Location management and Moving Objects Databases

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Location based services

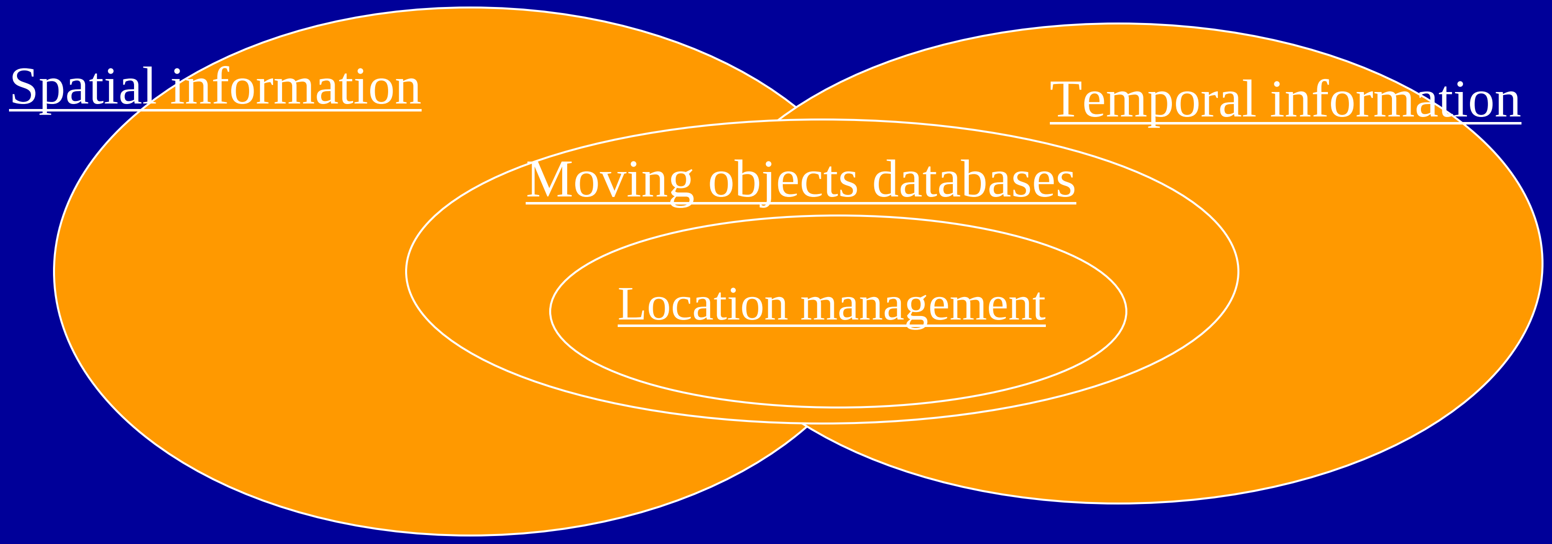
Examples:

- Where closest gas station? How do I get there?
- Track my pet/kid/bus
- Send coupon when "right" client close to store
- Ride-sharing: Share the cab with a waiting customer
- What is the average speed on the highway 1 mile ahead?
- What are the available parking slots around me?

Why now?

- E911 – FCC mandate
- drop in equipment/service prices
- portable/wearable/wireless device proliferation
- vehicular communication networks (UWB, 802.11)

Moving Objects Databases: Software infrastructure for providing location based services


Spatial information
Temporal information
Moving objects databases
Location management

Outline

- Background
  - Location technologies, applications ←
  - demo
- Research issues
  - Location modeling/management
  - Linguistic issues
  - Uncertainty/Imprecision
  - Indexing
  - Synthetic datasets
  - Compression/data-reduction
  - Joins and data mining

Fundamental location sensing methods

- Triangulation
- Proximity
- Scene analysis
  - camera location + shape/size/direction of object ==> object location)

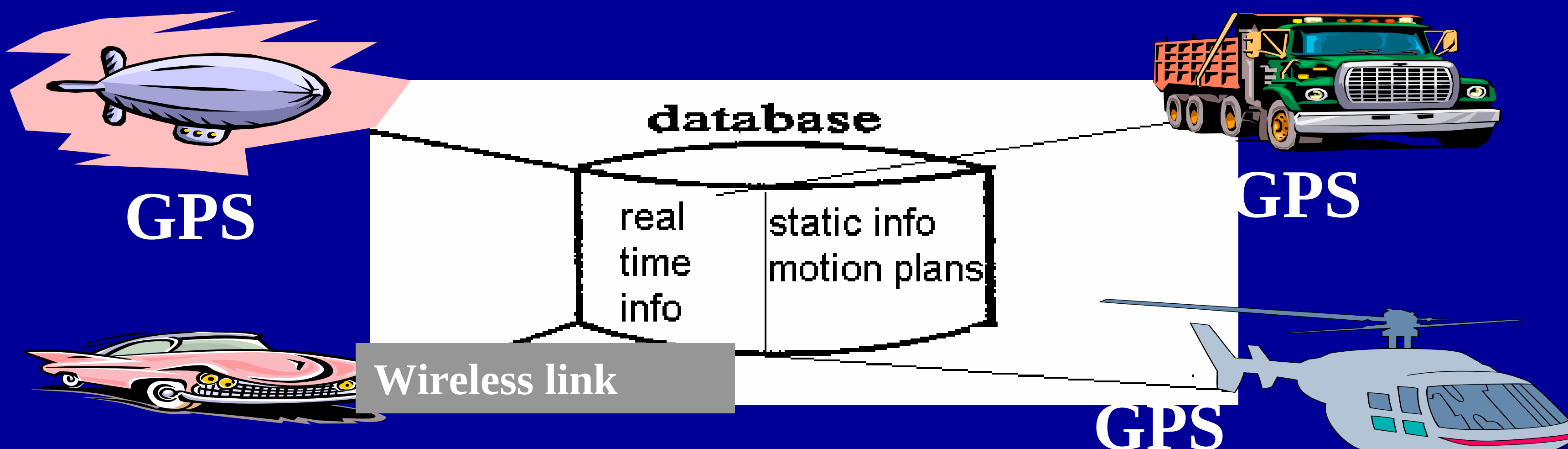
Location/Positioning technologies

- Global Positioning System (GPS)
  - Special purpose computer chip
  - cost < $100
  - As small as a cm^2
  - Receives and triangulates signals from 24 satellites at 20,000 KM
  - Computes latitude and longitude with tennis-court-size precision
  - Used to be football field until May 1st, 2000; US stopped jamming of signal for civilian use. Same devices will work.
  - Differential GPS: 2-3 feet precision

Location technologies (continued)

- Indoor (sonar) GPS
- Sensors – e.g. toll booth that detects card in windshield.
- Triangulation in cellular architecture
- Cell-id
- Bluetooth (proximity positioning)
- calendar system

Moving Objects Database Technology



Query/trigger examples:

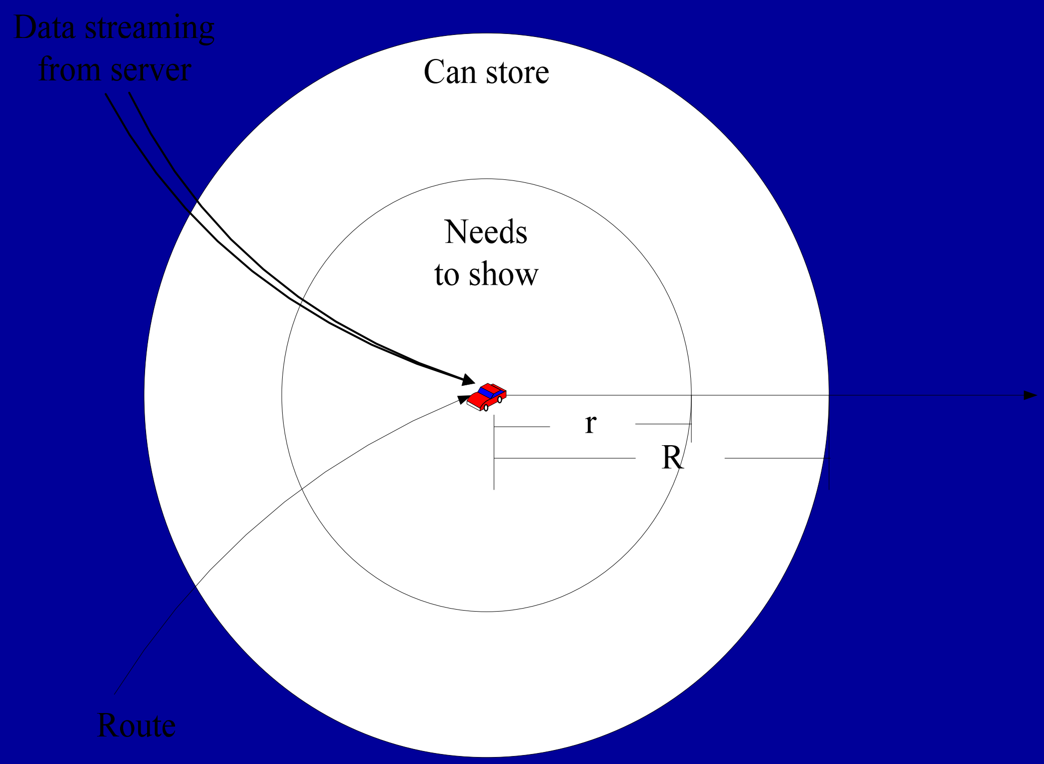
- During the past year, how many times was bus#5 late by more than 10 minutes at station 20, or at some station (past query)
- Send me message when helicopter in a given geographic area (trigger)
- Trucks that will reach destination within 20 minutes (future query)
- Taxi cabs within 1 mile of my location (present query)
- Average speed on highway, one mile ahead
- Tracking for “context awareness”

Context Awareness Examples

- Automatically display resume of a person I am speaking with
- Display wiring/plumbing behind wall utility-worker is viewing
- Display seismographic charts, maps, graphics, images, concerning a terrain a geologist is viewing

Importance of Tracking Accuracy

Example:



Server errs by > R-r ➔ Disturbs real time

Mobile e-commerce

- Remind me to buy drinks when I'm close to a supermarket
- Send a coupon (10% off) to a customer with interest in Nike sneakers that is close to the store
- Inform a person entering a bar of his "buddies" in the bar

Mobile e-commerce

- Alert a person entering a bar if two of his "buddies" (*wife and girlfriend*) are both in the bar; he may want to turn around

- Antithesis of e-commerce, which is independent of location.

Applications-- Summary

- Geographic resource discovery-- e.g. “Closest gas station”
- Digital Battlefield
- Transportation (taxi, courier, emergency response, municipal transportation, traffic control)
- Supply Chain Management, logistics
- Context-awareness, augmented-reality, fly-through visualization
- Location- or Mobile-Ecommerce and Marketing
- Mobile workforce management
- Air traffic control (www.faa.gov/freeflight)
- Dynamic allocation of bandwidth in cellular network
- Querying in mobile environments

Currently built in an ad hoc fashion

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Outline (continued)

– Querying in mobile environments

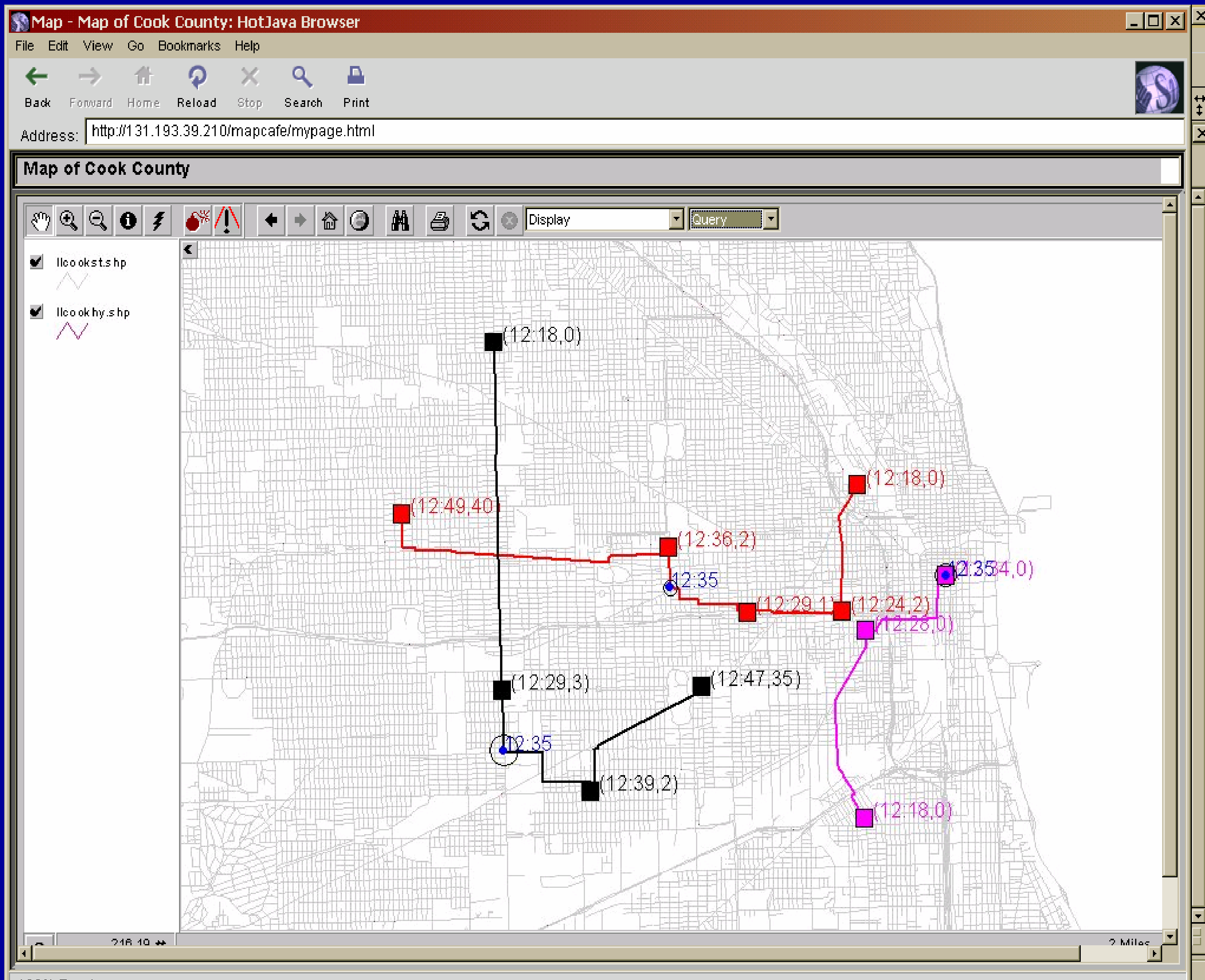
Moving Objects Database Architecture

- Envelope software on top of a Database Management System and a Geographic Information System.

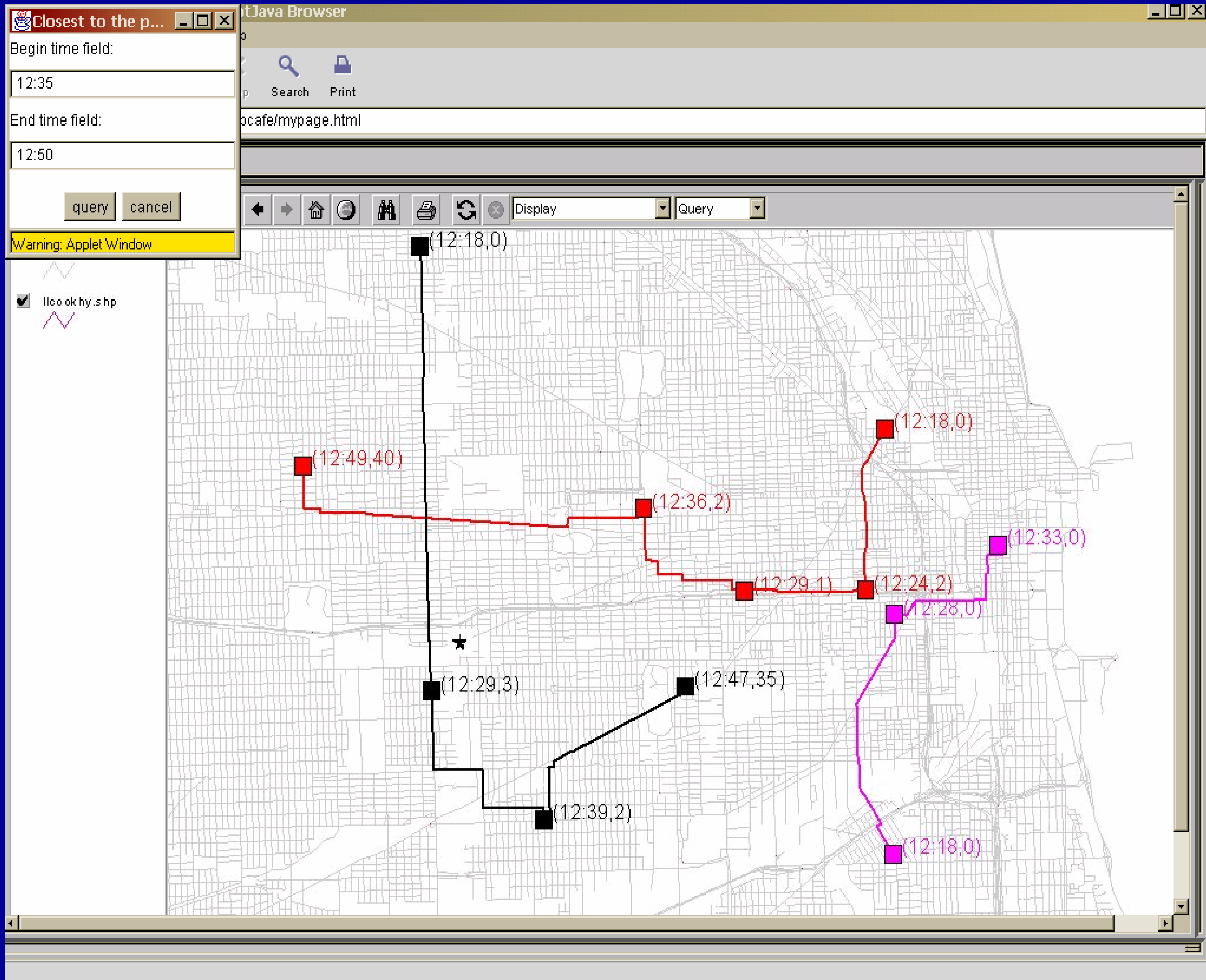
- Platform for Location-based-services application development.

Demo at ACM-SIGMOD'99, NGITS'99, ICDE'00

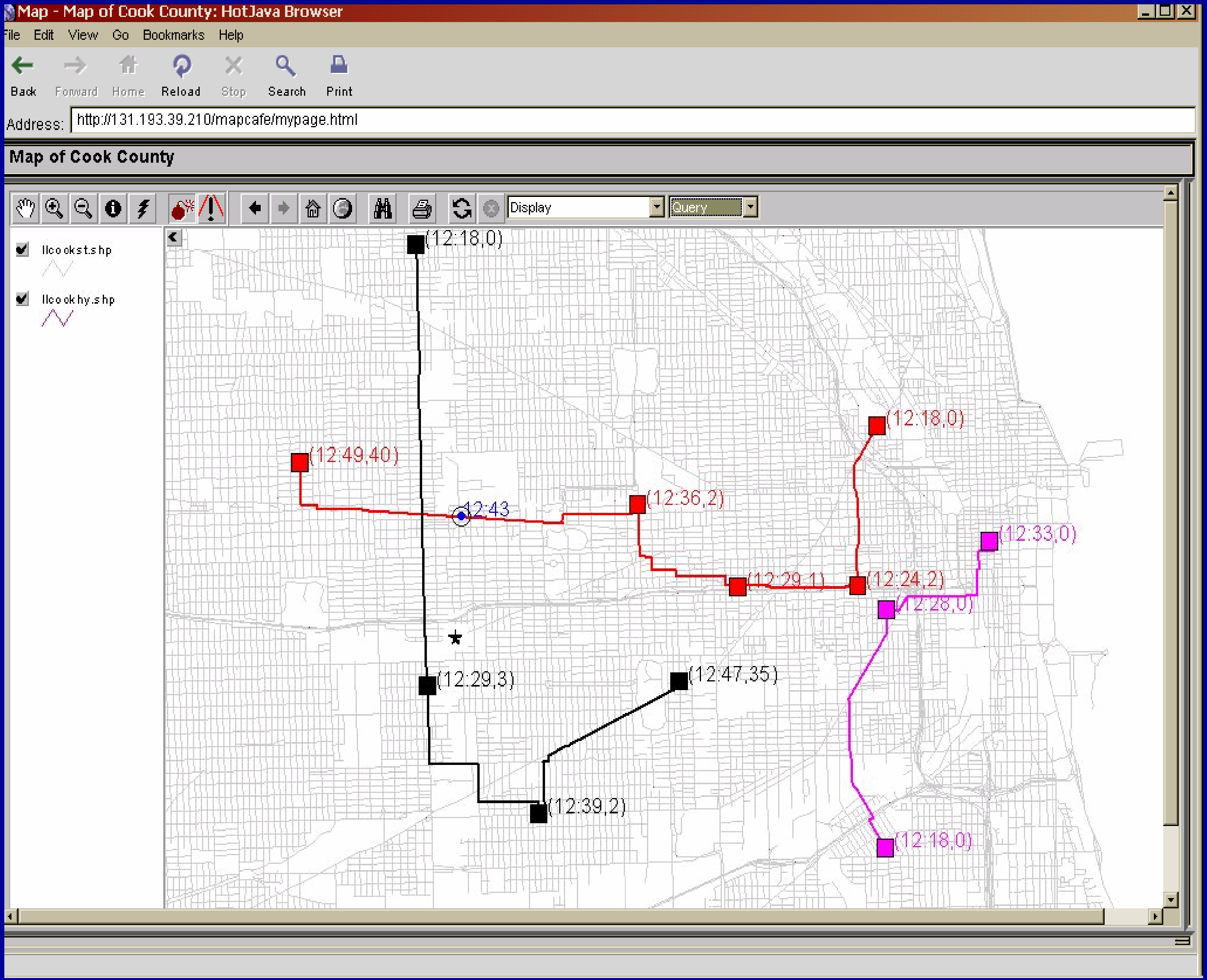
Query result showing all vehicle's locations at 12:35



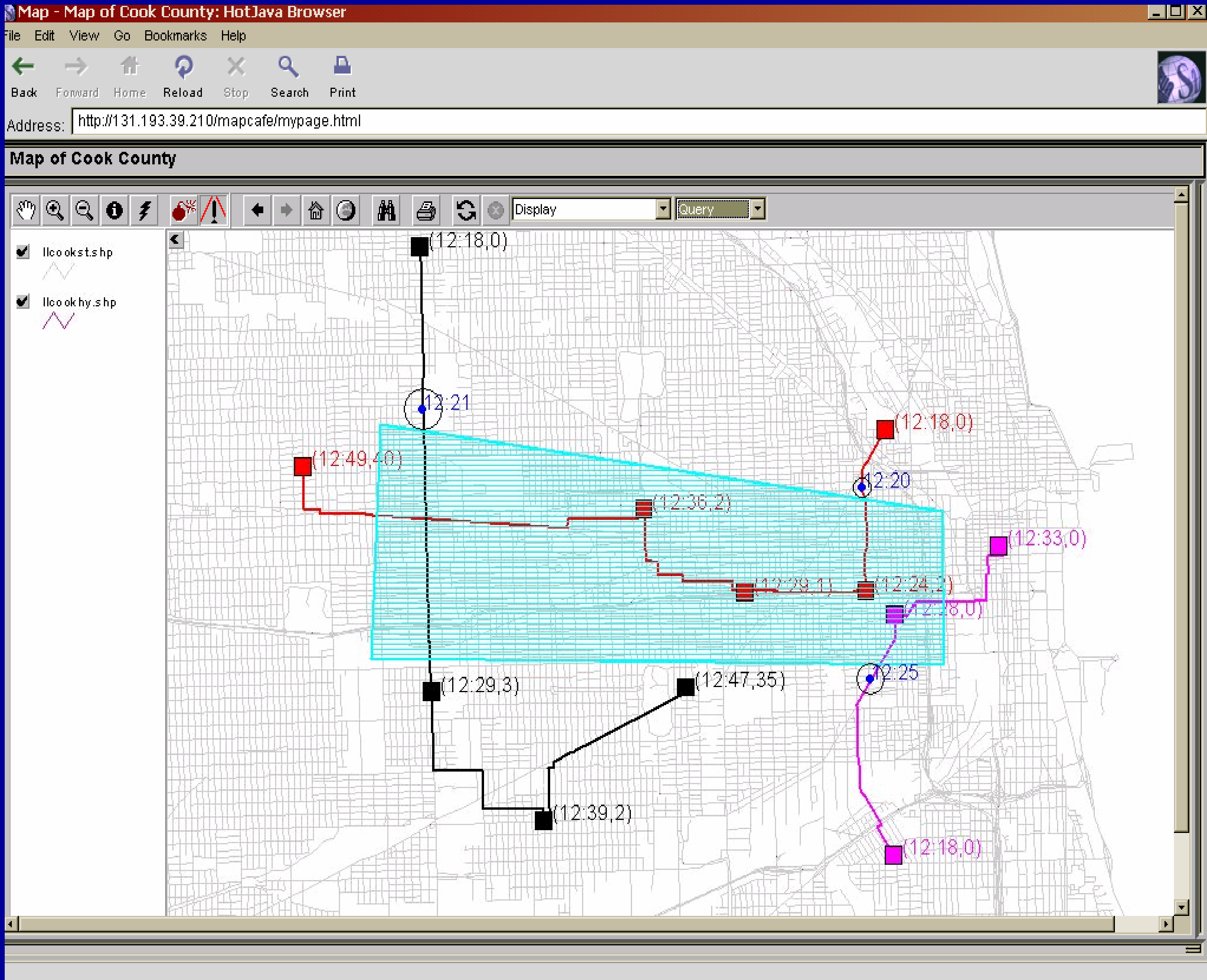
Which vehicle will be closest to the “star” between 12:35 and 12:50?



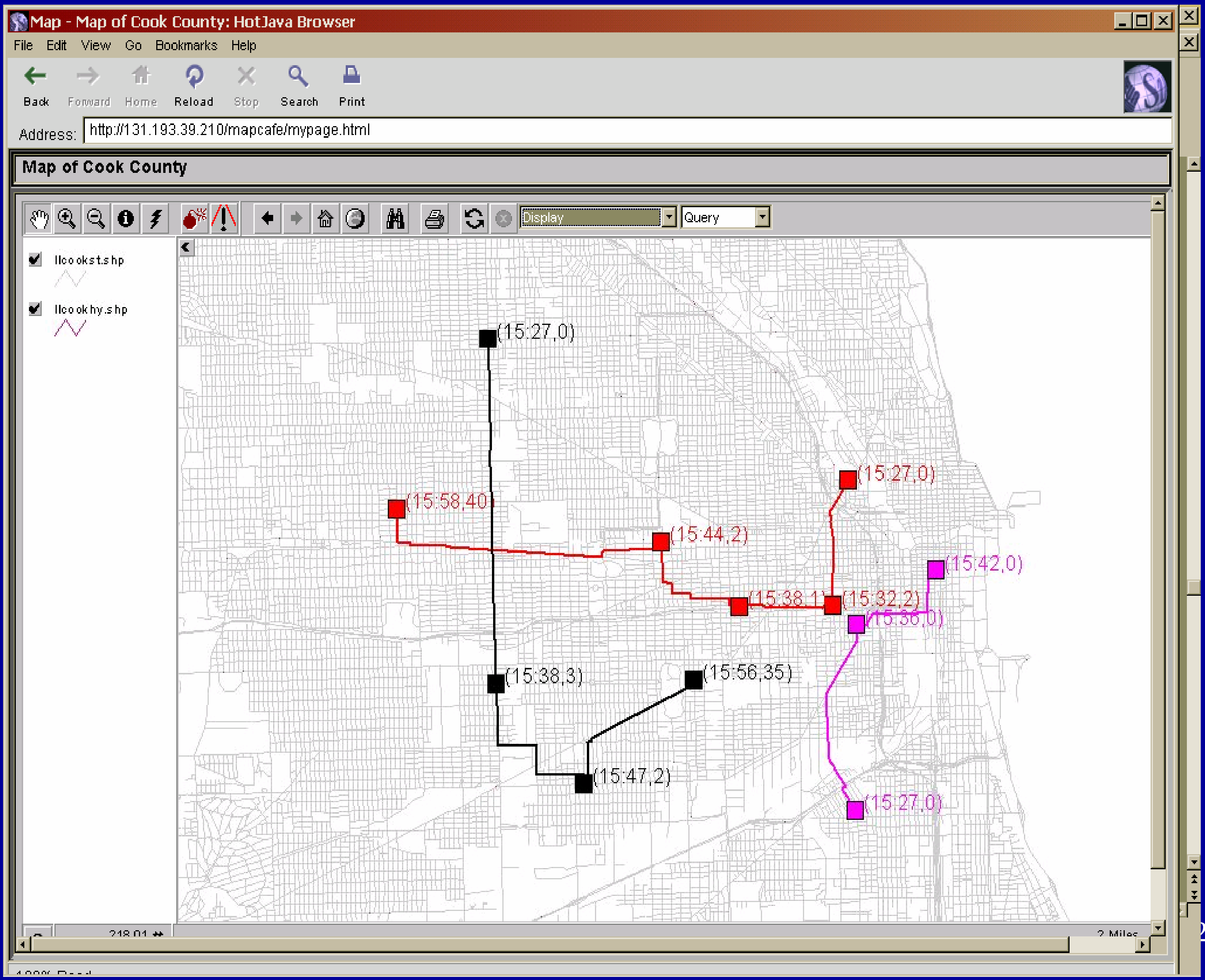
Answer: The vehicle on the red route



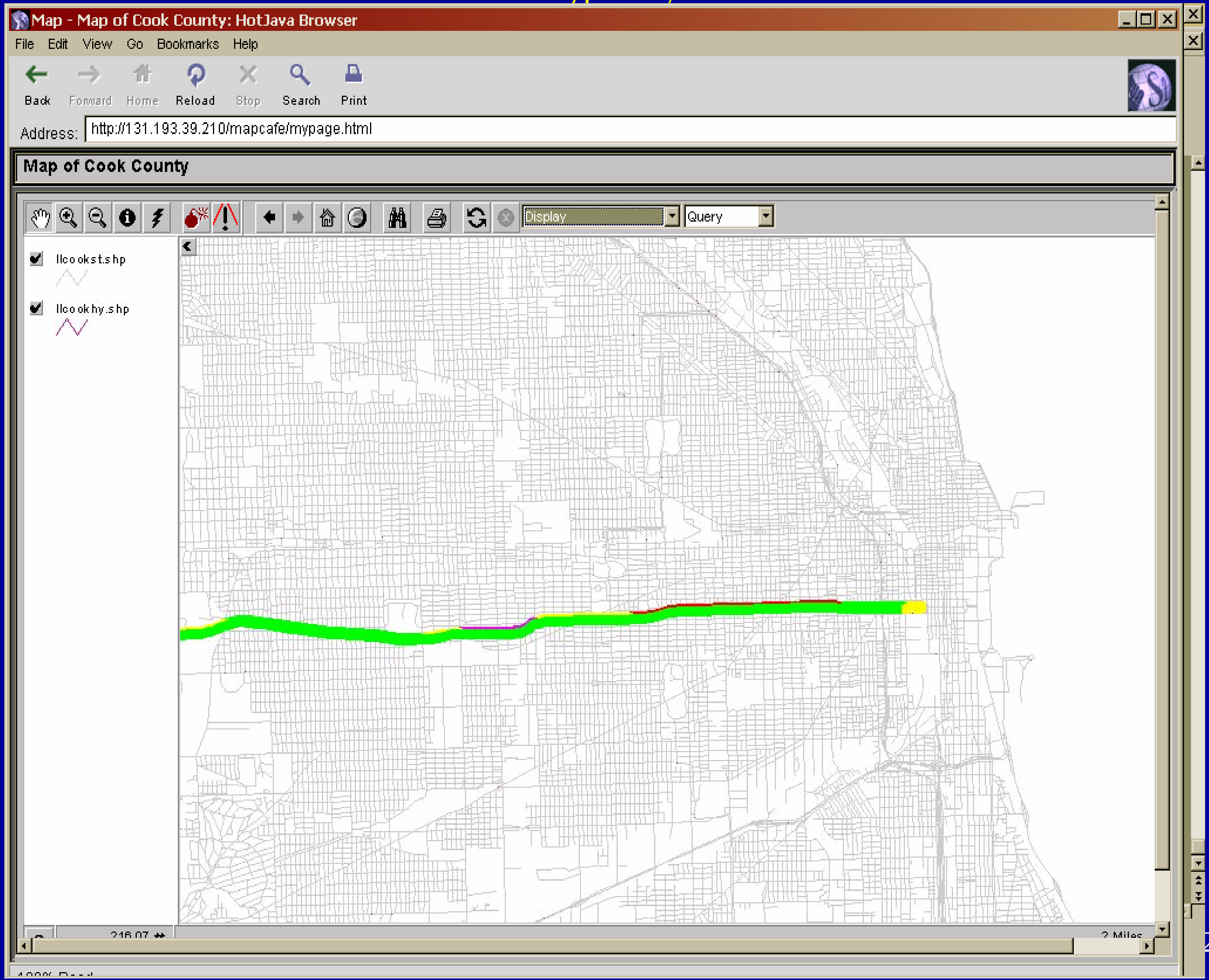
When will each vehicle enter the specified sector?



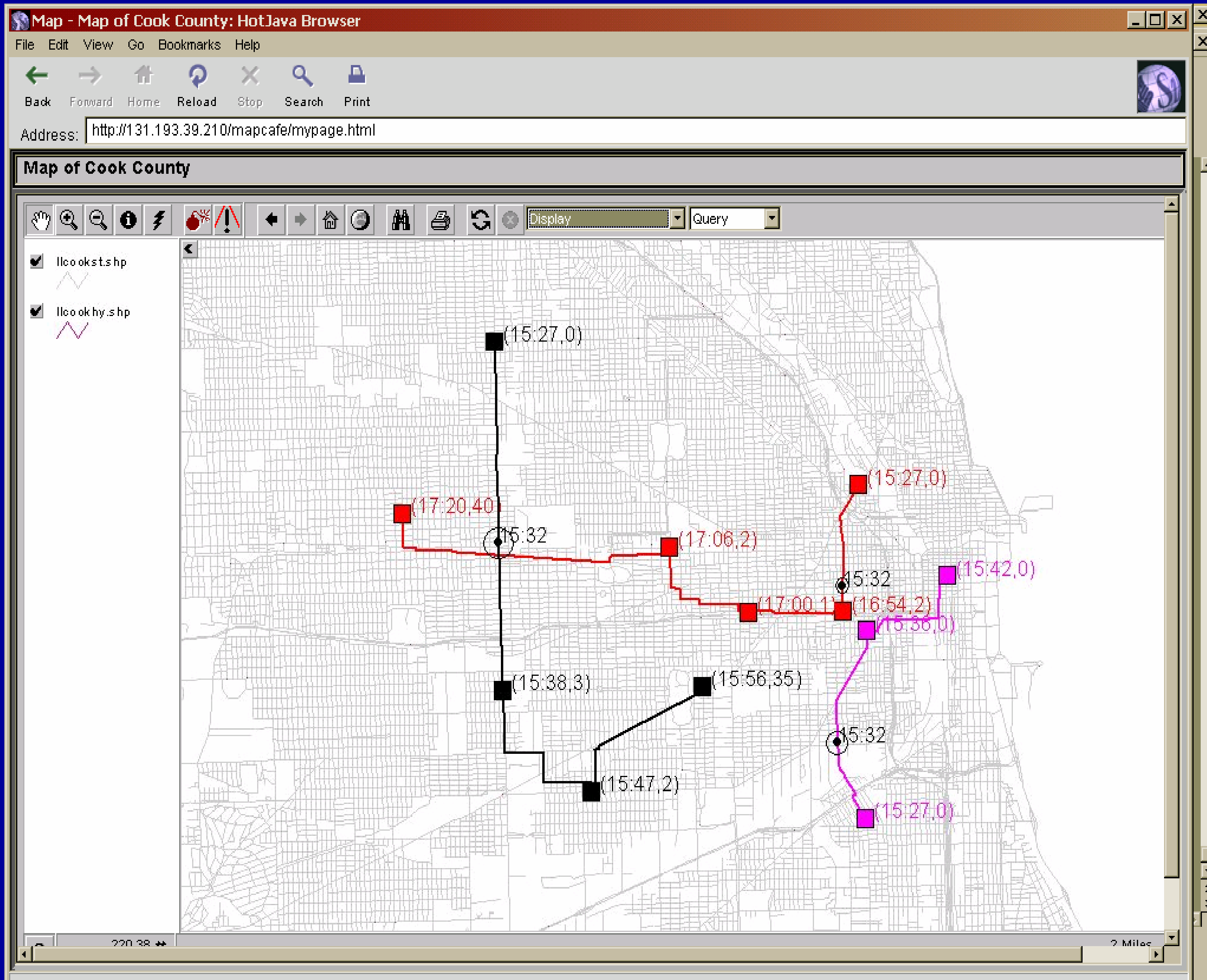
Routes prior to overlaying current traffic conditions



Real-time traffic showing delays on east/west road



Impact of traffic slows down vehicle on red route



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Location modeling/management

- In the cellular architecture (network location management)
- In Moving Objects Databases (geographic location management)

Location management in cellular architecture

- Network finds out location (cell) of moving object when turned on.
- Location database consists of records (key, cell-id)

- It supports 2 types of operations.
  - Point Query: Find the *current* location (cell) of moving object with key 707-476-2276
  - Point Update: Update the *current* location (cell) of moving object with key 707-476-2276
- These operations must be executed very efficiently

Main Research Issue

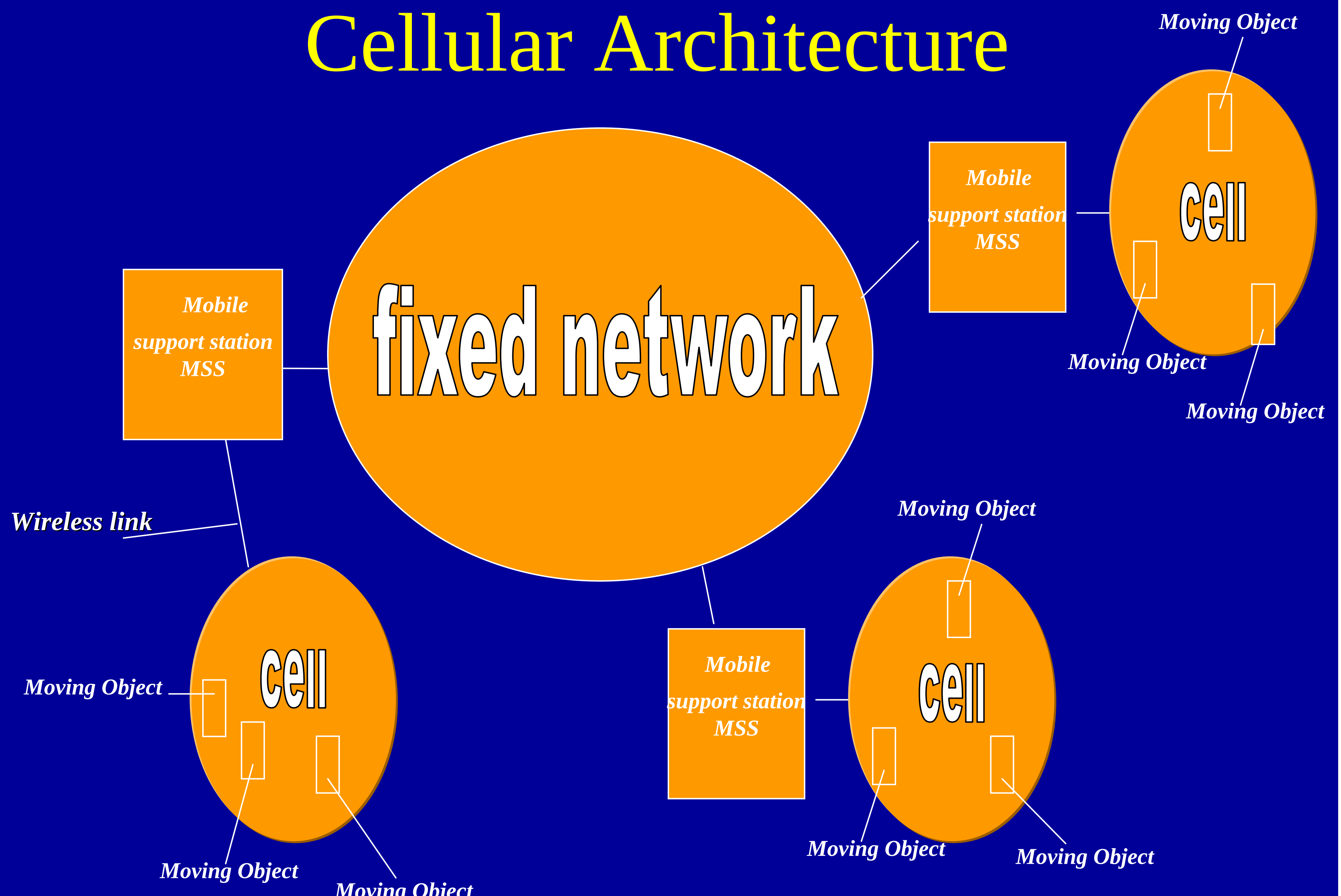
- Data allocation and replication of the location records (key, cell-id)

Where is each record stored/replicated/cached ?

