Spatio-temporal GIS Design for Exploring Interactions of Human Activities

Hongbo Yu

ABSTRACT: An effective representation of human activities in geographic information systems (GIS) presents a challenging research topic. Recent developments of information and communication technologies (ICT), which enable a virtual space and allow people to interact with others remotely, make such efforts even more difficult. This paper first extends the space–time path concept of Hägerstrand's time geography to represent both physical and virtual activities in a space–time context. A spatio-temporal GIS design which can accommodate the extended space–time path concept is proposed to support the exploration of spatio-temporal patterns of human interactions in physical and virtual spaces. Using time as a linear referencing system, a temporal dynamic segmentation method was developed to dynamically locate physical and virtual activities on space–time paths. The GIS design supports the identification of four different spatio-temporal patterns (i.e., co-existence, co-location in space, co-location in time, and no co-location in either space or time) of human interactions through their space–time paths. Using a hypothetical activity dataset, a prototype system is implemented as a three-dimensional GIS (i.e., two-dimensional space + one-dimensional time) in ArcGIS. The prototype system demonstrates the feasibility and potential of applying spatio-temporal GIS concepts to extend Hagerstrand's time–geographic framework for the representation and analysis of human interactions in both physical and virtual spaces. The proposed GIS design can be useful in such applications as understanding traffic congestion, tracking terrorist activities, and modeling the spread of infectious diseases.

KEYWORDS: Human activities and interactions, spatio-temporal GIS, temporal dynamic segmentation, spatio-temporal relationships

Introduction

Human lives involve various activities in a space–time context. As social beings, people cannot avoid interacting with others in activities. These interactions enable flows of information and material among people and keep the society functioning. Because activities are distributed at different locations, travel is usually used to help people participate in activities and complete interactions. Considering travel as a derived demand, transportation researchers have recognized that the spatial and temporal distribution of activities can determine where and when people travel (Damn and Lerman 1981; Kitamura et al. 1990; Hanson 1995). Therefore, a better grasp of spatial and temporal characteristics of human activities and interactions can help researchers gain a better understanding of the transportation system, and the urban landform in the long run.

Hägerstrand (1970) proposed a framework to examine the relationships between various constraints and human activities in a space–time context. The framework was advanced with further efforts made by Hägerstrand and his research collaborators and is now known as Time Geography (Wachowicz 1999). In an integrated space–time system, time geography uses the concept of *space–time path* to describe an individual's trajectory in physical space over time and the concept of *space–time prism* to depict the space–time extent that can be accessed by an individual under certain constraints.

Human activities and interactions are predominately performed in physical space, through physical presence or physical contact of the participants. With a space–time explicit representation of an individual's trajectory, the space–time path concept of time geography provides an effective support to the study of spatial and temporal characteristics of human activities and interactions. However, recent developments in information and communication technologies (ICT)—such as cellular phones and the Internet—are changing how people carry out their activities and interactions. The information and communication technologies enable a different space, which can connect people electronically and transmit information among people more efficiently than physical space. This space has been named virtual space or cyberspace in the literature (Janelle and Hodge 2000).

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Virtual space allows people to participate in activities remotely instead of by physical presence in physical space. This new presence mode through virtual space is known as tele-presence. Therefore, people now can choose to conduct activities through either physical presence in physical space or tele-presence in virtual space. The availability of tele-presence is changing the conventional role of physical space to contain human activities. The use of ICT frees certain activities and interactions from various spatial and temporal constraints. For example, people can enjoy more freedom in space by getting in touch with others using their cellular phones because they do not have to attach to fixed locations. People are no longer restricted to the open hours of airline agencies to book air tickets, and they can do it on the Internet at any time in a day. The freedom and flexibility gained from the use of ICT have important implications to the spatial and temporal aspects of human activities. With representation for physical space only, the space–time path concept of time geography falls short of portraying human activities and interactions in virtual space. Therefore, the concept needs to be extended to handle activities in both physical and virtual spaces, and support the exploration of human interactions in today's society.

Geographic information systems (GIS) are specifically designed to handle spatial data. Due to the spatial nature of human travels and activities, GIS have been considered as a powerful approach to study human activities (Pipkin 1995). Several attempts have been made to represent and explore activity/travel data in GIS (e.g., Shaw and Wang 2000; Wang and Cheng 2001; Frihida et al. 2002). Although these studies demonstrate the potential of GIS in supporting the organization of activity/travel data and the exploration of human activities at the individual level, they focus on human activities in physical space only.

Kwan (2000a) presented an attempt to visualize an individual's activities in both the physical and the virtual space, using the space–time path concept and a multi-scale GIS environment to portray the three different spatial ranges of an individual's activities through physical presence and tele-presence. However, most existing studies concentrate on the representation and exploration of activities of a single person, and limited efforts have been made to study the interactions among people in a GIS environment. Therefore, a GIS design, which can effectively organize human activity data and help explore interactions of human activities in physical and virtual spaces, remains a challenging research topic.

This paper presents a spatio-temporal GIS design to support the exploration of spatio-temporal characteristics of human activities and interactions in physical and virtual spaces. An extended space–time path concept of Hägerstrand's (1970) time-geographic framework was used to help organize and visualize human activities and interactions in a GIS environment. Spatio-temporal analysis functions were developed within the framework to help explore the spatial and temporal patterns of human interactions.

This paper is organized into five sections. The next section discusses theoretical issues involved in the study. The following section presents a spatio-temporal GIS design that supports representation and spatio-temporal analysis of human activities and interactions. Based on the proposed GIS design, I then implement a prototype system with a hypothetical activity dataset in ArcGIS. Customized analysis functions and user interfaces in the prototype system are also demonstrated in this section. A discussion of potential applications of the system and future improvements concludes the paper.

Human Activity and Human Interaction

Every human activity takes place in a particular spatial and temporal context (Golledge and Stimson 1997). As activities are often distributed at different locations in space, an individual has to trade time for space so that she or he can be physically present at activity locations and participate in the activities (Hanson 1995). Travel is a conventional means for people to trade time for space, which means that traveling across the space takes time (Miller and Shaw 2001). Because time is a scarce resource, the more time is used for travel, the less is left for activities. Therefore, both space and time can constrain a person from performing certain activities. Using an integrated space–time system, time geography provides an effective framework to examine the relationships between constraints and human activities in a space–time context (Hägerstrand 1970). The framework has been frequently used by researchers to portray and study spatial and temporal characteristics of human activities in physical space (e.g., Carlstein et al. 1978; Parkes and Thrift 1980; Ellegård 1999).

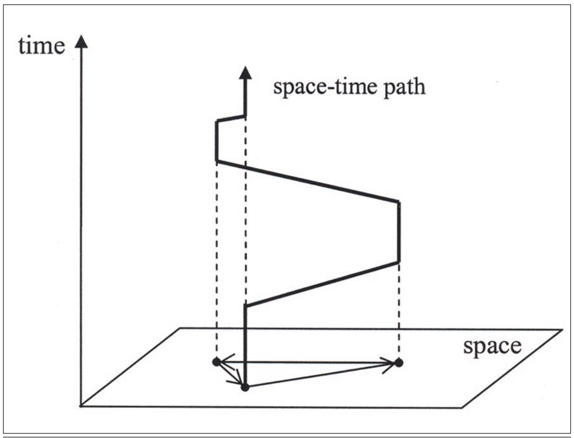


Figure 1. Space–time path.

at the new location is shortened accordingly. The feasible locations that can be visited by a person within a given time duration form a continuous extent in the orthogonal space–time coordinate system, the so-called space-time prism (Lenntorp 1976). When a space–time prism is projected onto a two-dimensional space, the result is a region, also known as the potential path area. Figure 2 shows a space–time prism, which has constraints on both the origin and the destination. The shaded area in the 2D space plane in the figure is the corresponding potential path area. A space–time path is usually used to represent the historical movements of a person, and a space–time prism or a potential path area portrays the feasible space that can be accessed by an individual under certain constraints.

Time geography considers the time dimension to be equivalent to that of space in the study of human activities. The framework adopts a three-dimensional orthogonal coordinate system to portray spatio-temporal aspects of human activities, with time as the third dimension added to a two-dimensional space. The two-dimensional space is used to measure the location changes of objects, and the time dimension is used to order the sequence of events and synchronize human activities.

