Adding Meaning to your Steps

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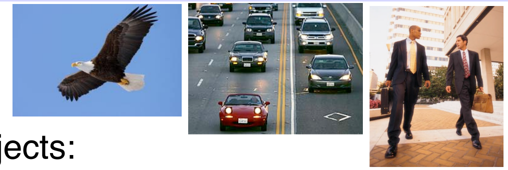
MODAP

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Outline

- Overview
- Trajectory Modeling
- Trajectory Reconstruction
- Data Schema for Semantic Trajectories
- Trajectory Behavior

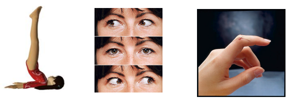
Movement



- … of moving objects:
  - changes in the spatial position of the moving object
  - persons, cars, animals, parcels, …

Let's call it "mobility data"

- No stationary movement:
  - gymnastic,
  - eye or finger movement, …
- No shape deformation



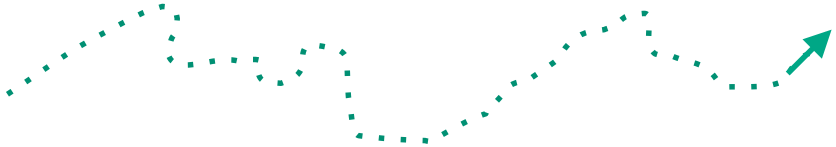
Abundance of mobility data

- A large number of applications in a variety of domains are interested in analyzing movement of some type of objects or phenomena.
  - city traffic management and planning
  - goods delivery
  - analysis of social habits of populations
  - animal tracking, animal behavioral analyses
  - (epidemic monitoring, pollution monitoring, hurricane monitoring)
  - ……..
- GPS devices, sensors and alike nowadays allow capturing the position of moving objects.
- Movement can be recorded, either continuously or discretely, as a new spatio-temporal feature of moving objects.

Movement tracking

Movement track

- Movement: f(t) → space
- Movement is continuous and never-ending



the movement track of a moving object (illustrated in 2D space)

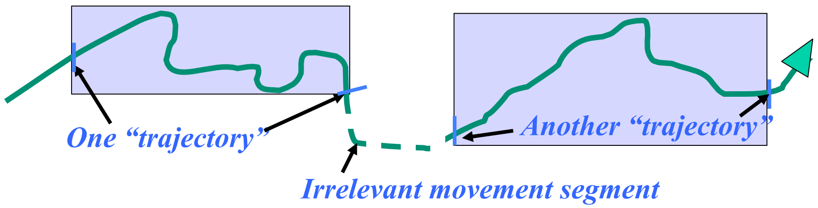
- *Raw data*: the physical positioning acquired using GPS

  a sequence of (point, instant) pairs (sample points):

  < (p1,t1), (p2,t2), (p3,t3), …….., (pn,tn), …>

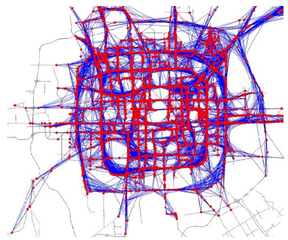
Trajectories: A meaningful piece of movement

- Usually, we don't "keep moving", we move from one place to another place.
- Later we go back or we go to yet another place.



- Movement segment: *raw* trajectory

Trajectory Examples



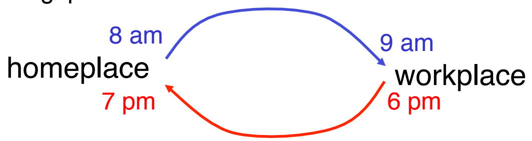
Traffic trajectory
http://research.microsoft.com/en-us/projects/urbancomputing/

bird migration

product tracking (RFID)

Trajectories as a Semantic View of Movement

- Application view on movement:
  - Semantic units of movement, i.e.
    movement from one place to another
    movement with a meaning
    movement with a purpose
    ==> semantic trajectories
- Trajectory identification (Begin, End) depends on rules defined by the application:
  - are *home-to-work* and *work-to-home* two different trajectories, or are they a single daily trajectory that comprises two segments and a temporal gap in-between?



Several Kinds of Trajectories

- Raw Trajectories: sequence of (x,y[,z],t)
- Structured Trajectories: sequence of episodes
- Geo-localized Trajectories:
  - sequence of (episode, geo-object)
- Semantic Trajectories
  - sequence of (episode, geo, semantic annotations)
- Abstract Semantic Trajectories
  - sequence of (episode, semantic annotations)

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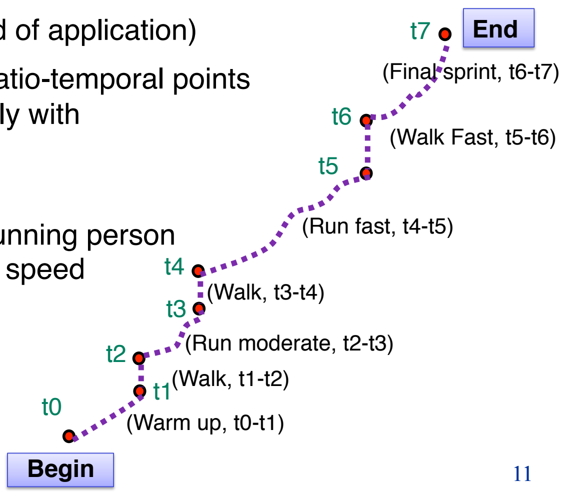
- Metaphorical Trajectories
- Mathematical Trajectories

