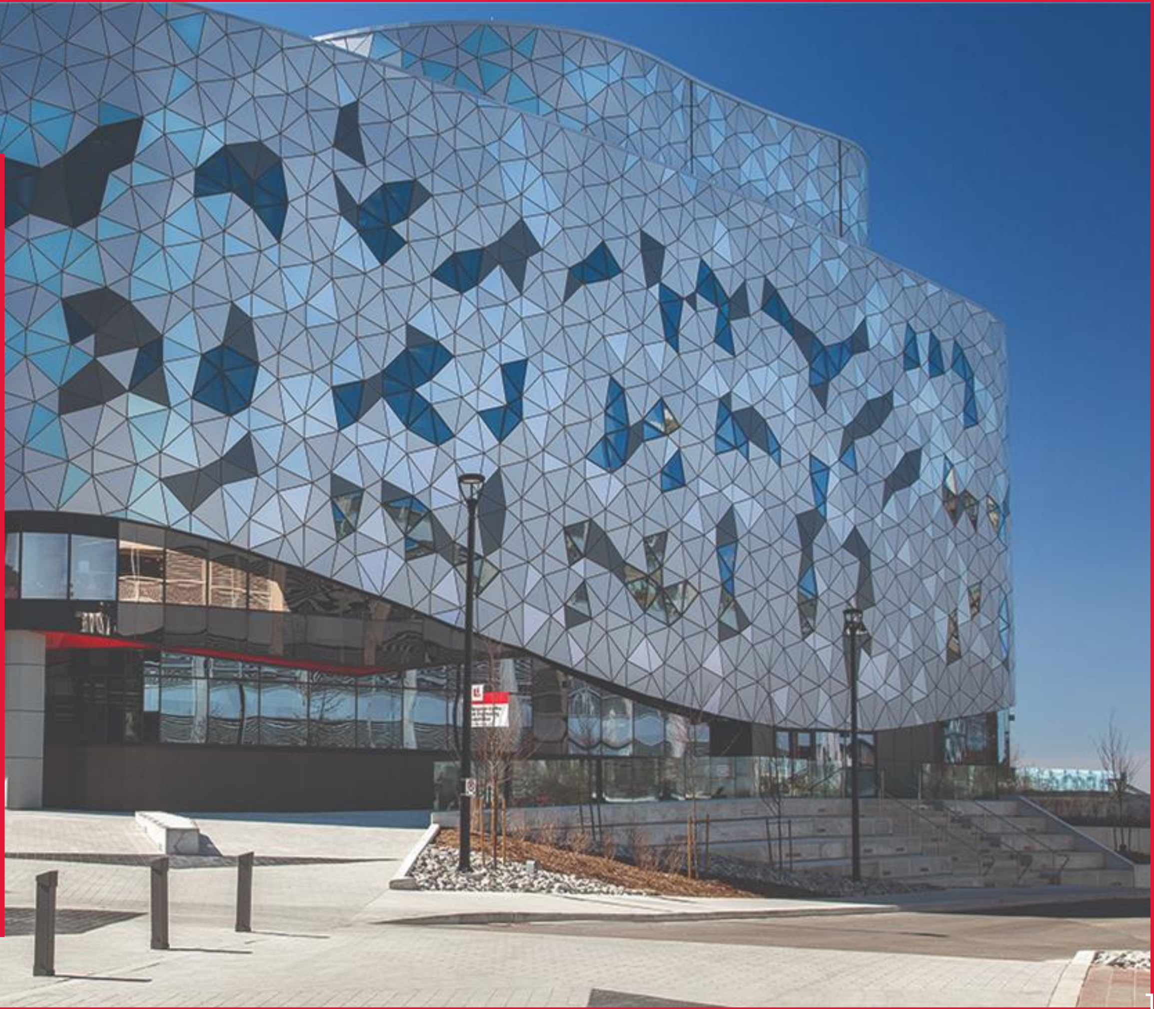
Trajectory Data Mining in the Age of Big Data and AI

Ontario Database Day
(OnDBD 2023)



Manos Papagelis

Wed, Dec 13, 2023
McMaster University

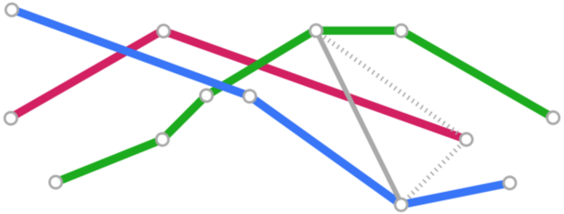
Background & Motivation

Trajectory/Mobility Data

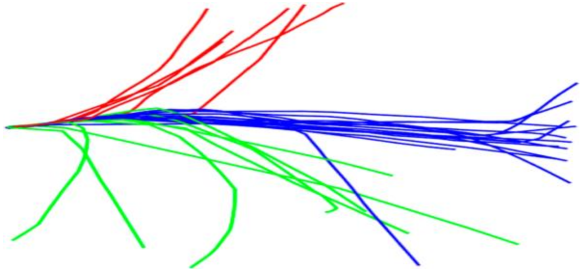
Trajectory: A Sequence of (Spatiotemporal) Points

Vast Amounts of Trajectory/Mobility Data

Trajectory Data Mining



trajectory similarity



trajectory clustering

trajectory anomaly detection
trajectory network mining
trajectory classification
...

challenging computational problems

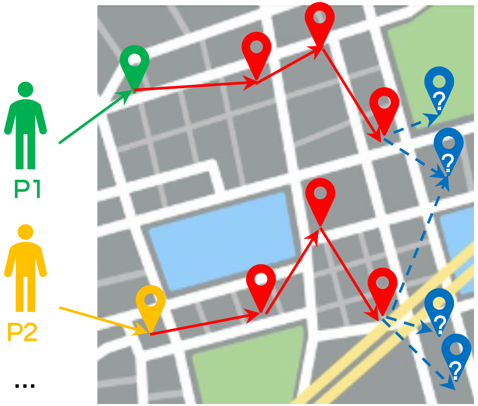
Trajectory Data Mining in the Age of Big Data and AI

a symbiotic relationship that presents a new strategy for addressing complex problems in trajectory data mining

