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Mobility Data: Modeling, Management, and Understanding

Stefano Spaccapietra, Esteban Zimányi

Chiara Renso

Tutorial, October 26, 2010, Toronto

Tutorial Outline

- Mobility Data Representation *(Stefano)*
- Spatio-Temporal and Trajectory Data Warehousing *(Esteban)*

Coffee break

- Trajectory Data Mining and Knowledge Extraction *(Chiara)*
- Research agenda (*Stefano*)
- Questions and discussion (*all*)

Part 1
Mobility Data Representation

Stefano Spaccapietra

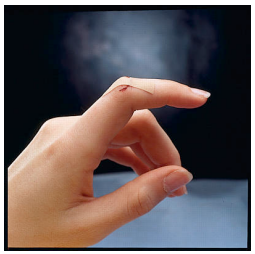
EPFL, Switzerland

Movement

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

Let's call it "mobility data"

- Not stationary movement:
  - gymnastic,
  - eye or finger movement, …

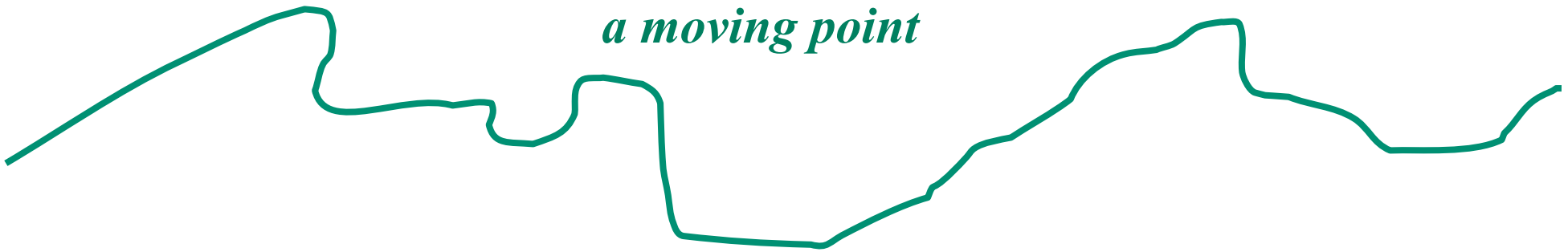


Abundance of mobility data

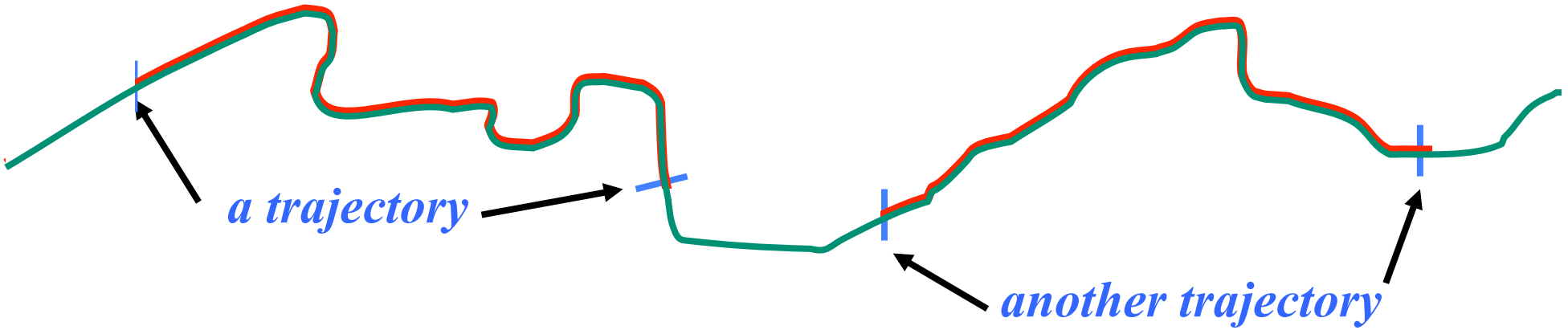
- A large number of applications in a variety of domains are interested in analyzing movement of some type of objects or phenomena.
  - city traffic management and planning
  - goods delivery
  - social habits of populations
  - epidemic monitoring, pollution monitoring
  - animal tracking
  - ……..
-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

From movement to trajectories

- Movement is continuous and never-ending

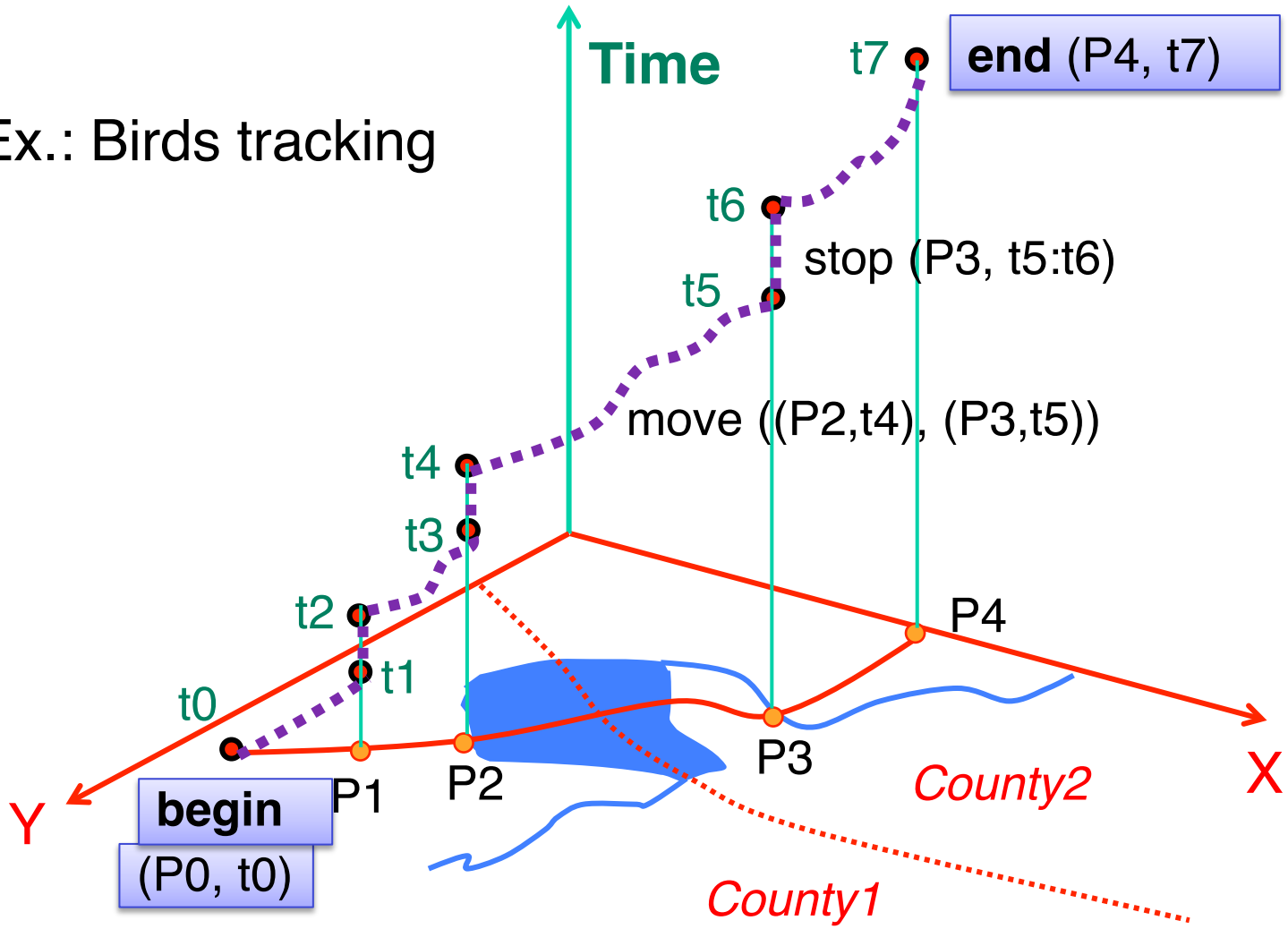


- A trajectory is a finite meaningful movement segment



Spatio-Temporal Trajectories

- Travel in physical space, i.e. a continuous space where position is defined using spatial coordinates
- Ex.: Birds tracking



Some Trajectory Examples

traffic trajectory

bird migration

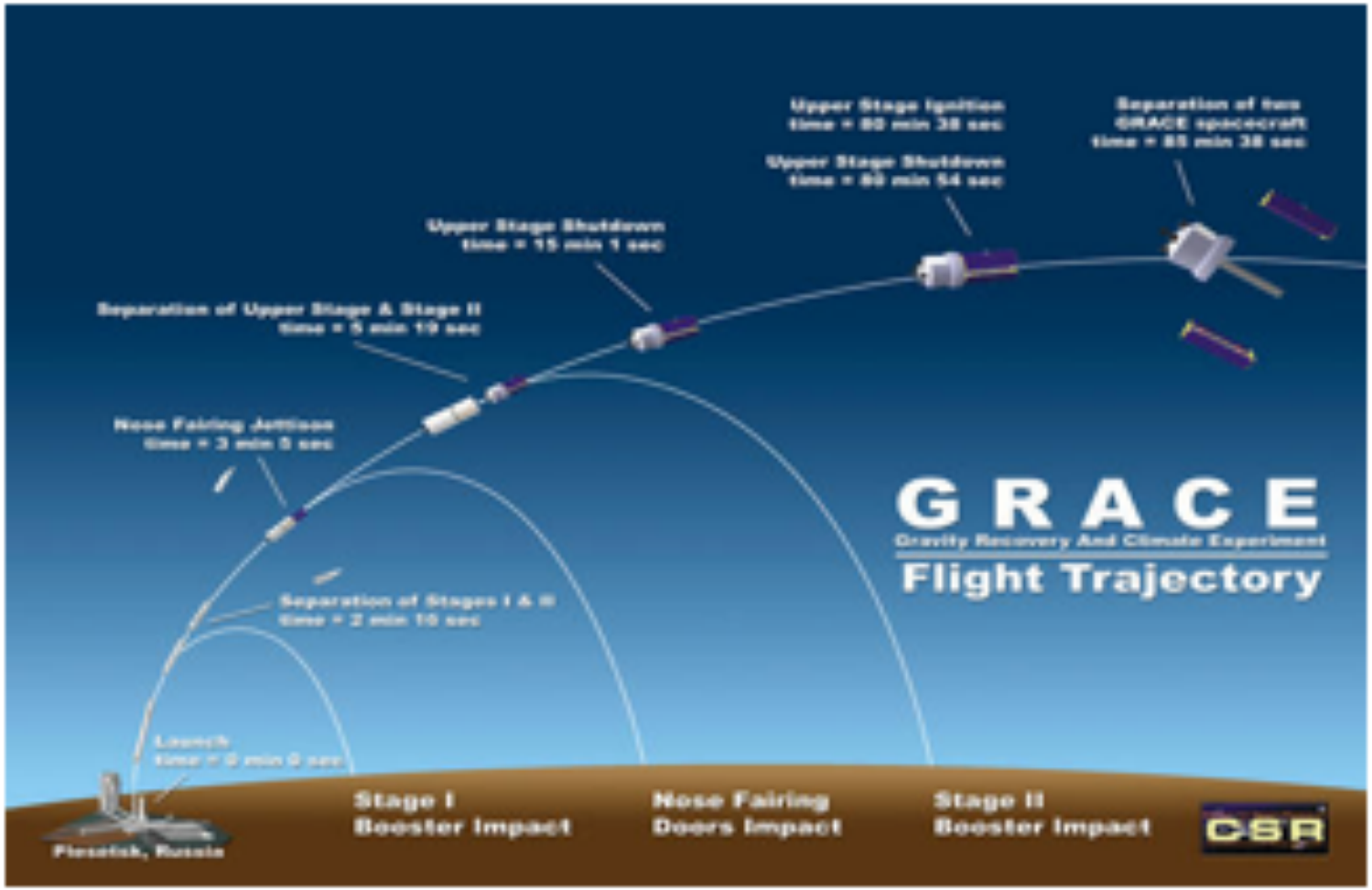
product tracking (RFID)