Two fundamental concepts—space–time path and space–time prism—were developed in the time–geographic framework to depict an individual's activities in space and time. A space–time path is the trajectory of an individual's movements in physical space over time (Figure 1). A space–time path provides a space–time explicit representation for an individual's activities, including the starting/ending time and location of an activity, and the sequence of activities. Therefore, the spatial and temporal characteristics of an individual's movements are integrated under the concept of space–time path (Miller 2005).

A space–time path is composed of a series of tilted and vertical segments. The tilted segments indicate an individual's movements in space and the vertical segments indicate an individual's stays at particular locations. The slope of a tilted segment represents the travel speed, with a steeper slope indicating a slower travel speed. Transportation is considered as a means to trade time for space. Given a location and a time period, an individual can stay at the same 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 the available time for activities

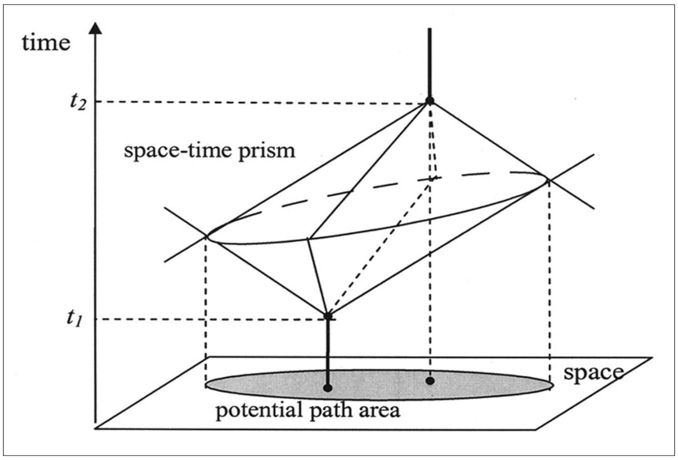


Figure 2. Space–time prism and potential path area.

Physical space is the conventional stage for people to conduct their activities. Without the help of ICT, human activities and interactions can only be completed in physical space, which requires physical presence of the participants. In this case, the location and time of a person's presence are closely related to the content of the activity that is carried out by the person (Couclelis and Getis 2000). For example, a person's visit to the downtown area during office hours usually indicates that the person works there, while a visit to the downtown in the evening is probably related to an entertainment activity.

The space–time path concept thus gives a proper representation of a person's activities and their spatio-temporal contexts. However, the relationship between an activity's content and its venue and time is weakened when ICT are used to complete the activity. ICT offer more freedom in space and time for people to conduct activities and interact with others. A person can use ICT to participate in an activity remotely through tele-presence, without physically moving to the specific location of the activity. For example, business partners can communicate and interact with each other through a videoconference while they are physically at different locations.

The detachment of an activity from a fixed location can also lead to higher flexibility to arrange the activity in time. With e-journals available on the Internet, searching literature does not have to be conducted in a library. With a networked computer, a professor can search articles at home even after the library is closed. With the help of ICT, a person can conduct activities through physical proximity (i.e., being physically present) or from a distance through tele-presence. A representation of an individual's physical proximity only will not allow the space–time path concept to depict the complete spatial and temporal characteristics of activities and interactions conducted by individuals. This suggests that the space–time path concept of Hägerstrand's (1970) time geography needs to be extended to handle human activities and interactions in the physical as well as the virtual space.

Adams (1995; 2000) recognized the limitations of using space–time paths to represent human activities, if the spatial range of human activities is restricted to the physical proximity of people's movements. Considering people as social agents and sensate beings, he argued that the sensation of people could be stretched over physical space with the help of ICT. Adams (2000) grouped the spatial ranges that are involved in people's activities at different social scales into six categories. These categories include the physical proximity of people, which is for physical presence, and five other spatial ranges that can be reached through tele-presence, varying from the local to the international level. Using computer-aided design (CAD) diagrams, Adams (2000) displayed the physical proximity of individuals as space–time paths and sensations over distance as bars extending from the paths.

Similarly, Kwan (2000a) used three spatial levels to depict the extended agency of an individual: a local level which can be reached by physical presence, and national and international levels which can be reached through tele-presence. To represent the different spatial ranges involved in a person's daily activities, Kwan (2000a) proposed a multi-scale GIS environment where space–time paths denoted the person's physical movements and the links extending from the paths were virtual activities. Depending on the distance covered by a virtual activity, one of the three pre-defined scales is chosen and used to represent the spatial range of that activity.

The combination of extensible agents and Hägerstrand's space–time paths can provide effective descriptions of human activities in both physical and virtual spaces. These two concepts were adopted in this study to develop an extended space–time path representation of human activities in today's society. All activities take place at certain locations and time periods, and each of them occupies a portion of a space–time path. Thus, a space–time path can be considered as the container of all the activities conducted by a person. Virtual activities can only take place at ICT-enabled locations, such as at an Internet café or within a cellular phone service area, because they need the support of ICT facilities. The difference between physical and virtual activities is that they have different action spaces. Physical activities impact only the physical proximity of a space–time path, while virtual activities can reach out and impact distant locations.

Figure 3 shows a conceptual representation of an extended space–time path. Five physical and virtual activities of an individual are represented on the space–time path. The physical activities are: going to work (a), meeting (c), and going home (d); they are represented as segments on the path as they take place only within the physical proximity of the path. Instant messaging (b) and e-mailing (e) are virtual activities. They are represented as links reaching out, which still occupy particular portions of the path. The links indicate the individual's connections with others over space.

As some virtual activities may experience delays in time, their corresponding extended links may not always be horizontal but tilted like the e-mailing activity shown in the Figure 3. Unlike the slope of a segment on a space–time path for a physical activity, which indicates the travel speed, the slope of a link for a virtual activity does not have particular meaning. It only indicates that the interaction between two individuals in virtual space experiences delay in time. The time delay can be derived by comparing the positions of the two ends of a tilted link in the time dimension.

The new freedom in space and time offered by ICT provides additional ways for people to interact with each other. Interaction through cellular phones or the Internet has fewer constraints in space and time. Four communication modes with different spatial and temporal requirements have been

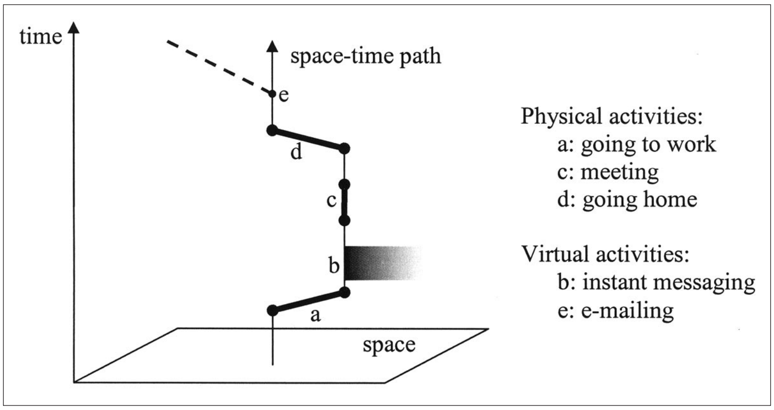


Figure 3. An extended space-time path representation for both physical and virtual activities.

Temporal / Spatial	Synchronous	Asynchronous
Physical presence	SP Face to face (F2F)	AP Post-it® notes Traditional hospital charts
Tele-presence	ST Telephone Chat rooms Teleconferencing	AT E-mail Webpages

Table 1. Communication modes based on their spatial and temporal constraints. [Adapted from Miller 2003].

Thanks to ICT, people are no longer required to be present at the same physical location to communicate. "Synchronous Tele-presence" (ST) communications only require participants to be coincident in time (e.g., two friends at different locations doing instant messaging over the Internet), while "Asynchronous Tele-presence" (AT) communications are free from coincidence requirements in space and time. E-mailing between people belongs to this type of communication. A person sends an e-mail and another person can receive it at a different location at any later time.

This classification system can be adopted 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 were the predominant modes for people's interactions with others before ICT were widely adopted. The ST and AT modes of human interaction are proposed (Table 1; also see Janelle 1995; 2004; Harvey and Macnab 2000; Miller 2003). A conventional face-to-face meeting requires participants to be at the same location during the same time period. A communication mode requiring coincidence in both space and time is known as "Synchronous Presence" (SP). Communications using Post-it® notes or bulletin boards require people to visit the same location, but maybe at different times, to complete the information exchange. This type of communication, which requires coincidence in space but not in time, is called "Asynchronous Presence" (AP).

