

Modeling Moving Objects over Multiple Granularities

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Abstract

This paper introduces a framework for modeling the movement of objects or individuals over multiple granularities. *Granularity* refers to selecting the appropriate level of detail for a task. At fine granularities, spatio-temporal information is revealed that was not previously known, such as additional locations that an individual visited or multiple visits to the same location. Conversely, moving to a coarser granularity or simpler view generalizes spatial and temporal aspects of movement allowing for an improved understanding of movement. Movement is modeled as *geospatial lifelines*, time-stamped records of the locations that an individual has occupied over a period of time. Depending on the desired granularity, lifelines are modeled as lifeline beads, necklaces, or more general approximations of these structures and this paper examines how different aspects of lifelines become relevant at refined or coarse granularities.

1. Introduction

People move through space. Different types of movements occur, such as the movement of a person who walks, runs, or rides a bus; a taxi that travels through city streets; or an oil spill, carried by currents and waves that spreads along coasts and diffuses through bays and inlets. Although these movements occur continuously in geographic space, people conceptualize certain movements as being discrete, while others are conceptualized as being continuous [1]. Movement in space-time often exposes people to illnesses or to environmental factors that can lead to eventual health problems. Efforts to enhance approaches for the study of environmental health sciences include developing new tools for the analysis of spatially and temporally referenced medical information, and new methods for reasoning about movement and its consequences over space and time [2]. These efforts coincide with an interest by the database community in spatio-temporal databases [3-5] including moving object databases [6-10] that provide support for querying moving objects [6, 8, 11].

The focus of this paper is to model movement of objects or individuals over multiple granularities. *Granularity* refers to the notion that the world is perceived at different grain sizes or granules [12] and, in this paper, the use of granularity relates to the cognitive aspects of selecting the appropriate level of detail for a task. At a fine-grained level of detail information is revealed that otherwise is unknown. Who else has visited this location? How many times? To what other locations has individual *X* traveled? How did the speed of movement vary? Conversely, moving to a coarser view improves our understanding of phenomena as irrelevant details are abstracted. Shifting between spatial granularities is a necessary routine for many tasks. The formalization of such shifts for implementation in an information system, however, is more complex [13-17]. It is insufficient to consider *only* the spatial aspects of objects at different

granularities. The temporal aspects of a scenario of movement are also very relevant and efforts have been made to provide a formal framework for temporal granularity [18-20]. Typically, of course, movement involves both spatial and temporal elements and ideally, data models should provide support for both dimensions combined. At refined granularities, for example, a view of a person's movement may include the time and place of departure, mode(s) of transport, time and place of arrival, travel speed, and the number of stops enroute, while a view at a coarser granularity gives only a general trend of movement, capturing basic facts, such as the person, moved from the East Coast to the Mid-west in the 1960s, where she lived for the next forty years. A set of temporal zoom operators has been proposed for aiding spatio-temporal knowledge representation over different granularities [21] including operators to assist with the summarization or coarsening of spatio-temporal aspects of large datasets [22].

This paper examines the nature of shifts in granularity on *geospatial lifelines*. A geospatial lifeline models an individual's movement. It is a time-stamped record of locations that an individual has occupied over a period of time [2]. The basic element of lifeline data is a space-time observation consisting of a triple $\langle \text{Id}, \text{Location}, \text{Time} \rangle$, where **Id** is a unique identifier of the individual used throughout all recordings of that individual's movements, **Location** is a spatial descriptor (such as a coordinate pair, a polygon, a street address, or some other locative expression), and **Time** is the time stamp when the individual was at that particular location (such as a clock time in minutes or event time in years). Lifelines are described at multiple granularities and a framework is developed for refining and coarsening the granularity of lifelines from a spatio-temporal perspective. A shorter, preliminary version of this paper appeared as [23].

The remainder of the paper is organized as follows: Section 2 introduces geospatial lifelines as a basis for modeling continuous movement in space-time. Section 3 presents the concept of modeling movement as lifelines over multiple granularities. Section 4 describes refining lifeline granularity through the addition of space-time sample points and from the perspective of more detail with respect to speed or modality of movement. The following section extends this work to how coarser views of movement can be derived through transforming lifelines into more general structures. Conclusions and future work are discussed in the final section.

2. Geospatial lifelines

Continuous processes are typically observed through a series of discrete samples, which are ordered by the times of their observations. These observations provide an approximation for the actual movement of an object. Different lifeline models are possible depending whether the movement being modeled is discrete or continuous. A *lifeline thread* refers to a linear approximation of an ordered sequence of space-time samples capturing the *likely* space-time points at which an object or individual may have been when moving continuously from *A* to *B* (Figure 1). A steeply sloping thread corresponds to scenarios where an object is moving at lower speeds, while slopes closer to the horizon model movements that occur at higher speeds. If part of a lifeline thread is parallel to the time axis then the object is not moving through space during that time interval [24]. Although such space-time measurements are subject to the usual measurement errors [25], we neglect their effects here.

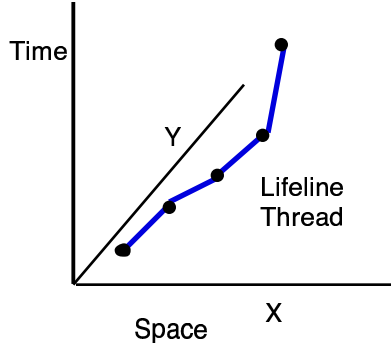


Figure 1: A lifeline thread.