How frequently is it updated?

How is it searched?

Cellular Architecture

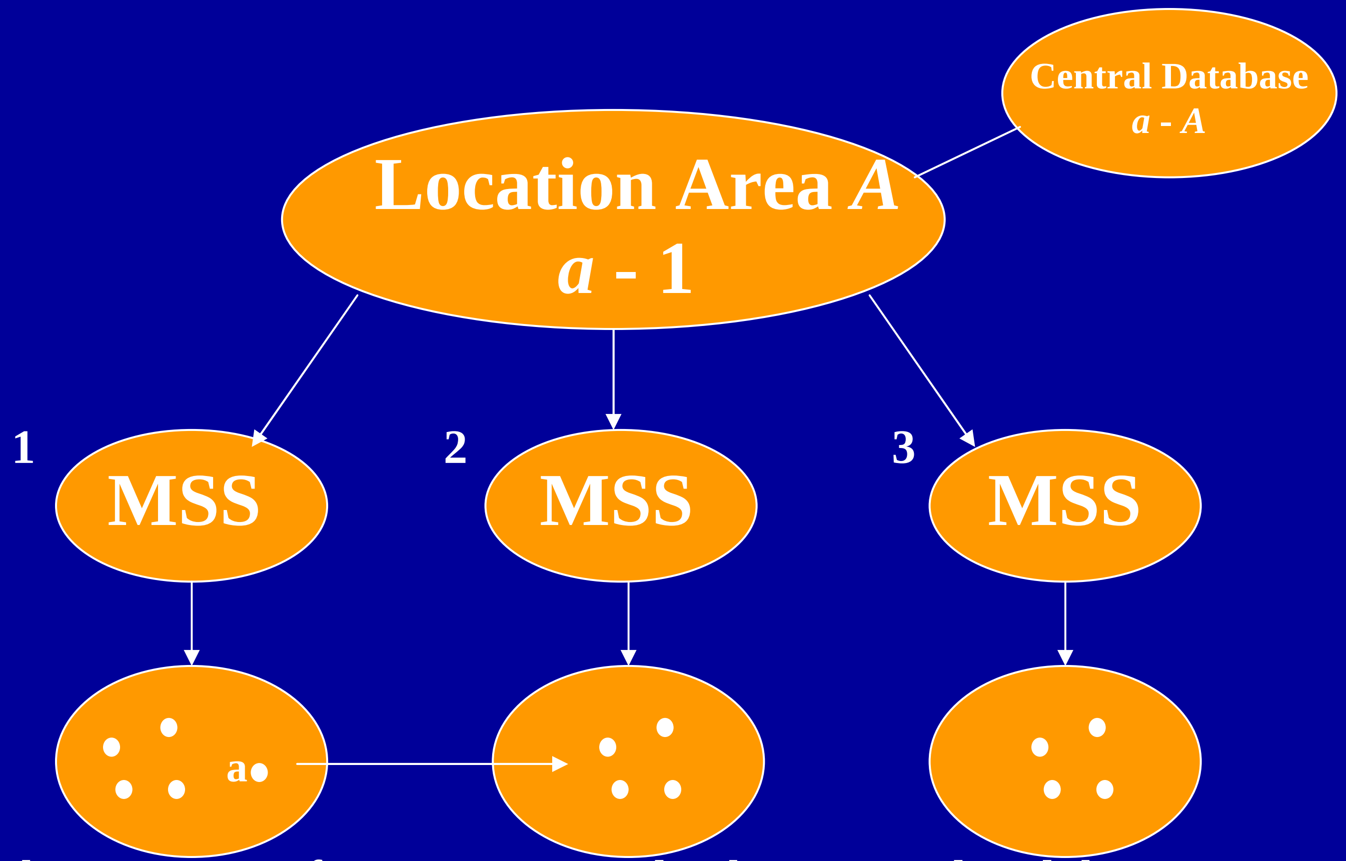


Cell size ranges from 0.5 to several miles in diameter in widearea terrestrial networks

Some naïve solutions

- Centralized database: all location records reside at a central location.
  - Drawback: Remote lookup for every call, and remote update for every cell crossing.
- Fully replicated: all location records are replicated at each MSS.
  - Drawback: for every cell crossing the database at every MSS has to be updated.
- Partitioned: each MSS keeps a database of the moving objects in its cell
  - Drawback: for every remote call the database at each MSS has to be queried.

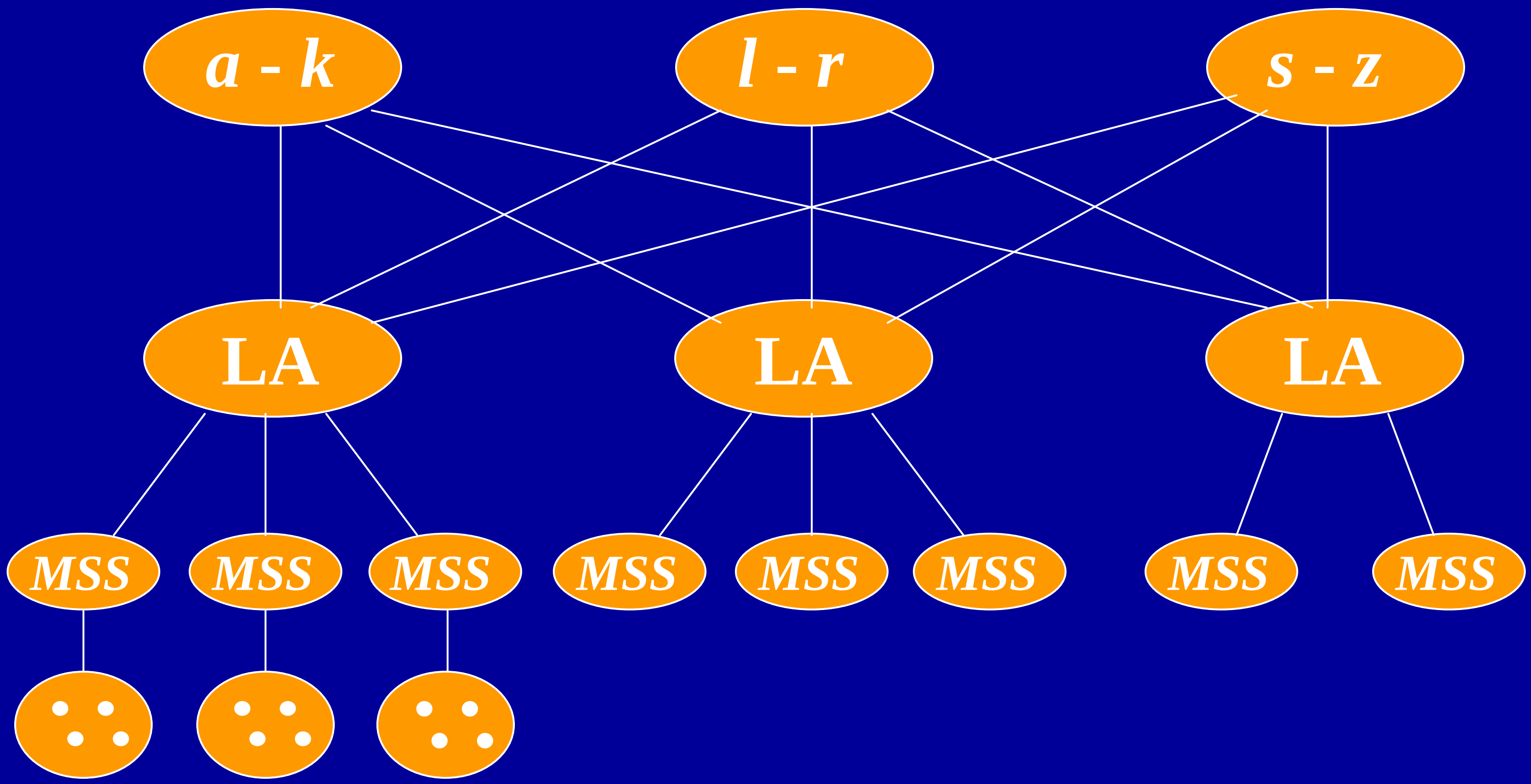
Hierarchical Solution



- When *a* moves from 1 to 2 LA database is updated, but not central database.
- A call that originates in 2 needs to search only the LA database.
- This scheme exploits the locality of calls and moves.
- Can obviously be generalized to arbitrary number of levels.
- Call execution uses a different network.

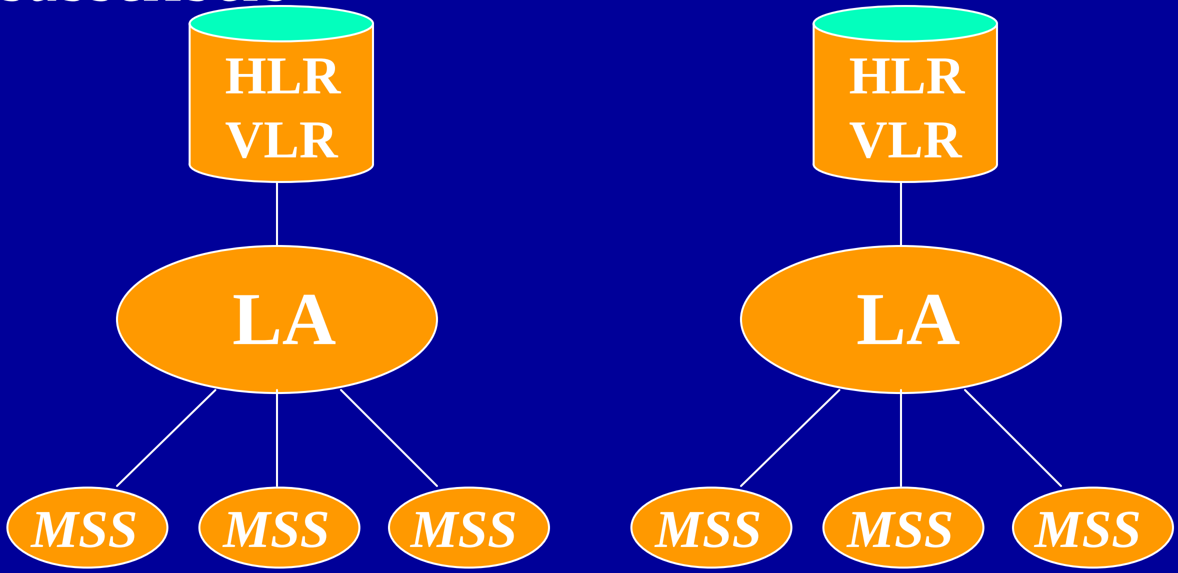
Variant

- Partition the centralized database



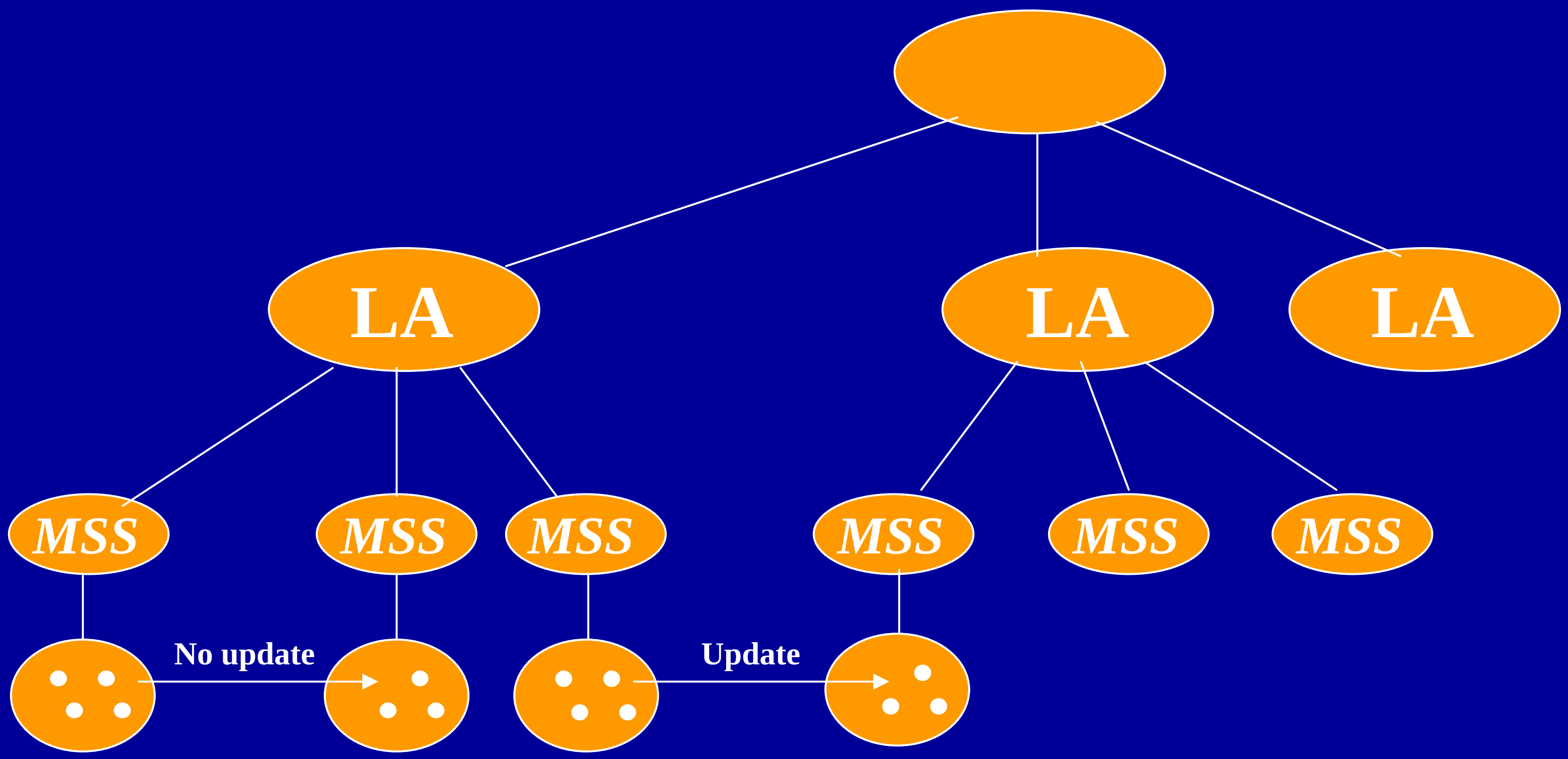
European and North American Standard

- Notion of home location
- Partition centralized database based on home location of subscribers



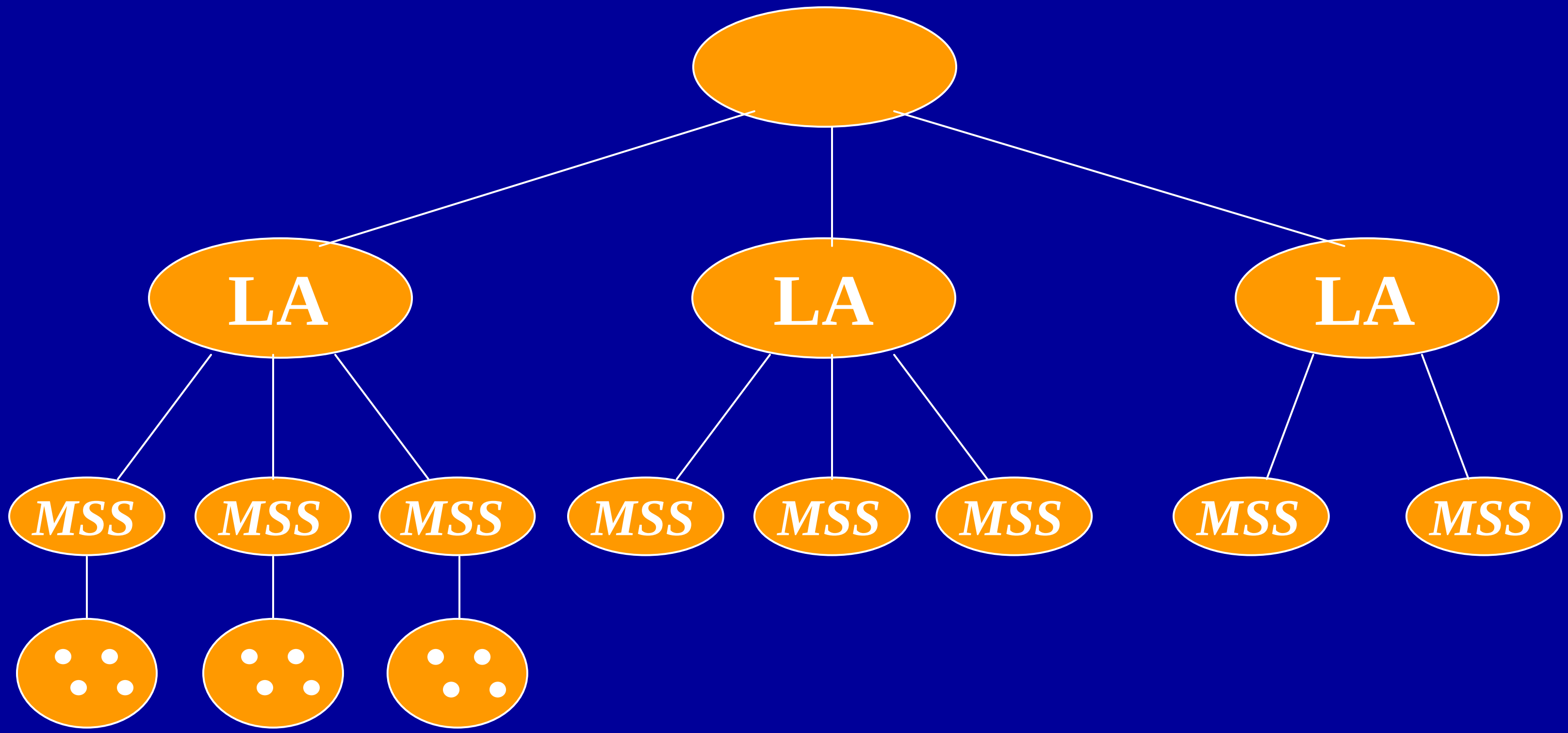
Home Location Register – Profile and MSS of local subscriber
Visitor Location Register – MSS of visitor in LA
Move – Update HLR to point to new MSS or foreign VLR, or update VLR
y call *x* – Check local VLR of *y*, if not found check HLR of *x*

Variant



- Don’t update on local cellular move, only LA move
- Call: Page in LA
- Database update activity is reduced at the expense of paging activity.
- Useful for users that move a lot, but do not get many calls.
- Paging overhead can be further reduced by prediction

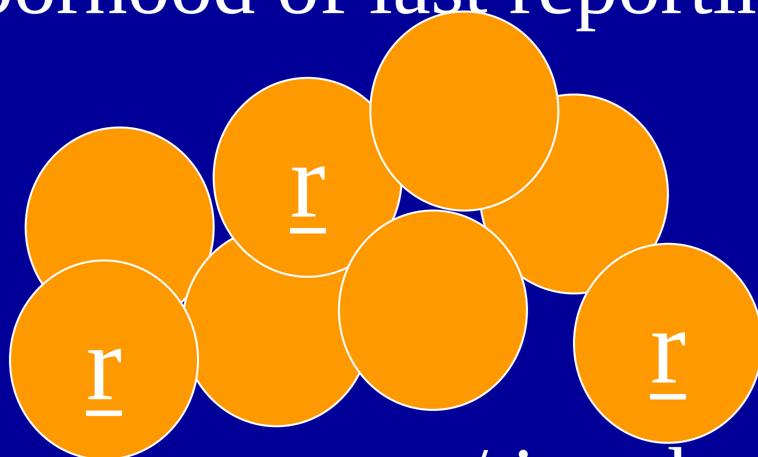
Variant



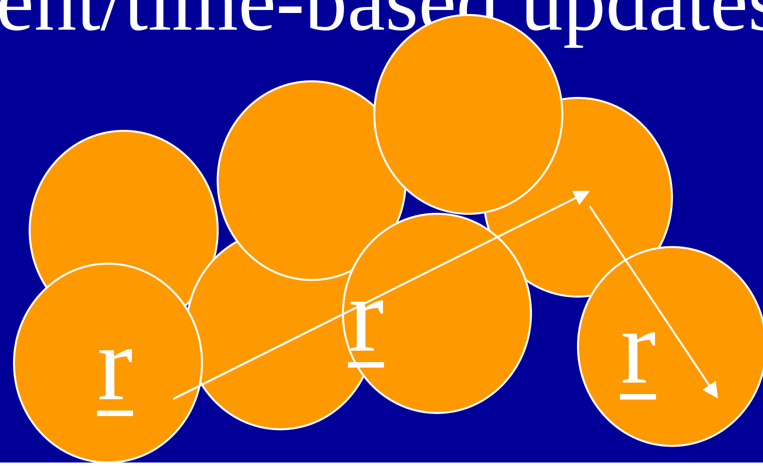
- Cache in LA database the MSS of remote users called recently

Other Variants

- Designate some cells as reporting cells (moving objects must update upon entering them); calls processed by paging neighborhood of last reporting cell



- Distance/movement/time-based updates



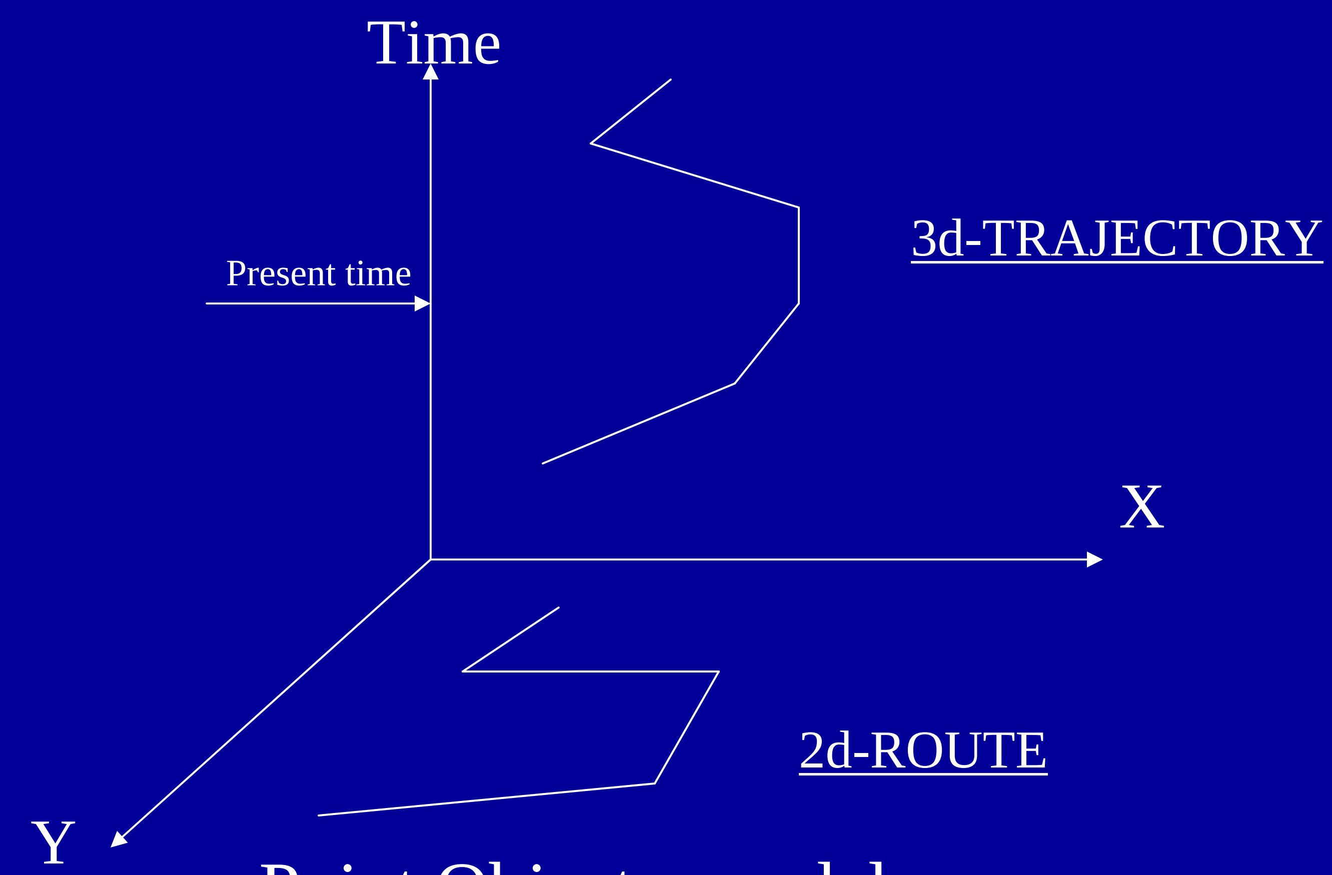
Other Variants (continued)

- Data mining and prediction mechanisms to reduce location-update traffic and compensate for this by a smart search/paging on calls.
- Objective: tradeoff between search and update overhead to balance total load
- Comprehensive survey: Pitoura & Samaras 99

Geolocation management

- Why is it different?
  - Higher resolution
    Joe, pick up a customer in cell 75 ! -- doesn't work since diameter may be > 3 miles
  - Interested in past and future location
  - Variety of queries

Model of a trajectory for geolocation management



Point Objects: model

needs to be extended for objects with extent, eg, hurricanes

Approximation: does not capture acceleration/deceleration

Trajectory Construction - example

- Based on GPS points (x1,y1,t1), (x2,y2,t2),…

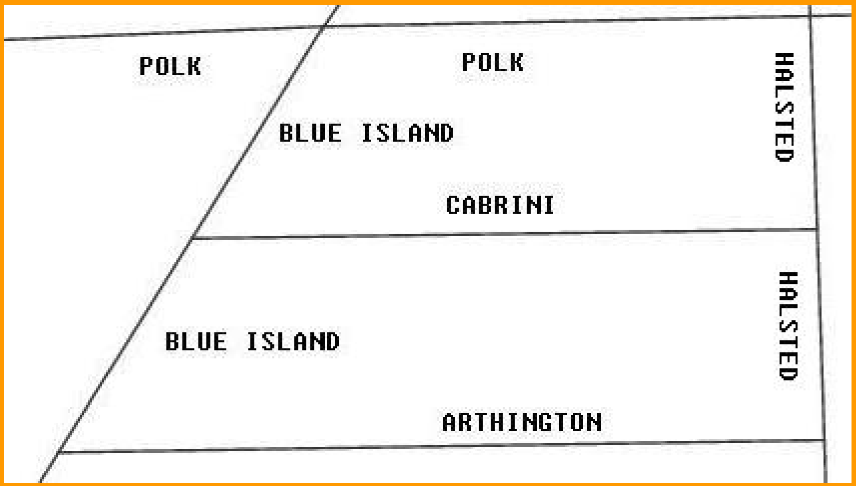
- For vehicles moving on road networks, construction uses a **map**.

Map

- A relation

  tuple <----> block, i.e. section of street between two intersections

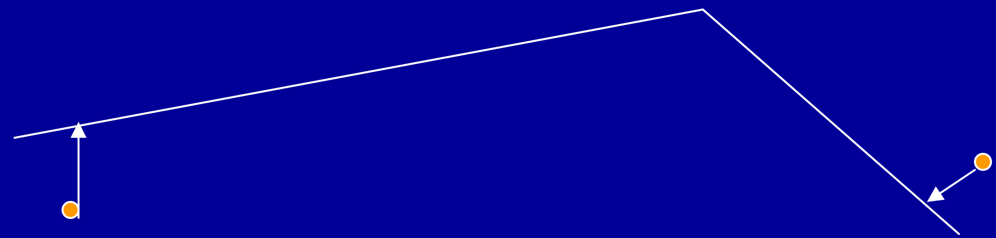
A region taken from the map of Chicago →



bid	polyline	name	category	Avg speed	one_way	R_f_add	R_t_add	… …
167980		ARTHINGTON	A40	25	No	312	398	… …
167985		CABRINI	A40	25	No	728	782	… …
167982		HALSTED	A31	25	No	906	956	… …
167981		HALSTED	A31	25	No	864	891	… …

Past-trajectory construction

- Based on GPS points (x1,y1,t1), (x2,y2,t2),…
- "Snap" points on road network



- Find shortest path on map between consecutive gps points

Future-trajectory construction

- Client informs location server of:
  - start-time of trip
  - start-location
  - destination(s)
- Server finds shortest path on a map
- Converts path into a trajectory using drive-time attribute

Enables Prediction

- Time-travel queries
  e.g. Where will object X be in 10 mins?

Trajectory Poly-line as Current-Location attribute

- Similar to Location attribute for static objects
- DBMS provides an abstraction of the trajectory data – Dynamic Attribute
- Value of Dynamic Attribute continuously changes as time progresses
- Vast implications for query processing -- open research problem
- Moreover: Dynamic Attribute should account for uncertainty.

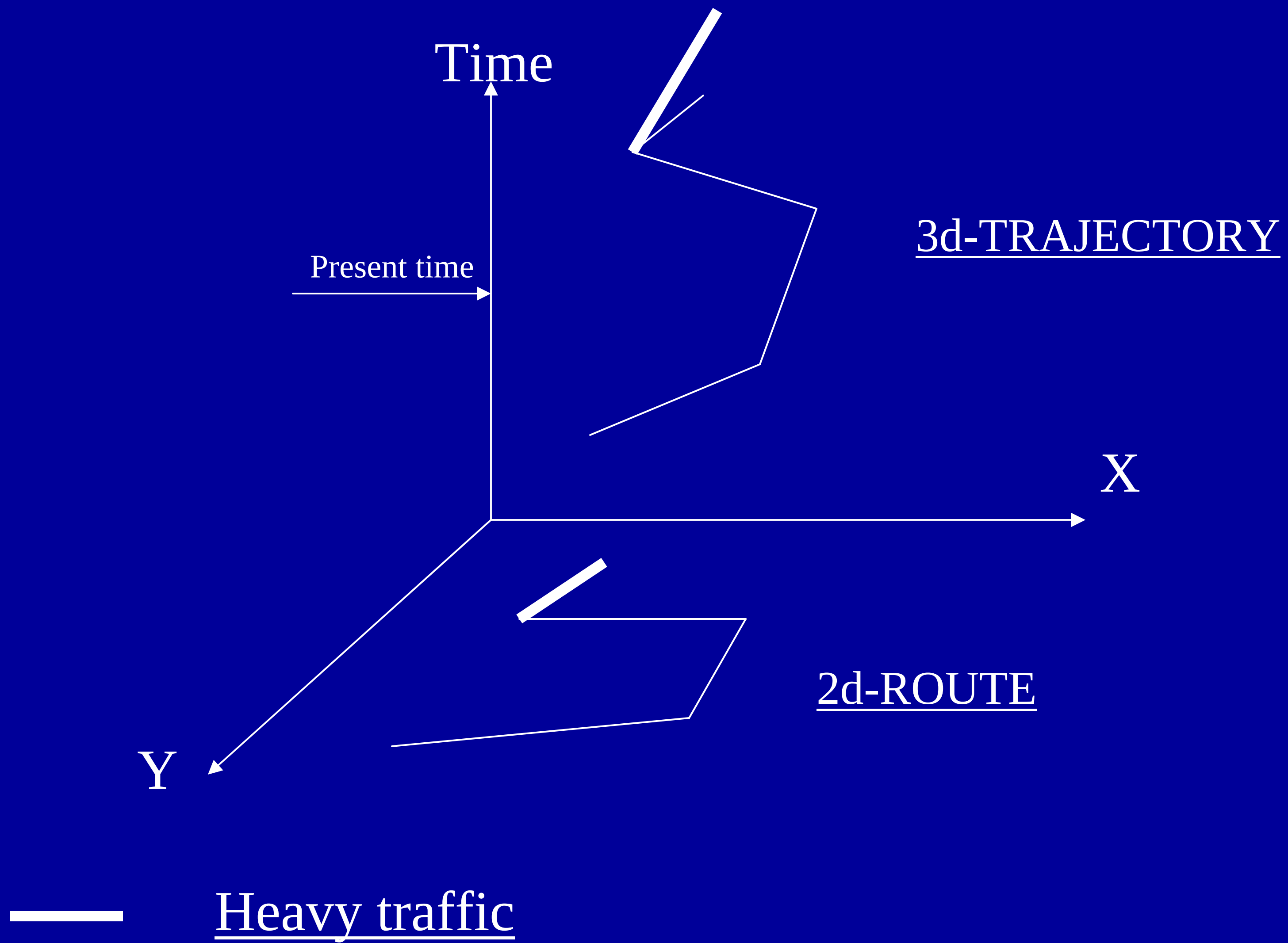
Other Applications of Dynamic Attributes – Modeling continuous phenomena

- Fuel Consumption
- Temperature
- Weather conditions

Traffic effects

OW2

Trajectory Modification

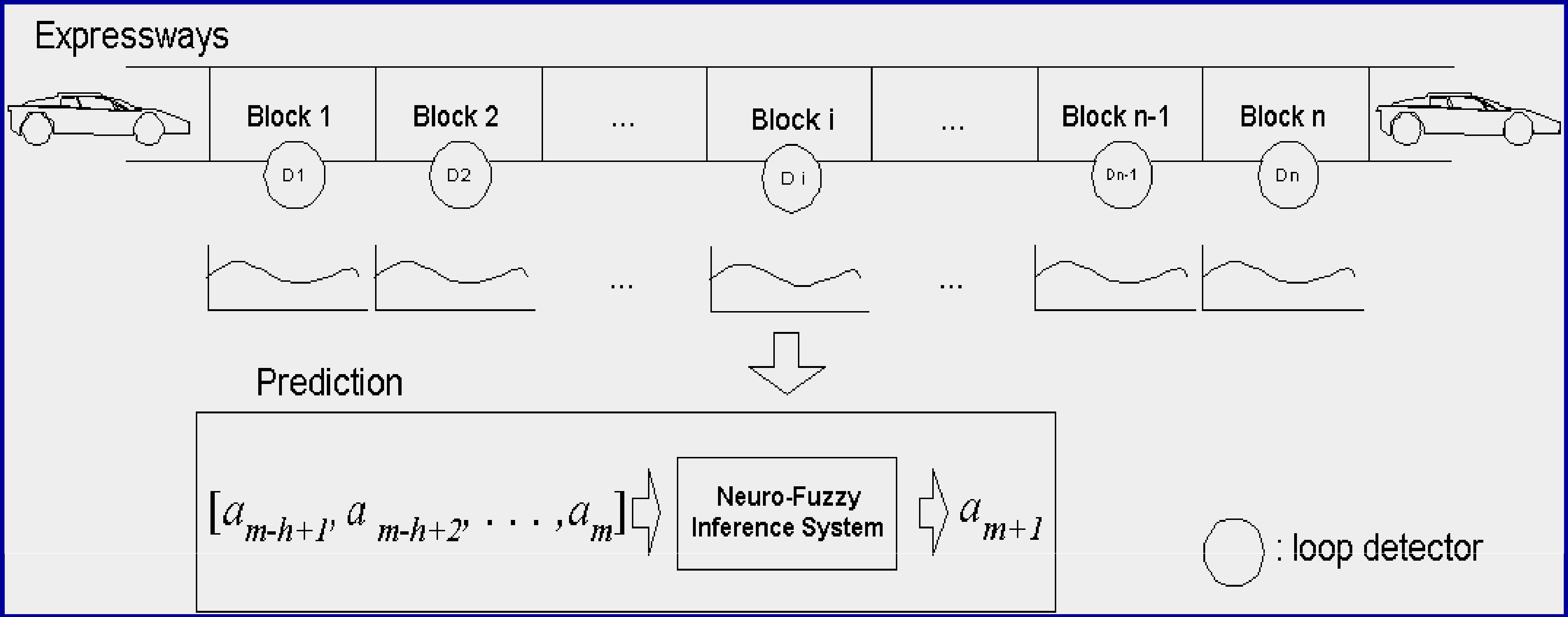


Slide 47

OW2 before present time: completed motion.
after present time: expected motion
Ouri Wolfson, 7/23/2003