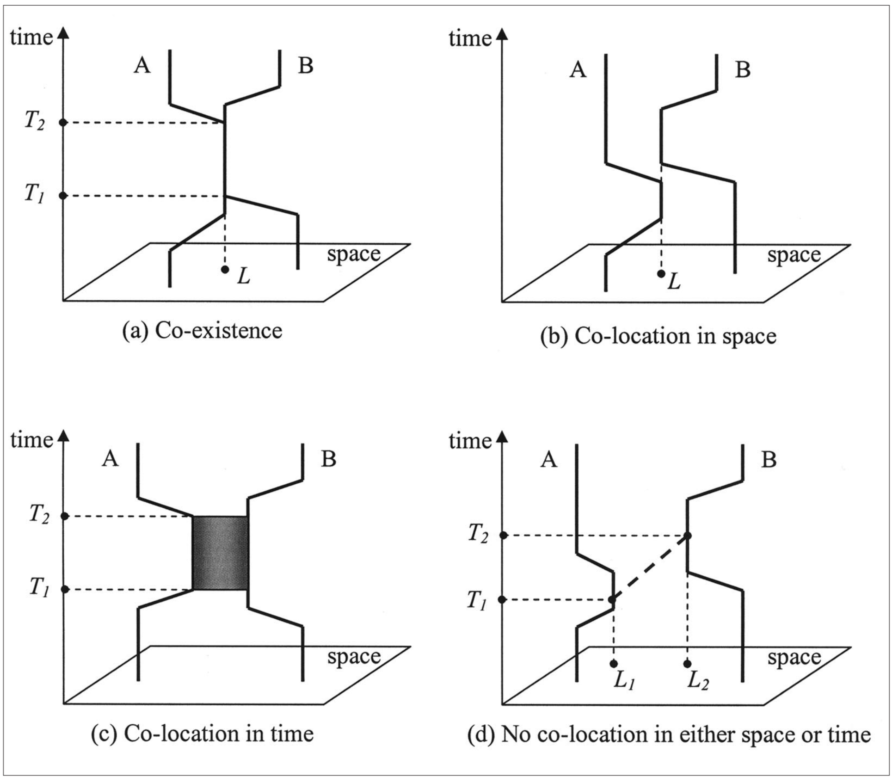


Figure 4. Spatio-temporal relationships of human activities.

made possible by ICT, and they are not only changing the way people communicate with each other but also the spatio-temporal patterns of human activities.

When the four types of human interactions are represented with extended space–time paths developed in this study, different patterns can be recognized with regard to their spatio-temporal relationships. Because an SP interaction normally involves physical activity, it can be represented through the physical proximity of the participants' space-time paths. The requirement for participants to be present at the same location (L) during the same time period (from T_1 to T_2) results in overlapping segments of the two space–time paths. This creates a "co-existence" relationship, as shown in Figure 4(a). An AP interaction is completed by sequential visits from different participants to the same location (L), as shown in Figure 4(b). Each space–time path has a segment sharing the same location (L) at different time periods. This leads to a relationship termed "co-location in space."

As both ST and AT interactions involve virtual activities, extended space–time paths are needed to represent their relationships. An ST interaction, such as a phone call or instant messaging, involves participants who interact with each other at different locations through virtual space at the same time. This creates a "co-location in time" relationship of participants' space–time paths (Figure 4(c)). The block between the space–time paths represents the interaction between the participants in virtual space, and the horizontal lines indicate the synchronization in time (from T_1 to T_2). An AT interaction further removes the requirement on time synchronization. A person can initiate communication from location L_1 at time T_1, while the receiver of this communication can pick it up at location L_2 and time T_2. This type of interaction is represented by a tilted link connecting specific positions on the space–time paths, and the relationship is that of "no co-location in either space or time" (Figure 4(d)). As each interaction type is represented as a different relationship between space-time paths, these interaction types can be used to examine spatio-temporal relationships of human activities and interactions.

Spatio-temporal GIS Design for Visualizing and Exploring Interactions of Human Activities

Researchers have been using GIS to organize human activity data, especially activity/travel diary data, and explore 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 locations and organized the activity/travel data in a GIS environment to support spatio-temporal queries on activities. 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 travel/activity data, they did not provide an effective GIS model that:

- Describes various activities/trips conducted by an individual with a continuous representation in an integrated space–time system; and
- Explores spatio-temporal patterns of interactions among multiple individuals.

Kwan (2000a; 2000b) demonstrated the advantages of using the space–time path representation to visualize individual activities in a GIS environment. However, a GIS design, which can provide a space–time explicit representation for physical and virtual activities and support exploration of spatio-temporal relationships of human interactions, remains a challenging research question. Building on these existing efforts, a spatio-temporal GIS design was developed, which incorporates the extended space–time path concept and supports the representation, visualization, and analysis of human activities and interactions in the physical and virtual space.

GIS Representation of Space–Time Paths: Spatio-temporal Line Features

The design of a conventional GIS usually takes a cartographic approach, which can only represent static spatial features (Spaccapietra 2001; Peuquet 2002). Consequently, current GIS methods fall short of representing time as an integrated dimension and cannot support the representation of space–time paths. A new GIS framework is needed to accommodate the space–time path concept and support spatio-temporal analysis on the paths. Based on Hägerstrand's (1970) time geography, a three-dimensional (3D) (i.e., two-dimensional (2D) space + one-dimensional (1D) time) GIS environment was developed to overcome the shortcomings of current GIS design. In the 3D

GIS environment, a 2D plane was devoted to the description of spatial information and an extra dimension was used to represent temporal information in a linear time structure. The features in this 3D GIS framework are spatio-temporal features. A spatio-temporal point feature, which occupies a single position in the 3D framework, is represented with a triplet of $<x, y, t>$, where x and y are for a location in the 2D plane and t is used for time. A spatio-temporal line feature is represented as a sequence of triplets ($\{<x_0, y_0, t_0>, <x_1, y_1, t_1>, \ldots, <x_n, y_n, t_n>\}$, where $t_0 < t_1 < \ldots < t_n$). Figure 5 shows how these spatio-temporal features are represented in the 3D GIS framework. A space–time path consequently can be represented as a spatio-temporal line feature in this 3D GIS framework.

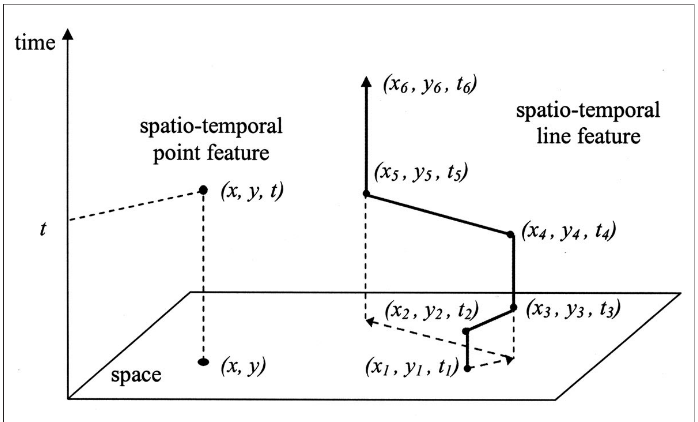


Figure 5. Spatio-temporal features in the 3D GIS framework.

