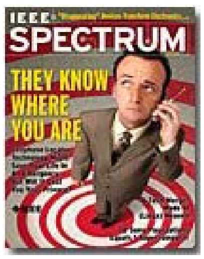
Private Queries in Location-Based Services



"New technologies can pinpoint your location at any time and place. They promise safety and convenience but threaten privacy and security"

IEEE Spectrum, July 2003

Motivation

- Big and growing mobile Internet
  - 2.7 B mobile phone users (cf. 850 MM PCs)
  - 1.1 B Internet users, 750 MM access the Internet from phones
  - 419 M mobile phones sold in 1Q 2012 (Source: Gartner)
  - Africa has surpassed North America in numbers of users
- The mobile Internet will be location aware.
  - GPS, Wi-Fi-based, cell-id-based, Bluetooth-based, other
  - A very important signal in a mobile setting!

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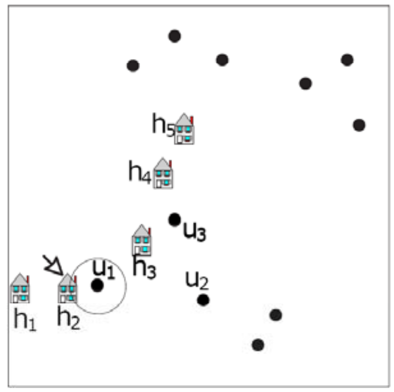
Location-Based Services (LBS)

- Location-based services
  - Location-based store finders
  - Location-based traffic reports
  - Location-based advertisements
- LBS users
  - Mobile devices with GPS capabilities
- Queries
  - Nearest Neighbor (NN) Queries

"Find closest hospital to my present location"



- Location-based services rely on the *implicit* assumption that users agree on revealing their private user locations
- Location-based services *trade* their services with privacy

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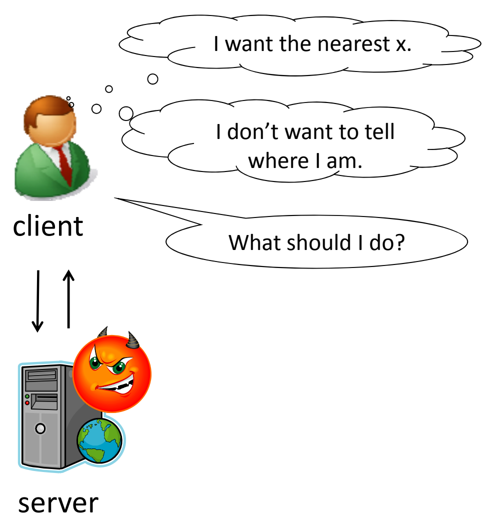
Query Location Privacy

- A mobile user wants nearby points of interest.
- A service provider offers this functionality.
  - Requires an account and login
- The user does not trust the service provider.
  - The user wants location privacy.



Problem Statement

- Queries may disclose sensitive information
  - Query through anonymous web surfing service
- But user location may disclose identity
  - Triangulation of device signal
  - Publicly available databases
  - Physical surveillance
- How to preserve *query source anonymity*?
  - Even when exact user locations are known

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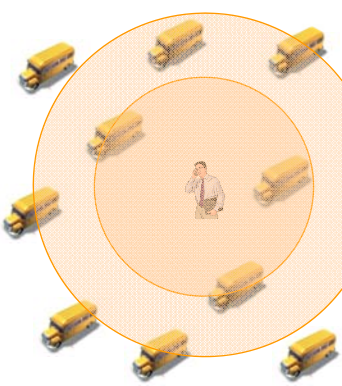
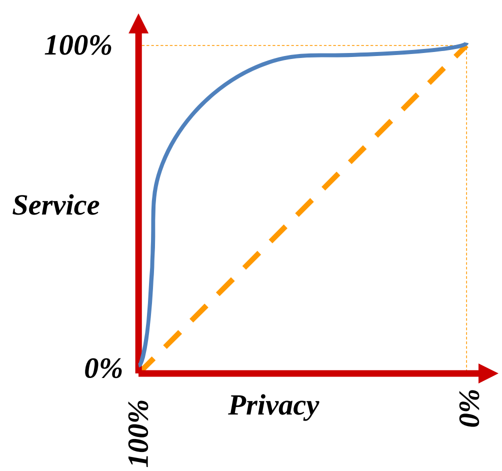
Service-Privacy Trade-off

- Example:
  - *Where is my nearest bus?*





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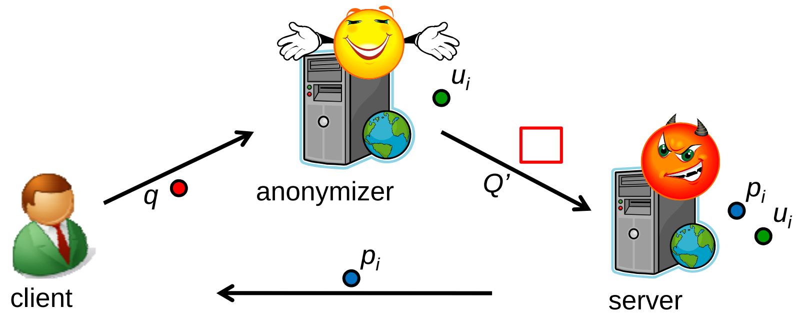
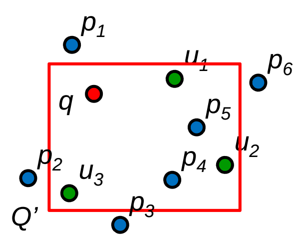
Spatial K-Anonymity: Spatial Cloaking

