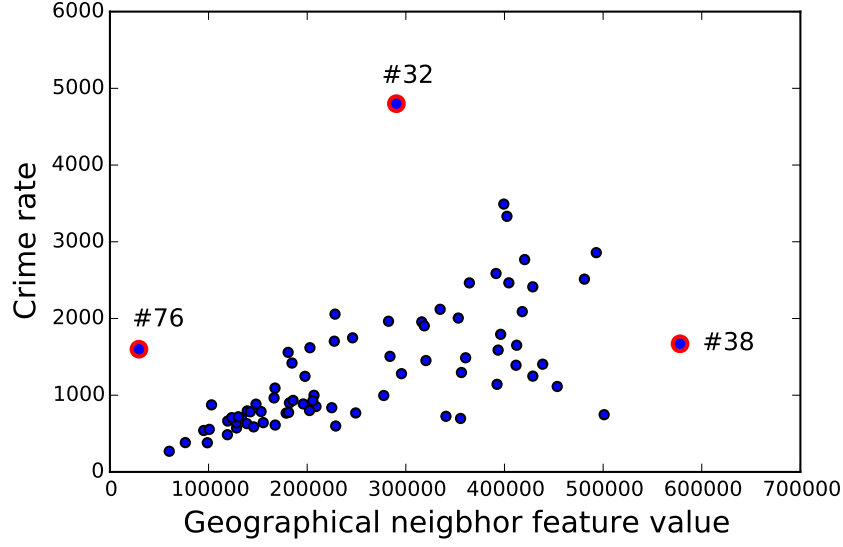


Figure 3.4. The geographical influence feature correlation with crime. In the plot we marked out three outliers and their corresponding community area ID.

3.3.3 Edge: Geographical Influence

Together with the US census demographics data, we also collected the boundary shape files of Chicago, which are used to calculate the geographical influence feature.

Previous studies have also shown that the crime rate at one location is highly correlated with nearby locations [37, 38]. Such geographical influence is also frequently used in the literature [39, 40], which is calculated as:

$$\vec{F}^g = W^g \cdot \vec{Y}, \quad (3.4)$$

where W^g is the spatial weight matrix. If region i and j are not geospatially adjacent, $w_{ij}^g = 0$; otherwise, $w_{ij}^g \propto distance(i, j)^{-1}$.

In Figure 3.4, we plot crime rate with respect to geographical influence calculated in Eq. 3.4. We observe an obvious positive correlation, which means if nearby neighborhoods have a high crime rate, the focal neighborhood is more likely to have a high crime rate. We also do observe a few outliers in Figure 3.4. These neighborhoods show different crime rate in their nearby neighborhoods compared to their own. For example, as we can also see in Figure 3.1, community area #38 locates in an area where the neighbors have high crime rates but its crime rate

is relatively low; in contrast, neighborhood #32 has a high crime rate even though its neighbors have relatively low crime. The community area #76 home of the O'Hare International Airport is far from most of other community areas, however its own crime rate is relative high.

3.3.4 Edge: Hyperlinks by Taxi Flow

In our Chicago taxi dataset, there are 1,048,576 taxi trips in total during the October to December in 2013. For each trip the following information are available: pickup/dropoff time, pickup/dropoff location, operation time, and total amount paid. We requested the taxi trip records from Chicago taxi commission pursuant of the Freedom of Information Law. Figure 3.5 shows a visualization of the major flows at community level.

One of our hypothesis is that the social interaction among two community areas propagates crime from one region to another. The Chicago taxi data captures the social interactions among various community areas. To calculate this first, we first map all taxi trips to community areas to get the taxi flow $w_{ij} \forall i, j \in \{1, 2, \dots, n\}$. Then the taxi flow lag is constructed by the product of social flow and the crime rate of neighboring regions as follows

$$\vec{F}^t = W^t \cdot \vec{Y}. \quad (3.5)$$

The taxi flow W^t is a matrix with entry w_{ij} denoting the taxi flow from i to j . Note that $\forall i, w_{ii}^s = 0$ in matrix W^t , because we have to exclude the crime in focal area from its own predictor. The semantic of this taxi flow feature is how many crime in the focal area is contributed by its neighboring areas through social interaction.