Image source: This image was created with the assistance of DALL·E 3

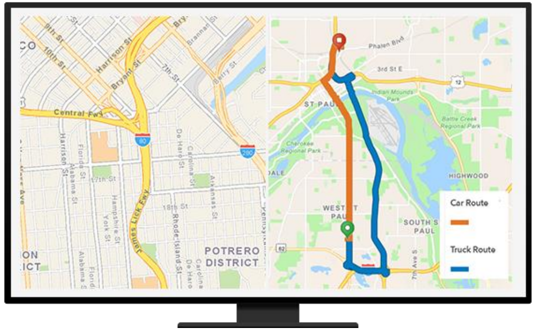
Plethora of Applications

ridesharing



trip/POI (point-of-interest) recommendation

traffic analysis



route planning and optimization

Data Mining Lab @ YorkU's Journey on Trajectory Data Mining

- Trajectory simplification [ACM SIGSPATIAL '23]
- Trajectory similarity [Submitted]
- Trajectory dataset and resources [ACM SIGSPATIAL '23]
- Trajectory prediction [Submitted]
- Trajectory classification [IEEE MDM '23]
- Trajectory network analysis [Big Data Research, IEEE MDM '20, GeoInformatica, IEEE BigData '18, 2 x IEEE MDM '18]
- Mobility + epidemics [ACM SIGSPATIAL/SpatialEpi '24, ACM SIGSPATIAL/SpatialEpi '23, IEEE MDM '22]
- Transportation optimization [ACM SIGSPATIAL '22, ACM SIGSPATIAL '22]

Trajectory Simplification

The Trajectory Pathlet Dictionary Construction Problem

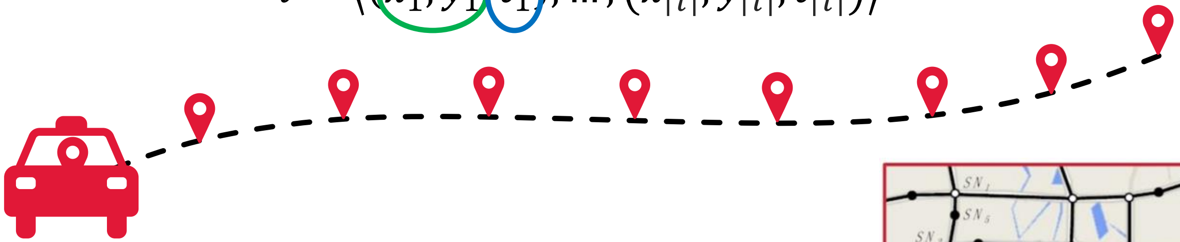
Trajectories on the Road Network

- Trajectory
  - Denoted by τ
  - Represented as:

object's geo-location

specific time instance

$$\tau = \langle (x_1, y_1, t_1), \ldots, (x_{|\tau|}, y_{|\tau|}, t_{|\tau|}) \rangle$$



- Road Network

  Modelled as a graph $\mathcal{G}\langle \mathcal{V}, \mathcal{E} \rangle$
  - $\mathcal{V}$: **Nodes** (set of road intersections)
  - $\mathcal{E}$: **Edges** (set of road segments)

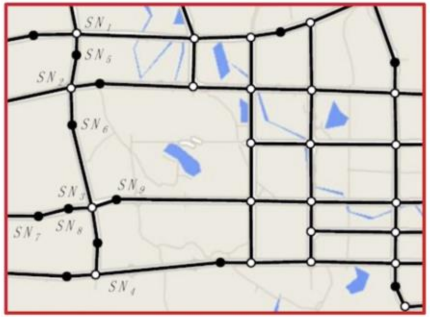
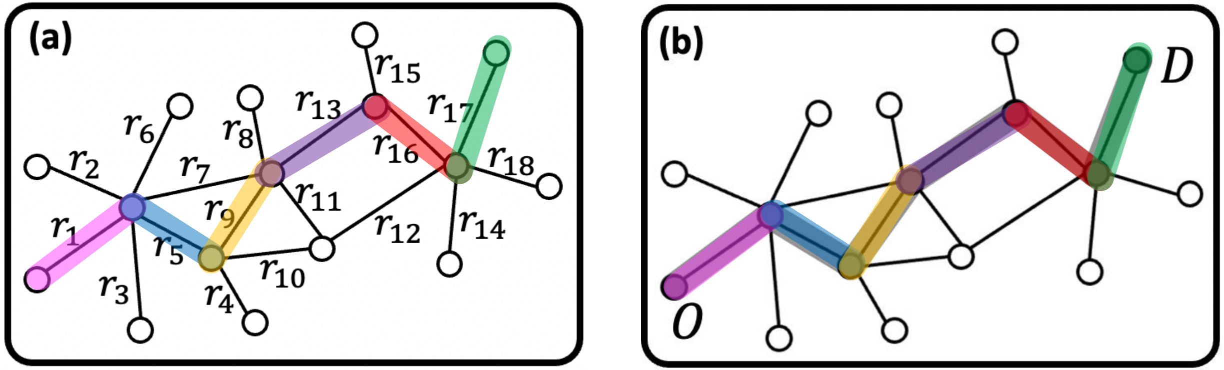


Image Source: "Updating Road Networks by Local Renewal from GPS Trajectories" [Wu et al, MDPI '16]

Road Segment-based Representation

- Each trajectory τ can be expressed as a set of road segments $\boldsymbol{R}_s \subseteq \boldsymbol{R}$
- This special representation is denoted by $\mathfrak{R}(\tau)$



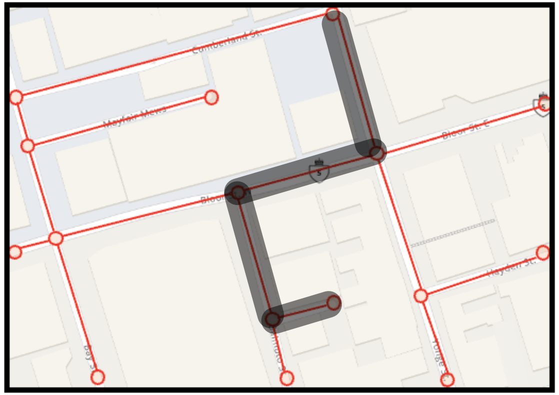
$$\mathfrak{R}(\tau) = \{r_1, r_5, r_9, r_{13}, r_{16}, r_{17}\}$$

Trajectory Pathlet Dictionary (PD) Construction

- Pathlet Dictionary: A small set of basic building blocks that can represent a wide range of trajectories
- Many names in the literature

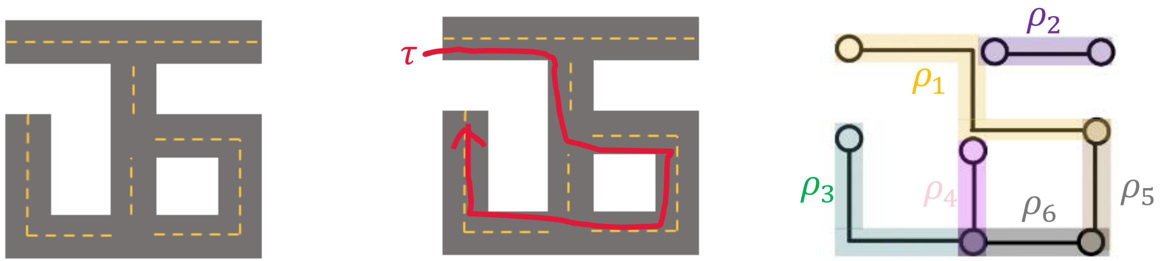
  [Panagiotakis et al – TKDE '12, Chen et al – SIGSPATIAL '13, Sankararaman et al – SIGSPATIAL '13, Agarwal et al – PODS '18, Li et al – TSAS '18, Zhao et al – CIKM '18]

  - Pathlet
  - Subtrajectory
  - Trajectory Segments
  - Fragments
  - ...



