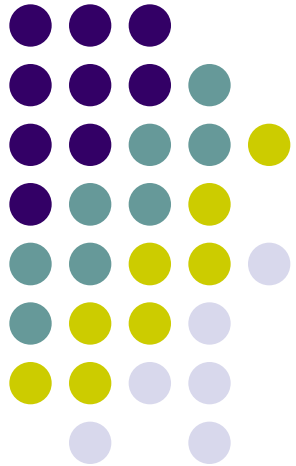
High-performance Management and Processing of Large-scale Moving Object Data



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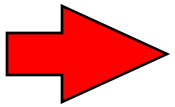
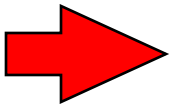
Location Based Queries





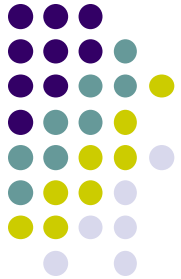
foursquare

Gowalla

Facebook Places
Who. What. When. And now where.

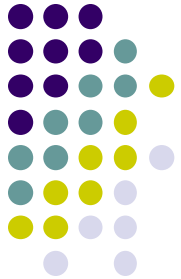
scvngr

Outline



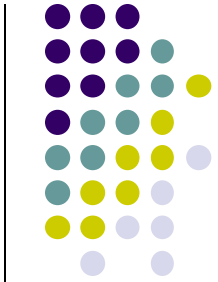
- A look back on components of location based queries: Spatial queries and Temporal queries
- Background for processing streaming location based queries
- Key techniques
  - Incremental computation and shared computation
  - Safe region
  - Time constraining
- A look forward

A Look Back



- Before 1995:
  - Spatial: static point queries, range/window queries
  - Temporal: version indexes, time interval indexes
- 1995 – 2000:
  - Spatial: nearest neighbor (NN) queries, selectivity estimation/cost models, high-dimensional data
  - Temporal: version indexes, time interval indexes
- 2000 – 2005:
  - Spatial: reverse nearest neighbor (RNN) queries, spatial joins, skyline queries
  - Temporal: time series, similarity queries
  - Spatio-temporal: point, range, and NN queries on moving objects
  - Data streams
- 2005 – 2008:
  - Spatial: trajectories, location selection,
  - Temporal: trajectories
  - **Continuously Moving Queries on static objects**
  - **Continuous Queries on moving objects**
- After 2008 (look forward)

Streaming Spatio-Temporal Queries



- Key Characteristics of Streaming
  - Query is continuous
  - Query answer may change anytime due to continuous change of the query itself or the data
  - Prompt answer is important: highly efficient algorithm
- Changes in Streaming Spatio-Temporal queries
  - Static query, data objects moving
  - Static data objects, query moving
  - Both query and data objects moving
- Key techniques
  - Incremental computation and shared computation
  - Safe region
  - Time constraining

Incremental and shared computation

- Continuous Retrieval of 3D Objects [ICDE'08, VLDB Journal'10]

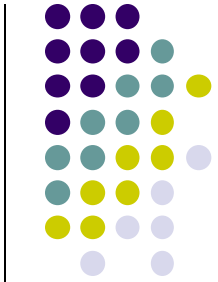
- Applications
  - Augmented reality

  - A rescue officer can see the structure of a building even if the building is on fire and filled with smoke

  - A smart phone to see the interior of restaurants

- Continuous window query on static 3D objects

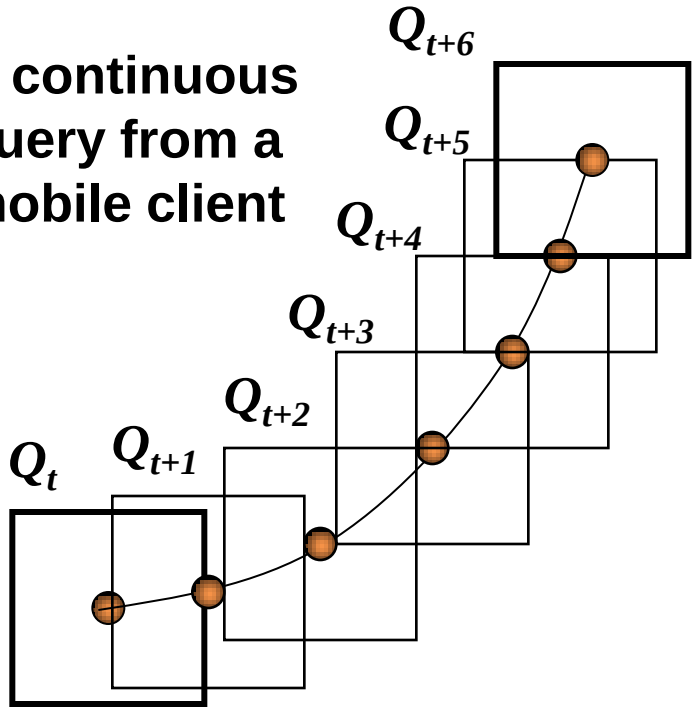
Problem



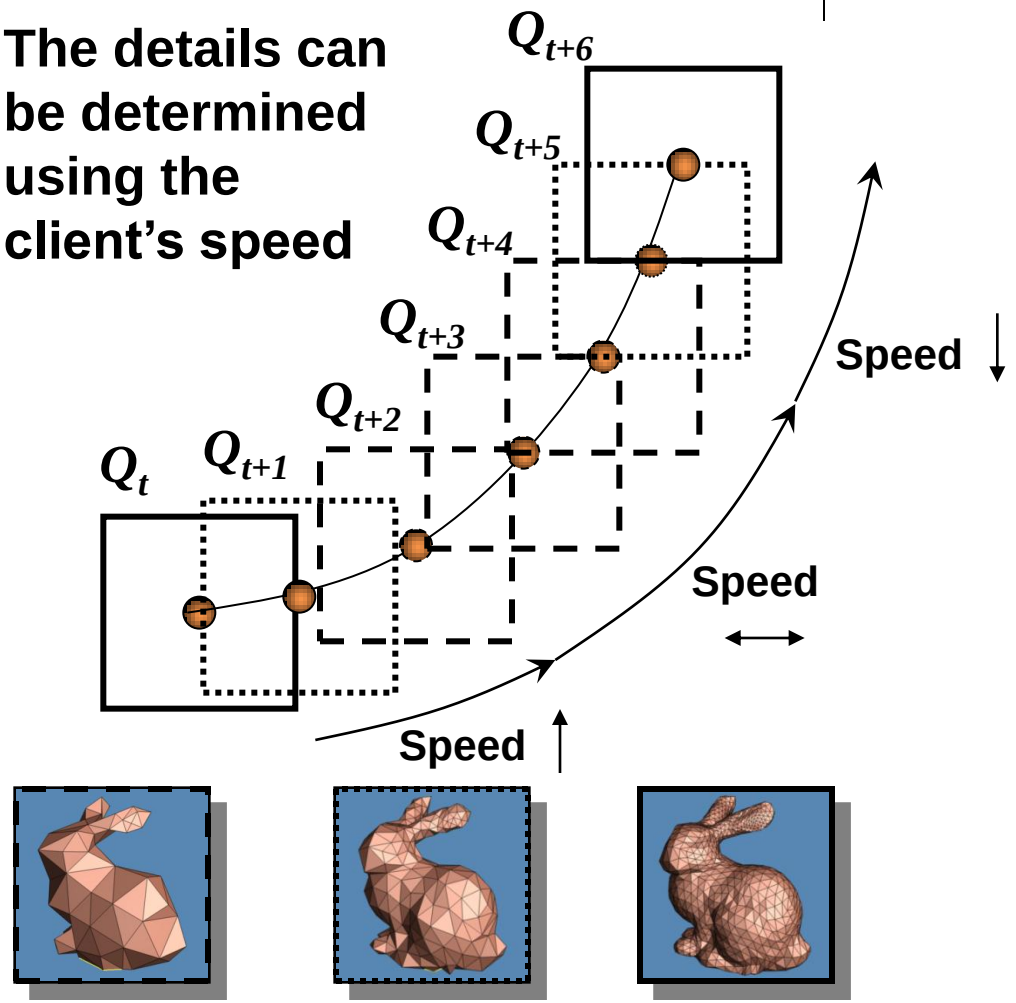
- Continuous retrieval of 3D objects in a window
- Model: client-server
- Bottle neck: bandwidth, especially when the view is moving fast
- To enable incremental/shared computation
  - Need to decompose the query answer into smaller components