Other Kinds of Trajectories

- Mathematical Trajectories
- Metaphorical Trajectories
- Geographical Trajectories

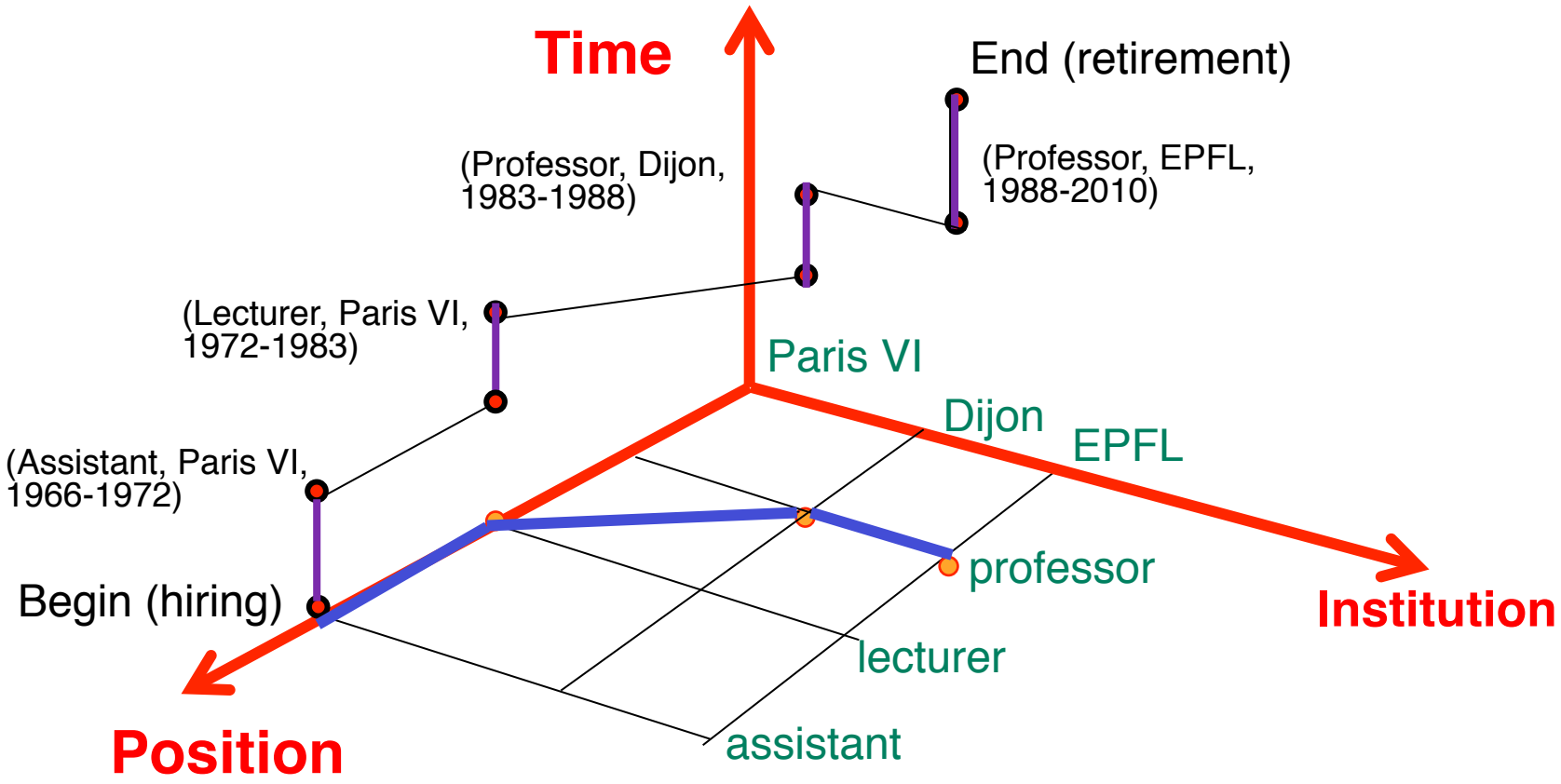
Mathematical Trajectories

- A predictable (computable) path of a moving object



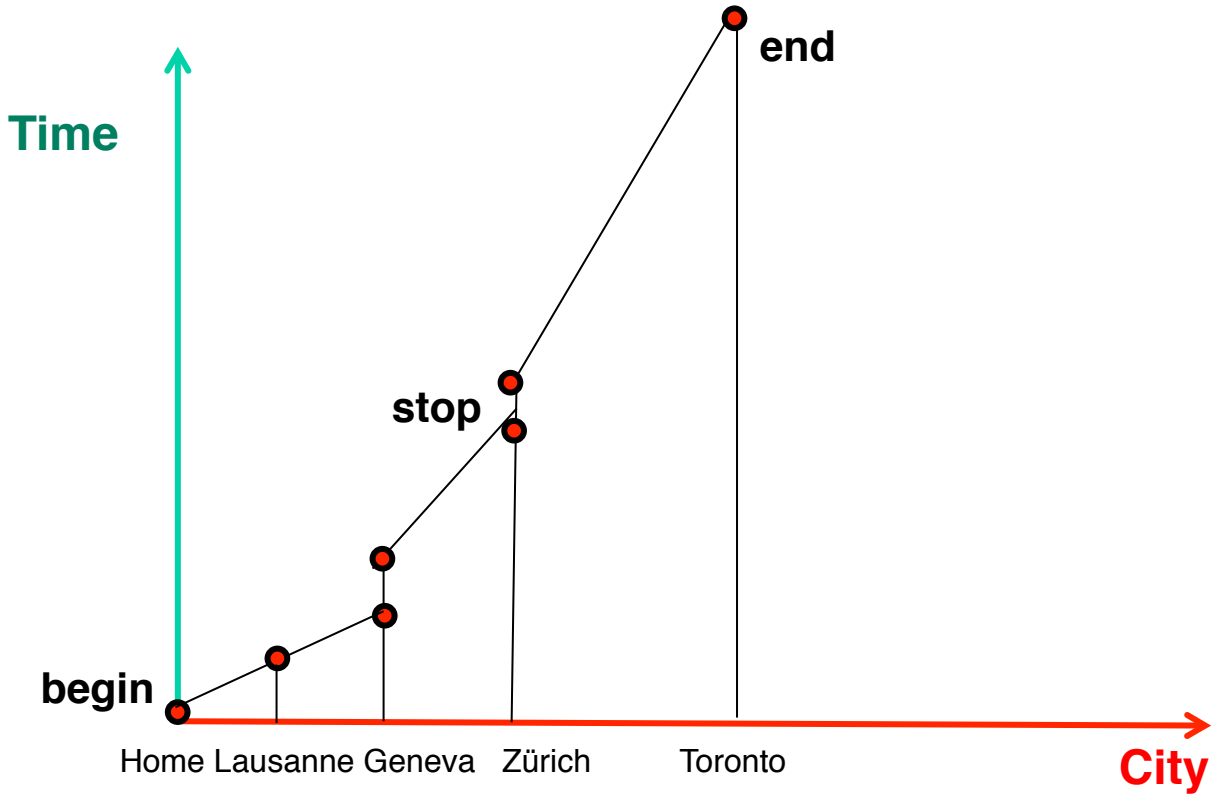
Metaphorical Trajectories

- An evolutionary path in some abstract space
  - *e.g.* a 3D professional career space
    <position, institution, time>
    with stepwise variability



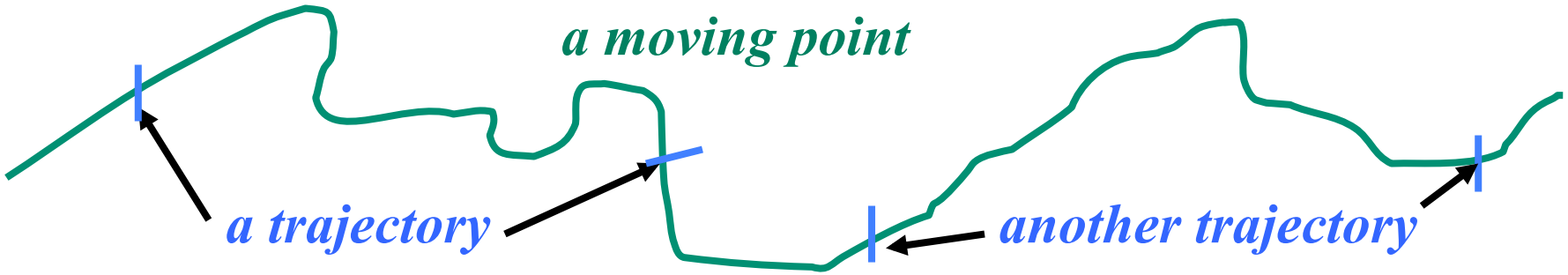
Naive Geographical Trajectories

- A travel in "geographical" space, i.e. a discrete space occupied by spatial objects
  - => time-varying attribute "current city"
  - a special case of metaphorical trajectories



