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Spatial Data Quality in the IoT Era

Management and Exploitation

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4.

EXPLOITATION OF LOW-QUALITY SID

By Bo Tang

Outline

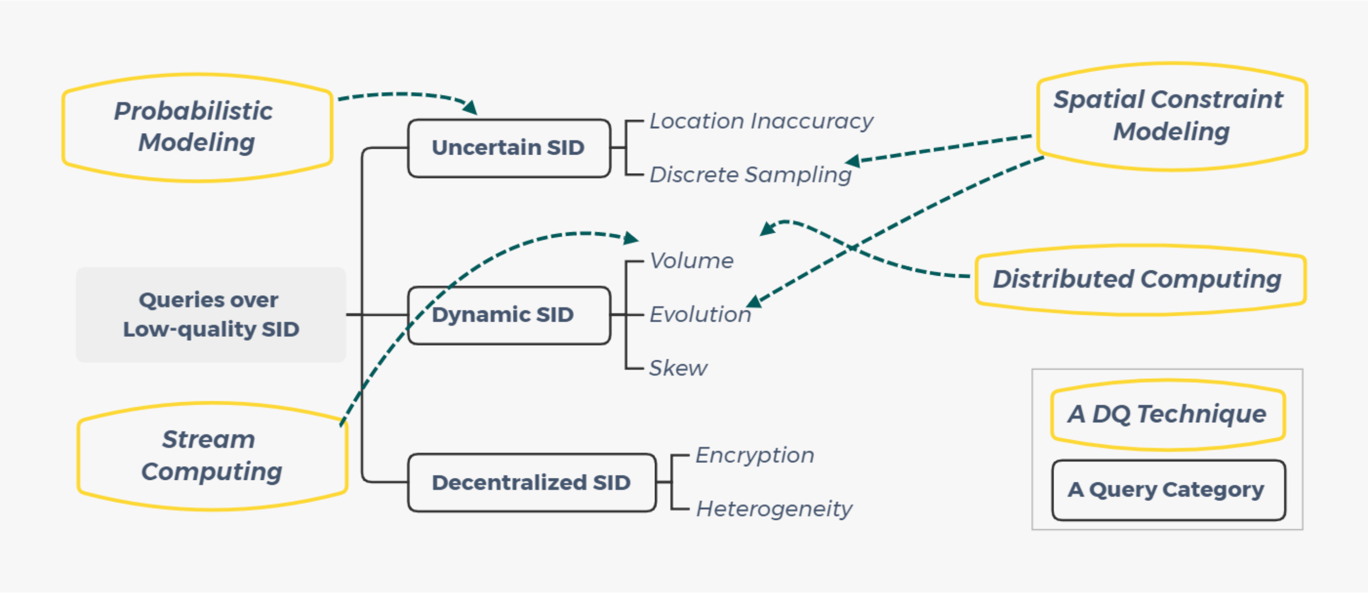
1. Queries
2. Analyses
3. Decision-making tasks