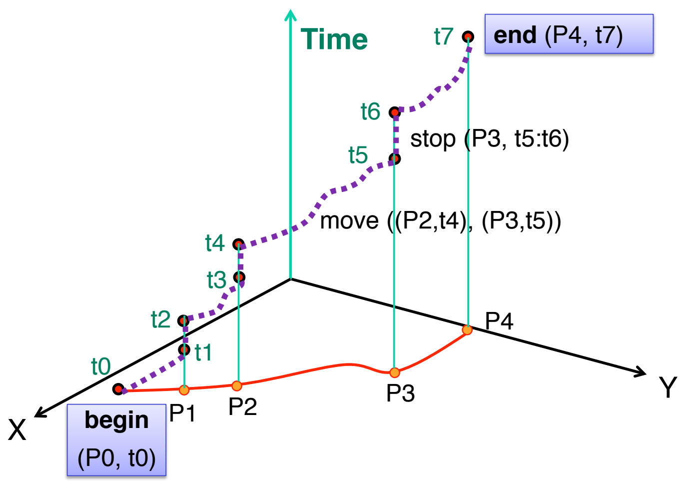
Structured Trajectories: episodes

- Partitioning of a trajectory into homogeneous parts called **episodes**
  (suitable for any kind of application)
- Homogeneity: all spatio-temporal points in the episode comply with a given predicate.
- Ex.: trajectory of a running person episodes defined by speed