Alternatively, given two known locations and a certain travel speed, it is possible to model the set of all possible locations that an individual could feasibly pass through or visit [24, 26]. This set of all possible locations is relevant for determining whether, for example, an individual could have come into contact with a known environmental hazard or disease, or whether a ship has passed through an oil spill, or an airplane through a storm [11, 25]. The approach for modeling the set of possible locations for an individual given a starting and ending point in space-time and a maximum velocity is based on a set of geometric constraints that describe the intersection of two inverted half cones that form a *lifeline bead* (Figure 2). The lower half cone captures the progression the individual makes when departing from the first sample (x_0, y_0, t_0) , while the upper half cone describes the space-time points at which the individual could have been while approaching the second sample (x_1, y_1, t_1) . The apex angles ω_0 and ω_1 are determined by c_0 and c_1 , respectively, the ratios between each cone's radius and height, such that $\omega_0 = 2 \arctan(c_0)$ and $\omega_1 = 2 \arctan(c_1)$ (Equations 1a and b).

$$t_0 + c_0^{-1} \sqrt{(x - x_0)^2 + (y - y_0)^2} \leq t \tag{1a}$$

$$t_1 - c_1^{-1} \sqrt{(x - x_1)^2 + (y - y_1)^2} \leq t \tag{1b}$$

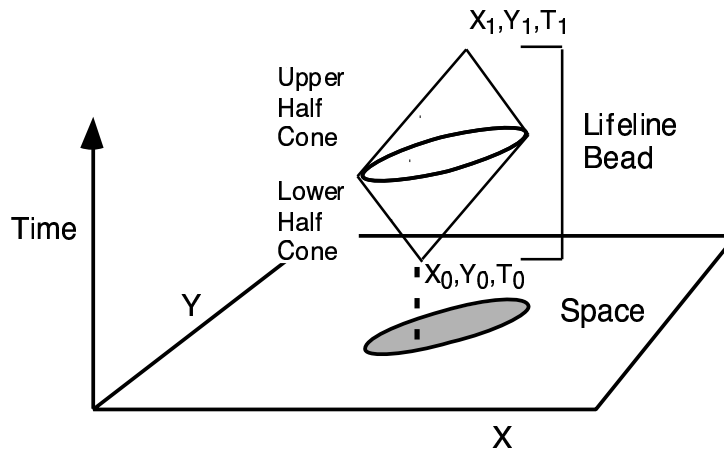


Figure 2: Lifeline beads based on all possible locations for an individual given a starting (x_0, y_0, t_0) and ending point (x_1, y_1, t_1) in space-time and given a maximum velocity.

For cases where an individual's spatial location is the same at two space-time samples, the set of possible locations forms a *right bead* (intersecting right half cones) (Figure 3a). All other

cases result in an *oblique bead* based on intersecting half cones (Figure 3b). The area of intersection of two oblique half cones is projected onto the x - y axes as an ellipse.

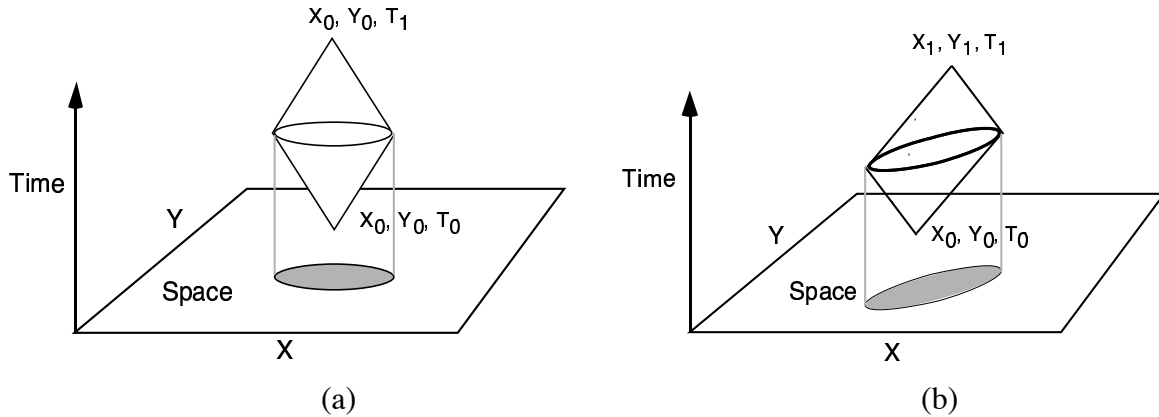


Figure 3: Lifeline beads: (a) a right bead where the intersection of two right half cones has apexes that are collocated in space but shifted in time and (b) an oblique bead where the apexes of two half cones are not spatially collocated.

Lifeline beads enable the processing of queries based on geometric intersections of the two half cones [27]:

- Is it possible that individual A was at location x_A, y_A ?
 A non-empty intersection between A's bead and a vertical line through x_A, y_A .
- How long could B have stayed at location x_B, y_B ?
 Calculation of the length of the intersection of a vertical line through x_B, y_B with B's bead.
- What are all the places at which C might have been at time t_C ?
 Intersection of C's bead with a plane through t_C .

Beads also enable the analysis of semantically meaningful spatio-temporal relations through the comparison of bead relations. If the beads of two separate individuals touch at a rim point, then they could have met (Figure 4a). If the intersection of two beads extends along a portion of the beads' rims, then the two individuals could have met for an extended time, but only while moving together (Figure 4b). Finally, two intersecting beads with a non-empty interior give rise to a stationary meeting between the two individuals (Figure 4c).

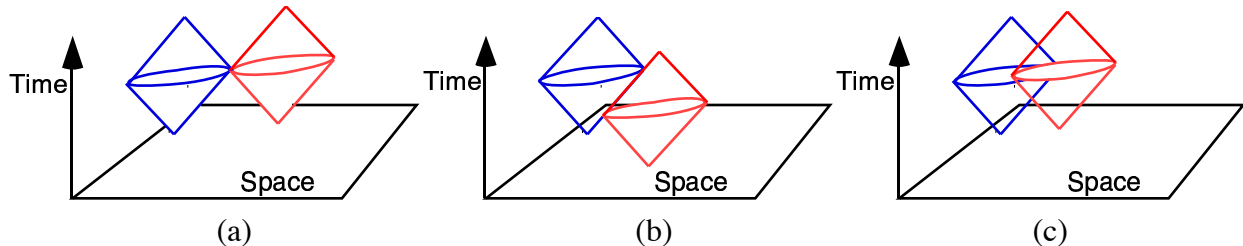


Figure 4: Lifeline beads that (a) meet at a rim point, (b) share a common part along two beads' rims, and (c) intersect.