} low-quality SID

Category based on problem settings

Representatives

1. Queries over Low-Quality SID



- **Uncertainty, Dynamics, and Decentralization**

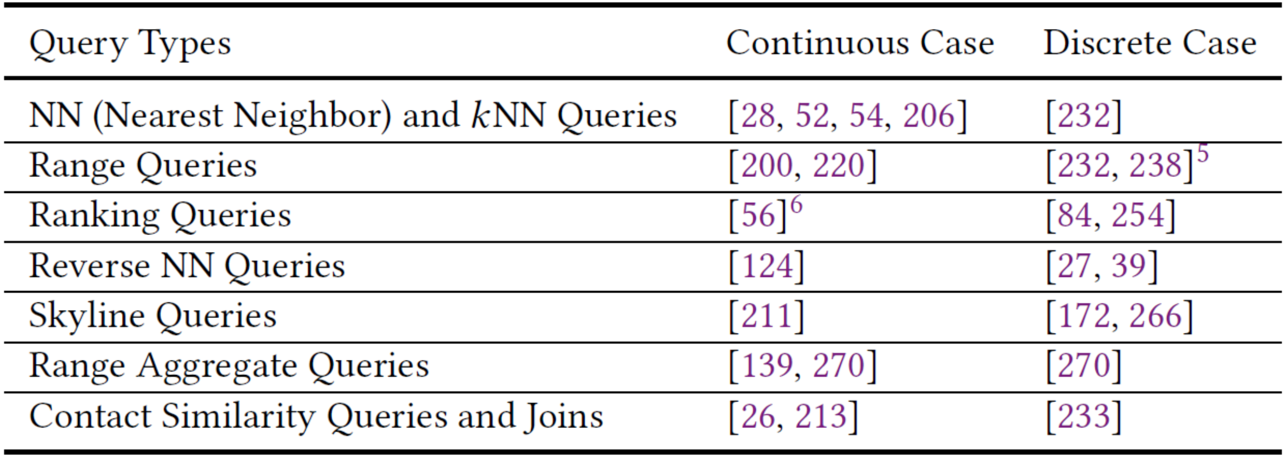
Queries over Uncertain SID

- Location Uncertainty: the major issue in *spatial queries* - Probability models [Cheng et al., 2014] [Züfle et al., 2020]
  - priority-oriented processing, object/data pruning

- Uncertainty caused by
  - **Inaccuracy of location algorithms**
  - **Discrete sampling of devices**

Queries over Uncertain SID

- ▷ Uncertainty caused by **location inaccuracy**
  - ○ a location at a time point -> probability density function
  - ○ *continuous* case: closed-form distribution
  - ○ *discrete* case: a set of samples with occurrence probabilities



Query Types	Continuous Case	Discrete Case
NN (Nearest Neighbor) and *k*NN Queries	[28, 52, 54, 206]	[232]
Range Queries	[200, 220]	[232, 238][5]
Ranking Queries	[56][6]	[84, 254]
Reverse NN Queries	[124]	[27, 39]
Skyline Queries	[211]	[172, 266]
Range Aggregate Queries	[139, 270]	[270]
Contact Similarity Queries and Joins	[26, 213]	[233]

Queries over Uncertain SID (cont.)

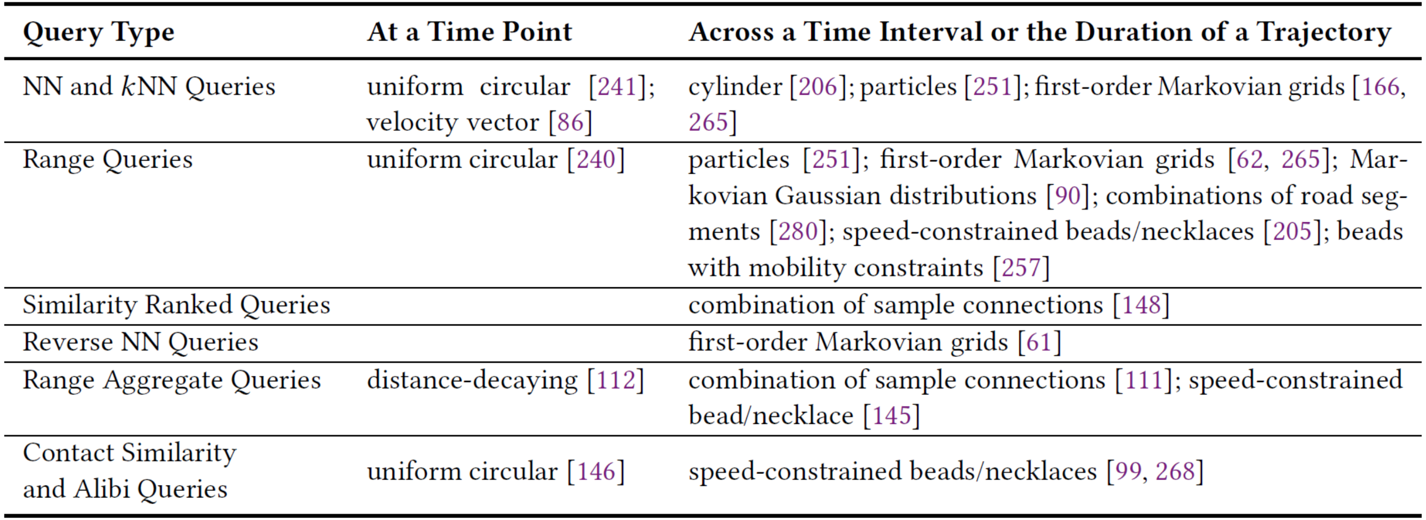
▷ Uncertainty caused by **discrete sampling**