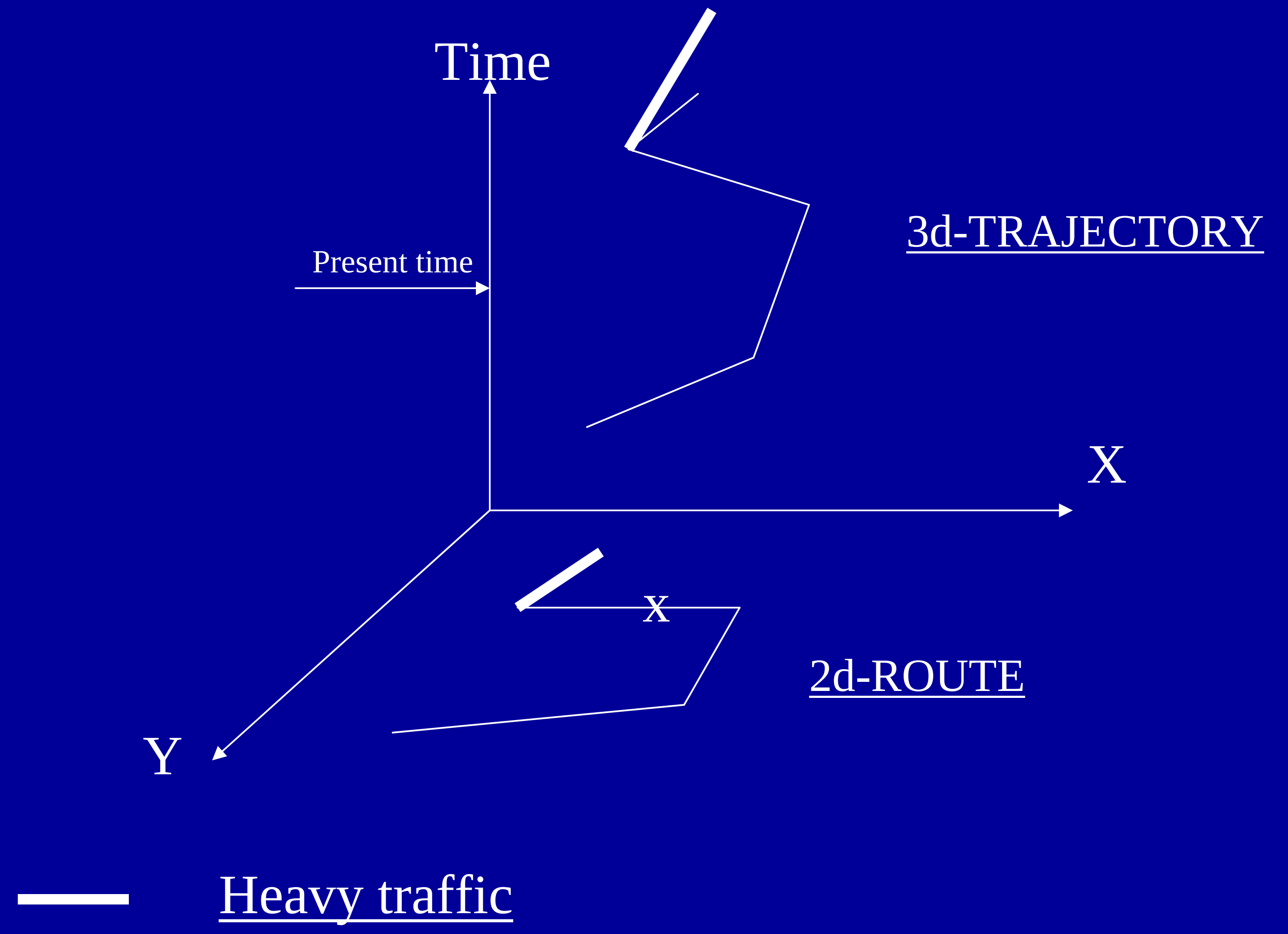
Traffic information sources

Loop sensors



Probe vehicles

Trajectory update involves speed prediction



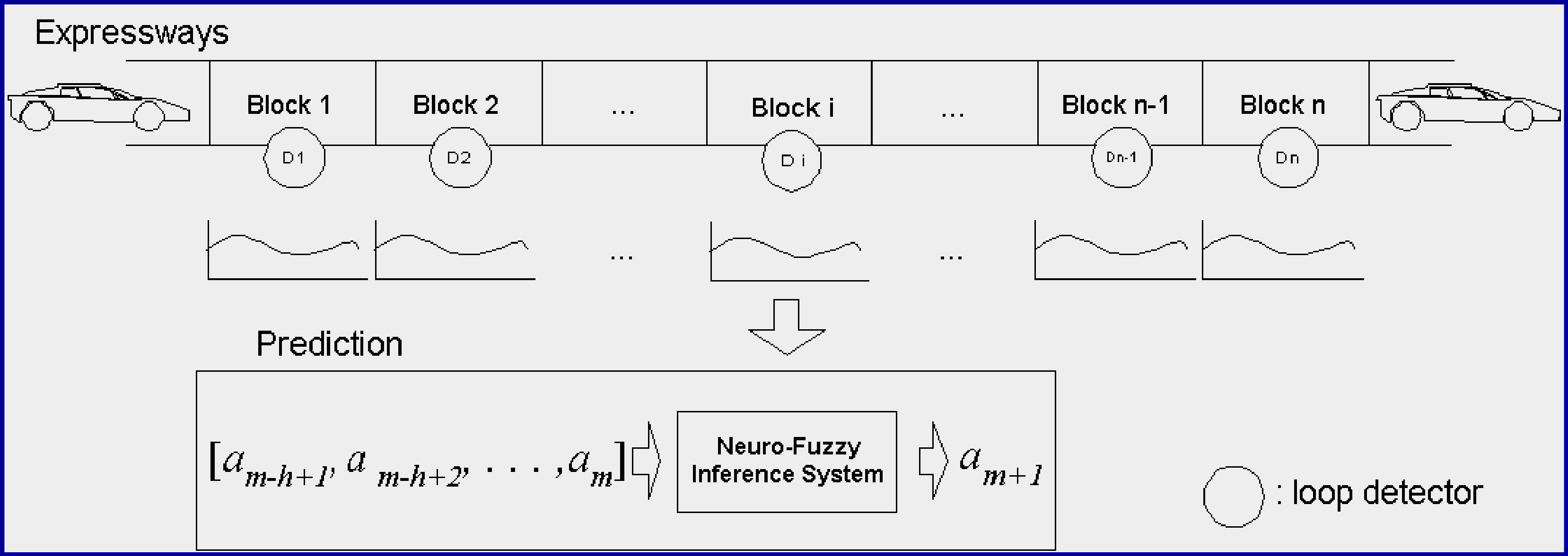
Problem 1: Speed (time series) prediction

- performance of different time-series prediction methods

Three Time-series Prediction Methods

- Two widely used methods:
  - Moving Averages: the next predicted value is the average of the latest *h* values of the series
  - Exponential Smoothing: The next predicted value is the weighted average of the latest *h* values, and the weights decrease geometrically with the age of the values
- Neural-Fuzzy Inference Systems (NFIS)
  - Fuzzy rule based inference +
  - Neural back-propagation rule base learning

Comparison by Experiments

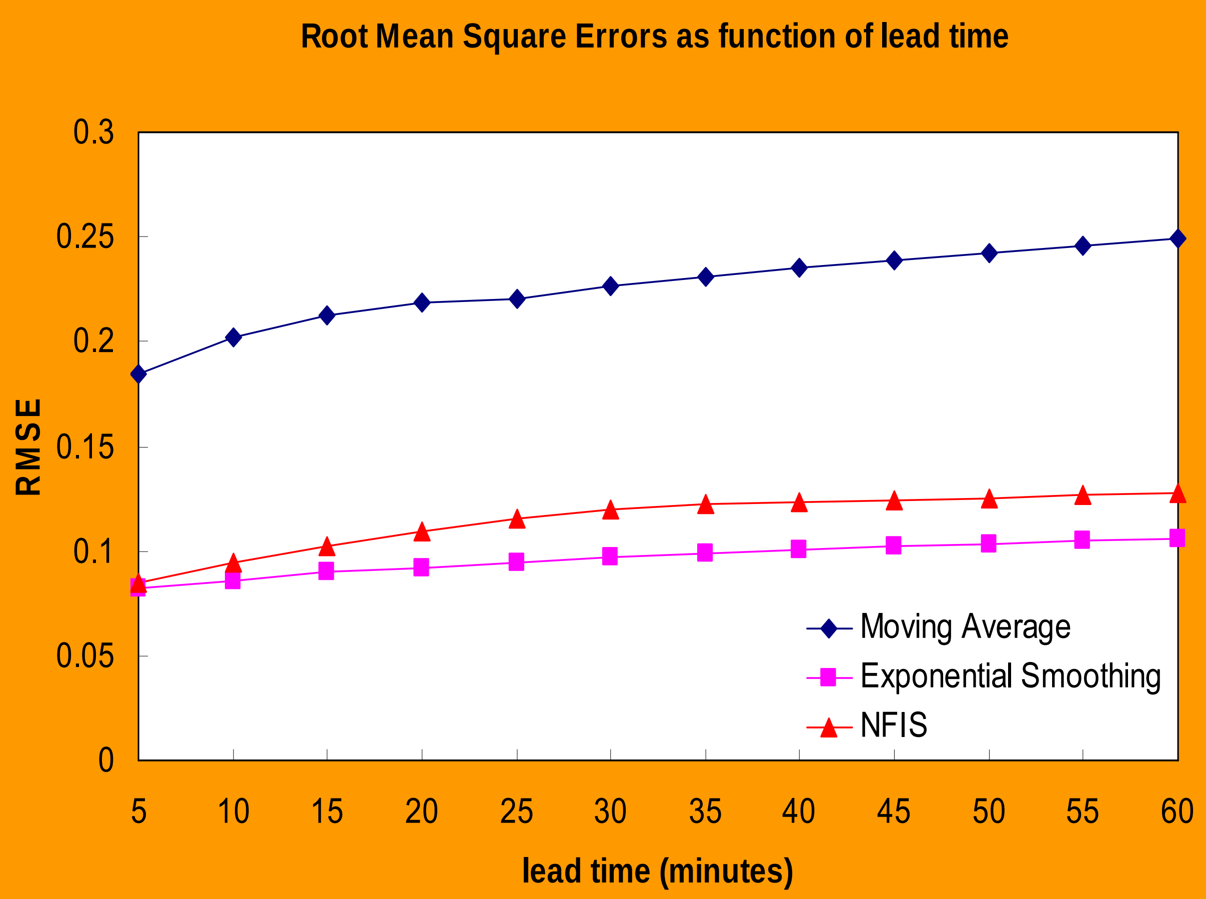


Experimental Environment

- Real speed time-series collected on the Edens Expressway in Chicago

- Speed data collected for each of the 72 blocks every 5 minutes for 20 days

Simulation Results



Prediction not beneficial beyond 15 minutes horizon

Problem 2: Avoid continuous trajectory revision

- Solution idea: filter + refinement at query time

Traffic prediction references:

[1] J. S. R. Jang, C. T. Sun, and E. Mizutani. .*Neuro-Fuzzy and Soft Computing*. Prentice-Hall, 1997.

[2] D.~C. Montgomery, L.~A. Johnson, and J.~S. Gardiner. *Forecasting and Time Series Analysis*. McGraw-Hill, 1990.

[3] Y. Ohra, T. Koyama, and S. Shimada. Online-learning type of traveling time prediction model in expressway. *In Proc. of IEEE Conf. on Intelligent Transportation System*, pages 350--355, Nov. 1997.

[4] H. Dia. An object-oriented neural network approach to short-term traffic forecasting. *European Journal of Operational Research*, 131:253--261, 2001.

[5] J. Anderson and M.~Bell. Travel time estimation in urban road networks. *In Proc. of IEEE Conf. on Intelligent Transportation System*, pages 924--929, Nov. 1997.

[6] G. Trajcevski, O. Wolfson, and B. Xu. Real-time traffic updates in moving objects database. *In the Fifth International Workshop on Mobility in Databases and Distributed Systems*, September 2002.

[7] L. Chen and F. Y. Wang. A neuro-fuzzy system approach for forecasting short-term freeway traffic flows. In *Proceedings of the IEEE 5th International Conference on Intelligent Transportation Systems*, September 2002.

[8] S. Pallottino and M. G. Scutella. Shortest path algorithms in transportation models: classical and innovative aspects. In *Equilibrium and Advanced Transportation Modeling*, Kluwer (1998) 245-281.

[9] J. Kwon, B. Coifman, and P.~J. Bickel. Day-to-day travel time trends and travel time prediction from loop detector data. In *Transportation Research Record*, number 1712, pages 120--129, 2000.

[10] G. Das, K. Lin, H. Mannila, G. Renganathan, and P. Smyth. Rule discovery from time series. In *KDD98*, pages 16--22, 1998.

Location Modeling References

[1] A. Prasad Sistla, Ouri Wolfson, Sam Chamberlain and Son Dao, *Modeling and Querying Moving Objects*, In Proceedings of the 13th International Conference on Data Engineering, p422-432, April 7-11, 1997 Birmingham U.K. IEEE Computer Society 1997.

[2] Evaggelia Pitoura and George Samaras, *Locating Objects in Mobile Computing*, Knowledge and Data Engineering, vol13, no.4, p571-592, 2001.

[3] Amiya Bhattacharya and Sajal K. Das, *LeZi-Update: An Information-Theoretic Approach to Track Mobile Users In PCS Networks*, In the proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking, p1-12, 1999.

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Spatio-temporal query/trigger languages

- Relational-oriented (Vazirgiannis and Wolfson 2001)
- Moving Objects Algebra (Gueting et. al. 98-2001)
- Future Temporal Language (Sistla, Wolfson 1997)
- Constraint Query Language (Moktar, Su, Ibarra 2000)

Types of Queries

- Instantaneous --- answer as of that time
    - Example: the motels within 5 miles of my current location
- Continuous --- the answer of the query is needed at each of the future instances. Query pertains to snapshot database
- Persistent: Like a continuous query but uses past as well future history.
    - Example: Trajectory updated twice within 3 miles / 3 mins

Queries may pertain to future

- Instantaneous: Which ambulances will be within 5 miles of hospital in the next 30 mins

  (a,b) – (12:00-12:20)
  (b,c) – (12:21-12:30)

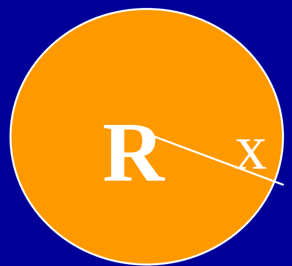
- Continuous: at 12:10 revised

  (b) – (12:10-12:20)
  (b,c,d) – (12:21-12:30)
  (b,c) -- (12:31-12:40)

Relational Oriented

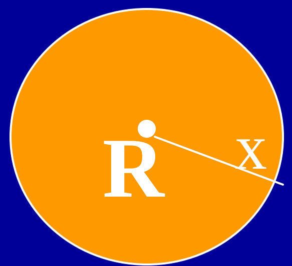
- Point queries:
  - **where** is object 75 at 5pm
  - **when** was object 75 at location (x,y)
- Range queries
  - temporal constructs
  - spatial constructs
  - processing of queries
- Join queries: Retrieve the objects that come within 3 miles of each other at some time-point

Spatio temporal range queries



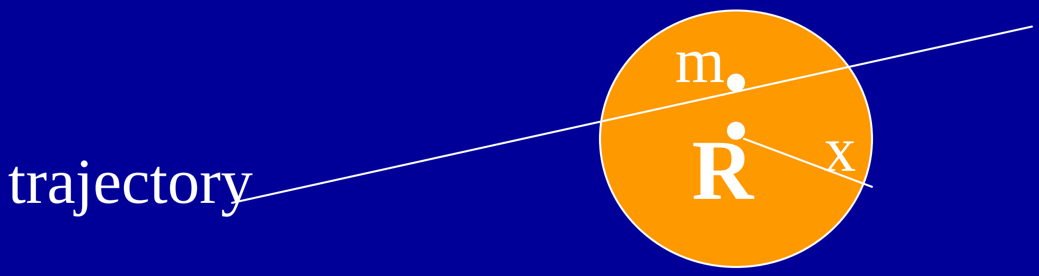
- R is a point
- Retrieve the objects that are within distance x from R, between times t1 and t2

<u>Range queries - option 1</u>



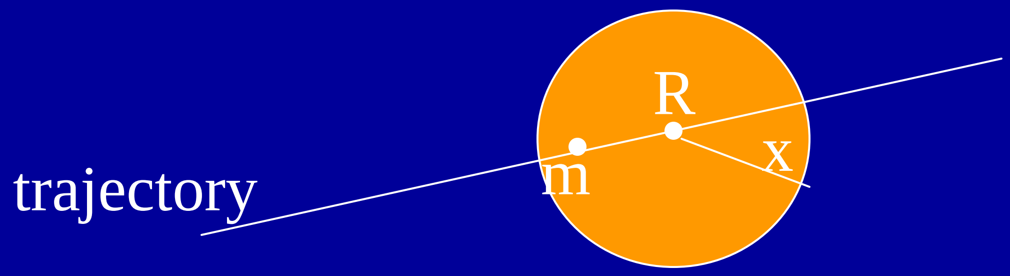
- Retrieve the objects that are <u>within</u> distance x from R, between times t1 and t2
  - – along shortest path
  - – along existing path

Range queries - option 1



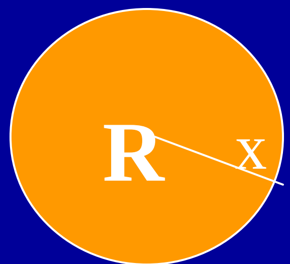
- Retrieve the objects that are <u>within</u> distance x from R, between times t1 and t2
  - along shortest path (police patrol vehicles)

<u>Range queries - option 1</u>



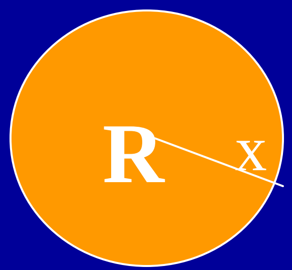
- Retrieve the objects that are <u>within</u> distance x from R, between times t1 and t2
  - along existing path (bus)

Range queries - option 2



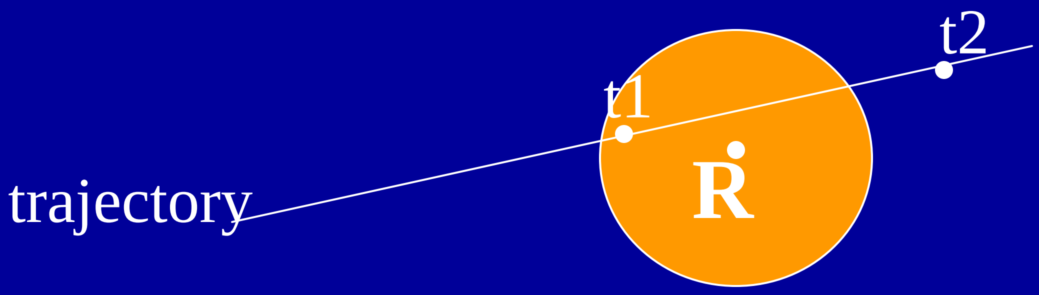
- Retrieve the objects that are within distance x from R, between times t1 and t2
- Cost metric
  - travel time
  - travel distance

Range queries - option 3



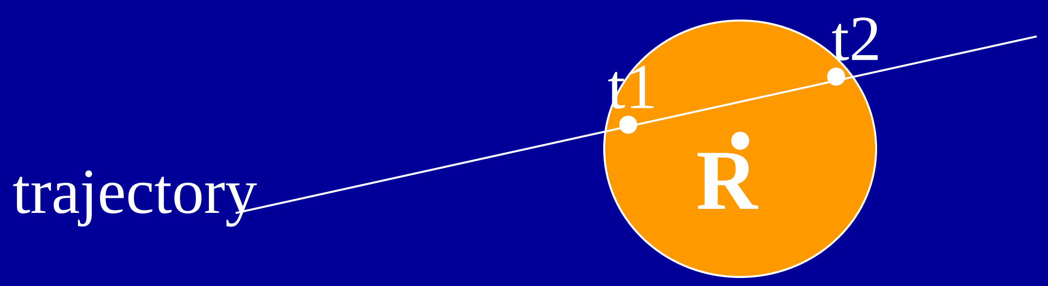
- Retrieve the objects that are in within distance x from R, between times t1 and t2
  - sometime
  - always

Range queries - option 3



- objects that are within distance x from R, <u>sometime</u> between times t1 and t2

Range queries - option 3



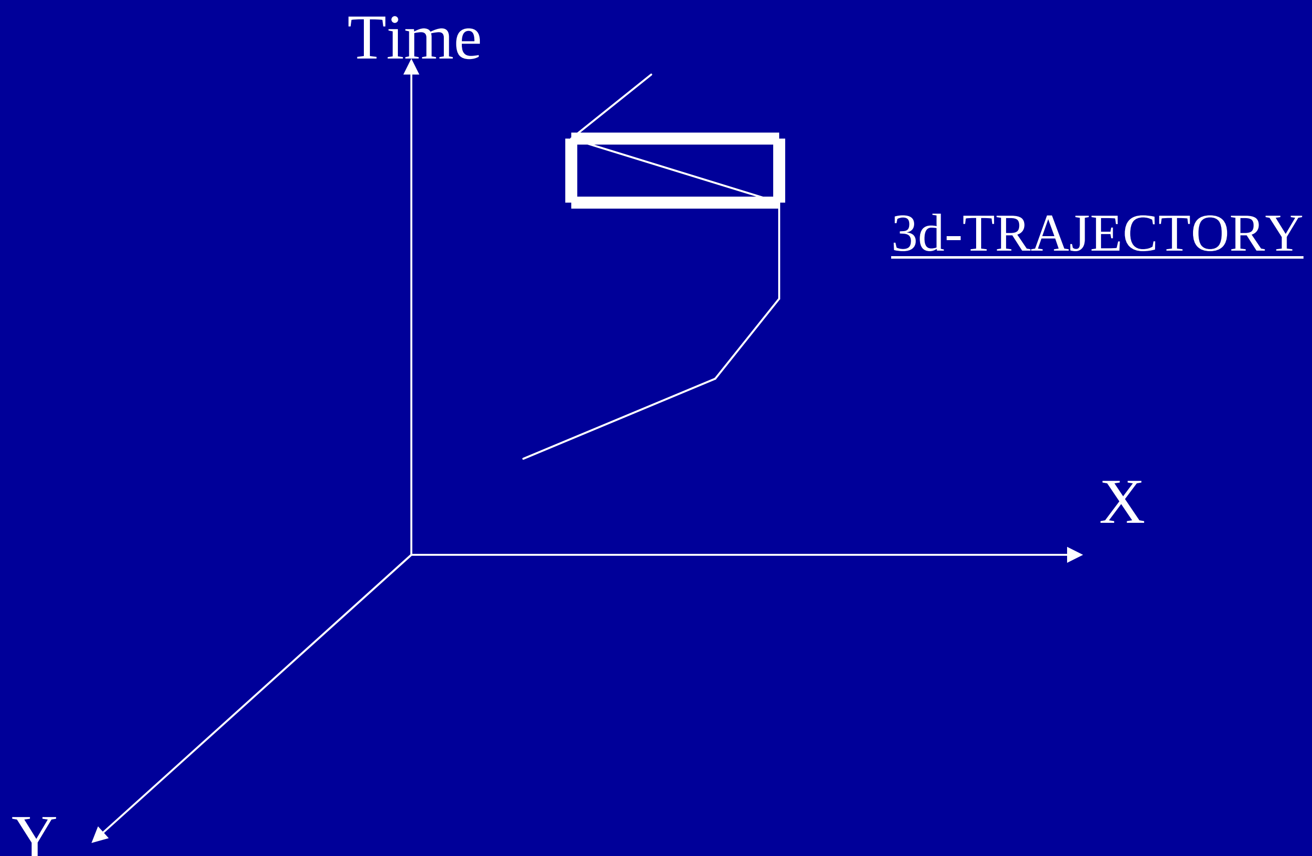
- objects that are within distance x from R, always between times t1 and t2

Range queries: 8 options

- R on object’s-route within travel-time 5 sometime between [t1,t2]
- R on object’s-route within travel-distance 5 sometime between [t1,t2]
- R on object’s-route within travel-time 5 always between [t1,t2]
- R on object’s-route within travel-distance 5 always in [t1,t2]

- R within travel-time 5 sometime between [t1,t2]
- R within travel-distance 5 sometime between [t1,t2]
- R within travel-time 5 always between [t1,t2]
- R within travel-distance 5 always between [t1,t2]

Trajectory Indexing



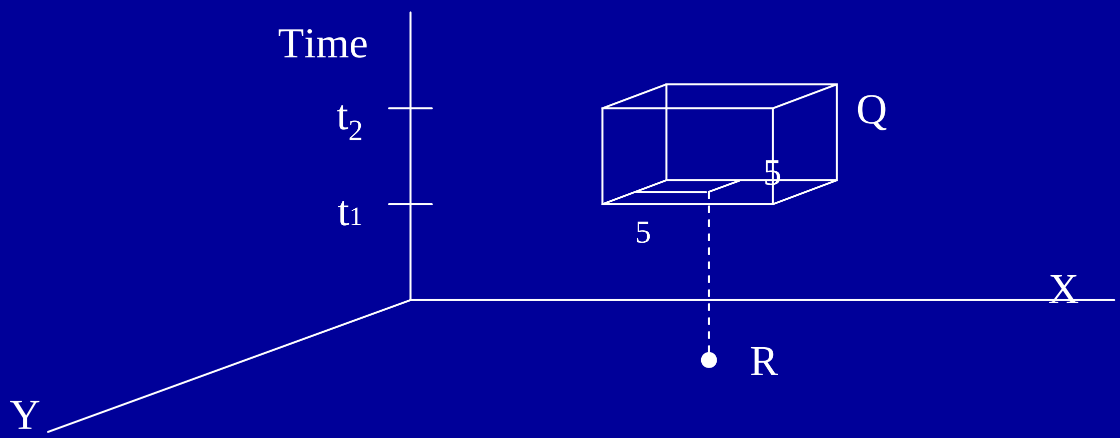
Enclose each trajectory segment in a 3d MBR and store in a spatio-temporal index (e.g. an R-tree) (Jensen and Pfoser)

Query Processing Strategy

- Filter -- represent a query as a geometric object Q, and retrieve all the rectangles of the spatio-temporal index which intersect Q
- Refinement -- Check for each trajectory that is stored in a retrieved rectangle whether it satisfies the query.
- Processing methods differ significantly

R on Route, within Distance 5, Sometime[t_1,t_2]

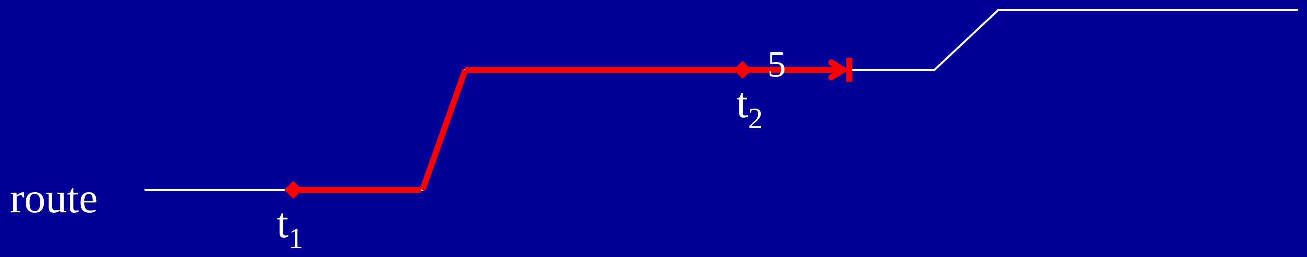
Filter:



S = set of trajectories that are at aerial distance 5 sometime [t_1,t_2]

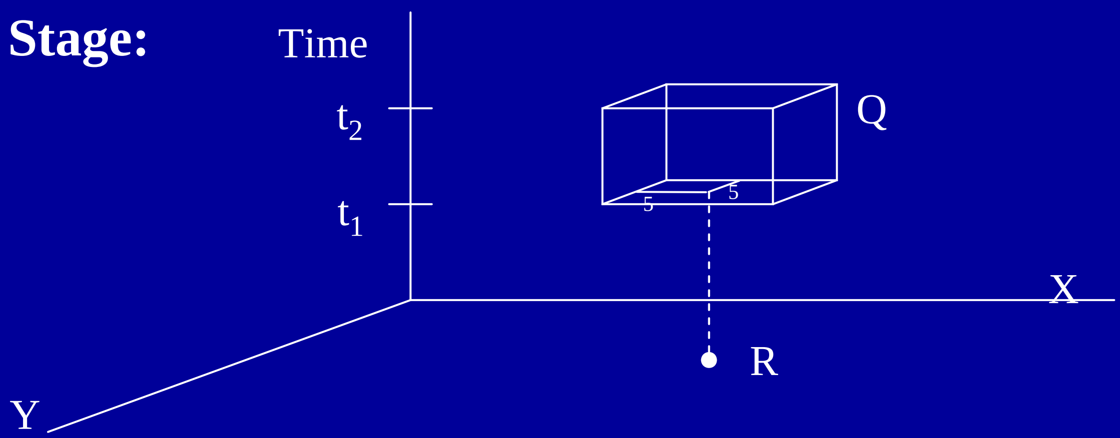
Refinement:

For each trajectory in S, Check that R is on the red route section.



R on Route, within Distance 5, Always[t_1,t_2]

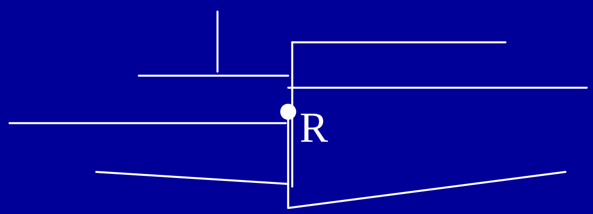
Filter Stage:



S = set of trajectories that are at aerial distance 5 sometime [t_1,t_2]

Refinement:

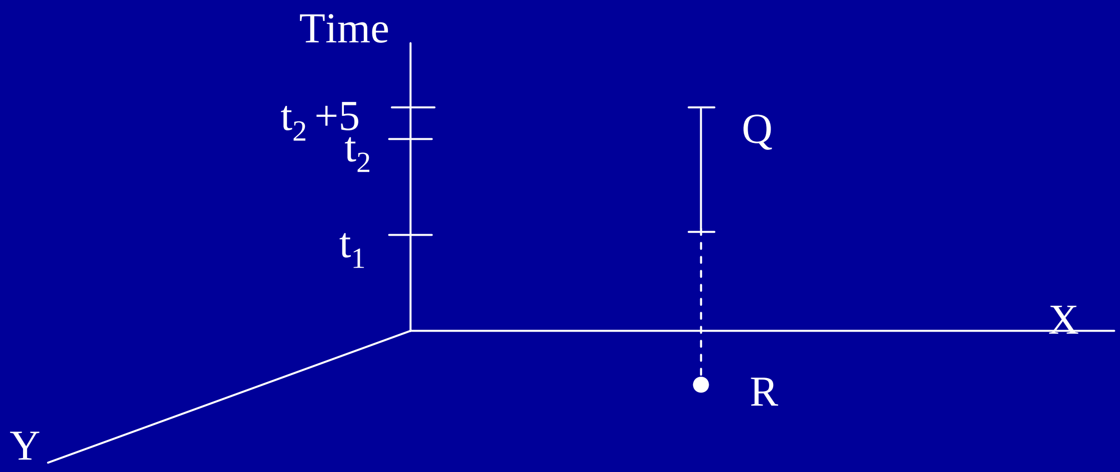
1) P := all route segments within distance 5 from R (using shortest path on map).



2) For each trajectory in S check whether all route segments traversed during [t_1,t_2] are in P.

R on Route, within Travel-time 5, Sometime[t_1,t_2]

Filter:



S = Trajectories in index blocks that intersect Q.

Refinement:

For each trajectory in S check that it crosses R sometime during interval [t_1, t_2 + 5] (there may be a trajectory of S that does not intersect R) .

Moving Objects Algebra Gueting et. al.

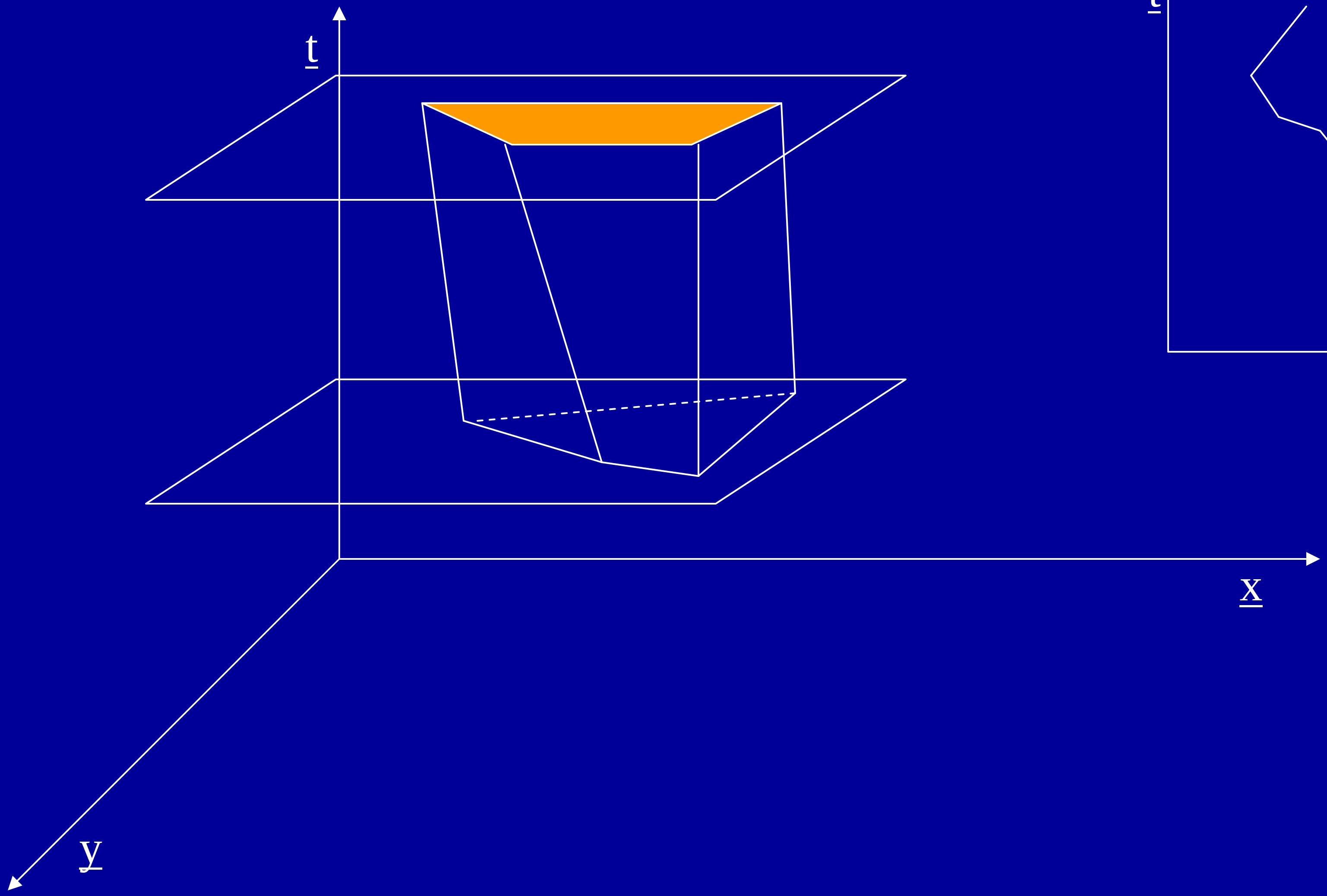
Guting et al proposed a rich framework of abstract data-types and a query language for moving objects.

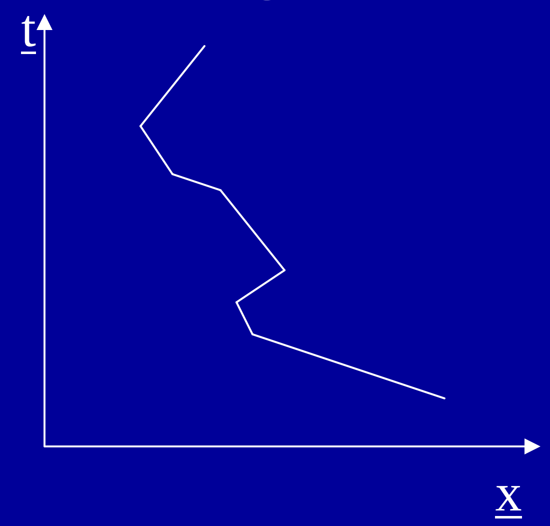
- Moving objects can be points or regions.
- Kernel(Spatial) algebra lifted to the time domain.
- The Kernel consists of spatial types such as points, lines, regions, and different spatial operators, aggregate operators.
- LIFTING: For each type T, a moving type mT.

mT is a function with real time line as the domain and with range of type T.

Guetting et al (cont…)

Examples – a moving region a moving point





Gueting et. al. Continued---

- Kernel Operators

- Spatial Operators/functions --- INSIDE, TOUCHES, OVERLAPS, DISTANCE.

- Aggregations : min, max, center, etc.

- Distance and Direction operators

- Temporal Operators --- Projection on time domain, **When, atinstant** and Rate of change operations etc.

Examples

Flight (airline:*string*, no:*int*, from:*string*, to:*string*,

trajectory:*mpoint*)

What is the distance traveled by flight LH287 over France?

LET trajectory287 = ELEMENT(SELECT trajectory FROM flight WHERE airline = “LH” and no = 257);

length(**intersection**(France, **route**(trajectory287))) s1

Examples for Lifting (1)

forest_fire (firename: *string*, extent: *mregion*)

Example 1. “When and where did the fire called 'The Big Fire' have its largest extent?“

LET TheBigFire = ELEMENT (
SELECT extent FROM forest_fire
WHERE firename = "The Big Fire");

LET max_area = **initial**(**atmax** (**area** (TheBigFire)));

atinstant (TheBigFire, **inst**(max_area));

s1 Relations "forest", "forest_fire" & "fire_fighter" are used in the examples of lifting.

The relation "forest" records the location and the development of different forests growing and shrinking over time through clearing, cultivation, and destruction processes, for example.

The relation "forest_fire" documents the evolution of different fires from their ignition up to their extinction.

The relation "fire_fighter" describes the motion of fire fighters being on duty from their start at the fire station up to their return.

Example 1: extent is a moving region.
TheBigFire is the name of this extent.
area in second Let statement is a function
of time. atmax defines pairs (time, area) when the area is maximum, and initial takes the first one.
so the second Let statement defines max_area to be a pair (time,value).
inst takes the 1st member of the pair (when) and atinstant gives the value of the moving region TheBigFire at that time, i.e. Where the polygon with the max area.

The area operator is used in its lifted version.

Operation atinstant restricts a moving entity to a given instant.

Operation inst returns the time of max_area.

ssss, 7/21/2003

A6

Examples for Lifting (2)

- *Example 3*. "When and where was the spread of fires larger than 500 km^2?“

- LET big_part = SELECT big_area AS extent
  when [FUN (r:region) area(r)>500]
  FROM forest_fire;

A6 The domain function deftime returns
the times for which a function is defined.

The second subquery reduces the moving region of each fire to the parts when it was large. For some fires this may never be the case, and hence for them big_area may be empty (always undefined). These are eliminated in the second subquery.
Administrator, 1/8/2003

Future Temporal Logic Language

•The language has the following SQL/OQL type syntax.

Retrieve <target-list> where <condition>

•The condition part is specified as a Future Temporal Logic (FTL) formula.

FTL employs --- spatial, temporal predicates and operators

FTL --- Continued

•Spatial Operators/predicates :

INSIDE(O,P), DISTANCE(O1,O2)<=5, etc.

•Temporal Operators::

Eventually-within-C, **Eventually-within-[C,D],** f **Until g**, **Always-for-C**, etc.

• Variables and assignment operators

Examples

- RETRIEVE O.name WHERE

  O.color = red and **Eventually-within-10** (INSIDE(O,P))

Retrieve names of red color objects that will be inside the region P within 10 units of time.

- RETRIEVE   O.name WHERE

  Always-for-5 (DISTANCE(O,O')<=10) and O'.type=truck

Retrieve names of objects that will be within a distance of 10 from a truck for the next five units of time.

Examples Contd---

• Retrieve all objects that enter a tunnel in the next 5 units

of time and stay inside it for the subsequent 10 time units.

RETRIEVE O.type WHERE

Not Inside(O,P) **and Eventually-within-5**(**Always-for-10** (Inside(O,P)) and P.type=tunnel

Semantics:

FTL formulas are interpreted over future histories specifying the object locations.

Static attributes remain unchanged

Dynamic attributes change according to their functions.

Processing Algorithm

The algorithm works inductively on the structure of the FTL formula.

•For atomic formulas p: Answer(p) is obtained using indexing and other traditional methods.

•If p = (p1 and p2) or (p1 **Until** p2) or **Eventually-within-C**(p1): Answer(p) is computed from Answer(p1) and Answer(p2) inductively.

CQL extensions (cont…)

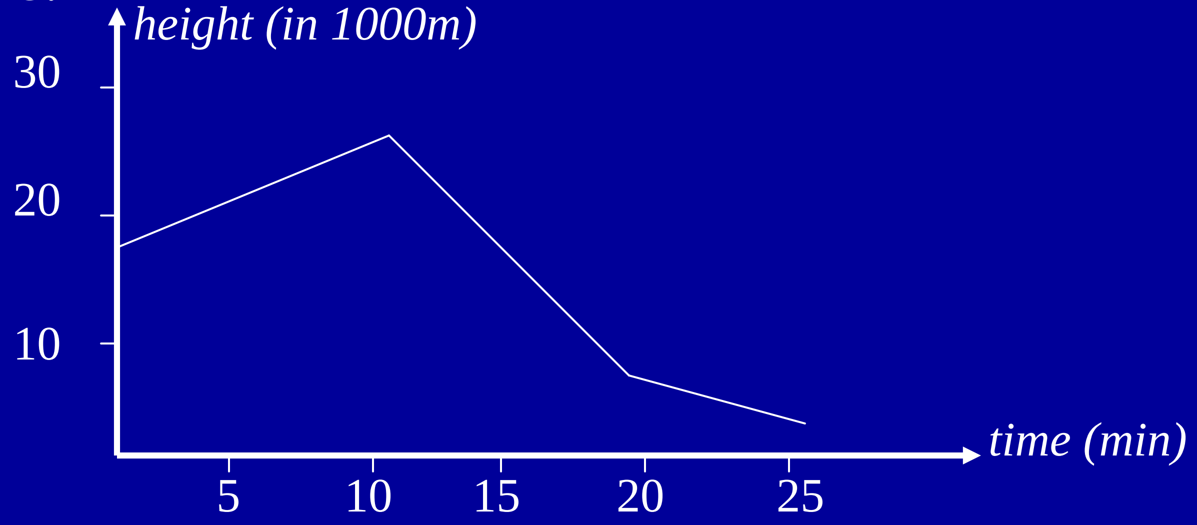
- Moktar, Su and Ibarra (PODS'00) – A query language based on the ideas of constraint databases and CQL

Constraint data model: Attribute > 5

(in contrast to the relational model in which Attribute=5)

Other Models and Languages - MSI'00 (cont…)

- Example: Constraint-based representation of 3D motion of an airplane:



$$x = 1200t + 18000 \wedge 0 \le t \le 12$$
$$\vee\ x = -2000t + 25200 \wedge 12 \le t \le 20$$
$$\vee\ x = -1000t + 9200 \wedge 20 \le t$$

MSI’00 (cont…)

Example: Find all the aircrafts entering Santa Barbara County between t1 and t2

Retrieve y such that:

y is an object AND

there exists a point x on traj(y) at time t, t between t1 and t2, AND

x is in Santa Barbara County AND

for every time t’<t the point of traj(y) at time t’ is NOT in SBC

Languages References

[1] A. Prasad Sistla, Ouri Wolfson, Sam Chamberlain and Son Dao, *Modeling and Querying Moving Objects*, In the proceedings of ICDE, p422-432, 1997.