3. Granularity of lifelines

An individual's movements may be monitored or sampled over different intervals. Sampling intervals may vary with the speed of the moving object where, for example, faster speeds are

associated with more frequent samples. Alternatively, speed may be constant over time and a regular sample interval is employed to monitor movement.

Shifting to more frequent sampling returns a new, more-detailed *view* of an individual's movements between two locations. This corresponds to a refinement of granularity over lifelines that model movement. Views here are not defined as visual representations, but rather as refinements or abstractions of lifelines. All lifeline models lend themselves to multiple views, each of them distinct from the others. Each view corresponds to a different way of perceiving movement over space and time and may be associated with a different sampling rate. If, for example, it is known that Mary rides a bus to work in the morning, at a finer granularity, more spatio-temporal detail may be relevant such that Mary leaves her house at 7:40am and takes a bus that drops her at 8:00am, 2 blocks from her office. She then walks the remaining distance, arriving at the office at 8:10am. Shifting to fine-grained view results in one or more of the following scenarios:

- expanded temporal detail such that more timesteps are relevant,
- additional locations through which the object passed, and
- more detail about the speed of movement between locations.

Other spatio-temporal aspects of movement also become relevant, for example, whether it is possible for an individual to have participated in certain activities or not. Could a person reach location *X* by a certain time? The varying lengths of time spent on each segment of movement yields useful information, which is uncovered at finer granularities. Additional spatial detail affords more information about the travel path and locations occupied, revealing possibly unknown or unexpected side trips, such as whether the individual visited a location more than once. Finer granularity may also reveal that portions of the movement took place at slower speeds, such as corresponding to periods of heavy traffic perhaps, or portions at faster speeds, as when traveling on a highway.

Conversely, coarser granularities correspond to sparser sampling regimes and offer less-detailed views. Coarsening granularity results in coarsening temporal detail, spatial detail, or the detail relating to speed of movement. This type of operation is particularly relevant to very large databases with detailed geospatial lifeline data that may require abstraction into simpler, generalized views of movements..

4. Refining granularity of lifelines

Refining granularity reveals additional spatio-temporal detail about the movement of an individual. At the detailed perspective, more temporal detail becomes available and more is known about locations occupied by the person. From the perspective of the model, refining granularity shifts the view of movement, for example, from a single lifeline bead to a detailed view where the single bead is replaced by a series of beads.

9. Adding space-time sample points

If additional space-time sample points become known or relevant, then information is gained about the movement of the individual or object. New information might be acquired, for example, that an individual was at a certain restaurant at lunchtime, or visited a particular town in the afternoon. For the case where an additional sample point, for example, is located on the lower rim of the bead (Figure 5a), the original bead geometry is refined such that part of the bead degenerates to a straight line originating with the start point of the bead and ending with the newly added sample point (Figure 5b). The additional sample point, therefore, has the effect of limiting the number of possible locations through which the object may have passed. An additional point that falls on the upper rim of the bead also results in revised bead geometry (Figure 5c).

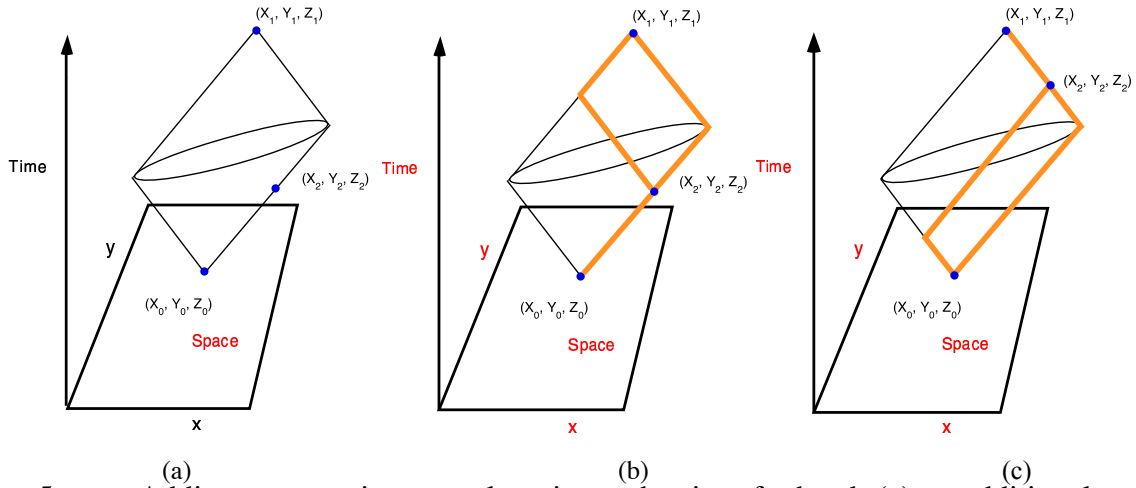


Figure 5: Adding a space-time sample point to the rim of a bead: (a) an additional sample point that lies on the rim of a bead becomes relevant, (b) the bead geometry is refined by the inclusion of this additional point and (c) bead geometry is refined to correspond to the addition of a sample point.

For cases where one or more space-time sample points are added such that they fall inside a bead (Figure 6a), the bead geometry is similarly affected. For these cases, however, the addition of such a point refines the original set of locations such that two (or more) smaller beads result (Figure 6b) restricting the set of possible locations through which an object might have passed. This *sequence* of lifeline beads that results from additional sample points being considered in the model, forms a *lifeline necklace* where the end point of one bead is the start point of the next bead (Figure 7). Shifting from a granularity where a single bead models an individual's movement, to a finer granularity where a necklace captures an object's movement in space and time, reveals more detail about movement and refines the set of possible locations visited by the individual.