Pathlet-based Representation of a Trajectory

Denoted by $\Phi(\tau) = \{\rho^{(1)}, \rho^{(2)}, \dots, \rho^{(k)}\}$



(a) (b) (c)

$\Phi(\tau) = \{\rho_1, \rho_5, \rho_6, \rho_3\}$

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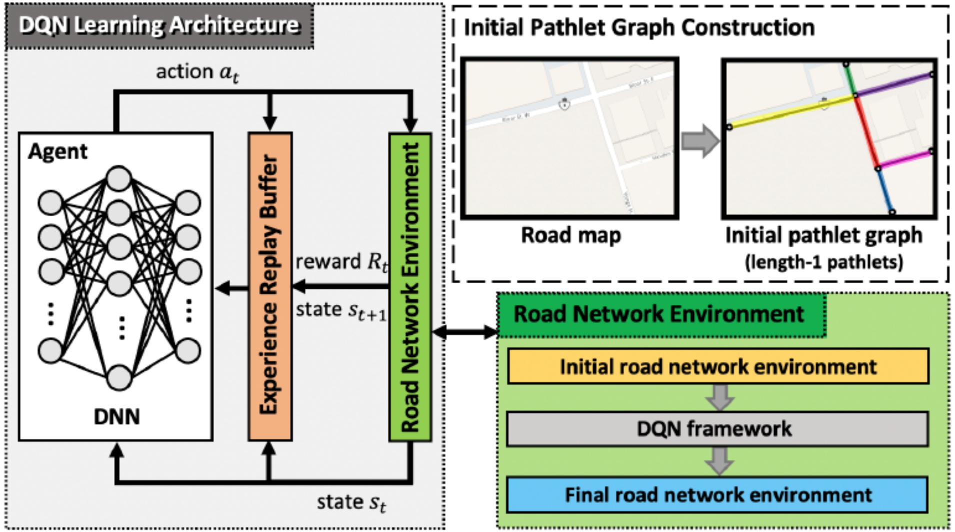
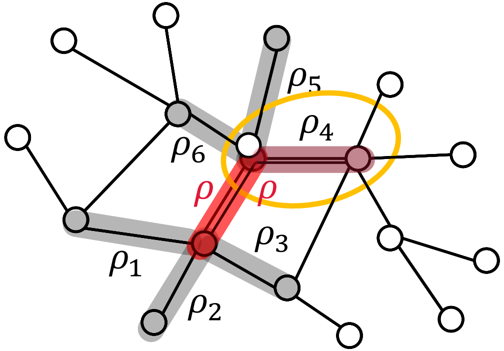
PathletRL - Overview

- Extracting candidate pathlets
- Deep Reinforcement Learning framework

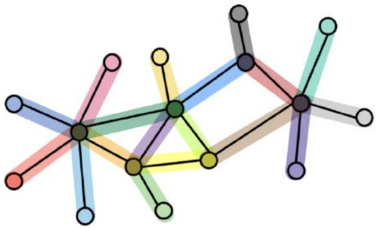


Extracting Candidate Pathlets - Example

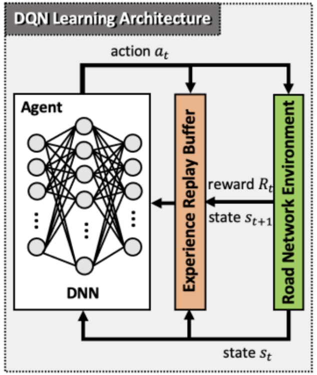


ρ_{merge}	Utility
MERGED(ρ, ρ_1)	+0.7
MERGED(ρ, ρ_2)	+1.8
MERGED(ρ, ρ_3)	-1.6
MERGED(ρ, ρ_4)	+5.5
MERGED(ρ, ρ_5)	-3.2
MERGED(ρ, ρ_6)	+2.9

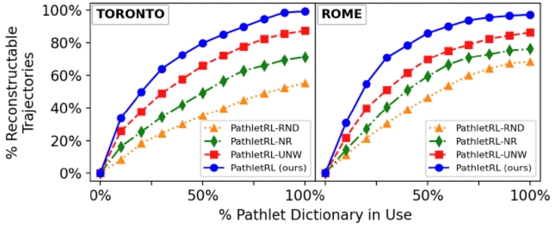
Approach & Contributions



Edge-disjoint pathlets



Deep Reinforcement Learning (DQN)



Partial trajectory reconstruction ~85%

Trajectory Similarity

The Top-k Trajectory Similarity Search Problem

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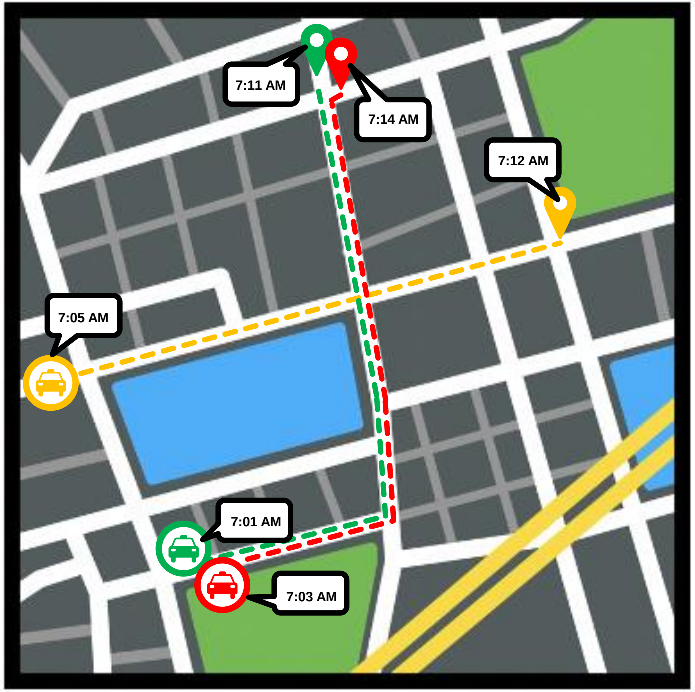
Trajectory Similarity