GIS Representation of Human Activities on Space–Time Paths: Temporal Linear Referencing and Dynamic Segmentation

A space–time path records the observed movements of an individual in physical space over time. Due to the indivisibility constraint in the physical space, each individual has only one observed trajectory in space and time (Carlstein 1982). A spatio-temporal line feature in the 3D GIS design can be directly used to represent an individual's space–time path. The triplets ($<x, y, t>$) stored at vertices of a line explicitly record the spatial and temporal information of an individual's movements. Assuming a person travels at a constant speed for each tilted segment on the space–time path, a linear interpolation method can be used to derive the person's location at any given time. For instance, a straight-line segment on a person's space–time path is represented as $\{<x_1, y_1, t_1>, <x_2, y_2, t_2>\}$, and we want to find the person's location in the 2D plane at time t_0 (where $t_1 < t_0 < t_2$). The person's location in the 2D plane $<x_0, y_0>$ can be calculated by the following formulae:

$$x_0 = x_1 + (x_2 - x_1)\frac{t_0 - t_1}{t_2 - t_1} \quad (1)$$

$$y_0 = y_1 + (y_2 - y_1)\frac{t_0 - t_1}{t_2 - t_1} \quad (2)$$

With the linear interpolation method, spatio-temporal line features provide a continuous representation for space–time paths, which means that the location of an individual at any given past time can be retrieved from the individual's space–time path. A space–time path always moves upward along the time dimension because time proceeds in one direction only, from the past to the future. An individual may visit the same location in 2D space multiple times. However, when a space–time path is used to store the trajectory, every point on the space–time path possesses a unique triplet of $<x, y, t>$, because a person can only stay at one physical location at any given time. Thus, time can be used as a linear referencing system to measure locations and store attributes along spatio-temporal line features.

Space–time paths are considered as containers for human activities. Both physical and virtual activities take place within their specific space–time contexts. Therefore, each activity, as an episode in one's life, occupies a portion on the space–time path of the individual. With an individual's space–time path and an activity carried out by this person, we should be able to locate the activity on the space–time path and derive spatial and temporal information of the activity from the path.

Linear referencing systems and dynamic segmentation have been widely used in transportation studies to associate information to specific points or segments along a road network. By defining a route in a road network (e.g., Interstate 40) and creating a linear referencing system (e.g., milepost system) along it, events that happen along the route can be dynamically located based on their references. For example, we can locate a point event (e.g., an accident) that takes place at milepost 30 along I-40, or a linear event (e.g., a construction zone) that starts at milepost 100 and ends at milepost 115.

Similar linear referencing systems and dynamic segmentation techniques can be adopted for locating individual activities on space–time paths. A new term of "temporal dynamic segmentation" was coined in this study to locate individual activity events on spatio-temporal line features. Time can work as the linear referencing system for space–time paths. An activity may have a starting and an ending time. If the duration of the activity is very short, it can be considered as an instance labeled with just one timestamp. An activity can be located on its corresponding space–time path by interpolating the beginning and ending points of the activity on the path based on its time references. A spatio-temporal line feature is used to represent an activity lasting for a time period, and a spatio-temporal point feature is used to represent an activity happening only at a time instant. Through temporal dynamic segmentation, the spatio-temporal environment that contains an activity can be retrieved from a space–time path. Figure 6 shows several physical and virtual activities that are attached to a space–time path based on their time references. Since people could conduct multiple tasks during the same time period, especially for virtual activities, activities are allowed to overlap along a space–time path. For example, the overlap of activity *d* (driving home) and activity *e* (receiving a phone call) in Figure 6 indicates that these two activities partially share the same space–time context, which is the case when a person driving home uses a cellular phone.

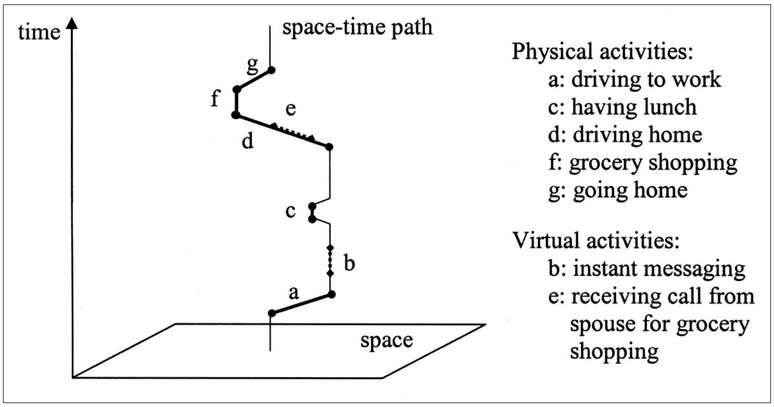


Figure 6. Locate individual activities on a space-time path using temporal dynamic segmentation.

GIS Representation and Visualization of Four Modes of Human Interactions

Human interactions can be considered as special cases of human activities. While an activity can be conducted by any number of individuals, an interaction involves multiple individuals, each of whom has to provide certain action to participate in the interaction. For example, in a traditional learning environment, an on-campus class is an interaction involving an instructor and a number of students. Both the instructor and the students need to visit the classroom and stay there during the same time period to complete the teaching and learning interaction. The spatio-temporal characteristics of an individual activity (e.g., the instructor's visit to the classroom) can be achieved from its corresponding space–time path (e.g., the instructor's space–time path), because it can be located on the path through temporal dynamic segmentation. However, effectively representing interactions with their spatio-temporal characteristics presents a more challenging task. The reasons are:

- An interaction has multiple participants and different interactions may involve different numbers of participants; and
- Participants may join in the interaction through various spatial and temporal situations due to the existence of virtual space.

Hence, interactions can vary greatly with respect to their spatio-temporal patterns, and this leads to the difficulties of their representations in GIS.

Semantic contents of interactions present an effective approach to the organization of interactions. Each interaction has its specific semantic content (e.g., a meeting). The semantic content is shared by all individual activities, each of which represents the involvement of a participant in the interaction, even though individual activities may have different spatio-temporal characteristics. Using semantic content, several individual activities sharing the same semantic content can be grouped together to represent an interaction among the individuals. In addition, the spatio-temporal pattern of an interaction can be determined by examining the spatio-temporal relationships of individual activities under the same semantic content.

The organization of interactions through their semantic contents in GIS is displayed in Figure 7. Four objects are included in the figure—activity, event, person, and space-time path. The general term "activity" was used in the figure instead of "interaction," since interactions are special cases of activities, and its function is to contain the semantic content of an activity or an interaction. The term "event" is used for individual activities that are conducted by people who participate in an activity. The object "person" contains attribute information about an individual and the object "space-time path" records a person's trajectory in space and time.

The relationships among these objects are described in Figure 7. An *activity* may involve multiple *persons*, who participate in the activity through their corresponding *events*. If an activity has only one event, it represents a regular activity with a single person's action to complete a task. If an activity has more than one event associated with it, the activity represents an interaction, which involves multiple persons. Each *person* has one space–time path. Individual activities (*events*) conducted by a person can be located on the person's space–time path through temporal dynamic segmentation. Then spatio-temporal characteristics of an event are available from its corresponding space–time path. As an individual may conduct none or multiple activities, zero or more events can be associated with a space–time path.

Through this model, individual activities related to the same interaction are organized under the semantic content of the interaction. These individual activities can be represented and visualized in the 3D GIS environment, which means that the spatio-temporal pattern of an interaction can be visualized and even determined by analyzing spatio-temporal relationships of spatio-temporal line features representing individual activities. If a dataset contains a well documented history of an individual's activity plus the interaction information, the interactions recorded in the dataset can be organized and visualized in the 3D GIS design through the method discussed here.

Exploratory Analysis Functions for Spatio-temporal Relationship of Human Interactions

Interactions that are initialized by people (e.g., an arranged meeting or a planned videoconference) can easily catch our attention. However, some other interactions are less noticeable, because even people who are involved in the interaction may not realize that it is taking place. For example, many people drive to a highway segment at the same time and cause a traffic jam, or a person goes to a restaurant just visited by another customer with an infectious disease and later gets sick. Unlike those interactions initialized by participants, these interactions are not planned in advance and participants may be reluctant to be involved. However, these interactions are also important for studies involving human interactions such as managing traffic congestion and tracking the spread of infectious disease.

Researchers in studies of daily human activities have noticed the difference between the two situations, and the terms "series" and "group" have been used to describe them in the literature (Ellegård 1999). Emphasizing participants' willingness to be involved in an interaction, this study uses "planned" and "unplanned" interactions to distinguish these two types of interactions.

Under normal conditions, a planned interaction involves a well defined activity content and clearly identified participants who may participate in the interaction through different spatial and temporal conditions. Thanks to complete records, this type of interaction can be represented effectively through the semantic organization method proposed in Figure 7. An unplanned interaction takes place without arrangements in advance and includes people who may not want to be involved, or who are not even aware of their involvement. Therefore, it is difficult to clearly identify all participants and spatio-temporal characteristics of their involvement. This means that unplanned interactions cannot be as well documented as planned interactions. The semantic organization method fails in this situation. For unplanned interactions, which usually have fewer well documented activity records (or none), the major concern is not to represent the interactions, but to identify possible interactions among people. In this circumstance, the spatio-temporal relationships of people can help explore possible human interactions.