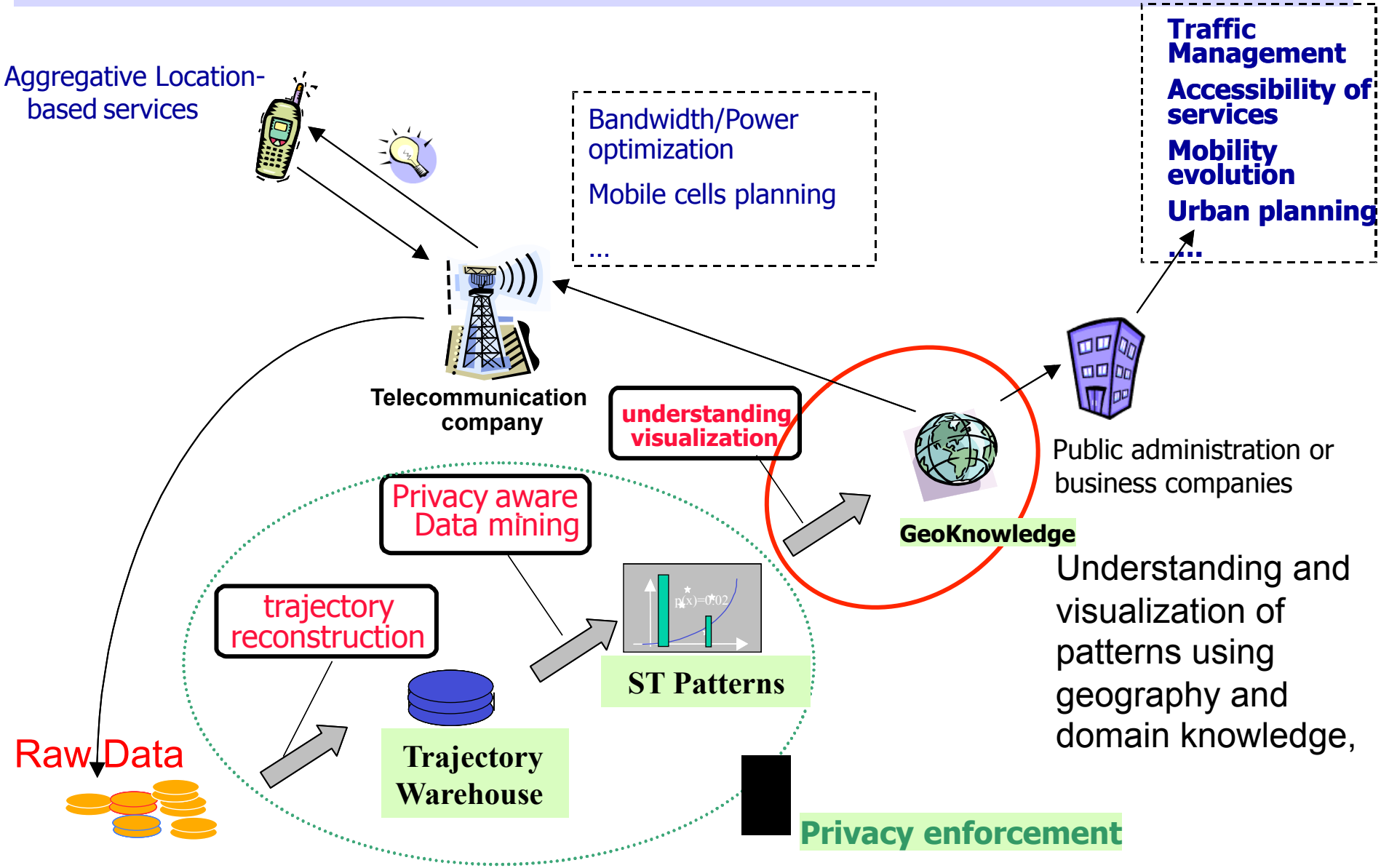
Trajectories: A semantic view of movement

- Movement: $\mathscr{F}$(t) → space
- …. But, usually, you don't "keep moving", you go from one place to another place
- Semantic units of movement: movements with a purpose = trajectories



- From home to university
- From university back home
- From class room to cafeteria

A Trajectory Application Scenario



Understanding and visualization of patterns using geography and domain knowledge,

Example 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? (e.g. use of clustering)
- Which are the sequences of places most visited on Sunday mornings? (use of patterns)

Analysis/Reasoning queries:

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

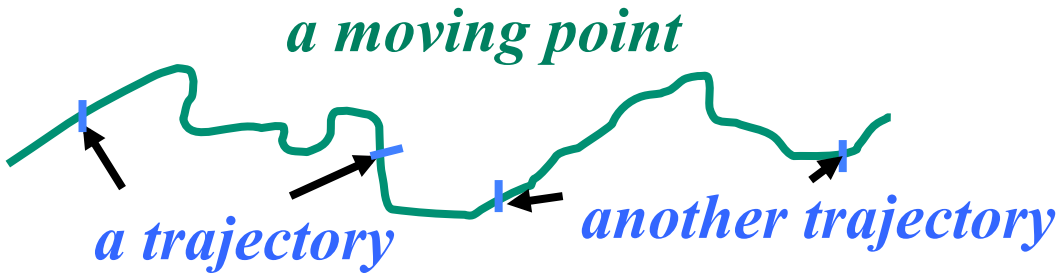
MODAP (2009-2012)

- Mobility, Data mining And Privacy
- An EU coordinated action: focus on dissemination
- www.modap.org
  - Privacy risks associated with the mobility behavior of people are still unclear, and it is not possible for mobility data mining technology to thrive without sound privacy measures and standards for data collection, and data/ knowledge publishing.
  - MODAP aims to continue the efforts of the previous EU GeoPKDD projects by coordinating and boosting the research activities at the intersection of mobility, data mining, and privacy.
  - MODAP welcomes new members (both active members and observers).

Trajectory Modeling

Trajectory Modeling

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



Basic 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.

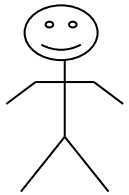
$$\textbf{trajectory: } \mathscr{F} \ [t_{begin}, t_{end}] \rightarrow \textbf{space}$$

  - A trajectory is a semantic object, different from the corresponding physical object built on raw data

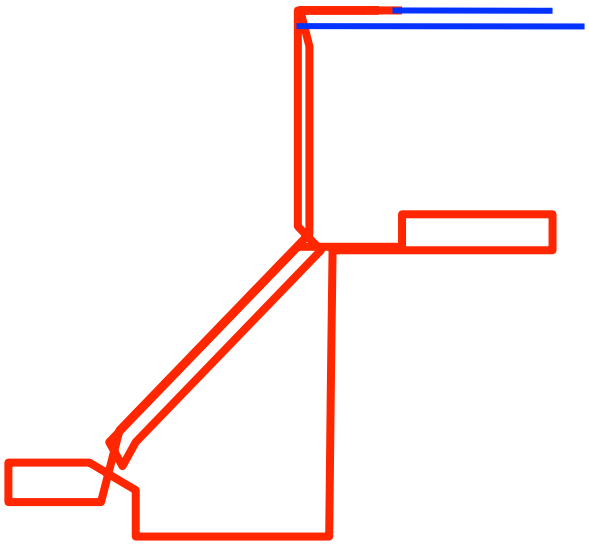
  - Raw data: the physical positioning acquired using GPS as a sequence of (point, instant) pairs (sample points):

$$(p_1,t_1), (p_2,t_2), (p_3,t_3), \ldots\ldots, (p_n,t_n)$$

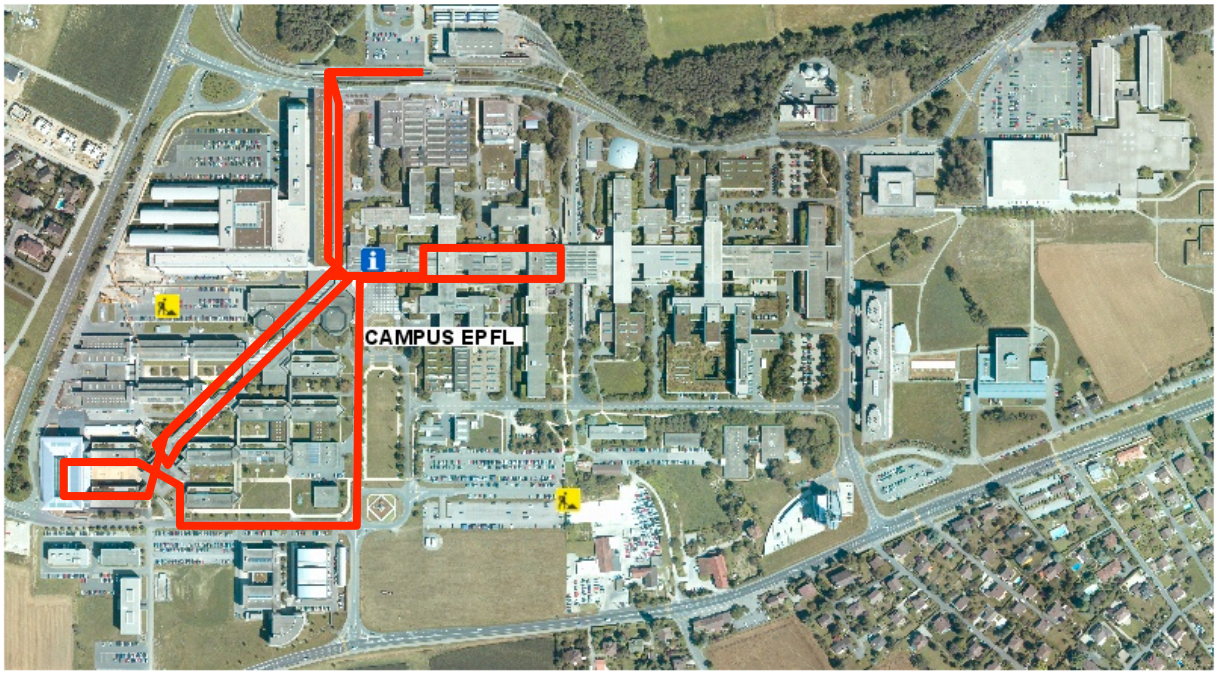
From (x,y,t) Movement to Trajectories



a moving object



September 8
Raw Data:
Movement Track

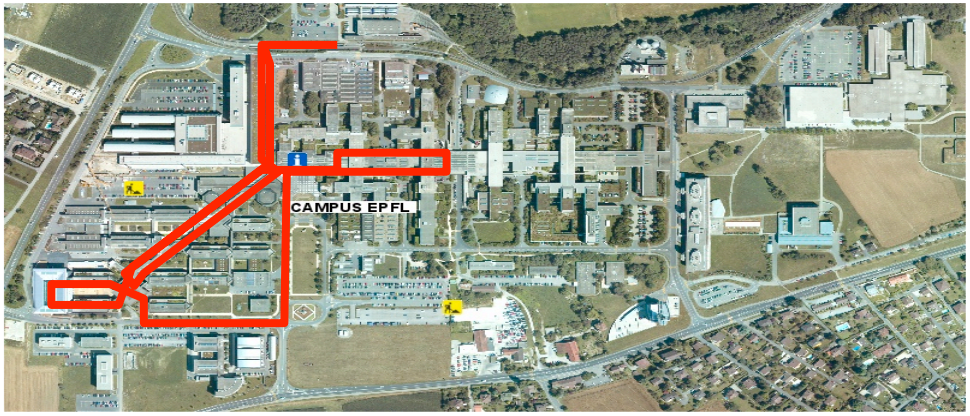


Movement into context:
Trajectory

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 constant (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)

