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Temporal GIS Design of an Extended Time-geographic Framework for Physical and Virtual Activities

Hongbo Yu
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Hongbo Yu entitled "Temporal GIS Design of an Extended Time-geographic Framework for Physical and Virtual Activities." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Shih-Lung Shaw, Major Professor

We have read this dissertation and recommend its acceptance:

Bruce A. Ralston, Thomas L. Bell, Lee D. Han, Cheng Liu

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Anne Mayhew
Vice Chancellor and
Dean of Graduate Studies

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TEMPORAL GIS DESIGN OF
AN EXTENDED TIME-GEOGRAPHIC FRAMEWORK
FOR PHYSICAL AND VIRTUAL ACTIVITIES

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Hongbo Yu
August 2005

DEDICATION

This dissertation is dedicated to my parents, who give me never-ending love and support, even when they are thousands of miles away.

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I am very grateful to my major advisor, Dr. Shih-Lung Shaw, for his consistent guidance, support, and encouragement on my study. Through numerous meetings with Dr. Shaw in the past four years, I gain a lot of invaluable knowledge, which I can benefit from for the rest of my life. Without his help, I would not be able to reach this point.

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ABSTRACT

Recent rapid developments of information and communication technologies (ICT) enable a virtual space, which allows people to conduct activities remotely through tele-presence rather than through conventional physical presence in physical space. ICT offer people additional freedom in space and time to carry out their activities; this freedom leads to changes in the spatio-temporal distributions of activities. Given that activities are the reasons for travel, these changes will impact transportation systems. Therefore, a better understanding of the spatial and temporal characteristics of human activities in today's society will help researchers study the impact of ICT on transportation. Using an integrated space-time system, Hägerstrand's time geography provides an effective framework for studying the relationships of various constraints and human activities in physical space, but it does not support activities in virtual space. The present study provides a conceptual model to describe the relationships of physical space and virtual space, extending Hägerstrand's time geography to handle both physical and virtual activities. This extended framework is used to support investigations of spatial and temporal characteristics of human activities and their interactions in physical and virtual spaces. Using a 3D environment (i.e., 2D space + 1D time), a temporal GIS design is developed to accommodate the extended time-geographic framework. This GIS design supports representations of time-geographic objects (e.g., space-time paths, network-based space-time prisms, and space-time life paths) and a selected set of analysis functions applied to these objects (e.g., temporal dynamic segmentation and spatio-temporal intersection). A prototype system, with customized functions developed in

Visual Basic for Applications (VBA) programs with ArcObjects, is implemented in ArcGIS according to the design. Using a hypothetical activity dataset, the system demonstrates the feasibility of the extended framework and the temporal GIS design to explore physical and virtual activities. This system offers useful tools with which to tackle various real problems related to physical and virtual activities.

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CHAPTER 1:

INTRODUCTION

1.1 Research Background and Objectives

Our daily lives are composed of various activities. Considered as derived demand, travel is of great importance to activities because it can take us to the right places to participate in the activities (Hanson, 1995; Miller and Shaw, 2001). Distributions of activities in space and time determine where and when travels are needed, and activity-based approach became a paradigm in transportation studies in the 1970s (Brög and Erl, 1981; Frusti *et al.*, 2003). A better understanding of the spatial and temporal characteristics of human activities, therefore, can contribute to transportation studies. Recent developments of information and communication technologies (ICT), such as the Internet and cellular phones, allow information to flow more efficiently. The use of ICT is changing how we carry out our daily activities in space and time. We can now conduct many activities, such as banking, shopping, entertaining, and even working, through the Internet without leaving home. We can easily get in touch with our families, friends, and colleagues almost at any time and in any place using cellular phones. These changes will have great impact on transportation systems and need more research attention.

Physical space is the conventional stage in which people carry out their activities, and it allows movements of both physical materials and information between places. When people perform activities in physical space, they need to be physically present in specific locations during particular time periods and travel is usually involved. This mode of participating in activities is known as *physical presence*, and it has been the predominant mode for people to conduct activities. However, ICT enable a different space, which can connect us electronically and transmit information more efficiently than physical space. This space is constructed using the facilities of ICT and provides electronic linkages among places; it has been named *virtual space* or *cyberspace* in the literature (Janelle and Hodge, 2000).

Virtual space allows people to conduct activities from distant locations instead of being physical present in physical space. This new mode is known as *tele-presence*. In other words, people now have the choice of conducting activities either through physical presence in physical space, or through tele-presence in virtual space. Activities conducted in physical space are named *physical activities* and those conducted in virtual space are called *virtual activities* in this study. With virtual space and tele-presence, we gain additional freedom in space and time to carry out activities and interactions. For example, mobile phones offer people new freedom in space because they are no longer constrained to the fixed locations of landline phone services. We can now purchase air tickets or search for literature on the Internet regardless of the business hours of travel agencies and libraries. The freedom gained can affect how we arrange our daily activities and how the activities are distributed in space and time. The subsequent changes of spatio-temporal patterns of activities can lead to changes in transportation systems. Therefore, it is a crucial research topic in transportation studies in order to understand spatio-temporal characteristics of human activities in today's society.

Each individual human activity takes place in a particular space-time context, and space and time are the two major factors that constrain an individual from carrying out activities (Golledge and Stimson, 1997). Activities are distributed at different locations. Travel is required to complete a physical activity because it helps overcome physical separation between activity locations. Travel takes time; the greater the distance of physical separation, the more time needed to overcome it. Therefore, travel is a means of trading time for space. In a limited time budget, if more time is needed for travel, less time becomes available for an individual to conduct activities. Researchers, aware of the relationship of space and time in controlling human activities, have argued that a framework integrating space and time can provide a more realistic approach to studying human activities (Hägerstrand, 1970; Parkes and Thrift, 1980). Torsten Hägerstrand (1970) proposed a framework to examine the relationships between various constraints and human activities in a space-time context, known as *time geography*. Further efforts were made by Hägerstrand and his research collaborators to advance the framework (Wachowicz, 1999). Adopting an integrated space-time system, time geography uses the concept of a *space-time path* to describe an individual's trajectory in physical space over time, and the concept of a *space-time prism* to depict the extent in physical space and time that is accessible to an individual under certain constraints. With these concepts, the framework provides an effective approach to studying human activities in a space-time context. Researchers have frequently used the framework to study spatial and temporal characteristics of human activities in physical space (Lenntorp, 1976; Carlstein *et al.*, 1978; Parkes and Thrift, 1980; Carlstein, 1982; Ellegård, 1999).

The developments of ICT have enhanced our ability to conduct activities and interact with others (Wiberg, 2005). Physical location is not as important to virtual activities as to physical activities. As some activities can be conducted in virtual space, people can engage in these activities remotely from locations where they have access to virtual space. Through tele-presence, physical separation is no longer a barrier to virtual activities, and the requirements of travel are reduced. Therefore, virtual activities are constrained by space-time constraints different from physical activities, which can lead to different spatio-temporal patterns of human activities. As an increasing number of activities are conducted in virtual space, the changes in spatio-temporal patterns of human activities will impact transportation systems, and eventually influence the urban form and structure of our society (Salomon, 1998; Couclelis and Getis, 2000). What are the constraints for virtual activities, and how do they constrain people from carrying out virtual activities in space and time? Since ICT were not very advanced and widely adopted during the time when Hägerstrand proposed time geography, the original time-geographic framework focused mainly on human activities in physical space. Consequently, the framework falls short of providing a complete view of human activities with their space-time constraints in today's society. Efforts are needed to extend the current time-geographic framework to deal with activities in both physical and virtual spaces.

The time-geographic framework offers an effective approach to many problems related to human activities. However, partially due to limited computational resources, it was used primarily as a conceptual model in most studies and limited progress has been made in implementing it with computational models (Yuan *et al.*, 2004). Geographic information systems (GIS), which are designed to efficiently handle spatial data and solve spatial problems, have experienced rapid development during the last several decades. Due to the increasing power of representing and solving space-related problems, GIS are considered a potential approach to managing human activities with their spatial and temporal characteristics (Pipkin, 1995). Attempts have been made to store and manage individual activities in GIS to support basic queries on their spatial and temporal attributes (e.g., Shaw and Wang, 2000; Wang and Cheng, 2001; Frihida *et al.*, 2002). Miller (1991) first brought time-geographic concepts into GIS, using space-time prisms to help study accessibility. A procedure was developed in GIS to calculate feasible space in a network that is accessible to an individual under specific space-time constraints. Additional efforts have been made to incorporate time-geographic concepts in GIS to facilitate analysis of human activities in a space-time context (Kwan and Hong, 1998; Kwan, 1999; Miller, 1999; Kwan, 2000a, b; Miller and Wu, 2000; Weber and Kwan, 2002; Kim and Kwan, 2003; Weber, 2003). These attempts provide valuable experience in representing activities with their spatio-temporal characteristics in GIS. However, a GIS design, which can provide an integrated space-time representation and support an effective implementation of the time-geographic framework, has not yet been developed. The University Consortium for Geographic Information Science (UCGIS) has recognized extending GIS with spatio-temporal representation as one of thehigh priority research issues in Geographic Information Science (GISci) (Yuan *et al.*, 2004). Efforts are needed to develop a GIS design that can accommodate the extended time-geographic framework to explore human activities in both physical and virtual spaces.

This study focuses on extending the time-geographic framework to deal with both physical and virtual activities and on developing a temporal GIS design to incorporate the framework for exploring spatial and temporal characteristics of human activities in today's society at the individual level. The three major research objectives in this study are identified as the following:

1) To gain a better understanding of the space-time constraints of human activities in physical and virtual spaces and extend Hägerstrand's time-geographic framework to examine both physical and virtual activities in a space-time context;
2) To bring explicit time representations into GIS, design a temporal GIS model to accommodate effectively the extended time-geographic framework and support analysis of the spatial and temporal characteristics of human activities;
3) To develop a prototype system to provide a proof-of-concept test for the feasibility of the extended time-geographic framework and the temporal GIS design.

1.2 Research Questions

A series of challenging research questions are involved in incorporating an extended time-geographic framework into a temporal GIS design study human activities in both physical and virtual spaces. Four research questions, which address selected fundamental research issues within this challenging topic, are identified in this study. The realization of research objectives of this study depends on working out proper answers to the following questions:

1) <u>What are the relationships of physical space and virtual space, and how do they serve as a stage for people to carry out activities?</u> Individuals in the

modern society are dealing with two spaces: they can conduct activities through either physical presence or tele-presence. Although the two spaces have very different natures when they serve as a stage for the performance of human activities, researchers have realized that they are not mutually exclusive, but intersect and impact each other (Batty and Miller, 2000). The existence of virtual space is supported by ICT infrastructures in physical space, and information retrieved from virtual space can impact people's travel decisions in physical space. Therefore, how do the two spaces interact to function as the stages for people to conduct their activities? A conceptual model representing the relationships between physical and virtual spaces is needed to guide this research.

2) How can Hägerstrand's time-geographic framework be extended to include both physical and virtual activities in a space-time context? Time geography identifies the constraints that can limit the performance of human activities in physical space and time. The space-time context of a physical activity can be explicitly represented through its space-time path, and potential physical activities that are available to an individual in physical space and time can be depicted by a space-time prism. However, virtual activities can be carried out through tele-presence in virtual space. Therefore, physical distance is not as important to virtual activities as to physical activities. What are the constraints for virtual activities? How will they impact virtual activities? Will space-time paths and prisms take different forms to describe virtual activities? How can these concepts be modified to represent virtual activities in a space-time

context? These questions need to be answered in order to extend Hägerstrand's time-geographic framework to handle both physical and virtual activities.

3) How can the time-geographic framework be incorporated into GIS? The time-geographic framework is developed in an integrated space-time system. Therefore, the time dimension must be included in a GIS design so that it can support representations of time-geographic concepts. Although temporal GIS has been an active research topic for about two decades, current GIS software packages are very limited in handling temporal data. How can the time dimension be brought into current GIS designs to incorporate time-geographic concepts? What types of time-geographic objects are needed for the time-geographic framework and how can they be explicitly represented in GIS? How can these time-geographic objects be used to represent physical and virtual activities with their space-time contexts and spatio-temporal patterns for human interactions? A temporal GIS design is needed to answer these questions and support the implementation of the extended time-geographic framework for physical and virtual activities.
4) What spatio-temporal analysis functions are needed to explore human activities and interactions, and how can they be implemented in GIS? GIS are not only for data representation and data visualization. The power of GIS relies on useful analysis functions provided to reveal information hidden in the datasets and gain a better understanding of the geographic phenomenon under study. Human activities and interactions take place in specific spatial

and temporal contexts, and they may share particular spatio-temporal relationships. What are the possible spatio-temporal relationships among people? What spatio-temporal analysis functions are needed to help researchers explore spatial and temporal characteristics of human activities and interactions? How can a temporal GIS be design to implement these functions with time-geographic objects? These analysis functions are needed in a GIS design that can effectively support exploration of physical and virtual activities in a space-time context.