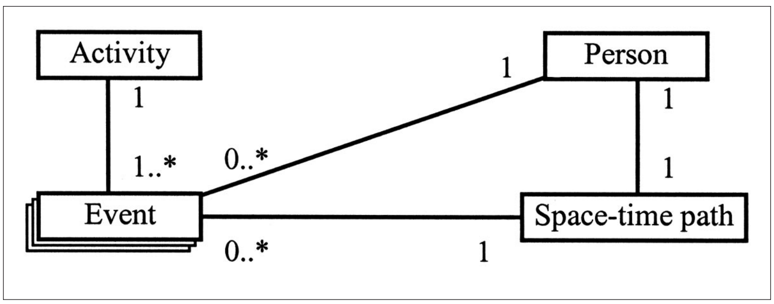


Figure 7. Semantic organization of human interactions in GIS.

People can interact with each other through four different modes—the SP, AP, ST, and AT interaction modes discussed previously. When represented with space–-time paths, these interaction modes present specific spatio-temporal patterns. The patterns have been identified as four spatio-temporal relationships of space–time paths, i.e., co-existence, co-location in space, co-location in time, and no co-location in either space or time. Since these spatio-temporal relationships are necessary for people to conduct different types of interactions, they can be used to reveal possible unplanned interactions among people. If a number of space–time paths share a particular spatio-temporal relationship (e.g., co-existence), it indicates that these people might have a corresponding type of unplanned interaction (e.g., an SP interaction such as stuck in the traffic jam). The possible interactions are not only unplanned, but they can also be planned. If some planned interactions are missing from an activity dataset, this approach can help locate possibly missing records of planned interactions among people in the dataset. Hence, exploring spatio-temporal relationships of space–time paths can help us identify all possible human interactions, including both planned and unplanned ones.

Analysis functions can be developed in the 3D GIS design to explore spatio-temporal relationships of space–time paths. As space–time paths are represented as spatio-temporal line features in the 3D GIS environment, exploration of spatio-temporal patterns of space–time paths can be processed by operations on spatio-temporal line features. The co-existence relationship can be identified by checking 3D intersections of space–time paths. The co-location in space relationship can be identified by projecting spatio-temporal lines into lines in the 2D plane and examining whether the 2D lines have intersections. Further temporal information for the intersections is available by querying temporal information of the intersection locations on space–time paths.

As both the co-location in time and the no co-location in either space or time relationships deal with virtual activities, in addition to the spatio-temporal requirements, all participants have to stay at ICT-enabled physical locations to access virtual space. To determine the co-location in time relationship, segments representing the same time period from space–time paths are extracted by temporal dynamic segmentation and projected onto the 2D plane. If the projected lines fall within ICT-enabled locations, the original space–time paths share a co-location in time relationship, and the individuals might have had ST interactions. Finally, if segments from space–time paths are confirmed to reside at ICT-enabled locations, but they do not share the same time period, the relationship is that of no co-location in either space or time, and the individuals might have had AT interactions. The results from these spatio-temporal analysis functions for space–time paths can help researchers reveal possible human interactions.

Implementation of the Design in ArcGIS

The spatio-temporal GIS design is implemented as a prototype system in ArcGIS, the commercial GIS software package of the Environmental Systems Research Institute (ESRI). Because the 3D (i.e., 2D space + 1D time) structure of the time–geographic framework is similar to the 3D spatial system used in ArcScene, which is the 3D viewer of ArcGIS, ArcScene was used as the implementation environment to visualize space–time paths and analyze spatio-temporal relationships of human interactions. The *z* value in ArcScene was used as the time dimension instead of the third dimension of space.

In ArcGIS, a conventional 2D spatial feature, such as a point or a line, can carry a *z* domain to store coordinates for the third spatial dimension (Zeiler 2002). Once the *z* domain is enabled for a feature, the feature is ready to represent a 3D spatial feature. With the time values stored, point and polyline features with *z* values in ArcGIS are used as spatio-temporal point and line features in the prototype system.

Visual Basic for Applications (VBA) programs with ArcObjects were used in the system implementation to create the customized user interfaces and functions. A hypothetical individual activity dataset was used to test the prototype system. The dataset contained 77 individual activities, both physical and virtual, of ten individuals located within a day in Knox County, Tennessee. Interactions among these ten individuals were recorded in the dataset. These included all four modes of interaction, i.e., SP, AP, ST, and AT. Figure 8(a) shows some activity records in the dataset.

Each individual activity in the data set was described with the following information: the individual who conducted the activity, the location of the activity (including both origin and destination, if the activity includes travel), time of the activity, and whether the individual activity is part of an interaction. The street network of Knox County was used, and trips for all travel activities in the dataset were

	PERSONID	NAME	STARTTIME	ENDTIME	STARTLOCT	ENDLOCATI	TRAVEL	ActivityID	EventDes
	4	GS A1	07:23:00	07:38:00	Home A	Agriculture	1	27	driving to school
	3	Prof C	07:30:00	07:52:00	Home C	Pellissippi Coll	1	20	driving to Pellissippi College
	9	SF E	07:40:00	07:57:00	Home D	UT Administra	1	51	driving to school
	3	Prof C	08:00:00	12:00:00	Pellissippi Coll		0	21	attending conference
	8	Prof D	08:13:00	08:30:00	Home G	Geography	1	45	driving to school
	5	GS A3	08:38:00	09:00:00	Home H	Geography	1	1	going to school by bus
	1	GS A	08:40:00	09:00:00	Home A	Geography	1	1	going to school by bus
	2	GS B	08:44:00	09:02:00	Home B	Geography	1	14	driving to school
	6	GS A2	08:45:00	09:00:00	Home F	Engineering	1	39	walking to school
	5	GS A3	09:00:00	09:05:00	Geography	Engineering	1	36	walking to engineering bldg
	1	GS A	09:05:00	12:05:00	Geography		0	2	teaching Lab at school
	2	GS B	09:05:00	12:05:00	Geography		0	2	teaching Lab at school
	6	GS A2	09:38:00	09:50:00	Engineering		0	3	sending email to GS A
	8	Prof D	10:34:00	10:36:00	Geography		0	46	calling UT administration
	9	SF E	10:34:00	10:36:00	UT Administra		0	46	receiving call from Prof D
	10	ST F	10:53:00	11:08:00	Residence Ha	Geography	1	53	walking to school
	10	ST F	11:10:00	12:00:00	Geography		0	2	having lab

Record: 0 Show: All Selected Records (0 out of 77 Selected.) Options

(a) Individual activity records in the hypothetical dataset (above). (b) Travel activity in the hypothetical dataset shown on a map (below).