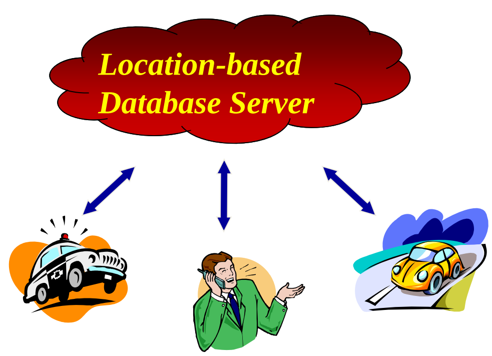


- kNN query (k=1)
- K anonymity
- Range kNN query
  - Anonymizing spatial regions (ASR)
  - User hides among K-1 users
  - Probablity of identifying user ≤ 1/K



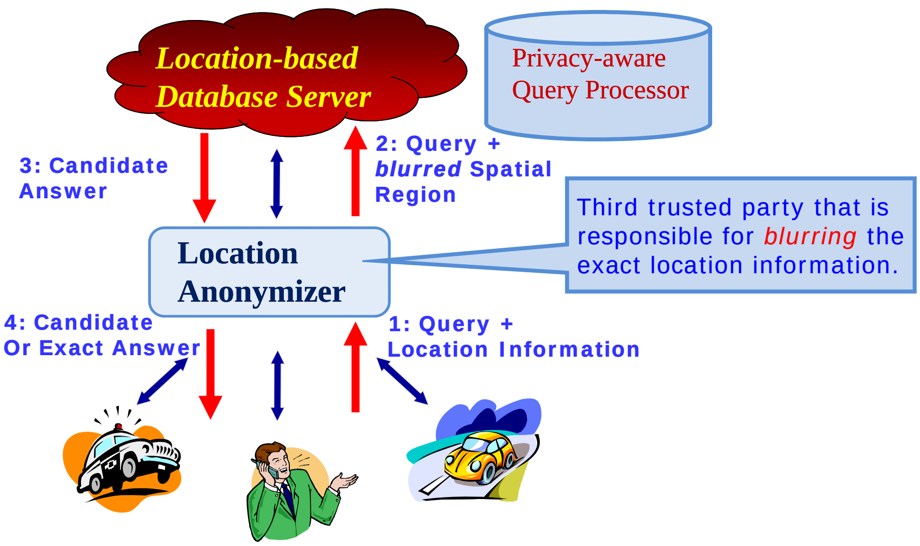
- Candidate set is $\{p_1, \ldots, p_6\}$
- Result is p_1

K-Anonymity in LBS: Architecture



Mokbel et al, The New Casper: Query Processing for Location Services without Compromising Privacy, VLDB 2006

K-Anonymity in LBS: Architecture



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The New Casper

- Each mobile user has her own *privacy-profile* that includes:
  - *K* – A user wants to be *k*-anonymous
  - A_{min} – The minimum required area of the blurred area
  - Multiple instances of the above parameters to indicate different privacy profiles at different times

Time	*k*	A_{min}
8:00 AM -	1	—
5:00 PM -	100	1 sq mile
10:00 PM -	1000	5 sq miles

Large K and A_{min} imply stricter privacy requirement

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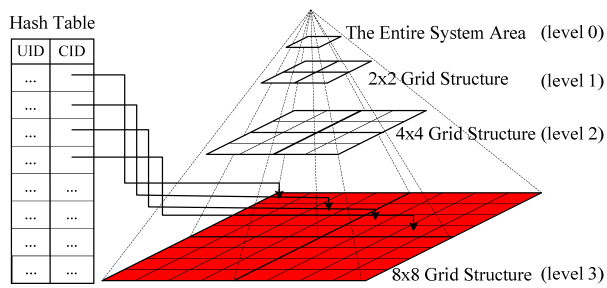
Location Anonymizer: Grid-based Pyramid Structure

- The system area is divided into grids at multiple levels in a quad-tree-like manner
  - Level h (root at level 0) has 4^h grids;
  - Each cell is represented as (cid, N) where N is the number of mobile users in cell cid
- The Location Anonymizer incrementally keeps track of the *number of users* residing in each grid.



(uid, profile, cid)

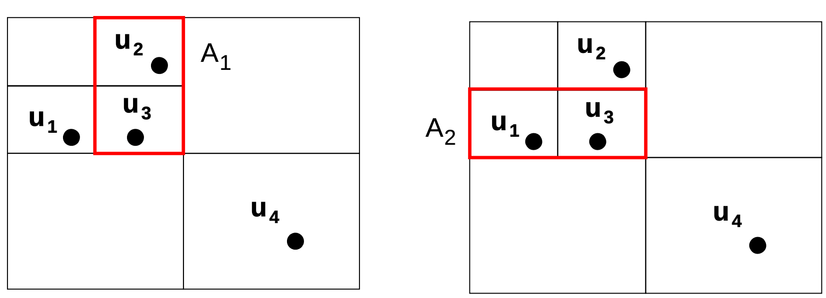
Location update (uid, x, y)

- If cid_{old} = cid_{new} done else (a) update new cell identifier in hash table; (b) update counters in both cells; (c) propagate changes in counters to higher levels (if necessary)
- New user – (a) create new entry in hash table; (b) counters of all affected cells increased by 1
- User departs – (a) remove entry; (b) decrease counters by 1

Location Anonymizer: Grid-based Pyramid Structure

Cloaking Algorithm

- Blur the query location
- Traverse the pyramid structure from the bottom level to the top level, until a cell satisfying the user privacy profile is found.