- a location at unsampled time points -> distribution referenced to sampled, known location(s) [Pfoser et al., 1999]

infer location *at* *a single time point*? →	infer locations *across a time interval*?
• (Uniform/Gaussian/Self-defined function) circular [Yang et al., 2009] [Li et al., 2018] • Velocity vector [Huang et al., 2009]	• Particles (MCMC) [Yu et al., 2013] • First-order Markovian grids [Zhang et al., 2009] • Markovian Gaussian distribution [Jeung et al., 2013] • Combination of road segments [Zheng et al., 2011] • Beads/Necklaces [Trajcevski et al., 2010] [Kuijpers et al., 2011]

Queries over Uncertain SID (cont.)

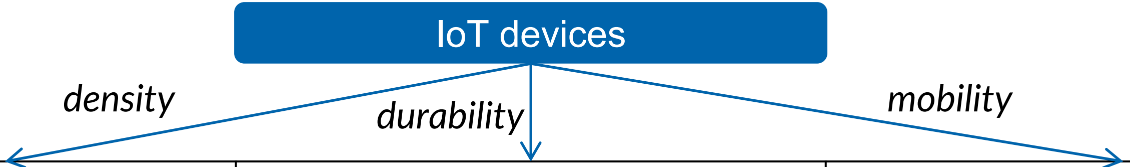
- Selected queries over uncertainty caused by **discrete sampling**



Query Type	At a Time Point	Across a Time Interval or the Duration of a Trajectory
NN and *k*NN Queries	uniform circular [241]; velocity vector [86]	cylinder [206]; particles [251]; first-order Markovian grids [166, 265]
Range Queries	uniform circular [240]	particles [251]; first-order Markovian grids [62, 265]; Markovian Gaussian distributions [90]; combinations of road segments [280]; speed-constrained beads/necklaces [205]; beads with mobility constraints [257]
Similarity Ranked Queries		combination of sample connections [148]
Reverse NN Queries		first-order Markovian grids [61]
Range Aggregate Queries	distance-decaying [112]	combination of sample connections [111]; speed-constrained bead/necklace [145]
Contact Similarity and Alibi Queries	uniform circular [146]	speed-constrained beads/necklaces [99, 268]

- **Opportunities**: resource-limited and stream setting queries?

Queries over Dynamic SID



Querying ***massive*** SID	Querying ***evolving*** SID	Querying ***skewed*** SID
• **Distributed + stream computing**: in-memory distributed similarity trajectory search [Wei et al., 2017] [Yuan et al., 2019]; Apache storm for spatio-textual queries [Mahmood et al., 2015]	• Construct a **safe region**, inside which object dynamics leave query result unchanged [Qi et al., 2018] • **Incremental evaluation** to reduce communication/computation cost at each timestamp: continuous shortest path finding [Yang et al., 2014], continuous trajectory similarity search [Zhang et al., 2020]	• **Node load-balancing**: performance heterogeneity issue [Ray et al., 2013] • **Data indexing and partitioning**: KR+-tree for skewed, multi-dimensional spatial data [Wei et al., 2014], data skew-aware partitioning with analytical strategy [Vo et al., 2014]
Opportunities: (1) high-speed yet low-cost computation? (2) decentralized edge computing nodes?		