[2] R. Guting, M. Bohlen, M. Erwig, C. Jensen, Lorentzos N, M. Schneider, and M. Vazirgianis. *A foundation for representing and querying moving objects*. Technical Report 238, FerUniversitat das Hagen (Germany), 1998.

[3] M. Vazirgiannis and O. Wolfson, *A Spatiotemporal Query Language for Moving Objects*, In the proceedings of the conference on Spatial and Temporal Databases, Los Angeles, CA, July 2001.

[4] Hoda Mokhtar, Jianwen Su and Oscar Ibarra, *On Moving Object Queries*, In Proceedings of the 21st ACM SIGMOD-SIGACT-SIGART symposium on Principles of database systems, June 2002.

Outline

- Background
  - Location technologies, applications
  - demo
- Research issues
  - Location modeling/management
  - Linguistic issues
  - Uncertainty/Imprecision ←
  - Indexing
  - Synthetic datasets
  - Compression/data-reduction
  - Joins and data mining

Where are we?

Relationship to location update policies

Linguistic Issues

Assumptions set 1

- No location prediction provided by human (e.g. cellular user)
- Fixed location-uncertainty tolerated
- Fixed amount of resources (b/w, processing) for location updates

Power of automatic predictions?

Distance Update Policy

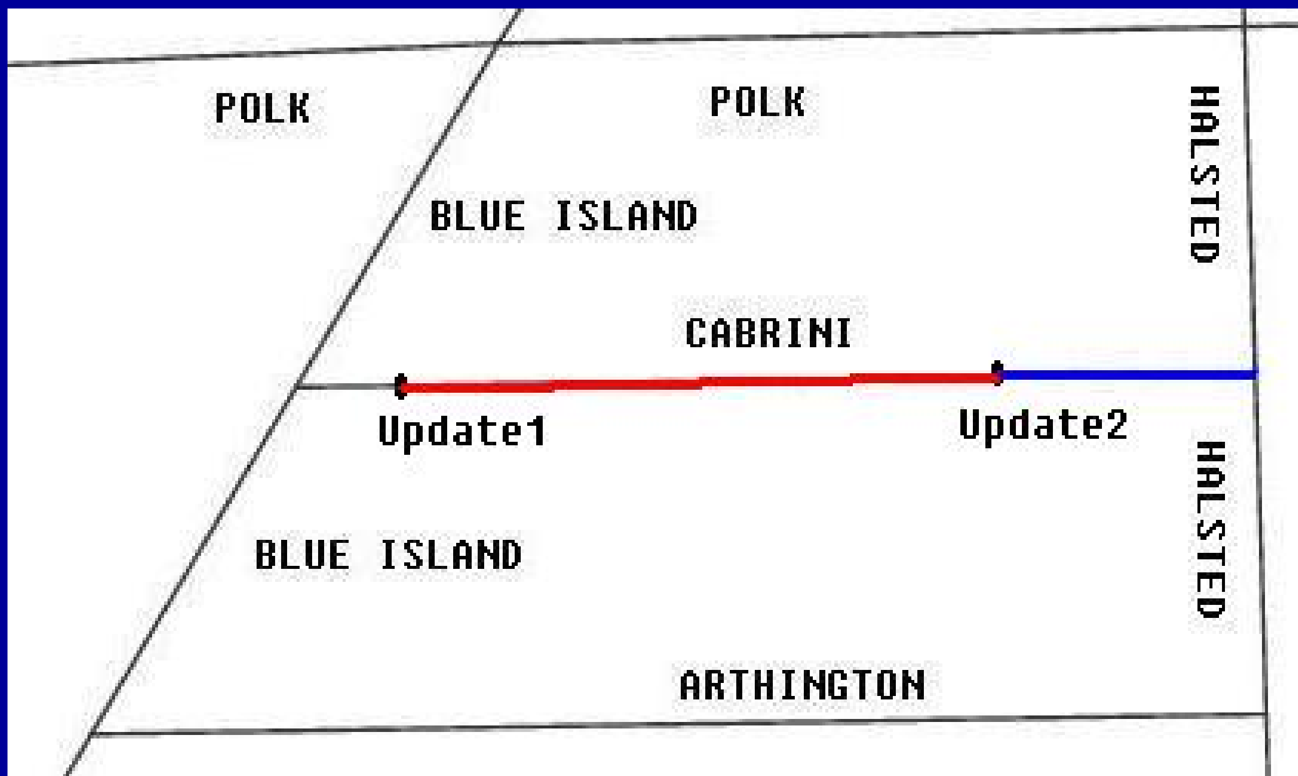
- Update when distance of current location from database location > x (uncertainty x)
  - Bound on error of answer to query

Deviation Update Policy (proposed)

- Moving object sends current location
- Implicit time/space prediction function (e.g. north at 50kph)
- New update when deviation > x
- Bounded location error: x

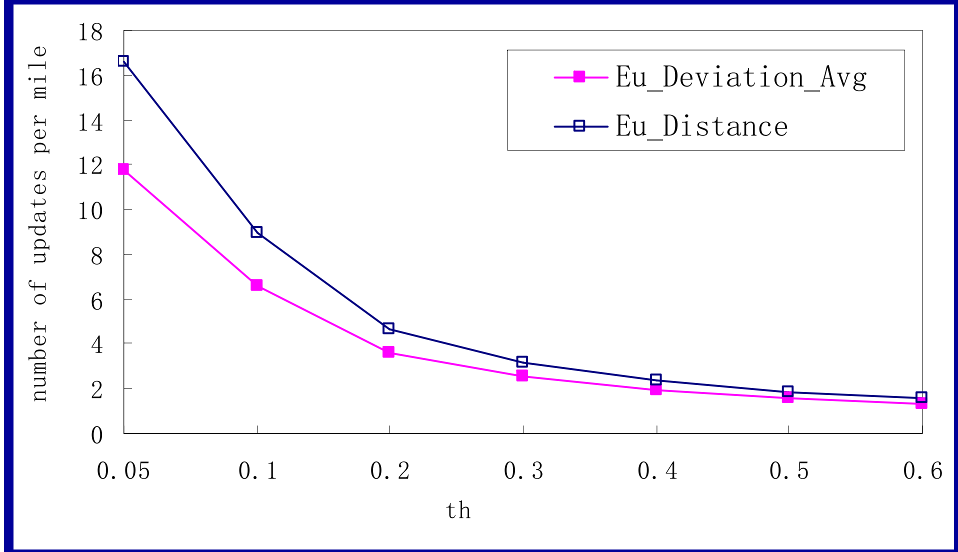
Our Prediction

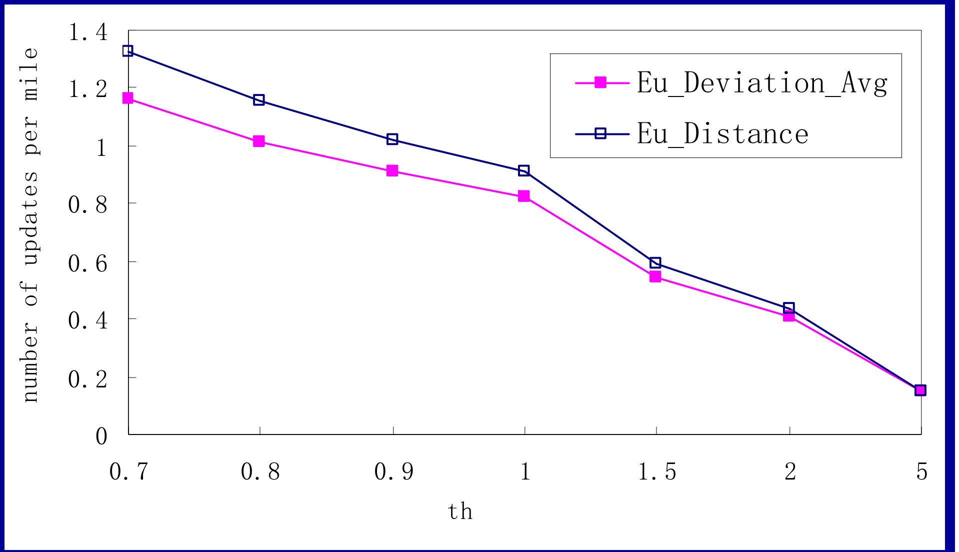
Continues on current street



With average speed since last update

Experimental Results – Euclidean Distance





The number of updates per mile with *th = 0.05 – 5.0*

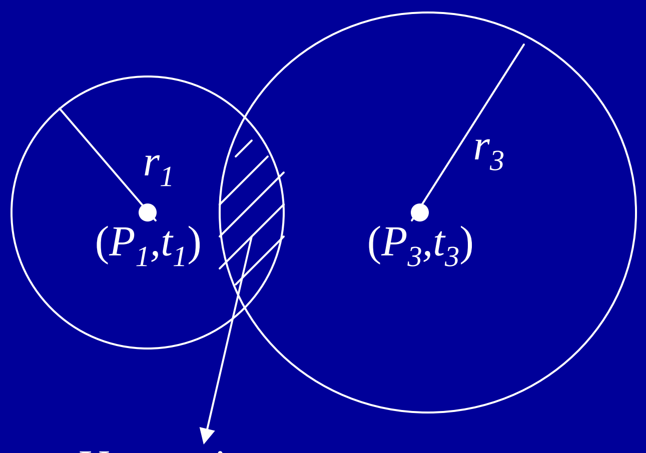
Up to 40% higher accuracy for a given update capacity

Assumptions set 2

- No location prediction provided by human (e.g. cellular user)
- Variable location-uncertainty
- Periodic location updates
  - automatic toll collection sensors,
  - heart beat every 30 mins

Interpolation

- Pfoster and Jensen '99.



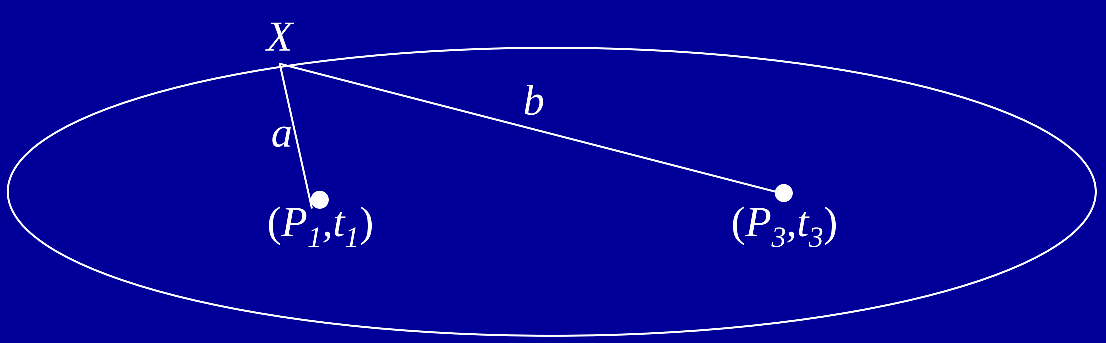
Location at time $t_1<t_2<t_3$ is intersection area of circles where

$r_1=(t_2-t_1) \bullet Vmax$

$r_3=(t_3-t_2) \bullet Vmax$

Interpolation (continued)

- Uncertainty area between times t_1 and t_3



Ellipse bounded by the points *X* such that

$\boldsymbol{a + b = V_{max} \cdot (t_3 - t_1)}$

Maximum distance traveled in interval $[t_1, t_3]$

Assumptions set 3

- Future route provided by human
- Variable location-uncertainty

Deviation Policy

- Location update message
  - Current location
  - Predicted Speed
  - New Deviation threshold

Adapt Uncertainty to Update frequency

Wolfson, Sistla, Chamberlain, Yesha ‘99

- Tradeoff :

  precision vs. performance (resource consumption)
- Cost based approach

OW3

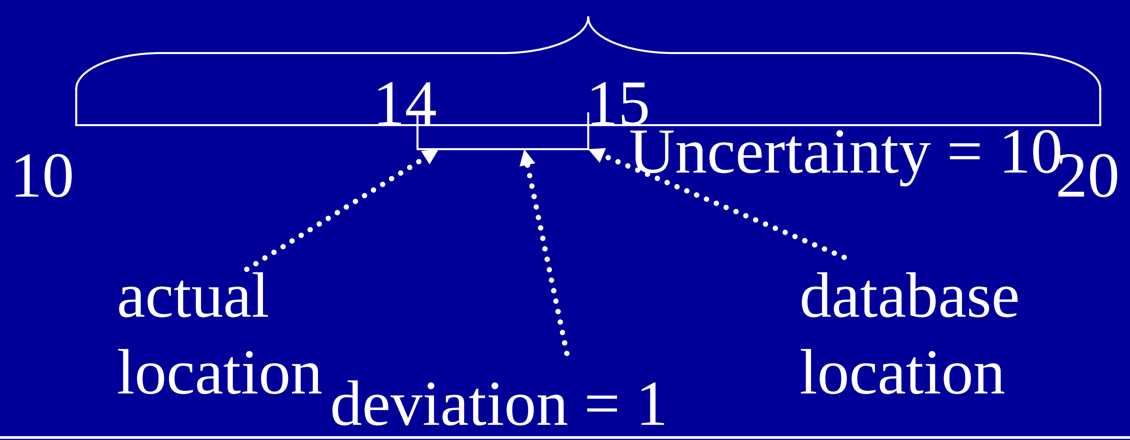
Information-Cost of a trip

Components:

- Cost-of-message
- Cost-of-imprecision
  - Cost-of-deviation
  - Cost-of-uncertainty

} proportional to length of period of time for which persist

Current location = 15 ± 5

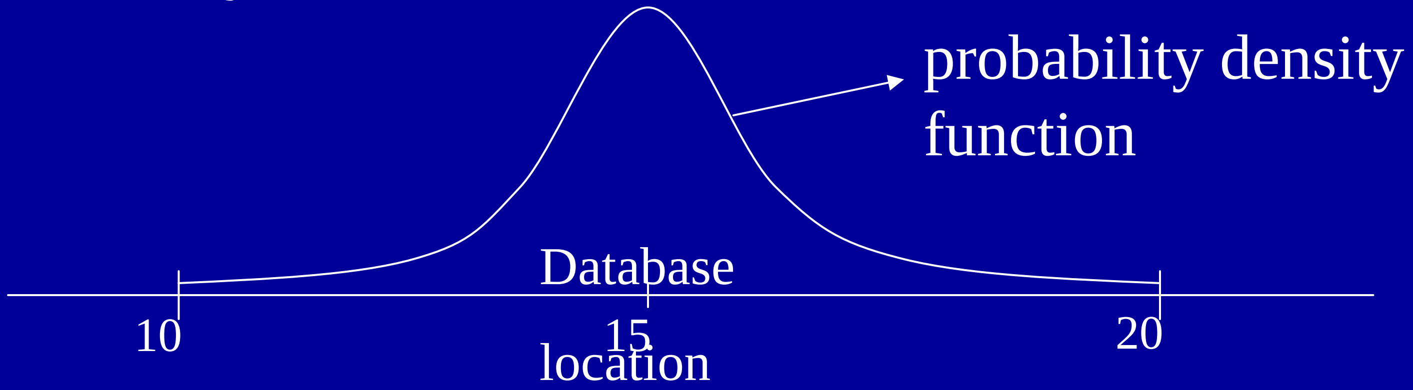


OW3 for a fixed uncertainty, the higher the deviation, the higher the error

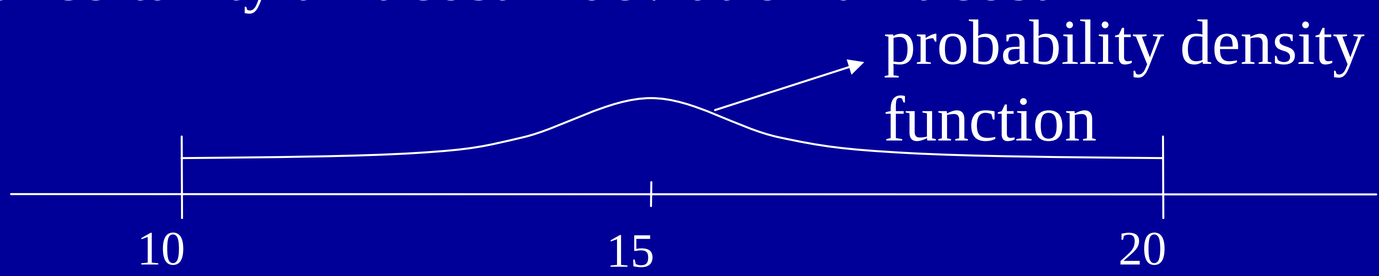
Ouri Wolfson, 7/23/2003

Probability Density Function <-> Imprecision Costs

uncertainty unit cost < deviation unit cost:

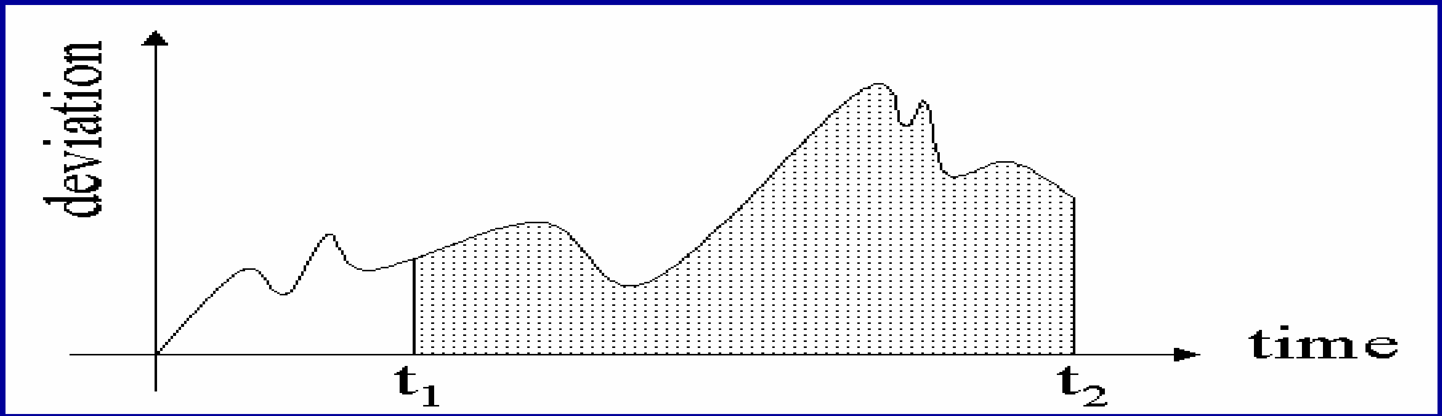


uncertainty unit cost > deviation unit cost



Cost of Deviation

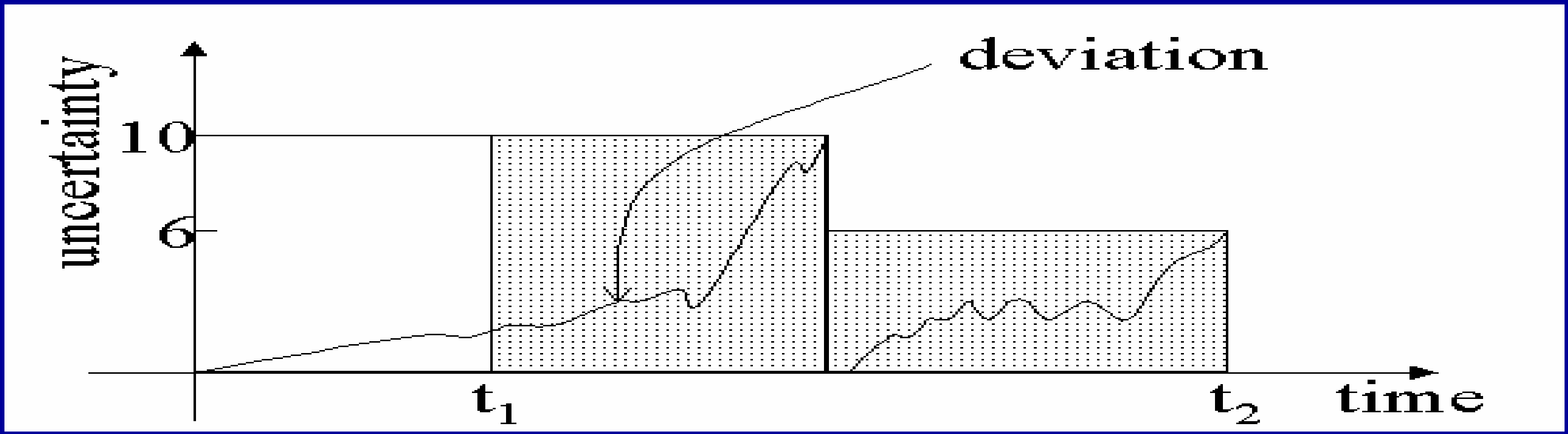
$$\text{Cost}\left(\frac{\text{unit of deviation}}{\text{unit of time}}\right) = 1$$



$$\text{Cost}_{\text{deviation}}(t_1, t_2) = \int_{t_1}^{t_2} \text{deviation}(t)\,dt$$

Cost of Uncertainty

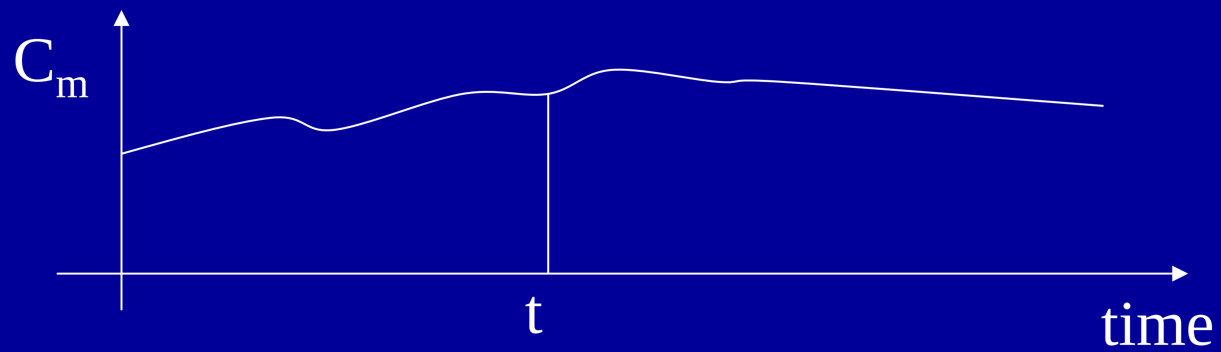
$$\text{Cost}\left(\frac{\text{unit of uncertainty}}{\text{unit of time}}\right) = C_u$$



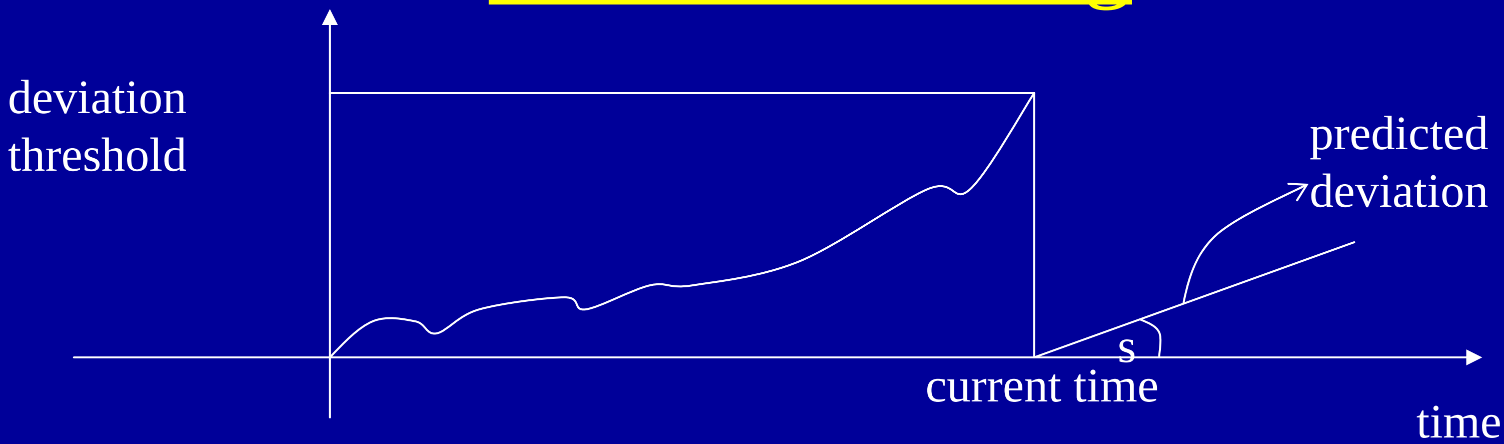
$$\text{Cost}_{\text{uncertainty}}(t_1, t_2) = C_u * \int_{t_1}^{t_2} \text{uncertainty}(t)dt$$

Cost of update Message -- C_m

- C_m determined -- how many messages willing to spend to reduce deviation by one, during one time unit
- C_m may vary over time, as a function of load on wireless network



Deviation Threshold Setting by Adaptive Dead Reckoning



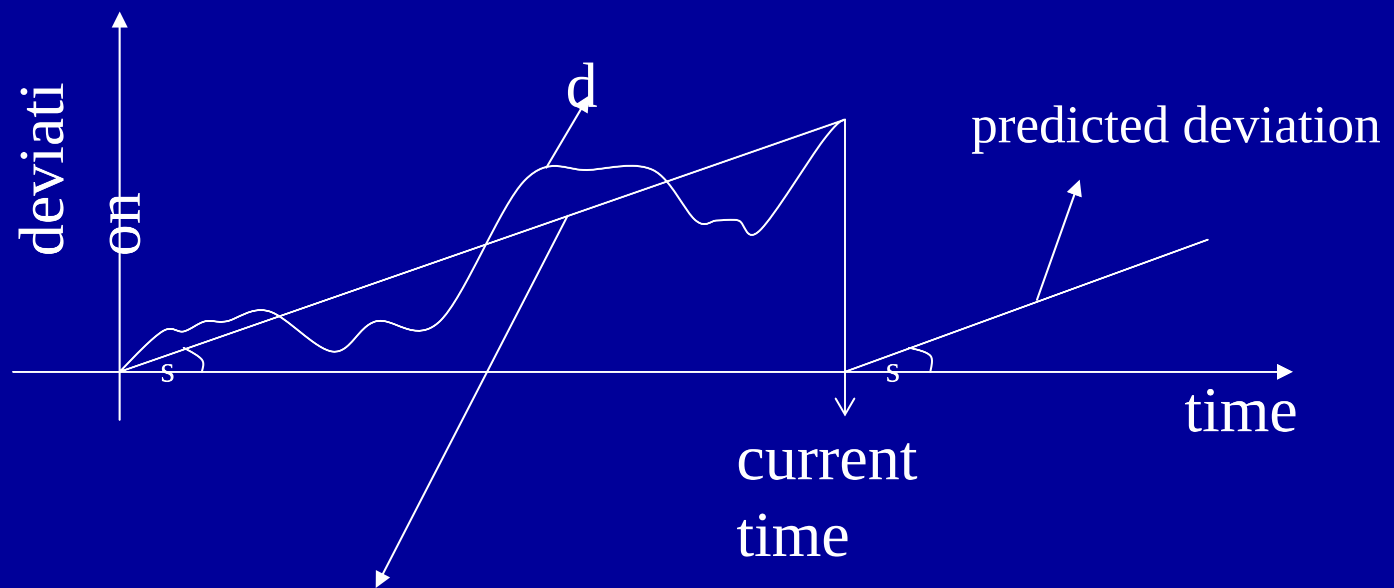
Expected total cost - f (threshold)

Theorem: Total cost minimized when:

$$\text{threshold} = \sqrt{\left(\frac{2 * s * C_m}{1 + 2 * C_u} \right)}$$

Wolfson, Jiang, Sistla, Chamberlain, Rishe, Deng; Proc. of the International Conf. on Database Theory, 1999

Slope of Predicted Deviation



Approximation of current deviation d by a linear function with same integral as d

Adaptive Dead Reckoning (Adr) - Properties

- Minimizes total cost
- Varies from update to update depending on C_m and deviation behavior
- Encapsulates communication-imprecision tradeoffs via unit-costs

Can there exist a better policy?

Maybe ...

But

Theorem: There does not exist a competitive online dead-reckoning algorithm.

(Algorithm A is competitive if there are α, β such that for every speed curve s:

$$cost_A(s) \leq \alpha * cost_{\text{optimal offline algorithm}}(s) + \beta)$$

Simulation

Adaptive threshold setting

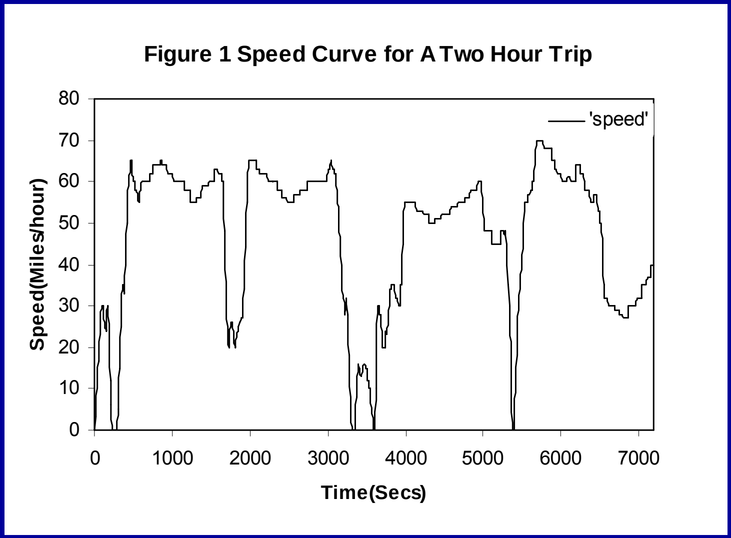
vs.

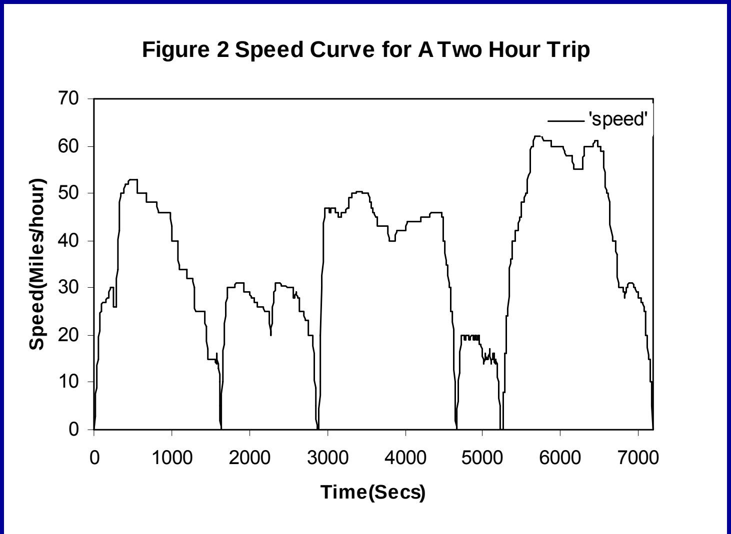
Fixed threshold

Adaptive consistently outperforms fixed (in terms of cost)

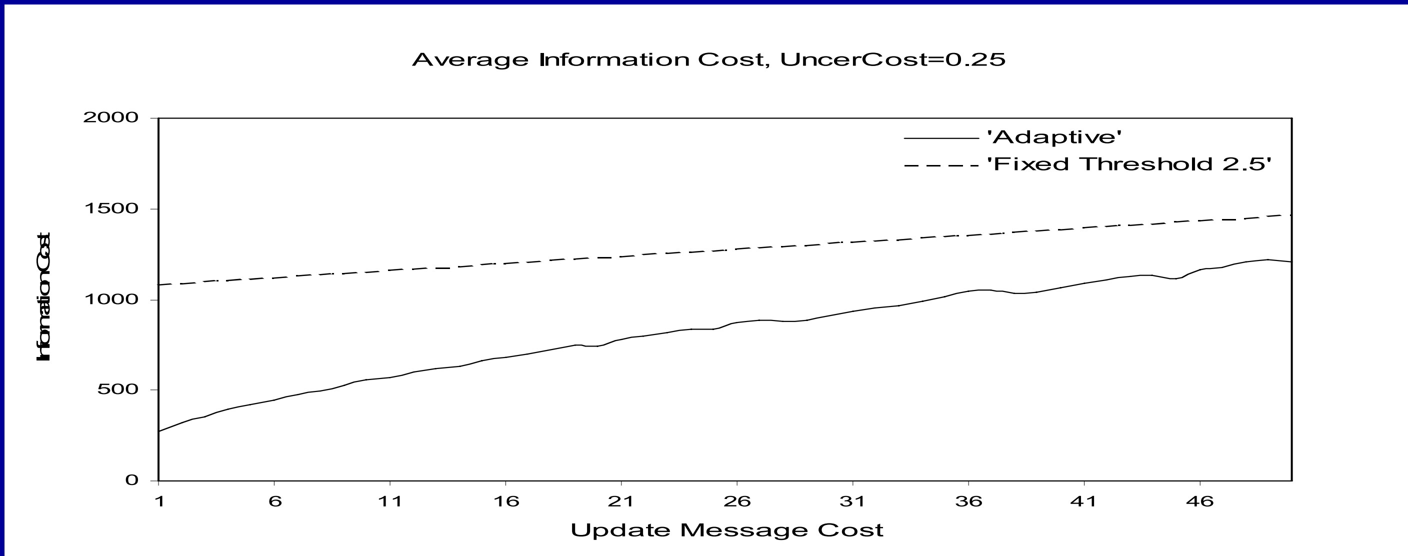
Methodology

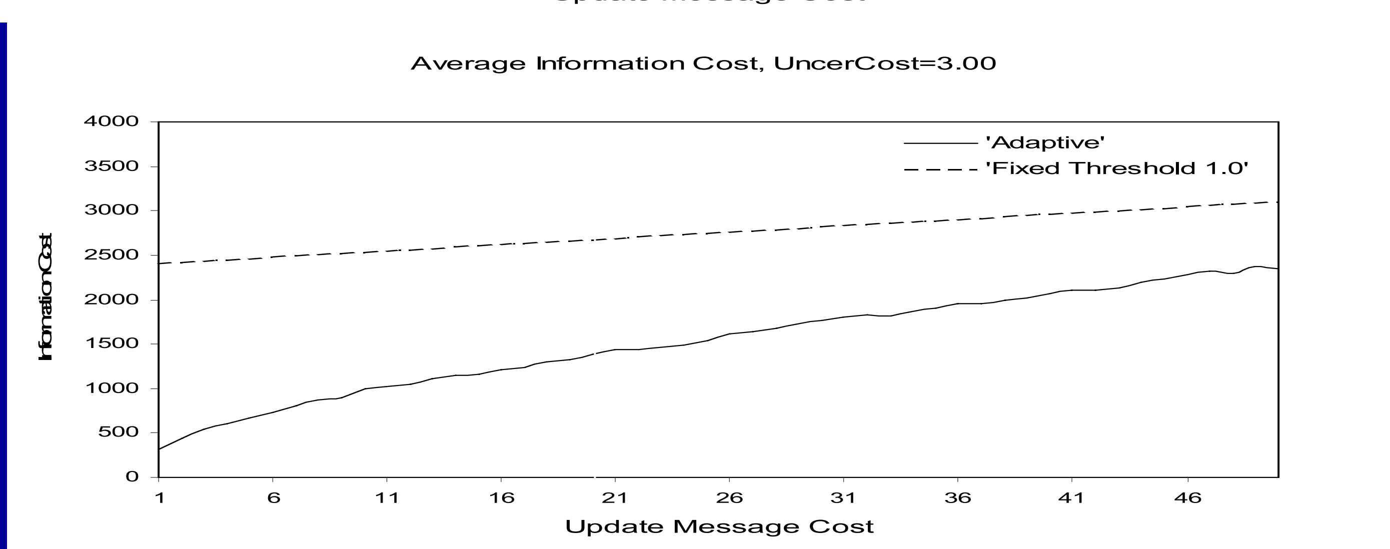
use a set of speed curves



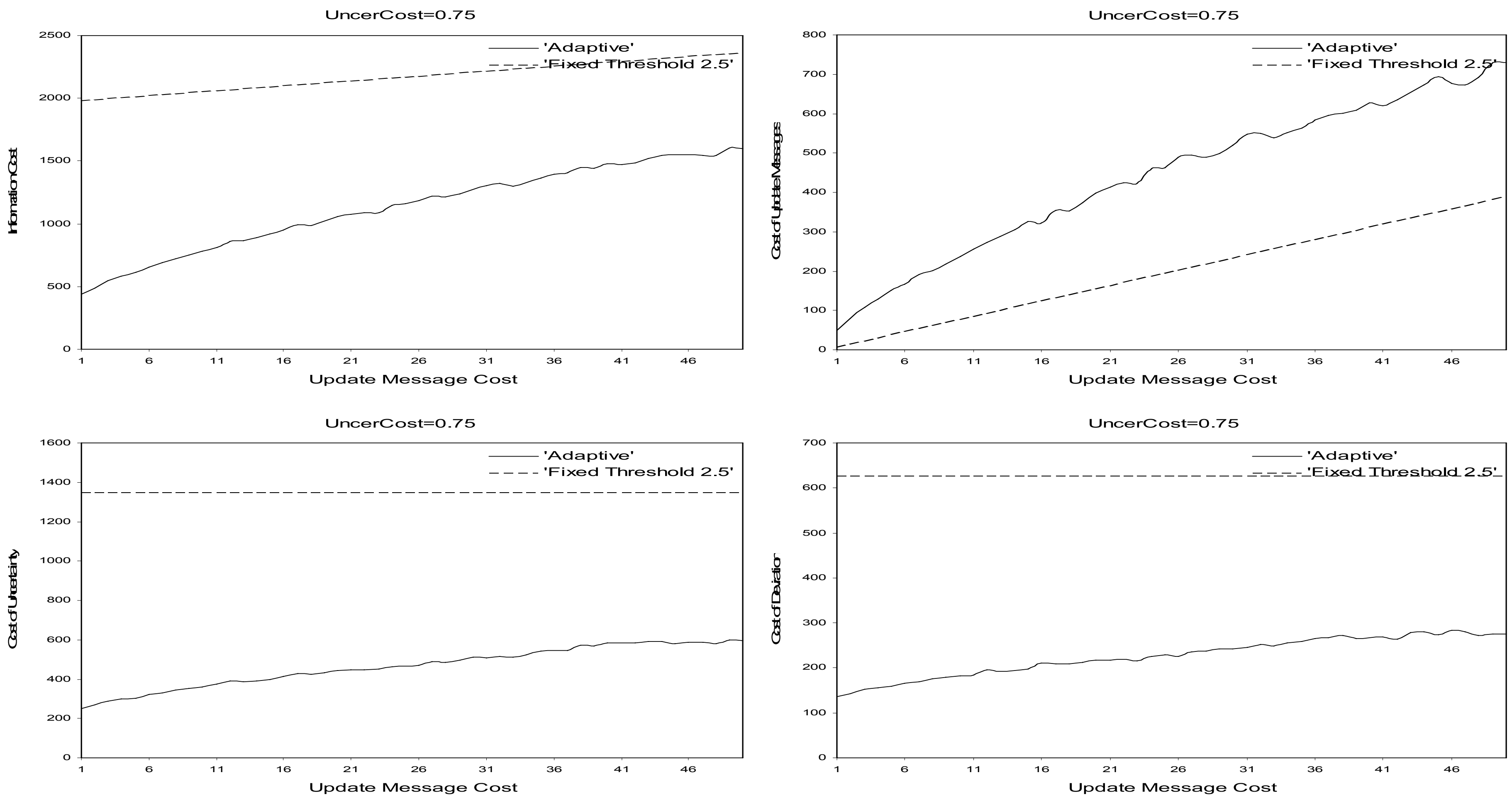


Average distance: 82 miles





- 1cent/msg, C_m=20 ⟹ Fixed=$1.35, Adaptive=$0.70
- Distance location update policy – cost many fold higher



The fixed threshold policy uses the same number of messages regardless of the message cost, therefore its uncertainty and deviation costs are constant.