Observation

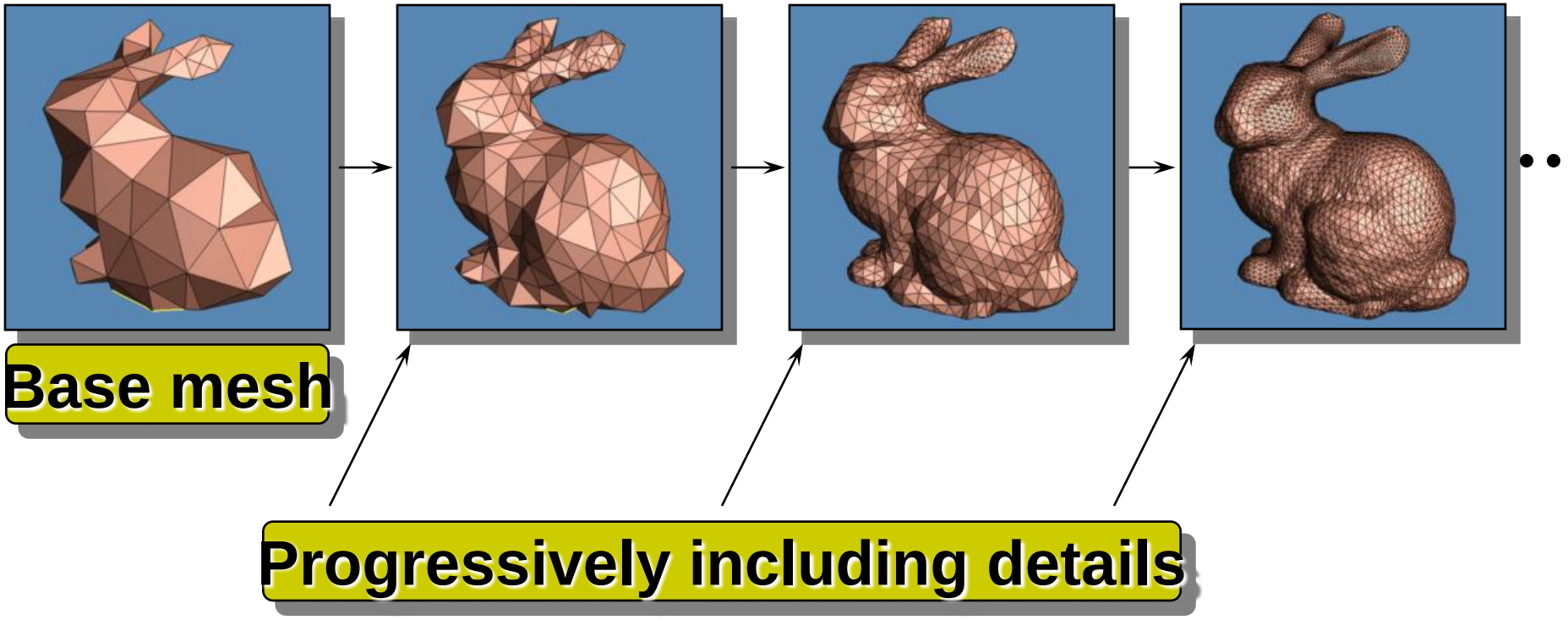
A continuous query from a mobile client



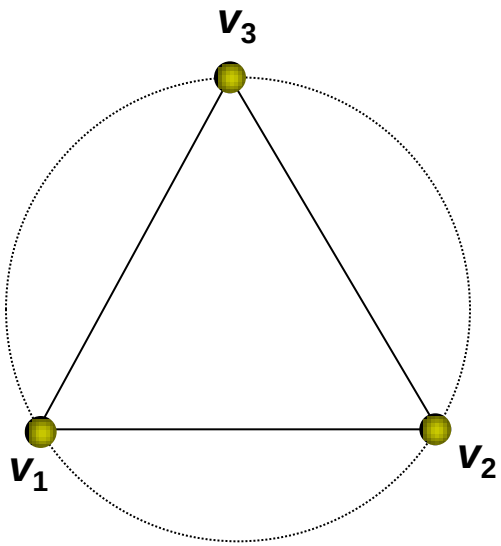
The details can be determined using the client's speed



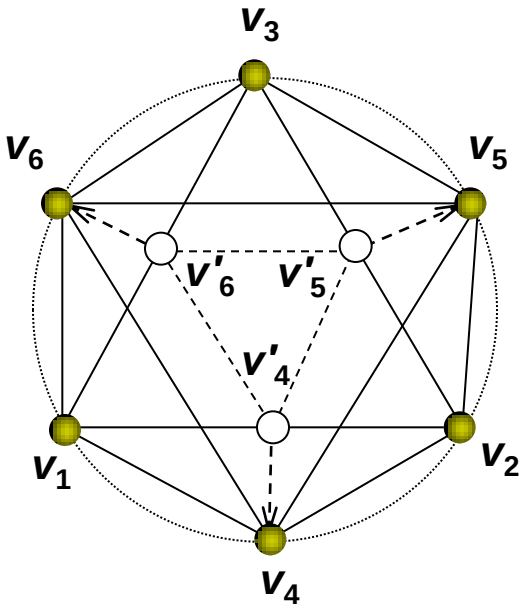
Multi-resolution Representations



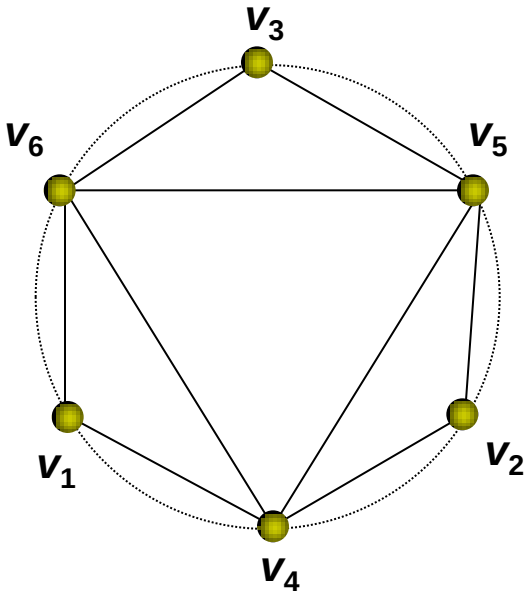
Example Wavelet Decomposition



Base Mesh (M^0)



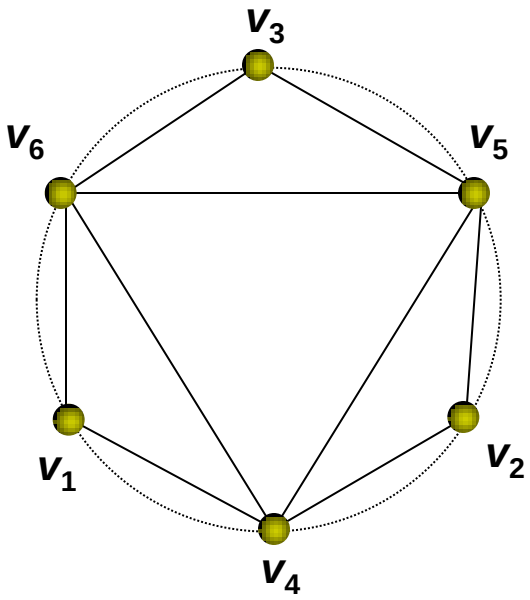
$M^0 \rightarrow M^1$



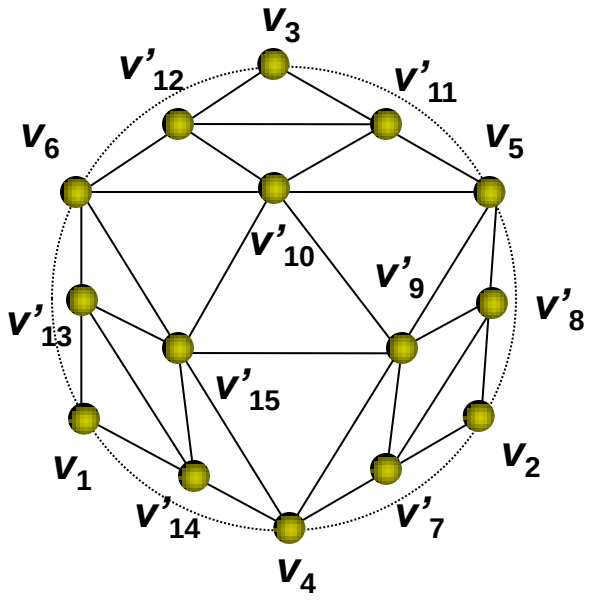
Mesh (M^1)

Wavelet coefficient, $d_4 = v_4 - (v_1+v_2)/2 = v_4 - v'_4$

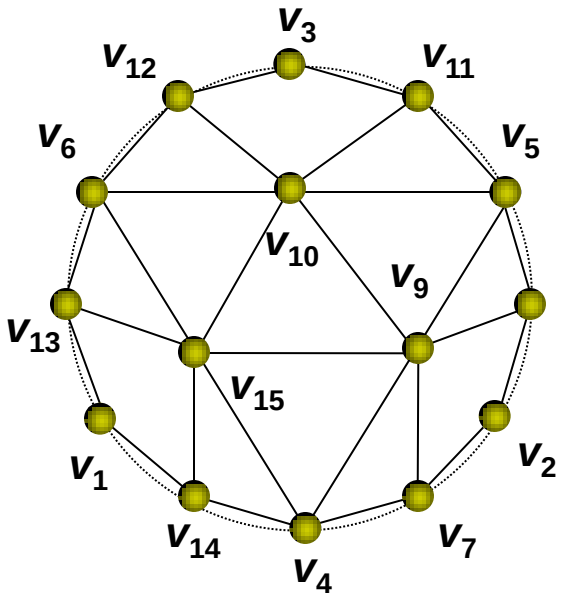
Example Wavelet Decomposition



Mesh (M^1)