- How similar two trajectories are
- Several ways to define



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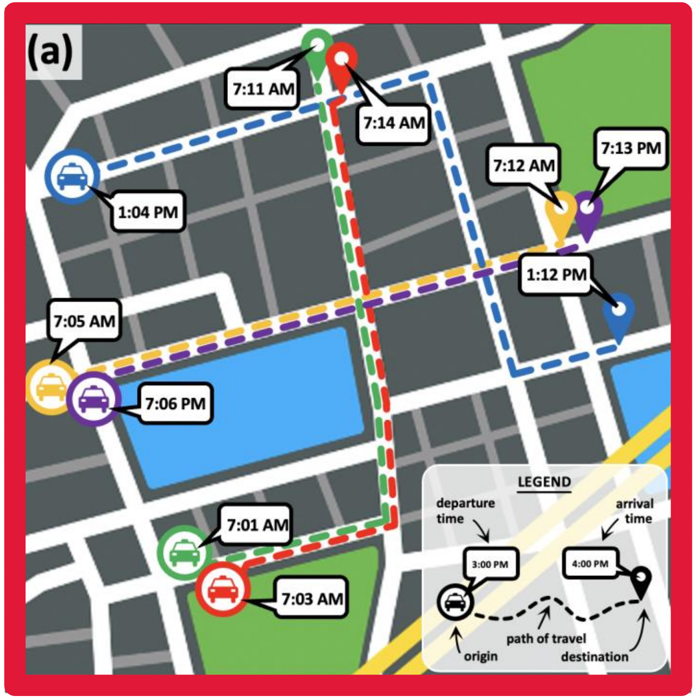
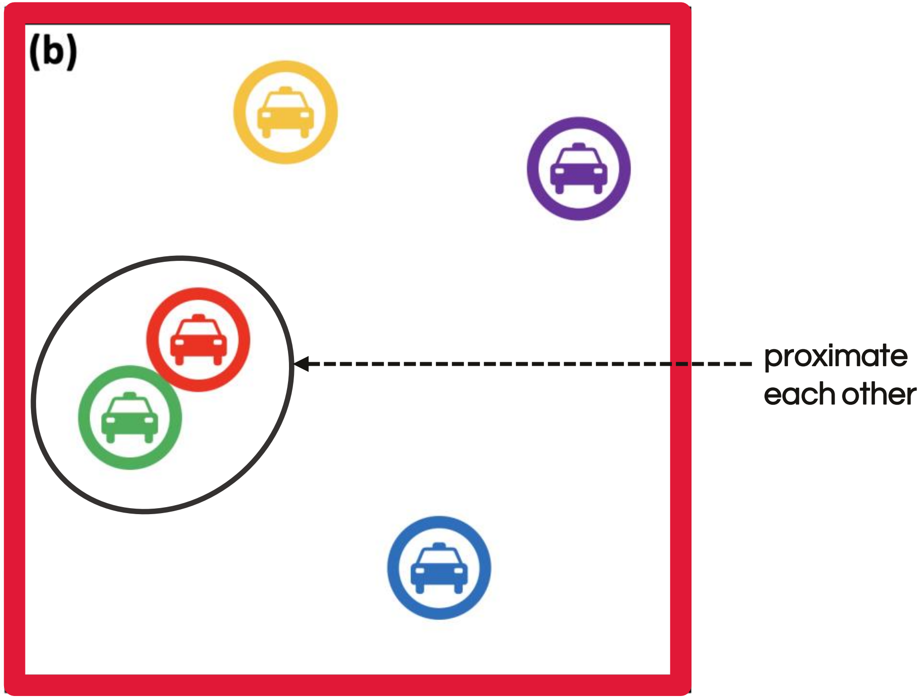
Spatiotemporal Similarity – Example



Taxi Trajectories



Embedding Space

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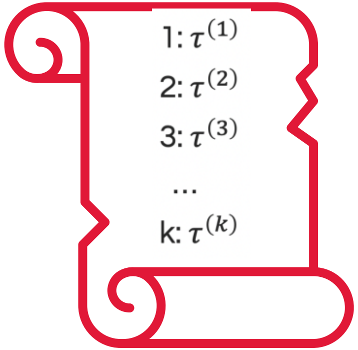
Problem Statement

- Top-k Trajectory Similarity Search Task
  - **Given**: Trajectory set $\mathcal{T}$

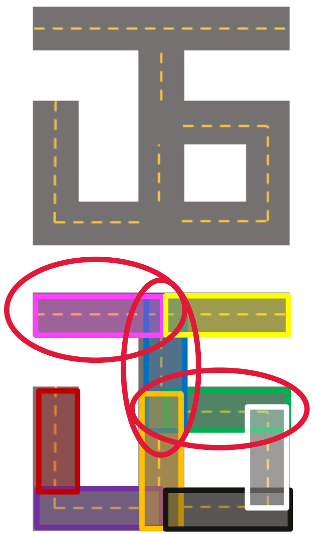
    Query trajectory τ_q

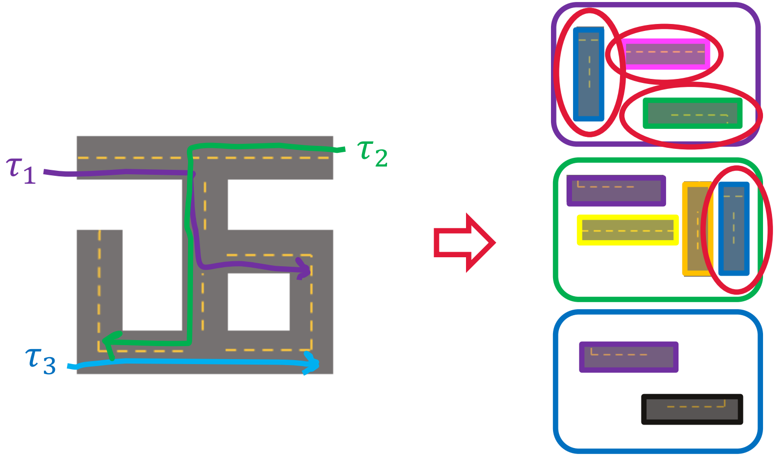
    Positive integer $k \geq 1$
  - **Find** the (ranked) list of top k trajectories in $\mathcal{T}$:
  - **Criterion**: Similarity with τ_q



Approach: Reducing Trajectory Similarity to Set Similarity Problem

- Treat each trajectory as a set; its elements are the road segments it has traversed (road-based representation $\Re(\tau)$)
- Similar (Dissimilar) trajectories map to similar (dissimilar) sets





Trajectories τ_1 and τ_2 are similar!