A simulation test-bed

How many mobile units can be supported for :

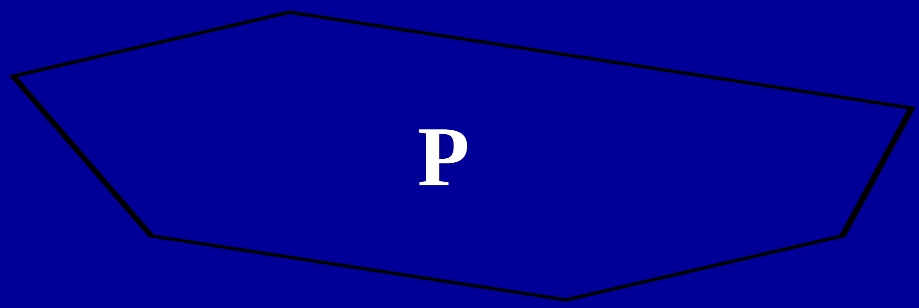
- given level of location accuracy

- given % of b/w for location updates

Relationship to location update policies

Linguistic Issues ←

Spatial range queries



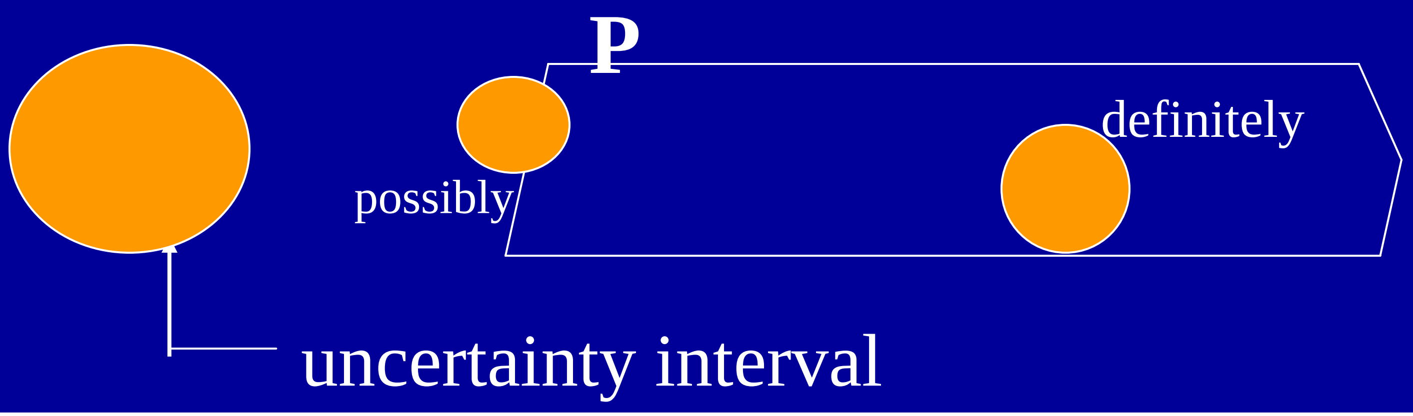
Retrieve the objects that are in P

SELECT o
FROM MOVING-OBJECTS
WHERE Inside (o, P)

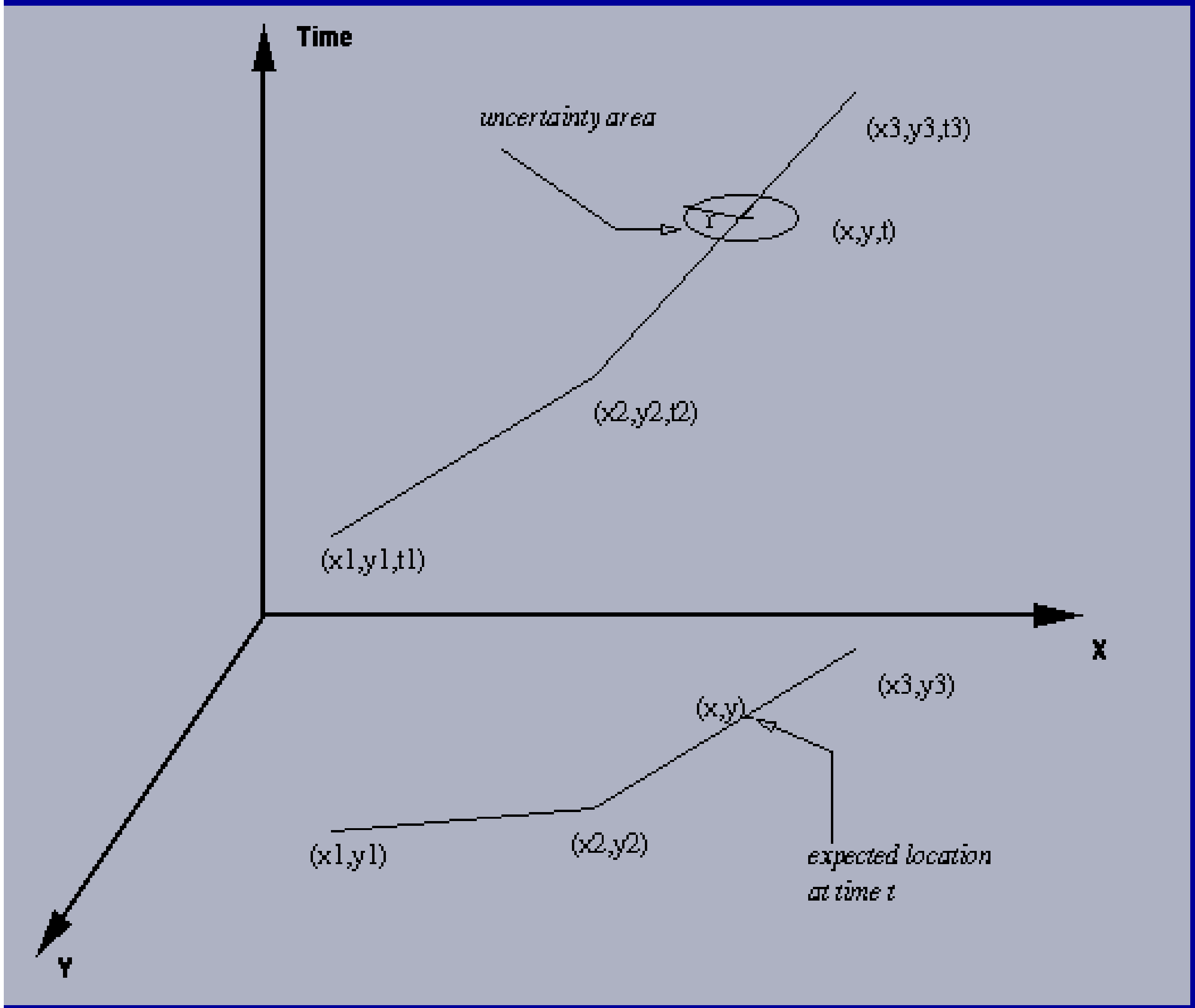
Uncertainty operators in spatial range queries

possibly and definitely semantics based on branching time

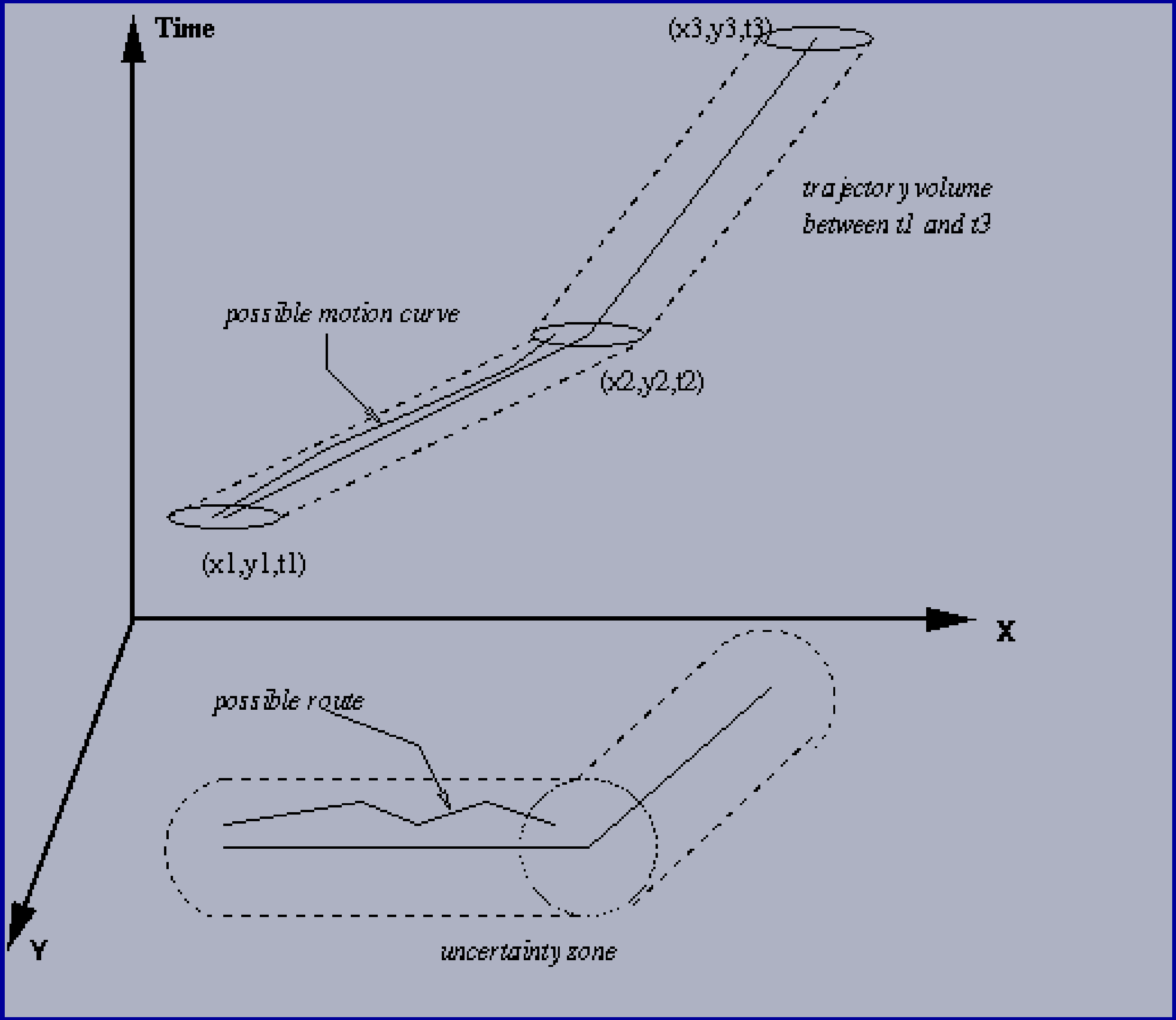
SELECT o
FROM MOVING-OBJECTS
WHERE Possibly/Definitely Inside (o, P)



Uncertain trajectory model



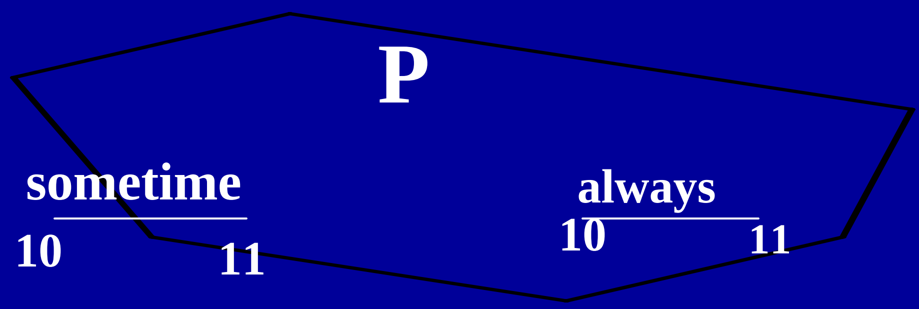
Possible Motion Curve (PMC) and Trajectory Volume (TV)



PMC is a continuous function from Time to 2D

TV is the boundary of the set of all the PMCs (resembles a slanted cylinder)

Temporal operators in spatial range queries



Retrieve the objects that are in P sometime/always between 10 and 11am

SELECT o
FROM MOVING-OBJECTS
WHERE Sometime/Always(10,11)
inside (o, P)

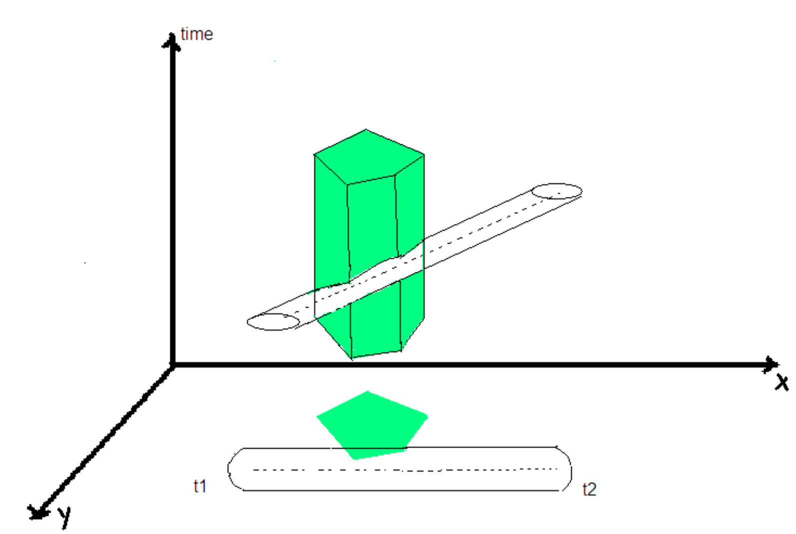
Predicates in spatial range queries

Possibly – there exists a possible motion curve
Definitely -- for all possible motion curves

- possibly-sometime = sometime-possibly
- possibly-always
- always-possibly
- definitely-always = always-definitely
- definitely-sometime
- sometime-definitely

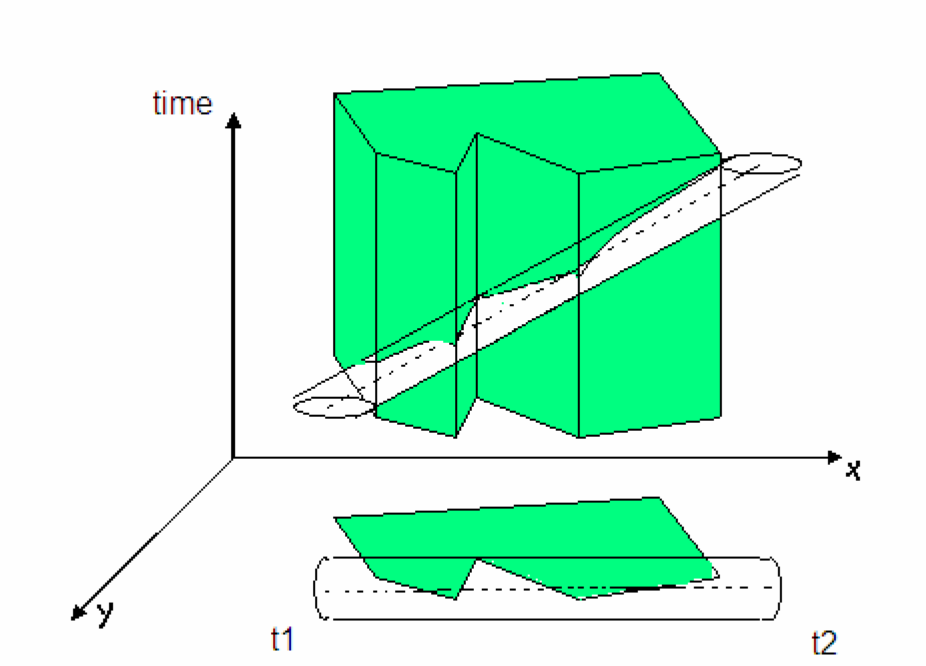
Possibly_Sometime

$$Possibly\_Sometime(Trajectory, Polygon, t_1, t_2)$$



There exists a possible motion curve PMC^T of Trajectory T and there exists a time $t \in [t_1, t_2]$ such that $f_{PMC^T}(t)$ such that is inside the Polygon P.

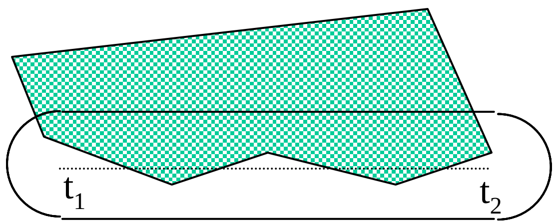
Possibly_Always



Possibly_Always (T, P, t_1, t_2) :

Returns true if there exists a possible motion curve PMC^T of Trajectory T such that for every $t \in [t_1, t_2]$, $f_{PMC^T}(t)$ is inside the Polygon P.

Possibly_Always

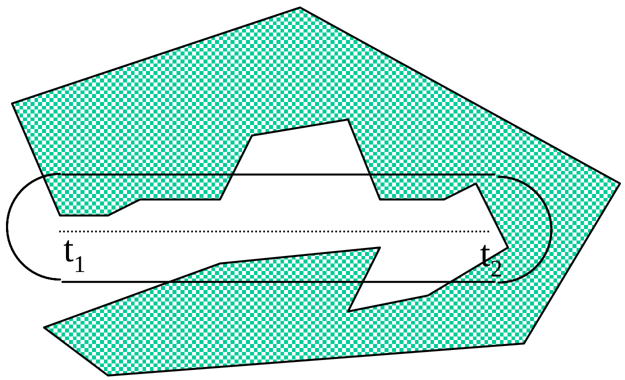


Possibly_Always (T, P, t_1, t_2):

Returns true if there exists a possible motion curve PMC^T of Trajectory T such that for every $t \in [t_1, t_2]$, $f_{PMC^T}(t)$ is inside the Polygon P.

Topologically: Intersection contains a continuous function on $[t_1, t_2]$

Always_Possibly

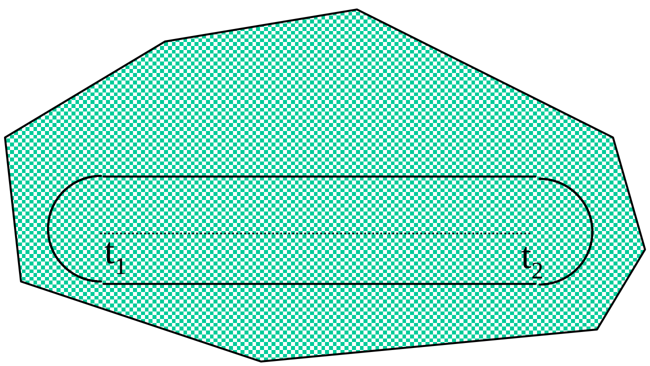


Always_Possibly (T, P, t_1, t_2) :

Returns true if, for every time $t \in [t_1, t_2]$, there exists some possible motion curve PMC^T of Trajectory T, such that the point $f_{PMC^T}(t)$ is inside the Polygon P.

Intersection nonempty for every t in [t_1, t_2]

Definitely_Always

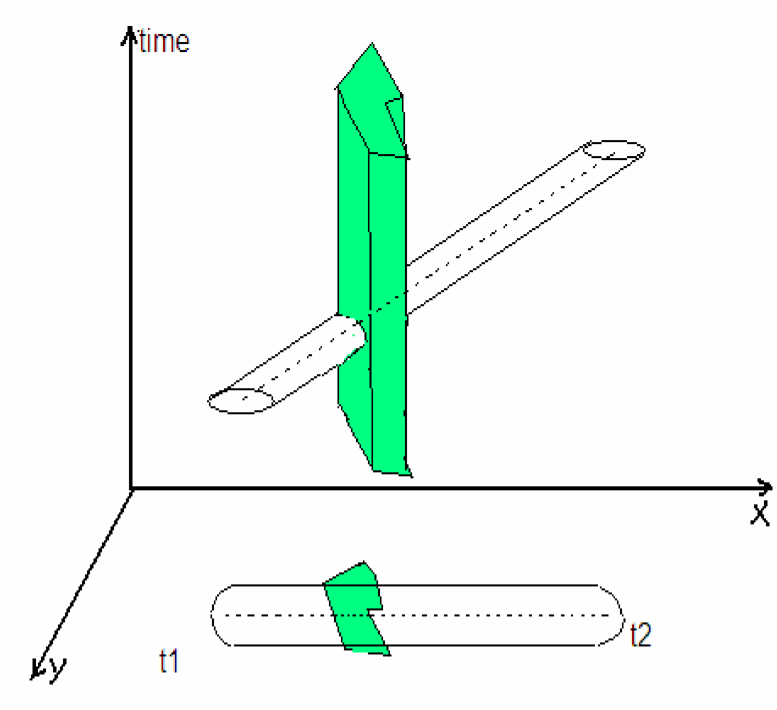


$\text{Definitely\_Always}(T, P, t_1, t_2):$

Returns true if for every possible motion curve PMC^T of Trajectory *T* and every time $t \in [t_1, t_2]$, $f_{PMC^T}(t)$ is inside the Polygon *P*.

Projection of trajectory contained in polygon

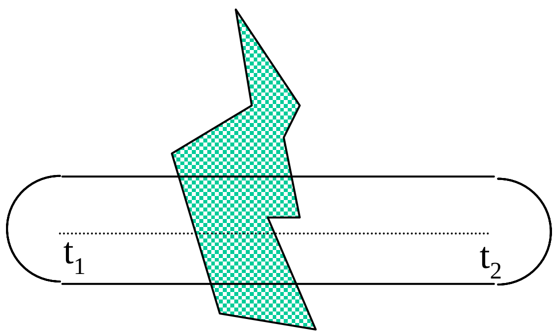
Definitely_Sometime



Definitely_Sometime (T, P, t_1, t_2) :

Returns true if, for every possible motion curve PMC^T of Trajectory T, there exists a time $t \in [t_1, t_2]$, such that $f_{PMC^T}(t)$ is inside the Polygon P.

Definitely_Sometime

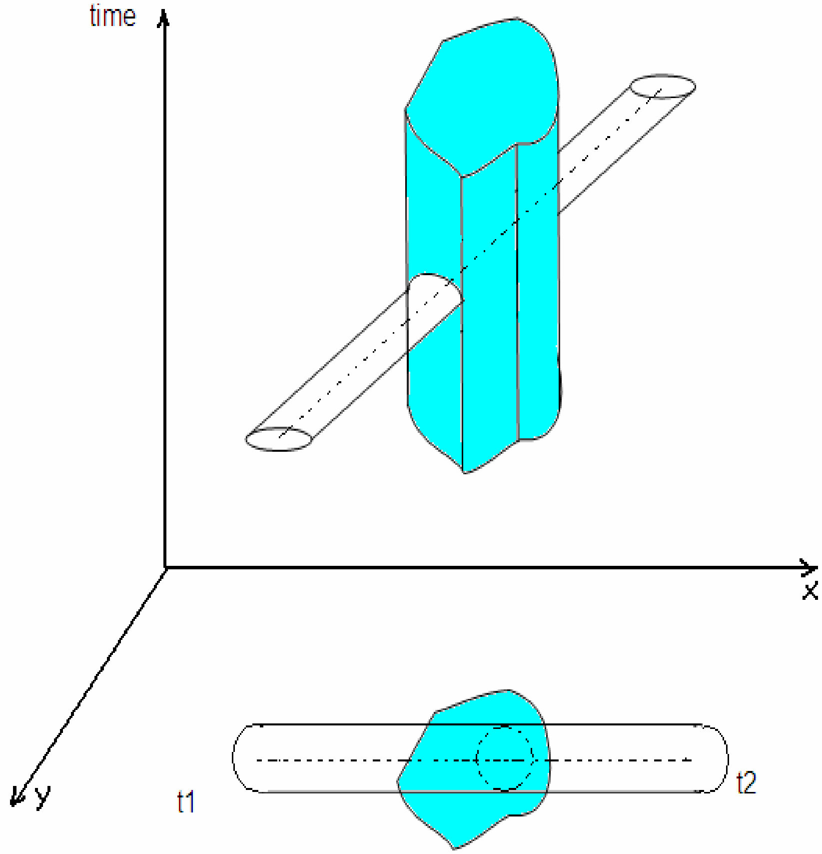


Definitely_Sometime (T, P, t_1, t_2) :

Returns true if, for every possible motion curve PMC^T of Trajectory T, there exists a time $t \in [t_1, t_2]$, such that $f_{PMC^T}(t)$ is inside the Polygon P.

Removing the intersection of polygon and trajectory-projection creates more than one connected component

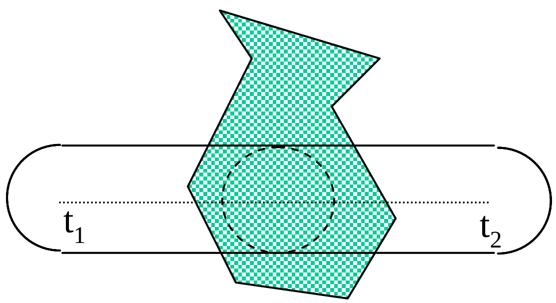
Sometime_Definitely



Sometime_Definitely (T, P, t_1, t_2):

Returns true if, there exists a time $t \in [t_1, t_2]$, such that for every possible motion curve PMC^T of Trajectory T, $f_{PMC^T}(t)$ is inside the Polygon P.

Sometime_Definitely

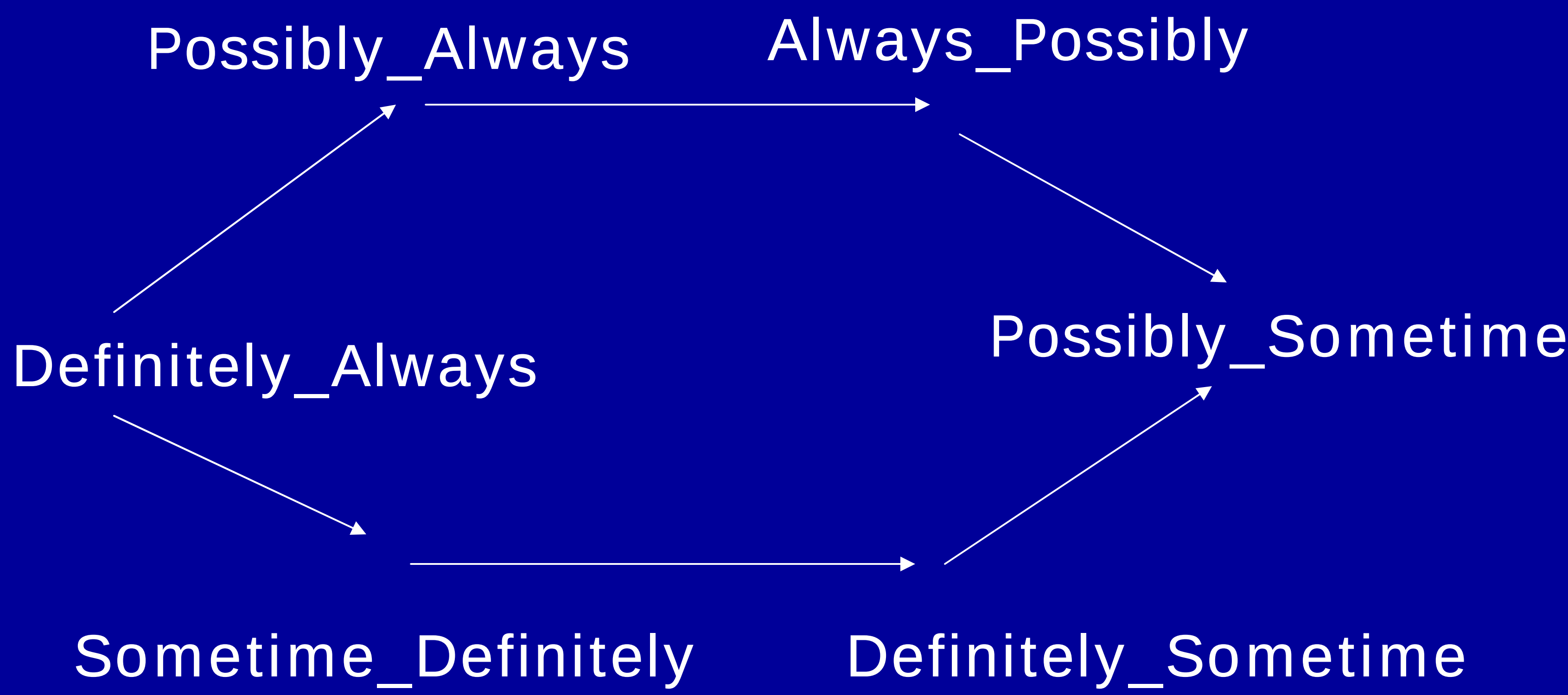


Sometime_Definitely (T, P, t_1, t_2) :

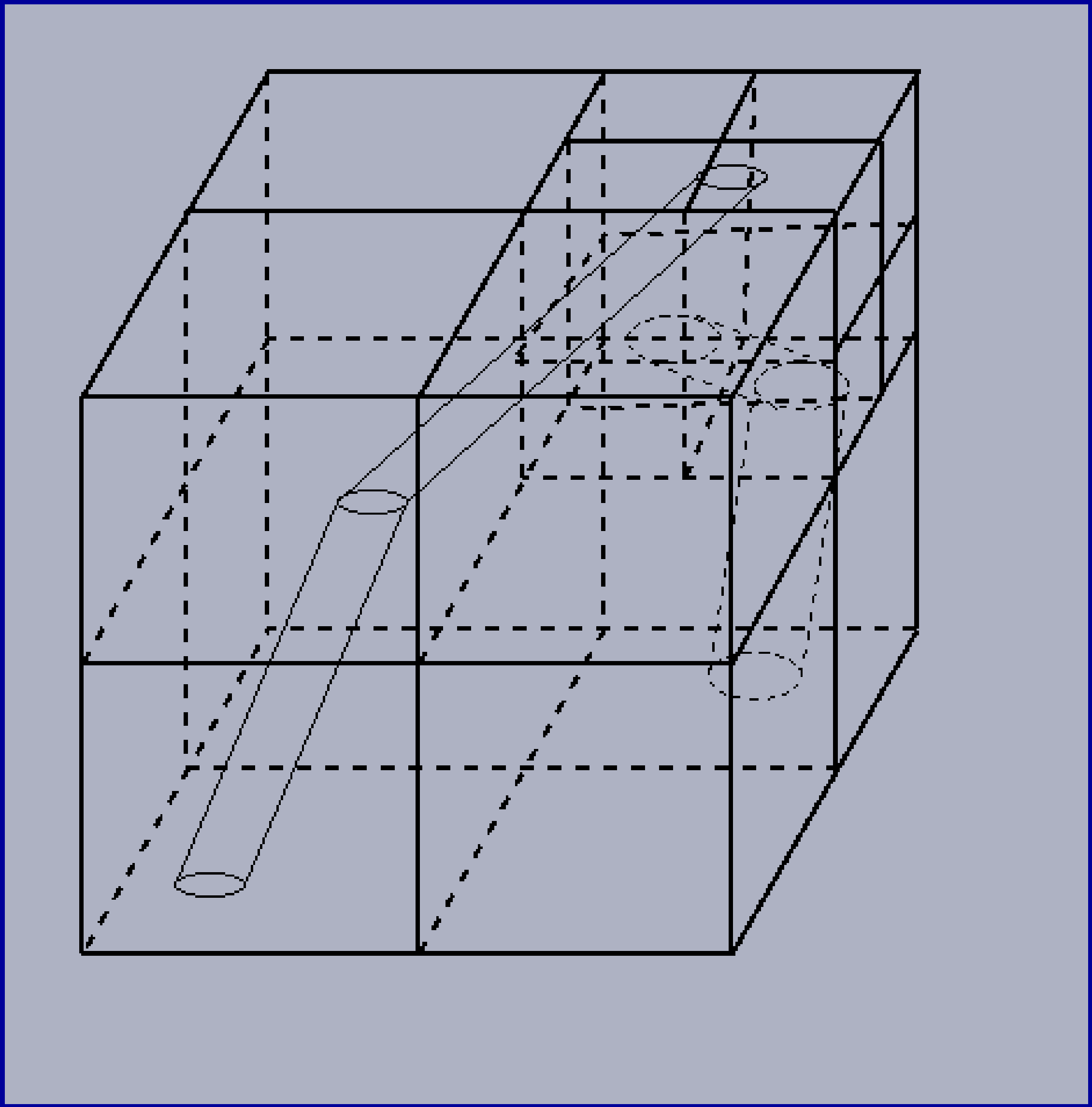
Returns true if, there exists a time $t \in [t_1, t_2]$, such that for every possible motion curve PMC^T of Trajectory T, $f_{PMC^T}(t)$ is inside the Polygon P.

The intersection contains an uncertainty area (i.e. a circle with radius = uncertainty threshold)

Relationship among the predicates:



Theorem: If the query region is convex then Possibly_Always = Always_Possibly. If Circle, also Sometime_Definitely = Definitely_Sometime



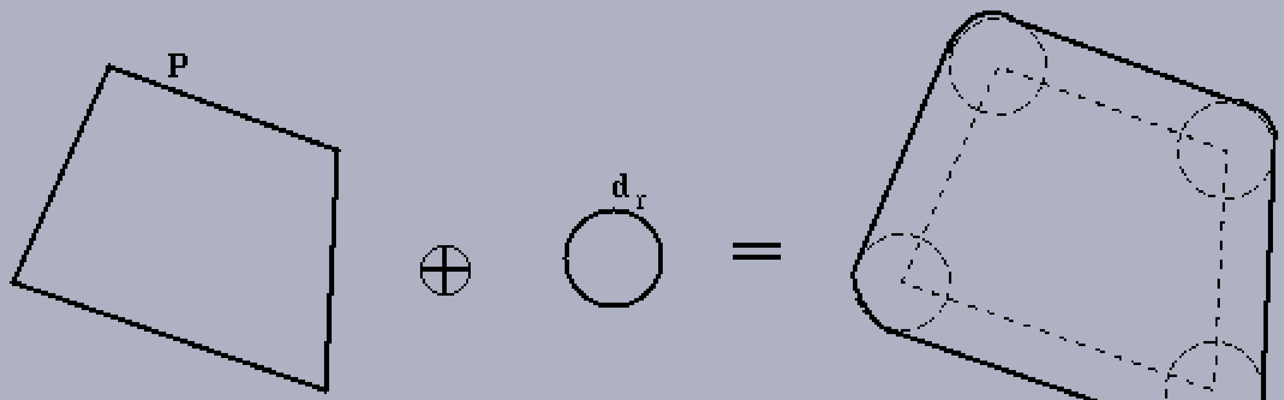
PROCESSING RANGE QUERIES=

Filtering using some index (e.g. R-tree or Octree (shown)

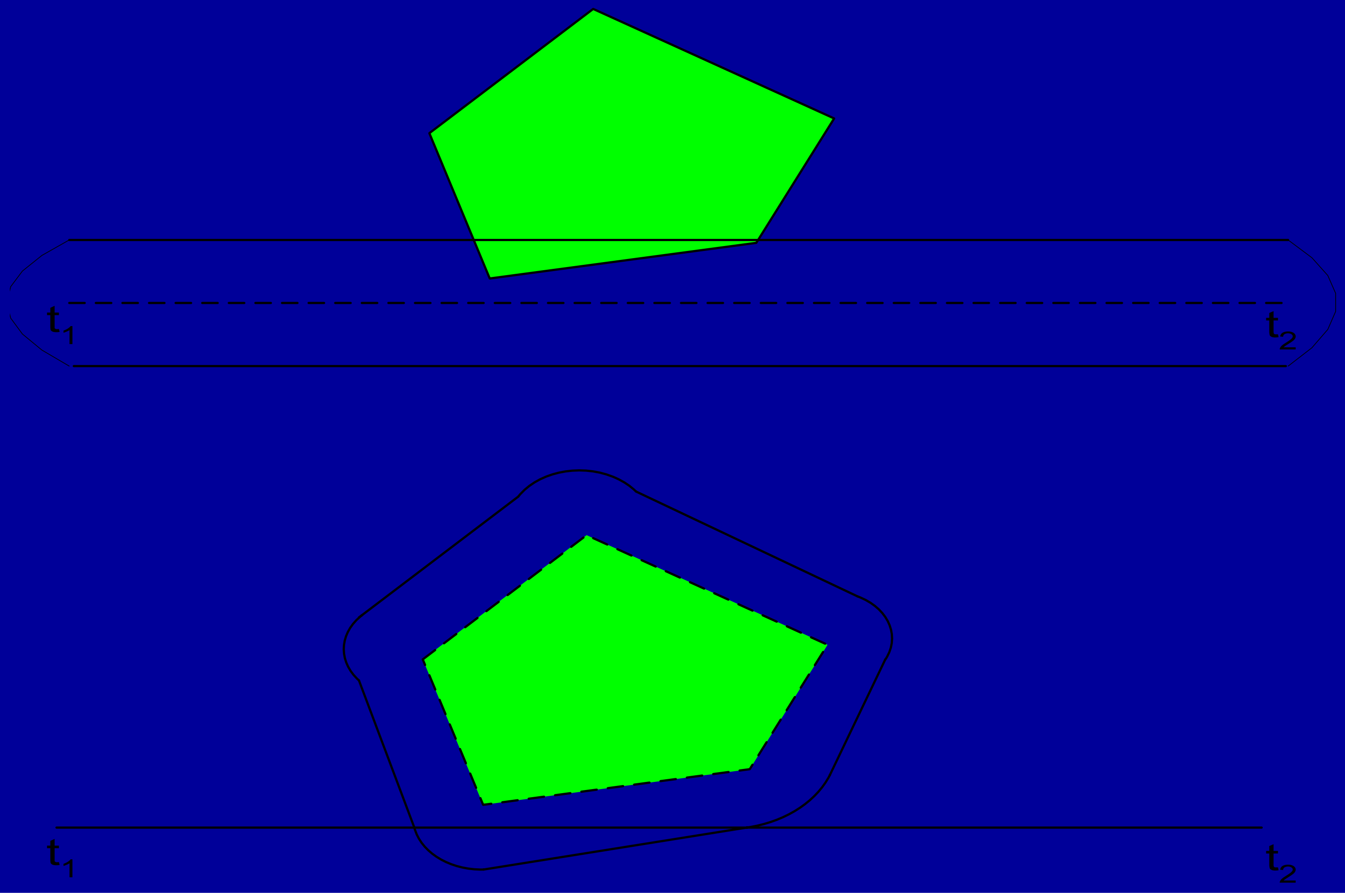
+

Refinement (can be done efficiently)