Huan Li, Lanjing Yi, Bo Tang, Hua Lu, Christian Jensen. ***Efficient and Error-bounded Spatiotemporal Quantile Monitoring in Edge Computing Environments.*** *PVLDB 2022.*

Queries over Decentralized SID

- ▷ **Data Encryption**: encrypted outsourced data
  - ○ balance between efficiency and privacy [Yiu et al., 2010]
  - ○ dynamic data setting [Kamel et al., 2017]
  - ○ uncertain data setting [Guo et al., 2019]

- ▷ **Data Heterogeneity**: format, logics, reliability
  - ○ unified presentation for locations [Xu et al., 2013] or trajectories [Sun et al., 2017]
  - ○ unified storage and computing engine [Ding et al., 2018]

2. Analyses on Low-Quality SID

- **Uncertainty**
  - Data inaccuracy and incompleteness
- **Dynamics**
  - Volume
  - Evolution

- Clustering, Anomaly Detection, Frequent/Popular Patterns, etc.

Analyses of Uncertain SID

Task	Issue	**probabilistic modeling**	**spatiotemporal dependencies**	**constraints**
Clustering	location inaccuracy [Pelekis et al., 2011]	fuzzy vector representation		
Anomaly Events	incomplete location trace [Liu et al., 2012]	stochastic model with transition probabilities	movement as state transition	
Frequent Sequential Patterns	location inaccuracy [Li et al., 2013]	possible world	sequential explosion	
Periodic Behaviors	incomplete sequences [Li et al., 2014]	periodic behavior modeled as a probability matrix	discover reference spots	
Stop-by Patterns	noisy RFID sequences [Teng et al., 2017]	possible world	event clustering + sequential explosion	deployment and spatial constraints
Popular Routes	incomplete trajectories [Wei et al., 2012]		mutual reinforcement of collective trajectories	

▷ **Opportunities**: techniques for real-time and decentralized settings?

Analyses over Dynamic SID

- ▷ **Data Massiveness**
  - ○ **Indexing and pruning** for trajectory clustering [Wang et al., 2019], anomaly trajectory [Bu et al., 2009], co-evolving pattern mining [Zhang et al., 2015]
  - ○ **Distributed computing** for RFID trajectory clustering [Wu et al., 2014] and subsequence pattern mining [Sun et al., 2014]
- ▷ **Data Evolution**
  - ○ **Online learning** of spatiotemporal dependencies
  - ○ vehicle behavior clustering [Wang et al., 2020], anomalies in partial trajectories [Wu et al., 2017] [Liu et al., 2020]
- ▷ **Opportunities**: services to IoT edge, reduce cost/latency?

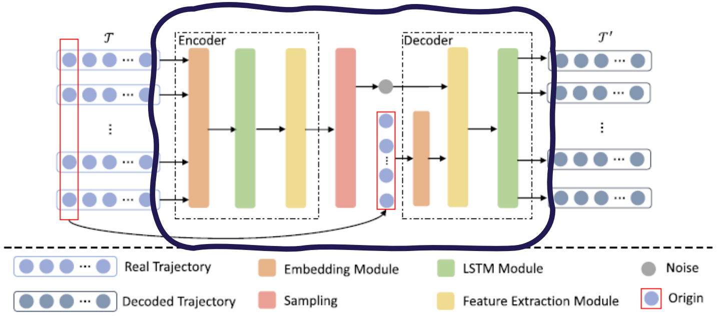
3. Decision-making using Low-Quality SID

- ▷ Predictions, Recommendations, Planning, etc.

- ▷ **Scarcity of labels**
- ▷ **Limited availability and bias of data**
- ▷ **Uncertainty of data**
- ▷ **Dynamics of data**
- ▷ **Heterogeneity and decentralization of data**

Scarcity of Labels

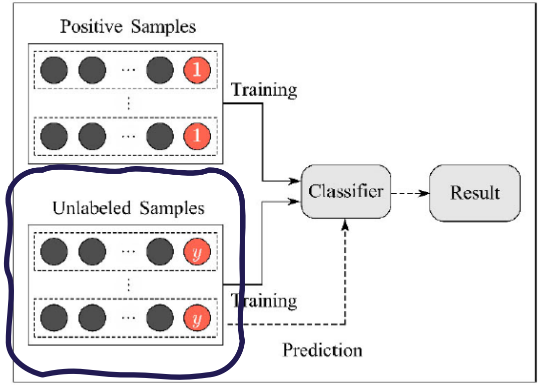
[Chen et al., 2021]