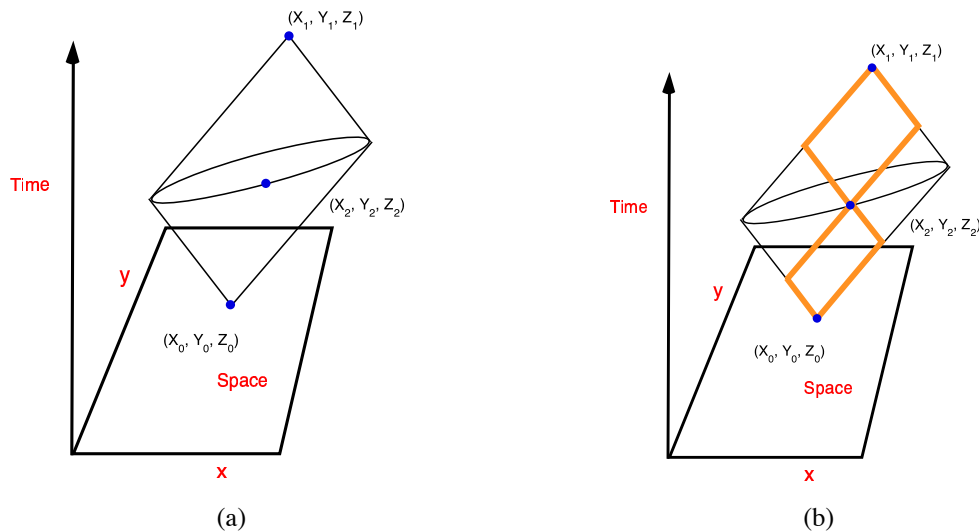


Figure 6: Adding a space-time sample point inside a bead: (a) an additional sample point that lies inside a bead becomes relevant, (b) the bead geometry is refined by the inclusion of this additional point such that two beads are formed.

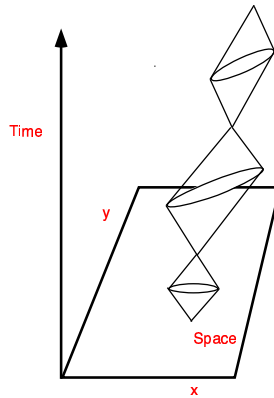


Figure 7: Movement can be modeled as a sequence of beads that form a lifeline necklace.

10. Refining granularity with respect to the speed or modality of movement

Changing a view of movement that captures a single modality of movement to a view based on multiple modalities involves a refinement of granularity. Consider a trip by car to a grocery store where movement is modeled as a single bead (Figure 8a). Refine the granularity to capture the fact that the person actually traveled only part of the way by car and then walked the remainder of the distance to the store. This results in a new view of movement. The model changes from a single bead to a view based on a necklace of beads (Figure 8b). The necklace models a variation in speed associated with different modalities of movement and distinguishes more space-time sample points, giving a more detailed view of the characteristics of an individual's movement. This new view contains two beads that describe respectively the vehicle portion of the trip and the walking portion. The vehicle portion most likely occurs at a faster speed than the walking portion. Therefore the two beads will have different apex angles where the wider bead corresponds to faster movement. More temporal detail about the movement is also revealed. It is now possible to derive, for example, what proportion of the trip occurred at the faster or slower speeds.

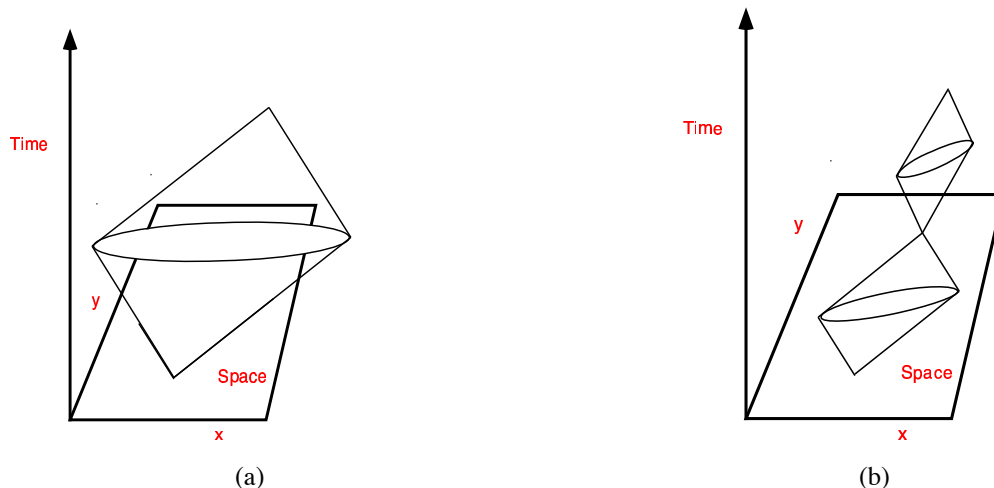


Figure 8: A trip to a grocery store modeled as: (a) a single bead and (b) two beads where the one bead captures part of the trip that happened at a faster speed than the other part.

Continuing to refine granularity can uncover or reveal other aspects relating to an individual's movements including periods of inactivity where maximum speed is zero. These periods are

modeled as degenerate beads (Figure 9a). Now the model of the shopping trip includes the portion of the trip where the individual stood talking to someone after parking his or her car or getting off the bus and before walking the final leg to the store. Additionally, return trips to the origin, for instance, returning home for a forgotten item, may be included at finer granularities. These return trips are modeled as right beads (Figure 9b).

