Learning to Rank for Spatiotemporal Search
时空搜索中的排序算法

Blake Shaw, Jon Shea, Siddhartha Sinha, Andrew Hogue
布莱克 · 肖，乔恩 · 谢伊，悉达多 · 辛哈，安德鲁 · 霍格

Foursquare
Foursquare
568 Broadway
New York, NY
纽约，纽约，
百老汇

{blake, jonshea, ssinha, ahogue}@foursquare.com
{ blake，jonshea，ssinha，ahogue }@foursquare. com

ABSTRACT
摘要

In this article we consider the problem of mapping a noisy estimate of a user's current location to a semantically mean-ingful point of interest, such as a home, restaurant, or store. Despite the poor accuracy of GPS on current mobile devices and the relatively high density of places in urban areas, it is possible to predict a user's location with considerable pre-cision by explicitly modeling both places and users and by combining a variety of signals about a user's current context. Places are often simply modeled as a single latitude and lon-gitude when in fact they are complex entities existing in both space and time and shaped by the millions of people that in-teract with them. Similarly, models of users reveal complex but predictable patterns of mobility that can be exploited for this task. We propose a novel spatial search algorithm that infers a user's location by combining aggregate signals mined from billions of foursquare check-ins with real-time contex-tual information. We evaluate a variety of techniques and demonstrate that machine learning algorithms for ranking and spatiotemporal models of places and users offer signifi-cant improvement over common methods for location search based on distance and popularity.

在本文中，我们考虑将用户当前位置的噪声估计映射到语义意义上的兴趣点的问题，例如家、餐厅或商店。尽管全球定位系统在当前移动设备上的准确性较差，而且城市地区的地点密度相对较高，但是通过对地点和用户进行明确建模，并结合关于用户当前情况的各种信号，可以相当准确地预测用户的位置。地点往往被简单地模拟为单一纬度和全方位，而事实上，它们是存在于空间和时间中的复杂实体，并由数百万与它们共同行动的人们塑造。类似地，用户模型揭示了复杂但可预测的移动模式，可以利用这一任务。提出了一种新的空间搜索算法，该算法通过结合从几十亿个 foursquare 签到中挖掘出的聚合信号和实时的虚拟信息来推断用户的位置。我们评估了各种技术，并证明了机器学习算法的排序和时空模型的地点和用户提供了重要的改进基于距离和流行度的位置搜索常用方法。

Categories and Subject Descriptors
类别及学科描述

H.2.8 [Database Applications]: Spatial databases; H.2.8
H. 2.8[数据库应用] : 空间数据库; h. 2.8
[Database Applications]: Data Mining; I.5.1 [Pattern
[数据库应用] : 数据挖掘; i. 5.1[模式
Recognition]: Statistical
认可] : 统计学

Keywords
关键词

spatial search, machine learning, learn to rank, spatiotempo-ral models, location data, data mining, geocoding, informa-tion retrieval, foursquare, human mobility, mobile devices
空间搜索，机器学习，学习排序，空间模型，位置数据，数据挖掘，地理编码，信息检索，foursquare，人类移动，移动设备

1. INTRODUCTION
引言

Today's location-aware mobile devices have dramatically increased the availability and usefulness of location infor-mation. Many applications take advantage of the ability of

当今的位置感知移动设备极大地提高了位置信息的可用性和有用性。许多应用程序利用

WSDM'13, February 4–8, 2012, Rome, Italy.
13，February 4-8,2012，Rome，Italy.

these devices to report a user's location in terms of latitude and longitude, providing useful services to the user such as maps, driving directions, tourist guides, photo sharing, and more. Other services allow users to store content that has been "geotagged" with a location and share it with friends.
这些设备可以根据经纬度来报告用户的位置，为用户提供有用的服务，如地图、行车路线、导游、照片共享等。还有一些服务允许用户存储与某个地点"地理标记"的内容，并与朋友分享。

Several applications go one step further than raw coor-dinates, attaching a *semantically meaningful* name to a lo-cation. The coarsest form of this labeling involves using a reverse geocoding service [2] to find a city or neighborhood name for a given location. Examples include Twitter, which allows users to attach a location to a tweet, displaying it as a city or neighborhood, and Facebook, which tags most posts by default with a user's current city.
有几个应用程序比原始协调更进一步，将语义上有意义的名称附加到元素。这种标签最粗糙的形式包括使用反座标化服务[2]为给定的地点找到一个城市或邻里名称。例如 Twitter，它允许用户将一个地点附加到一条 tweet 上，显示为一个城市或社区，还有 Facebook，它默认将大多数帖子标记为用户的当前城市。