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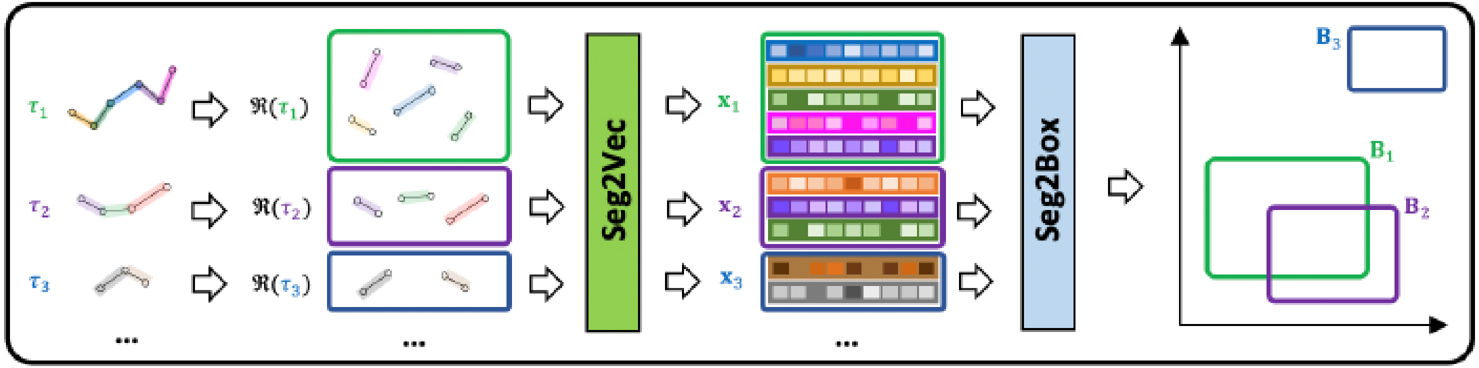
ST2Box Overview

- Spatiotemporal Trajectories to Box Embeddings for Similarity Learning



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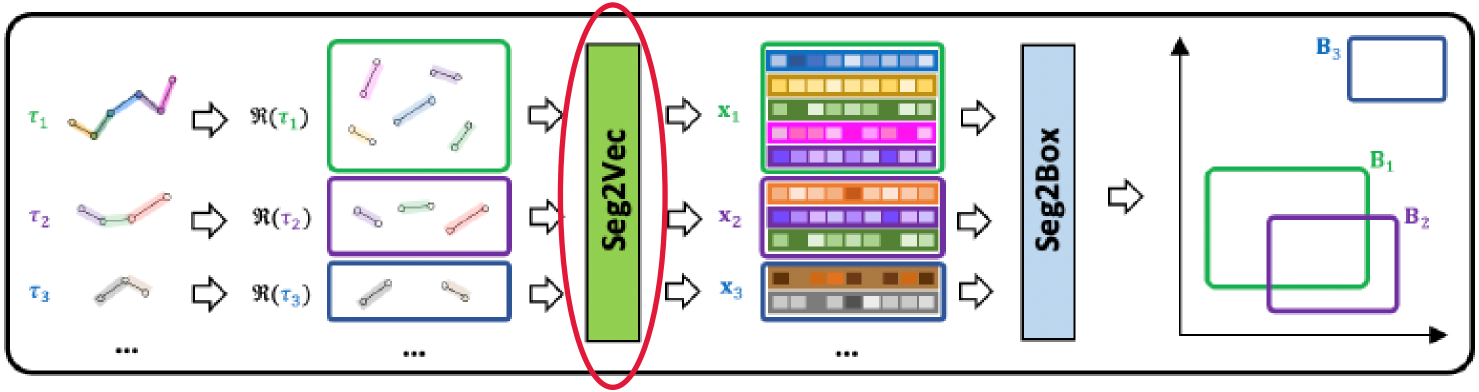
ST2Box Overview

- Spatiotemporal Trajectories to Box Embeddings for Similarity Learning



- Seg2Vec – spatiotemporal vector representations of road segments

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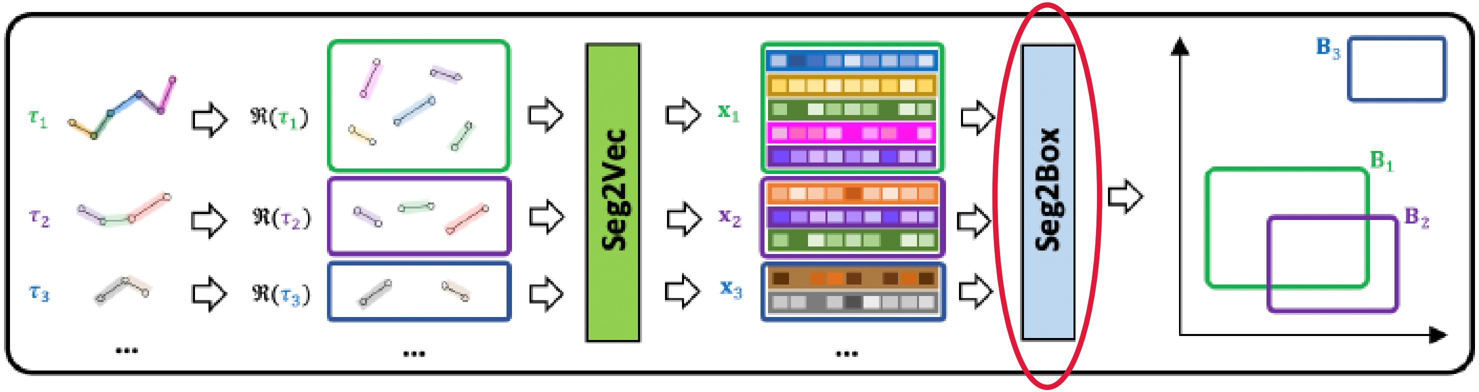
ST2Box Overview