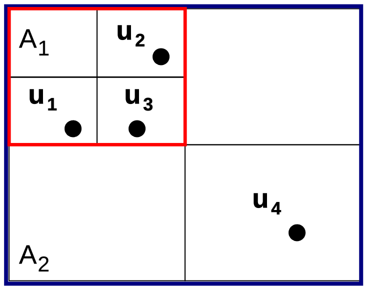


- Let K=2
- If u_3 queries, ASR is A_1 or A_2 (if the area > A_{min}) otherwise …

Location Anonymizer: Grid-based Pyramid Structure

Cloaking Algorithm

- Traverse the pyramid structure from the bottom level to the top level, until a cell satisfying the user privacy profile is found.

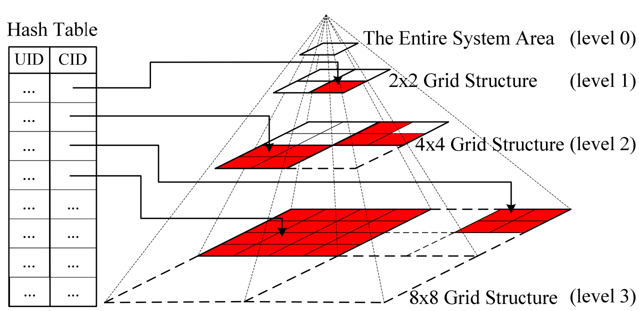


- Let K=3
- If any of u_1, u_2, u_3 queries, ASR is A_1
- If u_4 queries, ASR is A_2

- Disadvantages:
  - *High location update cost*
  - *High cloaking cost*

Adaptive Location Anonymizer

- Each sub-structure may have a different depth that is adaptive to the *environmental changes* and *user privacy requirements*
  - Stricter privacy requirements => higher level
    - All users at the higher level have strict privacy requirements that cannot be met by the lower level



Adaptive Location Anonymizer

- ***Cell Splitting:*** A cell *cid* at level *i* needs to be split into four cells at level *i*+1 if there is at least one user *u* in *cid* with a privacy profile that can be satisfied by some cell at level *i*+1.
  - Need to keep track of most relaxed user u for each cell
  - If newly arrived user, v, to cell has a more relaxed profile than u
    - If splitting cell can satisfy v's requirement, split and distribute content to the 4 children cells; otherwise, replace u by v
  - If u departs, need to find a replacement
- ***Cell Merging:*** Four cells at level *i* are merged into one cell at a higher level *i*-1 only if all users in the level *i* cells have strict privacy requirements that cannot be satisfied within level *i*.
  - Need to keep track of most relaxed user u for the 4 cells of level *i*
  - If u departs, find v to replace u. If v's requirement is stricter than can be handled by the 4 cells, then merge them
  - If v enters cell at level *i*, we replace u if necessary

Same cloaking algorithm applies at the lowest existent levels.

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The Privacy-aware Query Processor

- Embedded inside the location-based database server
- Process queries based on cloaked spatial regions rather than exact location information
- Two types of data:
  - *Public* data. Gas stations, restaurants, police cars
  - *Private* data. Personal data records
- Three types of queries
  - *Private* queries over *public* data, e.g., *What is my nearest gas station?*
  - *Public* queries over *private* data, e.g., *How many cars in the downtown area?*
  - *Private* queries over *private* data, e.g., *Where is my nearest friend?*
- Focus on the first query type

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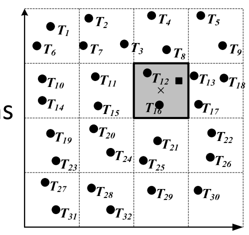
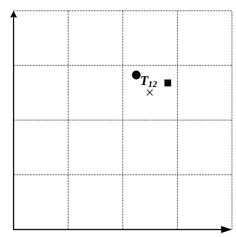
Private Queries over Public Data: Naïve Approaches

- Complete privacy
  - The Database Server returns all (or a sufficiently large superset that contains the answer) the target objects to the Location Anonymizer
  - High transmission cost
  - Shifting the burden of query processing work onto the mobile user



Server



- Nearest target object to center of the spatial query region
  - Simple but NOT accurate

Location Anonymizer
(The correct NN object is T_{13}.)