A conceptual model of relationships between physical and virtual spaces will be developed to help identify constraints in space and time applied to virtual activities. Such an effort leads to the development of an extended time-geographic framework for both physical and virtual activities. The concepts of space-time path and prism will be extended to represent virtual activities. Based on the needs of this framework, a temporal GIS will be designed to support representations of time-geographic objects in the framework. Spatio-temporal analysis functions, which can help explore spatio-temporal relationships of people who are involved in interactions, will be defined and implemented in the GIS design. The temporal GIS design of the extended time-geographic framework will present an effective approach to the study of spatio-temporal characteristics of human activities in both physical and virtual spaces at the individual level.

1.3 Organization of the Dissertation

This dissertation is organized into six chapters. The next chapter reviews the literature relevant to this study, including activity-based approach in transportation studies, time geography, ICT and human activity, and temporal GIS. The literature review identifies the specific efforts needed to extend the time-geographic framework and develop a temporal GIS design for exploring physical and virtual activities in a space-time context. Chapter 3 is devoted to extending the time-geographic framework to handle both physical and virtual activities. Beginning with discussions of relationships of physical and virtual spaces, this chapter re-visits the space-time constraints that limit human activities in physical and virtual spaces. Concepts in Hägerstrand's time geography are then extended to describe human activities in physical and virtual spaces and are used to assist in analysis of spatio-temporal relationships of individuals involved in interactions. With the extended time-geographic framework, the design of a temporal GIS model is presented in Chapter 4. How can time dimension be integrated into GIS? How can the concepts in the extended time-geographic framework be modeled in GIS? How can a temporal GIS be designed to help analyze spatio-temporal relationships of activities? Chapter 4 provides answers to these questions. Chapter 5 focuses on the creation of a temporal GIS prototype system implementing the design developed in Chapter 4. The feasibility of the framework and temporal GIS design are demonstrated in the prototype system with a set of functions developed to examine spatio-temporal characteristics of physical and virtual activities. A hypothetical human activity dataset is used to run the functions and the results are shown in this chapter. Chapter 6 summarizes the major achievements of this study and provides examples of potential applications of the system. Future research directions are also discussed in this final chapter.

CHAPTER 2:

LITERATURE REVIEW

Several research fields that can help investigate the relationship of activities and transportation in today's society are closely related to the study of a temporal GIS design for an extended time-geographic framework with physical and virtual activities. Transportation studies experienced a paradigm shift in the 1970s (Brög and Erl, 1981; Frusti *et al.*, 2003). Researchers began to take an activity-based approach to transportation studies in which the distributions of activities in space and time can determine where and when people travel. More studies focus on individual activities because the relationships between activities and travels can be clearly examined at the individual level. Time geography (Hägerstrand, 1970), which studies the relationships of constraints and human activities in a space-time context, offers a useful framework to support activity-based transportation studies. However, the framework mainly deals with activities in physical space. With the development of virtual space enabled by ICT, people are changing the ways they carry out activities in space and time. These changes will impact transportation systems. Therefore, the time-geographic framework needs to be extended to deal with activities in both physical and virtual space. GIS have been considered a powerful tool to solve spatial problems and efforts have been devoted to integrate time into GIS. This chapter provides literature reviews of the activity-based approach to transportation studies, time geography, ICT and transportation, and temporal GIS, which provide the research foundation for the study in this dissertation.

2.1 Activity-based Approach in Transportation Studies

An aggregate approach has been widely adopted in conventional travel studies, using pre-defined zones to examine travel patterns. Quantitative methods are frequently used to describe the characteristics of trips at the aggregate level, or to predict trips generated from a region or between regions. The well-known four-stage Urban Transportation Modeling System (UTMS) is based on aggregate travel data, and it is still used by many transportation planning agencies. However, the aggregate approach to travel studies has received many criticisms from transportation researchers due to its obvious deficiencies in providing an accurate picture of how and why people travel. For example, predicted trip distribution between traffic analysis zones are dependent on how the zones are delimited. Information about the various characteristics of trips is lost when trips are represented by aggregated numbers. Therefore, many researchers argued that geographic research should not be based on arbitrary spatial units (Webber, 1980), and transportation studies should take a disaggregate and behavioral approach (Brög and Erl, 1981; Pipkin, 1995). Moreover, most aggregate models "treat transportation as something desired for its own sake" (Miller and Shaw, 2001, p. 268). However, travel is usually required to fulfill other demands, such as social and physiological needs, and it should be treated as a *derived demand* (Hanson, 1995; Miller and Shaw, 2001). In the 1970s, a paradigm shift took place in transportation studies. An activity-based approach was proposed to replace the trip-based, aggregate approach of travel analysis (Brög and Erl, 1981; Jones, 1990; Frusti *et al*., 2003).

An activity-based approach focuses on trips made by individuals, which are closely related to their specific daily schedules (Kutter, 1973). This approach brings back various characteristics of trips that have been ignored in aggregate models (Pipkin, 1995). By looking into the reasons underlying trips made by individuals, activity-based analysis enhances the concept of treating transportation as a derived demand and ties travel to its contextual backgrounds. In an aggregate approach, trips are taken out of their contexts and treated as independent behaviors. However, from an activity perspective, individuals travel to connect daily activities distributed at different locations, such as home, work, and grocery stores (Damn and Lerman, 1981; Kitamura *et al.*, 1990). Also, people often arrange multiple purposes and make multiple stops along their trips. For example, a working mother does grocery shopping and picks up her child at a day-care center on her way home from work. Therefore, trips are chained and usually have multiple stops (Miller and Shaw, 2001). An activity-based approach also puts more emphasis on the importance of time for travel (Pipkin, 1995). As activities usually take place during specific time periods, transportation is required to take individuals to the activity locations in a timely manner; the temporal distribution of trips is of great importance to transportation studies. For example, morning rush-hour congestion occurs because too many individuals are on the roads during the same time when they all need to reach their work places around the same time. An activity-based approach takes the time dimension into account in transportation studies and provides more detailed descriptions on travel patterns than an aggregate approach.

An activity-based approach emphasizes not only travels but also individual participation in activities and the relationships among the activities (Hanson and Schwab, 1995). People do not undertake travel for its own sake. They travel to specific locations at the particular time periods that allow them to participate in a set of activities. Each individual has a daily schedule of activities. These activities may have different priorities. Kitamura and Fuji (1998) classified daily activities into two types: activities related to work or school are usually conducted at fixed locations during the fixed times, and they are considered as *fixed activities* and require *blocked periods;* activities related to shopping and entertaining are *flexible activities*, which can be carried out in *open periods* with higher flexibility. The spatio-temporal distributions of an individual's fixed activities can impact how the individual carries out flexible activities. The ways in which people arrange and choose to conduct their daily activities present very complex and challenging research issues (Pipkin, 1995). Examining human activities in a space-time context can help researchers gain a better understanding of spatial and temporal characteristics of activities. A proper theoretical framework is needed to assist in the activity-based transportation studies.

2.2 Time Geography and Spatio-temporal Characteristics of Human Activities

Time geography provides a framework to support activity-based transportation analysis and represent trips and activities with their space-time contexts (Pipkin, 1995). Originally proposed by Torsten Hägerstrand (1970), time geography was developed to study the relationships between human activities and various constraints applied to them in a space-time context (Golledge and Stimson, 1997; Miller, 2004b). Hägerstrand and his colleagues argued that time should not be considered as an external factor only when we examine human activities; time, as essential as space, should be involved in the process of examination. Treating time as a term equal to space, the framework adopts a three-dimensional orthogonal coordinate system, with time as the third dimension added to a two-dimensional spatial plane. The space dimensions are used to measure location changes of objects, while the time dimension is used to order the sequence of events and to synchronize human activities. Using this system, time geography is ready to model human activities and travels with their spatial and temporal characteristics.

2.2.1 Space-time constraints and human activity

Time geography assumes that an individual's freedom of movement is limited by various constraints (Hägerstrand, 1970). Different people may encounter different constraints and possess various levels of freedom to access activity opportunities around them. Even the same individual may experience different sets of opportunities under different spatio-temporal circumstances. These constraints are identified in the time-geographic framework to examine the reasons why an individual moves in a particular pattern (Golledge and Stimson, 1997). Three types of constraints that can impact an individual's ability to conduct activities in space and time are defined in time geography (Golledge and Stimson, 1997):

1) *Capability constraints* are attributes of individuals that can limit their participation in activities at specific locations during particular time periods. They include the physiological necessities of an individual (e.g., sleeping and eating), which limit an individual's ability to allocate large portions of time for activities, and the resources available to an individual (e.g., auto ownership), which determine the maximum distance that an individual can cover within a given time budget.

2) *Authority constraints* reflect general rules or laws that limit a person's access to either spatial locations (e.g., a military area) or time periods (e.g., a store's open hours). For example, only those with special permits can enter a military area and a customer has to visit a shopping mall during its hours of business. These types of constraint describe the relationship of human beings and the environment.

3) *Coupling constraints* are spatial and temporal requirements that allow an individual to bundle with other individuals to conduct certain activities. For example, in order to have a face-to-face meeting, all participants are required to be present at the same location (e.g., a conference room) during the same time period (e.g., from 2PM to 4PM).

Capability constraints emphasize characteristics of a single individual and authority constraints focus on impacts of physical or social environments applied to a single individual. However, coupling constraints deal with interactions among multiple persons, which makes these types of constraint more complicated than the other two. Because people are social beings, interaction is an important element of most daily activities. Coupling constraints directly define the requirements in space and time that allow people to interact with each other. Capability constraints and authority constraints indirectly determine whether two individuals can couple; they limit the movements of an individual and control whether each individual is able to be present at a certain location during a certain time period for interaction. Taken together these three types of constraints control the spatio-temporal patterns of people's movements.

2.2.2 Space-time paths and space-time prisms

Time geography has two basic concepts, known as *space-time path* and *space-time prism*, to portray human activities with their spatial and temporal characteristics in an integrated space-time system (Hägerstrand, 1970). A *space-time path* is the trajectory of an individual's movements in physical space over time (Figure 2.1a). A space-time path can be considered as a linear feature in the 3D space-time system, which provides a continuous representation for the history of an individual's locations in space. A path is composed of a connected set of vertical segments and tilted segments. Each vertical segment indicates that a person stays at a specific location for a time period; the individual may conduct activities at the location during the time period. Each tilted segment refers to a travel activity, with the slope of the segment representing the travel speed. Thus, a space-time path can be considered as a container of various activities and

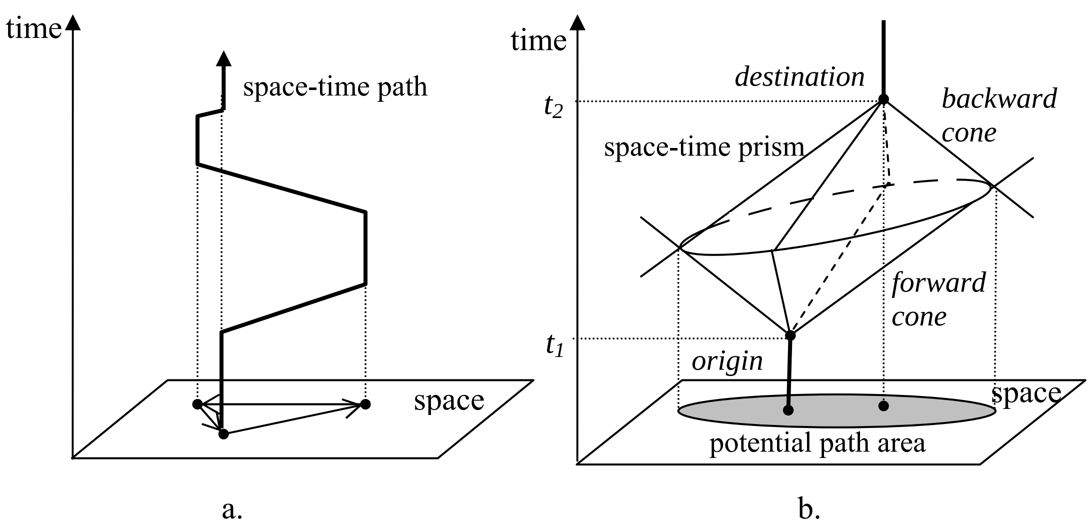


Figure 2.1. Space-time path and space-time prism.

travels (special types of activity) conducted by an individual during an observed time period. Travel activities can be easily retrieved from a space-time path by locating the tilted portions along the path. Activities other than travel can be correctly located on a path according to their temporal information (starting and ending times). Therefore, a space-time path can provide detailed information about the spatial and temporal characteristics of an individual's actions, including the starting/ending times and locations of activities, the duration of each activity, and the sequence of activities. Moreover, it organizes these characteristics of activities into an integrated space-time system (Miller, 2004b). Using such a form, the concept of a space-time path addresses the requirements for activity-based transportation analysis in the following ways:

1) The integrated space-time system enables explicit time representations for activities;
2) The concept of transportation as derived demand is represented in a space-time path by an alternating pattern of vertical segments (activities) and tilted segments (travels) on the path;
3) The issue of trip chaining and trips with multiple stops/purposes is solved by connecting all activities according to their time sequence in a space-time path.