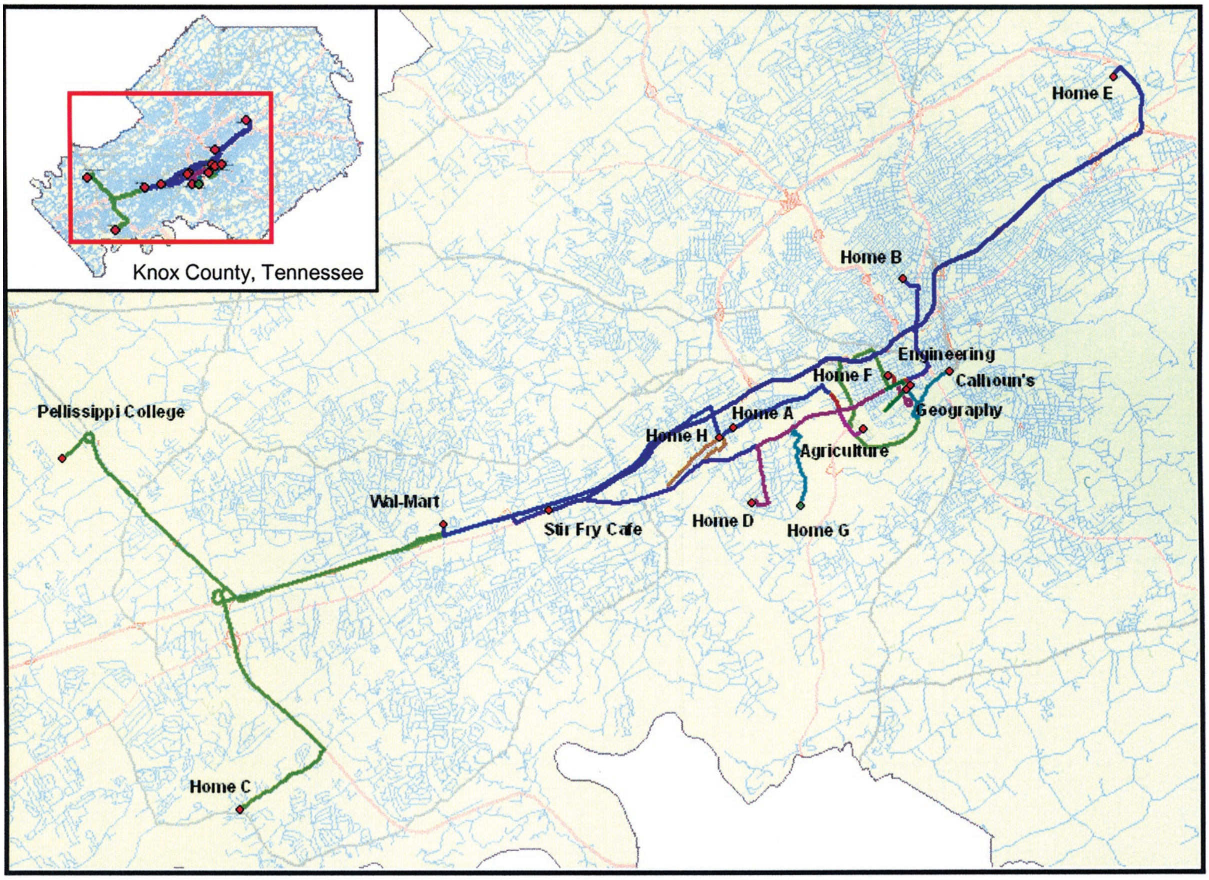


Figure 8. A hypothetical dataset with individual activities in a day.

created based on this network and the origins and destinations of the trips. Figure 8(b) displays all trips in the activity dataset stored in ArcGIS. The prototype system includes functions to generate and visualize spatio-temporal features, such as space–time paths and individual human activities; explore spatio-temporal patterns of well documented human interactions; and examine spatio-temporal relationships of space–time paths for identifying possible human interactions.

Creating and Visualizing Space–Time Paths and Individual Human Activities

A space–time path is composed of a sequence of stays and movements between locations (Wang and Cheng 2001). The trips made by a person form a chain, i.e., the ending location of a person's trip is the starting location of the next trip. The complete records of trips made by a person can thus be used to generate the space–time path for that person. In the prototype system, a function was created to generate space–time paths from travel diary data. All trips of a person were selected from the dataset and sorted by time. The starting and ending times of a trip were converted to *z* values and assigned to the starting and ending nodes of a *z*-value-enabled line representing the trip.

The *z* values for other vertices along the line can be calculated by linear interpolation. All the trips made by the same person were connected according to their time sequence, with extra vertical lines linking the ending nodes of previous trips with the starting nodes of the next trips. These vertical lines represent the stays between travels. One single polyline with *z* values was generated for each person, and the polyline is used to represent the space–time path for a person.

A function was also created to implement temporal dynamic segmentation for locating individual activities on space–time paths. Every activity has starting and ending times. Using methods discussed previously, a point can be located on a space–time path with a given time to indicate a person's position at that time. Therefore, two points can be located on a person's space–time for an activity with starting and ending times. The line segment falling in between the two points along the path was extracted and saved as a new polyline with *z* values to represent the spatio-temporal environment of that activity. Using 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 9(a) and 9(b) show the function interfaces for the creation of space–time paths and spatio-temporal segments for individual human activities respectively. Figure 9(c) displays how these spatio-temporal features are visualized in ArcScene.

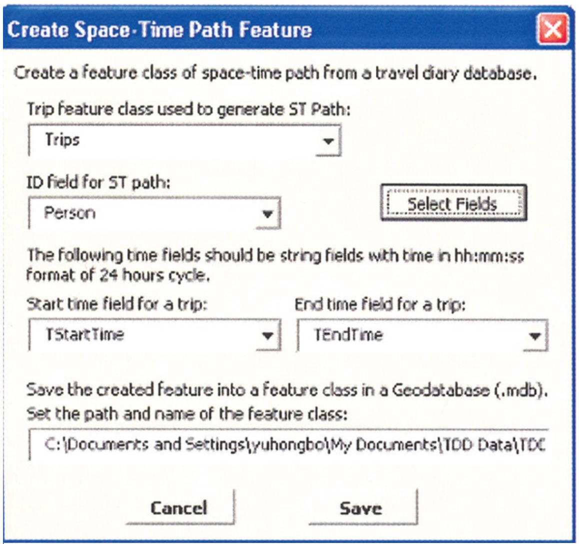
Organizing and Visualizing Planned Human Interactions

The semantic content approach discussed earlier was realized through relationship classes in ArcGIS, and it was used to organize the recorded interactions in the dataset. An activity table contains all activities and interactions conducted by the individuals, with descriptions of their semantic contents. 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 an activity ID attached to each event record to indicate which activity the event belongs to. As shown in Figures 10(a) and 10(b), the activities and events are connected through the activity ID field. When an activity is an interaction, it involves several events from different individuals. Customized interfaces were created to facilitate the exploration of spatio-temporal patterns of activities (interactions). When users query an activity, associated events are selected based on the relationship built between the two tables. The corresponding spatio-temporal line segments, which represent events (individual activities), are highlighted on the screen. Users can thus visualize events in a 3D environment and gain a better understanding of the spatio-temporal pattern of the activity. The four screen captures in Figure 10(c) show four interactions in the dataset, each with a different spatio-temporal pattern, and each visualized in the prototype system.

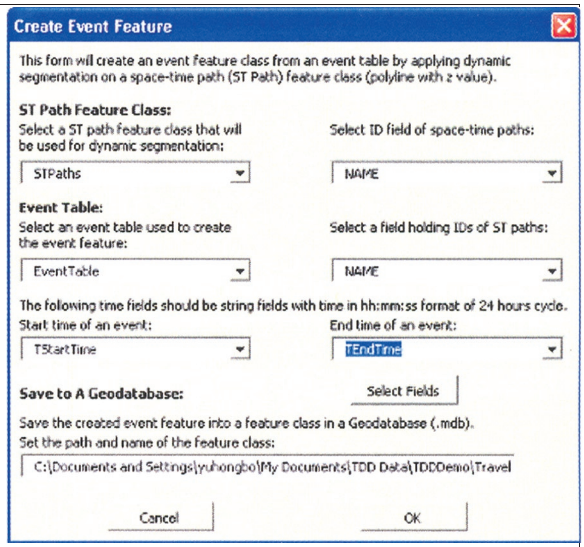
Exploring Spatio-temporal Relationships of Space–Time Paths

In the prototype system, three spatio-temporal analysis functions were developed to help users investigate the co-existence, co-location in space, and co-location in time relationships among people through their space–time paths. Methods for identifying spatio-temporal relationships among space–time paths were implemented by customized VBA programs with ArcOjects. Given a feature class of space–time paths, the co-existence analysis function was used to determine all the cases when any two persons stayed at the same location during the same time period. The results of the analysis were organized in the form of a report such as the one shown in Figure 11(a), where users can interactively select two persons and determine the co-existence relationship between them.