The correlation between taxi flow and crime rate is shown in Figure 3.6. From the scatter plot, we can see that overall the crime rate is positively correlate with the taxi flow. There are two outliers clearly shown in Figure 3.6. The community area #32 is the downtown Loop, which has the highest crime rate and is hard to predict by taxi flow. Another anomalous community area #47 has relatively low crime rate by itself. However, this area has a lot of in flows from high-crime communities.

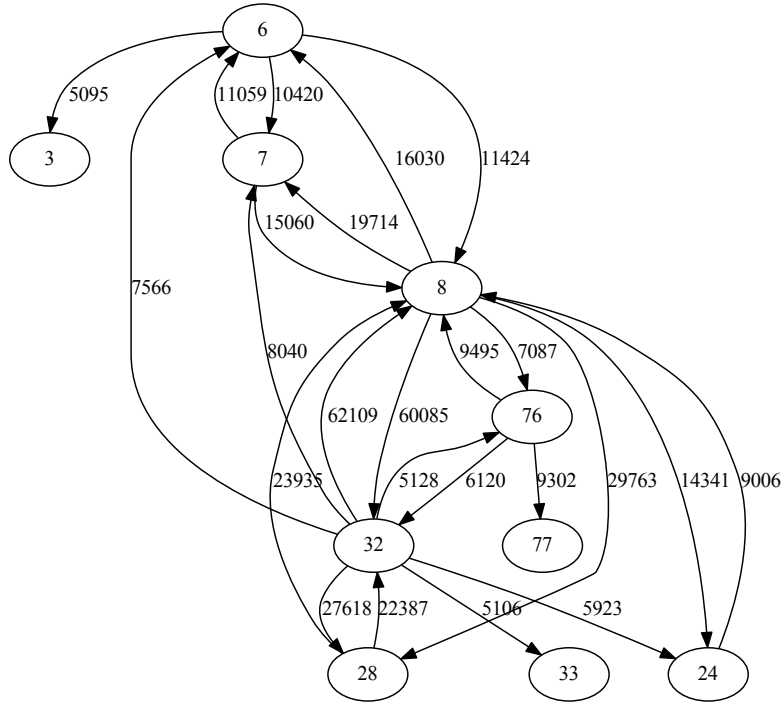


Figure 3.5. Major taxi flows between neighborhoods. We set a threshold ($> 5,000$) on the flow and only plot the high volume flow. The label on the node is the ID of the corresponding community areas. We can see that there are several hub community areas, such as #6, #8, #32, which are all in the downtown areas. The label on the edge shows how many taxi trips are commuting through the two community areas for three months in 2013.

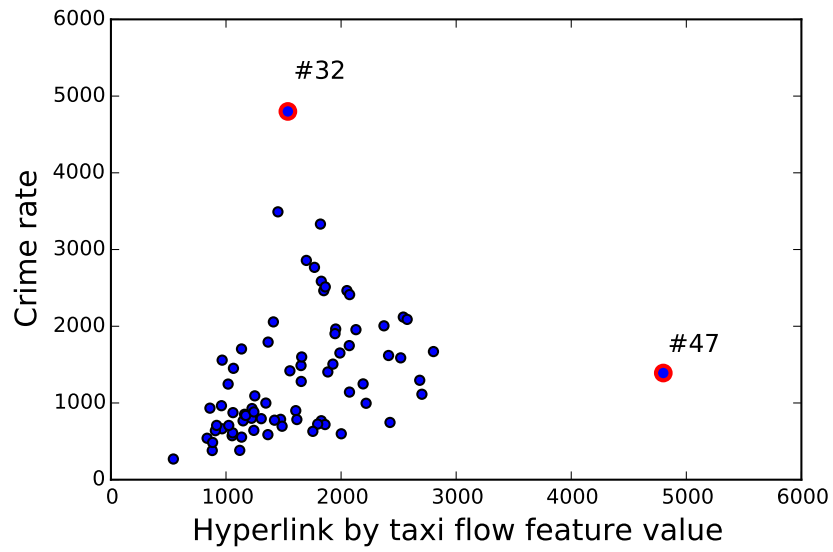


Figure 3.6. Correlation between taxi flow and crime rate. In the plot, we marked out three outliers and their corresponding community area ID.

Chapter 4 |

Title of the Fourth Chapter

Chapter 5 |

Title of the Fifth Chapter

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Vita

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The details of my childhood are inconsequential.