Hence, the space-time path concept offers an effective approach to representing the space-time contexts of human activities and supports spatio-temporal analysis of human activities. This approach has been used in several studies related to human activities (e.g., see Lenntorp, 1976; Carlstein *et al.*, 1978; Parkes and Thrift, 1980; Carlstein, 1982; Ellegård, 1999).

A *space-time prism* depicts the extent in space and time that can be accessed by an individual under a specific set of constraints (Lenntorp, 1976). A prism forms a continuous space in the orthogonal space-time coordinate system defined in time geography (Figure 2.1b). Transportation is considered as a means to trade time for space since movements in physical space take time (Miller and Shaw, 2001). Given a location and a time period, a person can stay at the location for the entire time duration. If s/he wants to move to a new location, the physical movement uses time, and the time available for activities at the new location is shortened accordingly.

The space-time prism in Figure 2.1b displays a situation with constraints at both origin and destination. An individual will start from the origin location at t_1 and need to reach the destination by t_2 within a time window of $(t_2 - t_1)$. The *forward cone*, which starts at the origin and goes upward in the figure, demarcates the extent that can be reached by this individual, and the *backward cone*, which ends at the destination and goes downward in the figure, demarcates the boundary that the individual can start out and arrive at the destination by the designated time. The space-time prism enclosed by these two cones indicates potential opportunities in space and time to the individual. The slope of the prism is determined by the travel speed. When the travel speed is higher, the slope of the prism is flatter, which indicates that an individual can trade time more efficiently for space and can cover a larger area within the same time period (Golledge and Stimson, 1997; Carlstein, 1982). Therefore, the volume of a space-time prism, which represents potential activity opportunities in space and time to an individual, is mainly determined by the travel speed of the person, available time budget, and the distance between the current location and the next location to visit.

If we project a space-time prism onto a 2D plane, the result will be a region, which is known as *potential path area* (shown as shaded area in Figure 2.1b). The concept of space-time prism can be used in activity-based transportation studies. Miller (1999) and Kwan and Hong (1998) used space-time prisms to identify the feasible choice sets for activities under space-time constraints. Kitamura and Fuji (1998) used prisms to assist in the task of arranging flexible activities in an open time period formed by two fixed activities.

2.2.3 Spatio-temporal relationships of space-time paths

Interacting with others is an important component of daily life. Most activities involve multiple individuals and require coordination among the participants. When space-time paths are used to represent activities of individuals, interactions will be reflected in particular spatio-temporal relationships of their paths. Therefore, if a specific spatio-temporal relationship is found among a set of space-time paths, it implies that these individuals may be involved in a certain type of interaction.

Three basic relationships of space-time paths have been described in the literature: *co-location in time*, *co-location in space*, and *co-existence* (Parkes and Thrift, 1980; Golledge and Stimson, 1997) (Figure 2.2). *Co-location in time* represents the situation that activities from different space-time paths exist in the same time duration. Hägerstrand used collateral processes to describe this spatio-temporal relationship (Wachowicz, 1999). *Co-location in space* exists when activities from different space-time paths occupy the same location during different time durations. *Co-existence* describes

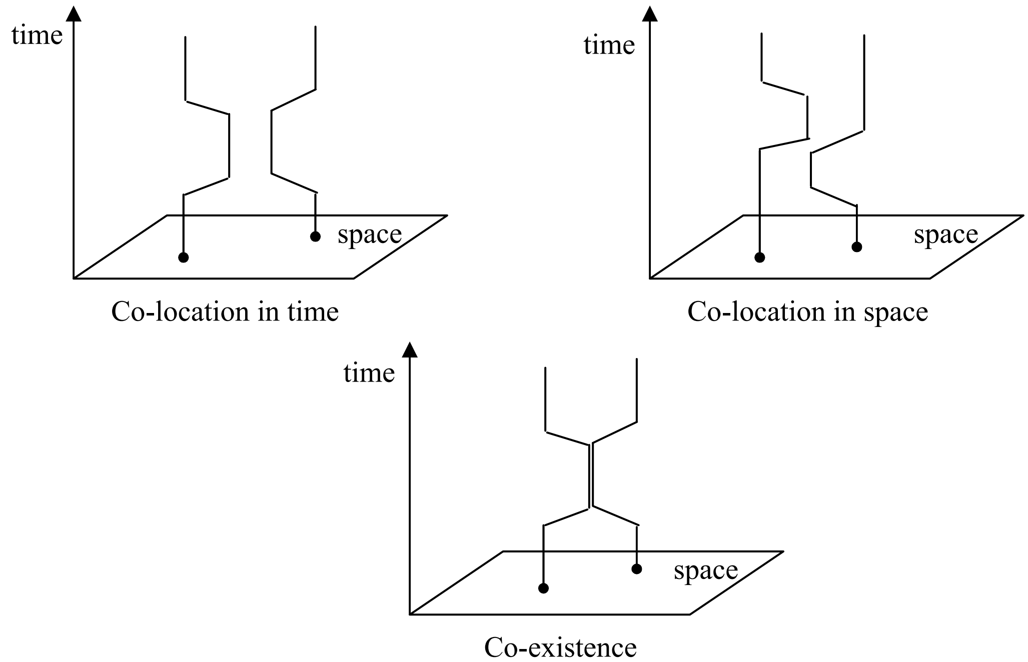


Figure 2.2. Basic relationships of space-time paths.
(*Source: Golledge and Stimson, 1997, p. 269*)

the condition when activities take place at the same location during the same time duration.

Co-existence is a very important spatio-temporal relationship among individuals. It describes the concurrence of activities of multiple individuals in both space and time. The coupling constraints of time geography, which define the spatial and temporal requirements for people to carry out certain activities together, refer to this type of spatio-temporal relationship. Figure 2.2 shows a case of co-existence in which individuals are coupled at a fixed location. However, it is not the only way for people to share the co-existence relationship. Miller (2005a) recognized that people could also have a co-existence relationship in dynamic situations. For example, when people ride a bus together or carpool to work, they share a dynamic case of co-existence relationship. The co-existence relationship is frequently adopted in interactions and is a dominant mode for people to carry out interactions in physical space.

2.3 ICT, Virtual Space, and Changing Patterns of Human Activity

In recent decades, our society experienced rapid developments of ICT, such as the Internet, cellular phones, and wireless-enabled personal digital assistants (PDA). Accompanying the developments of ICT, the number of ICT service providers and their users are growing at a fast rate. According an Internet domain survey conducted by the Internet Systems Consortium (2004), the number of Internet hosts increased nearly seven times from 29.67 million in January 1998 to 233.1 million in January 2004. During the twelve years from 1991 to 2003, subscribers of main telephone lines, cellular phone services, and the Internet users in the world have increased dramatically, from 546 million to 1147 million for main telephone lines subscribers, from 16 million to 1341 million for cellular phone customers, and from 4.4 million to 688 million for Internet users (International Telecommunication Union, 2004). The growing use of ICT has altered how people carry out their activities and how they interact with each other leading to changes in spatial and temporal characteristics of human activities.

2.3.1 Virtual space and the evolving concept of distance

The wide adoption of ICT in today's society has enabled the creation of a parallel space in addition to conventional physical space. The enabled space depends on the infrastructures and facilities of ICT that reside in physical space. This space can carry information flows efficiently and enhance the connections between people through electronic linkages: it is called *virtual space* or *cyberspace* in the literature (Janelle and Hodge, 2000). Different from physical space, which is made of atoms, virtual space is considered to be composed of bits of information (Negroponte, 1995).

The frictional effect of distance is one of the key concepts in physical space because it can be used to describe and measure physical separation. Therefore, the concept of distance plays an important role in transportation analysis in that transportation is the means to help people overcome physical separations. When transportation technologies make progress, people are able to move faster than before and have greater efficiency in trading time for space. The result is a shorter time needed to connect two geographically separated places. Janelle (1968, 1969) used the term *time-space convergence* to describe this process, which leads to a "shrinking world. " The time-space convergence invoked by transportation occurs at a relatively low rate. For example, a study has shown that London and Edinburgh have converged to each other at an average rate of 29 minutes per year from 1776 to the mid 1960s (Gillespie and Janelle, 2004). However, the existence of virtual space enabled by ICT brings the time-space convergence of our world to a different level. Information in the formats of text, voice, and image can be transmitted from one end of the world to the other through ICT infrastructures and facilities (e.g., telephone network and the Internet) without a significant time delay. Also, ICT provide various ways for people to interact with each other across the space and enhance the connectedness of people at different locations (Wiberg, 2005). Although the claim of "the death of distance" by Cairncross (1997) has been counter argued by geographers, there is little doubt that the traditional concept of distance is being altered by the use of ICT. As an alternative to transportation, ICT can also bring people together and can do it more efficiently than transportation over long distances. This can change the foundation of transportation in the future and demands careful considerations (Janelle, 2004).

2.3.2 ICT and transportation

The relationship between telecommunications and transportation is not a new topic of study. It has been discussed in transportation literature since the early 1970s, when researchers began to look into the possibility of telecommunication substitutions for transportation to deal with the energy crisis (Mokhtarian, 1990). However, recent rapid progress in ICT has made such studies even more urgent, since the users of ICT are growing and the usage of ICT is becoming part of everyone's daily lives. In today's society, more modes exist for people to communicate with each other, and the interactions among people have been enhanced by the use of ICT (Wiberg, 2005). Salomon (1986) argued that conveying information and interacting with others are among the major reasons people to travel.

The following four different types of relationships between ICT and transportation have been reported in the literature (Salomon, 1986; Mokhtarian, 1990):

(1) *Substitution*, which describes situations in which travel can be replaced by a communication through ICT (e.g., a person manages bank accounts through the Internet instead of visiting a local bank branch);

(2) *Enhancement*, which indicates situations when extra trips are stimulated due to the use of ICT (e.g., a person goes to a concert after finding out information on the Internet);

(3) *Operational efficiency*, which portrays the complementary relationship of ICT and transportation to complete individuals' activity needs (e.g., a person changes the route to avoid traffic congestion after receiving travel advisory messages over a cellular phone);

(4) *Indirect, long-term impacts*, which focuses on the long-term interactions between ICT and transportation (e.g., telecommuting, which allows people work at home while connecting to the central office through telecommunications, may eventually change the urban form, which in turn can affect transportation).

Different terms and classifications have been used to describe the relationships of ICT and transportation. In a slightly different classification proposed by Mokhtarian and Meenakshisundaram (1999), the category of indirect, long-term impacts is dropped. A new category of *neutrality*, which indicates that the use of one mode has no impact on the other, is added. The first three categories in this recent classification are the same, but different terms are used. G*eneration* (or *stimulation*, or *complementarity*) is used to replace the term *enhancement*, and *modification* is used to replace the term *operational efficiency*. Substitution implies that the use of ICT can reduce the number of trips, while generation indicates that the use of ICT introduces trips that have not been planned previously. Modification can lead to a better organization of trips, which may reduce travel. Neutrality indicates the use of ICT will not impact trips.

Salomon (1998) suggests that telecommuting, teleshopping, and teleconferencing are the three major applications of ICT to substitute travel. Empirical studies of the impact of telecommuting on transportation have been implemented during the past decade. Mokhtarian *et al.* (1995) reported several findings based on eight telecommuting pilot programs. Their findings partially confirmed Salomon's statement above. They found that the number of commute-miles of an individual participating in telecommuting reduced significantly, and that the number of non-commute travels and total weekday travels did not change significantly. They also detected the changes in temporal distributions of trips, as more trips shifted out of peak hours. Zumkeller (1996) conducted a disaggregate, cross-sectional study on the relationship of communication and transportation. Evidence of the complementarity effect is detected in the study and it is much stronger than substitution, which means the use of ICT introduces more trips in our daily lives. However, using disaggregate activity diary data, Mokhtarian and Meenakshisundaram (1999) conducted a complementarity effects study of telecommunication and transportation in the city of Davis, California. They found that the complementarity presented was not very strong and the substitution effect was even weaker.