These coarse location names provide some context, but in many cases it is desirable to be significantly more gran-ular when choosing a name for a location. For example, Instagram allows users to choose a specific location when sharing a photo, such as "Washington Square Park" or "The Blind Tiger." Similarly, foursquare, Path, and other mobile applications allow users to "check in" at a specific location such as a restaurant or museum. Tying users and their data to specific, semantically meaningful locations enables these services to provide richer experiences, such as showing the user relevant and timely information like a menu from a restaurant or a tip from a friend about what to order [31]. Moreover, identifying precise locations facilitates the sharing and aggregation of local information. For example, a user of foursquare can see not only recent places their friends have checked into, but also which of their friends have endorsed nearby venues.
这些粗糙的位置名称提供了一些上下文，但在许多情况下，在为一个位置选择名称时，最好使用更加复杂的名称。例如，Instagram 允许用户在分享照片时选择特定的地点，比如"华盛顿广场公园"或"盲虎"类似地，foursquare、 Path 和其他移动应用程序允许用户在特定地点(如餐馆或博物馆)"签到"。将用户及其数据绑定到具体的、语义上有意义的位置，使这些服务能够提供更丰富的体验，例如向用户显示相关的、及时的信息，比如餐厅菜单或朋友关于点什么的提示。此外，确定准确的地点有助于分享和汇总当地信息。例如，foursquare 的用户不仅可以看到他们的朋友最近登记的地方，还可以看到他们的朋友中哪些人在附近的地方做了背书。

Unfortunately, mapping a user's location to a database of known points of interest is complicated by several factors. While location services such as GPS, WiFi, and cell-tower triangulation can provide accuracies under 10 meters un-der ideal conditions [35], results in real-world environments are substantially worse, with median accuracies of 70 meters (see Figure 1). Additionally, many areas of the world are ex-tremely dense in terms of semantically meaningful locations; in many urban environments, interesting locations may even be located directly above or below each other. Finally, while a user's history may be useful in determining their location [7, 18], the system must still provide accurate results even for users with little or no history.

不幸的是，将用户的位置映射到一个包含已知感兴趣点的数据库由于几个因素而变得复杂。尽管 GPS、 WiFi 和手机基站三角测量等定位服务在理想条件下 10 米的范围内可以提供精确度，但是在现实环境中的精确度要差得多，中位精确度为 70 米(见图 1)。此外，世界上的许多地区在语义上有意义的位置方面异常密集; 在许多城市环境中，有趣的位置甚至可能直接位于彼此之上或之下。最后，虽然用户的历史记录可能有助于确定他们的位置[7,18] ，但系统仍然必须提供准确的结果，即使对于历史记录很少或没有历史记录的用户。

Despite these difficulties, there are many benefits to an accurate system for finding specific, semantically meaningful names for a given set of coordinates. Tuning such a system for high recall in the top few results allows users to choose their location from a list of results and more easily share and

尽管存在这些困难，对于一个精确的系统来说，为给定的一组坐标寻找具体的、语义上有意义的名称还是有很多好处的。通过调整这样一个系统，用户可以在前几个搜索结果中选择自己的位置，更容易分享和使用

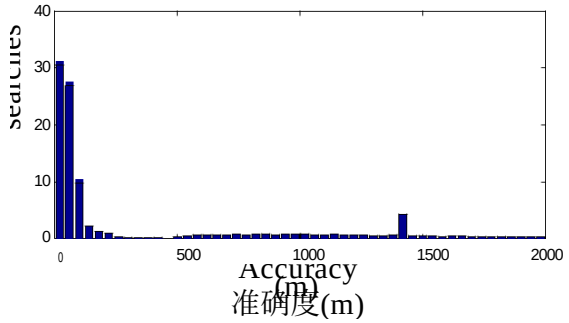

Figure 1: Distribution of reported location accuracy from 26,532 randomly sampled worldwide searches on foursquare. The median is 70 meters, and the mean is 551 meters.

图 1: 从 foursquare 上 26,532 个随机抽样的全球搜索中报告的位置准确性的分布。中位数是 70 米，平均值是 551 米。

retrieve local information. Alternatively, a system with high precision in the first position could be used to automatically label a user's location or content with a specific location name, or to tie together multiple pieces of content into a coherent grouping about a particular place. Furthermore, such a system could be used to trigger highly contextual notifications, such as transit information when a user enters a train station, or targeted deals when a user enters a store.