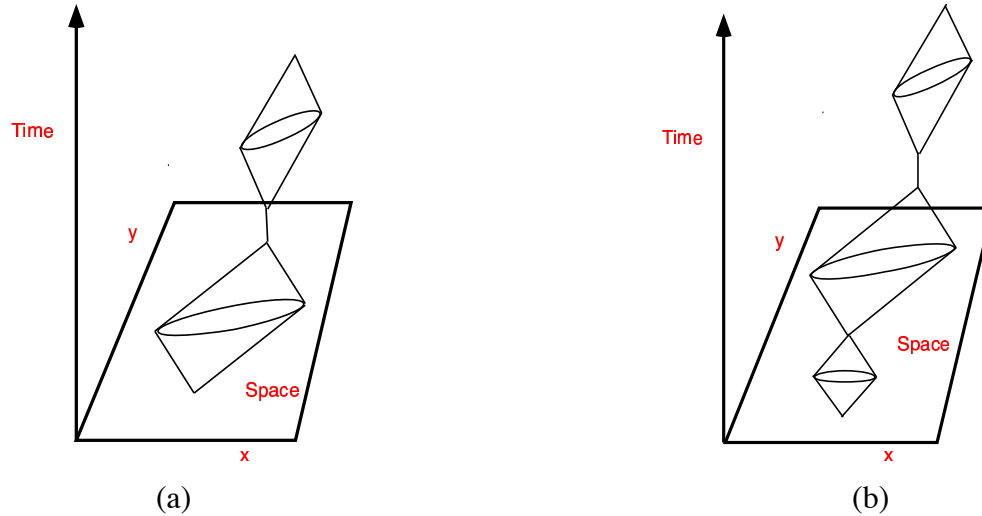


Figure 9: Refining granularity further reveals (a) a period of inactivity modeled as a degenerate bead and (b) a return trip to the origin modeled as a right bead.

5. Coarsening granularity of lifelines

Coarsening granularity returns a new, less-detailed view of an object's movement. *The person traveled to the West Coast last week* is a coarse view of a trip where there were actually many roads traveled, and frequent stopping points, etc., that could be modeled. Coarsening temporal detail occurs such that the model captures fewer and more general timestamps. Coarsening spatial detail results in fewer start and end point locations being modeled. Less detail with respect to the speed of movement is also maintained at a coarser view.

5.1 Deriving generalized beads from necklaces

Coarsening granularity can occur through aggregating the beads in a lifeline necklace into fewer, *generalized* beads. In this way, the overall trend of movement is preserved with sparser spatio-temporal detail. The start and end point of a necklace, or of certain beads in a necklace, form the start and end points of the generalized bead(s). A decision must be made as to what velocity should be used to compute the resulting bead. There are several options. Depending on the geometry of the necklace and the number of beads from which a generalized bead is derived, the maximum velocity of the starting and ending bead might be utilized for the generalized bead (Figure 10a). Under certain conditions, this approach has the advantage of retaining the form of the necklace and so preserving the trend of movement. If, however, there are beads in the necklace derived from different maximum speeds, this method may offer little advantage beyond capturing the apex angles of the starting and ending beads. Alternatively, the greatest value of maximum speed from beads in the necklace might be selected as the velocity for the generalized bead (Figure 10b). This approach ensures that the resulting bead encompasses all possible locations an individual might have passed, but also suffers from being too coarse. The set of all possible locations derived using this approach might be larger than the set of locations actually described by the necklace. Conversely, if the maximum velocity selected is less than that used for the others beads, then certain locations may be missed by the model and lie outside the

generalized bead (Figure 10c). Selecting an average velocity for the generalized bead may be a suitable alternative that minimizes some of these difficulties. In certain circumstances, however, all these approaches fall short of capturing all possible locations that an individual has visited.

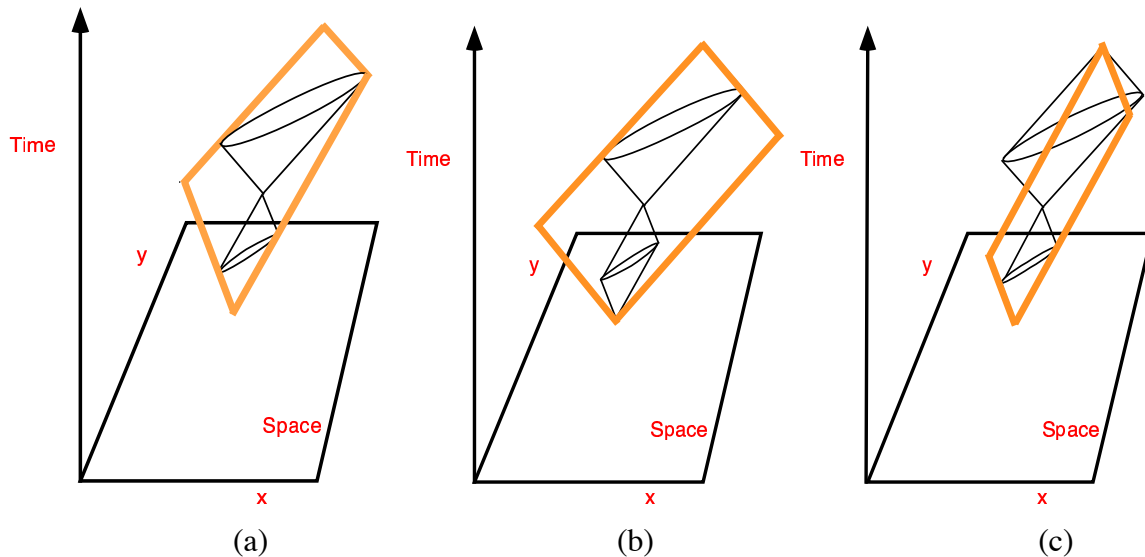


Figure 10: Coarsening granularity from generalizing lifeline necklaces:(a) a generalized bead is derived based on the start point and end point location of a necklace and the maximum speed of the start and end bead in the necklace, (b) a generalized bead is derived based on the greatest maximum speed of beads in the necklace, and (c) a generalized bead is derived based on the lowest maximum speed of beads in the necklace.