Researchers have recognized the difficulty and complexity of studying the relationships between ICT and transportation. Most existing empirical studies adopt aggregate approaches and use statistical methods to describe and examine the impact of ICT on transportation. As discussed above, various effects of ICT may apply to transportation (Salomon, 1986; Mokhtarian, 1990; Mokhtarian and Meenakshisundaram, 1999). On the one hand, ICT can be used to substitute for transportation, which can reduce the number of trips. But, on the other hand, ICT bring extra information and expose additional activity opportunities to individuals, which may generate more trips. When these effects are combined at the aggregate level, it is difficult to predict the direction of the changes (Mokhtarian, 1990). Therefore, aggregate approaches and statistical analyses cannot provide an accurate picture for the roles of ICT and transportation in people's daily lives. Mokhtarian (1990, p. 240) commented that "the most important impact of telecommunications may not be that it increases or decreases the amount of travel that takes place, but that it permits a great deal more flexibility in whether, when, where, and how to travel." ICT provide more choices in addition to transportation for individuals to carry out activities and offer more flexibility to conduct them. They allow people to schedule their activities with a higher degree flexibility (Golob and Regan, 2001), which can lead to structural changes of people's trips. A disaggregate approach can provide direct examinations of how an individual decides to conduct activities using both ICT and transportation. Therefore, a disaggregate approach presents an effective way to study the complex relationships between ICT and transportation.

2.3.3 ICT, human beings as extensible agents, and four communication modes

Researchers have recognized that ICT can enhance the connections between people by providing electronic linkages in virtual space (Janelle and Hodge, 2000). The electronic linkages can replace transportation in some situations to help people overcome physical separations and participate in activities. In social studies, human beings have been considered agents who can sense their environment and interact with each other (Janelle, 1973). Without the help of any appliance, the agency or the sensing capability of a person can only reach limited range, which is usually within the physical proximity of the person. Therefore, before an individual can efficiently sense a particular environment (i.e., participate in an activity) or communicate with another individual (i.e., interact with others), this individual needs to reach the physical proximity of the location or the other individual. Such a mode is known as *physical presence* (Miller, 2005b). Travel is usually required in physical presence so that people can appear in the physical proximity of desired locations. For example, participants from all over the country arrive at the same place, usually a conference center, to attend an annual meeting to exchange information and ideas. Before the wide adoption of ICT in our society, physical presence was the predominant mode for people to carry out their activities.

The agency and sensation of people are significantly extended with the intensive use of ICT in our daily lives (Adams, 1995, 2000; Kwan, 2000a). With the help of ICT, such as the Internet and cellular phones, an individual can reach out far beyond his/her physical proximity. For example, one person can contact another who is thousands of miles away through a telephone call or instant messaging over the Internet. With ICT, an individual can participate in an activity remotely, instead of through physical presence. This mode is known as *tele-presence*. Adams (2000) used six categories to define the spatial scopes that are involved in people's activities at different social scales. The categories include the physical proximity of people, which applies to physical presence. The other five scopes can be reached through tele-presence, ranging from local level up to the international level. Kwan (2000a) used three levels to depict the extended agency of an individual in her study, with a local level that can be reached by physical presence, and a national level and an international level that can be reached through tele-presence. As tele-presence can help people overcome the barrier of distance, activities carried out through tele-presence do not depend exclusively on travel as in the case of physical presence. Therefore, once people gain access to virtual space, they can conduct activities through tele-presence while they are still physically separated from activity locations or other participants.

People can enjoy more flexibility to carry out activities with the extended sensation enabled by ICT. Tele-presence allows participants to be involved in the same activity while they are at different locations. It provides people an extra choice in carrying out activities in addition to physical presence. Also, people can choose to participate in an activity during the same time or at different times. Recently, researchers have studied different types of communication methods based on their spatial and temporal characteristics (Janelle, 1995, 2004; Harvey and Macnab, 2000; Miller, 2005b). Four types of methods have been identified to categorize communications with physical presence and tele-presence (Table 2.1). Conventional face-to-face meetings require

Table 2.1. Communication modes based on their spatial and temporal constraints
(Adapted from Miller, 2005b)

Temporal / **Spatial**	*Synchronous*	*Asynchronous*
Physical presence	*SP* Face to face (F2F) meetings	*AP* Post-it® notes Traditional hospital charts
Tele-presence	*ST* Telephone calls On-line chat rooms Teleconferences	*AT* E-mails Web pages

participants to be at the same location during the same time period. A communication mode requiring coincidence in both space and time is classified as *Synchronous Physical presence* (SP). Post-it notes or bulletin boards require people visit the same location, although perhaps at different times, to complete the information exchange. This type of communication, requiring coincidence in space but not in time, is called *Asynchronous Physical presence* (AP). With the use of ICT, people are no longer required to be present at the same physical location for communication. *Synchronous Tele-presence* (ST) only requires coincidence in time (e.g., two friends at different locations instant messaging over the Internet). Finally, *Asynchronous Tele-presence* (AT) is free from coincidence requirements in either space or time. E-mail between people belongs to this type of communication. This classification system can also be applied to describe different types of human activities and interactions based on their spatial and temporal requirements. Prior to the wide adoption of ICT, human activities used to be carried out in physical space through either SP or AP mode. With tele-presence enabled by ICT, ST and AT modes have become available for interaction. As alternatives to SP and AP modes, ST and AT interactions are changing the ways people interact with each other and altering their spatio-temporal activity patterns.

2.3.4 Challenges to time geography

Time geography provides an effective framework to study human activities in physical space at the individual level. It is reasonable to consider it as a possible framework to study spatial and temporal patterns of individual activities under the impacts of ICT.

However, several research challenges need to be tackled to extend Hägerstrand's time geography to deal with human activities in both physical and virtual spaces.

The agency of an individual has been extended far beyond his/her physical proximity by the use of ICT. With electronic linkages, an individual can access many more activity opportunities in space and time. Based on physical distance, Hägerstrand's time geographic framework is limited to helping researchers explore activity opportunities within physical proximity of an individual. How can the framework be extended to identify activity opportunities through the electronic linkages?

Hägerstrand's time geography assumes the indivisibility of an individual to study space-time constraints for activities in physical space. Under this assumption, a person cannot be physically present at different locations at the same time, and the person can only commit to a single physical activity at one location at one time (Carlstein, 1982). Therefore, it is invalid for a person to be involved in multiple activities located at different locations. However, with virtual space and tele-presence, people can participate in different virtual activities at the same time without violating the indivisibility constraint in physical space, and multi-tasking becomes more feasible and common in our daily lives. For example, a teenager can chat with several friends at different locations at the same time using instant messaging on the Internet. How can the framework be extended to deal with this situation and represent multi-tasking?

People can be coupled for activities through different modes with the help of ICT. Although co-existence is still the major way for people to interact, more interactions now are carried out in alternative ways, especially remotely through tele-presence. Therefore, people can interact with each other in various spatio-temporal patterns. The concepts of the space-time path and prism of Hägerstrand's time geography can only represent the physical proximity of an individual. How can the framework be extended to effectively represent various interaction modes, especially those conducted through tele-presence?

An extended time-geographic framework is required to deal with these questions in supporting the exploration of human activities in a modern society. The space-time constraints for virtual activities need to be identified so that the extended framework can be used to explore opportunities for virtual activities. The concepts of space-time path and prism need to be altered so that they can represent virtual activities and electronic linkages between people. The extended framework also needs to be enabled to represent various spatio-temporal patterns of human interactions in different modes. The task is to extend Hägerstrand's time geography to handle the situations raised by ICT.

2.4 Temporal GIS

Time geography provides an explicit space-time framework to study the relationships of constraints and human activities in a space-time context. Although the structure of time geography is simple and clear, most studies adopt the framework as a conceptual model only, and very few attempts have been made to operationalize the framework in a computer system (Yuan *et al.*, 2004). Recently, the capacities of GIS have been improved in representing geographic phenomena and supporting spatial analysis. Considering their power in handling spatial data explicitly, researchers have recognized GIS as a potential approach to accommodating the time-geographic framework and support the examinations of spatio-temporal characteristics of human activities (Pipkin, 1995).

2.4.1 Representing time in GIS

Time geography requires explicit representations of space and time, since the framework is built on an integrated 3D orthogonal system of space and time. The early GIS design takes a traditional cartographic approach to the representations of geographic phenomena, which adopts a static view of geographic phenomena (Spaccapietra, 2001; Peuquet, 2002; Yuan *et al*., 2004). Time, which is a critical dimension for dynamic perspectives of geographic phenomena, has been missing in the design of GIS. Most current GIS designs have inherited this static approach to the representations of spatial information (Frank *et al*., 2001). Current GIS design is deficient in incorporating the time-geographic concepts because it only deals with explicit representation of spatial information and does not incorporate the time dimension.

Researchers have recognized that time should be included in GIS so that they can efficiently support the investigation of the dynamic nature of geographic phenomena (Renolen, 2000; Frank, 2001; Yuan *et al*., 2004). A new research direction, which is dedicated to integrating time into GIS, was initiated in the late 1980s, and has been a very active filed since then (Renolen, 2000). This research field is now known as temporal GIS or spatio-temporal GIS.

Time stamping is a straightforward approach to adding temporal information to geographic objects in GIS. Three major time-stamping methods have been developed to add temporal information to a relational database. A time-stamp can be attached to a table, and all records in the table will share the same temporal information (Gadia and Vaishnav, 1985). A time-stamp can be attached to a tuple in a relational database, and each record can have its own temporal information (Snodgrass and Ahn, 1985). A time-stamp can also be applied to a cell in a relational database (Gadia and Yeung, 1988). In this approach, a record can have different fields (cells) containing attributes of different time periods. Based on these time-stamping methods, different approaches have been tested for attaching temporal information to geographic objects.

Armstrong (1988) developed a snapshot model, which takes the approach of time-stamping tables. Time-stamps are not applied to individual spatial features in a snapshot layer. Instead, a single time-stamp is used for the entire layer. This means that all the spatial features in a layer share the same time. A series of snapshot layers at different times are used to represent the history of a particular geographic phenomenon. A space-time composite model (Langran and Chrisman, 1988; Langran, 1992) was developed to combine multiple snapshot layers into a single composite layer. A space-time composite layer consists of a set of space-time composites, which are homogeneous features sharing the same history and the same attributes. Therefore, each composite unit in the layer has its individual time-stamp, which can be implemented as either time-stamping tuples or cells.

The time-stamping approaches can bring temporal information into GIS. However, they have shortcomings in providing an integrated and efficient representation of space and time. The time-stamping methods cannot offer a clear and efficient representation of time. Although time has only one dimension and one direction, its representation can be very complicated. As shown in Figure 2.3, time can be represented as a point (for an instant) or an interval (with start and end times), depending on the temporal resolution. Figure 2.3 also shows that time can have various structures, such as linear, cyclic, and branching time (Frank, 1998). As attributes are stored in tables, it is

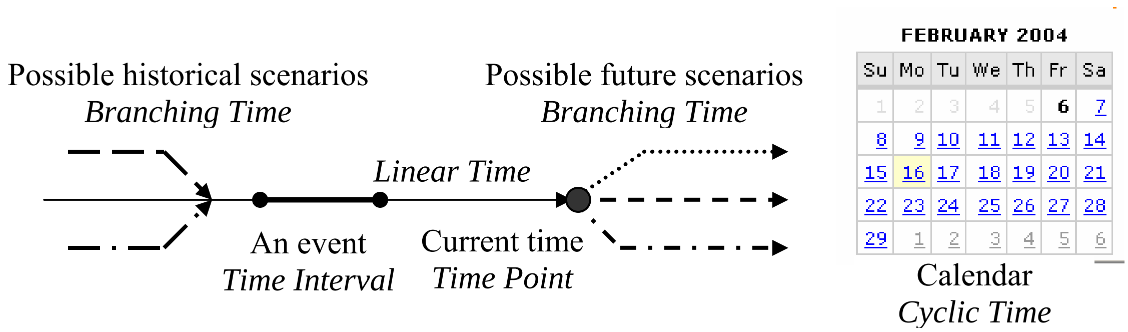


Figure 2.3. Different types and structures of time.
(Adapted from Frank, 1998)

difficult to represent various time structures and supporting temporal relationship analysis with time stamps. In addition, since time-stamping methods do not provide an integrated approach to representing the spatial and temporal information of a geographic object, they cannot efficiently support spatio-temporal analysis. Therefore, an integrated space-time representation is needed for an efficient temporal GIS design. Peuquet (2002) offered a systematic discussion on integrating space and time representations for geographic objects from philosophical, cognitive, and computational perspectives. Thoughtful consideration is needed to develop a proper representation for time and to accommodate time-geographic concepts in GIS.