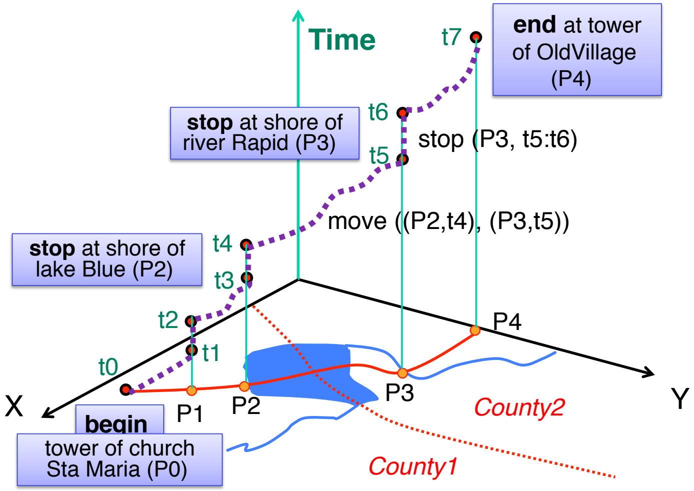
Structured Trajectories: episodes

- Stop and Move episodes for bird tracks



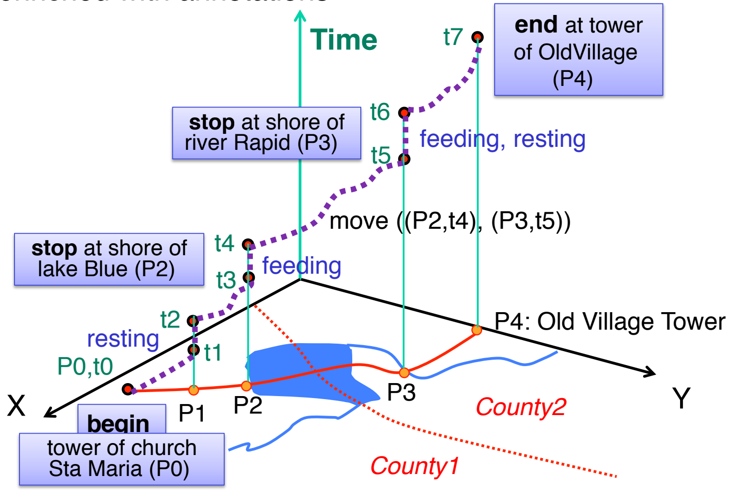
Geo-localized Trajectories

- Structured trajectories enriched with geo-objects



Semantic Trajectories

- Structured trajectories, possibly geo-localized, enriched with annotations



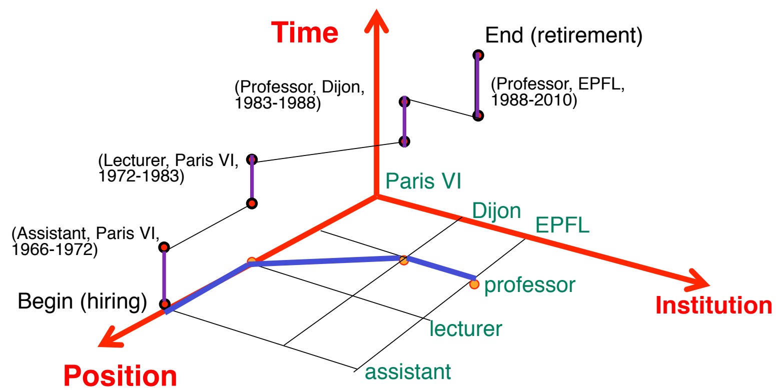
Abstract Semantic Trajectories

- My travel from Home to Brussels

- A busy day in the city …

Metaphorical Trajectories

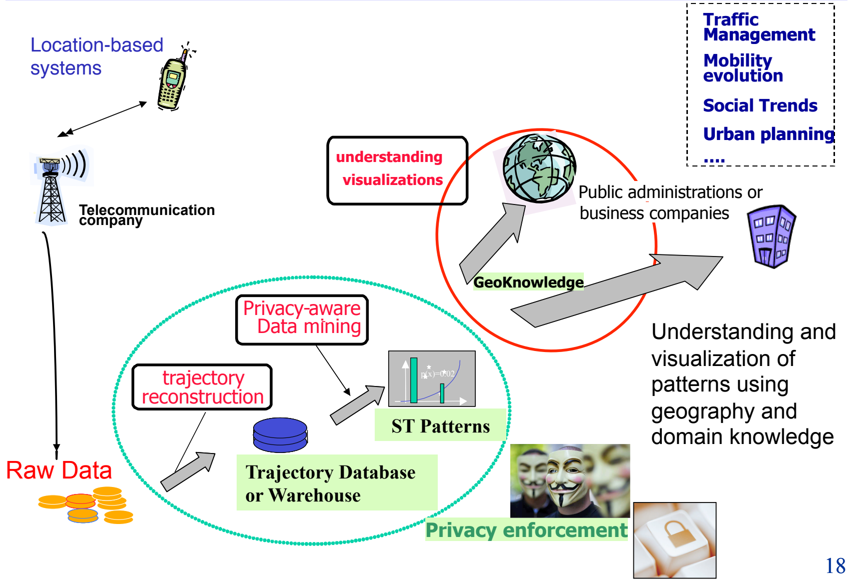
- An evolutionary path in some abstract space
  - *e.g.* a 3D professional career space
    sequence of (position, institution, time_interval)
    with stepwise variability



Mathematical Trajectories

- A predictable (computable) path of a moving object

A Trajectory Application Scenario



Examples of Queries on Trajectories

Database queries:

- How many cars are currently traveling along the Champs-Elysées avenue?

Data Mining queries:

- Which are the heaviest congestion areas in the city on weekdays?
- Which are the sequences of places most visited on Sunday mornings?

Analysis/Reasoning queries:

- Which are the suspicious/dangerous movements of visitors in a given recreational area?

MODAP (2009-2012) www.modap.org

- MObility, Data mining And Privacy
- EU coordinated action: focus on dissemination
- Main Goals
  - Clarify privacy risks associated with the mobility behavior of people and promote: 1) awareness of these risks, and 2) development of technical responses to these risks, in particular through adoption of privacy-aware techniques for data collection, analysis and dissemination
  - Coordinate and boost the research and monitoring activities at the intersection of mobility, data mining, and privacy (e.g., privacy observatory)
  - Ensure openness to new members (both active members and observers) and new ideas.

Trajectory Modeling

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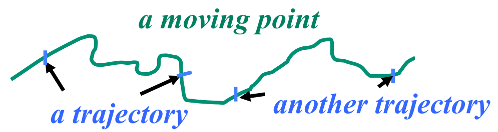
Trajectory Data Modeling

- A trajectory is a spatio-temporal object rather than a spatio-temporal property
- A trajectory has
  - generic features: application independent
  - semantic features: application dependent



Basic Formal Definition

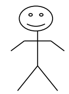
- *(Point-based)* **Trajectory**:
  - the record of the evolution of the position *(perceived as a point)* of an object traveling in space during a user-defined time interval in order to achieve a given goal.

trajectory: f (t) → space

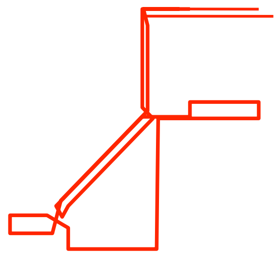
$[t_{begin}, t_{end}]$

  - A trajectory is a semantic object given that the choice of the Begin and End points is driven by the application semantics