9. Coarsening granularity based on speed or modality of movement

Coarsening granularity over a lifeline necklace may also be achieved through abstracting detail relating to the speed or modality of movement (Figure 11a). Retain the beads in a view, for example, that describe the fastest portions of movement while abstracting beads modeling slower portions. For this type of coarsening, a necklace can be simplified through beads being aggregated to form generalized beads based on criteria relating to the speed of movement (Figure 11b). Coarser views may also be motivated by capturing the most relevant aspects of movement, such as retaining the beads relating to the longest portion of the trip and abstracting the shortest legs. If, for example, a person takes a taxi to the airport and then travels for seven hours across the Atlantic on a jet, this movement might be modeled with beads that describe the plane trip while selectively omitting beads that model the details of the taxi ride (Figure 10c). Similarly, one may choose to leave out the details of any return trips for forgotten items or breaks in the journey for rest by omitting any right beads or degenerate beads from a view.

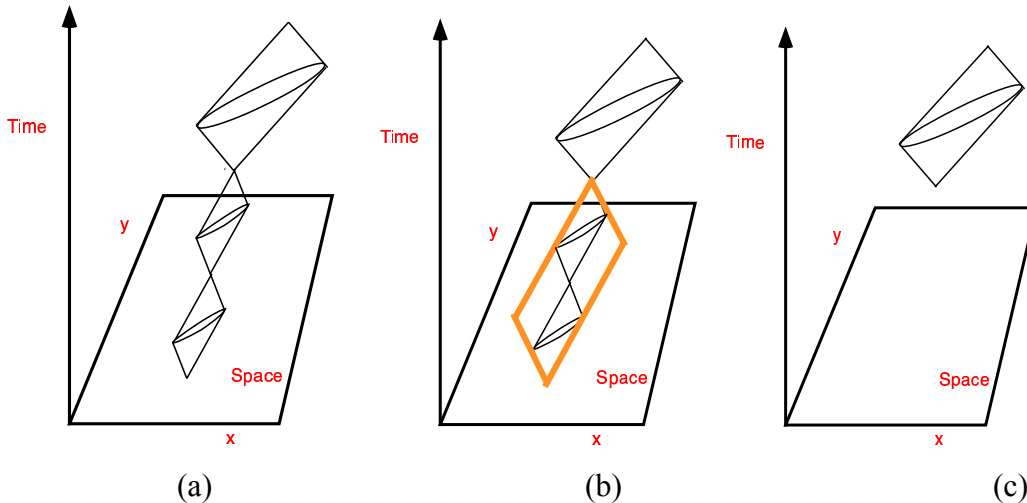


Figure 11: Coarser views based on speed or modality of movement (a) a lifeline necklace modeling movement, (b) beads of similar maximum speed are aggregated into a generalized bead, and (c) beads are selectively omitted from the view.

5.3 Other means of deriving coarser views of necklaces

From the previous solutions that take their form from the beads of the necklace, further simplification is still possible. If only the space-time sample points are known or are relevant, then coarsening can change the view from the set of all possible locations to the most likely locations. This shifts the model of movement from a necklace to a lifeline thread (Figure 12) where the start and end points of each bead of the necklace are retained in a view.

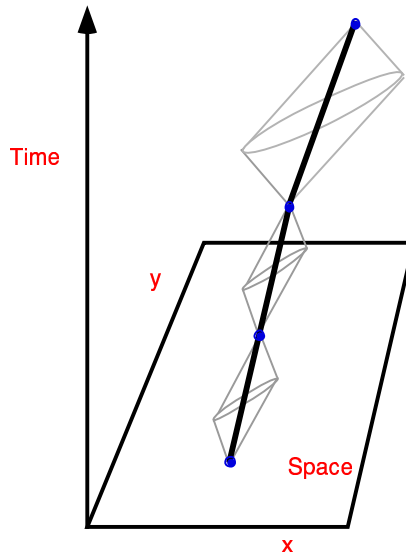


Figure 12: Coarsening granularity over a necklace can derive a lifeline thread.

Coarsening granularity over a lifeline necklace may also be achieved through approximations that capture the overall trend of movement, without much of the spatio-temporal detail. One approach is based on deriving a *convex hull* computed from the geometric properties of the necklace. The convex hull uses rim points from the beads in the necklace. Depending on the geometry of the necklace, however, the convex hull may or may not touch all the rim points of the beads comprising the necklace (Figure 13a). The convex hull is a coarser approximation of a lifeline necklace where the space-time start and end points of the interior beads of the necklace

have been abstracted. This structure captures the complete set of possible locations modeled by the necklace.

Alternatively, another shape-approximating approach based on the velocity at the start and end points of the necklace as well as selected point locations chosen from the rim of each bead in the necklace can be used to model movement (Figure 13b). This *tube* approximates the geometry of the necklace more closely than the previous approach based on convex hulls and also captures the complete set of possible locations associated with the movement of an individual. Depending on which rim points from the necklace are selected to influence the geometry of the generalized necklace, there are many different solutions that can be computed with this method.

