

# **Spatio-temporal GIS Design for Exploring Interactions of Human Activities**

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## **Abstract**

Designing a GIS data model that can help analyze spatial and temporal patterns and interactions of human activities presents a challenging research topic. Due to a growing adoption of information and communication technologies (ICTs) in today's society, an increasing number of human activities are performed in the virtual space. This paper presents a spatio-temporal GIS design to support exploratory analysis of interactions among human activities in both physical and virtual spaces. The conceptual framework extends the space-time path concept of Hägerstrand's time geography to represent both physical and virtual activities. Linear referencing and dynamic segmentation are employed in the design to dynamically locate physical and virtual activities on space-time paths. The system design also supports analysis functions to explore four different types of human interactions: co-location in space, co-location in time, co-existence, and no co-location requirement in either space or time. A prototype system based on a sample data set is implemented as a 3D GIS (i.e., 2D space + 1D time) in the ArcGIS environment. This paper demonstrates the feasibility and potential of applying temporal GIS concepts to extend Hagerstrand's time-geographic framework for representation and analysis of human interactions in both physical and virtual spaces. The proposed GIS framework can be useful in applications such as location-based services (LBS), modeling spread of infectious diseases, and tracking terrorist activities.

## **1. Introduction**

Participating in activities and interacting with other people are important components of an individual's life. The spatial and temporal aspects of human activities and interactions are key factors for understanding many phenomena at different scales in our society, such as daily peak-hour traffic congestion, the process of a rumor distributed among the public, and the formation of urban landscape. A better understanding on spatial and temporal characteristics of human activities and interactions can provide a clearer view of human behavior at an individual level and offer an assistance in exploring aggregate phenomena associated with human activities.

Human activities and interactions are predominately performed in physical space, with physical presence or contact of the participants. Recent development in information and communication technologies (ICTs, such as cellular phones and the Internet) and their quick adoption by the society are making significant changes to the ways that people conduct their activities and interact with each other. ICTs, which offer a new environment for people to exchange information and communicate with each other, have undoubtedly changed the traditional role of physical space for conducting human activities. Use of ICTs frees up certain human activities and interactions from various spatial and temporal constraints. The freedom and flexibility gained from the use of ICTs have important implications to spatial and temporal aspects of human activities.

In order to help analyze the spatial and temporal characteristics of human activities and interactions, some researchers used GIS as a platform to represent and explore travel and activity data (e.g., Shaw and Wang, 2000; Wang and Cheng, 2001; Frihida, Marceau, and Thériault, 2002). Although these attempts demonstrated that GIS could be useful to organize individual travel and activity data and to support the exploration of human activities, they focused on human activities in physical space only. Kwan (2000a) attempted to visualize both physical and virtual activities of an individual in a multi-scaled GIS environment. However, a GIS design that can efficiently organize human activity data to help analyze interactions of human activities in both physical and virtual spaces is an ongoing research topic. This paper presents a design of GIS framework to support the exploration of spatio-temporal characteristics of human activities and interactions in both physical and virtual spaces. Space-time path concept of an extended time-geographic framework is used for the organization and visualization of human activities within a GIS environment. Exploratory analysis functions are also developed under the extended time-geographic framework for investigating spatial and temporal patterns of human interactions.

This paper is organized into five sections. The next section discusses the research background and theoretical issues involved in this study. Section 3 presents the design of a GIS framework for data representation and spatio-temporal analysis of activities and interactions. Section 4 shows a prototype system implementation based on the proposed framework and a sample data set. Analysis functions and user interfaces of the prototype system are presented in this section. This paper concludes with a discussion of potential applications of the system and future improvements.

## **2. Human activity and human interaction**

Human activities are performed within a spatial and temporal context (Golledge and Stimson, 1997). As activities are often distributed at different locations across the space, an individual has to trade time for space so that he/she can participate in various activities (Hanson, 1995). Travel is a traditional means for people to trade time for space, which means traveling across the space takes time (Miller and Shaw, 2001). As time is a scarce resource, the capability of a person to participate in activities is constrained by the time availability and the distance between the person and the activity location. Hägerstrand (1970) proposed a theoretical framework to study the constraints that affect an individual's presence in space and time and to portray individual activities in a space-time context, which is known as Time Geography. The framework was adopted and developed by other scholars to study individual human activity and behavior (Carlstein, Parkes, and Thrift, 1978; Carlstein, 1982; Golledge and Stimson, 1997).

Time geography considers time as an equal term as space in the study of human activities. Treating time as the third dimension in addition to a 2-dimensional space, the framework adopts a 3-dimensional orthogonal coordinate system to portray spatio-temporal aspects of human activities. The 2-dimensional space is used to measure the location changes of objects, while the time dimension is used to order the sequence of events and to synchronize human activities. Three fundamental concepts, which are space-time path, space-time prism, and potential path area, are suggested under the time geographic framework to depict the capability of an individual to conduct activities in space and time. A *space-time path* is the trajectory of an individual's

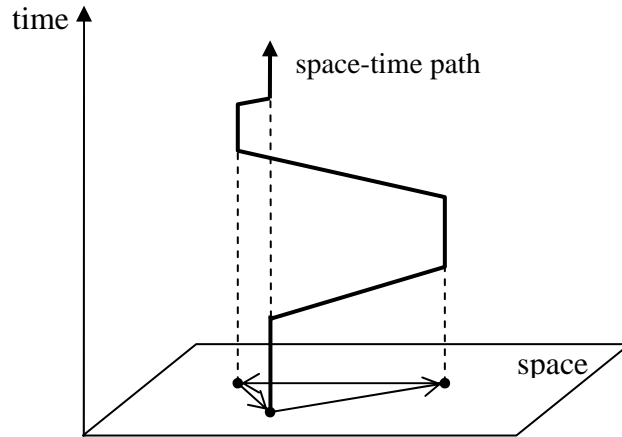


Figure 1. Space-time path of the time geography

movements in physical space over time (Figure 1). A space-time path provides detailed information about spatial and temporal characteristics of an individual, including starting/ending time and place of an activity, sequential order of events, and relative location of events that occurred in its lifespan. Therefore, the spatial and temporal characteristics of an individual's movements are integrated under the concept of space-time path (Miller, 2004). Transportation is often employed as a means to trade time for space since movements in physical space take time. Given a location and a time period, an individual can stay at the given location for the entire time duration. If the person wants to move to a new location, it will take time to make the physical movement and time available for activities at the new location is shortened accordingly. The possible locations that a person can travel within a given time duration forms a continuous space in the orthogonal space-time coordinate system, which is called *space-time prism* (Lenntorp, 1976). When a space-time prism is projected onto a two-dimensional space, the result is a region that is known as a *potential path area*. Figure 2 shows a space-time prism and its corresponding potential path area. While a space-time path is usually used to represent the historical movements of a person, space-time prism and potential path area portray possible accessible space and region under a certain set of constraints.