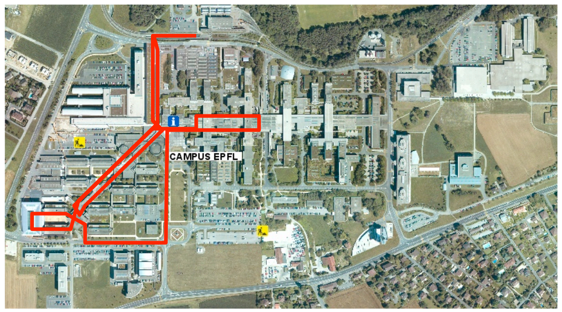
From Raw Data to Semantic Data



a moving object



September 8
Movement Track:
Raw Data / Raw Trajectory

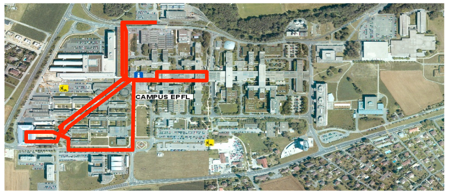


Movement into context: meaningful geo-localized trajectory

Enriching Trajectories with Annotations

- **Annotation**:
  Any application-specific data that adds knowledge about a trajectory or about any sub-part of the trajectory.
- Captured by observers (e.g., the activity of apes), or inferred by reasoning (e.g., the transportation means used by moving persons).
- Either a value (e.g., "playing" for the *activity* annotation) or a reference to an application object (e.g., the reference to the bus line #53 for the transportation means annotation).

Interpretations of Trajectories



Trajectory interpreted as a sequence of places (begin, stops, end)

(Begin, EPFL Metro Station, 8:40), move(),
(stop, INM202, 8:50-10:30), move(), (stop, INM0,10:32-10:58),
move(), (stop, INM202, 11:00-12:00), move(),
(stop, Parmentier,12:10), …

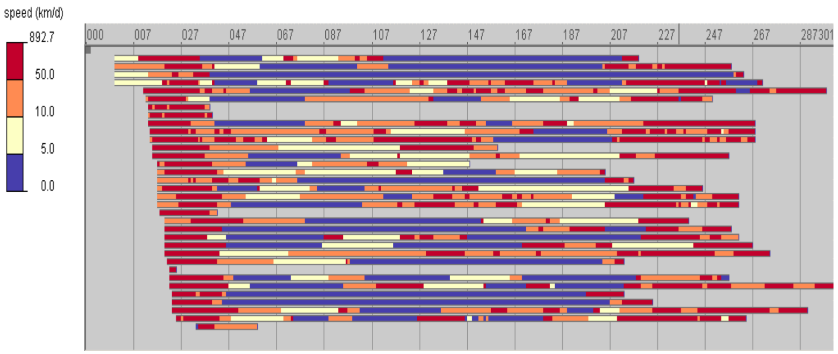
denotational annotation

(Begin, metro station, 8:40), move(), (stop, seminar room, 8:50-10:30),
move(), (stop, cafeteria,10:32-10:58), move(),
(stop, seminar room, 11:00-12:00), move(), (stop, restaurant,12:10), …

functional annotation

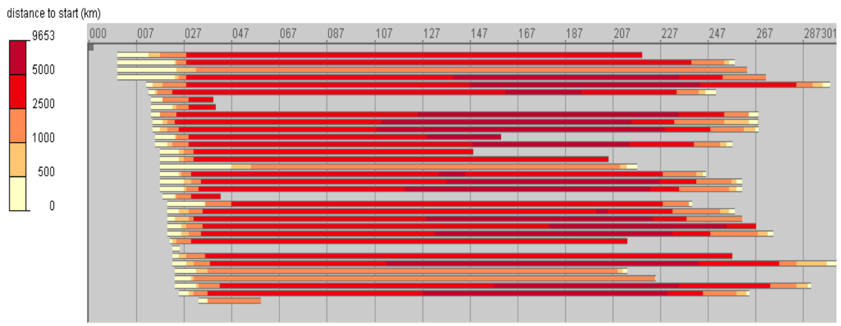
Episodes: a speed-based interpretation

- Trajectories of birds interpreted as a sequence of displacements. Visual coding: slow moving ➔ blue, fast moving ➔ red, intermediate speeds ➔ yellow and ochre.
- It is easy to see that for example fast-moving episodes are usually shorter in time than slow-moving episodes.



Episodes: distance-based interpretation

- The trajectories are segmented according to the spatial distance to the starting position. It is easy to see that relatively few trajectories do not reach very far (aborted probably due to some accident to the animal), while more than half of the birds' trajectories do come back.



Formal Definition

Trajectory =

(trajectoryID, MovingObjectID, Tannotations,

positions: LISTOF position(t, p, Pannotations),

gaps: LISTOF gap(t1,t2),

interpretations :

SETOF interpretation (InterpretationID, episodes:

LISTOF episode(t'1, t'2, type, Eannotations)))

Trajectory Characterization

- Trajectory Attributes (Tannotations)
  - e.g. the goal of the trajectory (e.g. visit a customer)
- Trajectory Links to other objects (Tannotations)
  - e.g. link to the car rental company used for this trajectory
- Trajectory Constraints
  - e.g. the trajectory of a car is constrained by the road network
- Trajectory Track (positions, Pannotations)
  - Finite list of unconstrained length
  - Gaps, if any
- Trajectory Interpretations with their (episodes, Eannotations)

Trajectory Components: Begin & End

- Mandatory Points
  - Delimit the trajectory
  - Spatial type: Point
  - Temporal type: Instant
  - Topological relationship (e.g. *inside*): links to a spatial object
    - Link (Instance level): this Begin point is *inside* Brussels
    - Constraint (meta level): for this class of trajectories, the Begin point has to be *inside* a City
  - + Attributes + Links to other objects + Constraints