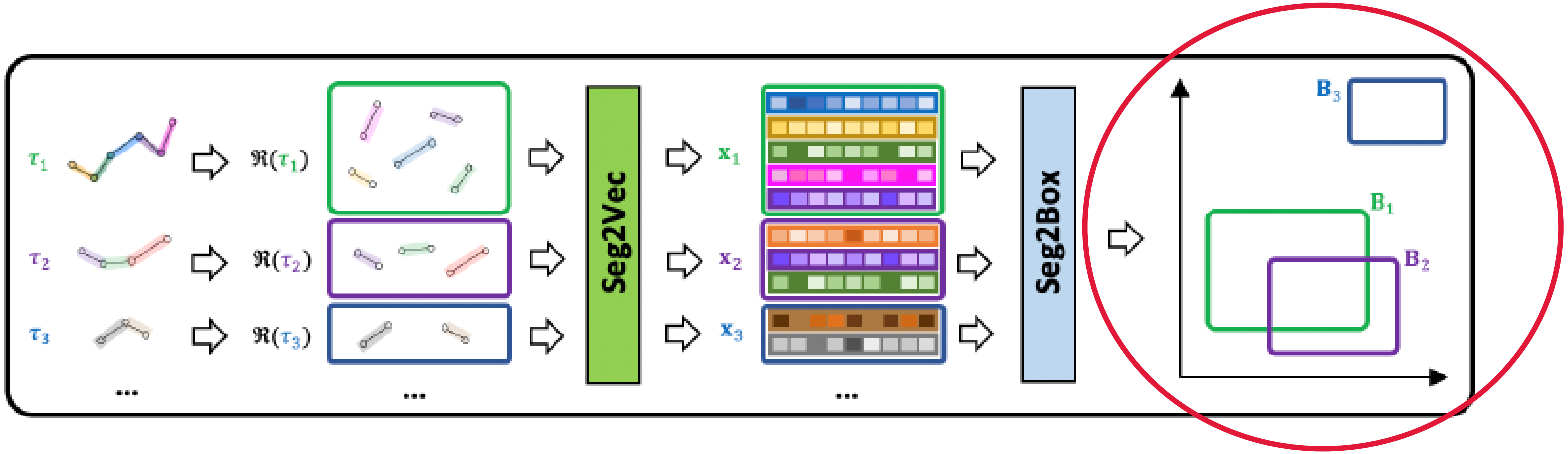
- Spatiotemporal Trajectories to Box Embeddings for Similarity Learning



- Seg2Box – box representations of sets of road segments

ST2Box Overview

- Spatiotemporal Trajectories to Box Embeddings for Similarity Learning



- Overlapping boxes ⇨ Similar sets ⇨ Similar trajectories

ST2Box Properties

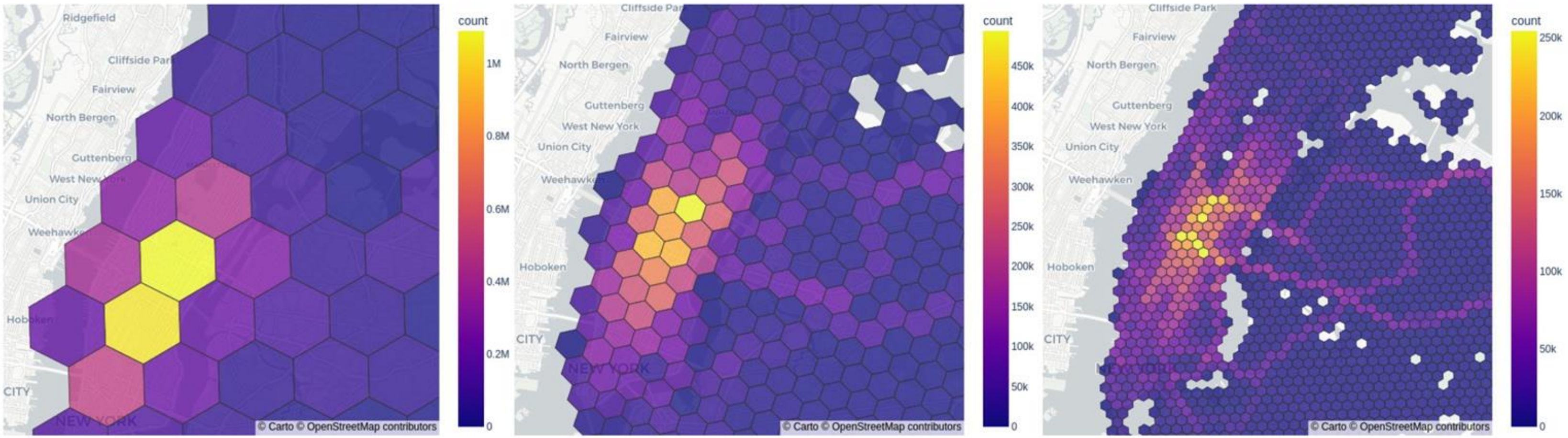
Accurate, Versatile, Generalizable, Robust, Fast, Scalable

Up to ~30% Performance Gain

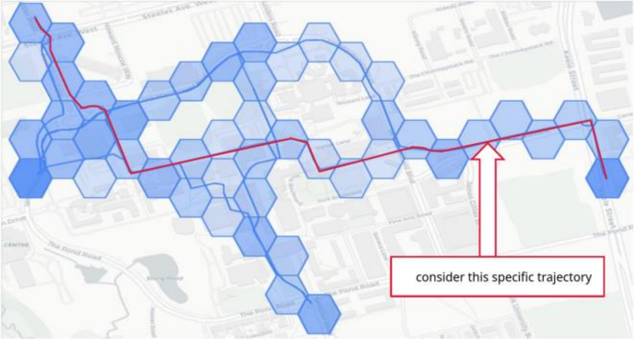
Higher-order Mobility Flow Data

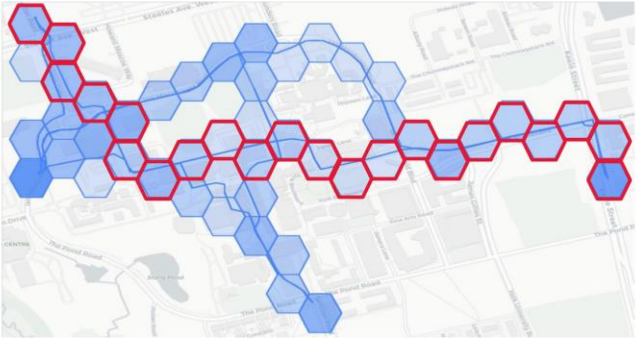
Map Tessellation

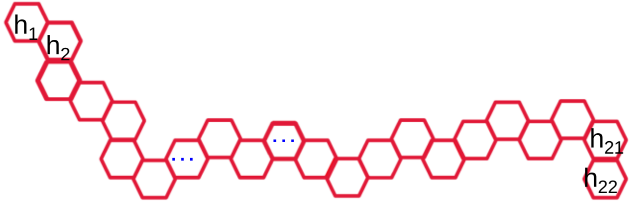
lower resolution → higher resolution



Trajectories: Sequences of Hexagons



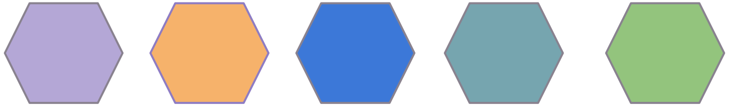




Trajectory: $h_1, h_2, h_3 \ldots h_{20}, h_{21}, h_{22}$

Treat Trajectories as Language Statements

Hexagons represent ‘tokens’ & trajectories represent ‘sentences’

Trajectory: 

Sentence: I like to learn English

Advantages:

- Reduced data sparsity
- More compatible with well-known ML models (e.g., sequence models, LLMs)