2.4.2 Representing spatio-temporal objects

Representing spatio-temporal objects is the main purpose of a temporal GIS design. Different spatio-temporal applications require different methods to represent spatio-temporal objects. Tryfona and Jensen (1999) categorized spatio-temporal applications into three types:

1) Applications dealing with objects with *discrete changes of shapes*;
2) Applications dealing with objects with c*ontinuous motion but without changes of shapes*;
3) Applications dealing with objects with *continuous motion and changes of shapes*.

The first type deals with objects that change their shapes discretely in time. For example, a land parcel in a cadastral system may change its shape, and the changes occur only at discrete time. More attention has been paid in temporal GIS to applications of this type, and several approaches have been proposed to model spatio-temporal objects. The aforementioned snapshot model (Armstrong, 1988) and space-time composite model (Langran and Chrisman, 1988), which adopt time-stamping methods to add time into GIS, are examples of this type of application; both have major shortcomings. Storing changes in separate snapshot layers and lacking a system to reference the same object across the layers, the snapshot model does not provide an explicit method to track changes of spatio-temporal objects. The space-time composite model requires the fragmentation of the study area and construction of space-time composites, which also makes it difficult to track the changing histories of objects. Three other approaches have been proposed to model objects with discrete shape changes: 1) the object-oriented approach (Worboys, 1992), 2) the event-based approach (Peuquet and Duan, 1995), and 3) the three-domain model (Yuan, 1996a).

Worboys (1992, 1994) suggested an object-oriented spatio-temporal data model consisting of multidimensional objects: two-dimensional spatial objects with a third dimension for the event time associated with each object. The basic element in the data model is a spatio-temporal atom (ST-atom) that has homogeneous properties in both space and time. ST-atoms are used to form spatio-temporal objects (ST-objects) that represent changes of real world entities. From the perspective of identifying homogeneous elements, this approach can be viewed as a 3D version of the space-time composite model. Worboys (1998) later extends the approach to a spatio-bitemporal model that includes both event time and database time to record the existence of an object in the real world and in a database system, respectively. Because this approach uses a 3D system, it provides an integrated space-time representation for spatio-temporal objects.

Peuquet (1994) proposed a TRIAD database framework to integrate time into GIS. One implementation of the TRIAD framework is the ESTDM model using raster GIS (Peuquet and Duan, 1995). The ESTDM builds an event list with time-stamped entries that record the grid cells experiencing attribute changes from t(i-1) to t(i) and the locations of those grid cells. Using the built event list, changes between raster GIS data layers can be effectively tracked. Having been developed for raster GIS, the model does not fit well with vector GIS data that do not share a fixed grid size among the snapshot layers.

Yuan (1996a, 1996b, 1999) proposes a three-domain data model that consists of semantic domain, temporal domain, and spatial domain, along with domain links. The semantic domain defines real world entities with unique identifiers throughout the study duration. The temporal domain stores each time instance as a unique object, while the spatial domain is based on the space-time composite data model to derive a set of common spatial features with unique identifiers. Domain links are used to record the links among semantic, temporal, and spatial objects with their unique identifiers.

The second application type deals with objects that continuously move in the space but do not change shape. The movements of human beings can be considered as examples of this case. These objects, which keep changing locations with fixed shape and identity, are also known as moving objects in the literature (Erwig *et al.*, 1999). As there are no shape changes involved in the movements of this type of object, they are usually represented as point features in the model. Efforts have been made to model moving objects in GIS (e.g., Wolfson *et al.*, 1998; Bian, 2000; Porkaew *et al.*, 2001; Vazirgiannis and Wolfson, 2001; Brinkhoff, 2002). Wolfson *et al.* (1998) and Porkaew *et al.* (2001) studied the movements of objects in 2D space, and proposed methods to predict objects' future locations based on their previous locations and recent movement parameters (i.e., direction and velocity). Bian (2000) took an object-oriented design and a simulation approach to study the movements of fish in a 3D space. Vazirgiannis and Wolfson (2001) and Brinkhoff (2002) developed models to record real-time object movements along road networks. Their models use universal time as the temporal reference system (for simulation purposes) and apply a time-stamping method to attach temporal information to an object's location. Each new location is added into the database as a separate record containing spatial coordinates, time, and object ID. Erwig *et al.* (1999) and Güting *et al.* (2000) also proposed a conceptual framework to model moving objects in a 3D system (2D space + 1D time). They used abstract data types to represent spatio-temporal objects and discussed the possible operations applied to them.

The last application type deals with objects that can continuously change their locations and shapes. Many natural phenomena belong to this category, such as storms and wild fires. In order to provide an efficient representation for continuous changes, researchers need to have a clear understanding of the dynamic geographic process behind the phenomenon. Representation of dynamic geographic processes presents a major research challenge for the GIS research field (Yuan *et al.*, 2004). For an application of this type, usually a narrowly defined domain is involved and mathematical simulations are used to model the process. Current efforts are mostly devoted to the development of an interface in GIS to link to a separate system running the simulation model. Erwig *et al.* (1999) provided discussions on modeling and recording moving 2D regions in an object-oriented conceptual framework, which can be used to support fundamental representations of continuous changing objects. However, "[t]he ability to represent and examine the dynamics of observed geographic phenomena within a GIS context, except in the most rudimentary fashion, is currently not yet available." (Yuan *et al.*, 2004, p. 137).

2.4.3 Representing human activities in GIS

The existing approaches to the representations of spatio-temporal objects demonstrate the efforts involved in integrating time into GIS to study the dynamic aspect of geographic phenomena. As a specific application domain, representations of human activities and time-geographic concepts in GIS require special treatments. Attempts have been made to model human activities in GIS with different emphases.

GIS have been used to organize disaggregate-level human activity data, especially activity/travel diary data, for exploring the spatio-temporal characteristics of trips and activities (Shaw and Wang, 2000; Wang and Cheng, 2001; Frihida *et al.*, 2002). 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. Adopting an activity-based approach to travels, 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 both trips and activities. Taking 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. Treating temporal information as an extra attribute, these approaches can support basic temporal queries on trips and activities in GIS. However, without an integrated representation of space and time, the spatial and temporal nature (e.g., trip chaining) of human activities cannot be properly modeled, and exploration of interactions between individuals will be difficult. A time-geographic framework is needed to manage human activities in an integrated space-time system.

Attempts also have been made to implement time-geographic concepts in GIS to assist in human activity analysis. Miller (1991) first implemented the space-time prism concept in a GIS environment and calculated the network-based potential path area for the study of individual accessibility. Recently, several more attempts have been made to use GIS to measure space-time constrained individual accessibility and to identify available opportunities (Kwan and Hong, 1998; Miller, 1999; Miller and Wu, 2000;

Weber and Kwan, 2002; Kim and Kwan, 2003; Weber, 2003). Based on existing 2D GIS design and representation, these studies offer procedures in GIS to delimit the extent in a road network that is physically accessible to an individual under certain constraints in space and time. However, a space-time explicit 3D representation of space-time prism in GIS has not yet been proposed. Another important time-geographic concept, the space-time path, has also been tackled with GIS representations. Kwan (2000b) and Kwan and Lee (2003) visualized space-time paths in a 3D GIS environment to assist in the exploration of spatio-temporal patterns of human activities. Using a multi-scale representation in GIS, Kwan (2000a) offered a conceptual model to represent the extensibility of a human agent, showing connections through virtual space as links stretched out from space-time paths. Using computer-aided design (CAD) diagrams, Adams (1995, 2000) also represented human activities with a space-time path approach. These attempts demonstrate the potential of GIS to incorporate time-geographic concepts in the design and to shed light on further implementations of time-geographic framework in a GIS environment.

2.4.4 Spatio-temporal reasoning

Spatio-temporal reasoning is another important topic in temporal GIS and it is important in analyzing the interrelationships among individual activities. Geographic information involves location, time, and attribute. However, only location and attribute are treated in conventional GIS (Langran, 1992). When the time dimension is involved, extra efforts are needed to examine temporal relationships. Based on time-stamps, Stefanakis and Sellis (2001) discussed and identified seven topological relationships between two time intervals: *before*, *equal*, *meet*, *during*, *overlap*, *end*, and *start*. As time changes, both of the other two components may alter. Therefore, when different spatio-temporal objects interact with each other over time, their interrelationships can become very complex. Research has been carried out to explore spatio-temporal relationships among objects under an assumption of no attribute changes of these objects (e.g., Egenhofer and Al-Taha, 1992; Cohn *et al.*, 1998; Erwig and Schneider, 2002). Yuan and McIntosh (2002) define eleven query types for spatio-temporal objects, which can be used to examine the spatio-temporal relationships of the objects. Shaw and Xin (2003) suggest six scenarios for exploring spatio-temporal interactions between land use and transportation systems. These studies provide a foundation to analyze the spatio-temporal relationships of geographic objects, and some of them can be used in identifying spatio-temporal characteristics and relationships of human activities in this study.

2.5 Summary

In the 1970s, researchers began to address travel as a derived demand, and activities are the reasons for people to travel. Based on this idea, a paradigm shift occurred in transportation studies in which a disaggregate activity-based approach began to take place of the conventional trip-based aggregate approach. In the activity-based approach, the distributions of activities in space and time determine the spatio-temporal patterns of travel. Therefore, a better understanding of spatial and temporal characteristics of human activities is of great importance to transportation studies. Hägerstrand's time geography provides an integrated space-time framework to study the relationships of various constraints and human activities in a space-time context. The concept of a space-time path can be used to represent individual activities with their space-time contextual situations, and the concept of a space-time prism can help researchers identify feasible activity opportunities for individuals under given constraints. Therefore, the time-geographic framework can support activity-based transportation studies.

Recent developments of ICT enable a virtual space for people to conduct activities through tele-presence. The existence of virtual space is affecting how people carry out their activities and how they travel in physical space. A better understanding of the spatio-temporal characteristics of virtual activities is needed to reveal ICT's impact on transportation systems. However, Hägerstrand's time geography only deals with activities in physical space and does not provide treatments for virtual activities. Therefore, the time-geographic framework should be extended to handle human activities in both physical and virtual spaces so that it can be used to study spatio-temporal characteristics of human activities in today's society.

GIS have been considered as a potential approach to operationalizing the time-geographic framework and assisting in transportation studies. The current GIS design does not include the time dimension, which makes GIS deficient to accommodate the time-geographic framework. Recently, temporal GIS have emerged to integrate time into GIS, and several models have been proposed to represent spatio-temporal objects. However, as activity-based study with the time-geographic framework presents a specific application domain, no efficient temporal GIS design has yet been proposed. It is crucial to develop a temporal GIS design with an integrated space-time representation in order to operationalize the time-geographic framework.

Based on the existing studies, the discussion of an extended time-geographic framework that can handle both physical and virtual activities is presented in Chapter 3, and the development of a temporal GIS design to accommodate the extended time-geographic framework is described in Chapter 4. The system will be used to support the study on spatio-temporal characteristics of human activities.

CHAPTER 3:

AN EXTENDED TIME-GEOGRAPHIC FRAMEWORK FOR PHYSICAL AND VIRTUAL ACTIVITIES

Time geography has provided an effective framework to depict human activities in the physical space with respect to various constraints. The trajectory of observed activities and the extent of potential activities in the physical space are represented with space-time paths and space-time prisms. However, virtual activities have a set of constraints different from those of physical activities. With tele-presence in virtual space, virtual activities may have traces on space-time paths different from physical activities, and the extent of potential virtual activities may take different forms of space-time prisms. In this section, a conceptual model is developed to represent relationships between physical space and virtual space. Based on the proposed conceptual model of physical and virtual spaces, an extended time-geographic framework is discussed by first re-examining the space-time constraints for human activities, especially for virtual activities. Modified space-time paths and prisms for virtual activities in the extended framework are also discussed and presented in this section.

3.1 Relationships of Physical Space and Virtual Space

Physical space and virtual space have different characteristics, although both can work as stages for people to carry out activities. Negroponte (1995) views physical space as a material world made of atoms and virtual space as a world composed of bits of information. While physical space can work as a container for both physical materials and information, virtual space is specialized to carry the flow of information efficiently. Movements of materials in physical space usually take significant time, but information can be transmitted in virtual space without significant delay. As activities in physical space are distributed at different locations, travel is usually involved for an individual to conduct each activity (Hanson, 1995). Therefore, an individual has to manage and balance the time spent for travel and activity, so that s/he is able to transport and participate in activities. However, activities in virtual space allow people to be involved through tele-presence. As long as an individual has access to virtual space, physical locations have no significant impact on the activities. When tele-presence is used instead of physical presence, an individual can save time on physical movements, which gives the individual greater flexibility to arrange activities.