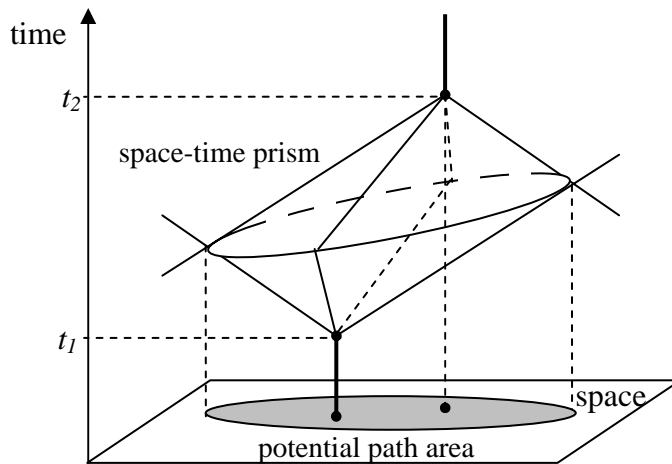


Figure 2. Space-time prism and potential path area

Physical space is the conventional stage for performance of human activities. Before the wide adoption of ICTs, most human activities and interactions were performed in physical space, which often require physical presence or physical contacts of the participants. In this case, the location and time of a person's presence are closely related to the type of activity that the person participates in (Couclelis and Getis, 2000). The space-time path therefore gives a good representation of the person's activities and their location changes in physical space over time. However, this relationship is broken when ICTs, such as cellular phones and the Internet, are used to carry out certain activities. ICTs enable a new environment for people to perform activities and interactions. This new environment allows people to carry out certain activities without a physical presence and is called virtual space in this paper. Use of ICTs frees up some human activities from certain constraints in the physical space. A person can use ICTs to participate in an activity or interact with other people without physically moving to a specific location. For example, a telecommuter can work from home rather than in the office. Managers of an international company can hold a videoconference while they are located across the globe. As a result, space-time path is no longer sufficient to depict the complete spatial and temporal relationships of activities and interactions conducted by an individual. This suggests a need of re-thinking the time-geographic framework in order to accommodate human activities and interactions in both physical and virtual spaces.

Adams (1995, 2000) suggested the limitations of using space-time paths to represent human activities as they restrict the scope of activities to the physical proximity of people's movements. Considering people as social agents and sensate beings, he argued that agency and sensation of people could be stretched out over space with the help of ICTs. Six social scales were categorized in Adams' study to depict the spatial scopes involved in people's activity, ranging from proximate of a space-time path up to the international level. Only the proximate level is represented with explicit locations while all other five scales are only categories without explicit spatial representations. He used CAD-based diagrams to represent activities of people, graphing over distance sensations depicted as extended bars from space-time paths (Adams, 2000). Using a similar extensible agent concept, Kwan (2000a) displayed a person's daily activities, including physical and virtual activities, in a multi-scale GIS environment with links extending out from a space-time path to represent virtual activities of a person. Our study adopts the extensible agent concept and Hägerstrand's space-time path concept to develop an extended space-time path representation for human activities in both physical and virtual spaces. A space-time path is the container of all activities performed by a person, since all activities take place at certain locations and time periods and each of them occupies a portion of the space-time path. For virtual activities, they can only take place at ICT-enabled locations, such as at an Internet Café or within a cellular phone service area. The difference between physical activities and virtual activities is that they take place at different action space. While physical activities impact only the physical proximity of a space-time path, virtual activities can extend to distant locations. Figure 3 shows the conceptual representation of an extended space-time path. The symbols for activities of instant messaging (b) and e-mail (e) in Figure 3 represent virtual activities. As some virtual activities may experience delays in time, extended links may not always be horizontal but tilted as the one for e-mail activity (e) shown in the figure.

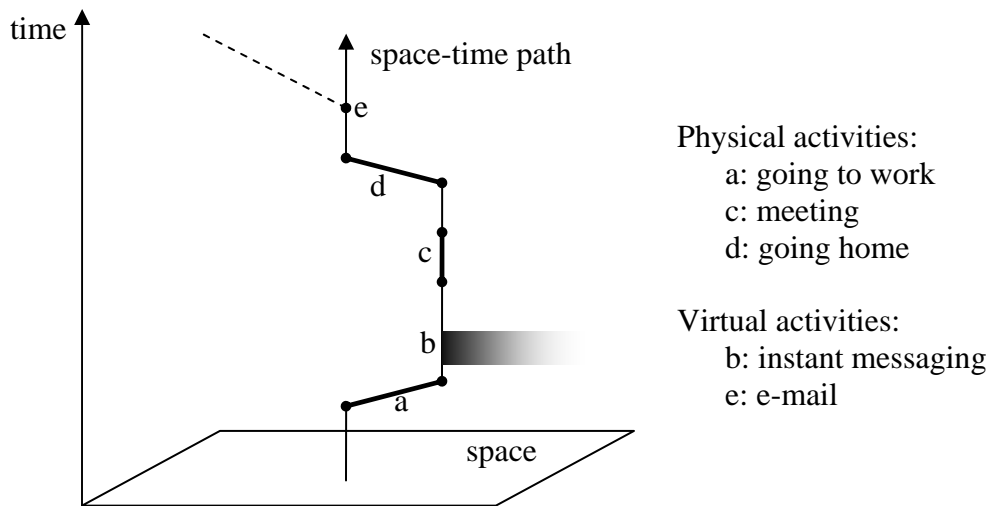


Figure 3. An extended space-time path representation for both physical and virtual activities

The extensibility and flexibility enabled by ICTs provides additional ways for people to interact with each other. People now can interact with others using cellular phones or the Internet that have fewer constraints on space and time. Four types of communication modes have been suggested in the literature according to their spatial and temporal requirements (Table 1; also see Janelle, 1995; Harvey and Macnab, 2000; Miller, 2003). Conventional face-to-face meetings require participants to be at the same location during the same time period. Communication mode requiring coincidence in both space and time is classified as *Synchronous Presence* (SP). Post-it notes or bulletin boards must have people visit the same location, but can be at different time, to complete the information change. This type of communications requiring coincidence in space, but not in time, is called *Asynchronous Presence* (AP). With the use of ICTs, people are no longer required to be present at the same physical location for communications. *Synchronous Telepresence* (ST) only requires coincidence in time (e.g., two friends at different locations doing instant messages over the Internet). Finally, *Asynchronous Telepresence* (AT) is free from coincidence requirements in either space or time. E-mail between people belongs to this type of communications. This classification system can be used to describe different types of human interactions based on their spatial and temporal requirements. The SP and AP types of human interactions are carried out in physical space and they are the predominant modes for people to interact with each other before the wide adoption of ICTs. ST and AT interactions are made possible due to ICTs. As alternatives to the SP and AP interactions, the ST and AT interactions are changing the ways people interact with each other and altering the spatio-temporal activity patterns.