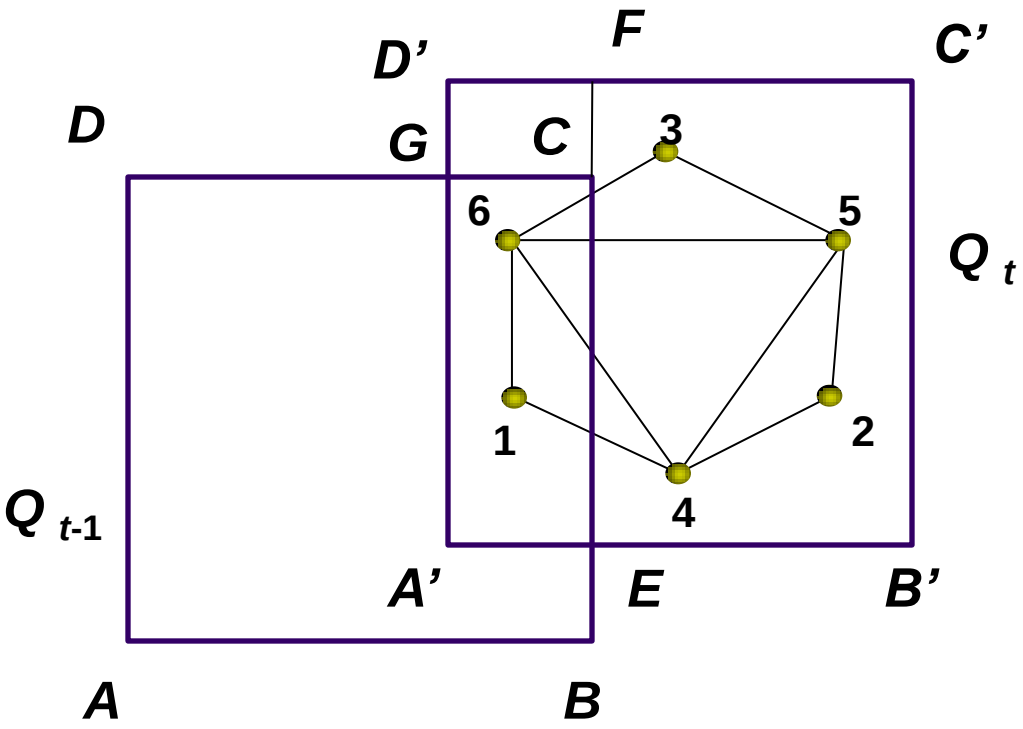


$M^1 \rightarrow M^2$

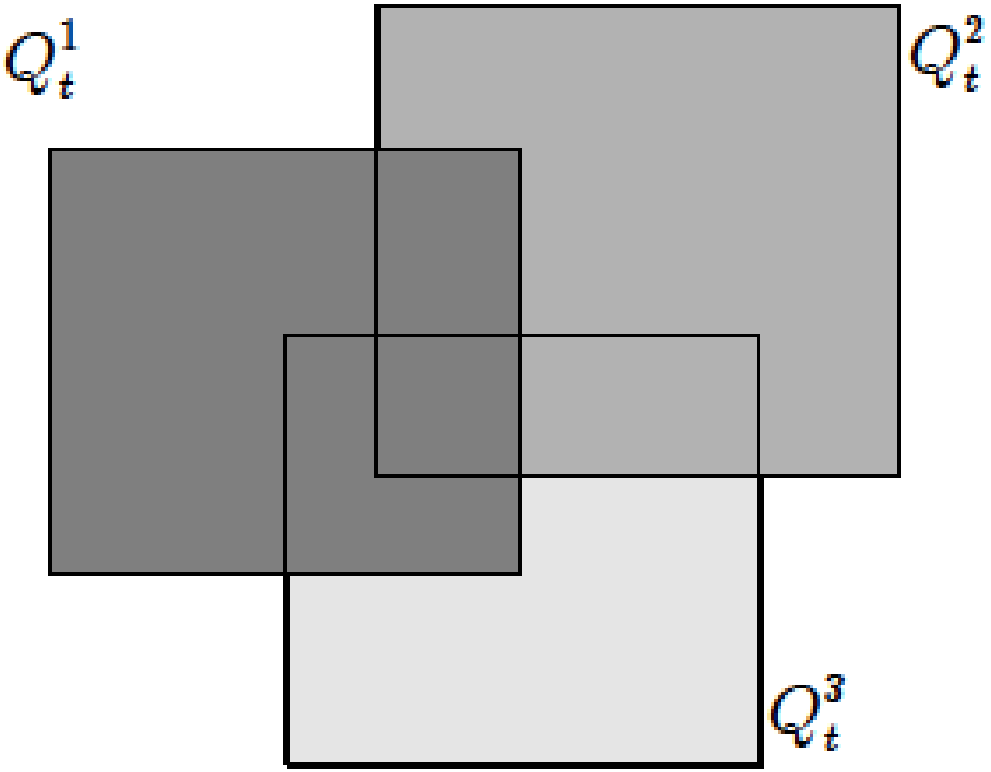


Mesh (M^2)

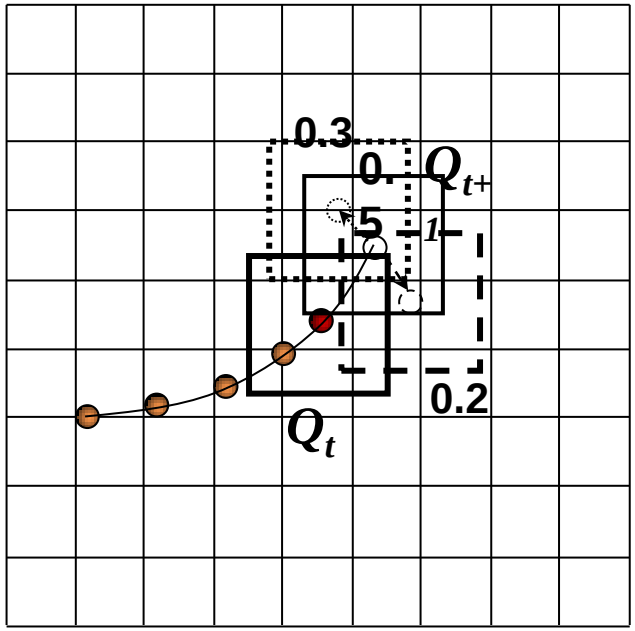
Incremental Retrieval

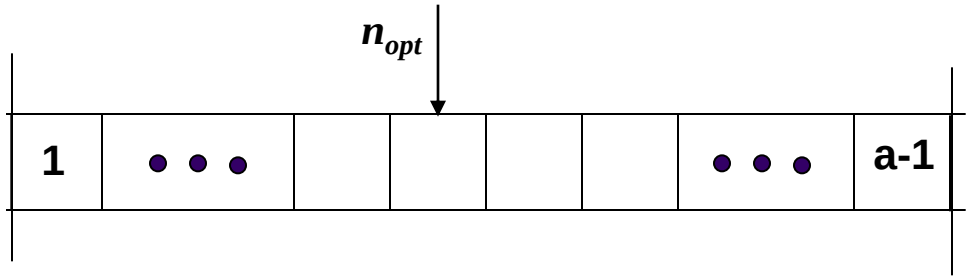


Group Queries



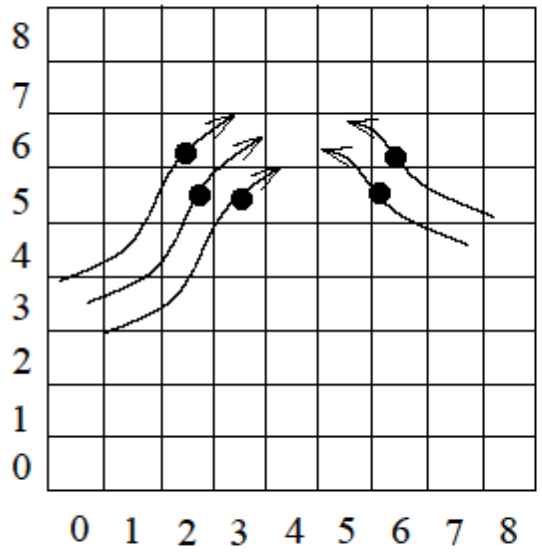
Motion-Aware Buffer Management



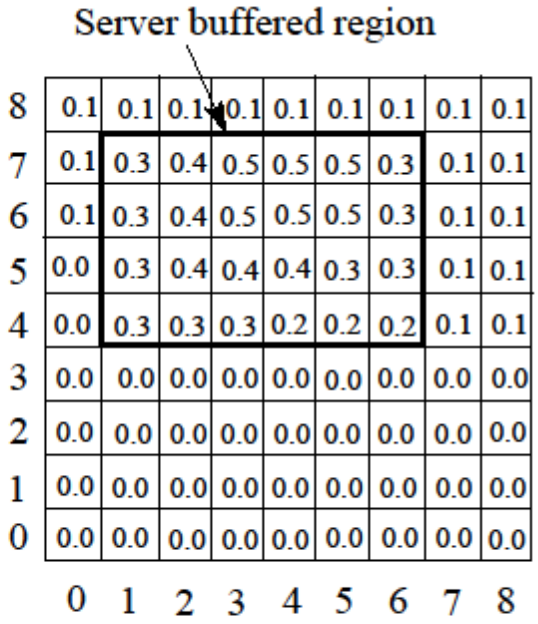


- Buffer: Given probabilities to move in one dimension to two directions
- Generalize one dimension to 2-dimensions

Buffer Management for Group Queries



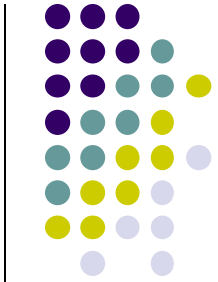
(a)



(b)

- (a) The paths for five different clients
- (b) combined weights of visiting probabilities of different data blocks