(EPFL Metro Station, 8:40)⇒(INM202, 8:50)
(INM202,10:30)⇒(INM0,10:32)
(INM0,10:58)⇒(INM202, 11:00)
(INM202,12:00)⇒(Parmentier,12:10)

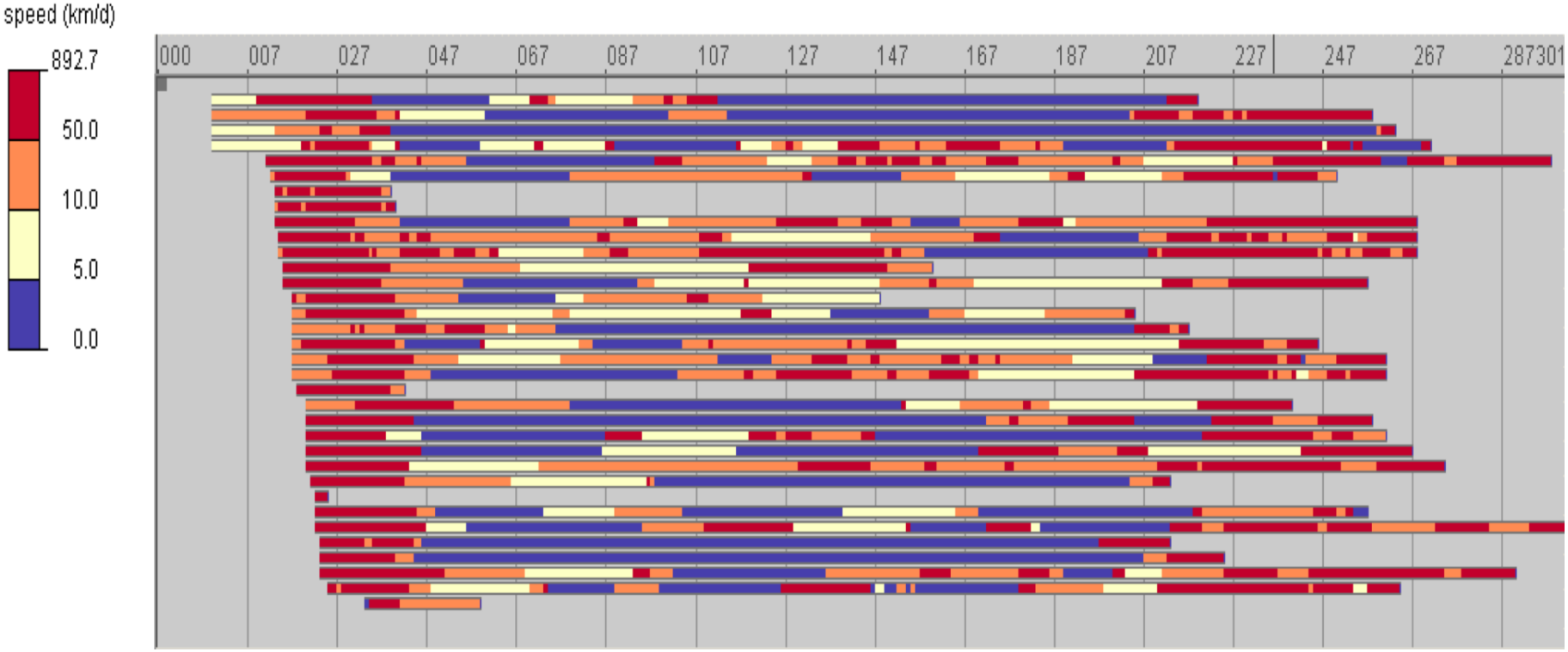
denotational annotation

functional annotation

(EPFL Metro Station, 8:40)⇒(seminar room, 8:50)
(seminar room,10:30)⇒(cafeteria,10:32)
(cafeteria,10:58)⇒(seminar room, 11:00)
(seminar room,12:00)⇒(restaurant,12:10)

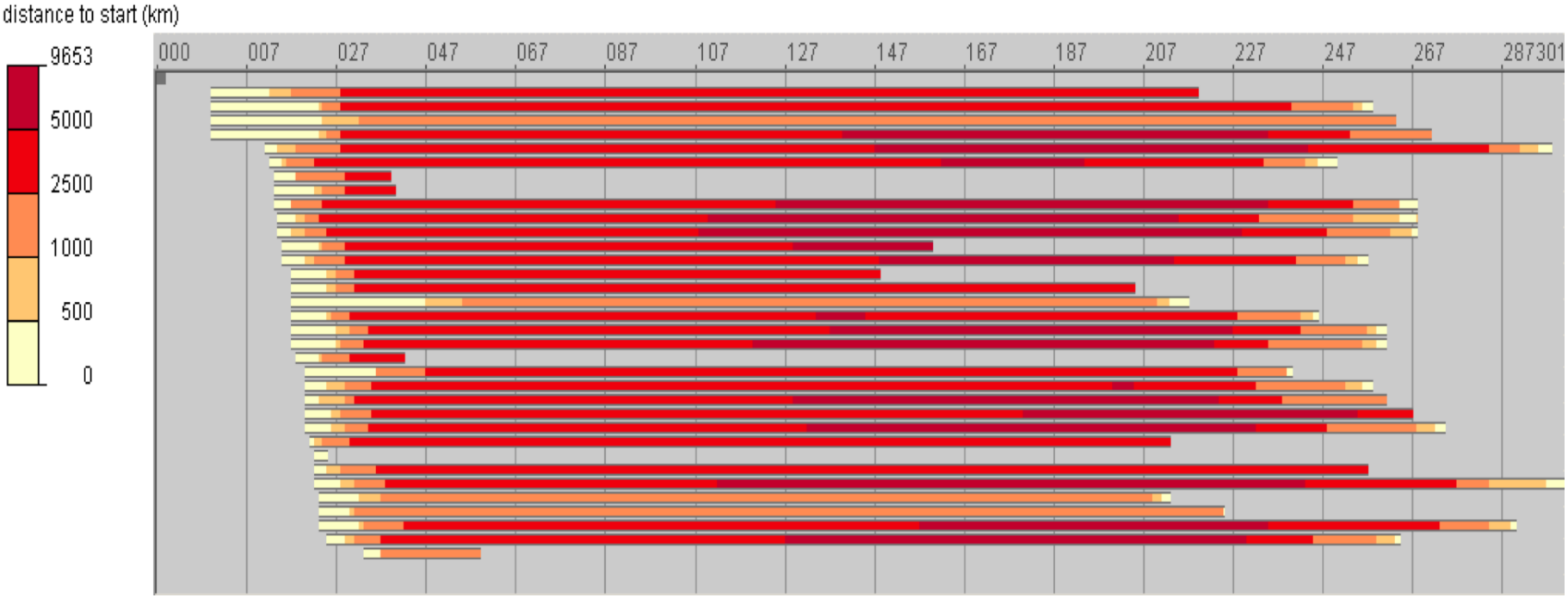
Birds: Speed Interpretation of Moves

- Trajectories interpreted as a sequence of displacements (moves): slowest moving - blue, fastest 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.



Birds Example: Distance Interpretation

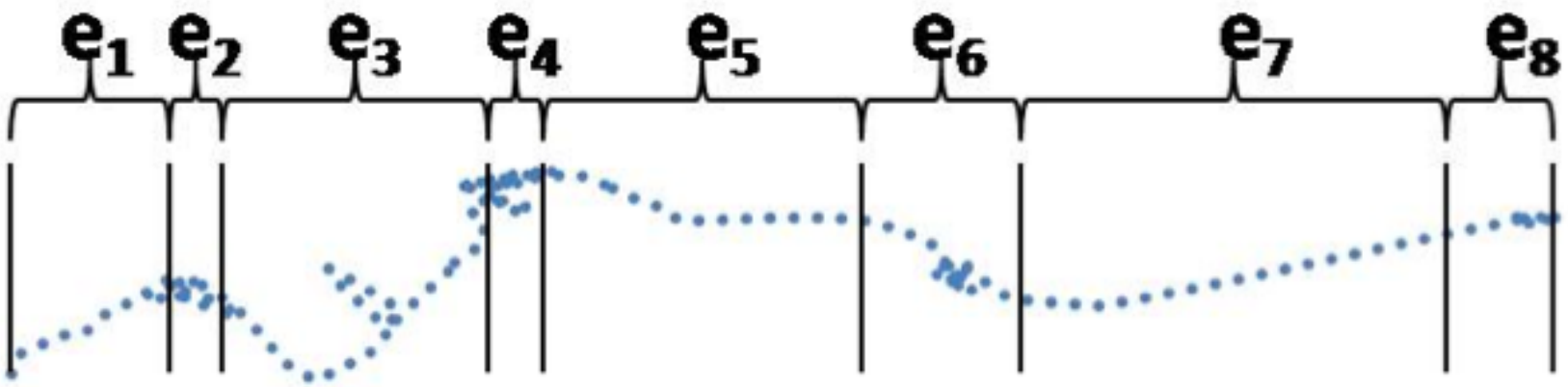
- The trajectories are segmented according to the spatial distance to the starting position. It is easy to see that relatively few trajectories do not reach very far, some other trajectories are very short (probably aborted due to some accident to the animal), and several are one-way trajectories (no coming back).