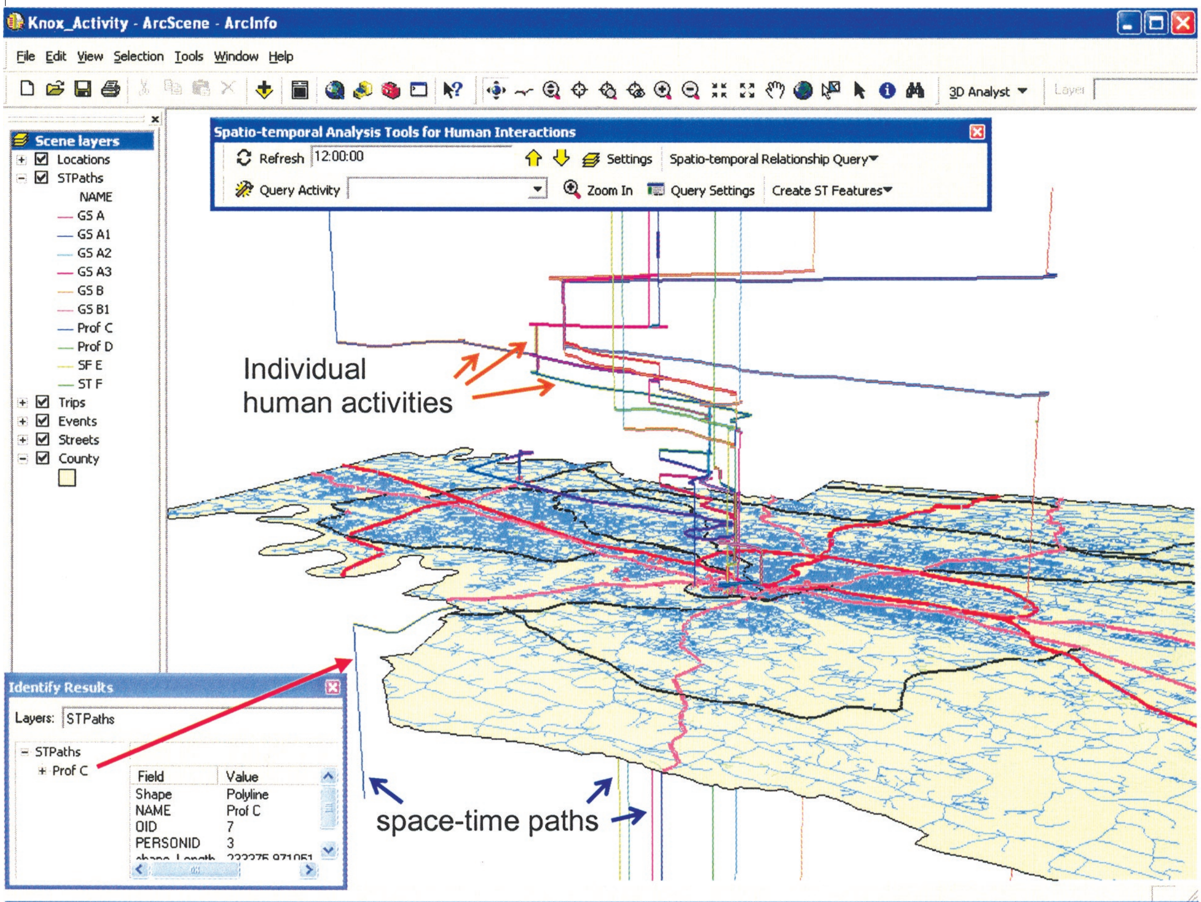
If the feature class of locations and the feature class of space–time path is known, the co-location function can locate the persons who have visited the interested locations. As shown Figure 11(b), the result can be organized in an interactive report



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



(b) The interface for creating individual human activities.

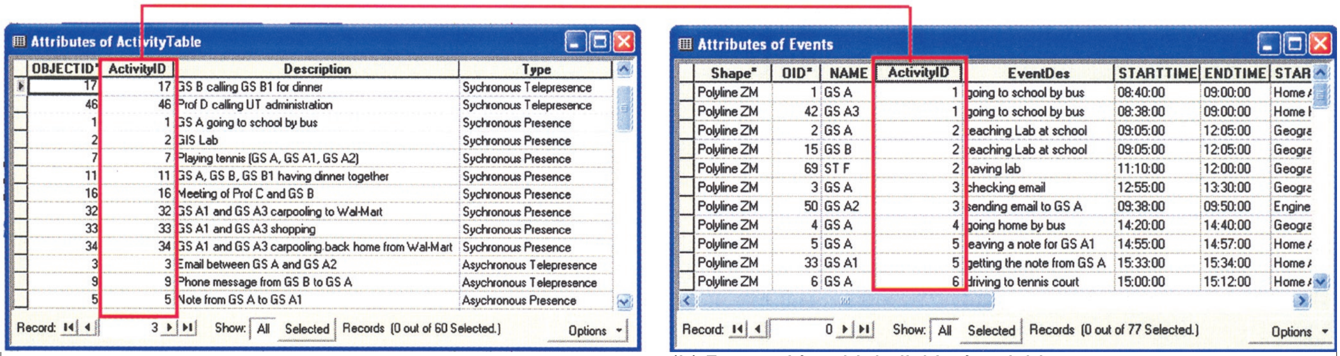


(c) Visualization of space–time paths and individual human activities.

Figure 9. Representation of space–time paths and human activities in the prototype system.

form, whereby users can select a location and a person to examine the person's visit(s) to that place with temporal information.

If the time and the feature class of space–time paths are known, the co-location in time function can report locations of all individuals at that par-



Attributes of ActivityTable

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

Record: 3 Show: All Selected Records (0 out of 60 Selected.) Options

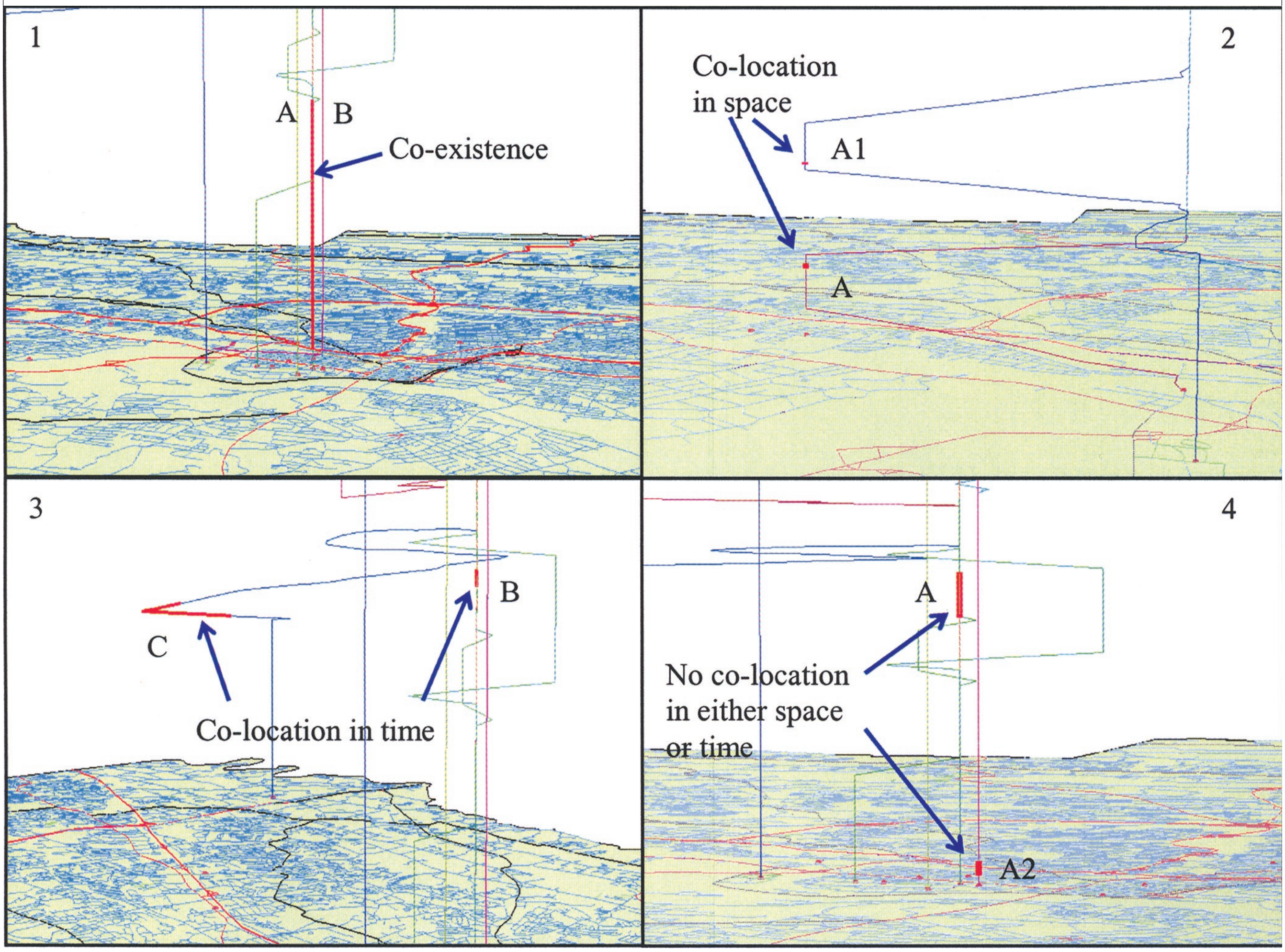
(a) Activity table.