Variational AutoEncoders
for trajectory generation

No labels

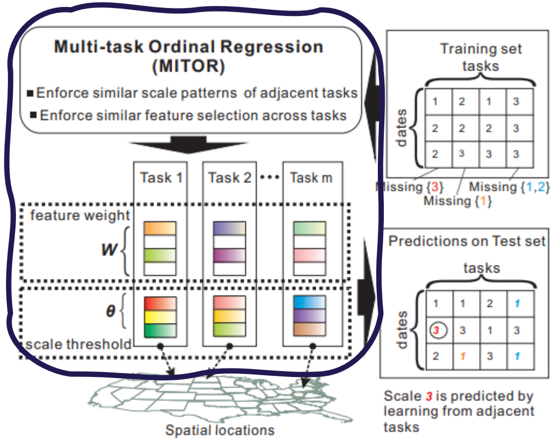
[Chen et al., 2020]



Positive-Unlabeled Learning
for site selection

Imbalanced labels

[Gao and Zhao, 2018]

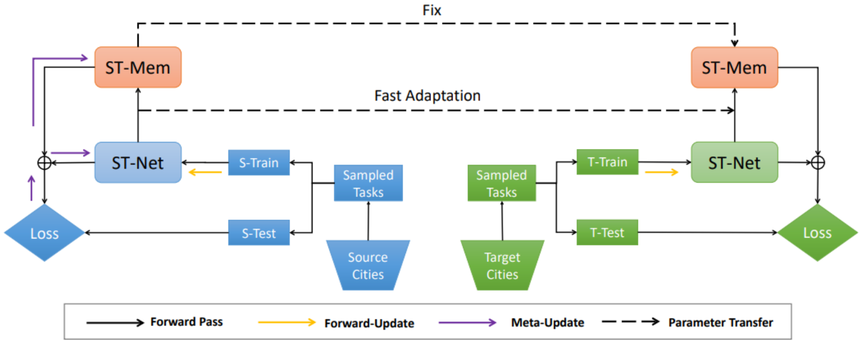

Multi-task Ordinal Regression (MITOR)
■ Enforce similar scale patterns of adjacent tasks
■ Enforce similar feature selection across tasks
Task 1
Task 2
Task m
feature weight
W
θ
scale threshold
Spatial locations
Training set tasks
dates
1 2 1 3
2 2 2 3
2 3 3 3
Missing {3}
Missing {1,2}
Missing {1}
Predictions on Test set tasks
dates
1 1 2 1
3 3 1 3
2 1 3 1
Scale 3 is predicted by learning from adjacent tasks

Multi-task Learning
for event scale prediction

Incomplete labels

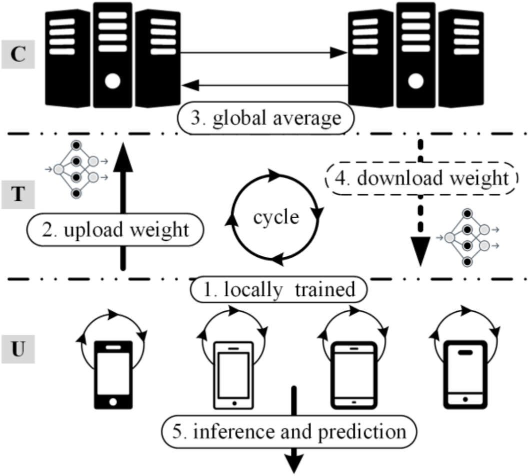
Limited Availability and Bias of Data

[Yao et al., 2019]



Meta Learning
for spatiotemporal prediction
(support multiple source cities)