Table 1. Communication modes based on their spatial and temporal constraints.  
(Source: Miller, 2003)

<b>Spatial</b> \ <b>Temporal</b>	<b>Physical presence</b>	<b>Telepresence</b>
<b>Synchronous</b>	<b>SP</b> Face to face (F2F)	<b>ST</b> Telephone Chat rooms Teleconferencing
<b>Asynchronous</b>	<b>AP</b> Post-it® notes Traditional hospital charts	<b>AT</b> Mail E-mail Web pages

When the four types of human interactions are represented with the extended space-time paths discussed earlier, different patterns can be recognized according to their spatio-temporal relationships. As the SP interaction normally involves physical activities, it can be represented through the physical proximity of participants' space-time paths. The requirements for participants to be at the same location ( $L$ ) during the same time period (from  $T_1$  to  $T_2$ ) result in overlapping segments of space-time paths and create a *co-existence* relationship as shown in Figure 4(a). The AP interaction is represented by sequential visits of different participants at the same location ( $L$ ) as shown in Figure 4(b). Each space-time path has a segment sharing the same location ( $L$ ) within different time periods. This leads to a *co-location in space* relationship. As both the ST and AT interactions involve virtual activities, extended space-time paths are needed to represent their relationships. The ST interaction, such as a phone call or instant messaging, involves participants at different locations interacting with each other using ICTs in the virtual space. This creates a *co-location in time* relationship of participants' space-time paths and is displayed in Figure 4(c). The block between the space-time paths represents the interaction between the participants across the virtual space and the horizontal lines indicate the synchronization in time (from  $T_1$  to  $T_2$ ). The AT interaction further removes the requirement on time synchronization. A person can initiate a communication from location  $L_1$  at time  $T_1$ , while the receiver can pick up the communication at location  $L_2$  at time  $T_2$ . This type of interactions is represented by a tilted link connecting specific positions on the space-time paths. This shows a relationship of *no co-location in either space or time* as portrayed in Figure 4(d). As each interaction type is represented by a different kind of relationship between space-time paths, these interaction types can be used to explore spatio-temporal relationships of human activities and interactions.

### 3. Spatio-temporal GIS design for visualizing and exploring interactions of human activities

GIS have been used for the organization of human activity data, especially activity/travel diary data, and for the exploration of their spatio-temporal characteristics. Using a path-based representation of trips, Shaw and Wang (2000) organized individual travel activities with their spatial, temporal, and event attributes in a relational GIS environment. Wang and Cheng (2001) conceptualized human activity patterns as a sequence of stays and movements between different

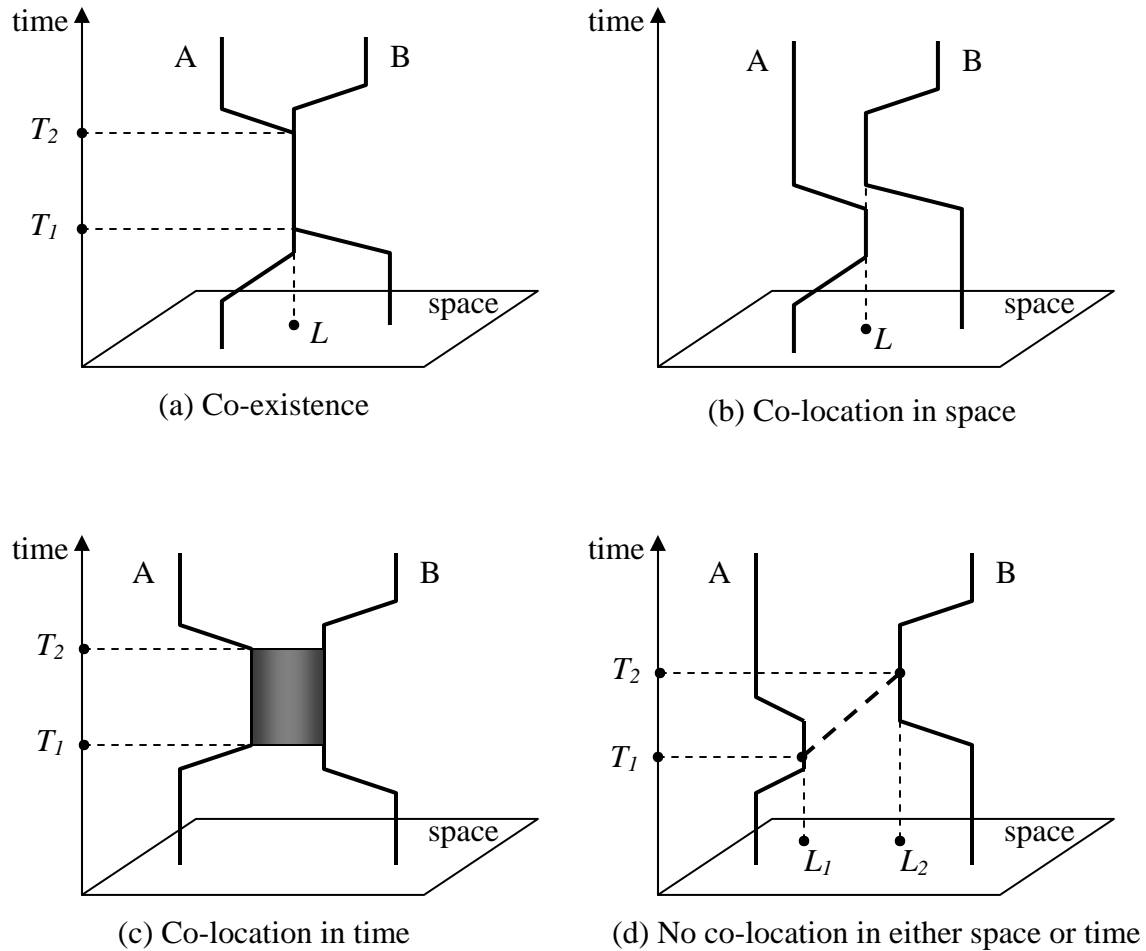


Figure 4. Spatio-temporal relationships of human activities

locations and organized the activity/travel data in a GIS environment to support spatio-temporal queries. Adopting an object-oriented approach, Frihida *et al.* (2002) presented a spatio-temporal data model and implemented it with an object-oriented GIS shell to support navigation and representation of individual travel behavior over space and time. Although these studies suggested different approaches to organize activity/travel data, they did not address the continuous representation of various activities/trips performed by an individual and interactions between activities performed by different individuals. Kwan (2000a, 2000b) demonstrated the advantages of using space-time path representation to visualize individual activities in a GIS environment. This paper builds on the previous studies and extends the space-time path framework to support representation, visualization, and analysis of activities and interactions in both physical and virtual spaces.