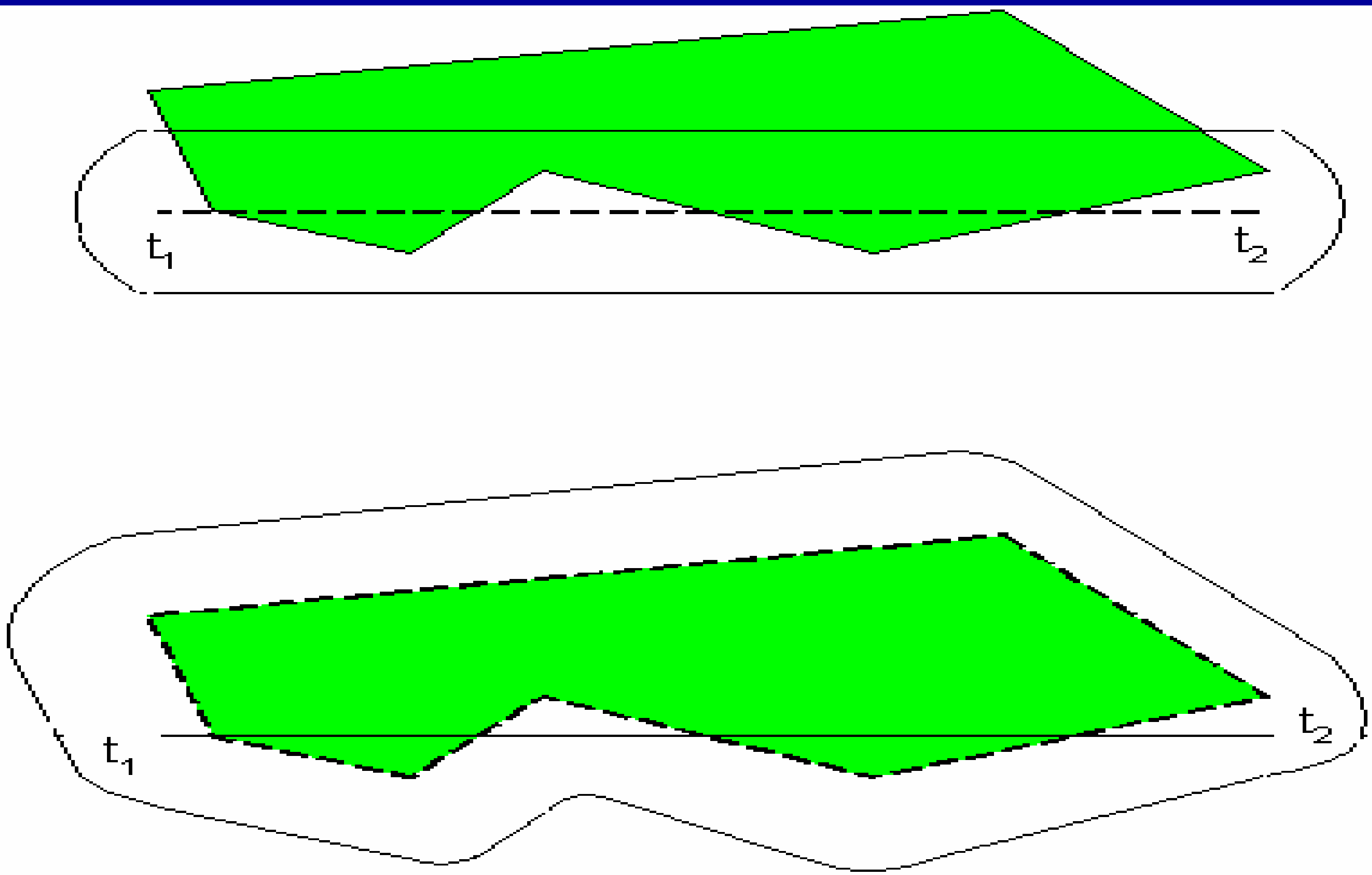
Minkowski Sum:



Possibly_Sometime



Possibly_Always



a1

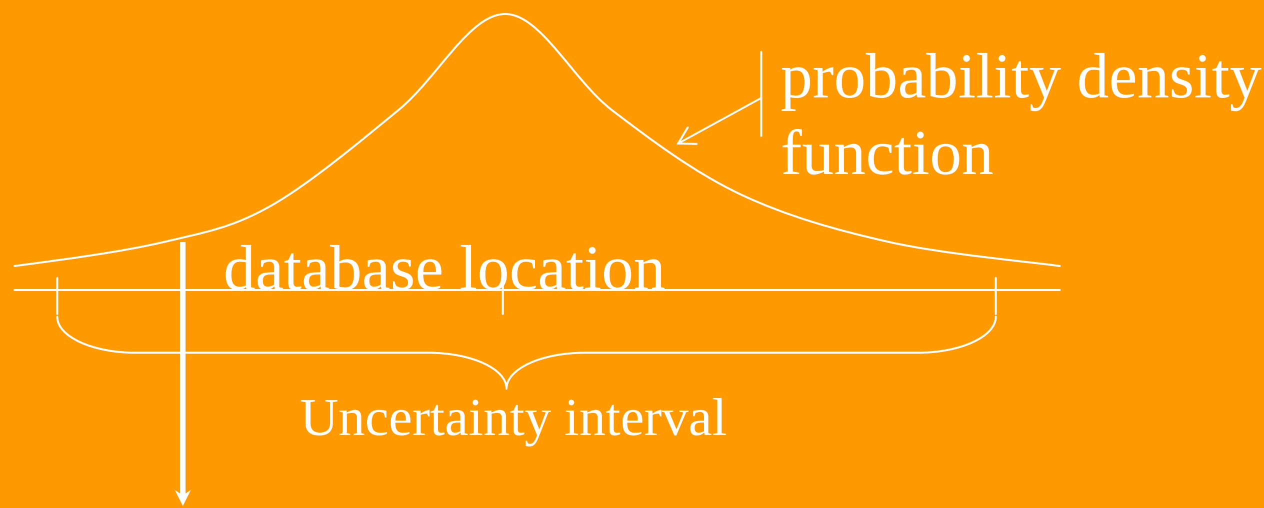
Time-complexity summary

Operator	Concave R	Convex R	Circular R
Possibly_Sometime	$O(nk)$	$O(nlogk)$	$O(n)$
Possibly_Always	$O(nk^3)$	$O(nlogk)$	$O(n)$
Always_Possibly	$O(nk)$	$O(nlogk)$	$O(n)$
Definitely_Sometime	$O(q^2nk + kk_rlogk)$	$O(q^2nk)$	$O(n)$
Sometime_Definitely	$O(nk + kk_rlogk)$	$O(nlogk + k)$	$O(n)$
Definitely_Always	$O(nk + kk_rlogk)$	$O(nlogk + k)$	$O(n)$

a1

n number of straight line segments in trajectory
k number of polygon vertices
kr number of reflex vertices
q number of intersections between route-segemnts and polygon
aa, 4/28/2004

Uncertainty in Language - Quantitative Approach



Standard deviation depends on :

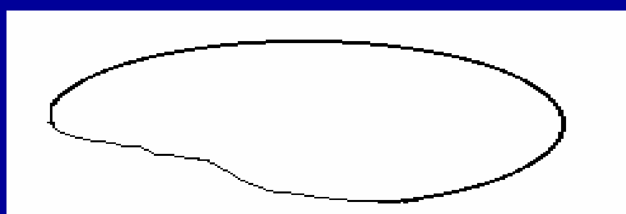
- time since last update
- network reliability

Probabilistic Range Queries

SELECT o

FROM MOVING-OBJECTS

WHERE Inside(o, R)



R

Answer: (RWW850, 0.58)

(ACW930, 0.75)

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Location updates

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Outline

- Background
  - Location technologies, applications
  - demo
- Research issues
  - Location modeling/management
  - Linguistic issues
  - Uncertainty/Imprecision
  - Indexing ←
  - Synthetic datasets
  - Compression/data-reduction
  - Joins and data mining

Indexing

Used for fast processing of range queries

• Range query: Given a spatial region R and a time interval [t1, t2], retrieve all objects that will be in R at some time during the interval.

• Restricted range query: Range query when the time interval is a single point t1.

• In case of one dimension, region R is a line-segment; in higher dimensions it is a hyper-rectangle.

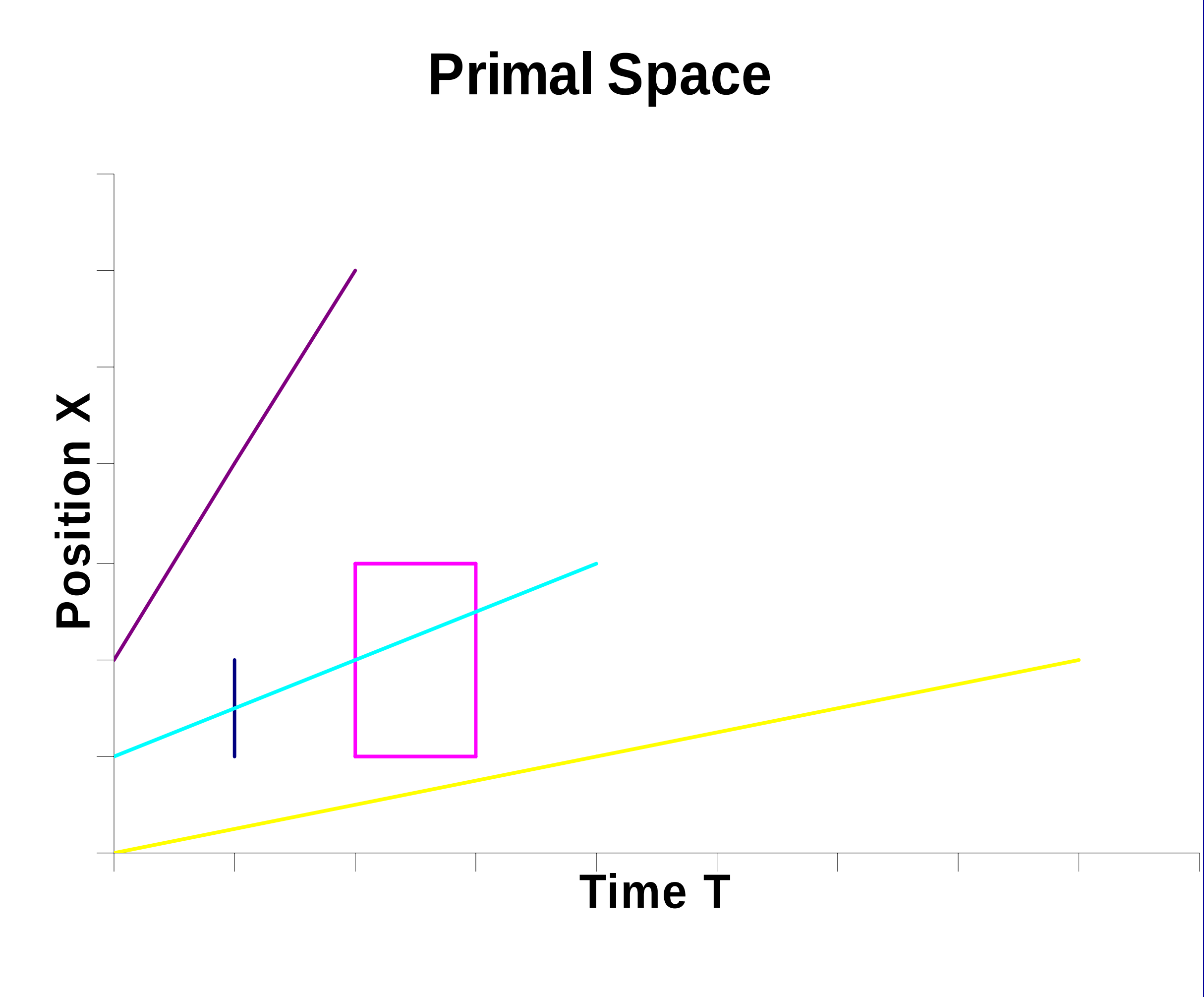
Performance measure: number of I/Os

Indexing Methods

•**Primal Space Method**:

• Consider the space together with time as an additional axis. Object movements form straight lines in this space (when moving with constant velocity).

•Consider the hyper rectangle X formed by the region R of the query and the given time interval. The answer is the set of objects whose lines intersect X.



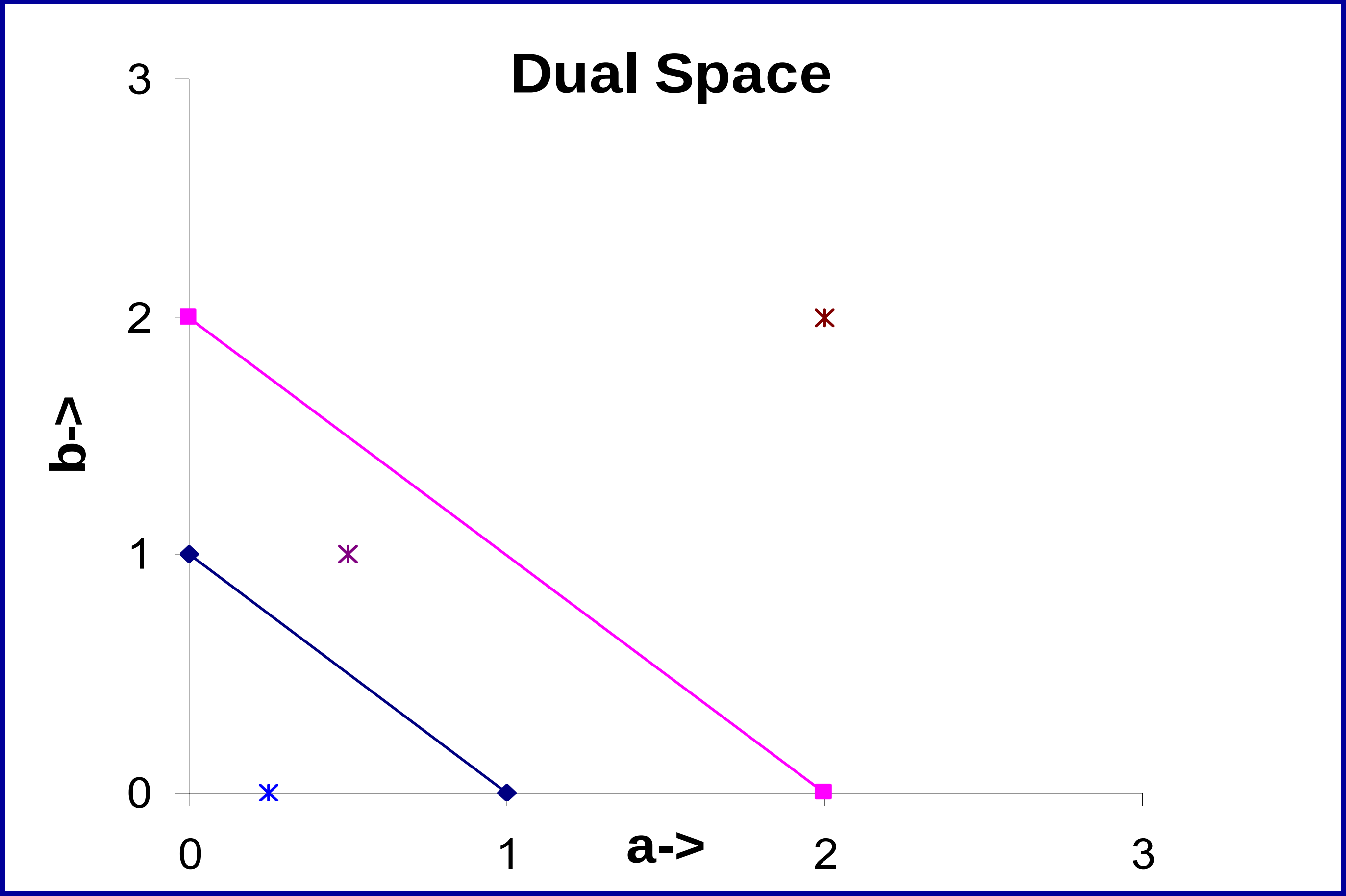
Query Q1: region R is the x-interval [1,2], time interval is the single point 1.

Q2: R is the x-interval [1,3], time interval is [2,3]

Dual Space Method: Consider the axes to be the coefficients in the equations of object motions.

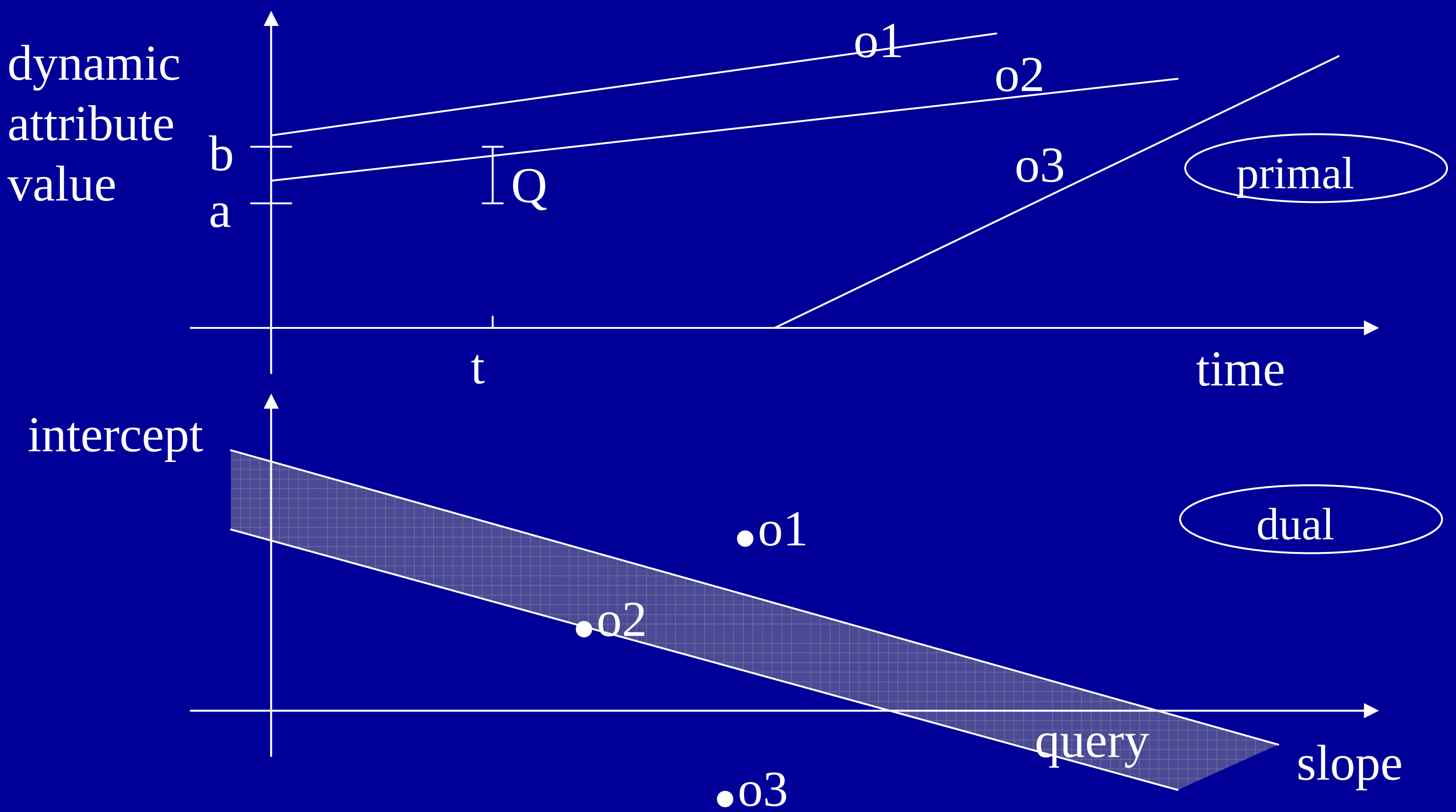
Ex: In 1-dimension, the equation of motion of an object is $x=at+b$.

- The dual space has two axes a and b.
- Each object is represented by a single point (a,b) in the dual space.
- The answer to a range query is the set of points in the dual space enclosed in a region satisfying some linear constraints.



Answer to query Q1: all the points in the strip.

Q: Retrieve objects for which dynamic attribute has value v $a \leq v \leq b$ at time t.



Spatial indexing to find objects that satisfy (intersect) query.

Primal Space Methods

First Method: (Sistla, Wolfson et al 97, Tayeb et al 98)

Divide time into periods of length T. For each period construct a multi-dimensional index using quad-trees.

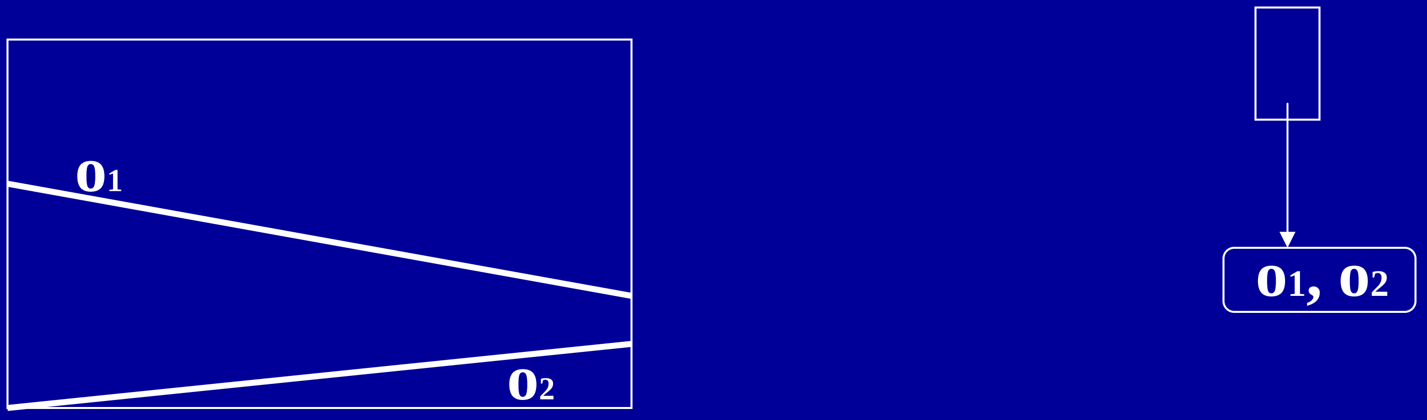
•Divide primary space recursively into cells

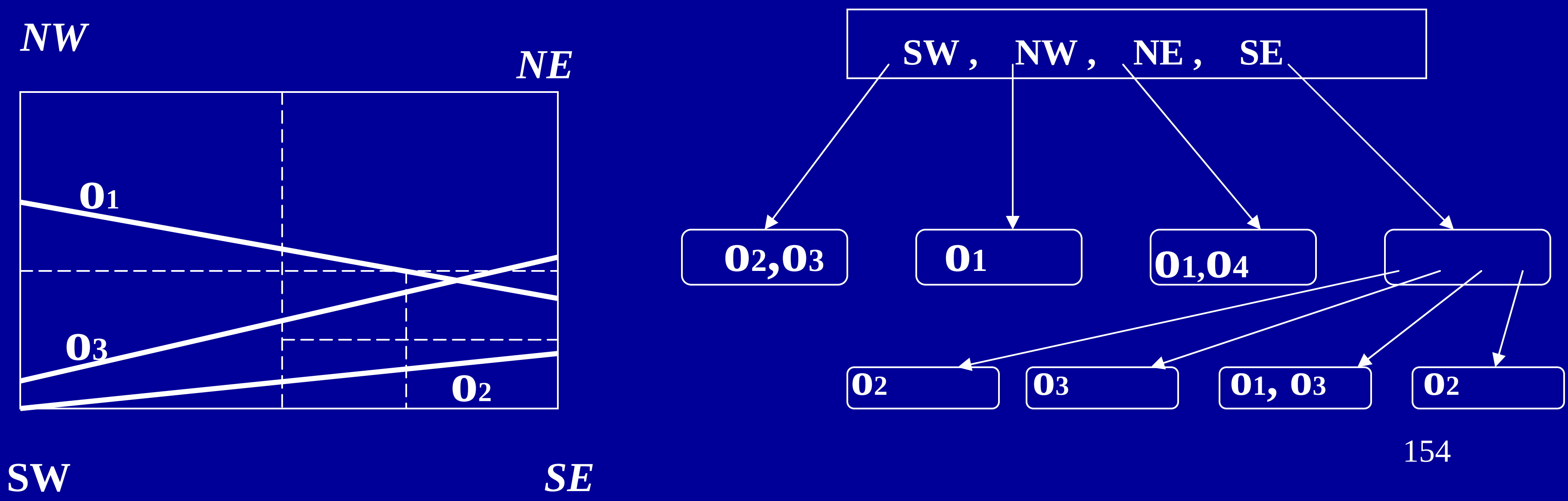
•Store an object in a cell that its trajectory intersects

•The index can get large as an object may appear in more than one cell.

Indexing (cont.) Primal Space Examples (TUW98)

assuming a bucket size of 2 for the leaf nodes:





Performance analysis of primal plane representation using quadtrees. Tayeb, Ulusoy, Wolfson; Computer Journal, 1998

Example of implication: $\Longrightarrow$

30,000 objects   3 I/O's per range query

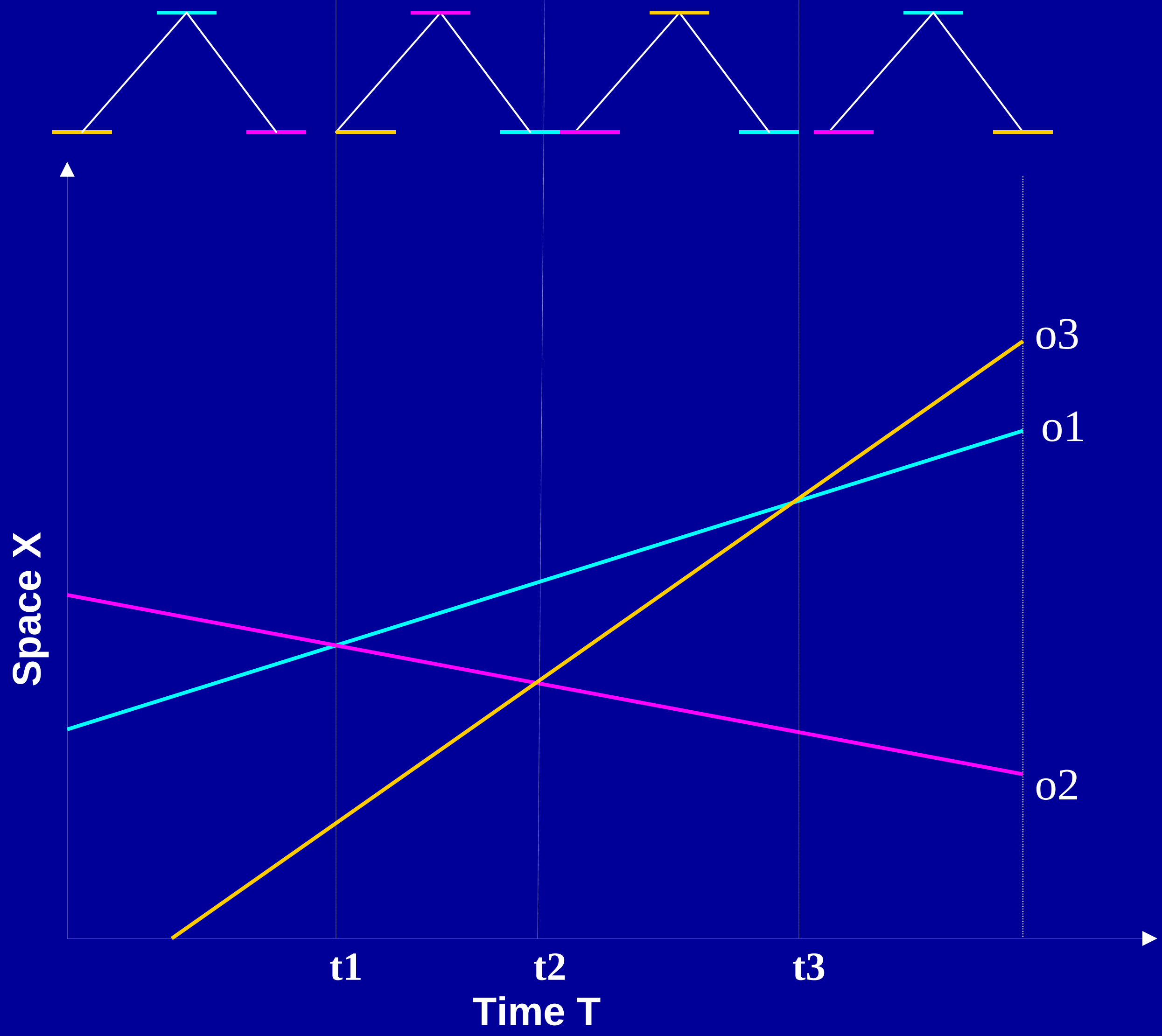
Primal Space Methods--- Contd

Second Method: (kinetic data structure**)** only for one dimensional motion.

•At any point in time we can linearly order objects based on their location. The ordering changes at those times when object trajectories cross.

•Fix a time period T and determine the orderings at the beginning and at T.

•Find the crossing points t1,t2,…,tm of the objects.



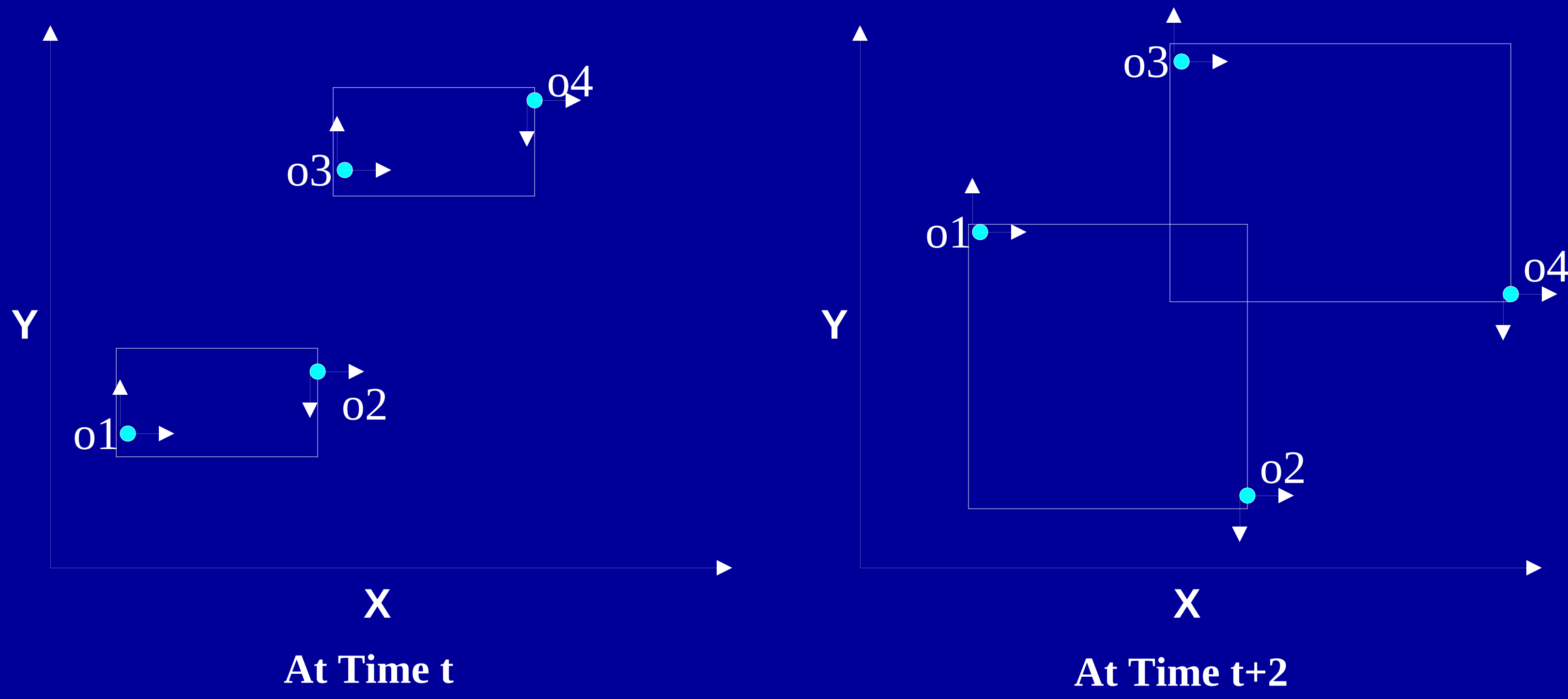
Determine ordering between crossing points

- Obtain the orderings between the crossings. Build binary search trees T1,…,Tm based on them.
- **To retrieve objects in the space interval I at time t do as follows**:
- Find a value j such that time t falls in the jth time interval.
- Use the search tree Tj to find all objects in the space interval I at that time.

Has space complexity O(n+m) and time complexity O(log (n+m)) where m is the number of crossings and n = N/B; N is the number of moving point objects, and B is the block size.

Primal Space Methods (continued)

- **Third method:** Saltenis et. al. 2000
- Time parameterized R*-trees (TPR)
  - works for motion in any number of dimensions.
  - Similar to R*-trees except that the MBRs are time parameterized.
- Objects are clustered and grouped into MBRs.
  - MBRs are enclosed into bigger MBRs.
  - They are arranged into a R*-tree.
- Each MBR has the following information.
  - Its coordinates
  - the min and max velocities of objects (in each direction).



Leaf level MBRs overtime

- The position and sizes (i.e. the coordinates) change with time. The actual values can be computed at any time.
- Searching is performed as in R*-trees except that whenever an MBR is used its actual coordinates at that time are computed.
- The tree is reconstructed periodically
- Tree construction and insertions are processed so as to reduce the average area of the MBRs over the time period.

Dual Space Methods

[Kollios et al 99 (1-dimension), Agarwal et al 00 (2-dimensions)]

• similar to quad trees except:

- Employs Partition trees (used in computational geometry)
- Partition trees use simplicial partitions of sets of points.
- A simplicial partition of S is a set of pairs (S1,D1),…,(Sr,Dr) such that S1, …Sr is a partition of S. Di is a triangle enclosing points in Si.

For the given set of moving point objects, a partition tree is constructed satisfying the following properties.

- The leaves are blocks containing moving objects.
- A triangle is associated with each node in the tree.
    - The vertices of the triangle are stored in the node.
    - This triangle contains all the object points of the sub-tree.
- The sets of points and triangles associated with the children of a node form a ***balanced*** simplicial partition of the set of nodes of the parent.
- The size of the tree is O(n) and the height O(log n).

Searching for the points enclosed in a time/space region X:

Recursively search starting from the root.

- If the triangle at a node is contained in X then output all points in the subtree.
- Otherwise, recursively search along the sub-trees of the children whose triangles intersect X.
- At a leaf node, output all points in the node that are in X.

Range query Complexity: approximately O(k+ Sqrt(n)); k is output size

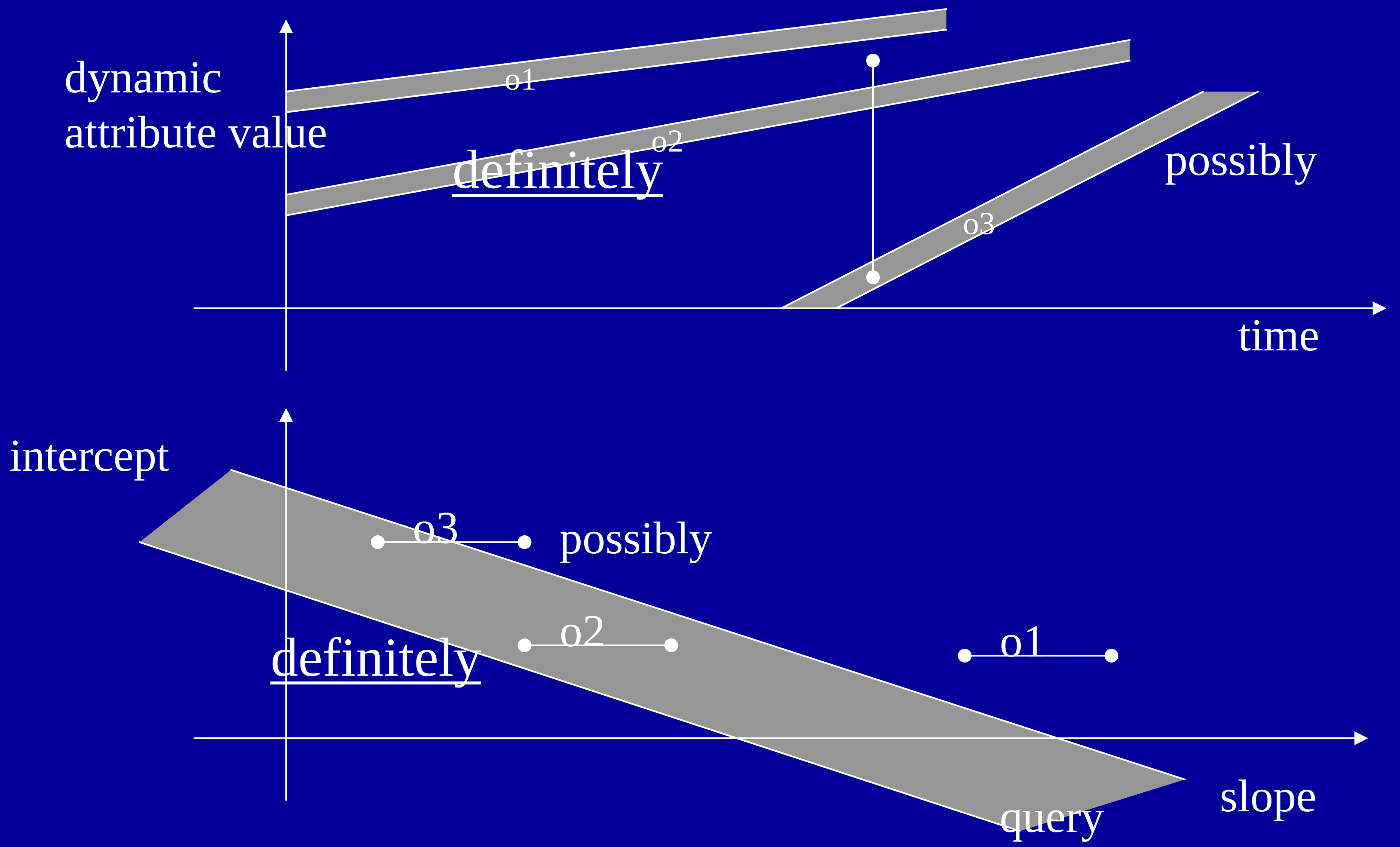
Insertion/deletion--- $O(\log^2(n))$ amortized complexity.

.