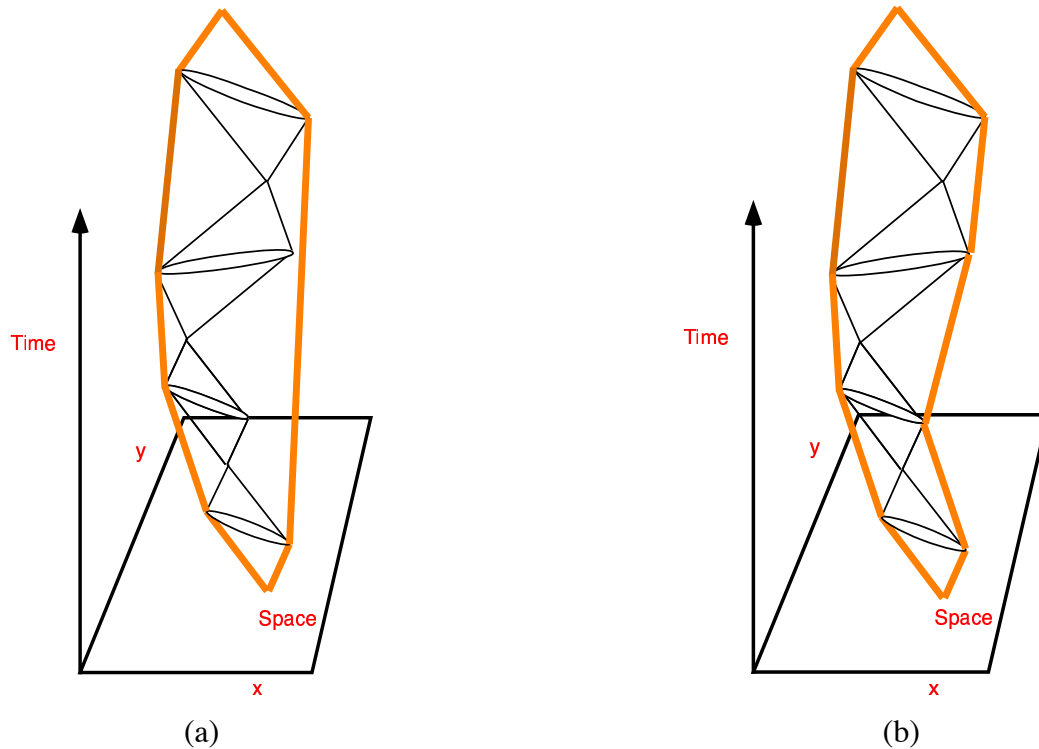


Figure 13: Coarser views of necklaces are obtained through: (a) convex hulls computed from the geometric properties of the necklace and (b) a shape-approximating solution that uses selected rim points from each bead in the necklace.

Coarsening can continue until the approximation is simplified to a skeleton or *trace* of a lifeline (Figure 14a). Similar to a lifeline thread, the semantics associated with a trace are different from those of a bead or necklace as a trace does not capture *all* the possible locations through which an individual may pass. A trace with only a start and end point, is even simpler than a lifeline thread, which can have any number of sample points that are known. The trace can be derived based on the center of the tube or it can be biased towards a side of the tube [28] (Figure 14b).

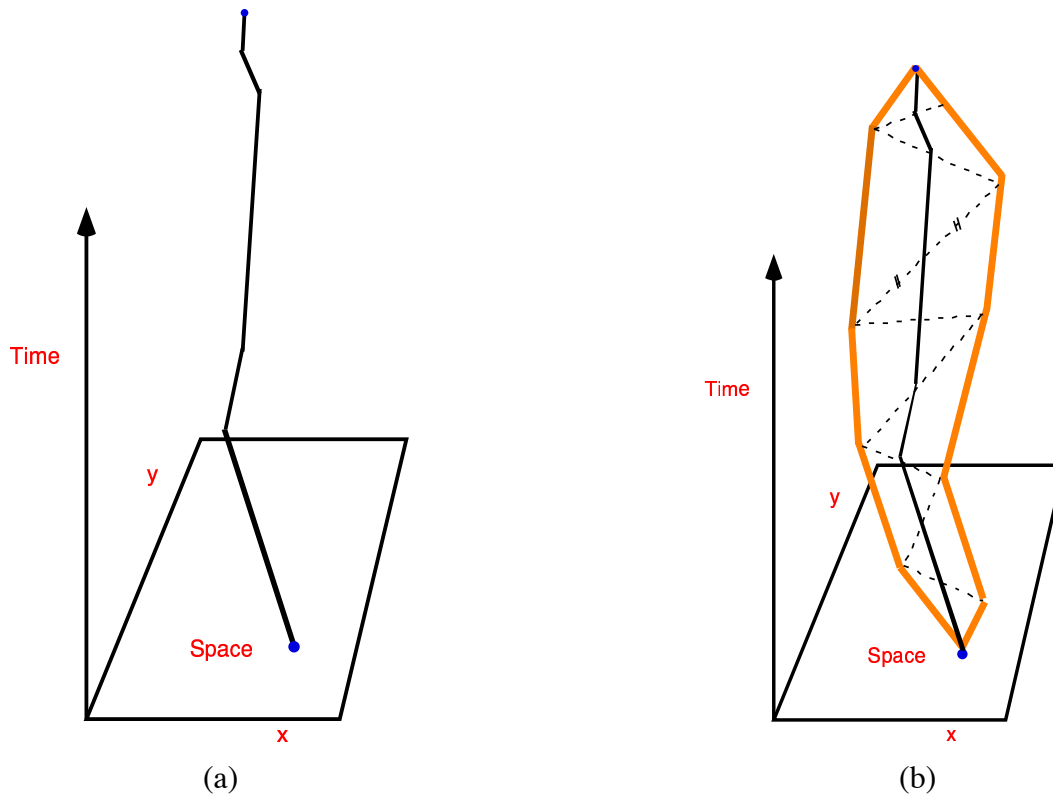


Figure 14: Coarsening granularity can continue until the tubal approximation is: (a) a trace of a lifeline necklace, (b) the trace may be centered or biased towards one side of the tube.

6. Shifting among multiple granularities of lifelines

Modeling movement over multiple granularities causes the view to shift among lifeline beads, necklaces, tubes, threads, and traces (Figure 15). Some of the particular transitions associated with refining or coarsening granularity have been discussed in previous sections, however, additional shifts are also possible. A coarser view of lifeline threads where intermediate space-time samples are abstracted, for example, returns a trace.

