Tri-Space:
Conceptualization, Transformation, Visualization

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The tri-space is a concept that has been periodically put forth within geographic information science over the last few decades, under various guises and names (Openshaw 1994; Peuquet 1994; Turton et al. 2000; Yuan 1994). It refers to the conjunction of three spaces: *geographic space*, *time space*, and *attribute space*. These three elements are easily identified in typical spatio-temporal data sets. For example, when such data are distributed in tabular form, we will often come across cases where a single row holds the observations for a particular geographic locus at a particular moment in time and a single column refers to all observations for a particular attribute. In other datasets, one might find rows referring to one attribute at one geographic location, while columns hold all values for a particular time slice. Interestingly, such different logical data structures could express absolutely identical source data, though we are looking at different reexpressions of such source data in the form of differently constructed objects existing in a differently constructed high-dimensional spaces. Take for example a data set consisting of observations for seven crime variables in fifty states captured in forty annual slices. Such a data set would thus consist of 14,000 atomic values. The proposal put forth here is that by interpreting such data within a tri-space based conceptualization we could derive *systematic* reexpressions, without requiring *any* data reduction or aggregation at an early stage of processing.

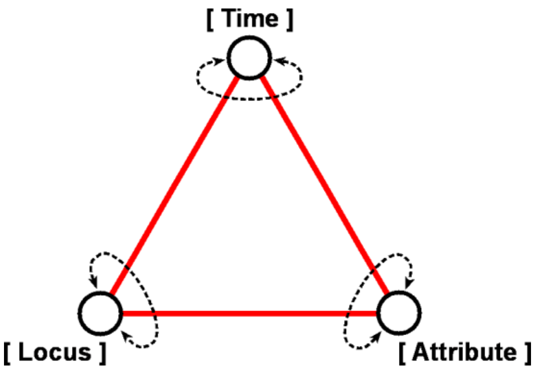

Figure 1. The tri-space formed by loci, attributes, and time.

Specifically, it is proposed that in a given spatio-temporal dataset we first identify the three tri-space elements of (1) locus, (2) attribute, and (3) time, with each being represented by one or more instances (e.g., one particular attribute) in the data set (Figure 1). It is further asserted that there are ***six*** distinct high-dimensional spaces within which such tri-space data can be conceptualized (assuming that no additional data or known relationships are exploited). The *dimensions* of each of those six conceptually constructed spaces derive from either a single tri-space element (e.g., only attribute space) or a combination of two tri-space elements (e.g., attribute space *and* time space). In either case, *objects* occupying that high-dimensional space are formed by the remaining tri-space element[s]. When the tri-space is represented as a triangle (Figure 1), then in any one of the six perspectives the *objects* correspond to either a particular corner or edge and *dimensions* correspond to the opposing edge or corner. Those objects then become the subject of further investigation. Note that internal relationships within each of the three tri-space elements could be exploited as well, such as spatial and temporal topology.

For a first example, consider the conceptualization of a space whose dimensions are defined by combinations of times and attributes and which is occupied by individual loci (Figure 2, top). This will be referred to as the ***L-AT*** perspective. If a tabular format is used, then loci become rows and attribute/time combinations become columns (Figure 2, middle), with l_1 referring to the first of m loci, a_1 to the first of n attributes, t_1 to the first of p time slices, and so forth. The apparent focus on tabular formats in this presentation is not meant to distract from the object-oriented conceptualization underlying the proposed tri-space approach. Instead, it is a reflection of the *typical* data sources and tools encountered by users, with the goal of enabling practical implementation in current systems.