### 3.1 GIS representation of space-time paths: spatio-temporal line features

Conventional GIS are designed for representation of static spatial features based on a cartographic approach (Spaccapietra, 2001; Peuquet, 2002). Current GIS therefore fall short of

representing time as an endogenous dimension and cannot support the representation of space-time paths. A new GIS framework is needed to accommodate space-time paths and support integrated spatio-temporal analysis. Based on Hägerstrand's time geography, a 3D (i.e., 2D space + 1D time) GIS environment is developed in this study. We call features in this 3D framework *spatio-temporal features*. The coordinates of a spatio-temporal point feature are represented as a triplet  $\{<x, y, t>\}$ , while a spatio-temporal line feature is composed of a sequence of triplets  $\{<x_0, y_0, t_0>, <x_1, y_1, t_1>, \dots, <x_n, y_n, t_n>\}$ , where  $t_0 < t_1 < \dots < t_n$ . A space-time path consequently can be represented as a spatio-temporal line feature in this 3D GIS framework (Figure 5).

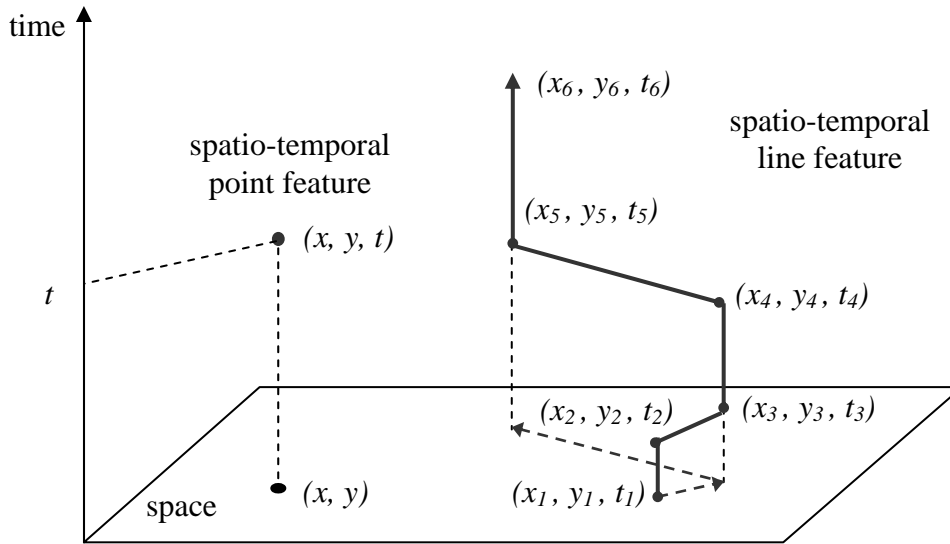


Figure 5. Spatio-temporal features in a 3D GIS framework

### 3.2 GIS representation of human activities on space-time paths: spatio-temporal linear referencing and dynamic segmentation

The trajectory of an individual's movements in the physical space over time forms a continuous trace. A space-time path offers a proper continuous representation of such a trajectory. Human activities are episodes with starting and ending times. Both physical activities and virtual activities performed by individuals leave traces in the physical space and time, which become contents of space-time paths. An individual's trajectory may pass through a location in the 2D space multiple times. When a space-time path is used to store the trajectory, every point on the space-time path possesses unique coordinates of  $(x, y, t)$  since a person only can be at a single physical location at any given time. Due to the exclusive property of human's presence in physical space and the monotonic flow of time in one direction, time can be used as a linear referencing system to measure locations and store attributes along spatio-temporal line features. Therefore, linear referencing and dynamic segmentation concepts can be applied to space-time paths to locate human activities. Each activity can be referenced to a single time point or to a time period along a space-time path (Figure 6). With the use of temporal dynamic segmentation approach, activities can be dynamically located on an individual's space-time path as either a spatio-temporal point feature or a spatio-temporal line feature. Since people could conduct

multiple tasks during the same time period, especially for virtual activities, we allow activities to overlap on segments along a space-time path. For example, activity d (driving home) and activity e (receiving phone call) in Figure 6 indicate that these two activities overlap in both space and time.

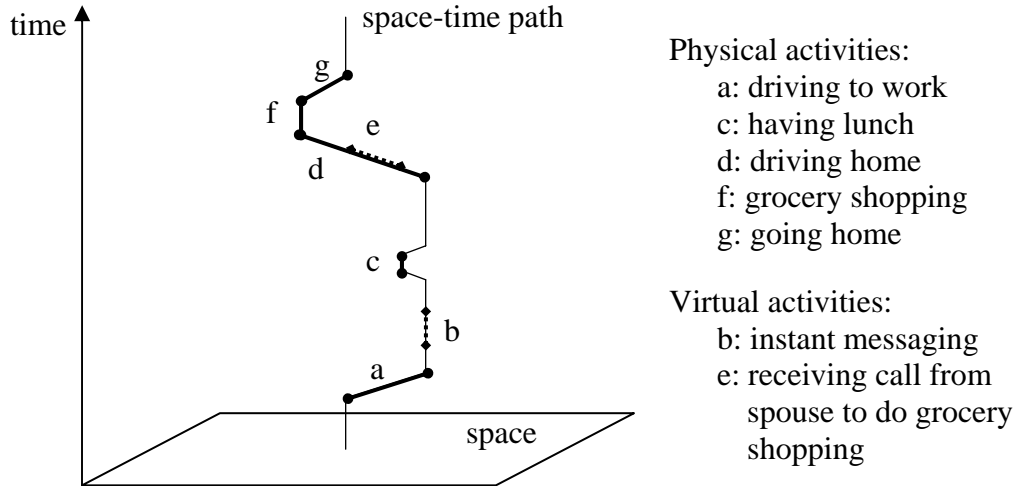


Figure 6. Locate individual activities on a space-time path using spatio-temporal dynamic segmentation