Attributes of Events

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 I
Polyline ZM	2	GS A	2	teaching Lab at school	09:05:00	12:05:00	Geogra
Polyline ZM	15	GS B	2	teaching Lab at school	09:05:00	12:05:00	Geogra
Polyline ZM	69	ST F	2	having lab	11:10:00	12:00:00	Geogra
Polyline ZM	3	GS A	3	checking email	12:55:00	13:30:00	Geogra
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	Geogra
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 /

Record: 0 Show: All Selected Records (0 out of 77 Selected.) Options

(b) Event table with individual activities.



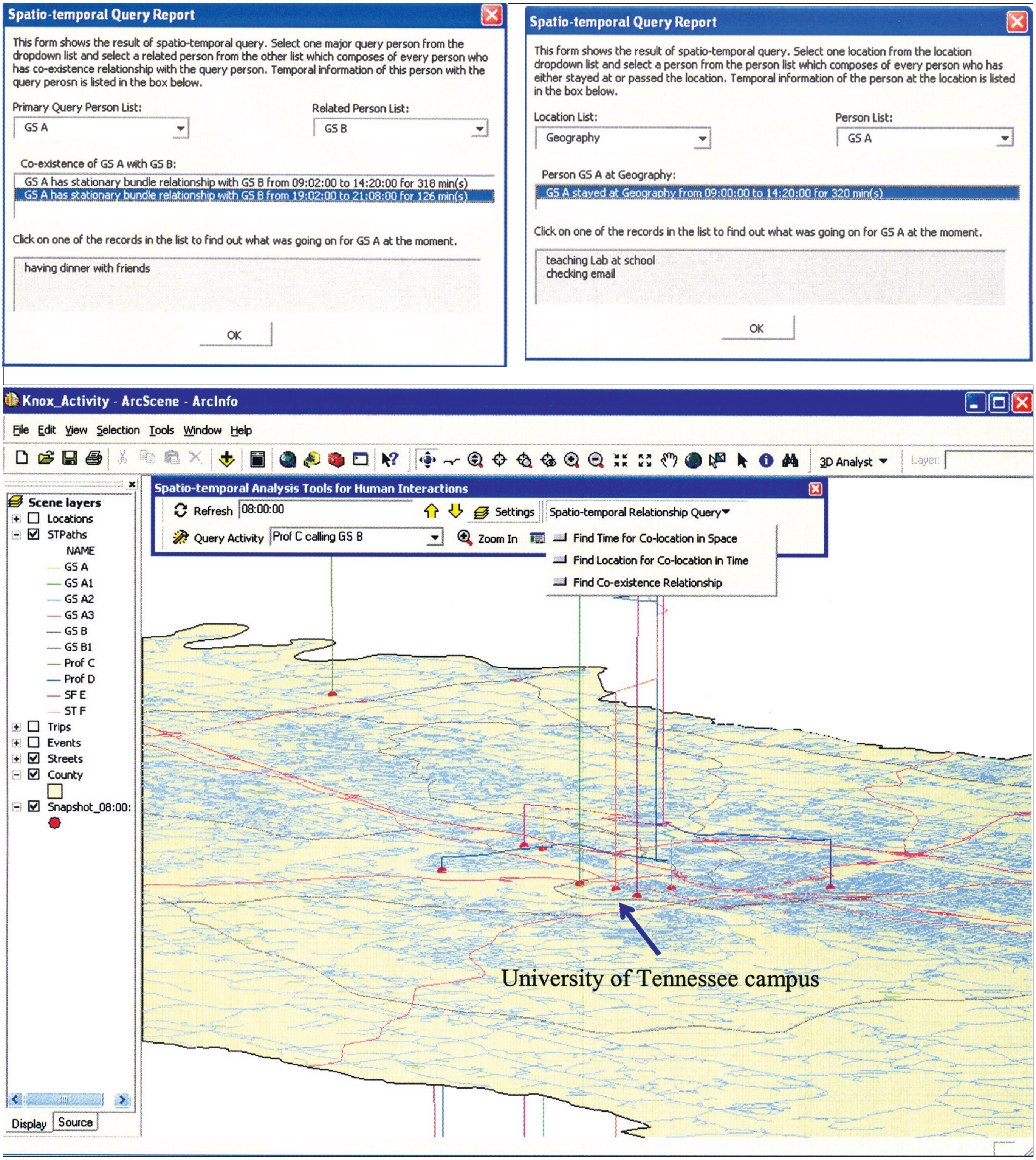
(c) Visualization of human interactions.

1. Graduate students A and B taught lab at school. 2. Graduate student A left a note at home and roommate A1 picked it up later. 3. During driving, Professor C called graduate student B. 4. Graduate student A2 sent otu an e-mail, which was received by A later.

Figure 10. Representation of human interactions in the prototype system.

ticular time. The result is also known as a snapshot of the individuals' movements in physical space, which can be used to study the spatial distribution of people at the time.

A new point feature class was created to store the locations of interested individuals at the particular time (e.g., Figure 11(c)). The red dots in Figure 11(c) represent the physical locations of



(a) The report form for co-existence relationship of space–time paths (upper left). (b) The report form for co-location in space relationship of space–time paths (upper right). (c) A snapshot of a report of locations of space–time paths at 8a.m.

Figure 11. Functions for exploring spatio-temporal relationships of space-time paths in the prototype system.

the 10 individuals in my dataset at 8 a.m. Three of the ten dots are located in the University of Tennessee campus area, which means that users could tell that three individuals were on campus at 8 a.m.

Conclusions

This paper presents a spatio-temporal GIS design for exploring spatio-temporal characteristics of human activities and interactions in the information age. The space–time path concept of Hägerstrand's (1970) time geography was extended to accommodate both physical and virtual activities. A 3D GIS framework was developed to implement the extended space–time path concept. Both physical and virtual activities were represented as segments attached to space–time paths through a temporal dynamic segmentation method developed in this study. Furthermore, four spatio-temporal relationships of extended space–time paths were used to represent four human interaction modes and explore human interactions in GIS. The prototype system implemented in ArcGIS demonstrates the feasibility of the design with functions supporting the representation, visualization, and analysis of spatio-temporal characteristics of human interactions.

The framework can be applied to various research domains related to human activities, such as for transportation studies aimed at understanding the process of traffic congestion. Traffic congestion involves vehicles occurring at the same road segment during the same time, which can be modeled as an unplanned co-existence relationship of vehicles. Intelligence agents in the Department of Homeland Security can use the tools in the framework to investigate and track both physical and virtual connections among suspects, thereby assisting in the process of identifying abnormal interaction patterns and evaluating the possibility of potential attacks. The spatio-temporal relationships of space–time paths can also be used by researchers in public health to track the distribution of certain infectious diseases and to identify high-risk population groups. For example, individuals who have physically contacted a person carrying Hepatitis B, 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 risk of disease exposure. The framework can be helpful in relevant analyses and studies in this field.

The framework described in this paper provides a good start for the study of human interactions. However, two issues should be improved in the future in order to strengthen its support for relevant research. The co-existence function in the prototype system requires users to provide a space–time path for the analysis and provides exhaustive search results. If a large dataset is involved, this could lead to cumbersome operations. A function that can heuristically find space–time clusters is needed for a broader adoption of the framework. Also, the current framework focuses only on the analysis of clearly documented historical data and does not address the issues of assisting in exploring future (potential) interactions among people. An ability to examine potential human activities and interactions is very important to studies of human activity. Such a capability will enable the framework to help people plan and schedule their activities. These two issues merit further research in the future.

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National and Regional Atlases
Geovisualization
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