Trajectory Components: Interpretations

- Many interpretations may coexist for a given trajectory
- Which ones to use has to be decided wrt application requirements
- Most popular examples:
  - Movement cycle: stop and move episodes
  - Transportation means: on foot, on bus, by car …
  - Animal activity: resting, feeding, moving, fighting, escaping, picking lice off, …
  - Human activity: sleeping, eating, shopping, …

Stop and Move Episodes

- **Stop**:
  - a part of a trajectory defined by the user/application to be a stop, assuming the following constraints are satisfied:
    - during a stop, traveling is suspended (the traveling object does not move wrt the goal of achieving its travel): the spatial range of a stop is a single point
    - the stop has some duration (its temporal extent is a non-empty time interval); the temporal extents of two stops are disjoint
  - NB: conceptual stops are different from physical stops
- **Move**:
  - a part of a trajectory between two consecutive stops, or between the starting point (begin) and the first stop, or between the last stop and the end point.
  - the temporal extent of a move is a non-empty time interval
  - the spatial extent of a move is a line (not a point)

Description of a Stop

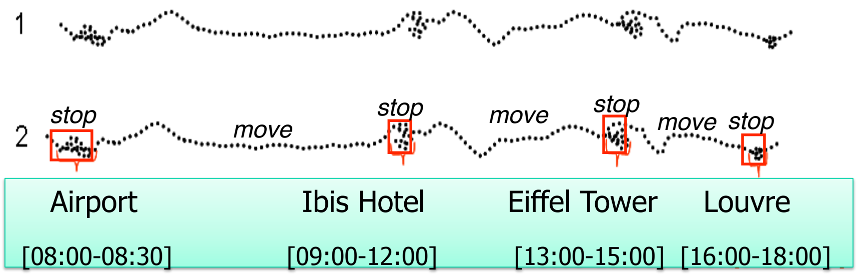
- Stop(s)
  - Point
  - Time interval
  - Topological *inside* (or *equal*) link to a spatial object
    - e.g. *inside* Brussels
  - Attributes
  - Links to other objects
    - e.g. Customers
  - Constraints

Description of a Move

- Move(s)
  - Time-varying point
  - Time interval
  - Topological *inside* (or *equal*) link(s) to (a) spatial object(s)
    - e.g. the move follows part of Highway 67
  - Attributes
    - Non-varying attributes, i.e. attributes that have a fixed value during the whole duration of the move (e.g. duration)
    - Varying attributes, i.e. attributes whose value varies during the move (e.g. the altitude of the plane)
  - Links to other objects
    - e.g. the move was done with other persons
    - Fixed link, i.e. the link links the same unique object during the whole move, e.g. link to the car used during the move
    - Varying link, e.g. link to the transport means used during the move: attached to object instance "bus 31" for the first 10mn, then attached to instance "bus 17" for the next 15mn, then ...
  - Constraints

Stops and Moves Interpretation

Part of a day in Paris: 1) raw data 2) episodes



Queries Using Stop and Moves

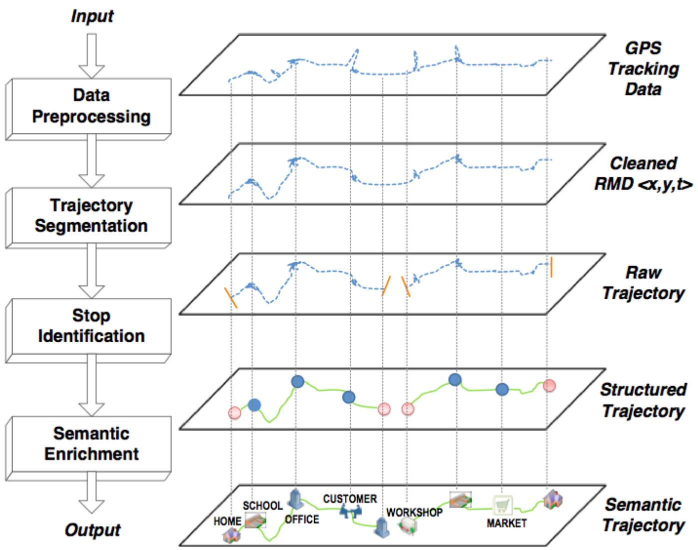
- On raw movement data
  - When did cars stop today at position (x,y)?
  - Which cars did stop today at position (x,y)?
- On semantic trajectory data
  - Which cars did stop today at a gas station?
  - For a given petrol company, return the number of cars that stopped today at a gas station owned by this company's retailers

Building Trajectories

Trajectory Reconstruction

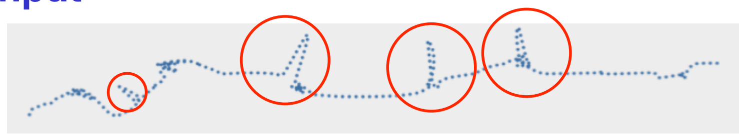
9:45

From raw data to semantic trajectories



Cleaning Raw Data

Input



Output

Methods: missing points interpolation, filtering, smoothing, outliers removal, …
map-matching, data compression, etc.