### 3.3 GIS representation and visualization of four modes of human interactions

Using space-time paths, spatio-temporal linear referencing, and dynamic segmentation functions, individual activities can be easily represented and visualized in a GIS environment. However, representation of interactions of human activities presents a more challenging task. An *activity* usually involves multiple individuals who interact with each other. Depending on the interaction method, an activity can be classified into one of the four modes discussed in section 2. In order to distinguish between “an activity involving multiple individuals” and “an activity carried out by a single individual to participate in an interaction”, we call the latter an *event*. Therefore, an activity is composed of multiple events performed by its participants. As indicated by the four modes, interactions among people have various spatio-temporal patterns and the events of participants for the same activity may have different spatial and temporal characteristics. It would be very difficult to organize human interactions through spatial and temporal aspects. However, despite of the variety of spatio-temporal patterns of interactions, each activity is associated with the relevant events which are performed by the participants and share the same thematic content. Therefore, interactions can be represented through activities and related events that are recorded along space-time paths (Figure 7). An activity may involve multiple individuals, who participate in the interaction through their corresponding events. A one-to-many relationship exists between activity and event objects. The spatial temporal information of the events can be retrieved from the space-time paths using temporal linear referencing and dynamic segmentation methods. These relationships are used to represent the interactions of human activities and to visualize their relationships in a GIS environment.

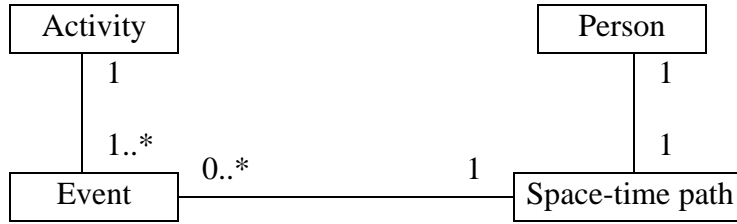


Figure 7. Organization of human interactions

### 3.4 Exploratory analysis functions for spatio-temporal relationship of human interactions

Interactions can be represented as spatio-temporal relationships between events performed by different individuals. Some interactions are initiated by the participants (e.g., a face-to-face meeting), while other interactions may involve involuntary participants (e.g., traffic congestion). In order to separate these two different types of interactions, the former type of interactions is called *planned interaction* and the latter is called *involuntary interaction* in this paper. Normally, a planned interaction involves well-defined activity content and clearly identified and anticipated participants while each of them may participate in the interaction with particular spatial and temporal characteristics. Therefore, this type of interactions can be represented effectively through the relationship class representation method mentioned in section 3.3. An involuntary interaction involves participants who may not intend to participate in the interaction or even be aware of their participation. For this type of interactions, it is difficult to clearly identify all the participants and organize them using the relationship class representation method. In such circumstances, instead of thematic connections among events of individuals, their spatio-temporal relationship stands out to be the key to organize involuntary interactions. As discussed in section 2, human interactions can be classified into four types according to their spatio-temporal characteristics, which are SP, AP, ST, and AT. With the space-time path representation of human activities, these interaction modes have special representation patterns with space-time paths, which are identified as relationships of co-existence, co-location in space, co-location in time, and no co-location in either space and time. Since these spatio-temporal relationships are necessary conditions for conducting the four interaction modes respectively, they can be used for exploring spatial and temporal aspects of human interactions, especially involuntary ones. By identifying spatio-temporal relationships of events of individual activities, researchers will have the opportunity to reveal the hidden and possible interactions among people.

The extended space-time path representation of human activities in GIS can be an effectively form for the employment of exploratory analysis functions for the investigation of spatio-temporal relationships of human interactions. As space-time paths are line features with integrated representation of space and time, traditional spatial analysis functions applied for line features can be extended and employed on space-time paths for spatio-temporal analyses. Co-existence relationship can be identified by checking whether space-time paths overlap with each other. Co-location in space relationship can be identified by examining whether space-time paths pass through the same location. As both co-location in time and no co-location in either space or time deal with virtual activities, besides the spatio-temporal requirements, all participants have to present at ICTs-enabled physical locations for the access to the virtual space. Therefore, co-location in time relationship can be determined by applying spatio-temporal dynamic

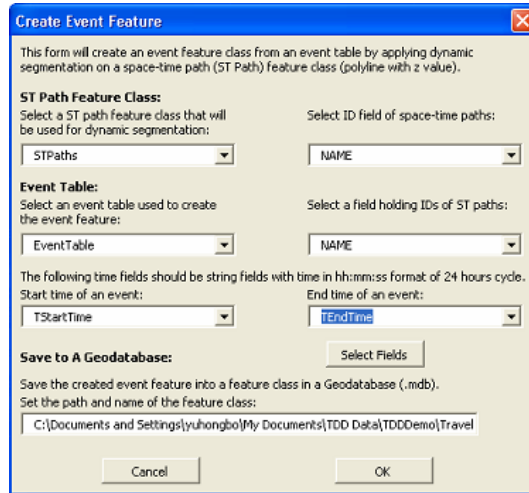
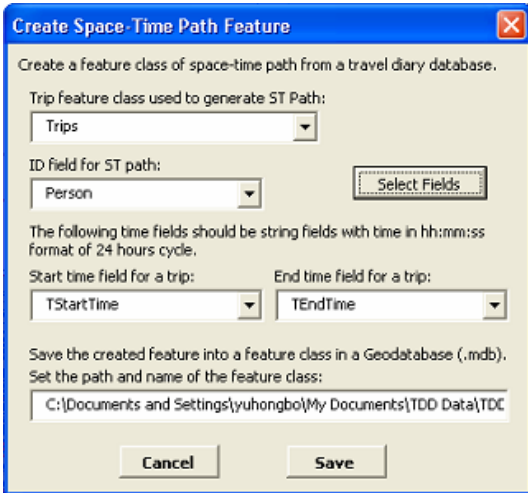
segmentation on space-time paths and checking whether the segments are ICTs-enabled. Finally, segments on the space-time paths that are located at ICTs-enabled locations but do not share the same time indicate a possible no co-location in either space or time relationship. These exploratory analysis functions for spatio-temporal relationships can help researchers investigate relationships among human activities and discover unrevealed patterns of human interactions.

#### **4. Implementation of the design with ArcGIS**

The theoretical framework and spatio-temporal GIS design are implemented in the 3D GIS environment of ESRI's ArcGIS. As the 3D (i.e., 2D space + 1D time) structure in the framework is similar to the 3D Cartesian coordinate system used in ArcScene, the 3D viewer of ArcGIS, it is used for the visualization of space-time paths and the analysis of spatio-temporal relationships of human interactions. The  $z$  value in ArcScene is used as the time dimension instead of the third dimension of space. Customized Visual Basic for Applications (VBA) code with ArcObjects is involved in the system implementation for the creation of user interfaces and functions. A sample data set is used to build a prototype system. The data set contains 77 individual activities, with both physical and virtual activities, of ten individuals within a day in Knox county of Tennessee. The interactions among these ten individuals include all four modes of interactions. The prototype system can support generation of spatio-temporal features, such as creating space-time paths from travel diary data and individual human activities through temporal dynamic segmentation, visualization of spatio-temporal features and their interactions, and exploration of spatio-temporal relationships of space-time paths.