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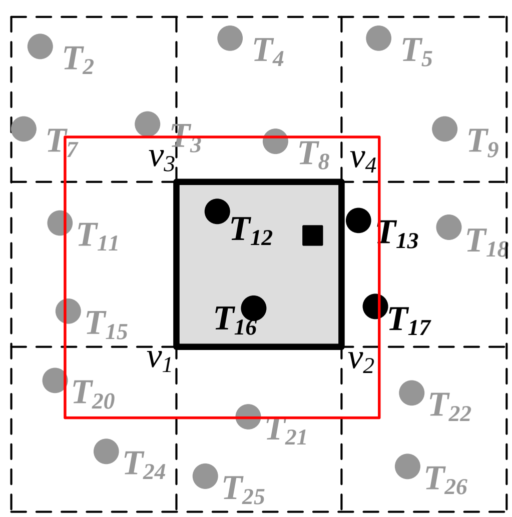
Private Queries over Public Data: The Casper Scheme

Basic idea:

- Find the smallest bounding region that contains the answer
- Return all points within the region



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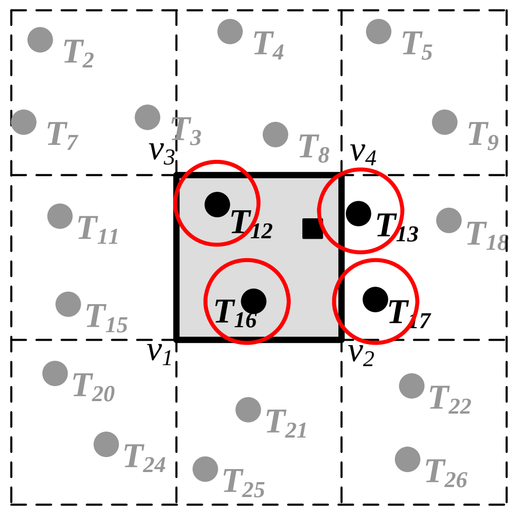
Private Queries over Public Data: The Casper Scheme

Step 1: Locate four filters

- The NN target object for each vertex



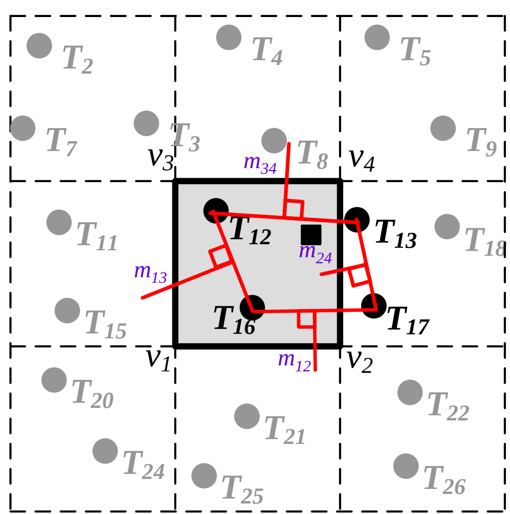
Private Queries over Public Data: The Casper Scheme

Step 1: Locate four filters

- The NN target object for each vertex

Step 2 : Find the middle points

- The furthest point on the edge to the two filters



Private Queries over Public Data: The Casper Scheme

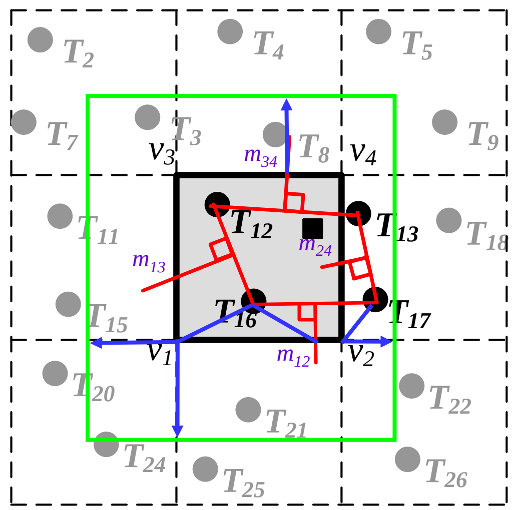
Step 1: Locate four filters

- The NN target object for each vertex

Step 2 : Find the middle points

- The furthest point on the edge to the two filters

Step 3: Extend the query range



Private Queries over Public Data: The Casper Scheme

Step 1: Locate four filters

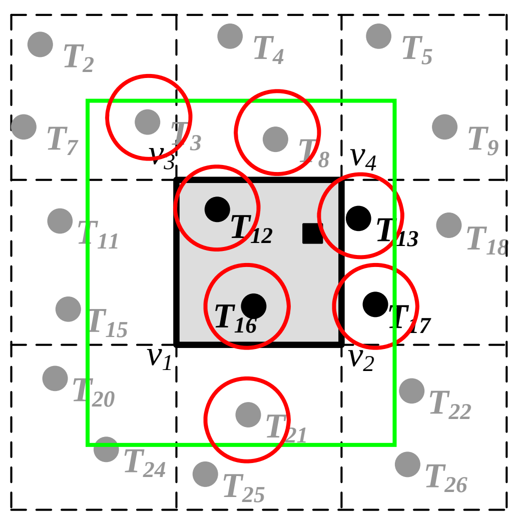
- The NN target object for each vertex

Step 2 : Find the middle points

- The furthest point on the edge to the two filters

Step 3: Extend the query range

Step 4: Candidate answer



Private Queries over Public Data: Correctness

- Theorem 1
  - Given a cloaked area *A* for user *u* located anywhere within *A*, the privacy-aware query processor returns a candidate list that includes the exact nearest target to *u*.
- Theorem 2
  - Given a cloaked area *A* for a user *u* and a set of filter target object t_1 to t_4, the privacy-aware query processor issues the ***minimum possible range query*** to get the candidate list.