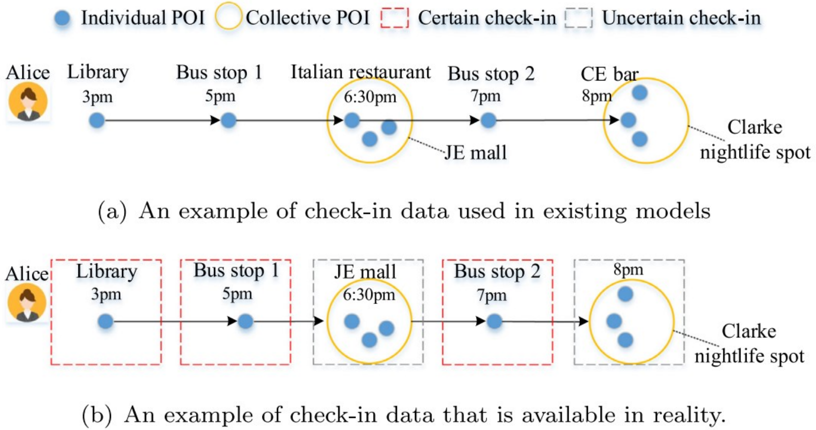
[Feng et al., 2020]



Federated Learning
for human mobility prediction
(privacy-preserving)

Uncertainty of Data

[Zhang et al., 2020-2]

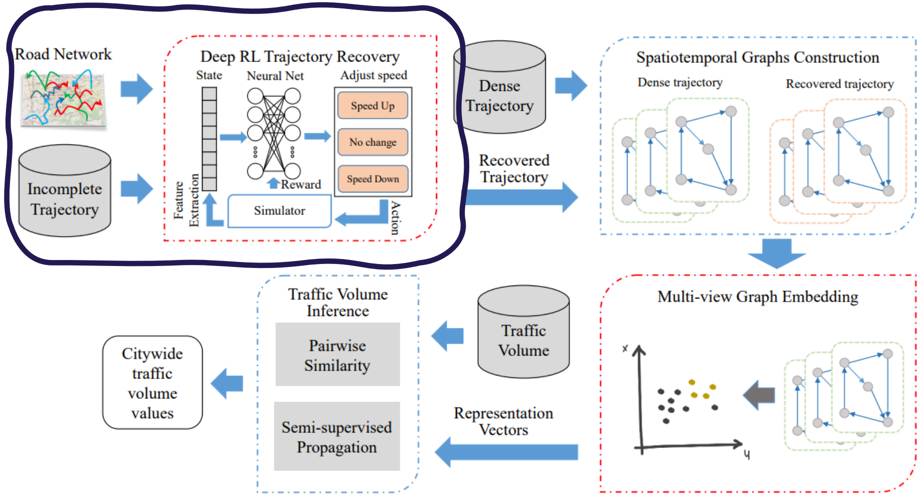


(a) An example of check-in data used in existing models

(b) An example of check-in data that is available in reality.

Probabilistic hierarchical category transitions for next PoI recommendation (coarser-grained and incomplete check-ins)

[Tang et al., 2019]



Reinforcement Learning based trajectory recovery for traffic volume prediction (incomplete radio network trajectories)

Dynamics of Data

- ▷ changing environment: accuracy
  - ○ **reinforcement learning** [Sun et al., 2021] for adaptive strategies in spatial task assignment

- ▷ streaming setting: latency
  - ○ **incremental learning** [Laha et al., 2018] updates model parameters in batches
  - ○ **edge-routing-central architecture** [Luo et al., 2019] to handle high-density IoT data

Heterogeneity and Decentralization of Data

- ▷ Fusing multi-source spatiotemporal data
  - ○ **multi-task learning** [Nguyen et al., 2019]: data aggregated at shared layers, labeled separated for different tasks
  - ○ **multi-view learning** [Zhang et al., 2015]: mutually-reinforced knowledge from multi-view data
- ▷ Building decentralized models
  - ○ **federated learning** [Liu et al., 2020-2]: secure parameter aggregation, global and local models

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