Trajectory Components: Episodes

- Spatio-temporal segments
  - Time varying point
  - Time interval
- Suitable abstraction any kind of application
- Example: Monitoring animal activity

Sleeping	Searching for food	Eating
Playing	Moving	Escaping (reaction to an alert)



Structured trajectory : a sequence of episodes

Formal Definition

Trajectory = (trajectoryID, AgentID, Tannotations,

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

gaps: LISTOF gap(t1,t2),

interpretations : SETOF interpretation
(InterpretationID, episodes:

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

Trajectory Characterization

- Trajectory Attributes
  - e.g. the goal of the trajectory (e.g. visit a customer)
- Trajectory Links to other objects
  - e.g. to the customer visited with this trajectory
- Trajectory Constraints
  - e.g. the trajectory of a car is constrained by the road network
- Trajectory Track (positions)
- Trajectory Interpretations with their Episodes

Trajectory Components: Begin & End

- Mandatory Points
  - Delimit a trajectory
  - Spatial type: Point
  - Temporal type: Instant
  - Topological relationships: e.g. *inside* links to spatial objects
    - Link (Instance level): this Begin point is *inside* Toronto
    - 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: Stops

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

Trajectory Components: Moves

- 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 ”walking” for the first 10mn, then attached to instance “bus” for the next 15mn, then ...
  - Constraints

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 spatio-temporal line (not a point)

Stops and Moves Interpretation

A day in Paris:

Airport	Ibis Hotel	Eiffel Tower	Louvre
[08:00-08:30]	[09:00-12:00]	[13:00-15:00]	[16:00-18:00]

Stop and Move are a special kind of annotation

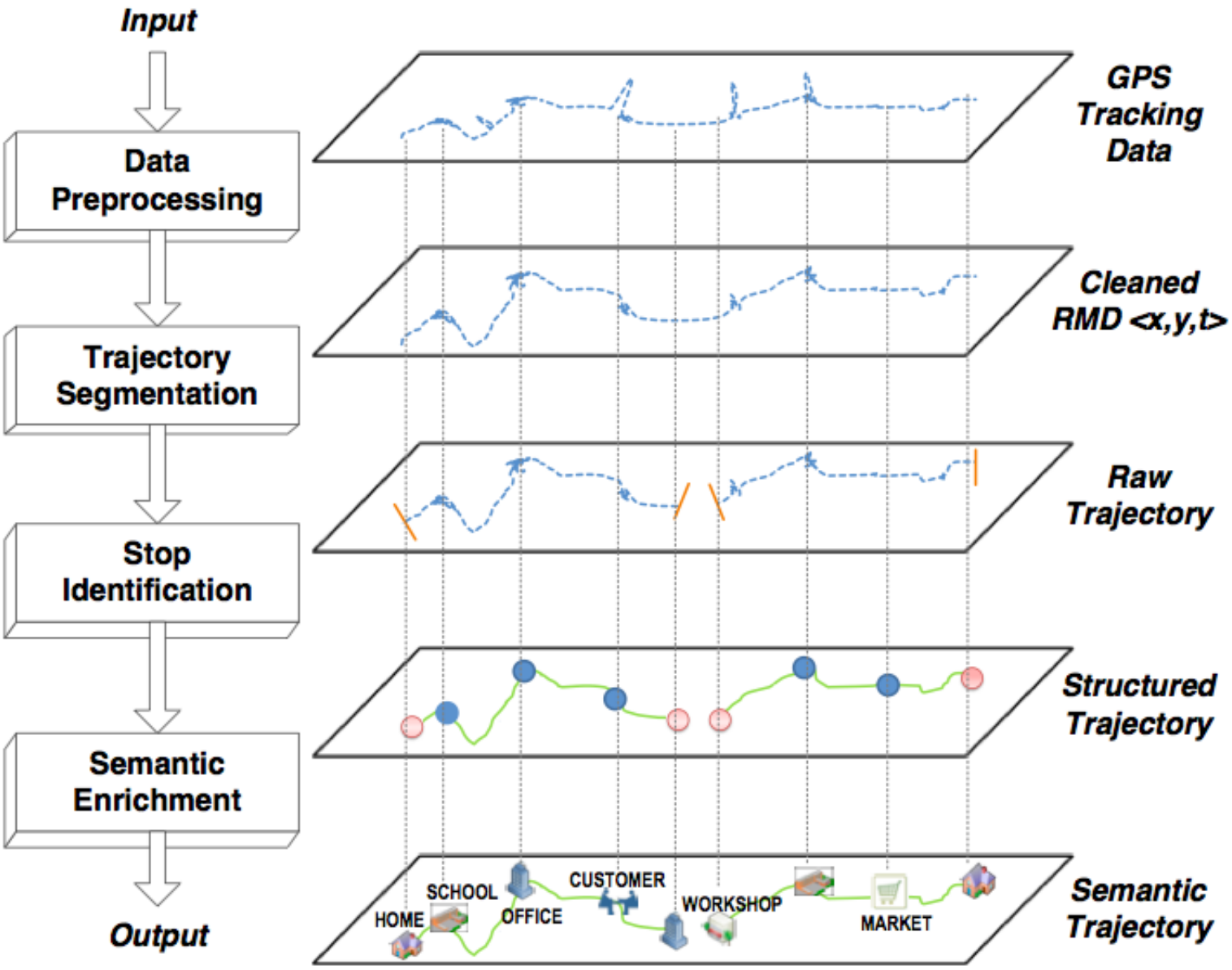
Queries Using Stop and Moves

- On 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 at a gas station?
  - For a given petrol company, return the number of cars that did stop today at a gas station owned by this company's retailers

Building Trajectories

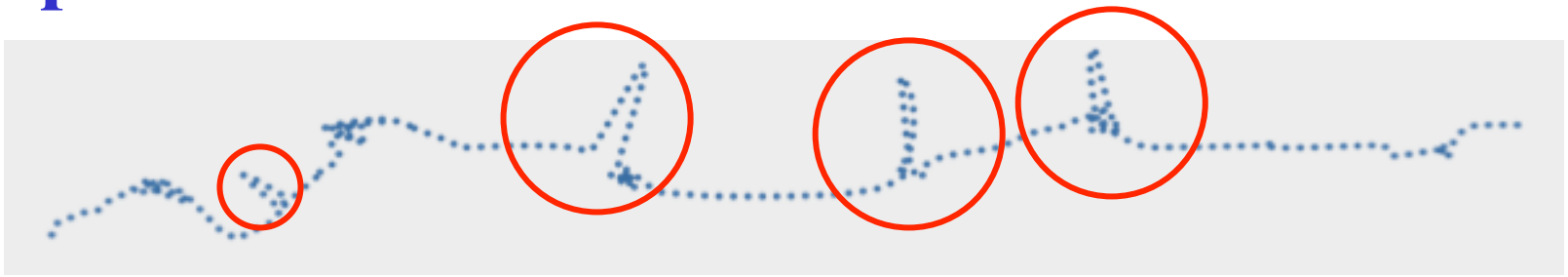
Trajectory Reconstruction

From raw data to semantic trajectories



Cleaning Raw Data

Input



Output

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

Segmentation into Trajectories

Input: Cleaned raw data

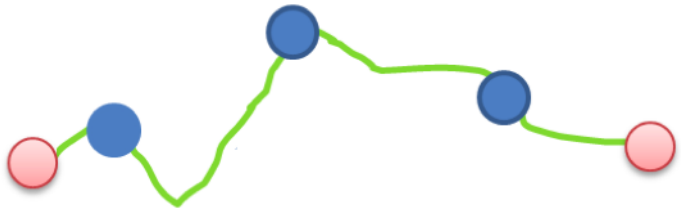
Output: Trajectories (Begin, End)

Methods: various segmentation algorithms, based on spatial gaps, temporal gaps, time intervals, time series, …

Trajectory Structuring (Stop & Move Episodes)

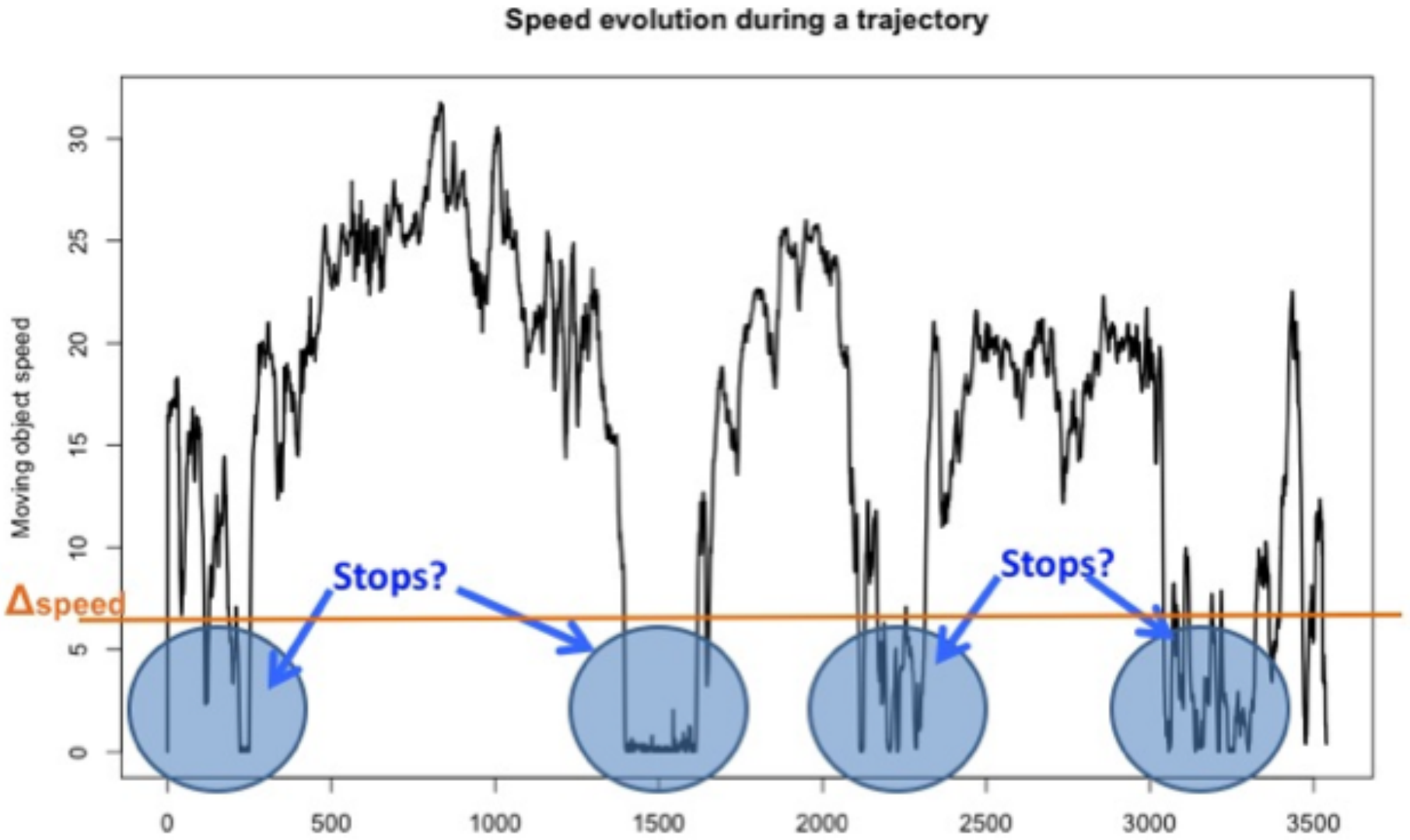
Input: Trajectories

Output: Trajectory sub-segments (Stop, Move)