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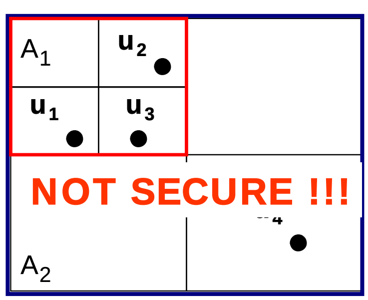
Casper may compromise location anonymity

- Quad-tree based
  - Fails to preserve anonymity for outliers
  - Unnecessarily large ASR size



- Let K=3
- If any of u_1, u_2, u_3 queries, ASR is A_1
- If u_4 queries, ASR is A_2
- u_4's identity is disclosed

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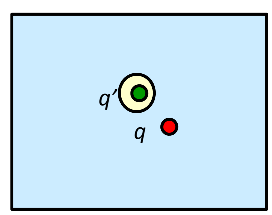
SpaceTwist: No Cloaking Needed

- Cloaking
  - Requires servers to support “specialized” techniques for processing cloaked queries
  - High communication overheads
- Computes kNN query *incrementally* until client is guaranteed to have accurate results
  - Server supports R-tree, and INN (incremental nearest neighbor) retrieval
  - Simple client-server architecture, i.e., no trusted components

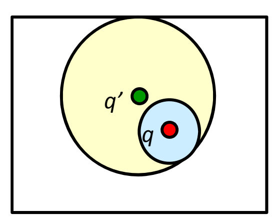
M. L. Yiu, C. S. Jensen, H. Lu. SpaceTwist: Managing the Trade-Offs Among Location Privacy, Query Performance, and Query Accuracy in Mobile Services. Proc. ICDE, April 2008.

SpaceTwist Concepts

- Anchor location *q’* (*fake* client location)
  - Defines an ordering on the data points
- Client fetches points from server (based on *q’*) incrementally
- Supply space — *supply space*
  - The part of space explored by the client so far
  - Known by both server and client
  - Grows as more data points are retrieved
- Demand space — *demand space*
  - Guaranteed to cover the actual result
  - Known only by the client
  - Shrinks when a “better” result is found
- Terminate when the supply space contains the demand space



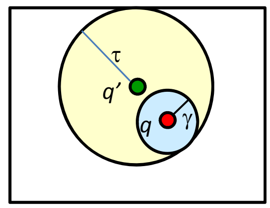
the beginning



the end

SpaceTwist

- Input: user location q, anchor location q' (NOTE: distance between q and q' affects privacy)
- Client asks server to report points in ascending distance from anchor q' iteratively
  - Note: server only knows q' and reported points
- Supply space radius τ, initially 0
  - Distance of the current reported point from anchor q'
- Demand space radius γ, initially ∞
  - Nearest neighbor distance to user (found so far)
  - Update γ to dist(q,p) when a point p closer to q is found
- Stop when dist(q,q') + $\gamma \le \tau$
  - Supply space covers demand space
  - Guarantee that exact nearest neighbor of q has been found



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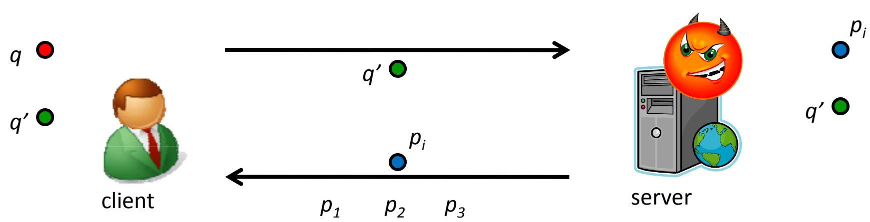
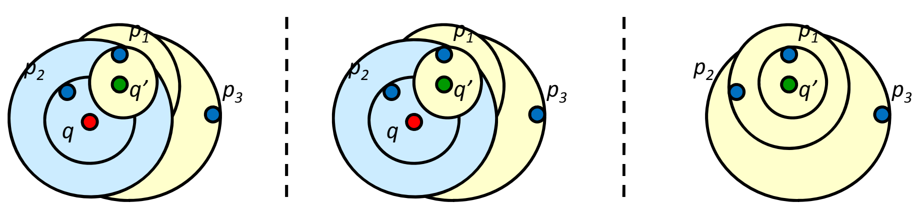
SpaceTwist Example





What client sees | The global view | What server sees

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Privacy Analysis

- dist(q, q') affects degree of privacy
  - If it is small, then few objects will be retrieved (and low cost), but less location privacy is achieved
- What does the server (malicious attacker) know?
  - The anchor location *q'*
  - The reported points (in reporting order): $p_1, p_2, \ldots, p_{m\beta}$ where β is the number of points per packet and m is the number of packets transmitted
  - Termination condition: $dist(q,q') + dist(q,NN) \leq dist(q', p_{m\beta})$
- Possible query location q_c
  - The client did not stop at point $p_{(m-1)\beta}$ (else packet m is not needed (?))
    - $dist(q_c, q') + \min\{ dist(q_c, p_i) : i \in [1,(m-1)\beta] \} > dist(q', p_{(m-1)\beta})$
  - Client stopped at point $p_{m\beta}$
    - $dist(q_c, q') + \min\{ dist(q_c, p_i) : i \in [1,m\beta] \} \leq dist(q', p_{m\beta})$
- *Inferred* privacy region Ψ: the set of all possible q_c
- Quantification of privacy
  - Privacy value: $\Gamma(q, \Psi)$ = the average dist. of location in Ψ from q
  - NOTE: Only user can compute this