Solution Paradigm

- Geometric Problem Representation in Multidimensional Time-Space
- Spatial Indexing of Geometric Representation

Indexing with Uncertainty



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- Background
  - Location technologies, applications
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  - Uncertainty/Imprecision
  - Indexing
  - Synthetic datasets ←
  - Compression/data-reduction
  - Joins and data mining

Contents

- Motivation: Collecting huge real spatio-temporal data is difficult.
- Idea: random generation of data
- Methods
  - Generate_Spatio_Temporal_Data(GSTD) [1, 2]
  - Brinkhoff's Approach [3, 4]
  - Saglio and Moreira's Generator [5]
  - CitySimulator [6, 7]
  - Generation of Pseudo Trajectories [8]

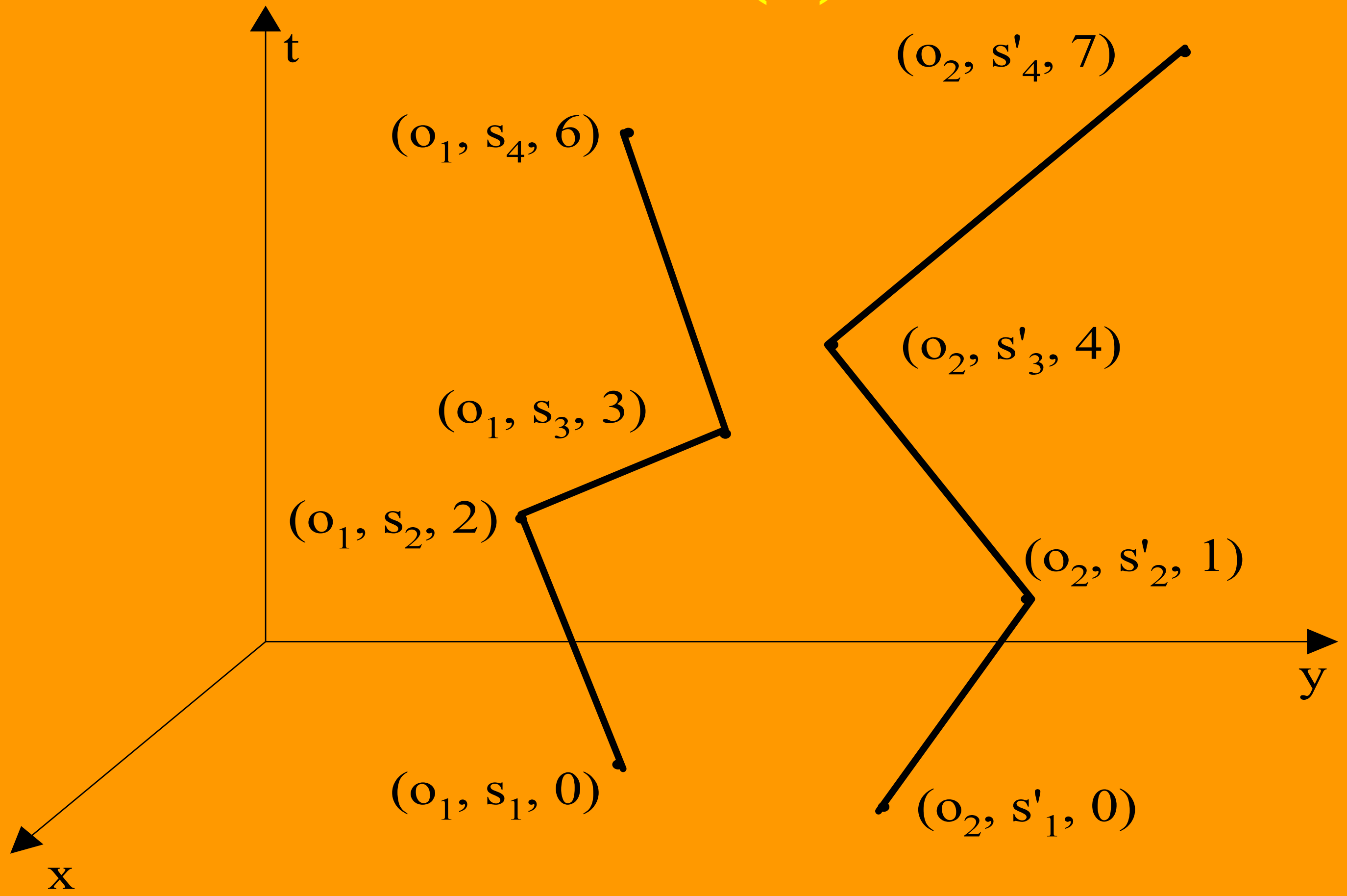
A1

GSTD (1)

- Model
  - Bounded 2D free space.
  - objects:
    - Point objects: vehicles, pedestrians
    - Region objects: weather phenomena
  - purpose: evaluation of indexing methods
- Basic operations
  - define a set of objects with starting position for each
  - compute new timestamp
  - compute new spacestamp
  - compute new spacestamp's extension

A1 Three random & probability distribution
uniform;
Skew;
Gaussian.
Administrator, 12/31/2002

GSTD (2)



Example: Two moving objects

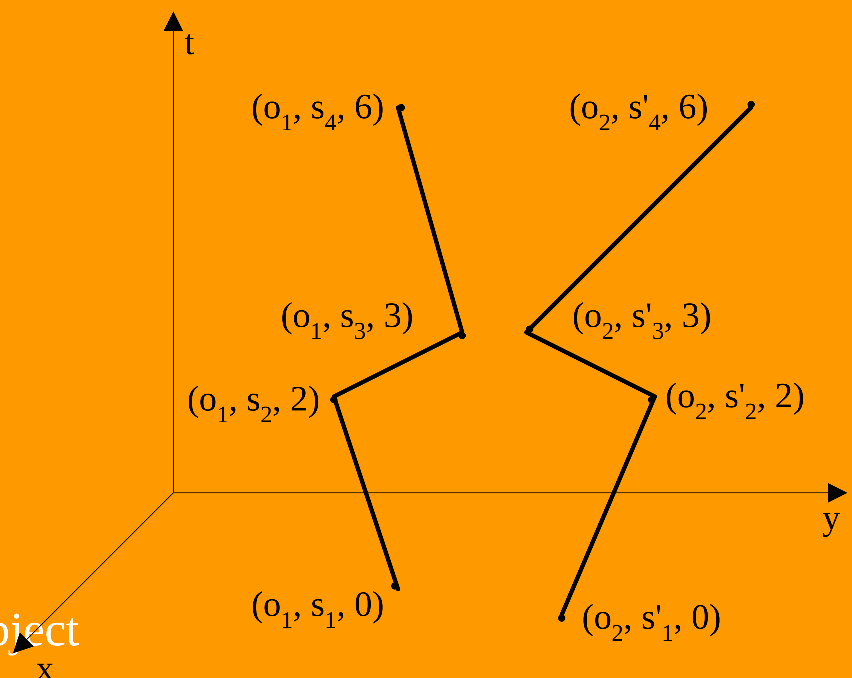
A2 This example is only for point objects

If an object leaves the spatial data space, different approaches can be applied:
the position remains unchanged;
the position is adjusted to fi into the data space;
the oject re-enters the data space at the opposite edge of the data space.
Administrator, 1/2/2003

A3

Brinkhoff's Approach

- Model
  - 2D
  - based on a network (TIGER files)
  - objects:
    - point objects
    - region objects (weather)
  - purpose: evaluation of indexing
- Basic operations
  - generate objects every time unit
    - generate starting points
    - generate length of route (depending on object class)
    - generate destination for each object
    - compute the route
    - compute the trajectory by generating a random speed every time unit (based on capacity, weather, edge class, etc.)



Example: Two moving objects:

o_1: A car; o_2: A truck

A3 The network can be

1. synthetic network
2. real network:
   - TIGER/Line files;
   - SEQUOIA 2000 Storage benchmark.

The destination is computed by the starting point & the length of route.

Three methods for computing the starting points:
- data-space oriented approach (DSO);
- region-based approach (RB);
- network-based approach (NB).

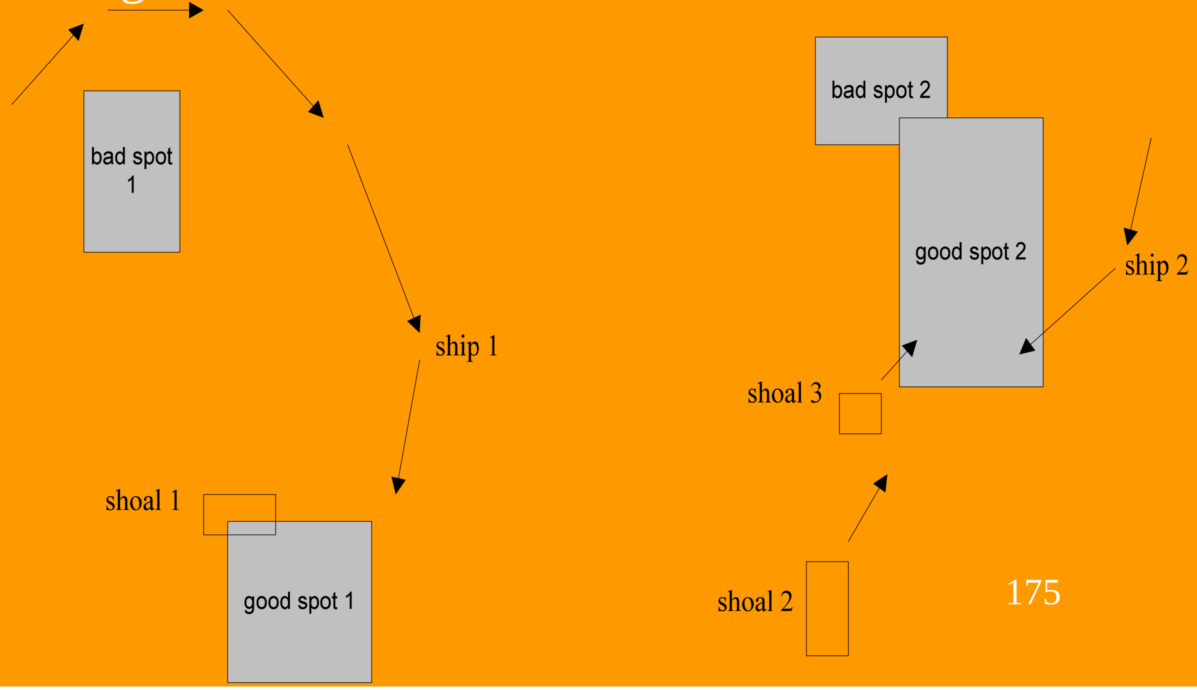
A* algorithm for computing the route.

Administrator, 12/31/2002

A4

Saglio and Moreira's Generator

- Model
  - 2D frame
  - Motivating scenario: *modeling the motion of fishing boats*
  - objects:
    - *Harbors*: static
    - *Fishing ships*: moving objects
    - *Good spots & bad spots*: center fixed, dynamic shape
    - *Shoals*: dynamic center & shape
  - purpose: evaluation of indexing methods
- Basic operations
  - define objects
  - define changes for each object
  - criterion for motion: proximity (e.g. shoals to good spots)

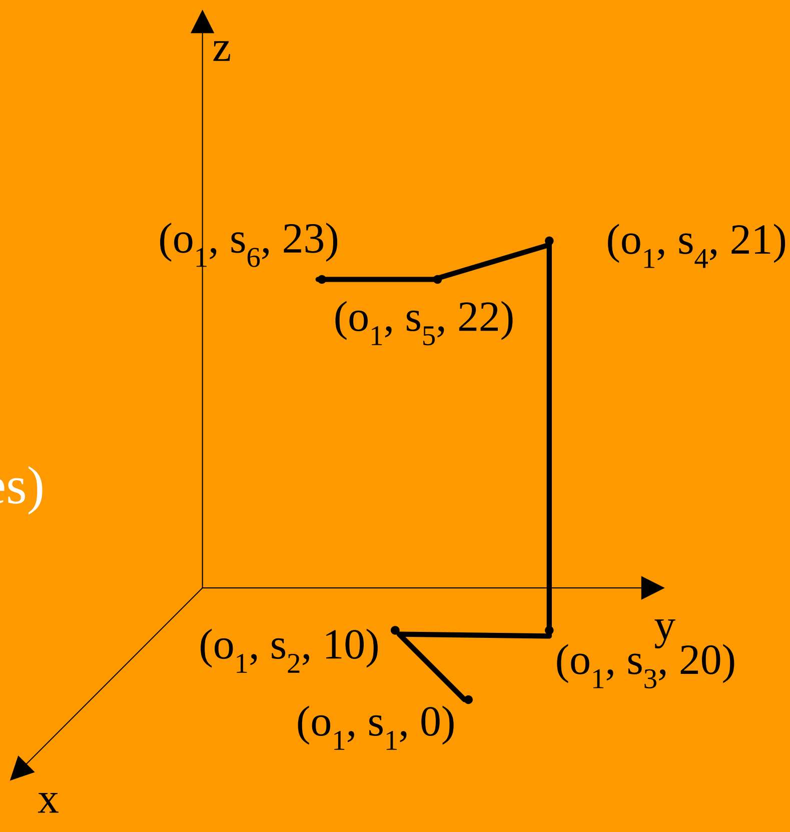


A4 spots (bad&good):
 appear at random locations & times & extension
 first expansion, then shrinking
shoals of fish:
 random center, velocity & extension
 seek for a good spot (the nearest one)
harbors:
 on the boundary of the frame
fishing ships:
 goes after a selected shoal (a good spot) & avoid storms(bad spots)
 criterion for selection: proximity
Administrator, 12/31/2002

A5

CitySimulator

- Model
  - 3D network (roads & buildings)
  - Based on a network
    - XML files (real/synthetic)
  - Objects:
    - Pedestrians & vehicles (points)
  - Purpose: indexing evaluation
  - Main difference from Brinkhoff's: 3D
- Operations
  - Generate objects (start point, # of moves)
- Trajectory point parameters
  - enter/exit probability;
  - up/down probability;
  - drift probability (on roads);



A5 For the object o1, locations s1, s2 & s3 are on the same plane z = 0; locations s4, s5 & s6 are on the same plane z = 18.

This example simulates one person drives a car to his office building, and go to his office which locates on the 18th floor (z = 18) (first by the elevator and then by walking).

Parameters:
- enter/exit probability;
- up/down probability;
- drift probability (on roads);
- scatter probability (on intersections);
- traffic model.

Administrator, 1/3/2003

Pseudo trajectories [8]

- Realistic synthetic trajectories by superimposing real speed variations on random routes

Real Trajectories Dataset

- *Real Trajectories*
  - Define Drive trip
  - Repeatedly read the (*longitude, latitude, time*) from a Differential GPS device connected to a laptop
  - Every *two* seconds

Define Speed Patterns

- *Speed-pattern for road of type A3*

  sequence of consecutive speeds read while driving on road of type A3 in one trip

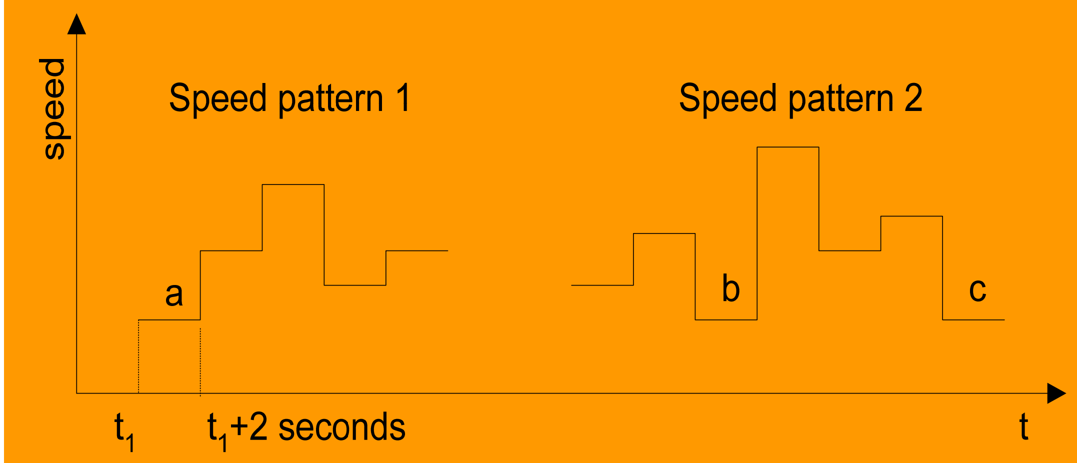
- Speed pattern set for A3

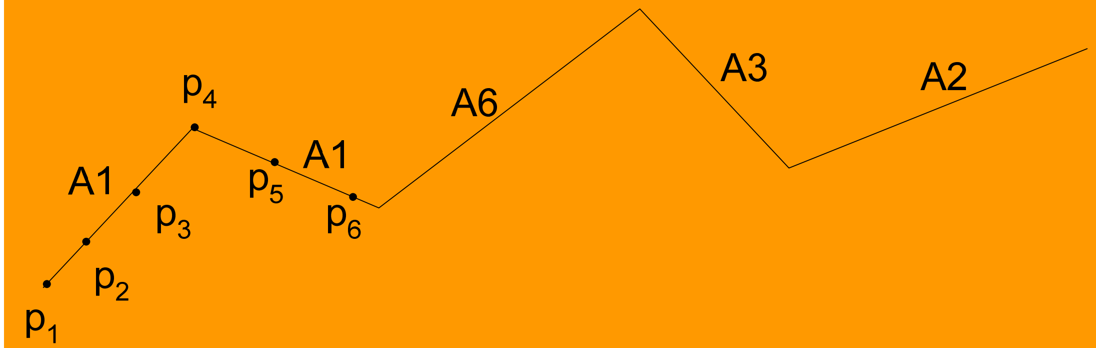
  all speed patterns, for all trips, for A3 road.

Speed pattern id	Speed id	speed
1	1	35
1	2	40
1	3	45
1	4	37
1	5	40
2	1	37
2	2	42
2	3	35
2	4	50
2	5	40
2	6	43
2	7	35

A13

Pseudo Trajectory Generation





The route

1. Generate random route and set v=0

2. Pick a random speed pattern R for the current street type that has speed v.

3. Continue R to the end of the pattern or end of road, whichever comes first.

4. Set v to last speed and go to 2.

A13 a, b, c are speeds that equal to current speed v = 35 mph.
Randomly select speed pattern 1, starting from a to compute the new position and timestamp on the first A1 street.
Administrator, 12/31/2002

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Outline

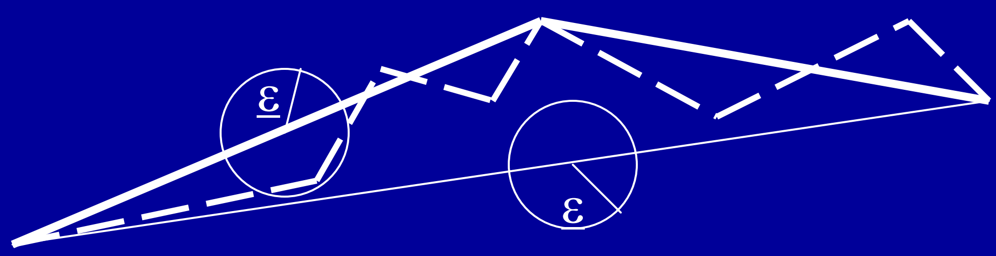
- Background
  - Location technologies, applications
  - demo
- Research issues
  - Location modeling/management
  - Linguistic issues
  - Uncertainty/Imprecision
  - Indexing
  - Synthetic datasets
  - Compression/data-reduction ←
  - Joins and data mining

Data Reduction -- Motivation

– **Tracking** the movements of all vehicles in the USA needs approximately **4TB/day** (GPS receivers sample a point every two seconds).

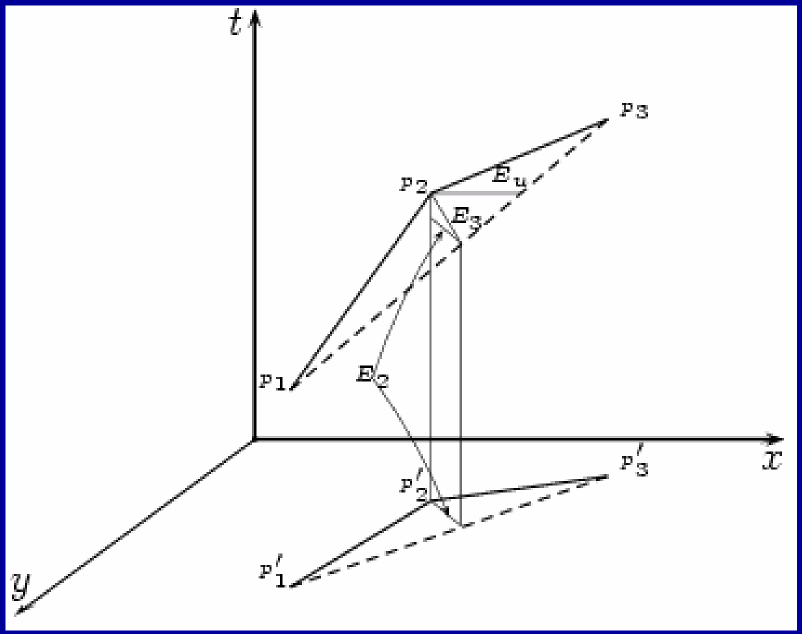
Trajectory Reduction

- Line simplification: approximate a trajectory by another which is not farther than ε.



Distance Functions

- The distance functions considered are:
  - E_3: 3D Euclidean distance.
  - E_2: Euclidean distance on 2D projection of a trajectory
  - E_u: the Euclidean distance of two trajectory points with same time.
  - E_t: It is the time distance of two trajectory points with same location or closest Euclidean distance.



- $\#(T'_2) \leqslant \#(T'_3) \leqslant \#(T'_u)$, which is also verified by experimental saving comparison.

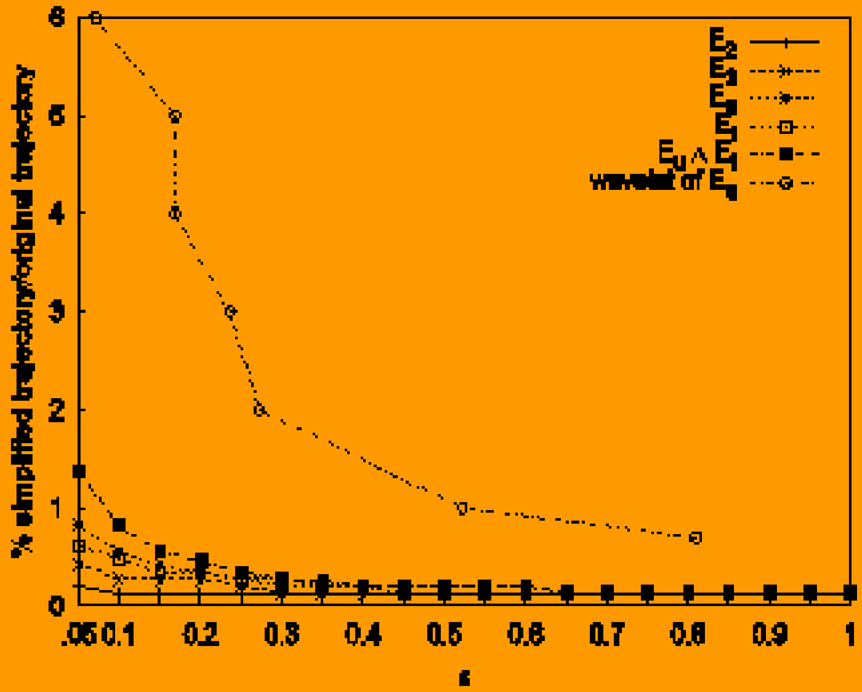
Soundness of Distance Functions

- Soundness: bound on the error when answering spatio-temporal queries on simplified trajectories.

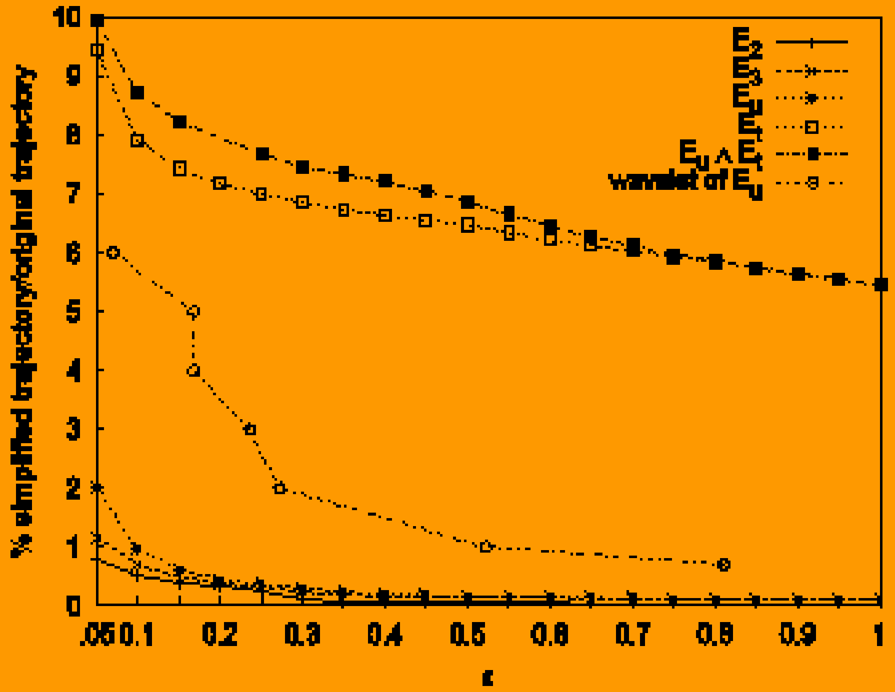
	Where_at	When_at	Intersect	Nearest_ Neighbor	Spatial Join
E_2	No	No	No	No	Sound when (a) the distance function D of join is metric (b) E is weaker than D.
E_3	No	No	No	No	
E_u	Yes	No	Yes	Yes	
E_t	No	Yes	No	No	

- The appropriate distance function depends on the type of queries expected on the database of simplified trajectories.
  - If all spatio-temporal queries are expected, then E_u And E_t should be used.
  - If only *where_at*, *intersect*, and *nearest_neighbor* queries are expected, then the E_u distance should be used.

Savings (of past trajectories):



The Optimal Simplification



DP Simplification

- ε =0.1 ==> reduction to at most 1% for most distances.
- Better than the Wavelet compression.

Aging of Trajectories

- Increase ε as time progresses

$$T' = Simp(Simp(T, \varepsilon_1)) = Simp(T, \varepsilon_2), \varepsilon_1 \leq \varepsilon_2$$

- Valid for all distance functions when using the DP simplification algorithm.

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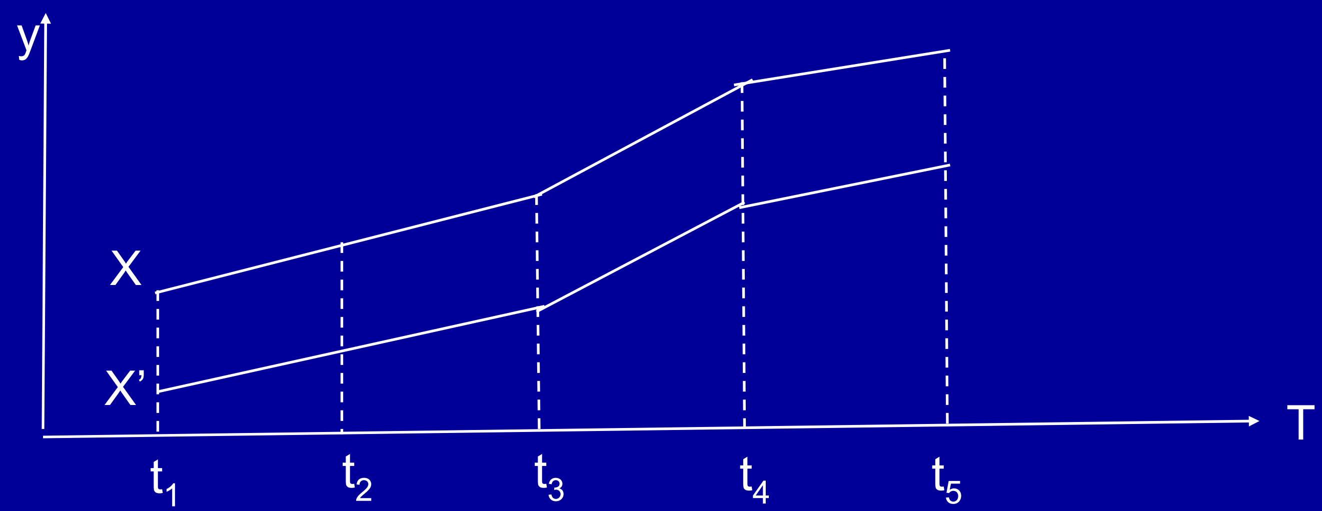
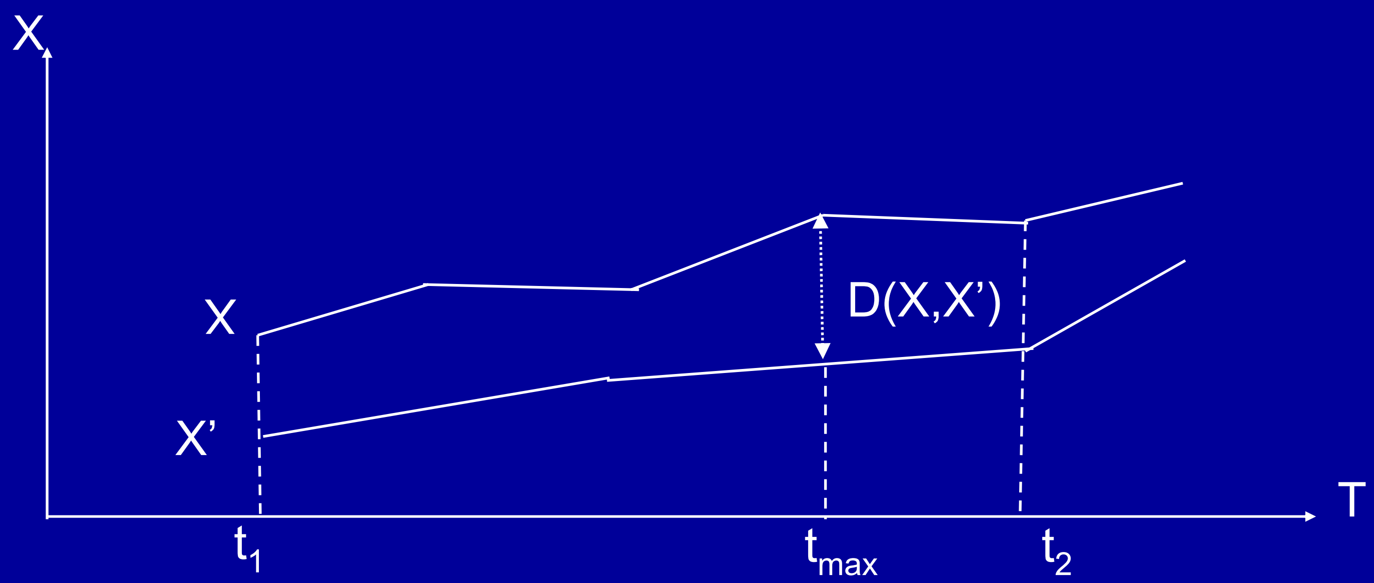
Whole Trajectory Matching

- Finding trajectories that are similar to a given trajectory.
- Works in
  - Computational Geometry
  - Time series matching extensions

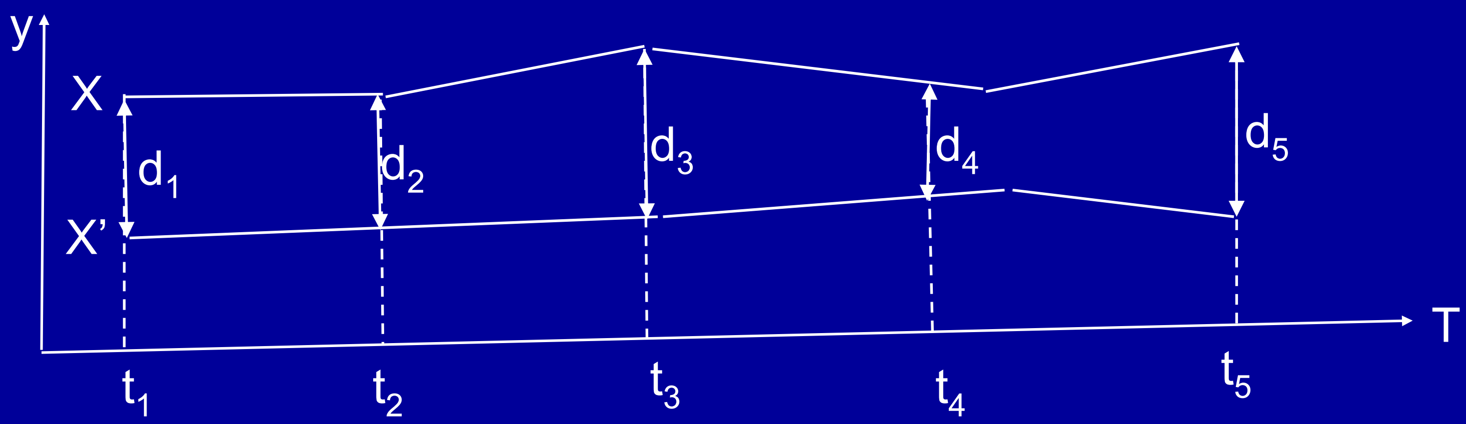


Maximum Euclidean Distance



$$D(X,X') = MAX_{t1 \leq t \leq t2} [d(X(t), X'(t))]$$

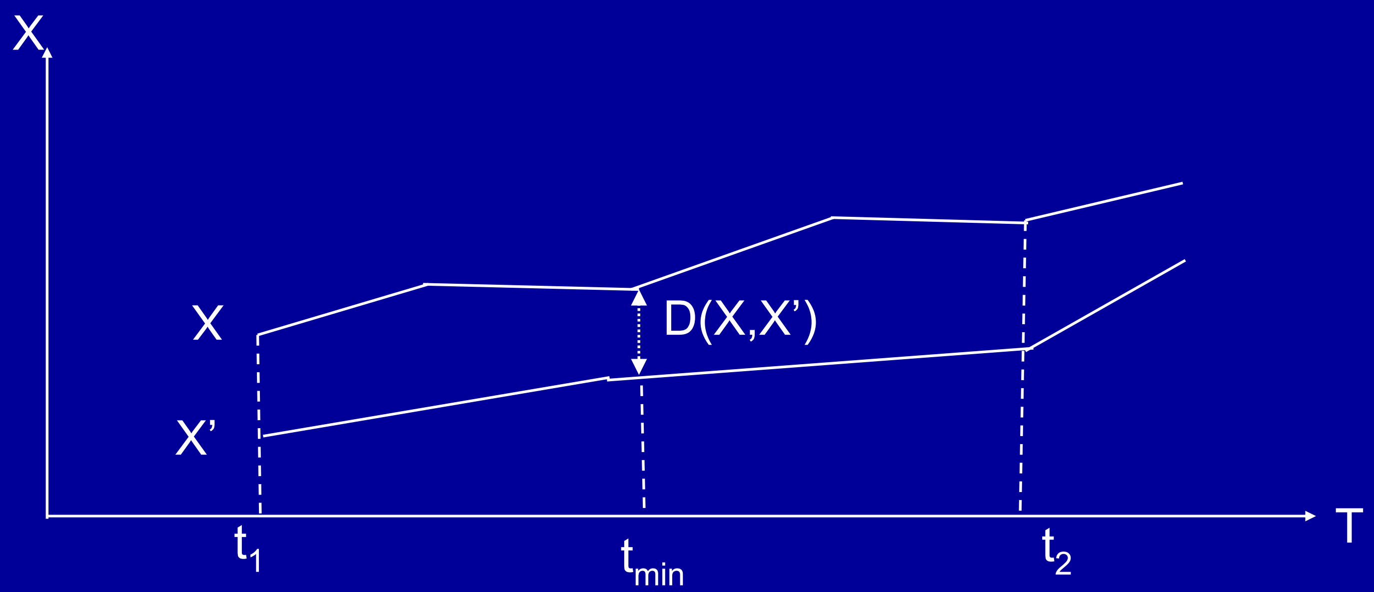
Root Mean Error Euclidean Distance



$D(\mathbf{X},\mathbf{X'}) = (1/5*(d_1^2 + d_2^2 + d_3^2 + d_4^2 + d_5^2))^{1/2}$

Example: Measuring the error of an estimated trajectory.

Minimum Euclidean Distance

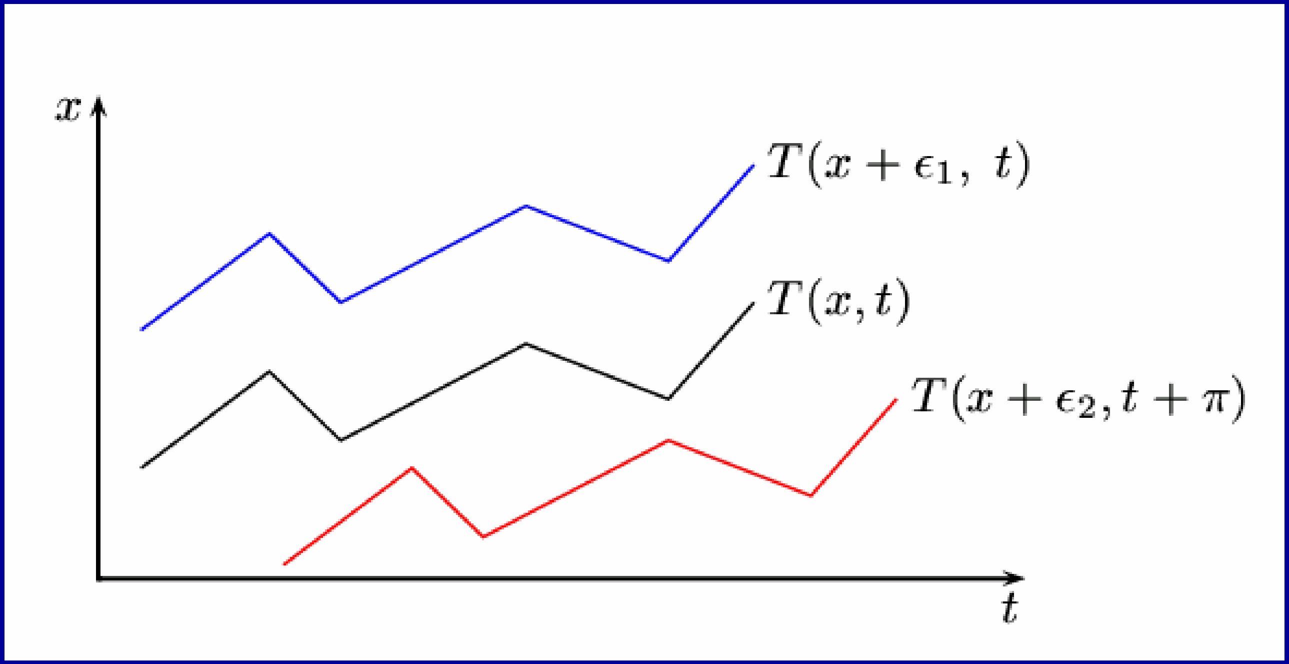


$$D(X,X') = MIN_{t1 \leq t \leq t2} [d(X(t), X'(t))]$$

Example: collision detection.

Geometric Transformation --- Translation

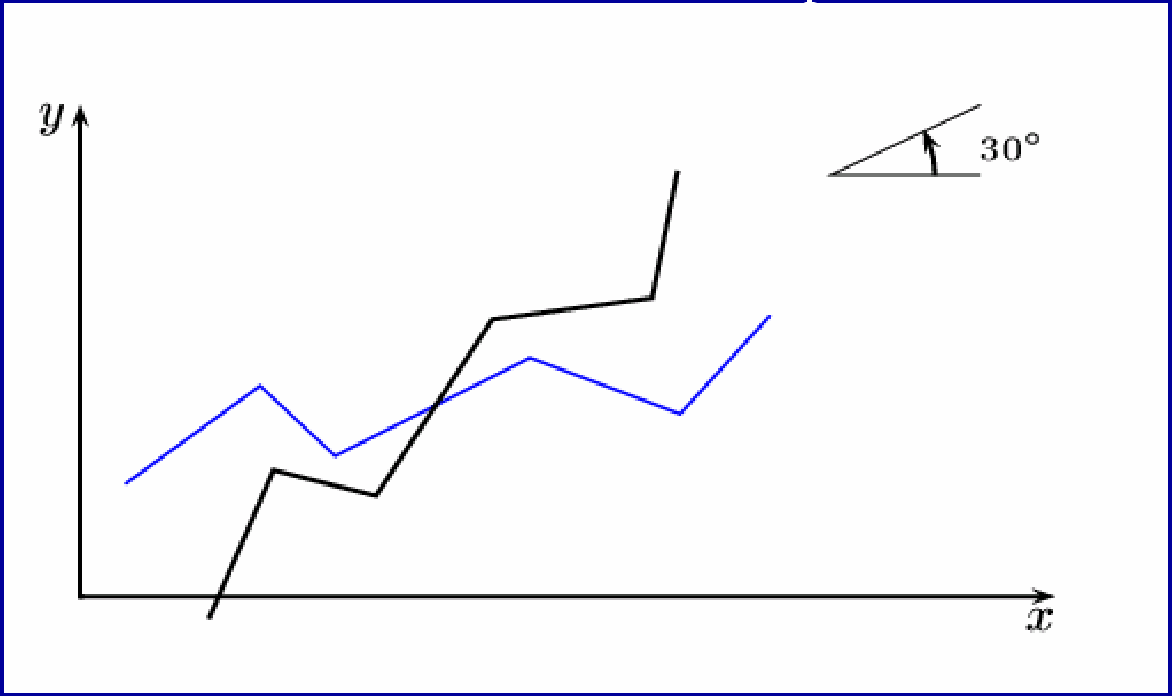
- A geometric transformation consisting of a constant offset
- every point (x, y, t) becomes (x+ε, y +δ, t + π) after a translation.



Example: 2 home-office trajectories (on different days) are similar after time-translation

Geometric Transformation --- Rotation

- Turns a trajectory by an angle about a fixed point.
- The rotation is limited in the X-Y sub-space.



Translation, rotation are rigid transformations.
Ex: similar motion patterns in different cities/times

Optimal Matching Similarity

- Optimal Matching: Given a set of operations (e.g. translation, rotation), an optimal match between trajectories T and T' with respect to a distance function f is to find a transformation minimizing the distance f(T, T').

- Work in computational geometry for the (translation, rotation) max Euclidean distance

  – An $O((mn)^3 \log^2(mn))$ algorithm for optimal matching; n and m are the vertex numbers of T and T'. (Chew et al.)