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

Velocity-based stop identification



Determining Stops and Moves

- User-defined (either interactively or via defined criteria)
- Geometric computation
  - Stops are abstractions (e.g. centroid) of an area where the moving object/point stays for a certain period of time
- Geometric + Semantic computation
  - Stops are all points representing selected objects of a certain type (hotel, restaurant, POI, …) where the moving object stays for a period whose duration is above a certain threshold associated with the object
  - Relevant objects may be defined at the type level (e.g. “hotel”, “restaurant”, …) or at the instance level (selected locations, e.g. Fairmont Hotel

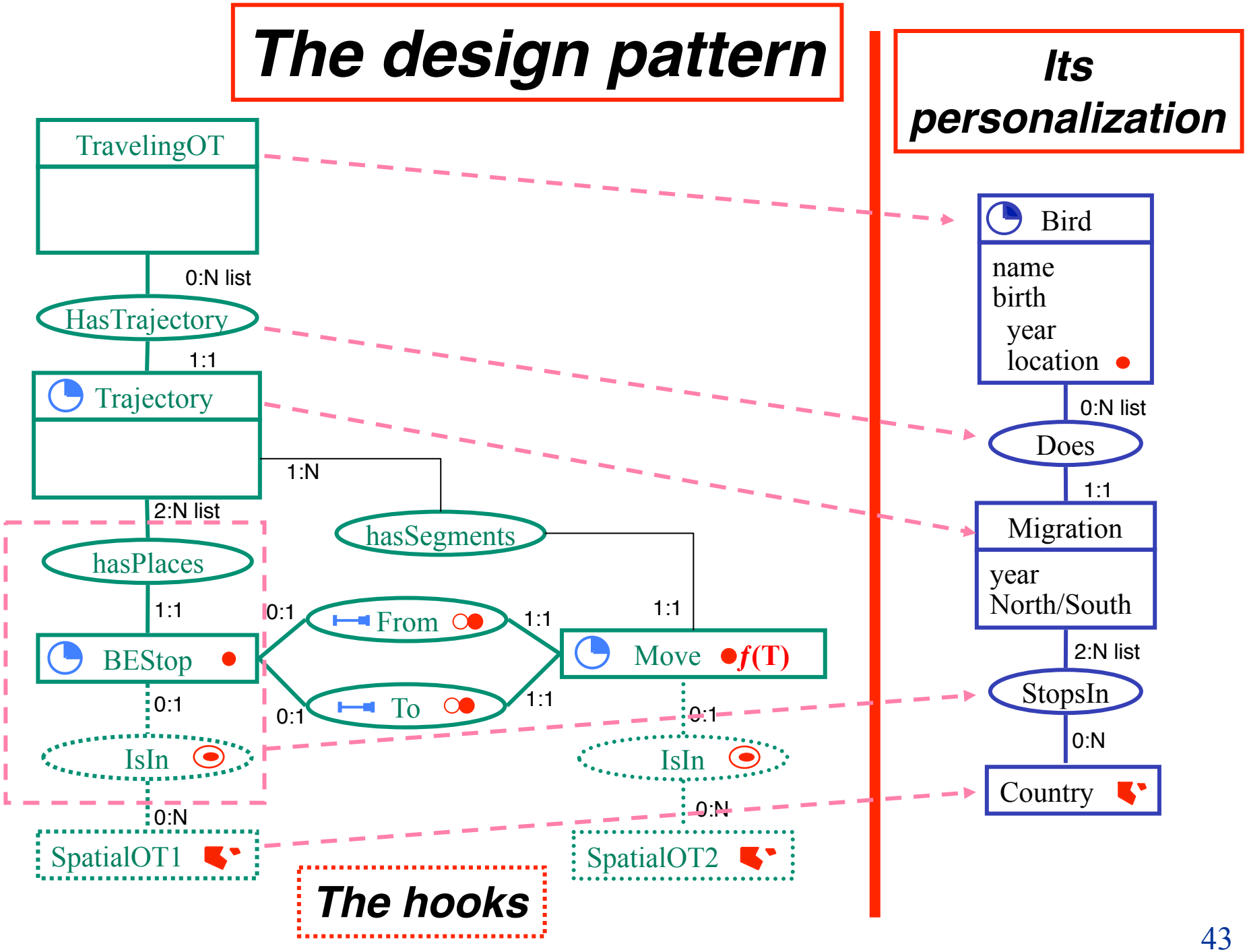
Semantic Enrichment

Input: Structured Trajectories

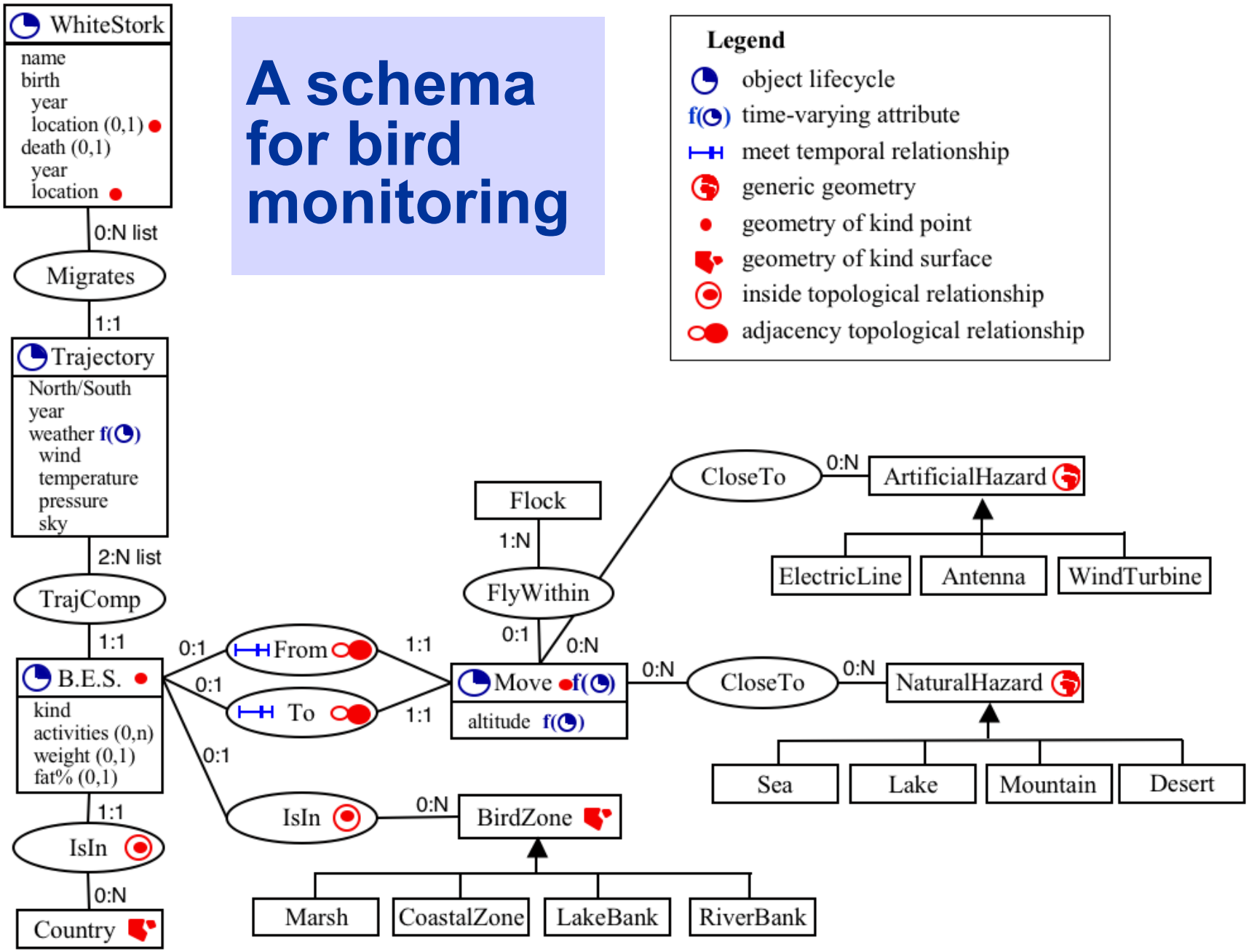
Output: Semantic trajectories

Methods: use relationships of each structured component (begin, end, stops, moves, …) to application knowledge, i.e. meaningful objects