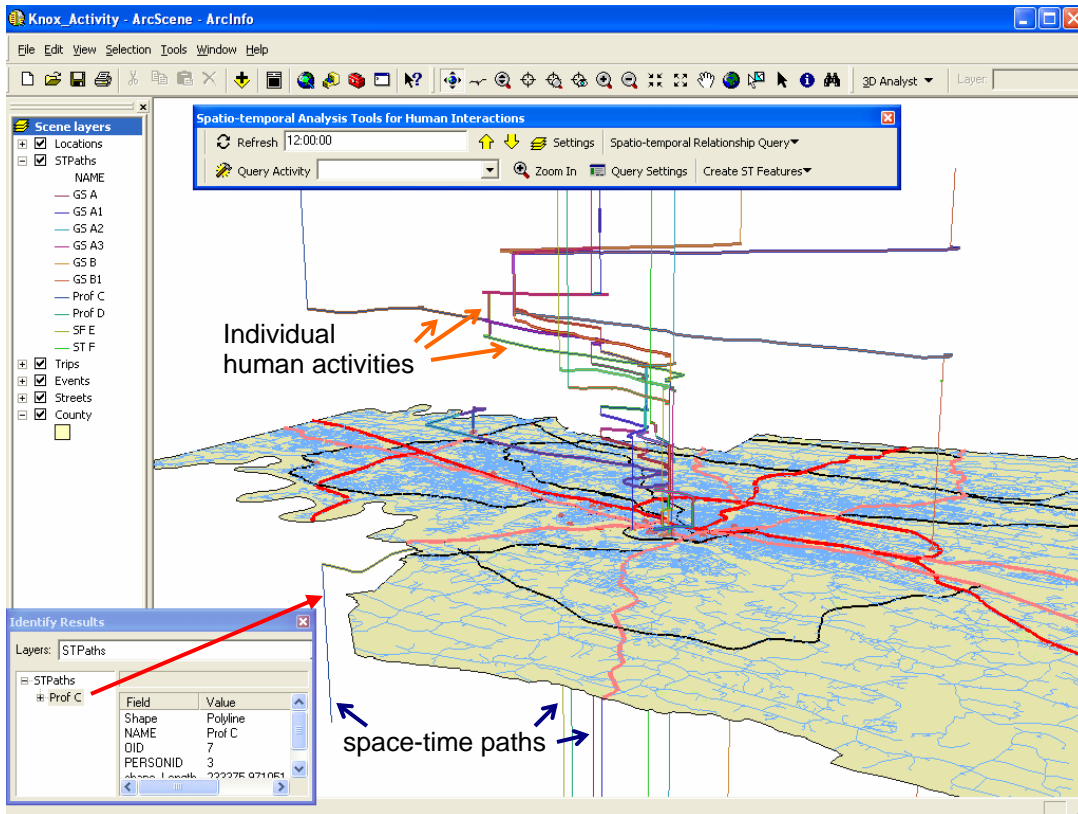
##### **4.1 Creating and visualizing space-time paths and individual human activities**

A space-time path depicts the physical movements of an individual. It is composed of a sequence of stays and movements between locations (Wang and Cheng, 2001). The trips made by a person form a chain, which means, for the same person, the starting location of a next trip is the ending location of the previous trip. Therefore, a complete record of trips made by a person can be used to generate the space-time path for the person. In the prototype system, a function is created to generate space-time paths from travel diary data. The travel activities of the same person are selected from the collection of all individual activities and sorted by time. Later on, the trips are connected according to their time sequence with extra lines linking the ending nodes of previous trips with the starting nodes of following trips, which represent the stays between two travels. The resulted single line then is raised along the  $z$  dimension, which indicates the time, to form a space-time path. A function is also created to implement temporal dynamic segmentation for locating individual activities on space-time paths. Given the starting and ending time stamps of an activity and its corresponding space-time path, the function can locate its position on the path and create a spatio-temporal segment for the activity. Through default and customized user interfaces, users can interactively visualize spatio-temporal features, space-time paths and space-time segments of individual activities, in ArcScene. Figure 8 shows the interface of functions for the creation of space-time paths and spatio-temporal segments of human activities and the visualization of spatio-temporal features in ArcScene.



(a) The interface for creating space-time paths from travel data

(b) The interface for creating individual human activities



(c) Visualization of space-time paths and human activities

Figure 8. Representation of space-time paths and human activities in the prototype system

## 4.2 Organizing and visualizing planned human interactions

The interactions of planned human activities are organized with relationship class in the prototype system. An activity table contains all the activity themes conducted by the individuals in the data set. Each activity is identified by a unique activity ID. All the individual human activities, which are known as events in the framework, are stored in an event table, with corresponding activity ID for each record in the table. As shown by the red boxes and the link in Figure 9(a) and 9(b), the activities and events are connected through the activity ID. An activity may have several events from different individuals involved. When users query an activity, events from participants associated with the activity are highlighted on the screen. Therefore, users can visualize the spatial and temporal positions of each event and spatio-temporal pattern of the activity. The four screen captures in Figure 9(c) shows how the four different human interaction modes conducted by the individuals in the data set are visualized in the prototype system.

## 4.3 Exploring spatio-temporal relationships of space-time paths

In the prototype system, three spatio-temporal analysis functions are created using customized VBA code with ArcObjects, which can help investigate the co-existence, co-location in space, and co-location in time relationships. Given a person and the space-time path, the co-existence analysis function can find out who has stayed at the same location during the same time period with the person. The co-location in space function will list all the persons who have visited a given location and when and for how long each person stayed there. The result of both co-existence and co-location in space functions is displayed in an interactive report as displayed in Figure 10(a) and 10(b), in which users can interactively view the result. The co-location in time function in the prototype system will report locations of all the individuals at a given time. The result is also known as a snapshot of individuals' movements in the physical space, which can indicate the spatial distribution of people at the time. The result can be displayed as point graph in the map or be stored as a point feature for further analysis. The red dots in Figure 10(c) represent the physical locations of all ten individual at 8am, with three individuals staying at the campus of the University of Tennessee.