Another possible shift is that traces can be refined into beads. This is particularly relevant when testing whether the paths of moving objects have intersected [27]. Intersections are relevant, for instance, for tracking the spread of contagious diseases among people or for testing alibis evaluating whether two individuals could have met or traveled the same route together. If the granularity of modeling movement of two individuals is refined from traces (Figure 16a) to beads (Figure 16b), situations where intersections are possible may become known.

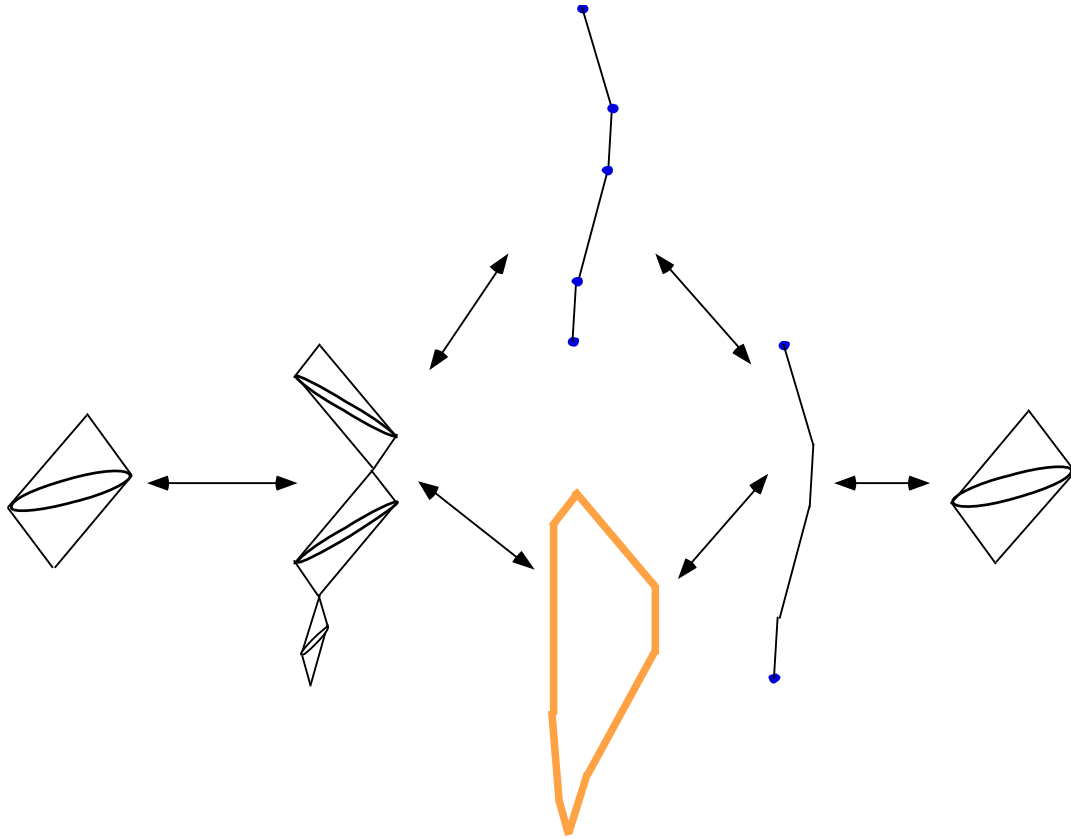


Figure 15: Modeling movement over multiple granularities causes views to shift among lifeline beads, necklaces, tubular approximations, threads, and traces.



Figure 16: Granularity of modeling movement of two individuals is refined from: (a) traces that model the movement to (b) beads.

7. Conclusions

Spatio-temporal knowledge representation often requires shifting among granularities such that users can carry out a desired task. Granularity refers the level of detail at which phenomena is perceived. This paper examines the nature of modeling movement of objects or individuals over multiple granularities. A more detailed perspective reveals information that was not previously known, such as additional locations that an individual visited or multiple visits to the same location. Conversely, moving to a coarser view generalizes spatial and temporal aspects of movement allowing for an improved understanding of movement. In this paper, movement is modeled as views of geospatial lifelines, time-stamped records of the locations that an individual has occupied over a period of time. Depending on the desired granularity, these varying views can be modeled as lifeline threads, beads, necklaces, convex hulls, tubular approximations, or traces.

Refining granularity shifts the view from beads to necklaces, resulting in a more detailed view of movement. Other refinements are possible through transforming traces into threads or tubes, threads into necklaces, or traces into beads. Coarsening granularity shifts the view of movement from the details captured by lifeline necklaces to more general beads or other coarser approximations, such as convex hulls and tubes. Coarsening can continue to form lifeline threads and the most general case of a trace. Coarsening may also occur through selectively omitting beads from a view. This corresponds, for example, to scenarios where short or slow portions of trips are abstracted from a view.

This paper has described some of the interesting aspects relating to granularity of movement modeled as geospatial lifelines. Further work is necessary on operations that move views between different granularities and especially relating to operations that result in coarser granularities of lifelines. Other possibilities are being explored including shifting the view of beads based on start and end *points*, to beads based on start and end *regions* (Figure 17). This captures scenarios such as, *the person traveled from Maine to Massachusetts*, where movement is described between places modeled as regions. Discussions of refinements or coarser views are also very relevant for studies relating to modeling uncertainty of movement. A coarser view, for example, might reflect a higher degree of uncertainty, where finer granularity relates to more precise or certain measurements. Further work is necessary to explore uncertainty as it relates to lifelines and modeling movement.

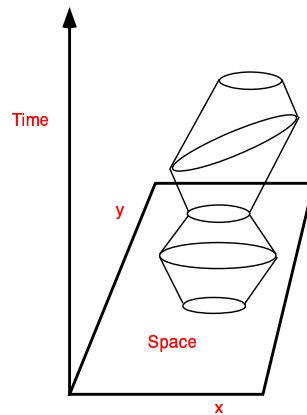


Figure 17: Modeling movement: the start and end of beads in this necklace are modeled as areas or regions rather than points.

8. Acknowledgments

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