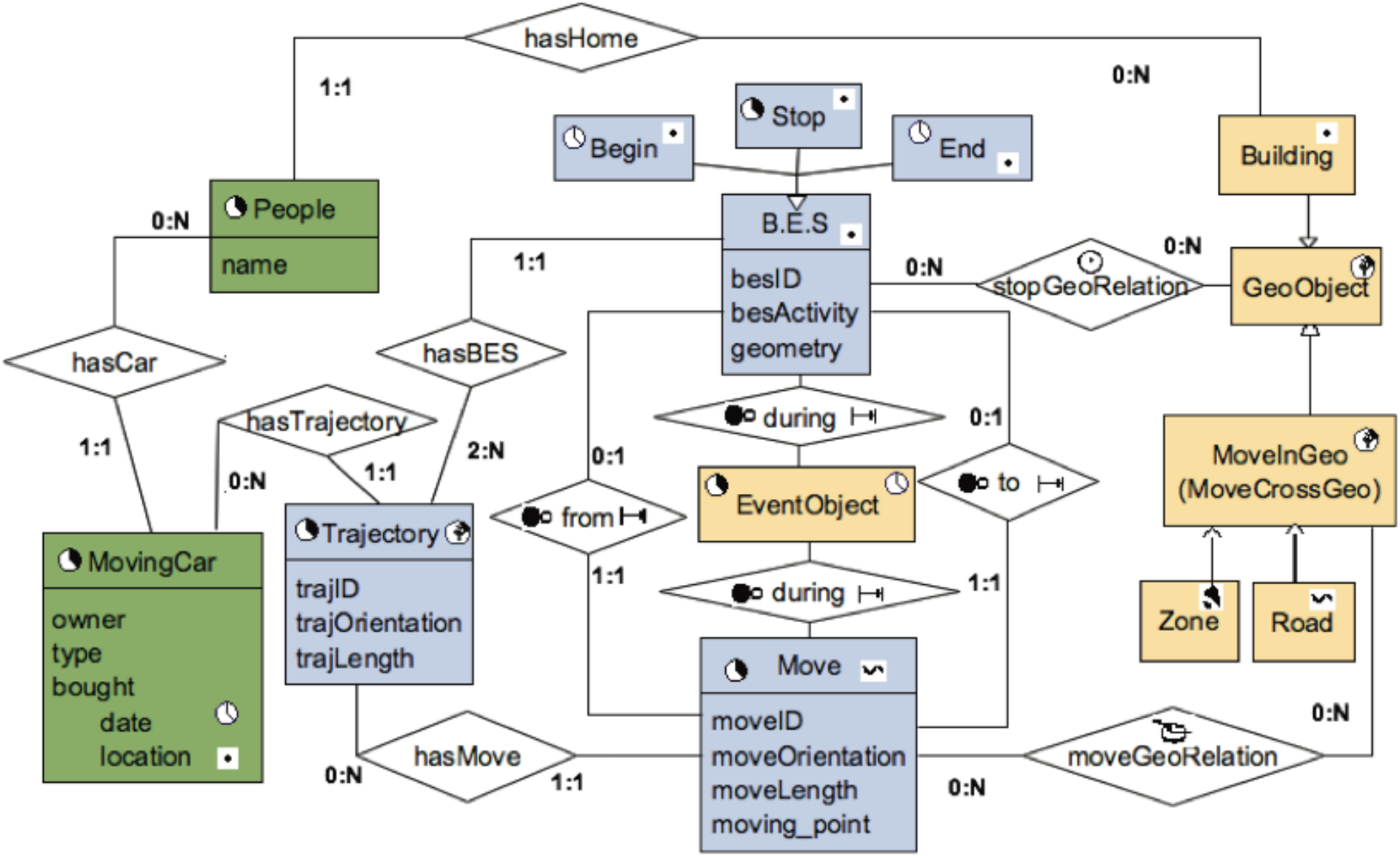
Modeling Semantic Trajectories


The design pattern
Its personalization
TravelingOT
0:N list
HasTrajectory
1:1
Trajectory
1:N
2:N list
hasSegments
hasPlaces
1:1
1:1
0:1
From
1:1
BEStop
Move
f(T)
0:1
0:1
To
1:1
0:1
IsIn
IsIn
0:N
0:N
SpatialOT1
SpatialOT2
The hooks
Bird
name
birth
year
location
0:N list
Does
1:1
Migration
year
North/South
2:N list
StopsIn
0:N
Country

A schema for bird monitoring



A Traffic Database with Trajectories



Trajectory Behavior

Behavior of Trajectories?

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

Behaviors Classification

- Trajectory behaviors may be classified according to several alternate 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.
- Spatial behaviors
  - "pass by" pattern: 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.

Behaviors Classification, cntd

- Spatio-Temporal behaviors
  - pass by the geo-object O some time during a given time interval
  - cars speeding beyond the speed limit of the underlying road
- Semantic behaviors
  - persons' trajectories that stop at a restaurant
  - car trajectories that stop at a petrol station belonging to a competitor petrol company.

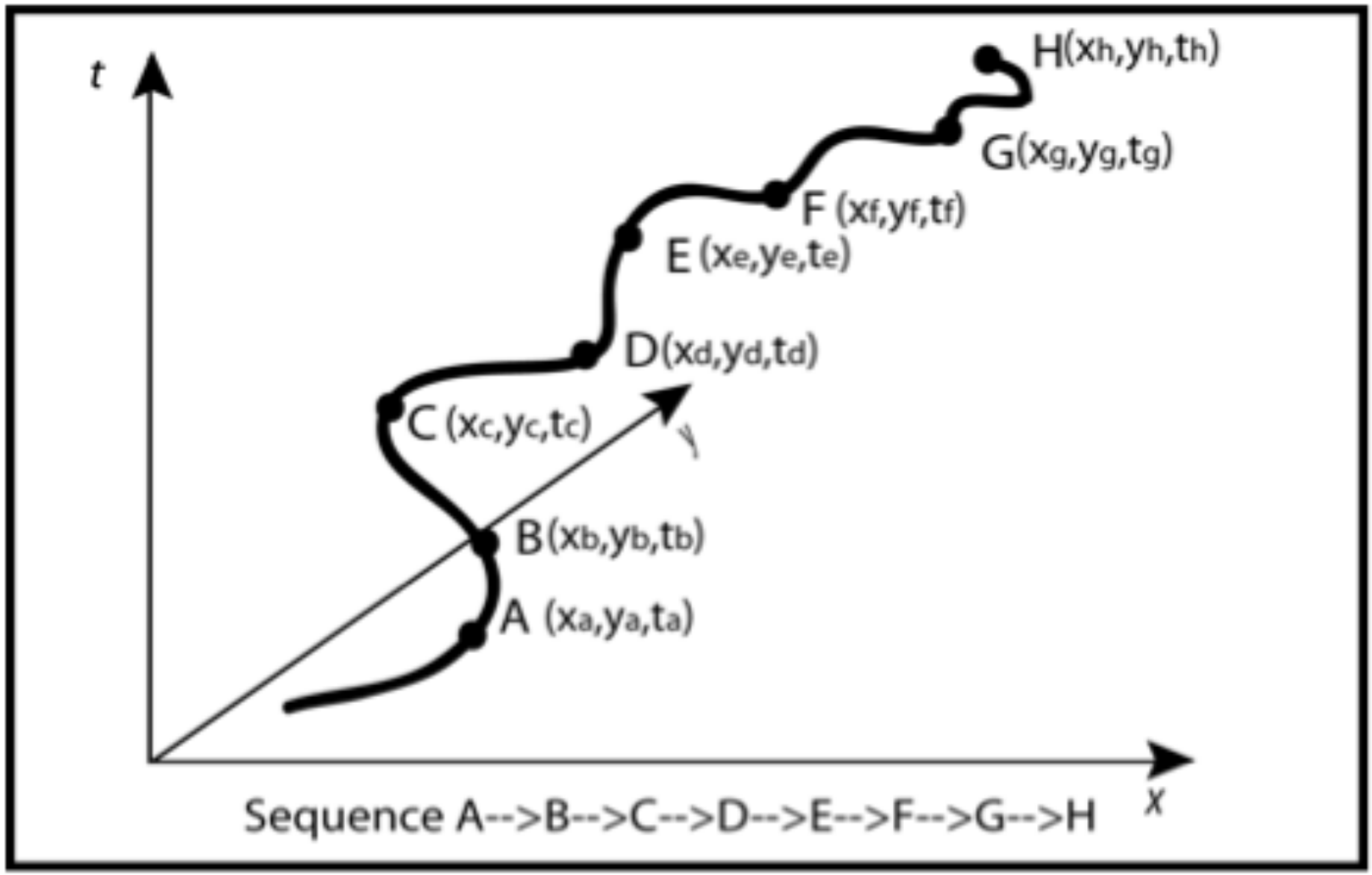
Another Classification

- 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.
  - Trajectories that start before 7am
  - trajectories that pass by a given geo-object during their first episode are two examples of local behaviors.

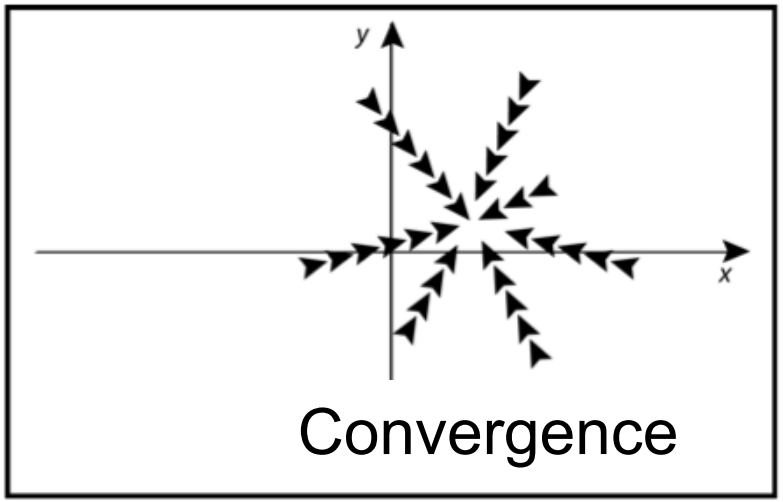
Third Classification

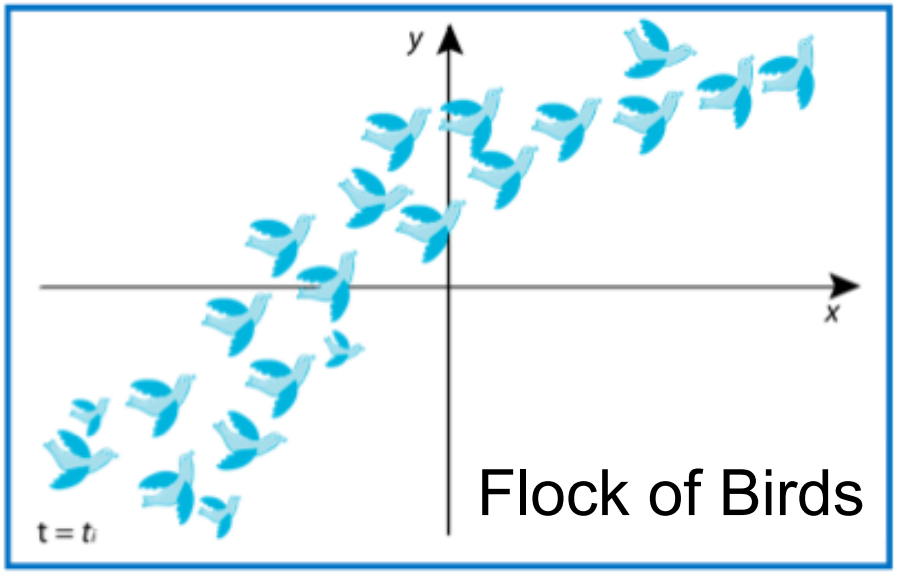
- Simple Behaviors
  - Defined by “simple” predicates
- Complex Behaviors
  - Defined by “complex” predicates: using sequence operators that are specific to temporal sequences
  - AND_LATER and its variants: AND_duration_LATER, e.g., AND_1 hour_LATER
  - The iteration operator: REPEAT (repeat any number of times), or REPEAT_N (repeat a given number of times). The repeat operator applied to a behavior B says that the trajectory must contain several successive segments such that each one satisfies the B behavior.