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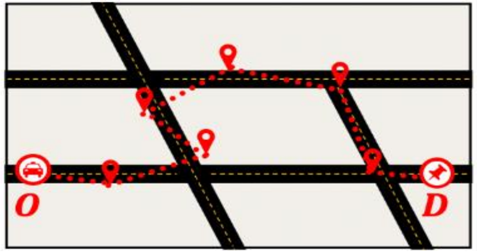
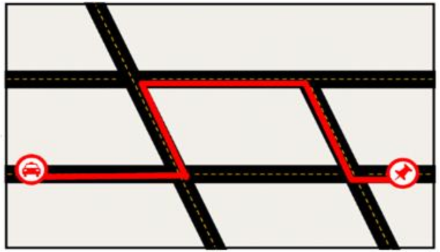
Point2Hex: Overview of the Pipeline

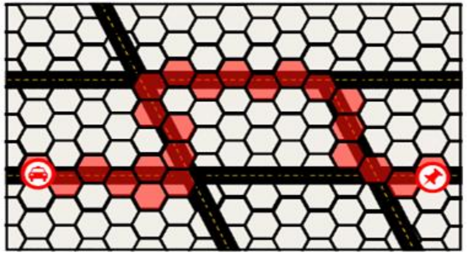


GPS Traces or POI Check-Ins
(**input**)

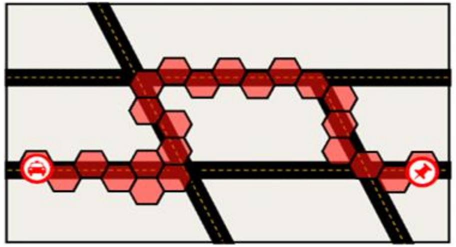


Linestring of Trajectories
(**Map-matching**)

Map Tessellation with Trajectories
(**Hexagon-shaped cells**)



Intersection of Linestrings and Polygons
(**Computational Geometry**)



Higher-order Mobility Flow
(**Output**)

Higher-order Mobility Flow: Datasets and Data Generator

Dataset	Trajectories	Time Period	Resolutions
HO-T-Drive	65,117	02/02/08 - 02/08/08	{6,...10}
HO-Porto	1,668,859	07/01/13 - 06/30/14	{6,...10}
HO-Rome	5,873	02/01/14 - 03/02/14	{6,...10}
HO-GeoLife	2,100	04/01/07 - 10/31/11	{6,...10}
HO-FourSquare-NYC	49,983	04/12/12 - 02/16/13	{6,...10}
HO-FourSquare-TKY	117,593	04/12/12 - 02/16/13	{6,...10}
HO-NYC-Taxi	2,062,554	01/01/16 - 06/30/16	{6,...10}

Datasets @ Zenodo

Data Generator @ GitHub

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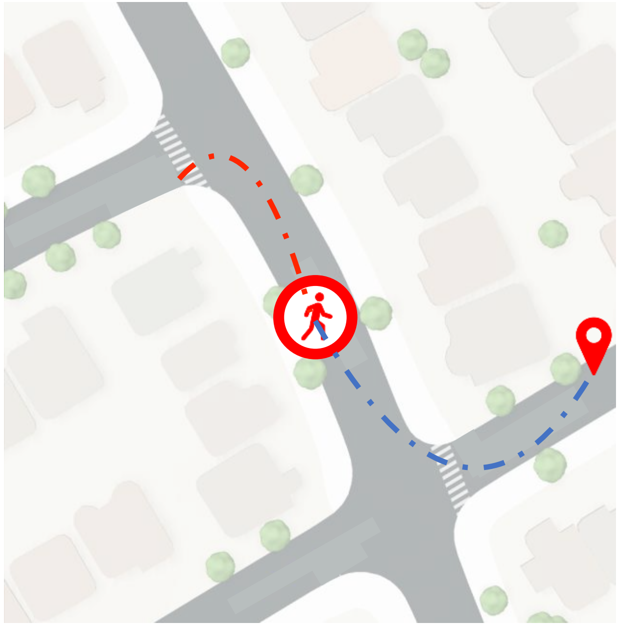
Trajectory Prediction

Predict the Next-k Trajectory Steps Problem

Problem of Interest: Trajectory Prediction

History trajectory



Predict future trajectory

Trajectory Prediction (Revisited)

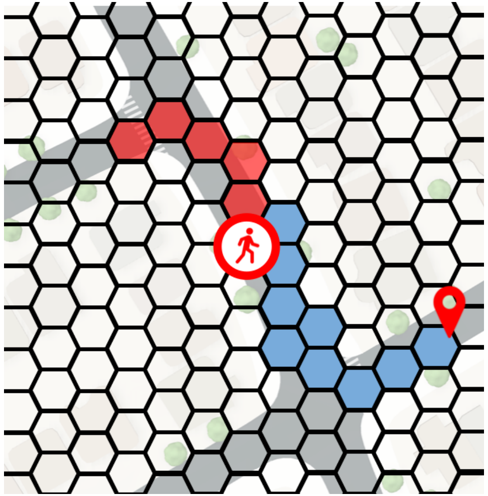
Let

- an observation area
- a set of objects and their history trajectories
- an observation period

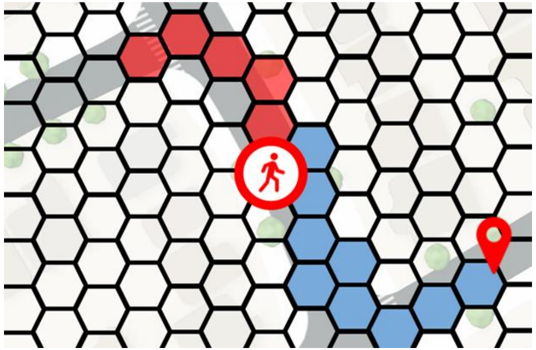
Input: Given

- a moving object n
- a partial trajectory = <p1, p2,...,pt>
- a prediction horizon k > 0

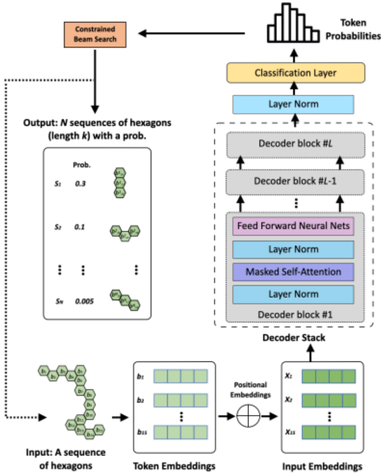
Output: We want to
predict the **next k hexagons** of the input partial trajectory