Safe Region

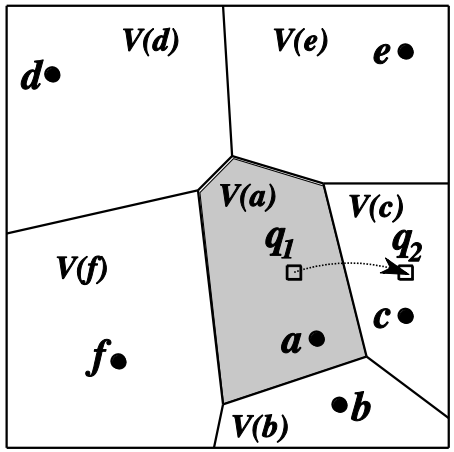


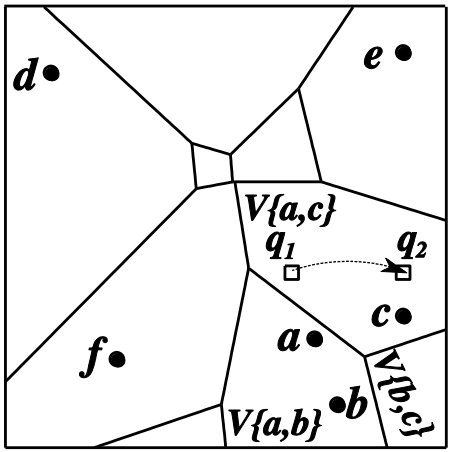
- Continuously returning k NNs for a moving query point [VLDB'08, VLDB Journal'10]

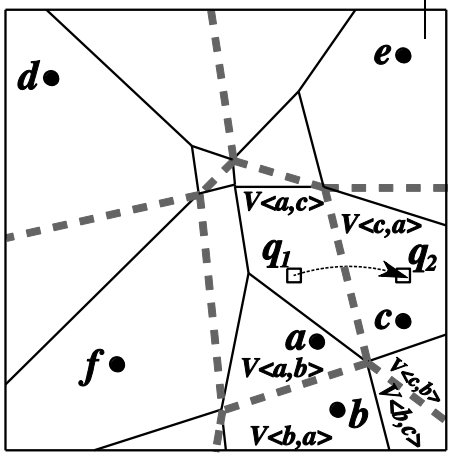
- Applications
  - Continuously reporting the nearest gas station, restaurant, ATM, etc.

- Continuous kNN query on static 2D points

Traditional Approach: Voronoi Diagram

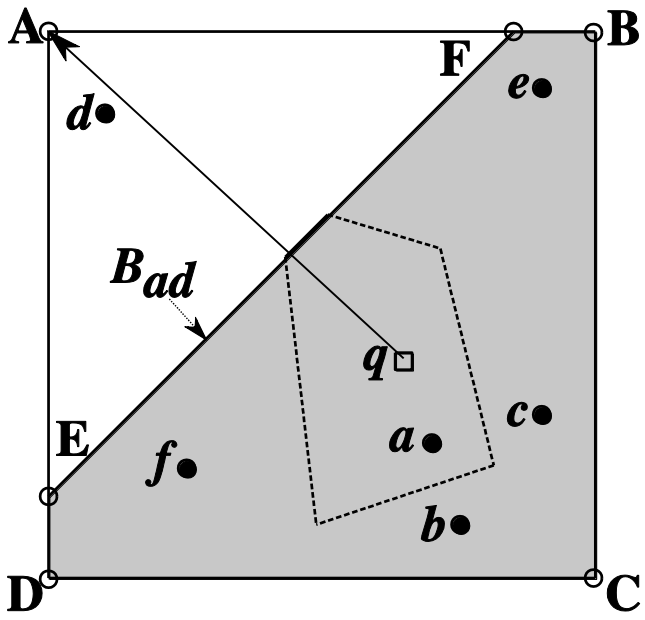


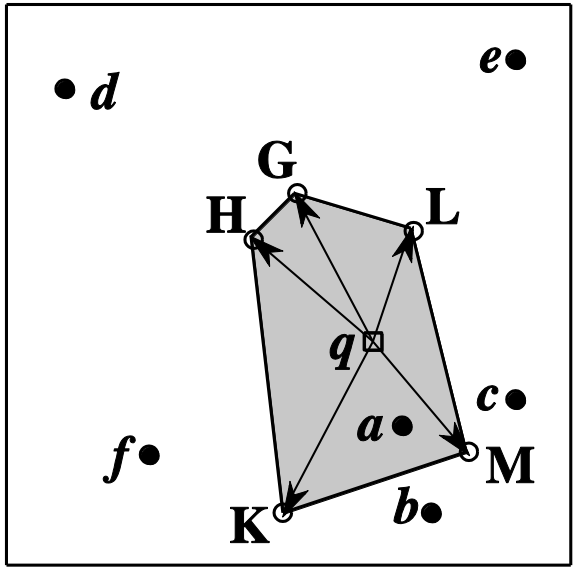




- Drawbacks:
  - Expensive precomputations (quadratic wrt k)
  - Inefficient update operations
  - No support for dynamically changing k values

Best Existing Approach

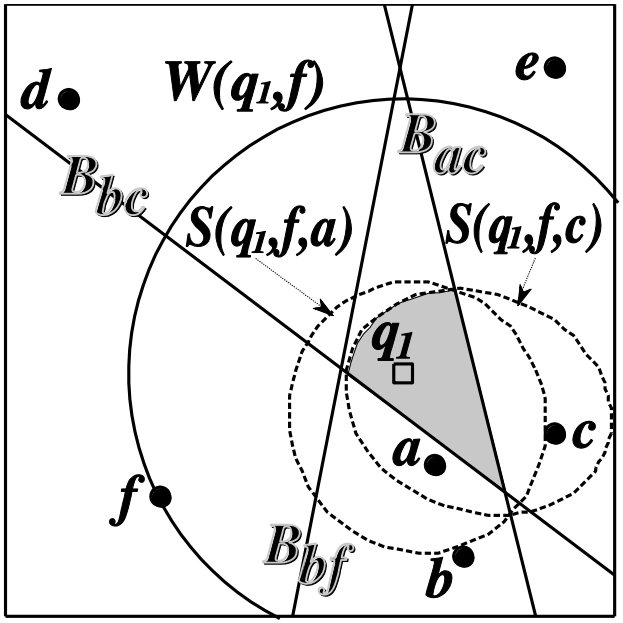




- Computing a Voronoi cell locally

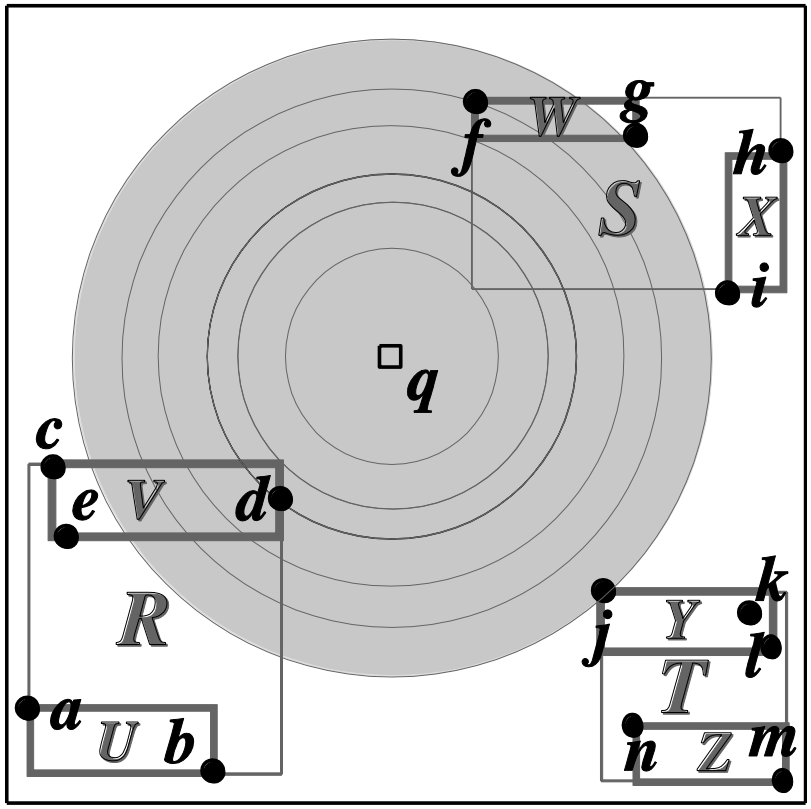
(Much) Better Approach: V*-Diagram

- Goals:
  - Requires no precomputation
  - Supports insertions and deletions of objects
  - Handles dynamically changing k