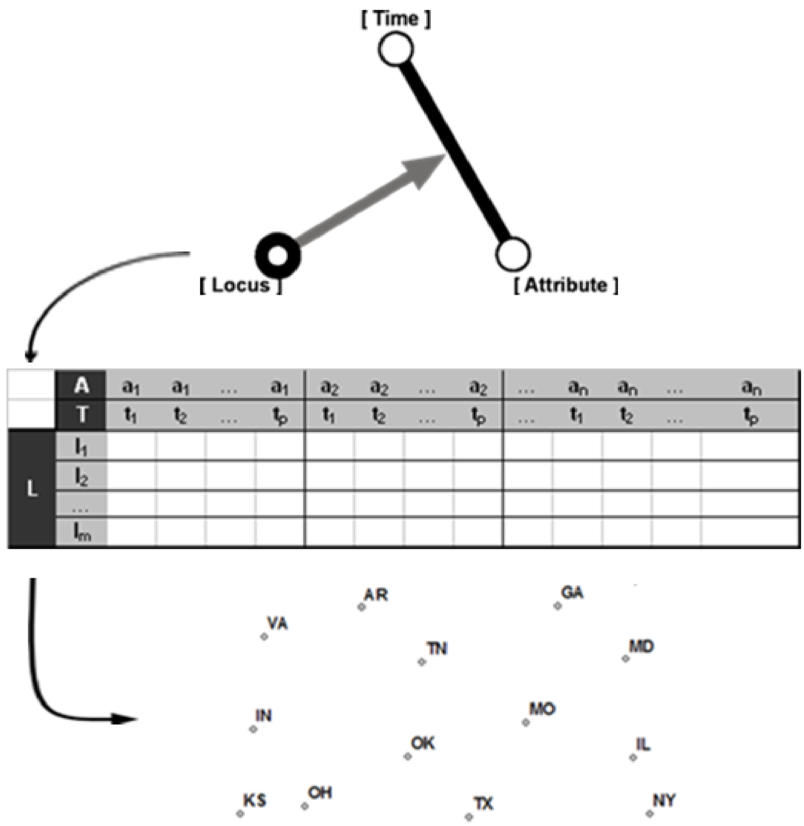

Figure 2. One out of six basic tri-space perspectives on the same multi-temporal, multi-attribute, geographic data set, from initial conceptualization through the corresponding table structure to the eventual spatialization.

Based on the ***L-AT*** perspective, one could ask questions about broad multi-temporal, multi-attribute similarity of geographic loci. A major challenge here is that objects in any tri-space perspective exist in a high-dimensional space that – cognitively – is just difficult to make sense of (Fabrikant and Skupin 2005). One possible approach to investigating such relationships is through spatialization in a two-dimensional display space (Figure 2, bottom). Note that this study by no means implies that such spatialization is absolutely necessary – since other computational approaches could also be applied – or that a particular spatialization method (in this case the self-organizing map) has to be employed. Spatialization is here meant to help us better understand the implications of the different tri-space perspectives.

Consider as an alternative the ***LT-A*** perspective (locus/time combinations as objects, attributes as properties), and how it supports more temporally fine-grained questions about relationships among loci. This is a perspective that – due to the participation of time in defining object identity – allows exploiting the known topology of time, thus leading to locus trajectories (Figure 3), akin to those described by Skupin and Hagelman (2005), albeit now within a more encompassing framework.

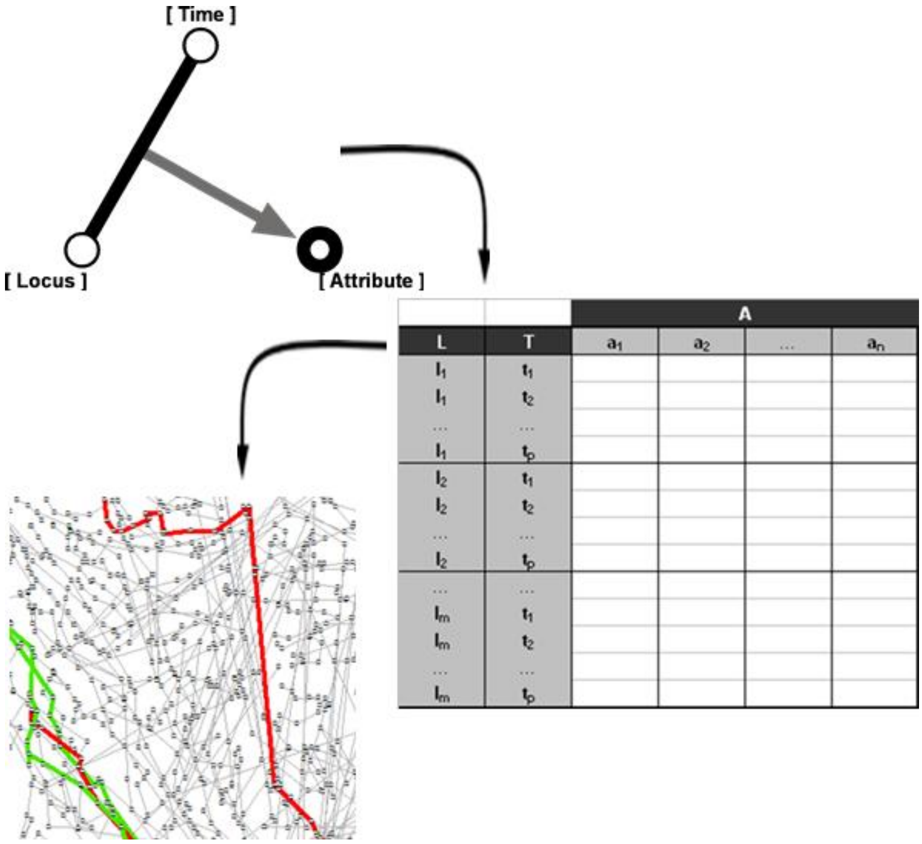

Figure 3. The ***LT-A*** perspective applied to the same dataset, from conceptualization through tabular structure to spatialization, with the time component exploited to generate locus trajectories.

Among the core challenges in *operationalizing* this tri-space approach are: (1) how to transform between tri-space perspectives, (2) how to transform within those perspectives, and (3) how to make use of the conceptualized high-dimensional space, i.e., how to understand it, for which in this study the SOM method is used.