检索本地信息。或者，在第一个位置具有高精度的系统可以用一个特定的位置名称来自动标记用户的位置或内容，或者将多个内容片段连接成一个关于特定地点的连贯分组。此外，这样的系统可以用来触发高度上下文通知，例如用户进入火车站时的交通信息，或者用户进入商店时的目标交易。

In this article, we describe the development, training, and evaluation of the spatial search engine that powers the four-square application and API. We first introduce our approach to modeling people and places using check-in data, and then describe how these models can be used for retrieval and rank-ing. We focus on using machine learning techniques to cre-ate an optimal ranking function, which learns from large amounts of implicit feedback. Finally, we demonstrate the fully working system and evaluate its performance in a vari-ety of real-world situations, showing significant improvement over common methods for location search and previously re-ported results.

在本文中，我们描述了空间搜索引擎的开发，培训和评估的权力四平方应用程序和 API。我们首先介绍使用签入数据对人员和地点进行建模的方法，然后描述如何使用这些模型进行检索和排序。本文主要研究利用机器学习技术构造一个最优排序函数，该函数可以从大量的隐式反馈中学习。最后，我们演示了完整的工作系统，并对其在各种实际情况下的性能进行了评估，显示了对于常见的位置搜索方法和以前的转移结果的显著改进。

1.1 Related Work

1.1 相关工作

The growing ubiquity of GPS-enabled consumer mobile devices has only recently enabled the study of user location at the scale described in the current work. Lian and Xie

支持 gps 的消费移动设备的日益普及，只是在最近才使得对用户位置的研究能够达到当前工作中描述的规模。连和谢

[18] describe a similar system for mapping a user to a point of interest (POI) trained on data from 545 users in a single city using a database of approximately 16,000 points of in-terest. The system uses several features, such as distance, time, POI popularity, and user history, to train a model that predicts a user's location with 64.5% recall in the top 5 results. Our work improves these results by introducing several new features, more robust models, and significantly more training data (in terms of both size and diversity) to search a much larger database of locations.

描述一个类似的系统，用于将用户映射到一个感兴趣点(POI)，这个系统使用一个大约有 16,000 个最近点的数据库，从一个城市的 545 个用户那里获取数据。该系统使用了几个特性，如距离、时间、 POI 流行度和用户历史，来训练一个模型，该模型可以预测用户的位置，前 5 个结果中有 64.5% 的回忆率。我们的工作通过引入一些新的特性、更健壮的模型和更多的训练数据(就大小和多样性而言)来改进这些结果，以搜索一个更大的位置数据库。

Similar techniques regarding context and personalization have been applied in the area of local business search and web search. Lane et al. [17] report relevance improvements of up to ten times in local search relevance by including simple context and behavioral similarity features in a rank-ing model. Church and Smyth [10] demonstrate the efficacy of including user-, location-, and time-dependent features in mobile web search. Many techniques incorporate signals mined from query logs to improve search results [34, 32].

关于上下文和个性化的类似技术已经应用于本地商业搜索和网络搜索领域。Lane et al. [17]报告说，通过在排序模型中包含简单的上下文和行为相似性特征，局部搜索相关性提高了多达 10 倍。Church 和 Smyth [10]展示了在移动网络搜索中包含用户、位置和时间相关特性的功效。许多技术合并从查询日志中挖掘的信号来改善搜索结果[34,32]。

Outside of the realm of search, significant work has been

在搜索领域之外，还有一些重要的工作

done with respect to analyzing and describing GPS data

在分析和描述 GPS 数据方面所做的工作

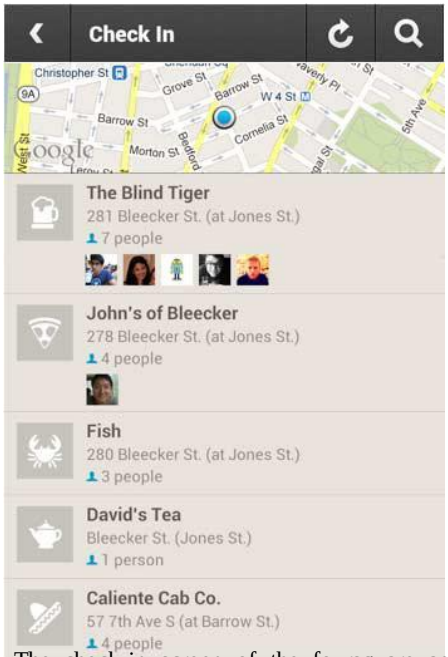

Figure 2: The check-in screen of the foursquare ap-plication where a user searches for nearby venues and selects a venue to check in to.