Batty and Miller (2000) argued that the two spaces share intersections and have influences on each other despite their differences. Research has shown that activities in physical space and virtual space can influence each other (Salomon, 1986; Shen, 1998). Various impacts of virtual interactions on physical activities, such as substitution, modification, and complementarity, have been observed in our daily activities. However, to understand and model the relationships of the two spaces remains a research challenge. We have seen that the significance of distance in our daily activities has been reduced by the use of virtual activities. With the help of ICT, people can participate in activities or interact with others while they are in different places; therefore, virtual space gives people increased flexibility to conduct activities. However, speculation about "the death of distance" (Cairncross, 1997) is arguable because virtual space access channels are not ubiquitous in physical space. Physical location is still meaningful as it controls where individuals can access virtual space. Therefore, it becomes a necessary condition that an individual be located in a place with virtual space access channels, so that s/he can access virtual space and conduct virtual activities; for example, an individual may need to travel to an Internet Café to receive and send e-mails. Virtual space contains information. An individual who has access to virtual space can retrieve the information, and the information can affect the individual's travel decisions and behaviors, which may change transportation distribution in physical space and time.

This study proposes a conceptual model to portray the roles of the two spaces in containing human activities (Figure 3.1). Both physical and virtual spaces can be considered relatively independent because each has specific characteristics when containing activities within the domain. Transportation can help people move around in physical space, while ICT are the means for people to navigate in virtual space. The two spaces are not totally separated from each other; they have intersection and they influence each other through the intersection. Two aspects of the intersection are identified in this study. On the one hand, physical space provides access channels to virtual space, as

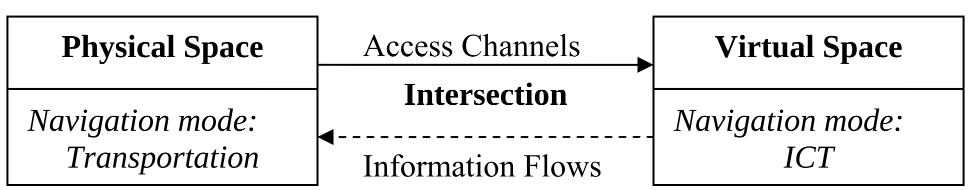


Figure 3.1. A conceptual model of physical space and virtual space.

virtual space is built on information and communication infrastructures that reside in physical space. Thus, if an individual wants to perform virtual activities, s/he has to reach these access channels in physical space. Consequently, movements in physical space may be required to help the individual find the access channels and connect to virtual space. In the meantime, virtual space can feed information back to physical space. The information can be retrieved from virtual space and has impacts on physical activity patterns through decisions made by individuals participating in virtual activities.

According to the proposed conceptual model, physical space plays two roles in supporting human activities: it is a *carrier of physical activities* and it is a *connector for virtual activities*. Being a carrier of activities is the conventional role that physical space plays in supporting physical activities. Therefore, the space-time prism concept of Hägerstrand's time geography can efficiently depict the relationship of activities with their space-time constraints. For virtual activities, on the other hand, physical space works as a connector to provide people virtual space access channels and support virtual activities by hosting ICT infrastructures and facilities. This role of physical space is not sufficiently addressed in Hägerstrand's time-geographic framework. Therefore, the time-geographic framework must be extended to handle the new role of physical space in supporting human activities. The three types of constraints (i.e., capability, authority, and coupling) for human activities in Hägerstrand's time-geographic framework need to be re-visited and the concepts of space-time paths and prisms need to be adjusted to deal with the different roles of physical space.

3.2 Re-visiting the Three Types of Constraints for Human Activities

Hägerstrand's time geography has described three types of constraints that can impact human activities in physical space (Hägerstrand, 1970; Golledge and Stimson, 1997). As ICT become more widely adopted in our daily lives, increasing numbers of activities take place through tele-presence in virtual space. Therefore, people can carry out both physical and virtual activities. Constraints addressed in time geography need to be extended to handle both physical and virtual activities. Although researchers have noticed that different constraints apply to virtual activities, limited progress has been made in identifying them in the similar structure used for physical activities in time geography. Harvey and Macnab (2000) studied the constraints of personal communications through the Internet, emphasizing new capability constraints and temporal coincidence of coupling constraints. Their study provides a good foundation to examine constraints for virtual activities using an r approach similar to that for physical activities in time geography. Based on the proposed conceptual model for relationships of physical and virtual spaces, this study re-visits the three types of constraints for human activities and extends their scope to cover both physical and virtual spaces.

3.2.1 Capability constraints

Capability constraints include human capabilities and characteristics of infrastructures or facilities that can support the conduction of human activities. Physiological necessities of a human being, such sleeping and eating, have been classified as this type of constraint. Both physical and virtual activities are constrained by these physiological necessities. Personal capabilities, which are skills and resources owned by an individual, are another subset of constraints under this type. Physical space acts as a carrier for physical activities. Therefore, auto ownership (resource) and driving skill (skill) determine the travel capability of an individual in physical space, which controls opportunities of activities in physical space. However, for virtual activities, physical space works as a connector to help individuals access virtual space. Therefore, the subscription of ICT services (e.g., dialup account or subscription of cellular phone service) and ownership of appropriate devices (e.g., computers with network card or cellular phones) can impact the performance of virtual activities. Without these resources, an individual is excluded from the intersection of the two spaces and is constrained from conducting virtual activities. In addition, capabilities of navigating in virtual space can also limit an individual's involvement in a virtual activity. For example, an individual needs basic computer and Internet knowledge to surf the Internet, and an individual must know a certain foreign language in order to browse a web site written in that language. The final subset of constraints under this type is the characteristics of the environment, which can constrain the performance of activities. Speed limits (e.g., 45 mph for a local road segment) for roads and road capacity are examples of these constraints for physical activities. On the other hand, bandwidth for Internet connection (e.g., 56KB/s for a dial-up connection) and the covering range of a cellular phone transmission tower are examples for virtual activities. The characteristics of facilities will indirectly impact an individual's capability to join in and conduct an activity.

3.2.2 Authority constraints

In time geography, authority constraints are defined as general rules or laws that limit the performance of activities at certain locations and/or time periods. As three domains (i.e., physical space, virtual space, and their intersection) have been classified in this study, the contents of authority constraints are examined for each of these three domains.

In physical space, certain locations are only accessible to specific groups of people. For example, a military area usually prohibits visits from the public, and private property allows access only to the owner(s) and persons with permission. Also, most service facilities have limited open hours. If an individual wants to visit a facility in person, s/he has to be there during the posted open hours, such as the open hours of a library. Restrictions of both physical location and time period can limit the access of a particular location to individuals and constrain the performance of activities at that location.

The intersection of two spaces indicates that physical space can provide access channels to virtual space. Because physical locations that host connection facilities to virtual space can be affected by the same situations discussed above, the performance of virtual activities is controlled by constraints in the intersection. When an individual does not have permission to visit a location hosting virtual space access channels or does not visit the location during its open hours, the individual will not be able to connect to virtual space and conduct virtual activities. Therefore, spatial and temporal authority constraints at those locations will restrict activities in virtual space. For example, a person has to be a member of a school to use networked computers in the school's library or go to an Internet café during its business hours to surf the Internet.

Virtual space has similar authority constraints as those of physical space. Although most resources on the Internet are free and available around the clock, some web sites do require membership and have limited hours of operation. For example, an on-line class registration web site of a university requires students to log onto the web site with their user names and correct passwords to browse their class registration information, and these functions may be available only during conventional business hours due to administrative reasons. Also, similar situations occur for telephone services. If a person does not accept roaming service on his/her cellular phone, when s/he is in a place that is only covered by another company's service, s/he will not be able to access the network.

3.2.3 Coupling constraints

Unlike capability constraints and authority constraints that focus only on a single person, coupling constraints focus on spatio-temporal relationships of multiple individuals. In order to participate in certain activities, individuals have to interact with others through certain modes. Conventional coupling constraints require all participants to be physically present at the same location during the same time period to conduct an activity. With tele-presence enabled by ICT, people can interact with others with higher flexibility in space and time. As mentioned in Chapter 2, people now can communicate and interact with each other through four different modes (i.e., SP, AP, ST, and AT). Therefore, people can be bundled for activities in different spatial and temporal contexts rather than only in the situation of concurrence in both space and time.

Physical presence has been the predominant mode for people to contact each other before ICT became available and popular in our daily lives. Both SP and AP interaction modes require the physical presence of the participants. SP interactions such as face-to-face meetings have been the major concern of Hägerstrand's time geography for coupling constraints. In order to conduct SP interactions, participants need to be physically present in the same location during the same time period. Under these circumstances, participants share a *co-existence* relationship in space and time. AP interactions, such as a bulletin board at a conference, relax the constraint on time. Although this type of interaction still requires participants to be physically present in the same location, the participants do not have to be there during the same time. Therefore, individuals involved in an AP interaction share a relationship of *co-location in space*.

Tele-presence has been considered as a means to overcome the barrier of physical distance. It can help people break the constraints in space to interact with others. Talking to three individuals in three different locations at the same time was considered impossible two decades ago due to the indivisibility constraint (Carlstein, 1982). It is impossible with physical presence, but it is possible with tele-presence. Tele-presence allows people from different locations to join into the same virtual activity and even allows an individual to be virtually present in multiple virtual activities. For example, a person can open multiple on-line chat rooms and talk separately with several friends across the world at the same time. Of the four interaction modes, ST and AT interactions take advantage of tele-presence. ST interactions can bring people from different locations together to conduct an activity, such as a videoconference or a session of instant messaging, but they require participants to access virtual space during the same time period. People bundled through this mode will have a *co-location in time* relationship. AT interactions relax constraints of both space and time. Participants of AT interactions do not have to be in the same location or be present at the same time. E-mails and web pages are popular examples of this type of interaction. By conducting AT interactions, participants can have a relationship of *no co-location in either space or time*.

Although tele-presence gives more freedom in space for people to conduct activities, its realization in the real world still needs the support of physical space as modeled in the conceptual framework for the relationships of physical and virtual spaces. In order to conduct activities involving tele-presence, an individual is required to access virtual space from where s/he is located and be connected through the entire duration of this activity. As access channels are not ubiquitous in physical space, physical locations will again control virtual activities. Although the existence of virtual space provides more choices and greater freedom in space and time to conduct activities, researchers realize that the cliché that virtual space "enable[s] people to interact with anyone, anywhere, at any time and in any place" is a "crude vision" of the emerging phenomena rather than a precise description (Batty and Miller, 2000, p. 138). After re-visiting the three types of constraints for human activities, we can see that capability constraints and authority constraints still apply to individuals in determining whether they can conduct activities in virtual space; coupling constraints can control whether individuals are able to interact with each other through tele-presence.

Table 3.1 sums up the contents of the three types of constraints for physical and virtual activities. The three types of constraints work together to determine which activities in physical and virtual spaces can be carried out by individuals. With the

Table 3.1. Constraints for human activities in physical and virtual spaces

Constraints	Contents
Capability constraints	Human capabilities and characteristics of infrastructures or facilities that can support the conduction of human activities. • Physiological necessities: sleeping, eating, etc. • Individual capabilities: o In physical space: auto ownership, driving skills, etc. o For intersection: accesses to virtual space – wired accesses (e.g., Internet ports, fixed phone lines, etc) and wireless accesses (e.g., cellular phones, wireless Internet ports, etc). o In virtual space: computer skills, language ability to browse foreign web sites, etc. • Characteristics of environment: types of roads, speed limit, band width of the Internet connections, etc.
Authority constraints	General rules or laws that limit the performance of activities at certain locations and/or time periods. o In physical space: military area, shopping mall open hours, etc. o For intersection: student computer labs in a university, open hours of an Internet café, etc. o In virtual space: membership controlled web sites, business hours for web services, etc.
Coupling constraints	Spatial and temporal requirements for people to interact with each other through either physical presence or tele-presence. • Co-existence (co-location in both space and time): synchronous physical presence (SP), e.g., face-to-face meeting, etc. • Co-location in space: asynchronous physical presence (AP), e.g., fridge note, post message board, etc. • Co-location in time: synchronous tele-presence (ST), e.g., instant messaging, videoconference, etc. • No co-location in either space or time: asynchronous tele-presence (AT), e.g., email, voice mail, etc.

discussion of constraints above, we can say that at the present time physical location still plays an important role in controlling human activities, even those conducted in virtual space. With this in mind, we can have a clearer view of activities carried out in both physical and virtual spaces.

3.3 Extended Space-time Paths and Prisms for Physical and Virtual Activities

In Hägerstrand's time geography, space-time paths are used to depict the trajectories of individuals' movements in physical space over time, and space-time prisms are used to demarcate the continuous extents in space and time that can be reached by individuals under particular constraints. Representation and calculation of space-time prisms are both based on physical distance; however, the existence of virtual space is changing the role of physical distance in our daily lives. How can space-time paths be used to represent both physical activities and virtual activities, and how can they show the diverse spatio-temporal relationships of individuals involved in different interaction modes? How can space-time prisms be used to depict potential opportunities for virtual activities? The space-time paths and prisms in Hägerstrand's time geography must be extended to give a more useful and accurate description of spatial and temporal characteristics of activities in both physical and virtual spaces.