Segmentation into Trajectories

Input: Cleaned raw data

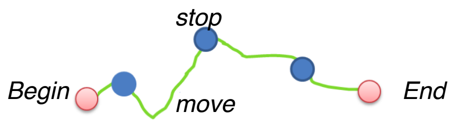
Output: Trajectories (Begin, End)

Methods: various segmentation algorithms, based on temporal gaps, spatiotemporal gaps, time intervals, space partitioning, …

Trajectory Structuring (Stop & Move Episodes)

Input: a trajectory

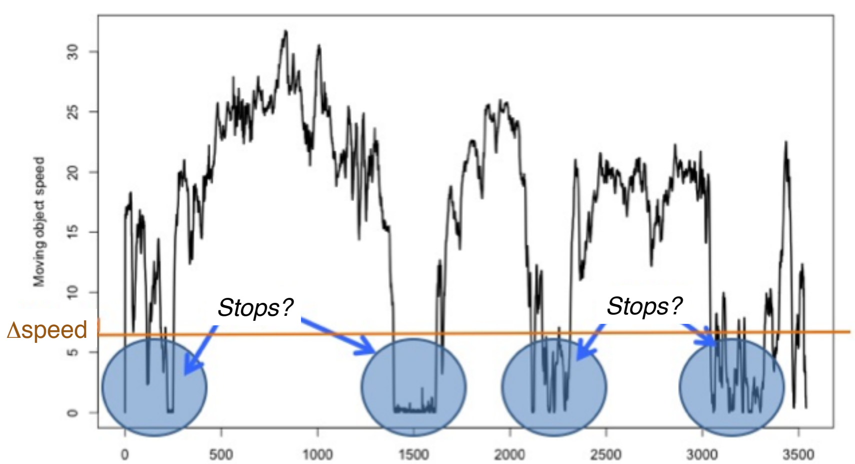
Output: Trajectory episodes (Stop, Move)



Methods: various stop identification algorithms, based on velocity, density, …

Velocity-based stop identification

Speed evolution during a trajectory



Determining Stops and Moves

- Either by computation rules or user-defined
- Geometric computation
  - Stops positions result from abstractions (e.g. centroid) of an area where the moving object/point stays for a certain period of time
- Geometric + Semantic computation
  - Stops are points representing selected objects of a certain type (hotel, restaurant, POI, …) where the moving object stays *for some time*
  - Relevant objects may be defined at the type level (e.g. “hotel”, “restaurant”, …) or at the instance level (e.g., Brussels Hotel)

POI: Point Of Interest

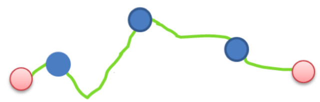
- Application-driven definition of significant points within the area at hand (could also be imported from an external source)

http://research.microsoft.com/en-us/projects/urbancomputing/

- POIs are used to interpret mobility related facts
  - E.g., for guessing why a person/car stopped in a given place
- Some applications may use ROIs

Semantic Enrichment using POIs (example)

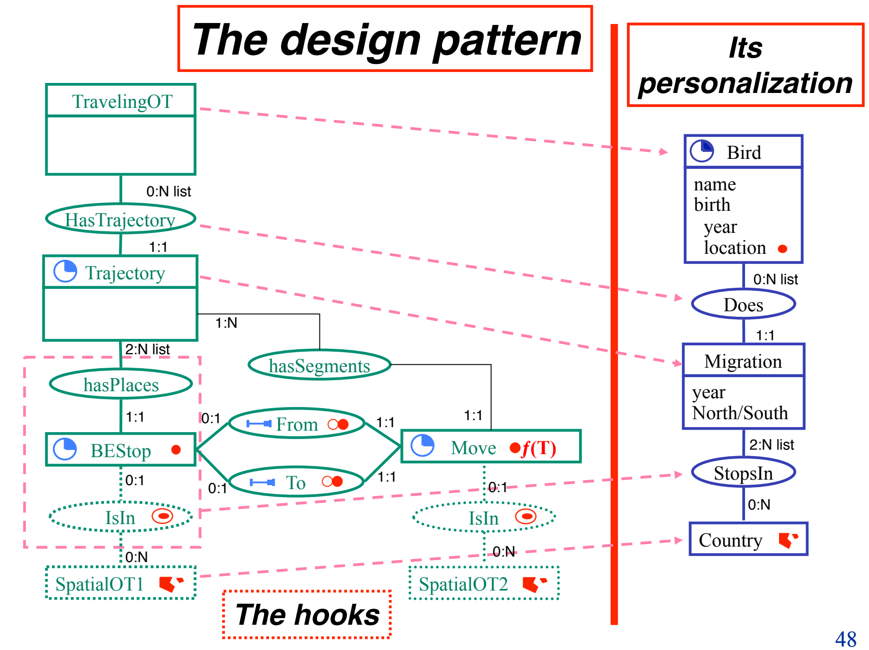
Input:



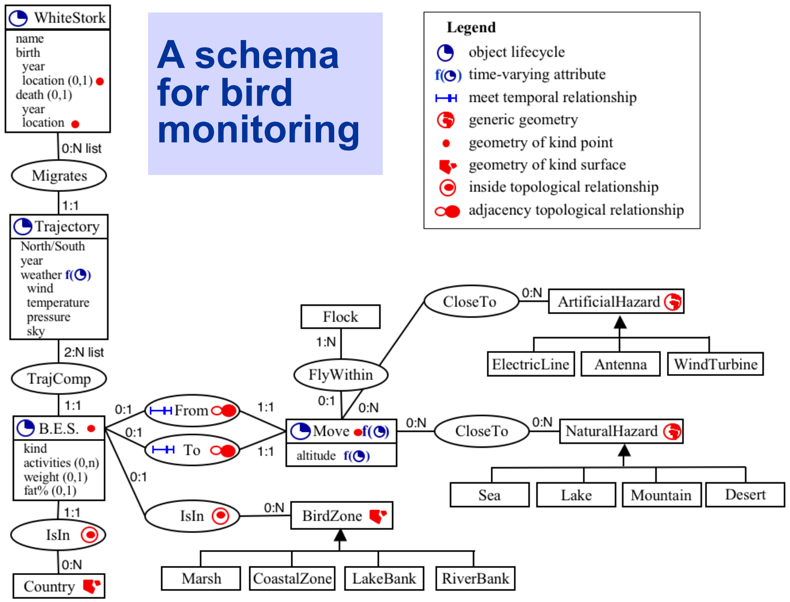
Output:

Method: find which POI is most likely related to each element (begin, end, stops, moves, …) of the structured trajectory

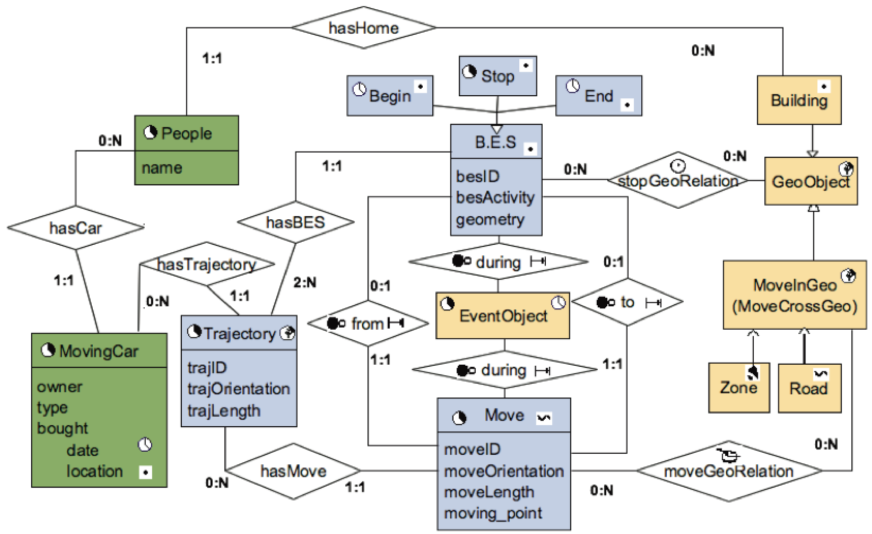
Data schema for Semantic Trajectories



A schema for bird monitoring



A Traffic Database with Trajectories



Trajectory Behavior

10:00

Behavior of Trajectories

- Trajectory behaviors are abstractions that may be used to characterize trajectories.
- Behaviors may be defined for
  - a single trajectory, e.g., a parent behavior
  - a group of trajectories, e.g., the behavior of a flock of geese flying in a V-shaped arrangement.
- A trajectory behavior (also called trajectory pattern) is a predicate that
  - 1) bears on the spatial, temporal, spatio-temporal, and/or semantic characteristics (i.e. the annotations and episodes) of the trajectories, and
  - 2) selects the trajectories that comply with the predicate.

Behaviors Classification

- Trajectory behaviors may be classified according to several criteria:
  - the kind of characteristics used in the predicate,
  - the scope of the predicate,
  - the usage or non-usage of sequence operators in the predicate,
  - the number of involved moving objects: one (an individual) or more (a group)

Classification by kind of characteristic

- Spatial behaviors
  - "pass by": trajectories that cross the spatial extent of some specified geo-object of the application
- Temporal behaviors
  - trajectories that start before 7am in the morning
  - trajectories whose total stop duration exceeds the total move duration
  - trajectories during a given event.
- Spatio-Temporal behaviors
  - pass by the geo-object O some time during a given time interval
  - cars speeding beyond the speed limit of 50 km/hour
- Semantic behaviors
  - persons' trajectories that stop at a restaurant
  - car trajectories that stop at a petrol station belonging to a competitor petrol company.