## 5. Conclusions

The spatial and temporal aspects of human interactions are key issues to understand human activity and behavior. Theories have been developed to investigate spatio-temporal characteristics of human activity and interaction. Recent development of ICTs introduces the virtual space to accommodate human activities, which can free up many constraints of human activity in space and time. The growing adoption of ICTs in our society changes the way that people used to interact with others from spatial and temporal aspects. This leads to an even more challenging situation for researchers to understand the spatio-temporal patterns of human activity and interaction. Therefore, a system that can help represent, visualize, and explore spatio-temporal characteristics of human interactions will be a helpful tool to reveal the mechanism of human activity and interaction. In this paper, a spatio-temporal GIS framework cooperating with an extended space-time path concept of Hägerstrand's time geography is developed to assist in the exploration of human interactions. The extended space-time path structure is able to represent

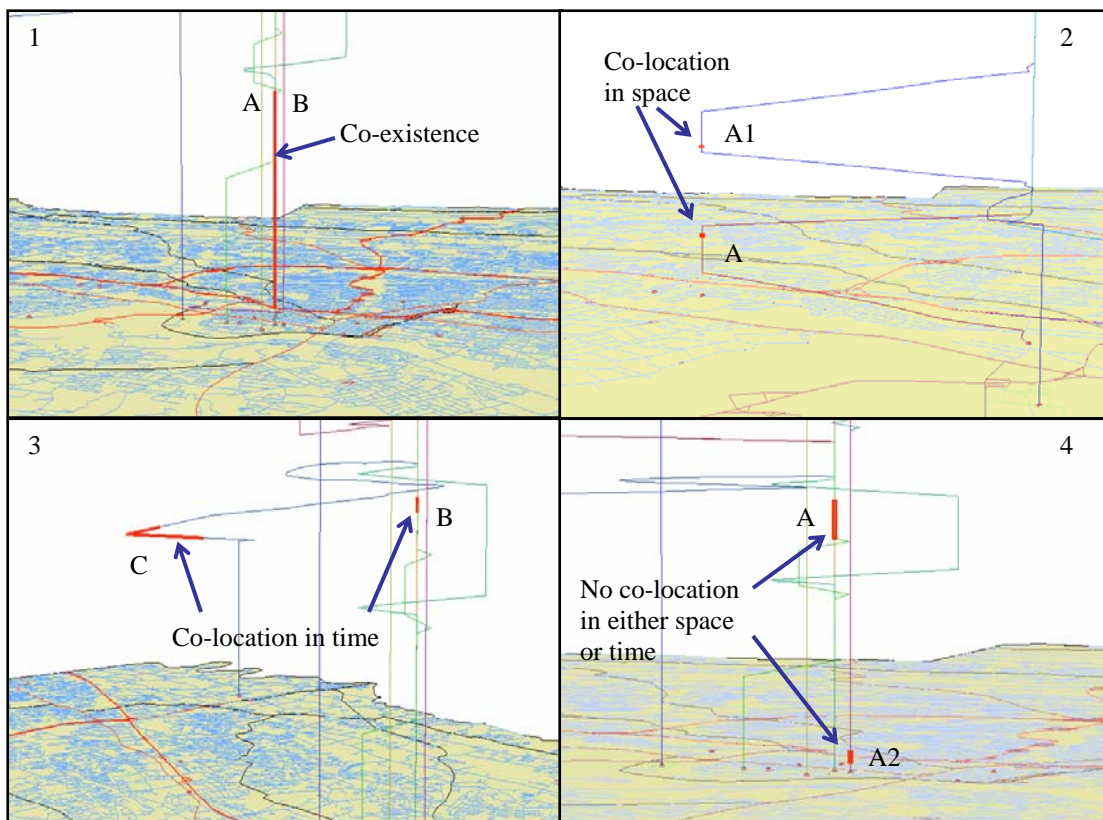
OBJECTID*	ActivityID	Description	Type
17	17	GS B calling GS B1 for dinner	Synchronous Telepresence
46	46	Prof D calling U.T. administration	Synchronous Telepresence
1	1	GS A going to school by bus	Synchronous Presence
2	2	SIS Lab	Synchronous Presence
7	7	Playing tennis (GS A, GS A1, GS A2)	Synchronous Presence
11	11	GS A, GS B, GS B1 having dinner together	Synchronous Presence
16	16	Meeting of Prof C and GS B	Synchronous Presence
32	32	GS A1 and GS A3 carpooling to Wal-Mart	Synchronous Presence
33	33	GS A1 and GS A3 shopping	Synchronous Presence
34	34	GS A1 and GS A3 carpooling back home from Wal-Mart	Synchronous Presence
3	3	Email between GS A and GS A2	Asynchronous Telepresence
9	9	Phone message from GS B to GS A	Asynchronous Telepresence
5	5	Note from GS A to GS A1	Asynchronous Presence

Shape*	OID*	NAME	ActivityID	EventDes	STARTTIME	ENDTIME	STAR
Polyline ZM	1	GS A	1	going to school by bus	08:40:00	09:00:00	Home /
Polyline ZM	42	GS A3	1	going to school by bus	08:38:00	09:00:00	Home /
Polyline ZM	2	GS A	2	teaching Lab at school	09:05:00	12:05:00	Geogre
Polyline ZM	15	GS B	2	teaching Lab at school	09:05:00	12:05:00	Geogre
Polyline ZM	69	ST F	2	having lab	11:10:00	12:00:00	Geogre
Polyline ZM	3	GS A	3	checking email	12:55:00	13:30:00	Geogre
Polyline ZM	50	GS A2	3	sending email to GS A	09:38:00	09:50:00	Engine
Polyline ZM	4	GS A	4	going home by bus	14:20:00	14:40:00	Geogre
Polyline ZM	5	GS A	5	leaving a note for GS A1	14:55:00	14:57:00	Home /
Polyline ZM	33	GS A1	5	getting the note from GS A	15:33:00	15:34:00	Home /
Polyline ZM	6	GS A	6	driving to tennis court	15:00:00	15:12:00	Home /