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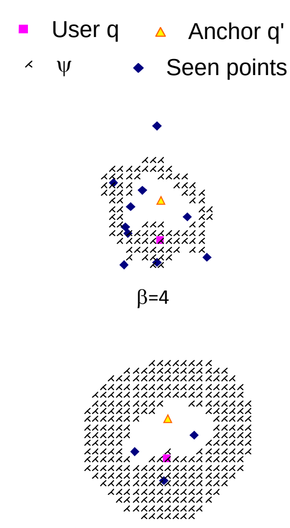
Visualization of Ψ

- Visualization with different types of points
- Characteristics of Ψ (i.e., possible locations q_c)
  - Roughly an irregular ring shape centered at *q'*
  - Radius approx. dist(*q,q'*)
  - $\Gamma(q, \Psi)$ is at least dist(q,q')



coarser granularity
(low data density)

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Privacy Analysis

- By carefully selecting the distance between *q* and *q'*, it is possible to guarantee a privacy setting specified by the user.
- SpaceTwist extension: Instead of terminating when possible, request additional query points.
  - This makes the problem harder for the adversary.
  - It makes it easier (and more practical) to guarantee a privacy setting.

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Granular Search

- What if the server considers searching on *a small sample* of the data points instead of all?
  - Lower communication cost
  - Ψ becomes large at low data density
  - But less accurate results
- Accuracy requirement
  - User specifies an error bound ε
  - A point $p \in P$ is a relaxed NN of *q* iff $\text{dist}(q, p) \leq \varepsilon + \min \{\text{dist}(q, p') : p' \in P\}$
- Granular search
  - Goal: Search at coarser granularity
  - Reduces communication cost; yet guarantees accuracy bound of results

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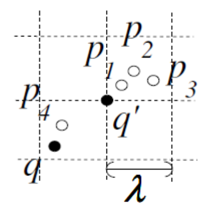
Granular Search

- Given an error bound ε, impose a grid in the space with cell length $\lambda = \varepsilon / \sqrt{2}$
- Slight modification of the incremental NN search
  - Points are still reported in ascending distance order from anchor q'
  - But the server discards a data point p if it falls in the same cell of any reported point (never reports more than one data point *p* from the same cell)
- Incremental granular searching at anchor q'
  - Server reports p1, client updates its NN to p1
  - Server discards p2, p3
  - Server reports p4, client updates its NN to p4
- Outcome: reduced communication cost (from 4 points to 2 points), yet with guaranteed result accuracy


regular grid

How users choose appropriate parameter values?

- Error bound ε
  - Set $\varepsilon = v_{max} \cdot t_{max}$
    - t_{max} : maximum time delay acceptable by user
    - v_{max} : maximum travel speed (walking, cycling, driving)
- Anchor point q'
  - Decide the anchor distance dist(q,q')
    - Based on privacy value, i.e., privacy value at least dist(q, q')
    - Based on acceptable value of m (communication)

$$N_\epsilon = \min\{N, 2k \cdot (U/\epsilon)^2\} \qquad dist(q,q') = \frac{U}{\sqrt{\pi} \cdot N_\epsilon} \cdot (\sqrt{m\beta} - \sqrt{k})$$

  - U is the extent of the space; $U/(\lambda) = \sqrt{2} \times U/\varepsilon$ is the length of each grid cell; so total number of cells = $2 \times (U/\varepsilon)^2$; each cell returns at most k points, so we have N_ε
  - Set the anchor q' to a random location at distance dist(q,q') from q

LBS Privacy with Computational Private Information Retrieval (cPIR)

- Limitations of existing solutions
  - Assumption of trusted entities
    - anonymizer and trusted, non-colluding users
  - Considerable overhead for sporadic benefits
    - maintenance of user locations
  - No privacy guarantees
    - especially for continuous queries (same user issuing the same query in different areas – correlation attack possible for cloaking methods)
- cPIR
  - Two-party cryptographic protocol
    - No trusted anonymizer required
    - No trusted users required
  - No pooling of a large user population required
    - No need for location updates
  - Location data completely obscured

Private Queries in Location Based Services: Anonymizers are not Necessary. G. Ghinita, P. Kalnis, A. Khoshgozaran, C. Shahabi, K.L. Tan International Conference on Management of Data (SIGMOD'2008)

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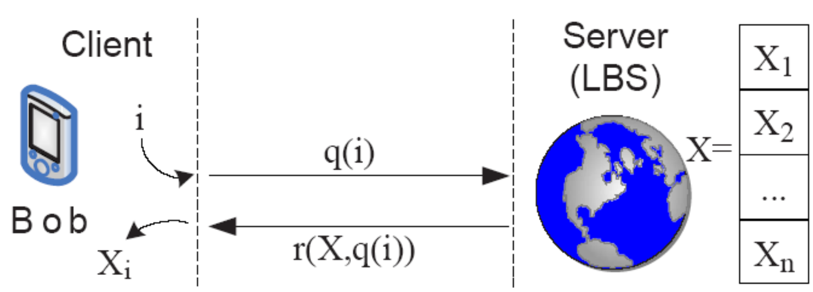
cPIR Overview