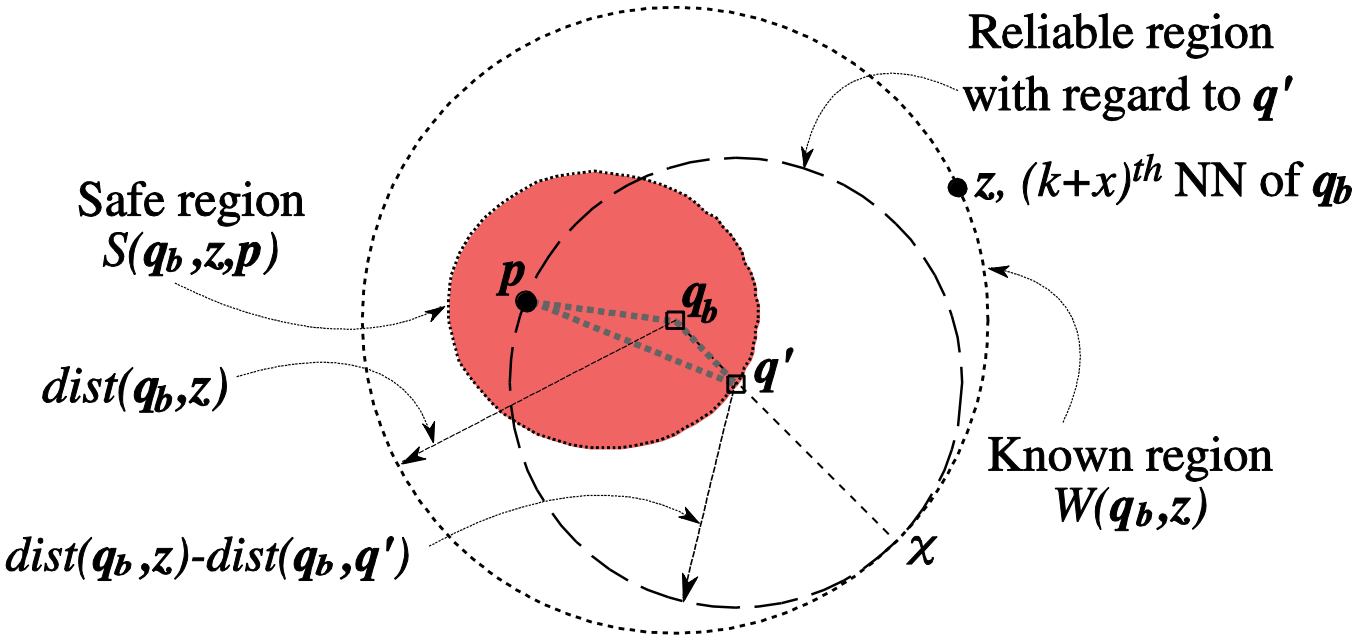
Preliminary

- Incremental kNN algorithm, and known region
  - If the known NNs to ***q*** are {***d***, ***f***, ***j***}, the known region *W*(***q***, ***j***) is {***v*** *: dist(****q****,* ***v****)* ≤ *dist(****q****,* ***j****)*}.



V*-Diagram: Safe region wrt a data point

- We retrieve (k + x) objects. In this example, k and x are both 1, so we retrieve $\boldsymbol{p}$ and $\boldsymbol{z}$.



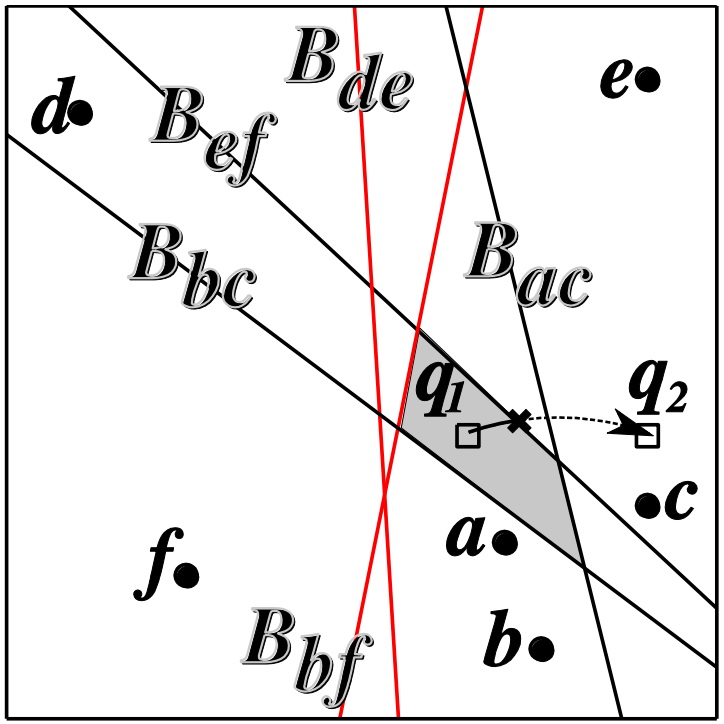
If $\boldsymbol{q}' \in S(\boldsymbol{q}_b, \boldsymbol{z}, \boldsymbol{p})$ then,

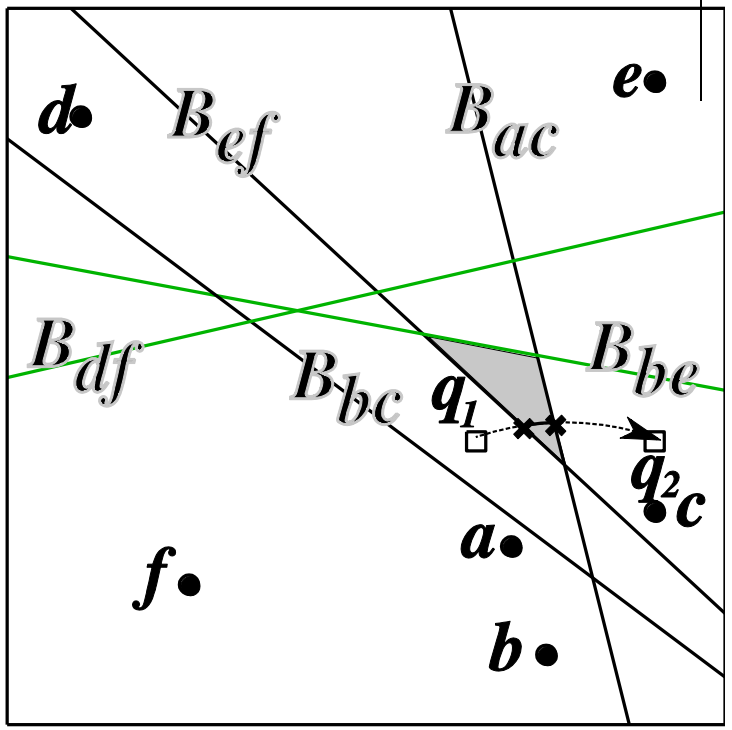
$\forall\ \boldsymbol{p}' \notin W(\boldsymbol{q}_b, \boldsymbol{z})$, dist($\boldsymbol{q}'$, $\boldsymbol{p}$) < dist($\boldsymbol{q}'$, $\boldsymbol{p}'$).

$S(\boldsymbol{q}_b, \boldsymbol{z}, \boldsymbol{p}) = \{\boldsymbol{q}' : \text{dist}(\boldsymbol{p}, \boldsymbol{q}') \le \text{dist}(\boldsymbol{q}_b, \boldsymbol{z}) - \text{dist}(\boldsymbol{q}_b, \boldsymbol{q}')\}$

$= \{\boldsymbol{q}' : \text{dist}(\boldsymbol{p}, \boldsymbol{q}') + \text{dist}(\boldsymbol{q}_b, \boldsymbol{q}') \le \text{dist}(\boldsymbol{q}_b, \boldsymbol{z})\}$

V*-Diagram: The Fixed-rank Region

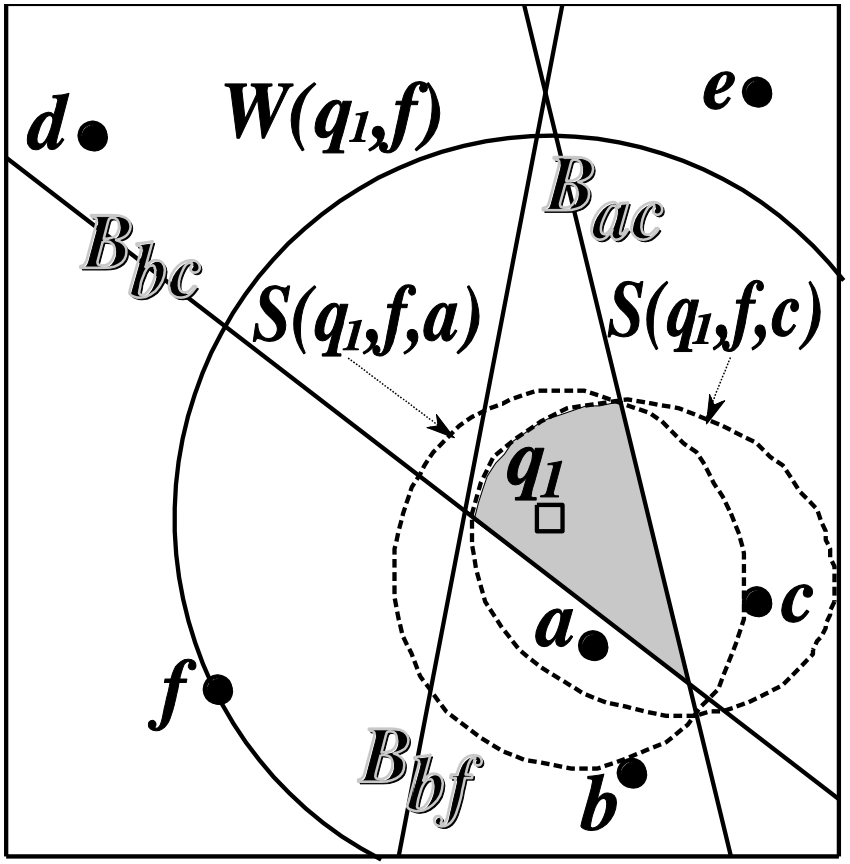




Incremental rank update

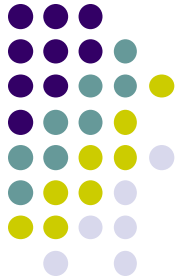
V*-Diagram: Integrated Safe Region

- ISR is an intersection of
  - The safe region wrt k^{th} NN, $S(\boldsymbol{q_b}, \boldsymbol{z}, \boldsymbol{p_k})$;
  - The Fixed Rank Region of the (k+x) NNs of $\boldsymbol{q_b}$.