3.3.1 Space-time paths with physical and virtual activities

A conventional space-time path represents only physical proximities around an individual in space and time. With tele-presence, an individual can reach out far beyond his/her physical proximity, and the conventional space-time path concept cannot portray individuals' characteristics in today's society. Janelle (1973) made an argument considering the individual as an extensible agent, who can take advantage of technologies (e.g., transportation and communication) to overcome the distance friction in physical space. ICT enhance individual's capability to extend over physical space and strengthen the connections and interactions among individuals across the distance (Wiberg, 2005). Based on this concept, Adams (2000, p. 218) portrayed communications as linkages created through space and time by a person to relate to others, and considered "these connections as *part of* people rather than *between* people." Using CAD diagrams, Adams displayed a person's communications as arms reaching out in space and time from that person. Adopting a similar idea, Kwan (2000a) visualized virtual activities as extended links from an individual's space-time path in a multi-scale 3D GIS environment. The concept of human extensibility and the effort to represent this concept provides a good foundation for the representation of space-time paths with both physical and virtual activities in this study.

A space-time path is considered to be the container of all activities performed by a person because all activities take place at certain locations and time periods, and each of them occupies a portion of the space-time path. Activities can be located on a space-time path based on their time references. Although both types of activities are segments on space-time paths, they have different action spaces. While physical activities impact only the physical proximity of a space-time path, virtual activities can extend to distant locations. Virtual activities can only take place at ICT-enabled locations, such as at an Internet Café or within a cellular phone service area. Figure 3.2 shows the conceptual representation of an extended space-time path. Extended links from space-time paths are

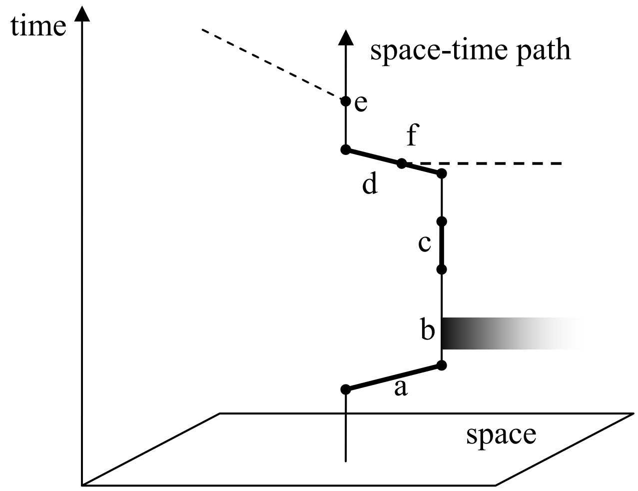


Figure 3.2. An extended space-time path with physical and virtual activities.

used to represent virtual activities, which indicate the extent of these activities over distance. For example, the symbols for activities of (b) instant messaging, (e) e-mailing, and (f) calling through a cellular phone in Figure 3.2 represent these virtual activities. Because some virtual activities may experience delays in time, extended links may not always be horizontal, but tilted as the one for e-mail activity indicates in the figure. Also, as tele-presence allows multi-tasking, an activity like calling through a cellular phone can overlap a driving activity, which indicates that an individual makes a phone call through a cellular phone during driving.

3.3.2 Extended space-time prisms for potential virtual activities

Space-time prisms describe the potential space and time available to a person for potential activities under certain circumstances. The shape of a space-time prism is determined by capability and authority constraints applied to an individual. As mentioned in section 3.1, physical space has two different roles for people conducting activities: the carrier of physical activities and the connector for virtual activities. For physical activities, the space-time prism concept in Hägerstrand's time geography provides an effective approach to identifying potential activity opportunities in physical space and has been widely adopted in related research (Hägerstrand, 1970; Lenntorp, 1976; Miller, 1991, 2004a; Kim and Kwan, 2003). For virtual activities, the concept needs to be adapted to identity potential activity opportunities while physical space plays the role of connector for virtual activities.

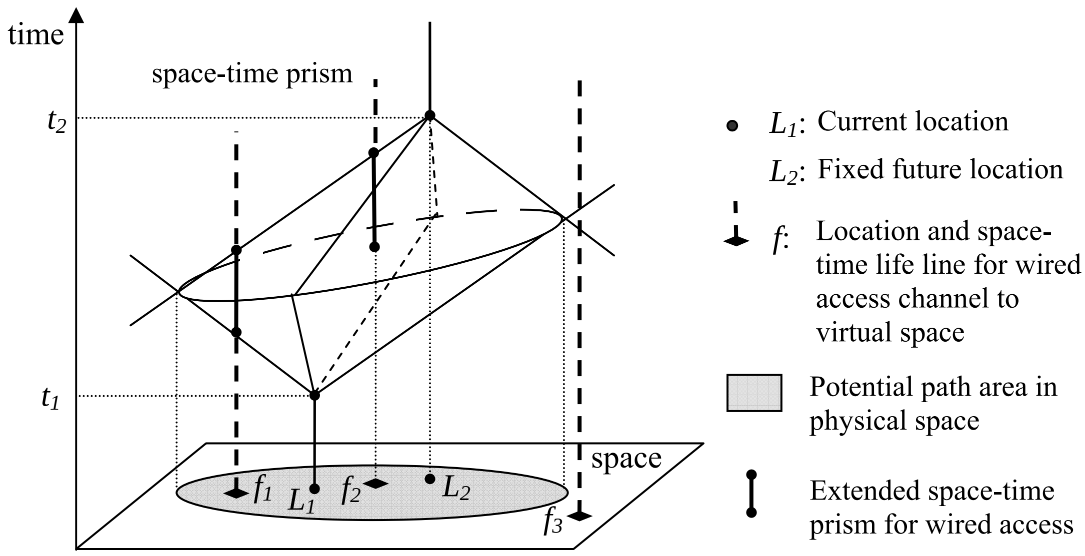
When people conduct virtual activities, they have to be able to connect to virtual space. As virtual space access channels are not ubiquitous in physical space, physical presence in a location with access channels becomes a necessary condition for people to conduct virtual activities. Subsequently, physical movements undertaken to reach the access channels become a prerequisite for most virtual activities. Based on this discussion, we can see that the performance of activities in virtual space is still controlled by constraints in physical space and time. Therefore, the definition of an *extended space-time prism* for virtual activities can be described as the opportunities in physical space that allow an individual to connect to virtual space and carry out virtual activities under a set of constraints. In other words, the identification of potential virtual activities is a process of locating virtual space access channels in physical space under certain space-time constraints.

Based on the definition of an extended space-time prism in this study, the prism can be achieved by intersecting a conventional space-time prism with *space-time life paths* of virtual space access channels in physical space. In this study, the term *space-*

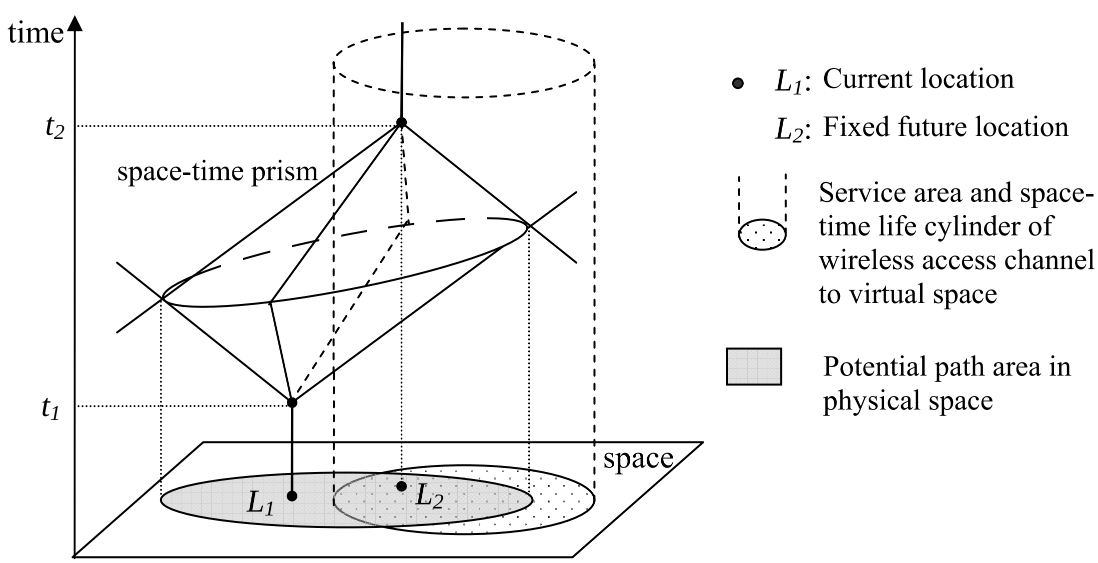
time life path is used to describe the existence of a virtual space access channel in space and time. Unlike a space-time path, which portrays an individual's trajectory, a space-time life path represents a virtual space connection service at a specific space-time extent. A space-time life path is attained by extruding a virtual space access channel along time dimension according to its operational hours. Therefore, it represents the time period during which individuals can access virtual space from that specific location.

Two types of virtual space access channels, *wired access channels* and *wireless access channels*, are identified in this study according to their connection methods to virtual space. *Wired access channels* provide connections to virtual space at fixed portals, such as fixed phone lines and wired Internet ports. This type of virtual space access channel usually resides at fixed locations and can be considered a point-like geographic feature. *Wireless access channels* can offer connections to virtual space from continuous regions instead of discrete locations. An individual with suitable ICT devices can access virtual space from any location within the region. A cellular phone service area or a wireless network covering area is a typical example of this type of access channel. Wireless access channels are considered to be real geographic features.

Two types of extended space-time prisms for virtual activities can be achieved based on these two types of virtual space access channels. Figure 3.3a shows the extended space-time prism for virtual activities with wired access channels. The conventional space-time prism demarcates the space-time extent that an individual can reach under the given constraints. Three wired access channels are located at different locations (f_1, f_2, and f_3). Their space-time life paths are represented as space-time life lines, which are shown as thick dashed lines in Figure 3.3a. While both f_1 and f_3 have 24-



a. A space-time prism for virtual activities with wired access channels



b. A space-time prism for virtual activities with wireless access channels

Figure 3.3. Extended space-time prisms for virtual activities.

hour access to virtual space, f_2 provides access only after a certain time. The space-time life lines of f_1 and f_2 intersect with the conventional space-time prism and their intersections are shown as thick solid lines in Figure 3.3a. The thick solid lines indicate that the person has opportunities to reach these two locations, to access virtual space, and to conduct virtual activities. The time window for accessing virtual space at each location is indicated by the length of the line segment, with its ends marking starting and ending times. Therefore, the extended space-time prism with wired access becomes a collection of vertical line segments in the 3D coordinate system. Figure 3.3b demonstrates the case of wireless access channels. As wireless access channels are regions in the physical space, their space-time life paths are represented as cylinders in the 3D system. Figure 3.3b shows one wireless access region whose space-time life cylinder intersects with the conventional space-time prism. The intersection of the conventional space-time prism and the space-time life cylinder depicts the opportunities in space and time that can be accessed by the person to connect to virtual space for virtual activities. The extended space-time prism for virtual activities with wireless access differs from the result of wired access in that it has a continuous extent in space and time. A person can keep accessing virtual space while moving around within those confines.

3.4 Human Interactions and Spatio-temporal Relationships of ST Paths and Prisms

The extended concepts of space-time path and prism provide representations for observed and potential human activities in both physical and virtual spaces for a single individual. As social beings, people cannot avoid communicating and interacting with others, and most human activities involve multiple individuals. With physical presence and tele-presence, people can interact with one another through one of the four interaction modes (SP, AP, ST, and AT) discussed in Chapter 2. Participants involved in an interaction through each mode share a specific spatio-temporal relationship. These spatio-temporal relationships of individuals can be represented through their extended space-time paths. Also, these spatio-temporal patterns can be used to identify potential human interactions in different modes with extended space-time prisms (Miller, 2004a).

When the four types of human interactions are represented with extended space-time paths, different patterns can be recognized according to their spatio-temporal relationships (Figure 3.4). As an 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 in the same location (*L*) during the same time period (from T_1 to T_2) result in an overlapping segment of space-time paths and create a co-existence relationship as shown in Figure 3.4a. An AP interaction is represented by sequential visits by different participants at the same location (*L*) as shown in Figure 3.4b.