- Computationally hard to find *i* from *q(i)*
- Bob can easily find X_i from *r* (trap-door)

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QR: Quadratic residue
QNR: Quadratic non-residue

cPIR Theoretical Foundations

- Let $N = q_1 * q_2$, q_1 and q_2 large primes

$$\mathbb{Z}_N^* = \{x \in \mathbb{Z}_N | gcd(N, x) = 1\}$$

$$QR = \{y \in \mathbb{Z}_N^* | \exists x \in \mathbb{Z}_N^* : y = x^2 \mod N\}$$

- E.g. N=5*7=35, 11 is *QR* (9^2=11 mod 35), 3 is *QNR* (no y exists for y^2=3 mod 35)
- Let $\mathbb{Z}_N^{+1} = \{y \in \mathbb{Z}_N^* | \left(\frac{y}{N}\right) = 1\}$ where $\left(\frac{y}{N}\right)$ is the Jacobi symbol

  then exactly half of the numbers are in QR and the other half in QNR
- *Quadratic Residuosity Assumption (QRA)*
  - QR/QNR decision computationally hard (if q1 and q2 are not given)
  - Essential properties:

*QR * QR = QR*

*QR * QNR = QNR*

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cPIR Protocol for Binary Data

N=35

QNR={3,12,13,17,27,33}

QR={1,4,9,11,16,29}

u

Get $M_{2,3}$

4 16 17 11

QNR

Server computes (Server knows N):

$$z_i = \Pi_{j=1}^{t} y_j \cdot y_j^{1-M_{i,j}} \pmod N$$

$M_{i,j} = 0$ → y_j^2

$M_{i,j} = 1$ → y_j

public data size: n = 16 let t = √n

Organize data in a t × t (4×4) binary matrix M

$M_{2,3}$ (axes: e, g)

0	1	1	0	→ 17
1	1	1	0	→ 33
0	1	1	0	→ 17
0	1	1	1	→ 27

$z_2 = 4^2 x16x17x11^2$ mod 35 = 17

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cPIR Protocol for Binary Data

N=35

QNR={3,12,13,17,27,33}

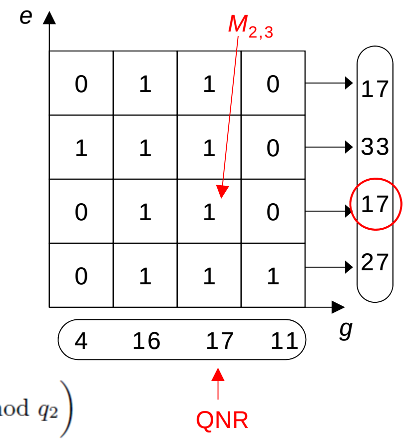
QR={1,4,9,11,16,29}

u

Get $M_{2,3}$

public data size: *n* = 16 let t = √n

Organize data in a t × t (4×4) binary matrix *M*



Server computes:

$$z_i = \Pi_{j=1}^{t} y_j \cdot y_j^{1-M_{i,j}}$$

Client computes:

$$\left(z_a^{\frac{q_1-1}{2}} = 1 \mod q_1\right) \wedge \left(z_a^{\frac{q_2-1}{2}} = 1 \mod q_2\right)$$

If expression is true, then Z is in QR.

z_2=QNR => $M_{2,3}$=1

z_2=QR => $M_{2,3}$=0

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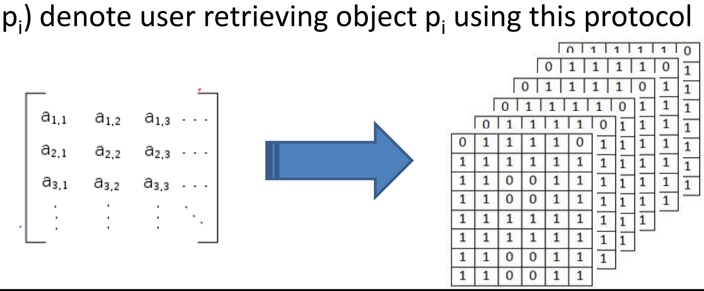
cPIR protocol for objects

- Same idea for binary data can be easily extended
  - Organize collection of objects as a matrix
  - Conceptually, this is like having m matrices (assuming each object is represented by m bits)
  - Server applies the computation on each of these matrices, and m answer messages will be returned
  - Communication overhead is m times larger (m . √n)
- PIR(p_i) denote user retrieving object p_i using this protocol



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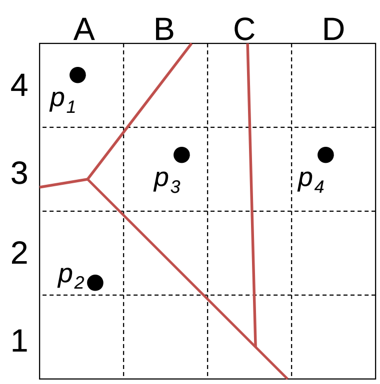
Exact Nearest Neighbor Queries