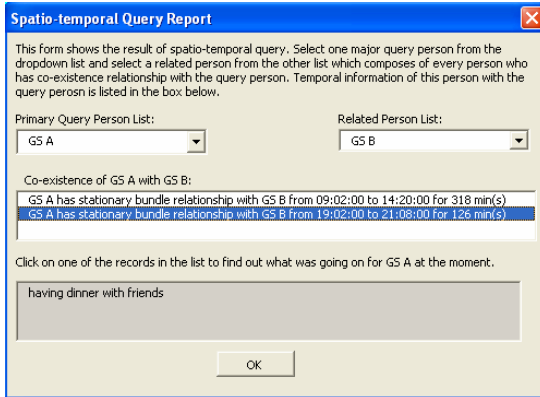
(a) Activity table

(b) Event table with individual activities

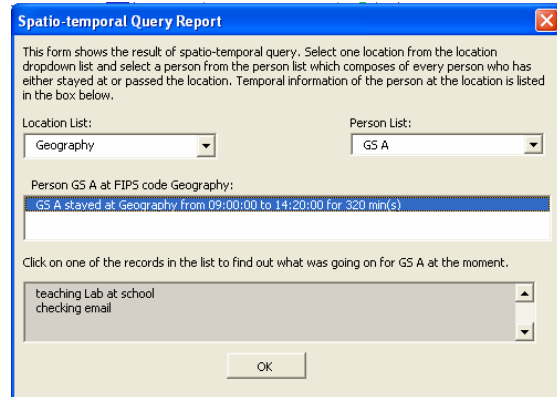


(c) Visualization of human interactions

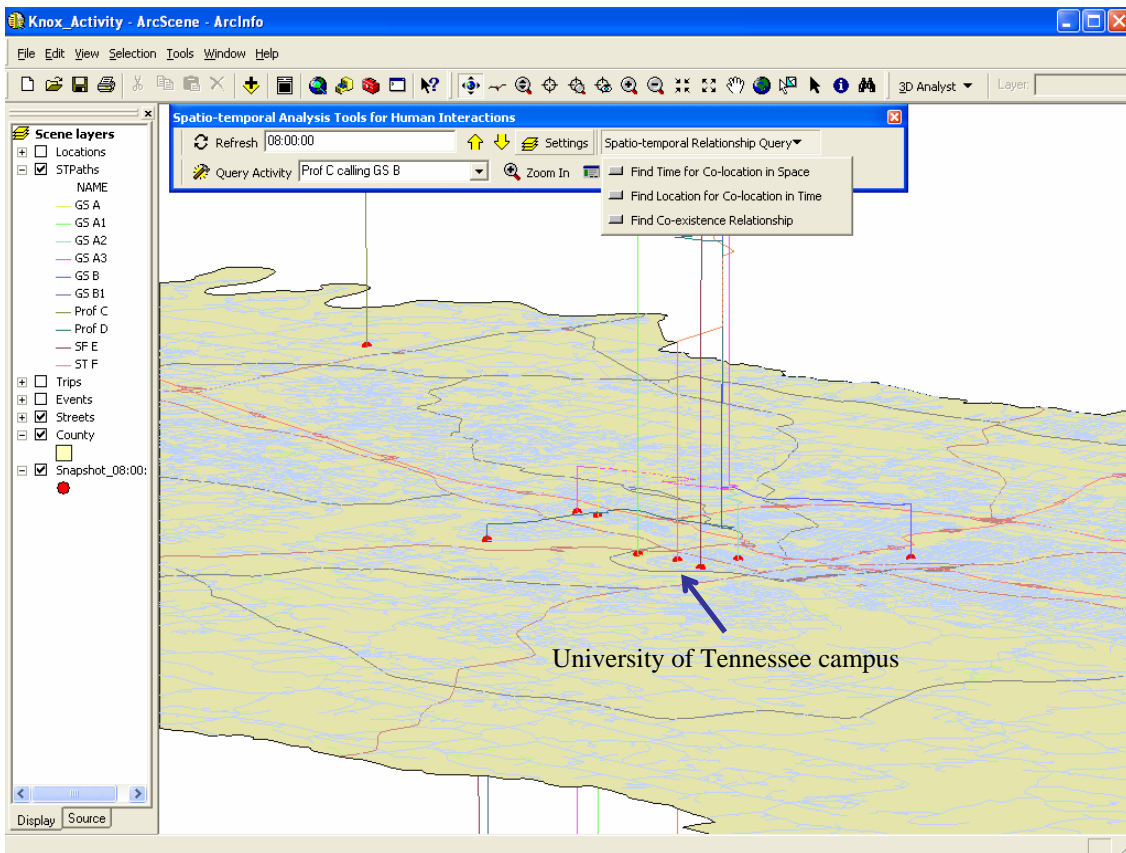
Figure 9. Representation of human interactions in the prototype system



(a) Report for co-existence relationship of space-time paths



(b) Report for co-location in space relationship of space-time paths



(c) Snapshot to report locations of space-time paths at 8 am

Figure 10. Functions for exploring spatio-temporal relationships of space-time paths in the prototype system

both physical and virtual activities. Based on the extended space-time path concept, four types of spatio-temporal relationships of space-time paths are identified in this study and used to

represent the different modes of human interactions in GIS. A prototype system is successfully set up with a sample data set in a commercial GIS software environment, which implements the framework design and contains functions to represent, visualize, and analyze spatio-temporal relationships of human interactions.

The framework can be applied to various research domains which are related to the study of human activity. The extended space-time path representation of activities provides an efficient structure for visualizing and investigating spatial and temporal characteristics of human behavior. The exploratory analysis functions of spatio-temporal relationship of human interactions offer powerful tools for the exploration of human interactions, especially involuntary interactions. The framework provides extra opportunities for scholars to understand the possibility of interactions among interested population and reveal the potential connections among people. The framework can be used for transportation study to understand the process of traffic congestion, which can be modeled as an involuntary co-existence relationship of cars on the same segment of a road. Intelligence agents in the Department of Homeland Security can use the tools to investigate and track both physical and virtual connections among suspects and to assist in the process of identification of abnormal interaction patterns of suspects and evaluation of potential attacks. The spatio-temporal relationships of space-time paths can help researchers in the disease control field track the distribution of certain infectious diseases and identify the high-risk population group. For example, individuals who have physically contacted a person with Hepatitis B disease, which indicates a co-existence relationship, or have visited a restaurant after a recent visit of the patient, which indicates a co-location in space relationship, may have a higher possibility to get the disease. The framework can be helpful in relevant analyses and studies in this field. Also, the recent growing studies in location-based services (LBS), which focuses on helping people arrange their activities according to their locations, can benefit from the framework by adopting the extended space-time path concept, its representation in GIS, and spatio-temporal analysis functions to identify possible future activities in both physical and virtual spaces.

The framework provides a good start for the study of human interactions. However, two issues can be strengthened in the future development in order to strengthen its support for relevant research. Co-existence is an important spatio-temporal relationship even in today's society with ICTs. It is quite often that researchers are exploring a large data set for this relationship. The co-existence function in the prototype system needs users to provide a given space-time path for the analysis and provides exhaustive searching results. This will become cumbersome when dealing with large data sets. A function that can heuristically find space-time cluster is needed for a broader adoption of the framework in the relevant research fields. Also, the current framework focuses on the analyses of clearly documented historic data only and does not touch how to plan for future activities. However, being able to dealing future cases of activities is an important issue in human activity study and it is essential for LBS applications. These two issues can be improved in the future development of this study.

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