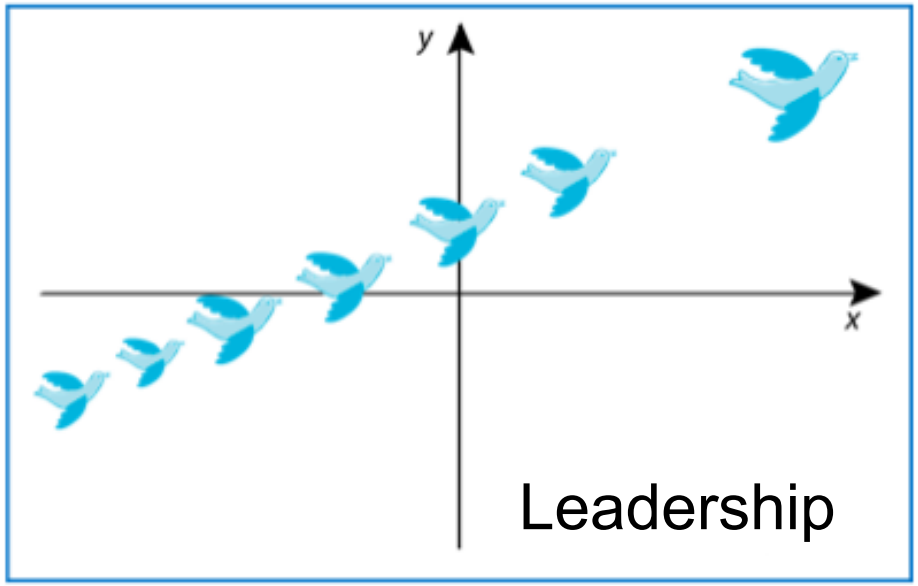
Example: Sequence

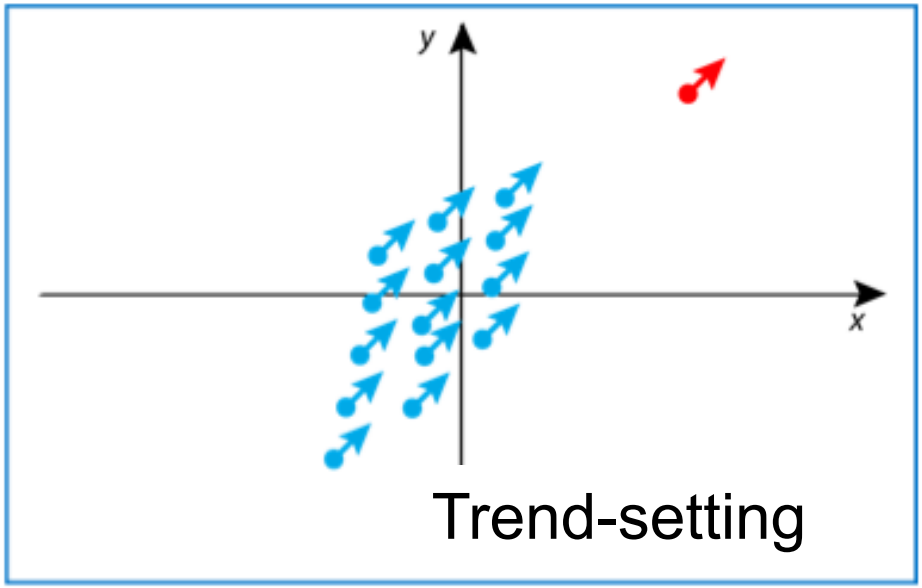


Examples


y
x
Convergence

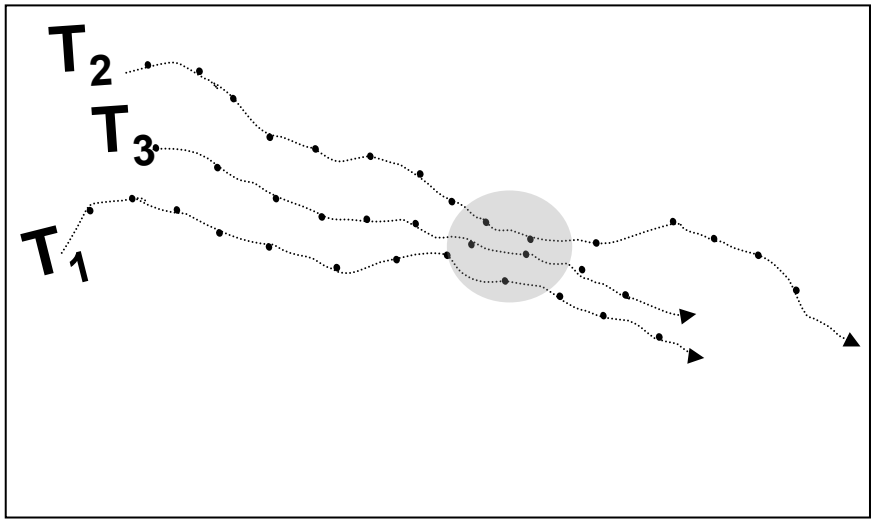

y
x
t = t
Flock of Birds


y
x
Leadership

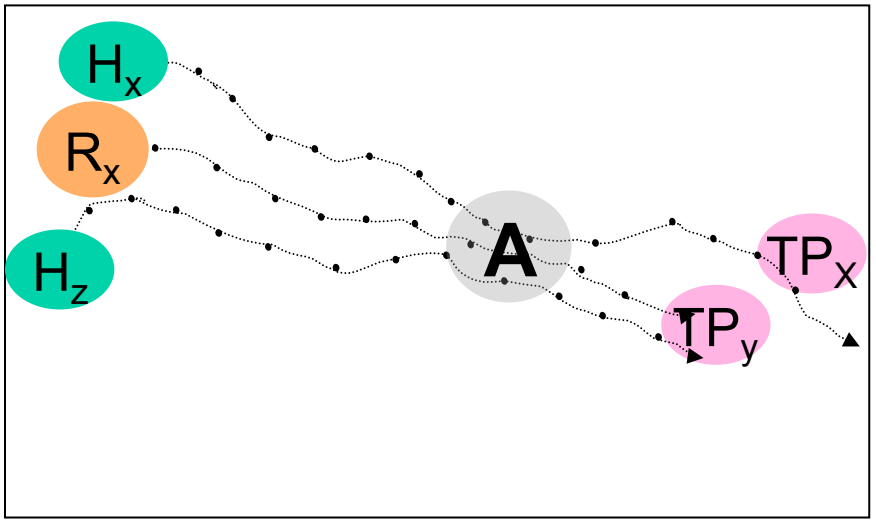

y
x
Trend-setting

Geometric versus Semantic

SpatioTemporal (Flock of Birds) behavior



Semantic (Flock of Tourists) Behavior



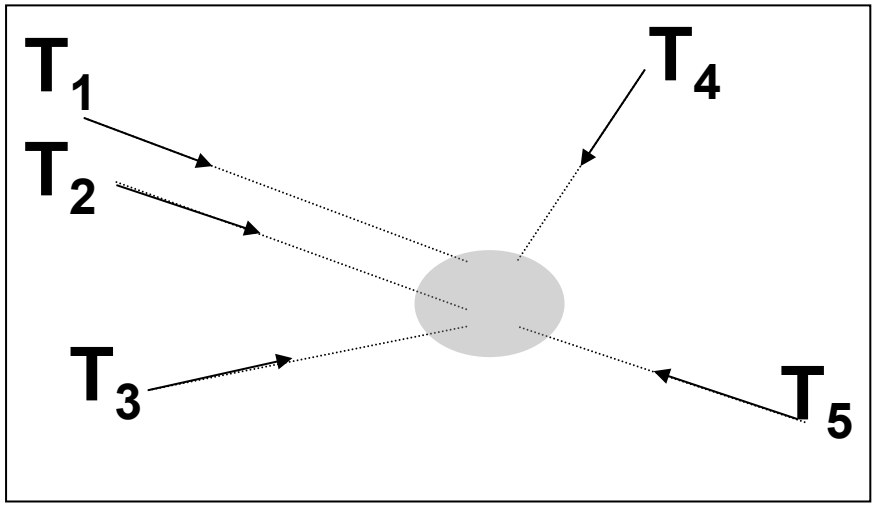
H Hotel R Restaurant TP Touristic Place

Semantic trajectory Behavior

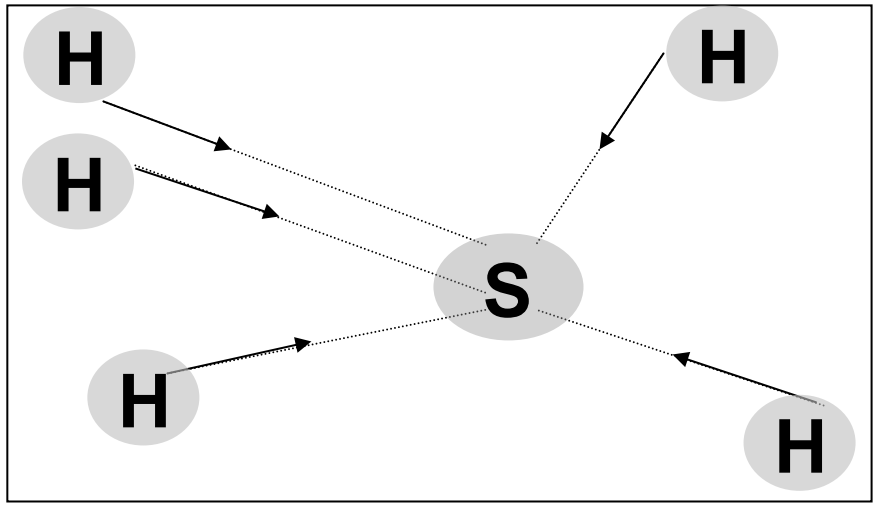
Hotel ∧ TouristicPlace → cross(A)

Geometric versus Semantic - 2

SpatioTemporal Behavior



Semantic Behavior



S School

Semantic trajectory Behavior
Home (H) to School (S)

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

- Warehousing, Classification, Data mining, and Knowledge extraction are the ultimate challenge
- 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?
- → Privacy preserving analysis methods
  - Join us at www.modap.org

Some References

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Thanks