图 2: foursquare 应用程序的签到屏幕，用户在其中搜索附近的场地并选择要签到的场地。

collected over time from users. Ashbrook and Starner [6, 7] cluster GPS locations to model significant locations and predict user movements using a Markov model. Gonzalez et al. [13] develop similar models to predict where a user will be based on their history. Liao et al. [19] predict signifi-cant locations for a given user using hierarchical conditional random fields, while Marmasse and Schmand [21] describe a similar system to collect GPS trails and prompt the user to label the significant locations. Furthermore, many tech-niques combine social and location-based signals to signifi-cantly boost the accuracy of models for predicting user loca-tion as well as determining attributes of social relationships [30, 8, 28, 20].

随着时间的推移从用户那里收集。阿什布鲁克和斯塔纳[6,7]集群 GPS 定位模型的重要位置和预测用户的动向使用马尔可夫模型。冈萨雷斯等人[13]开发了类似的模型，以根据用户的历史预测他们将在哪里。Liao et al. [19]使用分层条件随机场预测给定用户的重要位置，而 Marmasse 和 Schmand [21]描述了一个类似的系统来收集 GPS 踪迹并提示用户标记重要位置。此外，许多技术人员将社交信号和基于位置的信号结合起来，以显著提高预测用户位置以及确定社会关系属性的模型的准确性[30,8,28,20]。

Geolocating other types of data has also received substan-tial attention. Systems for mapping text to a location have been described for tweets [9], blogs [11], and web pages [5] using a variety of lexicographic and user features. Similarly, Serdyukov et al. [29] describe techniques for mapping photos to geographic coordinates using language models and user annotations.

对其他类型数据的地理定位也受到了极大的关注。使用各种字典和用户特性的 tweets [9]、 blog [11]和 web 页面[5]描述了将文本映射到位置的系统。同样，谢尔久科夫等人描述了使用语言模型和用户注释将照片映射到地理坐标的技术。

1.2 Venue Search in Foursquare

1.2 地点搜索

Foursquare is a location-based service which handles more than 5 million check-ins each day, mapping each to one of more than 40 million locations worldwide. Foursquare has accumulated over 2.5 billion historical check-ins.[1] These ac-tions are enabled by a search engine that maps user locations into a database of points of interest with high accuracy. This service is also provided as an API for external developers to add location mapping to their applications [1].

Foursquare 是一个基于地理位置的服务，每天处理超过 500 万个签到，每个签到点覆盖全球 4000 多万个地点中的一个。Foursquare 已经积累了超过 25 亿个历史检查点。这些检查是通过一个搜索引擎实现的，该引擎可以高精度地将用户位置映射到一个感兴趣点的数据库中。这个服务也作为一个 API 提供给外部开发人员，用于向他们的应用程序添加位置映射[1]。

Figure 2 shows the check-in screen from the foursquare

图 2 显示了来自 foursquare 的签入屏幕

[1]As of August 2012.