- Preprocess the data
  - Compute Voronoi tessellation of the set of objects
    - NN of any point within a Voronoi cell is the point enclosed in that cell
  - Superimpose a regular G x G grid on top of the Voronoi diagram
    - For each cell C, determine all Voronoi cells that intersect it; C keeps track of the corresponding objects
    - C contains all potential NNs of every location inside it

Exact Nearest Neighbor

A3: p_1, p_2, p_3

A4: p_1, --, --



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Exact NN

- Query processing
  - User u initiates query
  - Server returns the granularity of the grid ($\sqrt{n}$)
  - u can figure out the cell of the current location, and corresponding column, say b
  - u issues PIR(b) (which is essentially y)

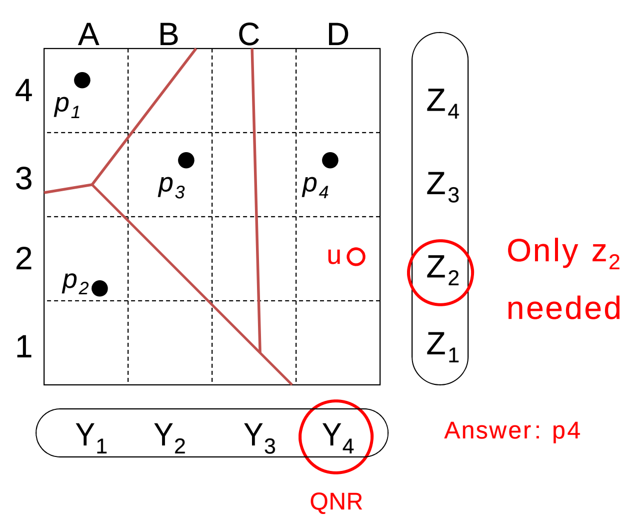
$$y = [y_1 : y_{\sqrt{n}}],\ y_b \in QNR,\ \text{and}\ \forall j \neq b, y_j \in QR$$

  - From the answers returned, NN of u can be determined

Exact Nearest Neighbor

A3: p_1, p_2, p_3

A4: p_1, --, --



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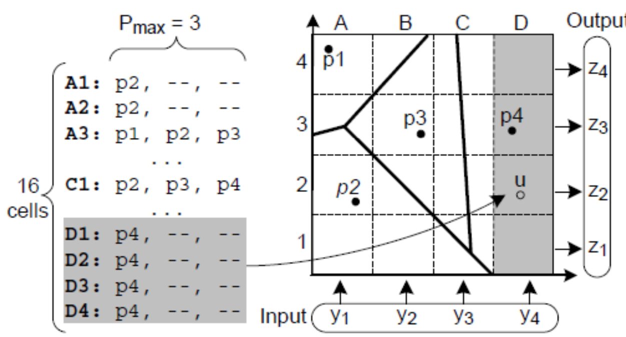
Exact NN

- Cells may be associated with different number of points
  - "Object" of each cell has different size!
  - Need to "force" them to be the same size, otherwise, server will know which cell u is targeting.
  - Fix the size to the maximum number of data objects, and pad with dummy those cells that have fewer than P_{max}

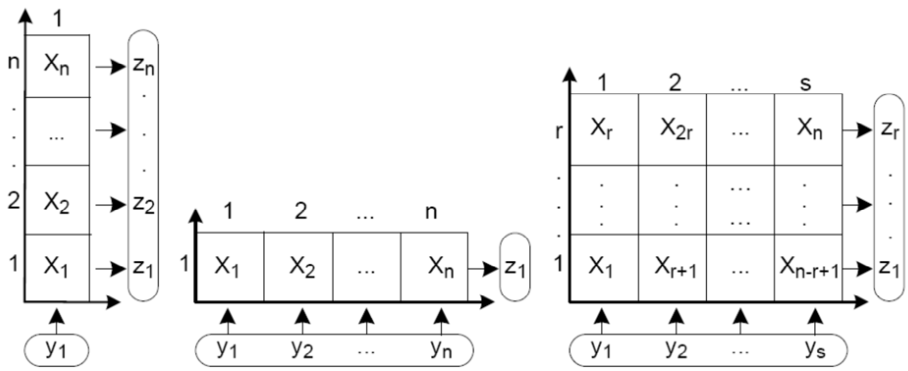


Exact NN

- Concern
  - Since information of entire column b is returned, potentially reveals to user $\sqrt{n}$ x P_{max} points!
  - However, many of these are also duplicates, e.g., D1, D2, D3 and D4 contains only P4
    - Compression can be used to reduce overheads of sending duplicates to user
- Effect of grid size
  - As number of grids increases, communication cost reduces (since P_{max} decreases); however, beyond certain point, it starts to increase again since it reaches the lower bound (and replication effect kicks in)
  - CPU cost increases with number of grids

Rectangular PIR Matrix

r < s may be beneficial:
- Since "object" size is larger
- For exact NN, user learns fewer other objects



(a) M: n×1 (b) M: 1×n (c) M: r×s

Summary

- LBS services is here to stay
- User privacy needs to be preserved
- Various methods have been developed for user location privacy
  - Spatial K-Anonymity
  - SpaceTwist
  - cPIR
- What else?
  - Continuous queries
  - Road networks
  - …