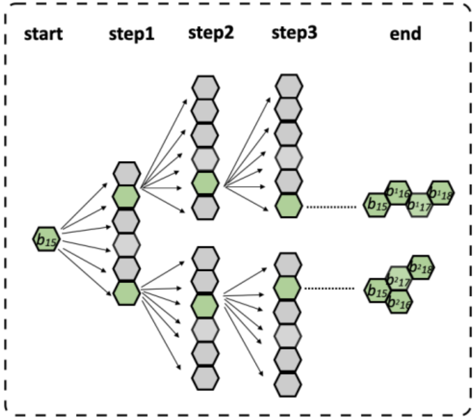
Approach & Contributions



Trajectory Prediction
(Revisited)



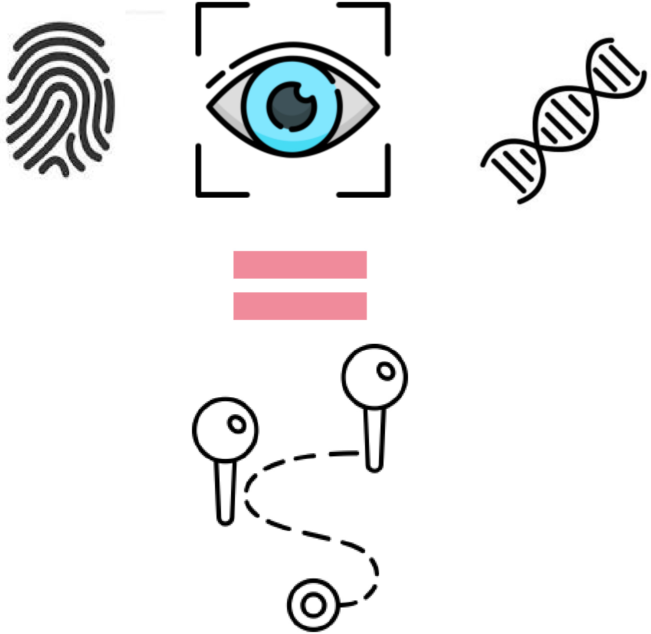
TrajLearn: Trajectory
Deep Generative Model



Beam search

Trajectory Classification

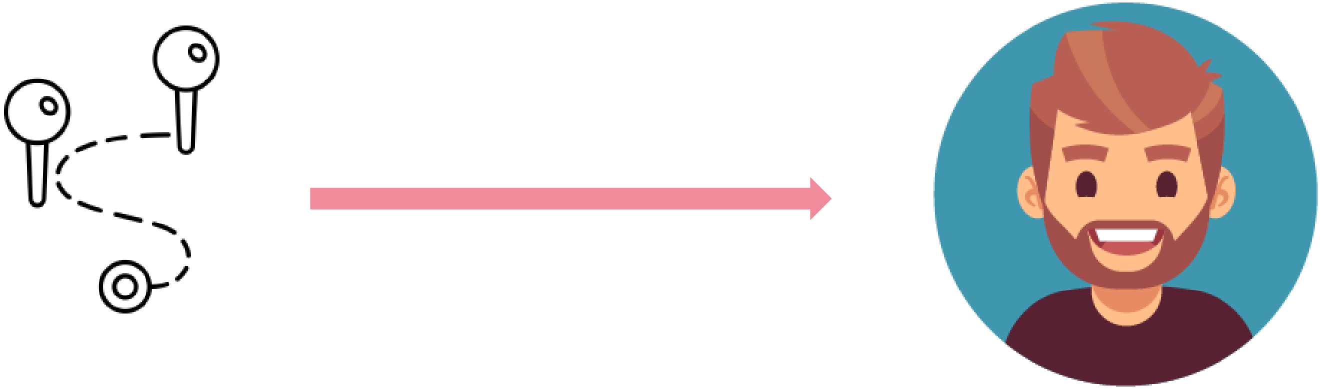
The Trajectory-User Linking Problem



can trajectories

help to identify a person?

Trajectory-user Linking (TUL)



trajectory-user linking **aims at linking** anonymous trajectories to users who generate them

Problem Definition

Trajectory-user linking aims at linking anonymous trajectories to users

Given:

$\mathcal{U} = \{u_1, u_2, u_3, .., u_c\}$ – users
$\mathcal{T} = \{Tr_1, Tr_2, \ldots, Tr_n\}$ – unlinked trajectories

TUL is defined as **a multiclass classification problem**

$$\min_{f \in \mathcal{F}} \mathbb{E}[\mathcal{L}(f(Tr_i), ui)] \ over\ \mathcal{F}$$

where $\mathcal{F}$ *is the set of all classifiers in the hypothesis space*
$\mathcal{L}(\cdot)$ *is the loss between the predicted label* $f(Tr_i) \in \mathcal{U}$ *and the true label* $u_i \in \mathcal{U}$

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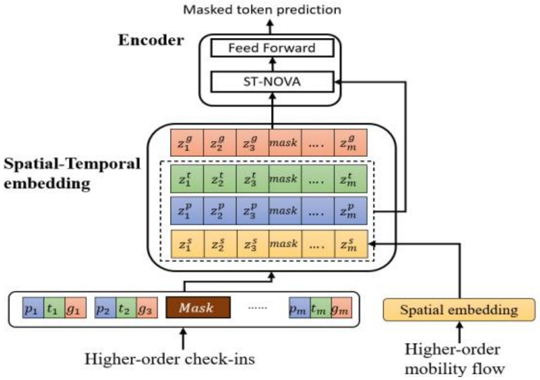
Approach & Contributions

Higher-order mobility flow data generation



TULHOR: A spatiotemporal model that deals with sparsity and low data quality of the TUL problem

TULHOR outperforms baselines by up to 8%

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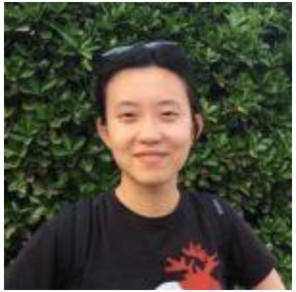
Questions

Credits

Gian Alix

Mahmoud Alsaeed

Ali Faraji



Jing Li

Nina Yanin

Amirhossein Nadiri

PathletRL: Trajectory Pathlet Dictionary Construction using Reinforcement Learning. G. Alix, M. Papagelis. **ACM SIGSPATIAL 2023**.

Trajectory-User Linking using Higher-order Mobility Flow Representations. M. Alsaeed, A. Agrawal, M. Papagelis. **IEEE MDM 2023.**

Point2Hex: Higher-order Mobility Flow Data and Resources. A. Faraji, J. Ling, G. Alix, M. Alsaeed, N. Yanin, A. Nadiri, M. Papagelis. **ACM SIGSPATIAL 2023**.

St2Box: Trajectory Similarity Learning using Set to Box Representations. G. Alix, M. Papagelis. **Submitted**.

TrajLearn: Leveraging Generative Models for Trajectory Prediction Learning. A. Nadiri, A. Faraji, J. Ling, M. Papagelis. **Submitted**.

Thank you!