Example V*-diagram: k =2 , x = 2

Time Constraining



- Continuously returning join result for continuously moving objects [ICDE'08, VLDBJ'11]

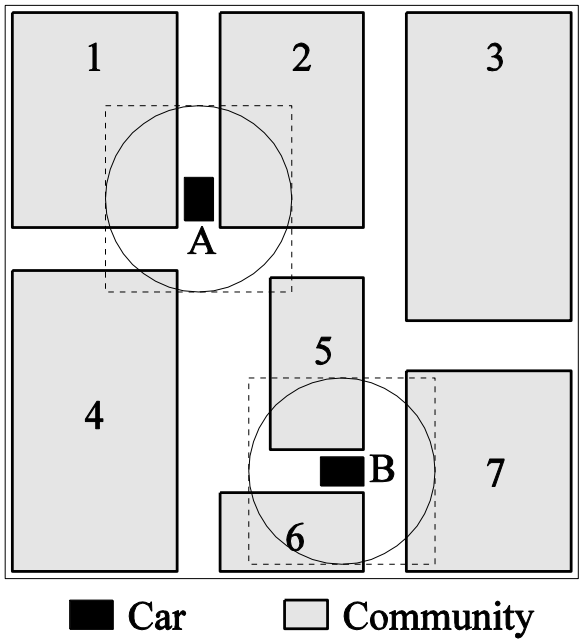
- Applications
  - Monitoring potential attackers in virtual military training programs, large scale multiplayer games

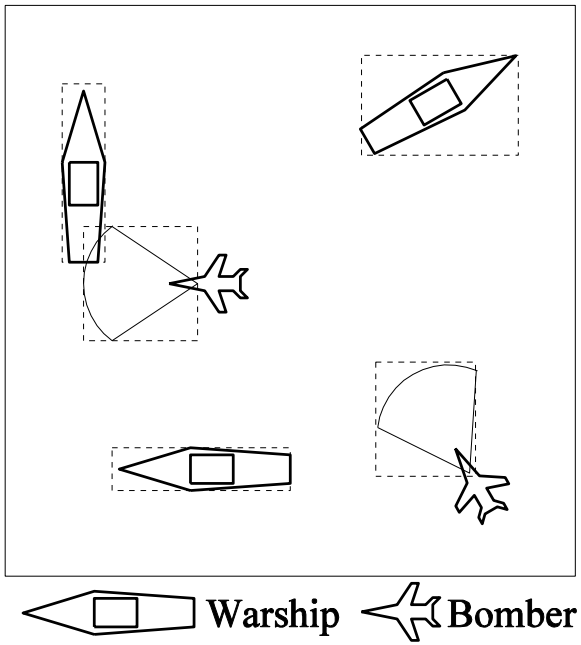
- Continuous intersection query on moving 2D objects

Motivation

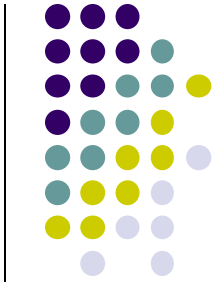
- (Traditional) Intersection join
  - Given two sets of spatial objects A and B, find all object pairs ‹i,j›, where i∈A, j ∈B, such that i intersects j.

- Intersection join on moving objects
  - Moving
  - Continuous





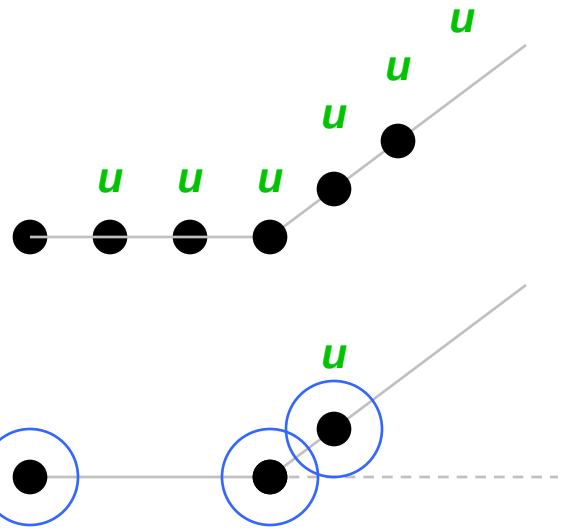
Join Algorithms

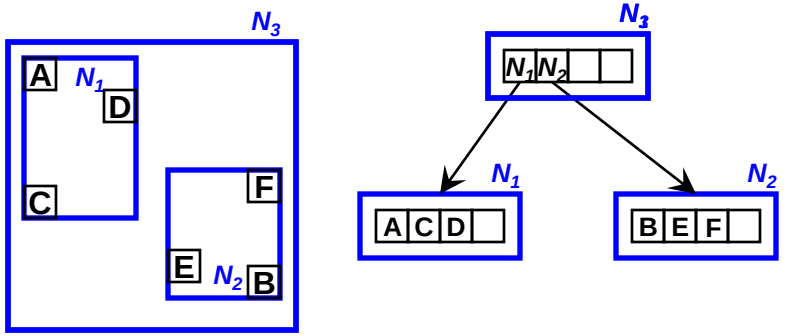


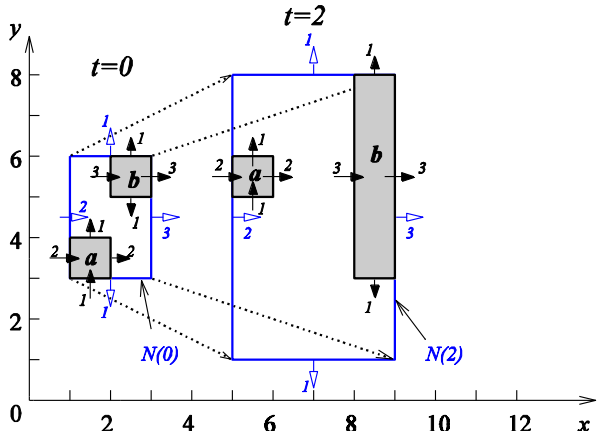
- Nested loops join
  - Basic
  - Expensive
- Block nested loops join
  - Efficient
  - Dependent on buffer size
- Index nested loops join
  - Efficient and robust
- Sort-merge join
  - Efficient
  - Difficult for spatial objects

Indexing Moving Objects

- Monitoring moving objects
  - Sampling-based
  - Trajectory-based
    - $\boldsymbol{p} = \boldsymbol{p}\,(t_{ref}) + \boldsymbol{v}\,(t - t_{ref})$
    - T_M : maximum update interval
- R-tree [SIGMOD'84]
  - Minimum bounding rectangle (MBR)
- TPR-tree [SIGMOD'00]
  - Add time parameters to the R-tree
- Other indexes: B^x-tree [VLDB'04], STRIPES [SIGMOD'04]
  - Only for points

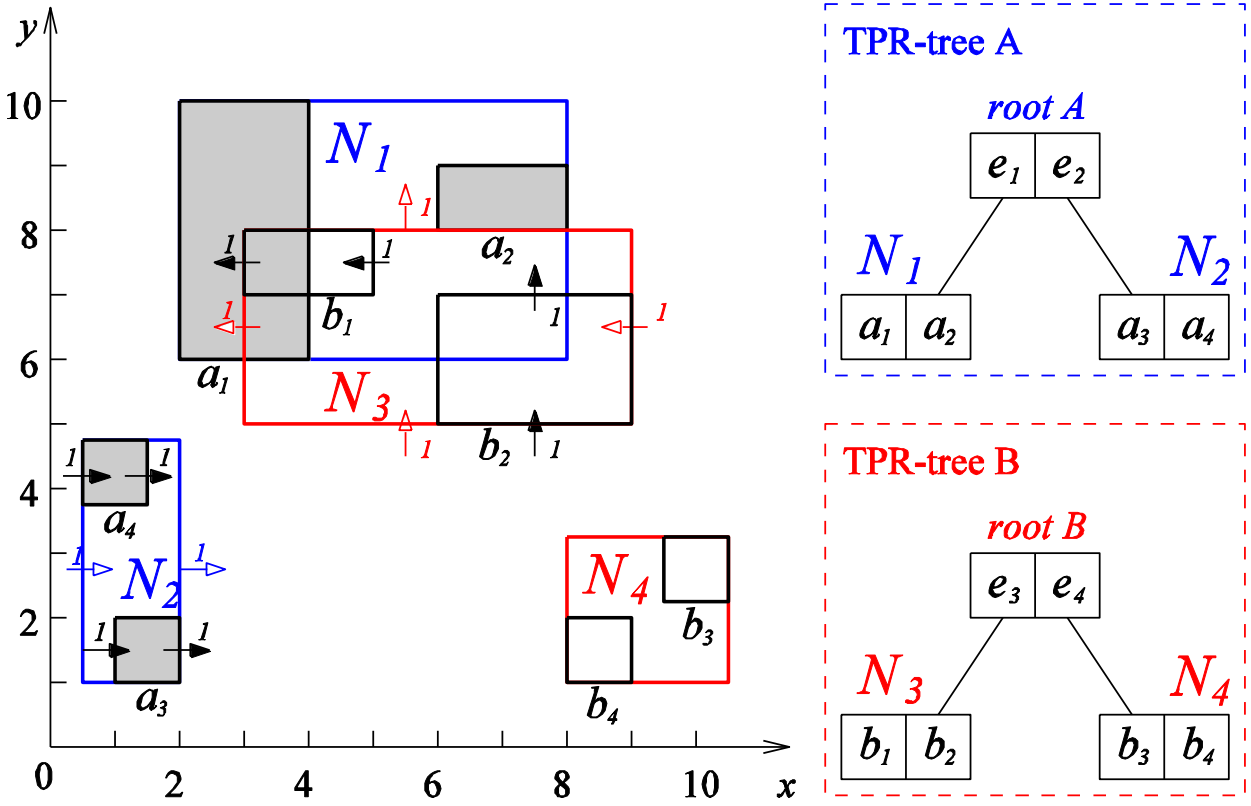






Naive Algorithm (NaiveJoin)