One of the main practical challenges to performing transformations *between* the six perspectives (such as between the three perspectives shown in Figure 4) arises when the data contain missing or incomplete observations. For example, not all loci might have observations for all attributes and all time slices. That is of course common when dealing with multi-temporal geographic data, but it is more disruptive to some tri-space perspectives then to others. Some transformations are also generally much easier to implement than others, such as transposing (e.g., from ***L-AT*** to ***AT-L***) as opposed to breaking up combinations of two tri-space elements (e.g., from ***L-AT*** to ***LT-A***).

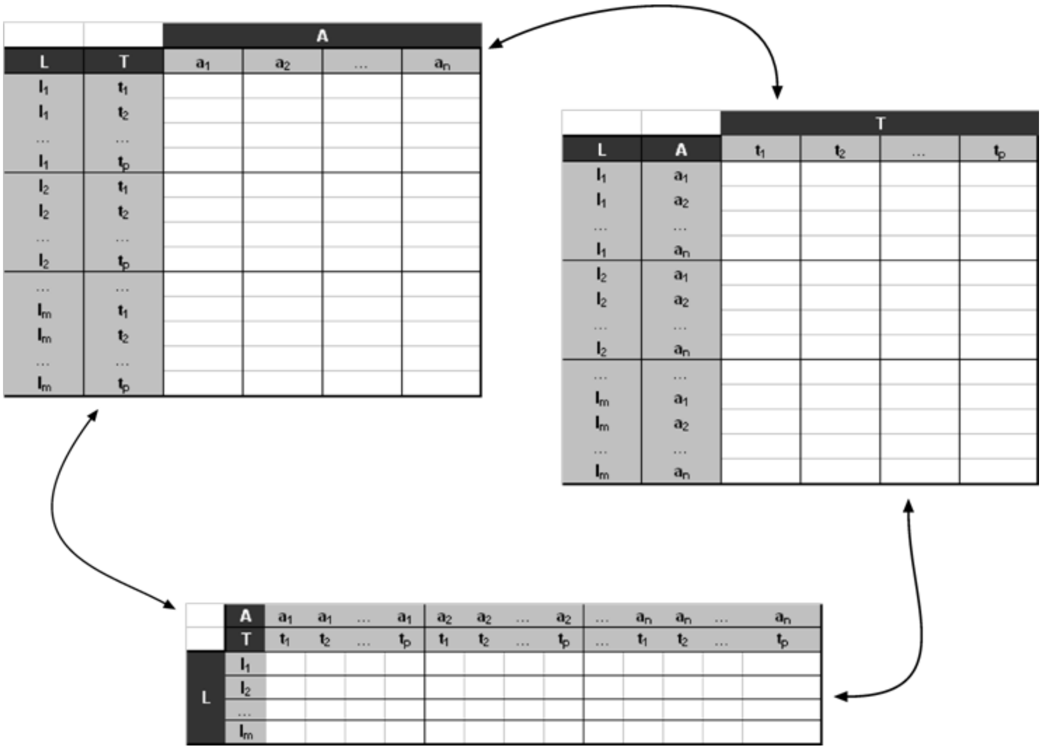

Figure 4. Practical transformations between tri-space perspectives can be challenging, especially in the presence of incomplete data.

Before high-dimensional relationships can be meaningfully analyzed, certain transformations also have to be performed *within* a particular perspective. As a simple example, in the ***LT-A*** perspective (see Figure 3) different attributes should be normalized/weighted before further processing. For a more complex case, consider that one may want to compare loci (i.e., the ***L-AT*** perspective in Figure 2) based on the multi-temporal signatures for particular attributes. That is easiest to accomplish by first generating the ***LA-T*** perspective (see right portion of Figure 4), normalizing across properties of all objects in it and only then converting to ***L-AT***. Again, while we may conceptualize such transformations in an object-oriented or object-relational framework, actual relational systems currently in use are far from providing easy access to this kind of functionality to the user.

In addition to a detailed explanation of the proposed tri-space framework, the oral presentation will present results of several recent studies in which this approach to tri-space conceptualization, transformation, and visualization has been systematically employed. These applications span the gamut of contemporary spatio-temporal data sets, from census-type statistics to ground-based and satellite-based environmental sensors:

(1) annually aggregated crime data for U.S. states for 1960-2000;.
(2) spatially and temporally integrated air pollution data for 204 geographic cells in California for 1988-2002;
(3) satellite-based snow water equivalent data (SWE) for 90,000+ cells in the northern hemisphere, captured in 8-day intervals for 1988-2007.

In addition, the presentation will elaborate on the possible construction of an interface widget for tri-space exploration based on the graphical formalism explicated at the top of Figures 2 and 3. Another aspect to be discussed is the potential for each of the six perspectives to provide sockets allowing multiple tri-spaces to be linked via snap-on connectors. Finally, the applicability of this approach to data sets involving non-geographic loci is discussed, such as in scientometric modelling.

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