Classification by scope of the predicate

- Global behaviors
  - Defined by predicates that constrain the whole trajectory, like selecting trajectories that spend more time during the stops than during the moves, or trajectories whose global shape is a star.
- Local behaviors
  - Defined by predicates that constrain only a segment of the trajectory: the predicate selects the trajectories that contain at least a segment that satisfies the predicate.
  - Example: Trajectories that start before 7am
  - Example: Trajectories that pass by a given geo-object during their first episode.

Classification by complexity

- Simple Behaviors
  - Defined by “simple” predicates
- Sequenced Behaviors
  - Defined by “complex” predicates: using sequence operators that are specific to temporal sequences
  - AND_LATER, AND_duration_LATER,
    e.g., AND_1 hour_LATER
  - The iteration operator: REPEAT (repeat any number of times), or REPEAT_N (repeat a given number of times).

Sequenced Behavior Examples

- ST Sequence Example:
  - Begin-in point P1, …, Pass-by point P2, …, End-in point P1

- Semantic Sequence:
  Tourist behavior example:
  - Begin-in a hotel, …, Pass-by a tourist place, …, Pass-by another tourist place …, End-in the same hotel as Begin

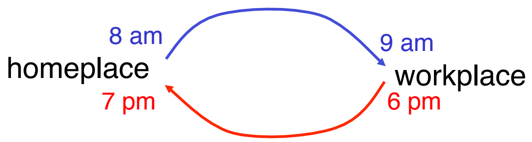
Classification by # of involved objects

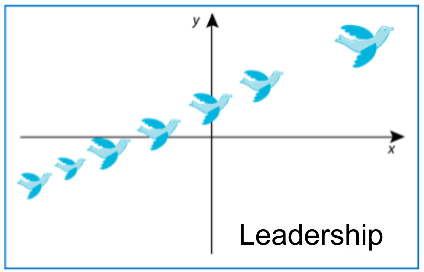
- **Let T be a trajectory**.
  A *trajectory* ***individual behavior*** is a Boolean predicate p(T).
  The predicate can bear on any characteristics of the trajectory.
  E.g. HomeToWork, Star-shaped, Leadership

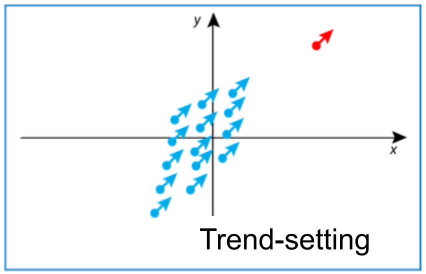
- **Let ST be a set of trajectories** such that card(ST)>1.
  A *trajectory* ***collective behavior*** is a Boolean predicate p(ST).
  The predicate can bear on any characteristics of the trajectories.
  E.g. Meet, Flock

Examples of Individual Behavior

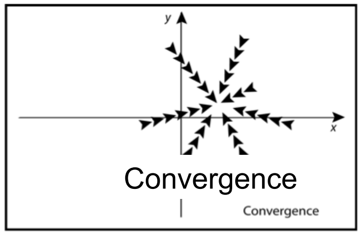
- Home-to-work

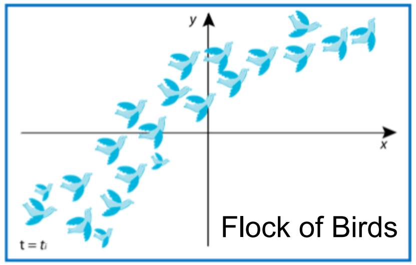






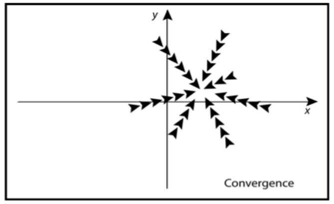
Examples of Collective Behavior





Semantic vs ST Behaviors

- ST convergence:
  converge at the same point
- Semantic convergence:
  Example: Converge in a place of kind "Hotel"



Conclusion on Modeling

- Conceptual Modeling concepts are *relatively* simple
  - Raw Data, Trajectory, Begin, End, Annotations, Episodes, Stop, Move, Behaviors, …
  - Consensus *relatively* easy to reach
- Instantiating the concepts is the challenge
  - Many algorithms
  - Raw data cleaning
  - Trajectory identification
  - Trajectory segmentation
  - Automatic computation of annotations: stops and moves, mode of transportation, activity, suspicious behaviors, …

Conclusion on Behavior

- From semantic trajectories we can aim at understanding the behavior of moving objects
- Example: converging patterns of people may indicate an intention to perform a joint action
  - Ethically appropriate or not?
- Example: from trajectories of firemen we may guess how a fire situation evolves
  - Ethically appropriate or not?
- Warehousing, Classification, Data mining, and Knowledge extraction are the ultimate challenge
- → Privacy preserving methods for data collection, dissemination, and analysis
  - Join us at www.modap.org

Last but not least

Some (personal) comments on privacy

- It's mostly about anonymization and fuzzification
- Anonymization: non disclosure of "sensitive" information, either to hide it or to prevent the identification of the moving object

- Fuzzification (k-anonymity): replacing a moving object by a bunch of similar moving objects

- IMHO, this privacy domain may benefit from a stronger semantic framework

Thanks for your attention