- Join nodes from two TPR-trees recursively
  - If intersected, check on children
  - Otherwise, disregard it
  - For an update, compute its join pairs and update the answer

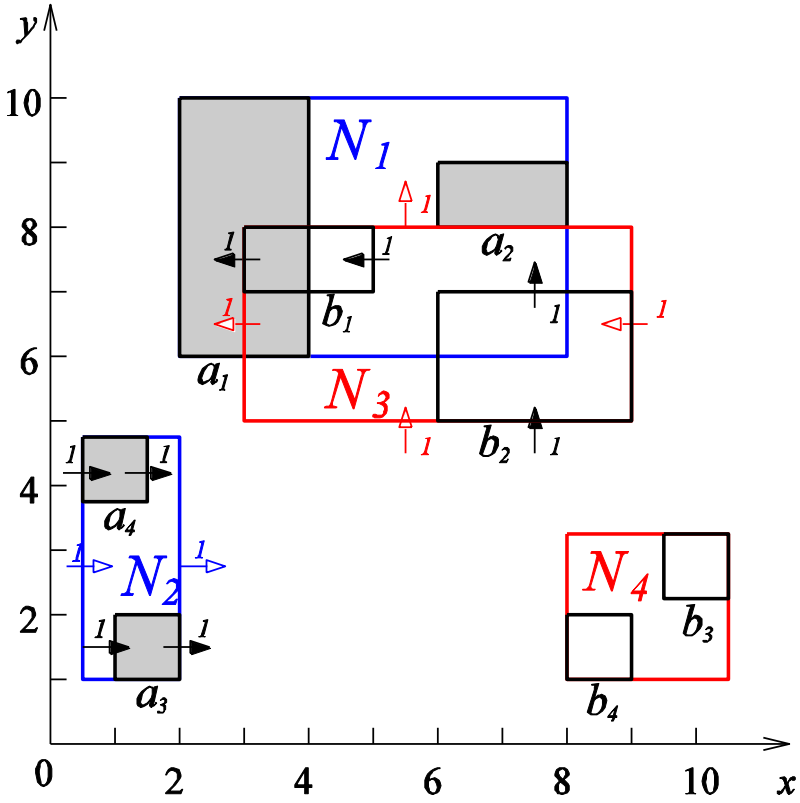


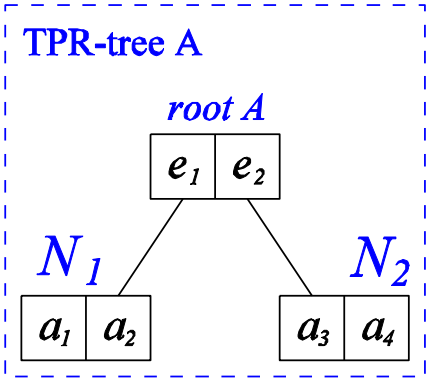
Join result
‹a_1,b_1›, [0,3]
‹a_2,b_2›, [1,4]
‹a_3,b_4›, [6,8]

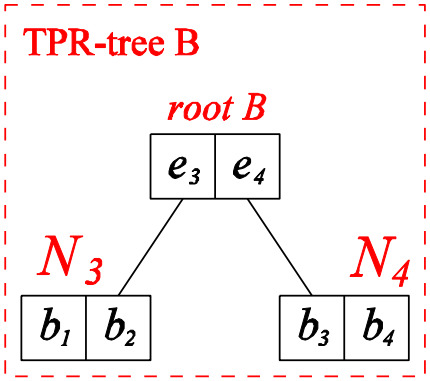
Node access (IO)
roots, N_1, N_2, N_3, N_4
Comparison (CPU)
root A vs root B, N_1 vs N_3, N_2 vs N_4

Extended TP-Join Algorithm (ETP-Join)

- Time Parameterized Join (TP-Join) [SIGMOD'02]
  - Current result ‹a_1,b_1›
  - Expiry time 1
  - Event that causes the change ‹a_2,b_2›







Join result
‹a_1,b_1›, [0,3]
‹a_2,b_2›, [1,4]
‹a_3,b_4›, [6,8]

For the 1st TP-Join

Node access (IO)
roots, N_1, N_3
Comparison (CPU)
root A vs root B, N_1 vs N_3

Summary

- NaiveJoin
  - One tree traversal per update, but expensive traversal

Node access (IO)
roots, N_1, N_2, N_3, N_4
Comparison (CPU)
root A vs root B, N_1 vs N_3, N_2 vs N_4

Too long

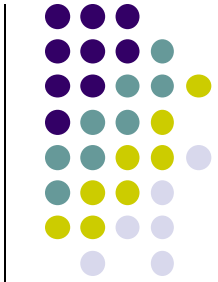
- ETP-Join
  - Cheaper traversal, but too frequent traversals

For the 1st TP-Join

Node access (IO)
roots, N_1, N_3
Comparison (CPU)
root A vs root B, N_1 vs N_3

Too short

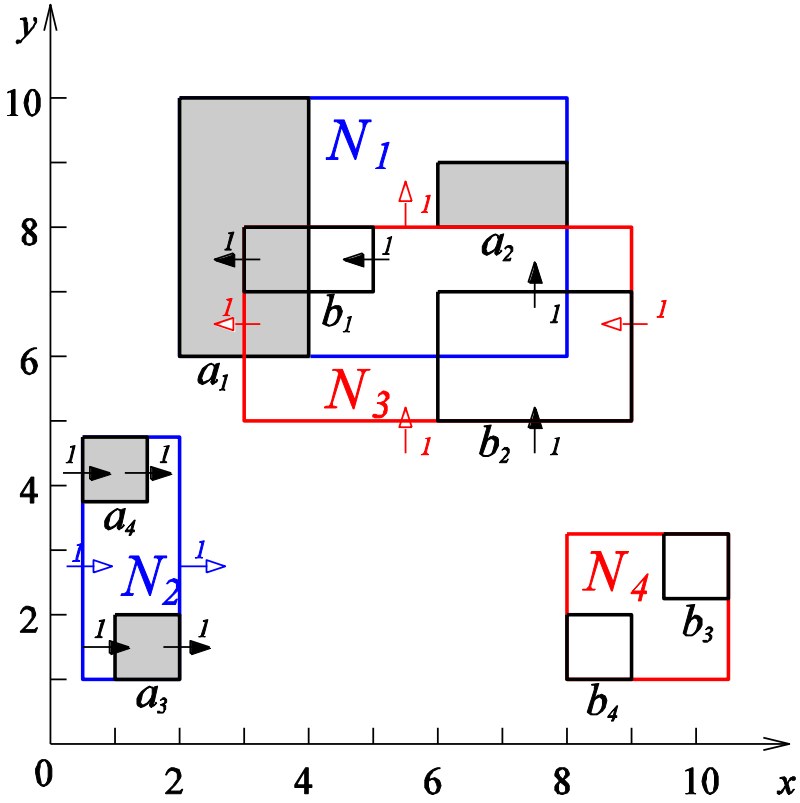
Key Problem

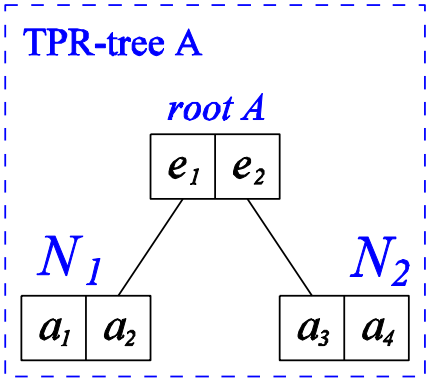


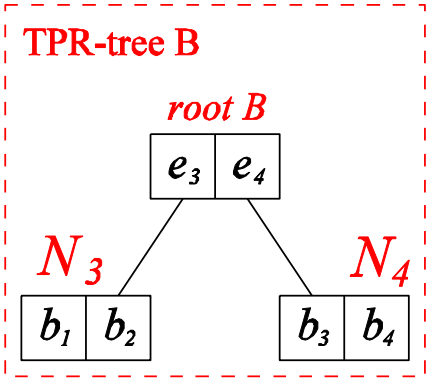
- Find a **good** time range for computing the join pairs
- Observation
  - Consider object a and b
  - Let the next update time for them be t_a and t_b
  - Perfect time range for computing their join result is $[t_c, \mathit{min}(t_a,t_b)]$
- How do we know t_a or t_b?
  - T_M gives a bound for them
  - Time range is cut from $[t_c, \infty]$ to $[t_c, t_c+T_M]$
- Is this correct for all objects?
  - Yes. Proof in technical report: http://www.cs.mu.oz.au/~rui/publication/TR_mj.pdf