1 截至 2012 年 8 月。

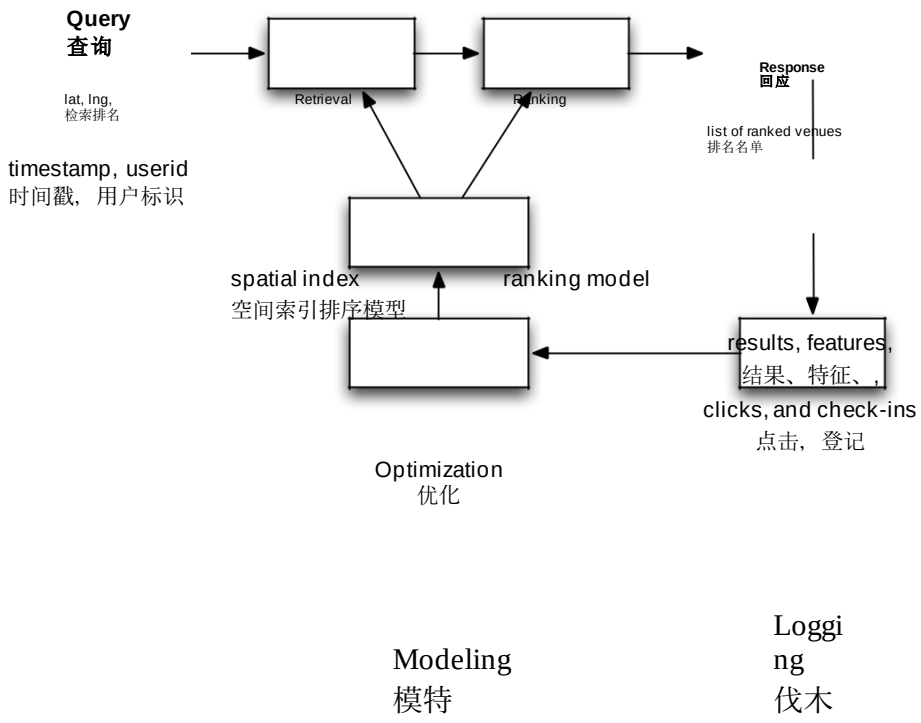

Figure 3: Overview of our system architecture. There are two main stages to responding to a query to produce a response: retrieval, where a spatial index is used to generate a set of candidate venues, and ranking where a machine-learned ranker is used to sort the response venues. Data is then logged from the search process and used offline for modeling and optimization.

图 3: 我们的系统架构概述。响应查询产生响应有两个主要阶段: 检索(其中使用空间索引生成一组候选场所)和排序(使用机器学习的 ranker 对响应场所进行排序)。然后，从搜索过程中记录数据，离线使用数据进行建模和优化。

application. Upon pressing the “Check in” button, the application sends the user’s ID and current location to the server. The user ID is a unique identifier that is used to retrieve the user’s history, friends, interests, and other per-sonalized information used for ranking. The user’s location is reported by the mobile device, and includes latitude, lon-gitude, and a horizontal accuracy reading. A timestamp is generated at query time on the server in UTC, and is used to identify historical patterns in venue popularity for ranking.

应用。按下“ Check in”按钮后，应用程序将用户的 ID 和当前位置发送到服务器。用户 ID 是一个唯一标识符，用于检索用户的历史记录、好友、兴趣和其他用于排名的声音化信息。用户的位置由移动设备报告，包括纬度、距离和水平读数。时间戳是在服务器上以 UTC 格式进行查询时生成的，用于识别场馆流行度的历史模式以便进行排名。

The interface presents the user with a list of nearby loca-tions, along with a map for context. The locations shown are chosen based on a variety of factors outlined below, including their popularity, distance from the user, and compatibility with the user’s history. In particular, the current number of other users checked into each venue is displayed, which can help give the user an indication of the current popularity of the venues. For similar reasons, avatars for any of the user’s own friends that are currently checked in are also shown. An icon indicating the location’s primary category (e.g. Pub or Pizza Place) is also displayed to provide context for the user.

该界面向用户提供了附近地点的列表，以及一个用于上下文的地图。所显示的位置是根据下面列出的各种因素来选择的，包括它们的受欢迎程度、与用户的距离以及与用户历史记录的兼容性。特别是显示每个场地目前登记的其他用户数量，这可以帮助用户了解场地目前的受欢迎程度。基于类似的原因，当前签入的用户好友的头像也会显示出来。还会显示一个图标，指示该位置的主要类别(例如，Pub 或 Pizza Place)，以便为用户提供上下文。

In certain situations, if the location in which the user is interested is not returned, they may perform an explicit tex-tual query to find the correct venue. We term these searches *query* searches, to differentiate them from the *nearby* searches described above. We do not describe the system for query searches in this paper, but it is an extension of the techniques described here using standard text retrieval methods.

在某些情况下，如果没有返回用户感兴趣的位置，他们可能会执行显式的特克斯查询来找到正确的地点。我们称这些搜索为查询搜索，以区别于上述附近的搜索。我们在本文中没有描述用于查询搜索的系统，但是它是使用标准文本检索方法描述的技术的一个扩展。

If the user still cannot find the desired location after a query search, they are offered the option of creating a new venue in the database. This venue is immediately included in the search engine and made available to the user (and others) to check in to. In this way, the system can adapt to new and missing locations and other recall failures.

Relative to other search systems, foursquare’s check-in search has the benefit that the user provides direct feed-back about the correct answer to their query by checking into that location after their search. Even in cases where the system fails to provide an accurate answer using nearby