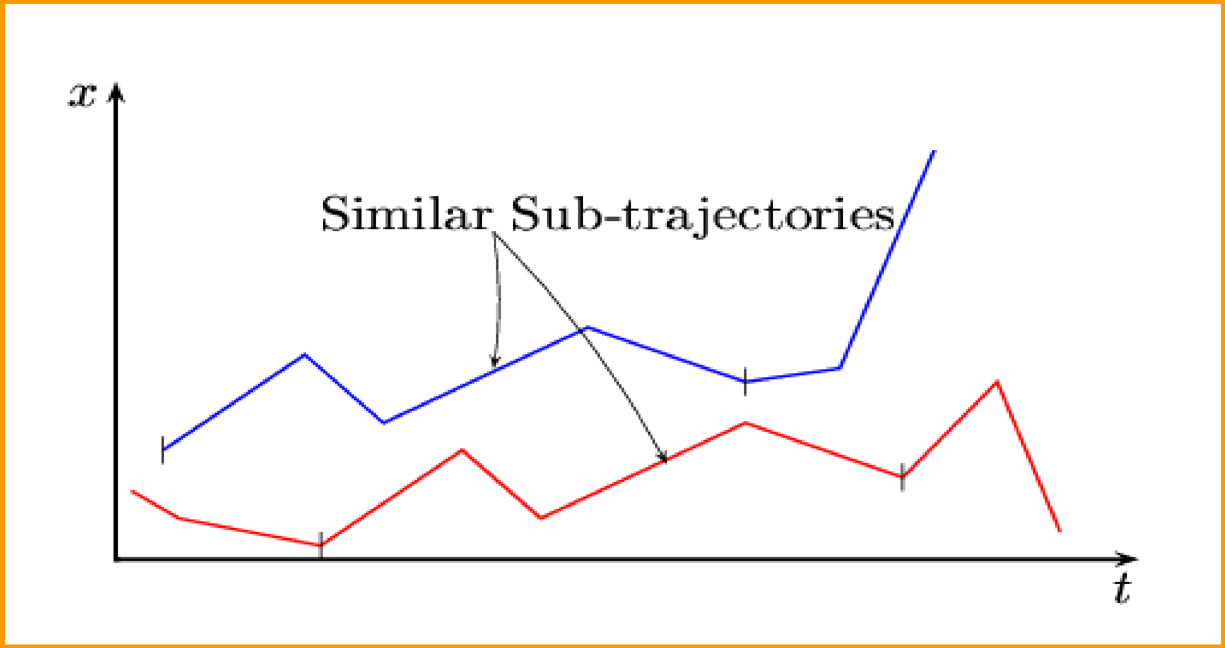
- For L_1 or L_∞

  – An $O((mn)^2 \alpha(mn))$ algorithm, by extending the vornoi diagram approach (Huttenlocher et al.)

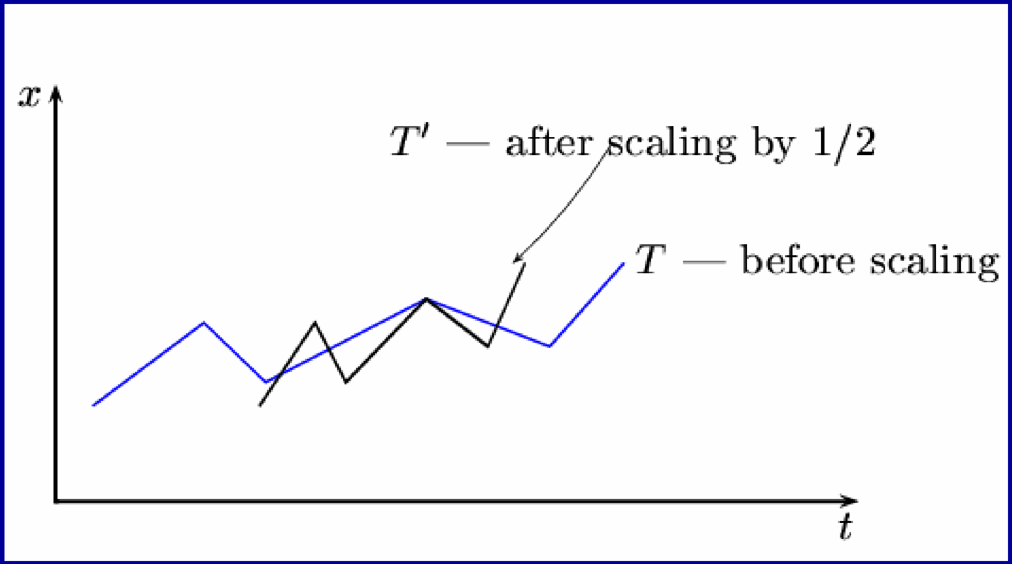
Longest Common Subtrajectory Similarity

- Trajectories maybe similar in pattern but of different length.
- Longest Common Subtrajectory Similarity(LCSS) uses the length of continuous similar subtrajectories to evaluate the similarity:

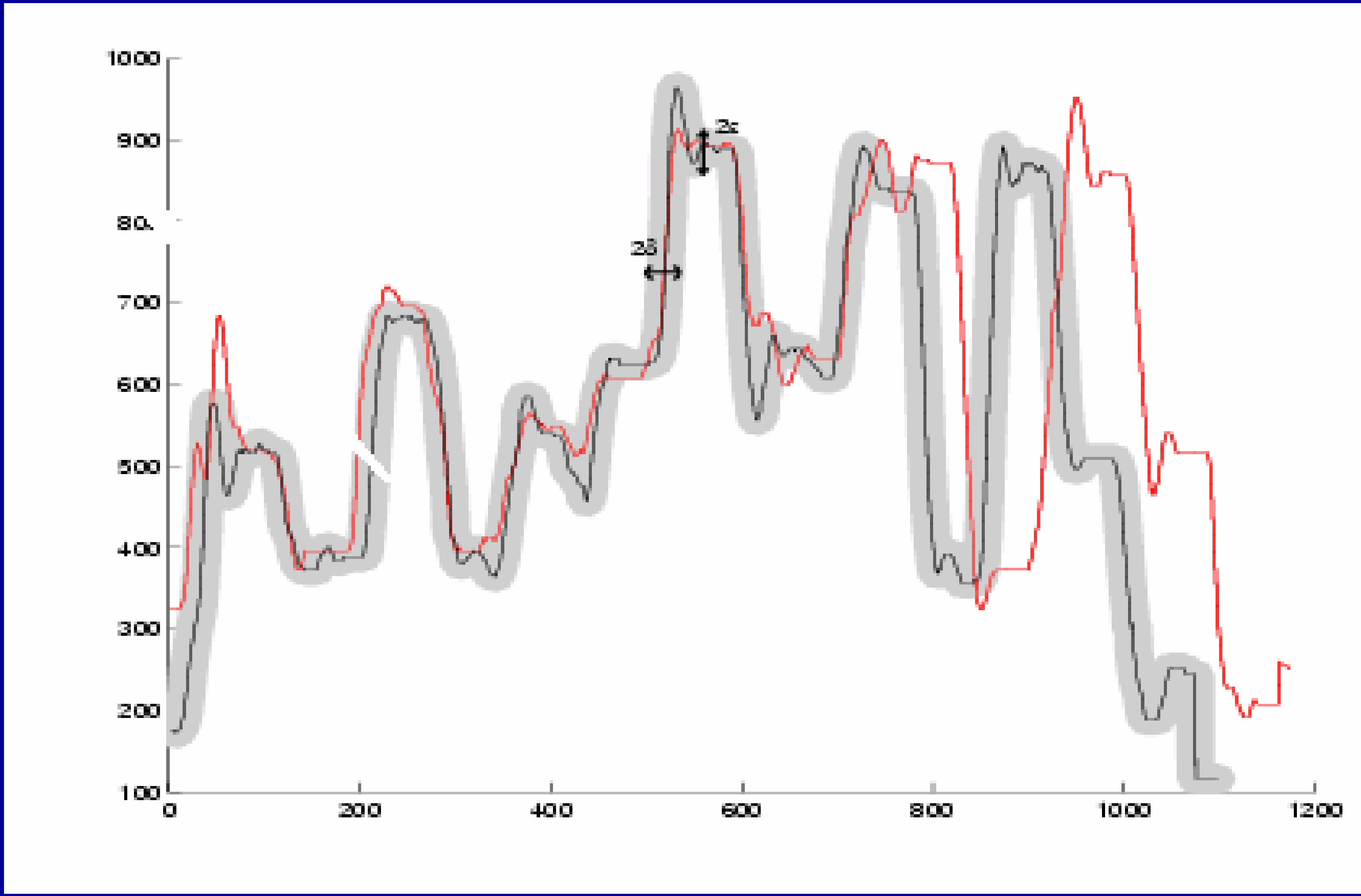
$$\frac{LNSS(T, T')}{\min(Length_T, Length_{T'})}$$



Time Scaling



Approximate Matching



Finding the Longest Common Subtrajectory

- M. Vlachos et al. give a dynamic programming algorithm using
  - *translation,*
  - *approximate matching, and*
  - *time scaling*

  to compute the LCSS.

- The time complexity of their algorithm is $O(n+m)^3\delta^3)$, where m and n are the numbers of vertices, δ is the maximal allowed time difference between two compared points

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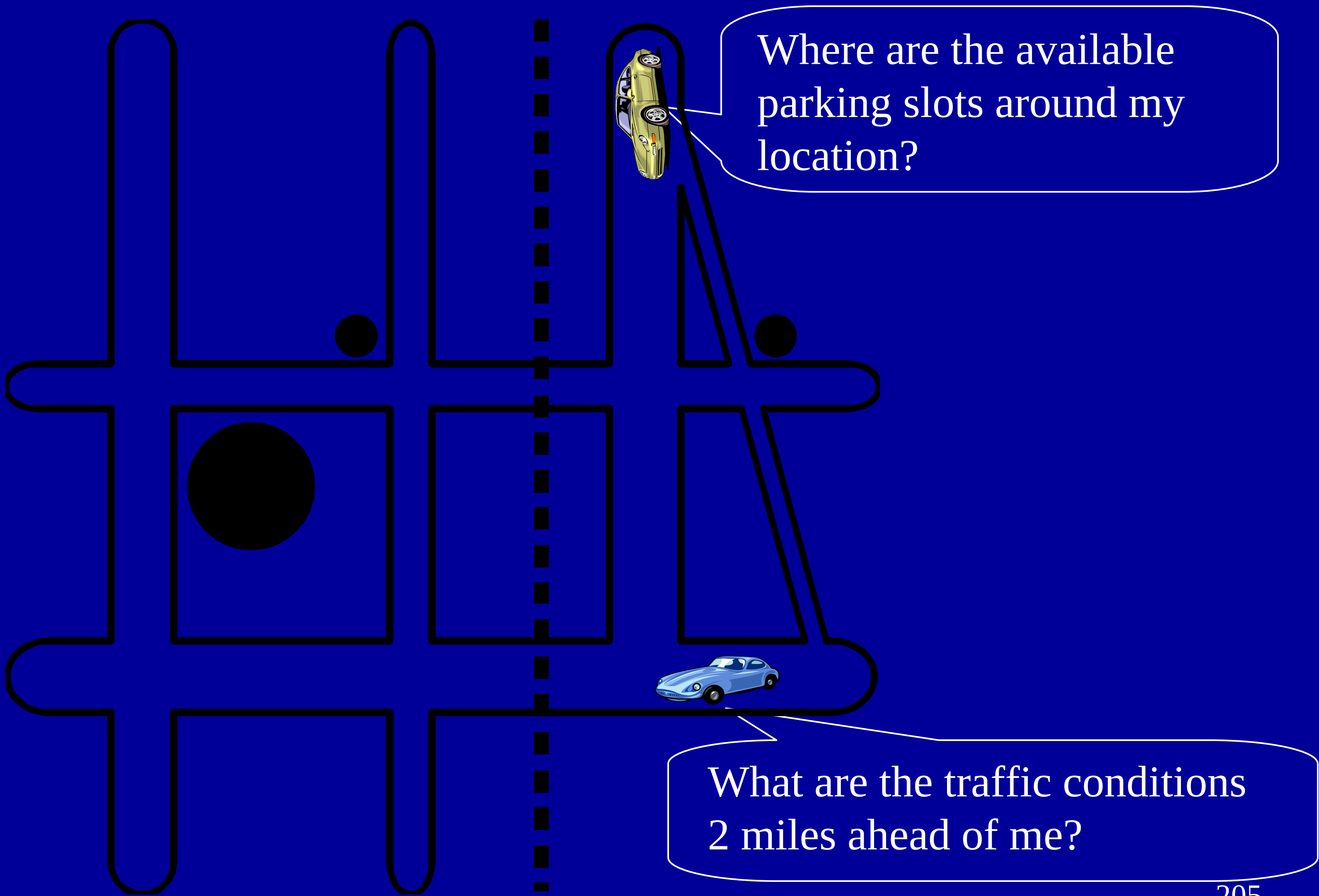
Location Awareness in Querying Mobile Environments

- An application of distributed/mobile/incomplete location database

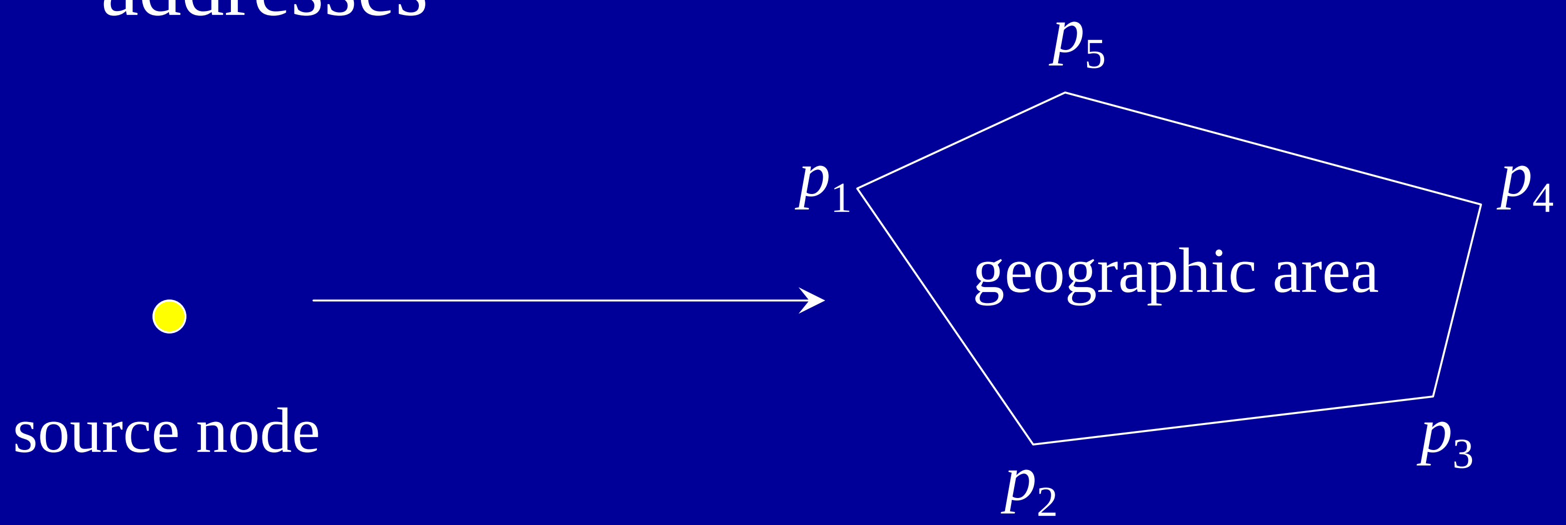
- Each node stores its location, location of its neighbors, possibly location of destination of query

Example Applications



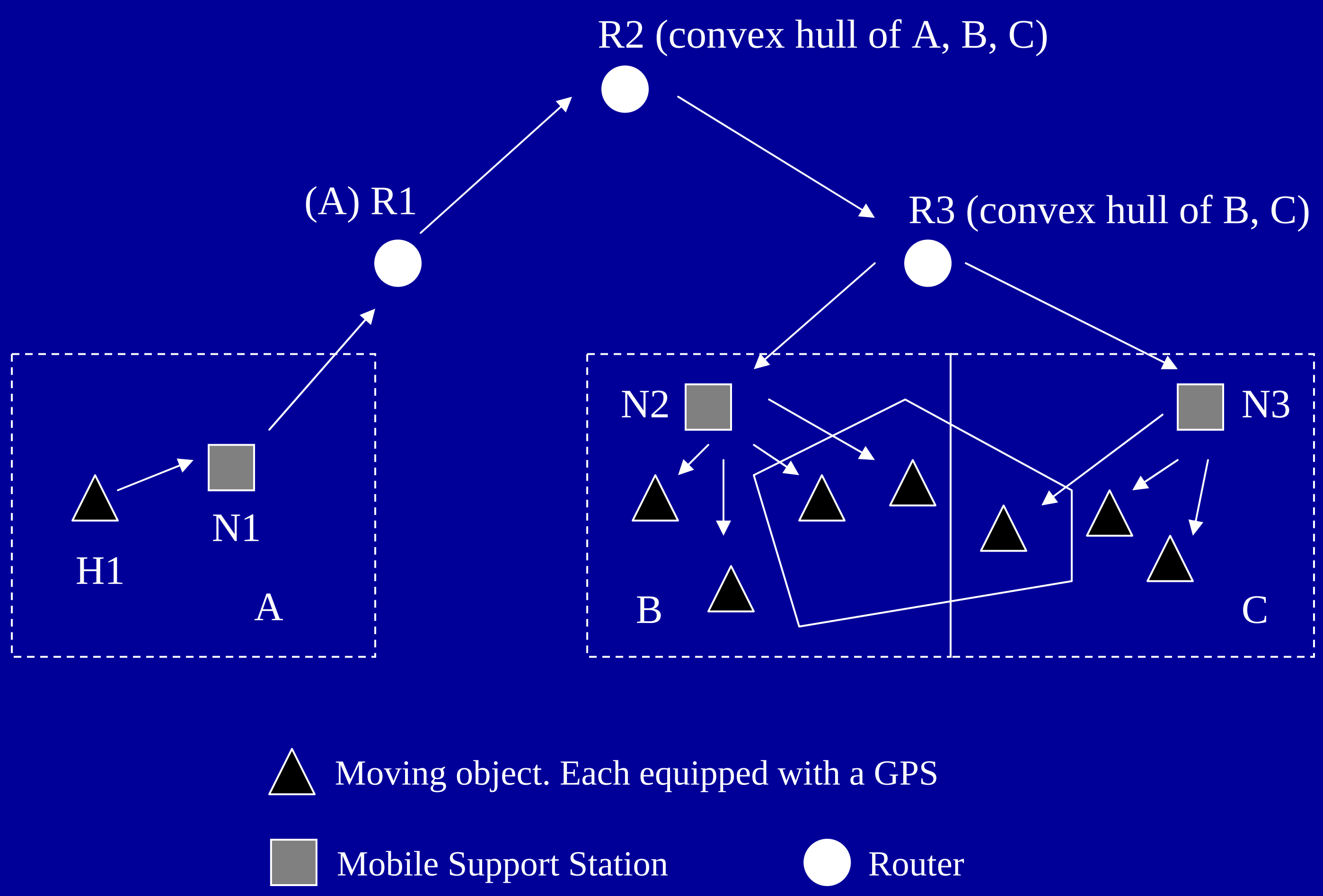
Infrastructure Solution: GeoCast [2]

- Using geographic addresses instead of IP addresses



destination address: polygon(p_1, p_2, p_3, p_4, p_5)

How GeoCast Works



Infrastructureless Solution: Mobile Ad-hoc Networks

- MANET: A set of moving objects communicating without the assistance of base stations
- A MANET uses peer-to-peer multi-hop routing to provide source to destination connectivity
- Need to do better than flooding (in b/w, power)
- See [9] for a survey of routing in ad-hoc networks

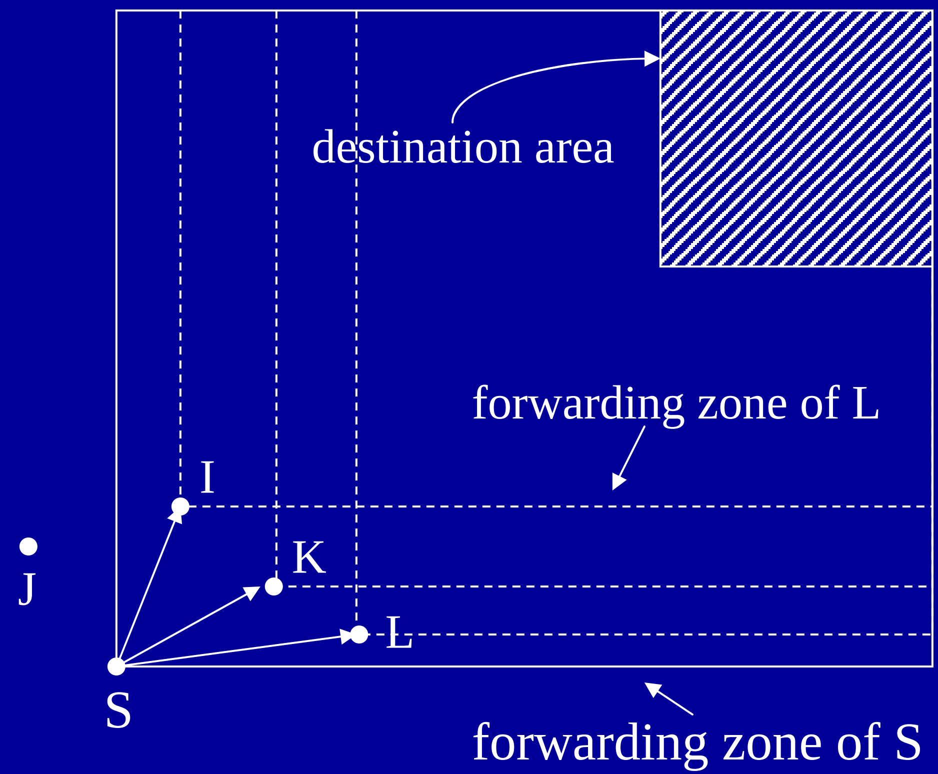
Location Based Routing

- The destination area or the location of the destination node is known by the source and used for message delivery.
- An intermediate node discovers neighbors and their locations and moving directions.

Classification

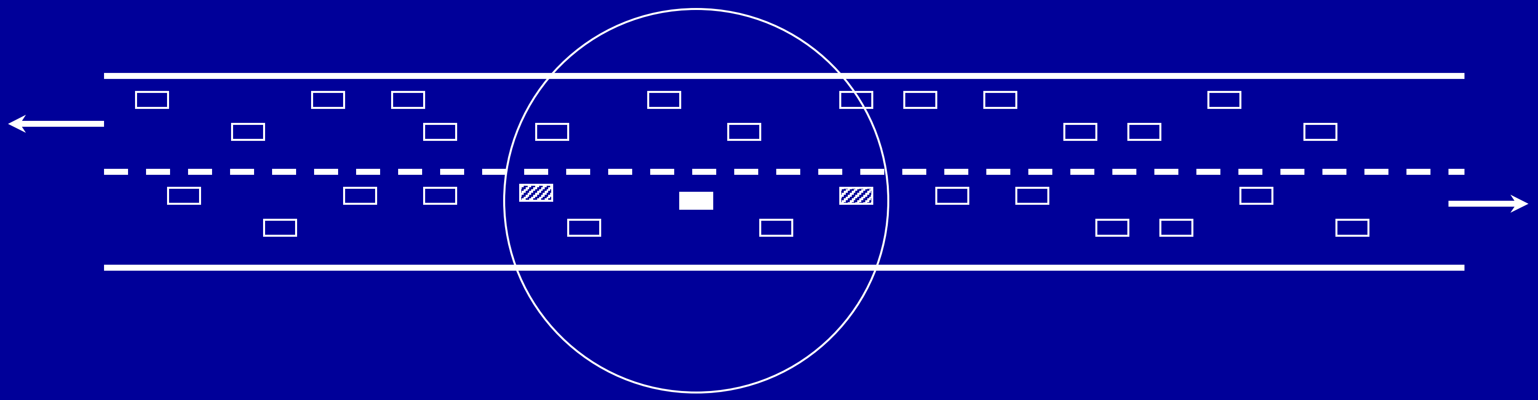
	Multicast	Unicast
General Purpose	LBM [10]	DREAM [3], GPSR [1]
Vehicular Oriented (high mobility and underlying road network)	V-TRADE [6]	Spatially Aware Routing [5]

Location Based Multicast (LBM)



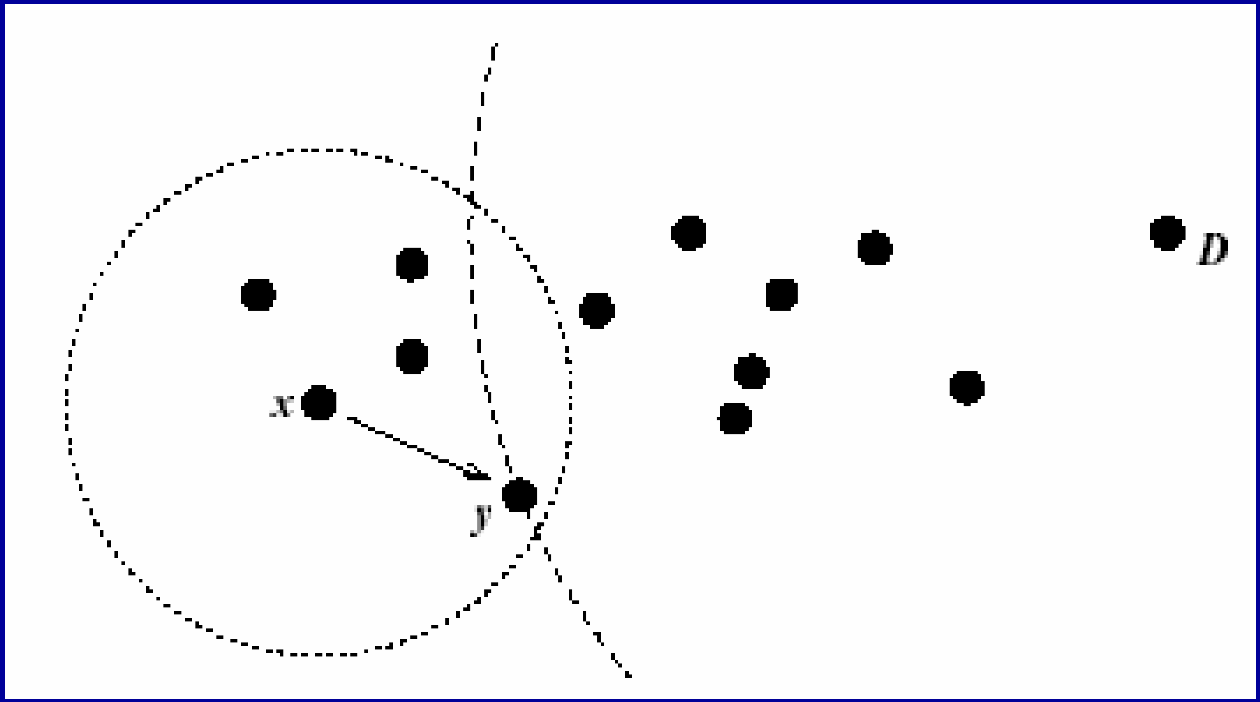
Each node floods to all the nodes within a forwarding zone.
Each node is aware of its location and forwarding zone.

V-TRADE Multicast



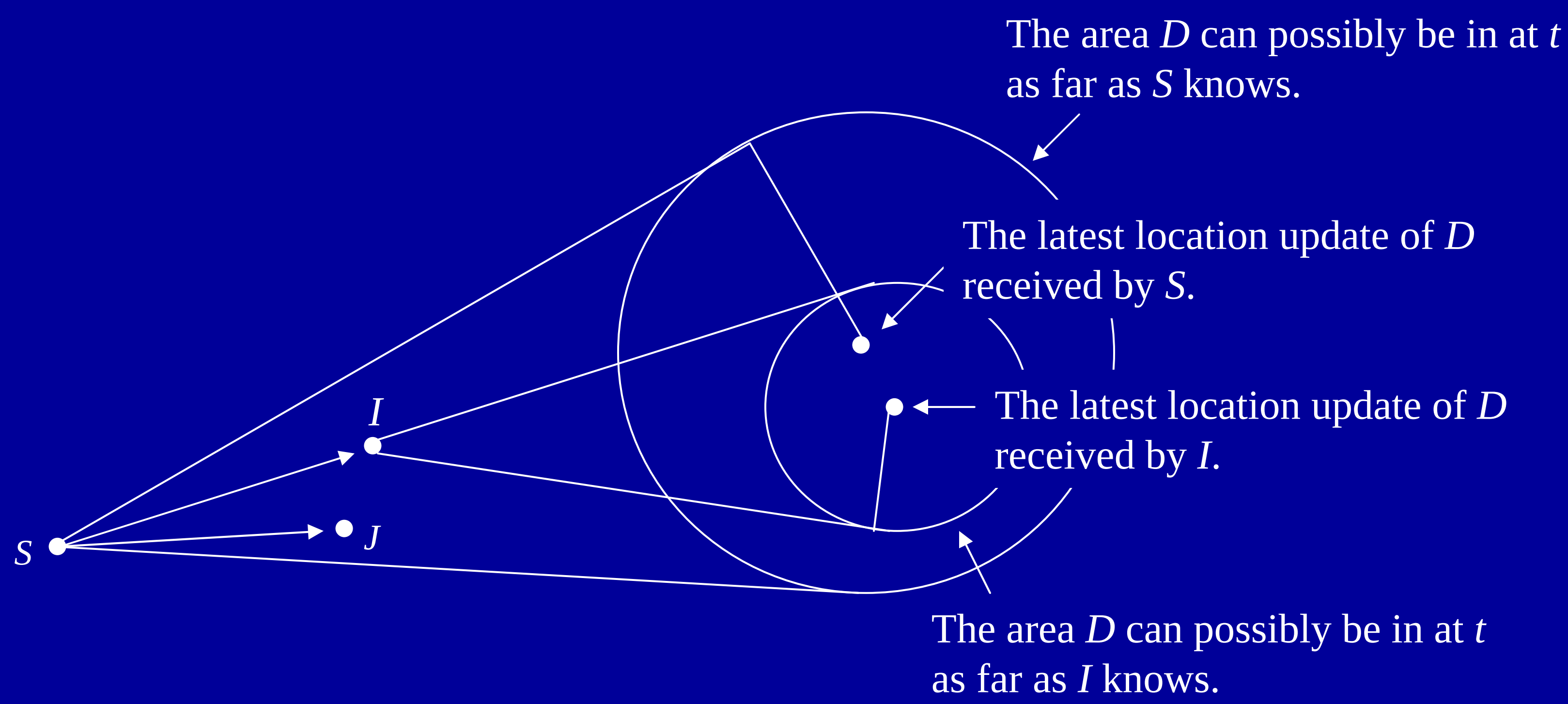
- Vector based TRAck DEtection Protocol (V-TRADE)
- Multicast to all vehicles on the same road and in the same direction as the source vehicle (the white one). The shadowed vehicles are the border vehicles for the first hop. Only border vehicles relay the query.
- Other multicast types:
  - all vehicles on all roads in an area
  - all vehicles on the same road and in the opposite direction as the source vehicle
  - all vehicles on the same road and in the same direction and ahead of the source vehicle
  - ...

Greedy Geographic Unicast



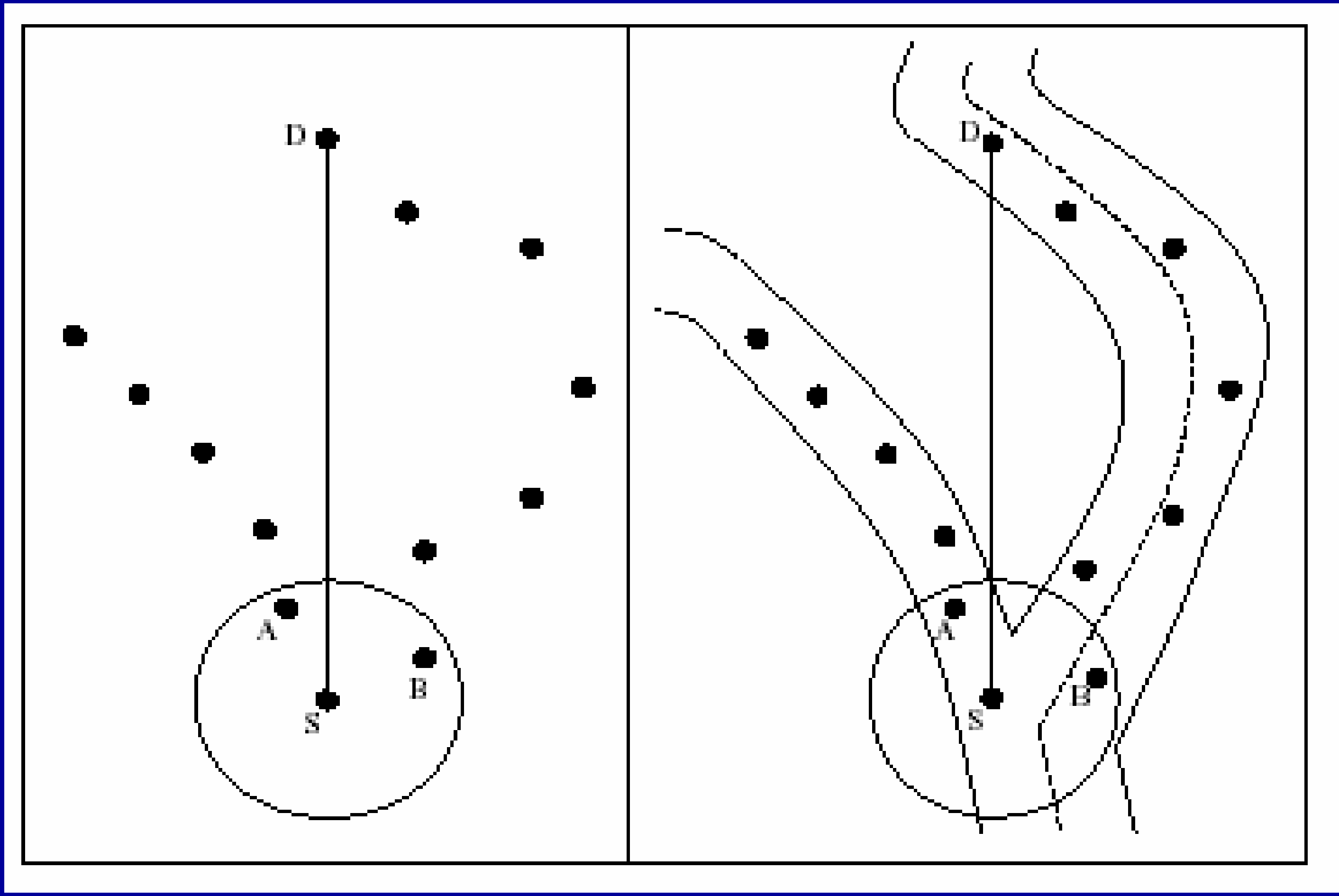
When there is no neighbor closer to the destination than x:
select a farther neighbor, according to planar graph face traversal rule.

Distance Routing Effect Algorithm for Mobility (DREAM)



- *S* sends a message to *D* at time *t*.
- Always floods to all the objects within the wedges.

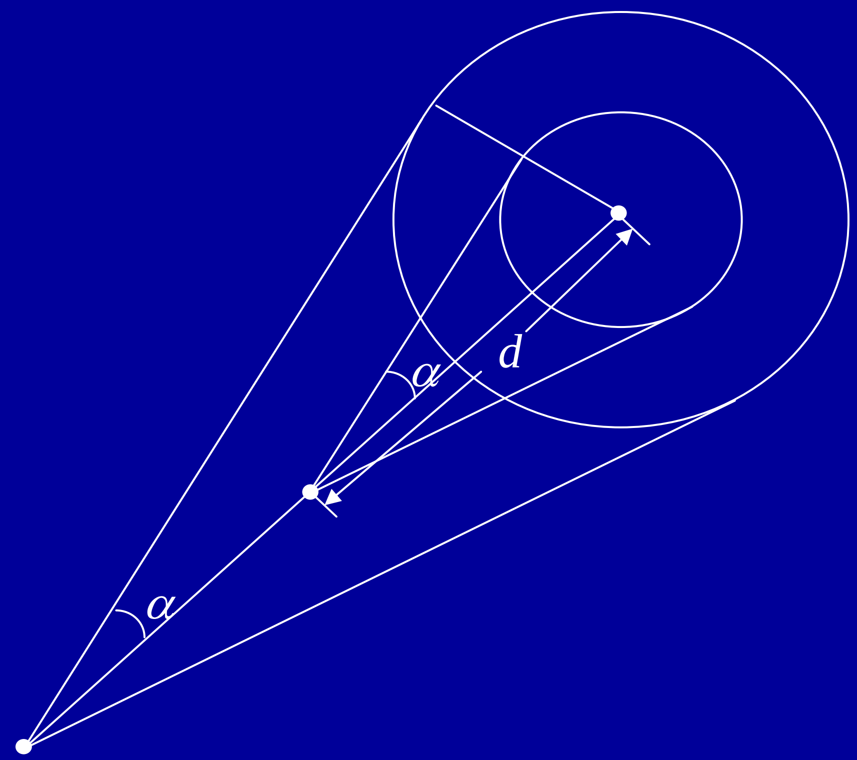
Spatial Constraint of Vehicular Networks



The road network determines proximity.

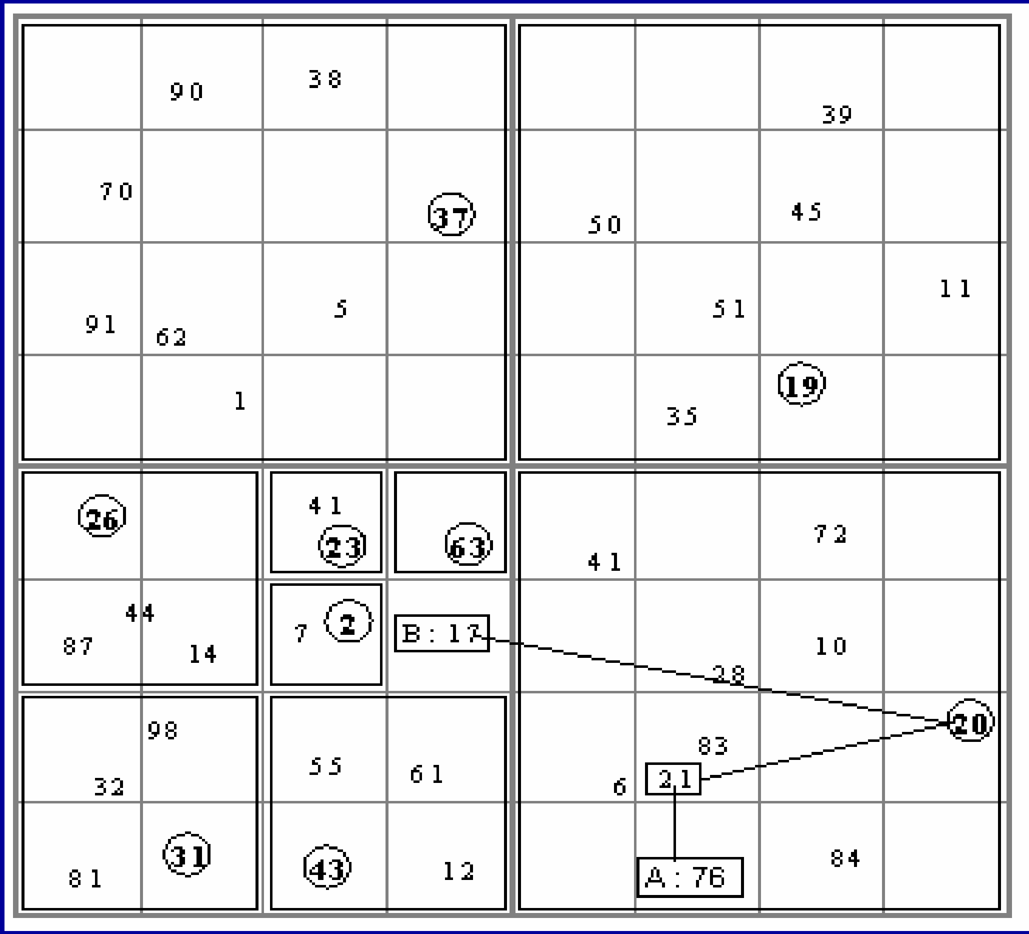
How to map from the ID of a node to its location ?

Location Service in DREAM



- Each node periodically floods its locations.
- The location message in the 2*i*-th period travels twice as far as the one in the *i*-th period. (radius indicated in the message)

Grid Location Service



- Fixed hierarchical partition
- Location servers of 17 is the least ID higher than 17 in each partition

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Conclusion

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  - Indexing
  - Synthetic datasets
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  - Joins and data mining

New Research Topics

- Distributed/Mobile query and trigger processing with incomplete/imprecise location information
- Extensible and visual languages
- Comparison of indexing methods
- Uncertainty for moving objects that do not report their location
- Data Mining

New Research Topics (Continued)

- Privacy/Security
- Location prediction
- Performance/indexing for join queries