Time Constrained Processing (TC-Join)

- NaiveJoin with constrained processing time range $[t_c, t_c+T_M]$





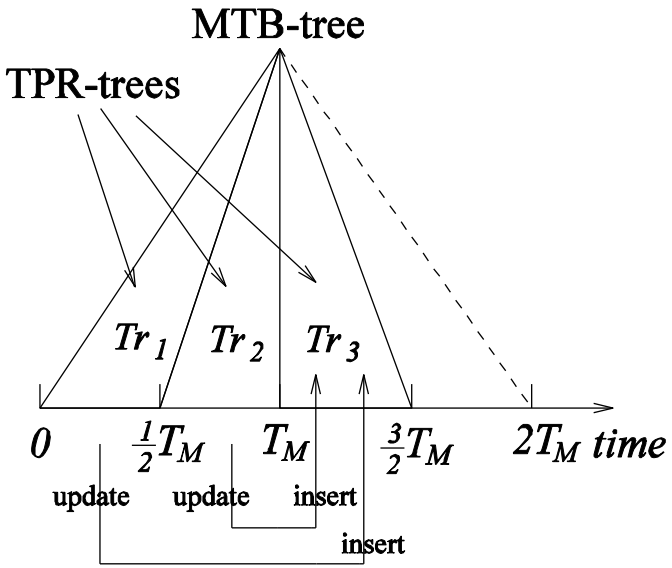


Join result
‹a_1,b_1›, [0,3]
‹a_2,b_2›, [1,4]
‹a_3,b_4›, [6,8]

Node access (IO)
roots, N_1, N_3
Comparison (CPU)
root A vs root B, N_1 vs N_3

Further Optimization (MTB-Join)

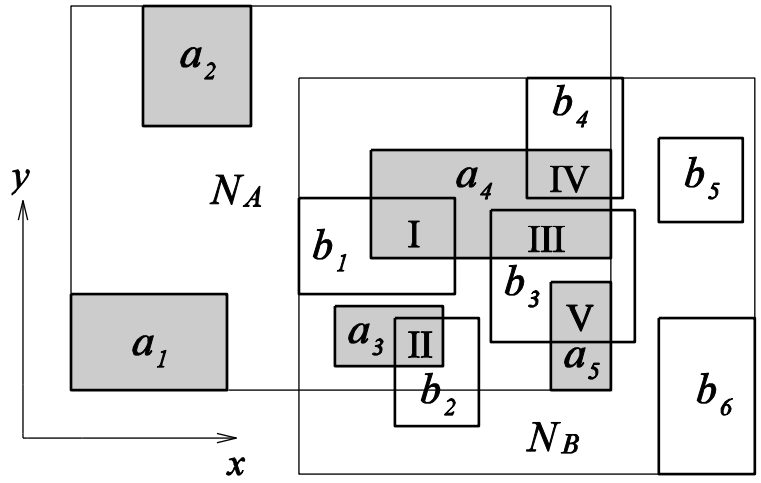
- Many objects will not update at the time bound
- Put objects in time buckets
  - Each time bucket has an associated TPR-tree
  - An object is inserted into the tree whose time bucket contains the object's latest update time



t_c is in $[T_M, 3/2T_M]$

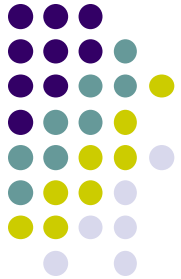
Improvement on the Basic Join Algorithm

- Plane Sweep
  - Sorting based on the lower left corner in dimension x
  - Two sequences: $S_a = \langle a_3, a_4, a_5 \rangle$; $S_b = \langle b_1, b_2, b_3, b_4 \rangle$



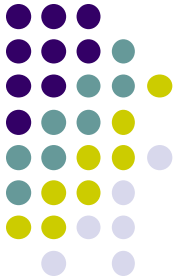
- Two essential components for PS
  - Lower bound
  - Upper bound

Reflect on the Three Techniques



- Incremental computation and shared computation
- Safe region
- Time constraining
- Can we use them in other problems?

Chronicle (not complete or thorough)

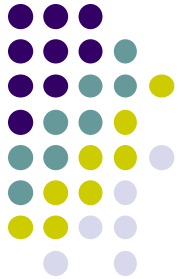


- Notation: S:static M:moving Q:query D:data
  - Glenn S. Iwerks, Hanan Samet, Kenneth P. Smith: Maintenance of Spatial Semijoin Queries on Moving Points. [VLDB'04]
    MQMD, time constraining
  - Hyung-Ju Cho, Chin-Wan Chung: An Efficient and Scalable Approach to CNN Queries in a Road Network [VLDB'05]
    MQSD, safe region, precomputation (shared computation)
  - Mohamed F. Mokbel, Xiaopeng Xiong, Walid G. Aref: SINA: Scalable Incremental Processing of Continuous Queries in Spatio-temporal Databases. [SIGMOD'04]
    MQMD, incremental/shared computation
  - Haibo Hu, Jianliang Xu, Dik Lun Lee: A Generic Framework for Monitoring Continuous Spatial Queries over Moving Objects. [SIGMOD'05a]
    SQMD, safe region
  - Kyriakos Mouratidis, Marios Hadjieleftheriou, Dimitris Papadias: Conceptual Partitioning: An Efficient Method for Continuous Nearest Neighbor Monitoring. [SIGMOD'05b]
    MQMD, safe region

Chronicle (continued)

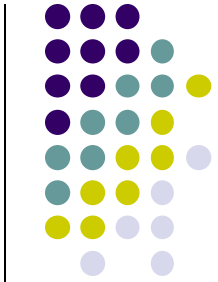
- Notation: S:static M:moving Q:query D:data
  - Mohammed Eunus Ali, Rui Zhang, Egemen Tanin, Lars Kulik. A Motion-Aware Approach to Continuous Retrieval of 3D Objects. [ICDE'08b]
    MQSD, incremental/shared computation
  - Rui Zhang, Dan Lin, Kotagiri Ramamohanarao, Elisa Bertino. Continuous Intersection Joins Over Moving Objects. [ICDE'08a]
    MD, time constraining
  - Sarana Nutanong, Rui Zhang, Egemen Tanin, Lars Kulik. The V*-Diagram: A Query Dependent Approach to Moving KNN Queries. [VLDB'08b]
    MQSD, safe region
  - Zaiben Chen, Heng Tao Shen, Xiaofang Zhou, Jeffrey Xu Yu: Monitoring path nearest neighbor in road networks. [SIGMOD'09]
    MQSD, incremental computation
  - Muhammad Aamir Cheema, Xuemin Lin, Ying Zhang, Wei Wang, Wenjie Zhang. Lazy Updates: An Efficient Technique to Continuously Monitoring Reverse kNN Queries [VLDB'09]
    MQMD, safe region

A Look Back



- Before 1995:
  - Spatial: static point queries, range/window queries
  - Temporal: version indexes, time interval indexes
- 1995 – 2000:
  - Spatial: nearest neighbor (NN) queries, selectivity estimation/cost models, high-dimensional data
  - Temporal: version indexes, time interval indexes
- 2000 – 2005:
  - Spatial: reverse nearest neighbor (RNN) queries, spatial joins, skyline queries
  - Temporal: time series, similarity queries
  - Spatio-temporal: point, range, and NN queries on moving objects
  - Data streams
- 2005 – 2008:
  - Spatial: trajectories, location selection,
  - Temporal: trajectories
  - **Continuously Moving Queries on static objects**
  - **Continuous Queries on moving objects**
- After 2008 (look forward)

Look Forward: Trend in the Last Few Years

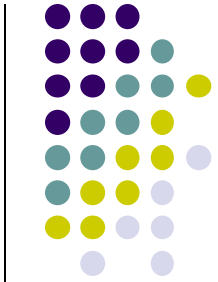


- Queries on continuous queries on moving objects
  - Predictive range and knn queries [InfSys'10]
  - Continuous retrieval of 3D objects [ICDE'08b, VLDBJ'10b]
  - Continuous intersection join [ICDE'08a, VLDBJ'12]
  - Continuous knn join [GeoInformatica'10]
  - (Continuous) Moving knn queries [VLDB'08b, VLDBJ'10a]
  - Other types of incremental queries [TKDE'10, TKDE'12]

- Handling very large and streaming temporal databases
  - Transaction time indexing with version compression [VLDB'08a]
  - The HV-tree: a Memory Hierarchy Aware Version Index [VLDB'10a]
  - Mining Distribution Change in Stock Order Streams.[ICDE'09]

- Exploring road network
  - Scalable network distance browsing in spatial databases. [SIGMOD'08]

Look Forward: Trend in the Last Few Years



- Moving objects index with variant properties
  - Handling velocity skew [VLDB'12]
  - Privacy preservation [VLDB'11]

- Mining locations and trajectories
  - Trajectory clustering: a partition-and-group framework. [SIGMOD'07]
  - On efficiently searching trajectories and archival data for historical similarities [VLDB'08c]
  - Fast approximate correlation for massive time-series data [SIGMOD'10]
  - Swarm: Mining Relaxed Temporal Moving Object Clusters. [VLDB'10b]
  - Mining Significant Semantic Locations From GPS Data [VLDB'10c]

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