Each space-time path has a segment occupying the same location (*L*) at different time periods. This leads to a co-location in space relationship. As both ST and AT interactions involve virtual activities, extended space-time paths are needed to represent their relationships. In an ST interaction, participants who may be located in different places interact with each other through virtual space in the same time period. Their space-time paths share a co-location in time relationship as displayed in Figure 3.4c. The block in the figure represents interactions between the participants across virtual space; the horizontal lines indicate the synchronization in time (the same duration from T_1 to T_2).

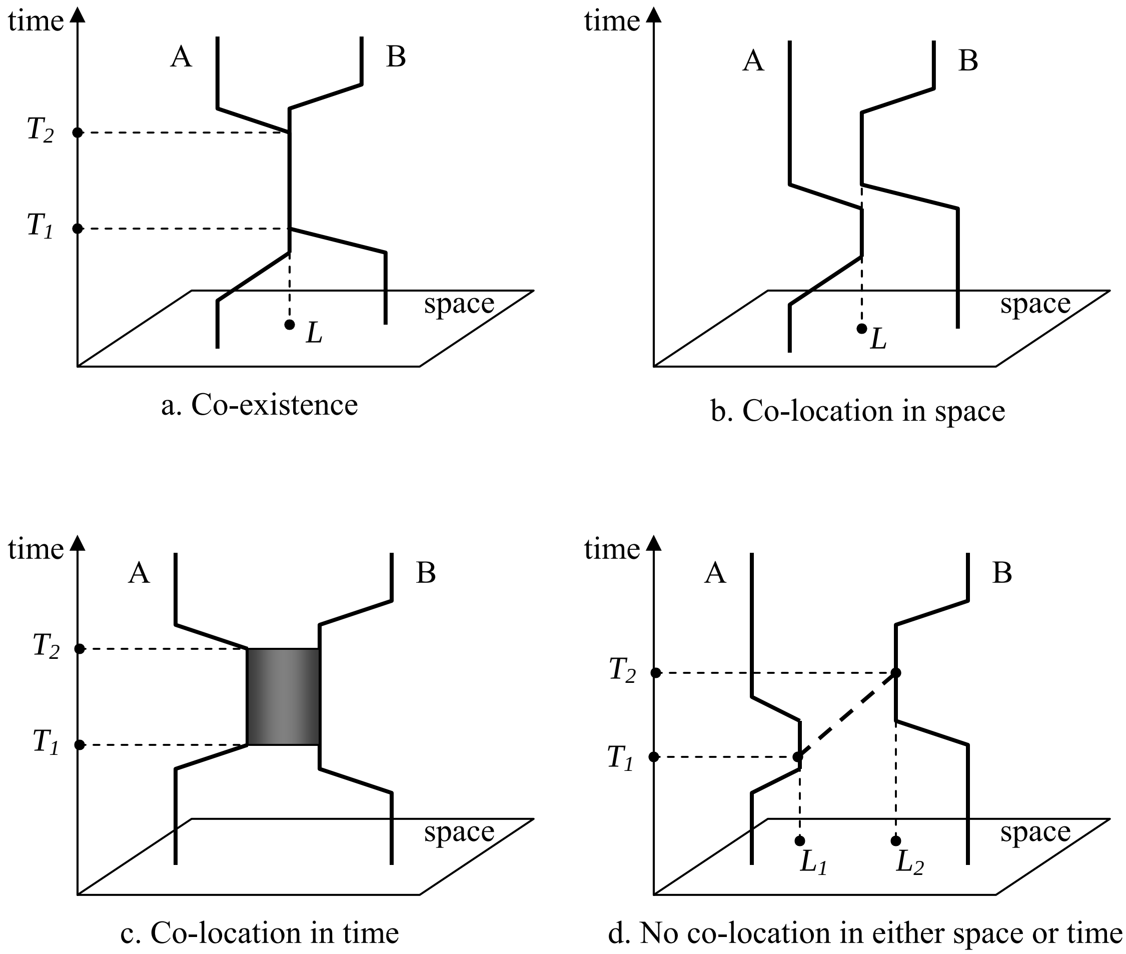


Figure 3.4. Spatio-temporal relationships of human interactions.

An AT interaction further removes the requirement on time synchronization. A person can initiate a communication by sending a message out from location L_1 at time T_1, while the receiver can pick up the message at location L_2 at time T_2 to complete the communication. As shown in Figure 3.4d, a link is used to connect the two space-time paths representing the relationship of an AT interaction between them. The ends of the link indicate when and where the interaction was initiated and picked up. Due to the asynchronous character of this type of interaction, the link is a tilted line in the space-time system as shown in the figure. This shows a relationship of no co-location in either space or time between the individuals.

These spatio-temporal relationships with their prisms can be used to examine the opportunities for potential interactions among people because different types of human interactions require different spatio-temporal relationships of their participants. As SP and AP interactions take place in physical space only, conventional space-time prisms are sufficient to investigate the potential interactions among individuals. If the conventional space-time prisms of two individuals overlap as shown in Figure 3.5a, it indicates that the individuals can reach the same location during the same time (i.e., co-existence); therefore, they can carry out potential SP interactions. The overlap (shown as shaded area in Figure 3.5a) depicts the extent in space and time for the opportunities of potential SP interactions among the individuals. Figure 3.5b shows that two conventional space-time prisms of individuals overlap in a space dimension, which indicates that these individuals will be able to reach the same locations (i.e., co-location in space). Such situations provide opportunities for individuals to carry out AP interactions. The shaded areas of prisms in Figure 3.5b demarcate the space-time extent for each individual to conduct

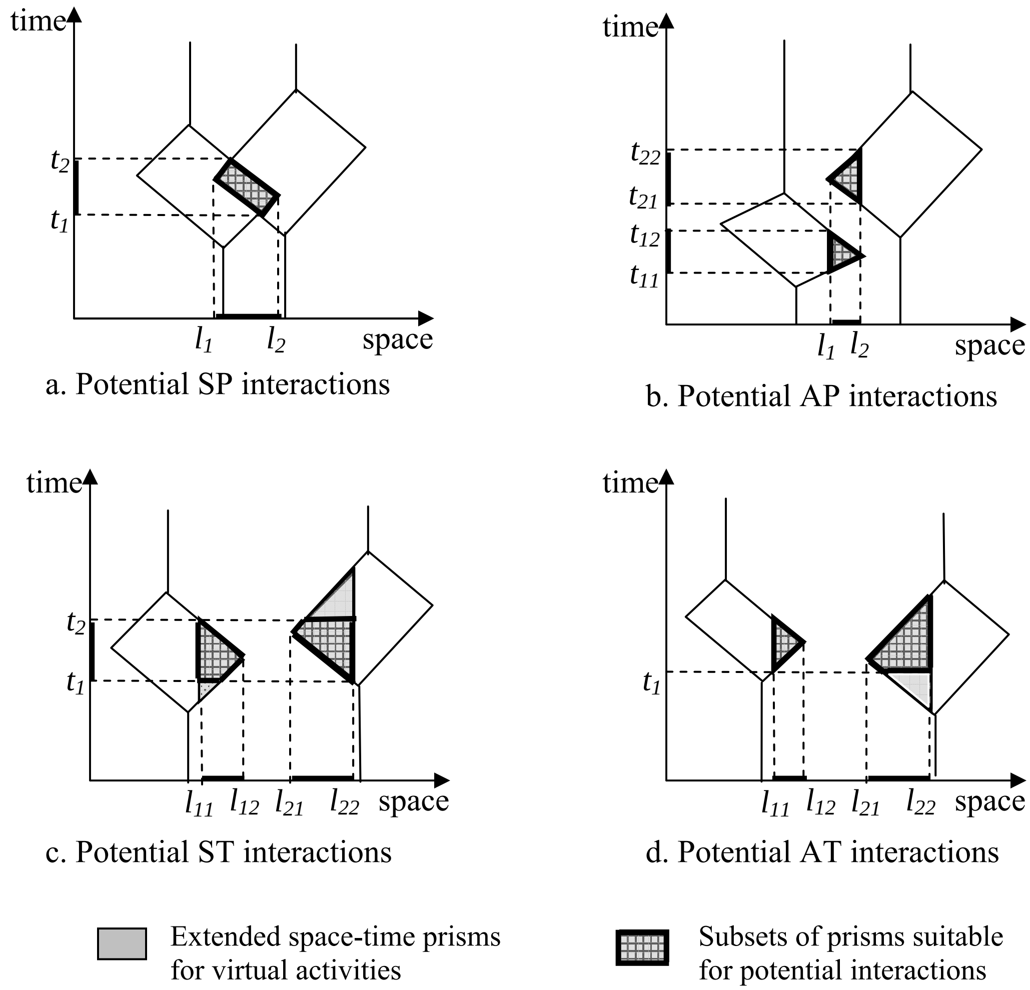


Figure 3.5. Spatio-temporal relationships of prisms and potential interactions.

potential AP interactions at the locations. Both ST and AT interactions involve activities in virtual space. Therefore, extended space-time prisms are needed to examine opportunities of these interactions. The gray-colored parts of the space-time prisms in Figure 3.5c and 3.5d indicate the space-time extents that allow individuals to access virtual space. ST interactions require participants to access virtual space at the same time, while having no requirements for locations (i.e., co-location in time). If prisms for virtual activities from individuals overlap along the time dimension as shown in Figure 3.5c, the individuals will have opportunities to conduct ST interactions. The shaded areas within the prisms for virtual activities depict the opportunities in space and time that allow ST interactions among individuals. AT interactions do not require coincidence in either space or time (i.e., no co-location in either space or time). As long as participants have access to virtual space and the receiver of an AT interaction has connection at a later time than the initiator, they will be able to conduct AT interactions. Figure 3.5d defines the situation for potential AT interactions, which shows that the receiver's extended space-time prism needs to last beyond the earliest boundary of the initiator's prism along the time dimension, and that the receiver has a chance to pick up the incoming message. These spatio-temporal relationships of prisms provide an approach to exploring potential human interactions in both physical and virtual spaces.

3.5 Summary

In this chapter, a conceptual model has been proposed for the representation of relationships of physical space and virtual space. Based on this conceptual model, an extended time-geographic framework is developed to handle human activities in both physical and virtual spaces. The three types of constraints for human activities in Hägerstrand's time geography are re-visited to include situations in both physical and virtual spaces. In addition, the concepts of space-time path and prism are extended so that they can be used to portray both physical and virtual activities. Using extended space-time paths, the specific spatio-temporal relationships of individuals involved in the four different interaction modes can be effectively represented. Potential human interactions through different modes can also be efficiently identified with extended space-time prisms based on their spatio-temporal relationships. This extended time-geographic framework provides an effective approach to explore human activities in both physical and virtual spaces of today's society.

CHAPTER 4:

TEMPORAL GIS DESIGN OF

THE EXTENDED TIME-GEOGRAPHIC FRAMEWORK

The extended time-geographic framework involves investigations of both spatial and temporal aspects of human activities. In order to provide an efficient computational representation, a GIS model must be able to support explicit representations of both space and time. Because the time dimension is not included in the mainstream of current GIS design, the development of a temporal GIS model that can accommodate the time-geographic framework is necessary. In this chapter, attention is focused on the design of a temporal GIS model that can support representations of time-geographic objects such as space-time paths and prisms and analyses of the spatio-temporal characteristics of human activities.

4.1 A 3D GIS Environment to Support Time-geographic Concepts

Hägerstrand's time geography adopts an orthogonal 3D coordinate system to study the spatial and temporal constraints of human activities, with 2D representing space and 1D representing time (Hägerstrand, 1970). In such a system, the spatial and temporal information about an individual's movements is integrated and represented as a space-time path, and the a space-time prism depicts the feasible extent in space and time accessible to an individual under specific constraints. Current GIS design can represent spatial information explicitly and efficiently. However, in order to represent these time-geographic concepts, a GIS design must introduce the time dimension into the system and provide an explicit representation for time. With regard to the space-time system used in time geography, it is reasonable to adopt a 3D environment for the representations of time-geographic concepts in GIS. In the 3D environment, a 2D plane is devoted to the description of spatial information of time-geographic objects, and a third dimension is used to represent temporal information in a linear time structure. Simulating the space-time system in the time-geographic framework, the 3D GIS environment is capable of supporting representation of time-geographic objects.

4.1.1 Spatio-temporal features

Different types of features, which are the fundamental elements to represent time-geographic objects, are developed in the 3D GIS environment. As these features reside in a space-time framework, they are named *spatio-temporal features* in this study. Figure 4.1 shows how these spatio-temporal features are represented in the temporal GIS framework. 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 a location in a 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 $t_0 < t_1 < \ldots < t_n$). A spatio-temporal 3D feature is an object that does not change shape in 2D space during its lifetime and has homogeneous properties in both space and time. It can be considered as a feature achieved from extruding a feature in 2D space along time dimension. The concept of ST-atom from the object-oriented approach (Worboys, 1992) can be borrowed to represent such a feature. With these basic spatio-temporal features, time-geographic

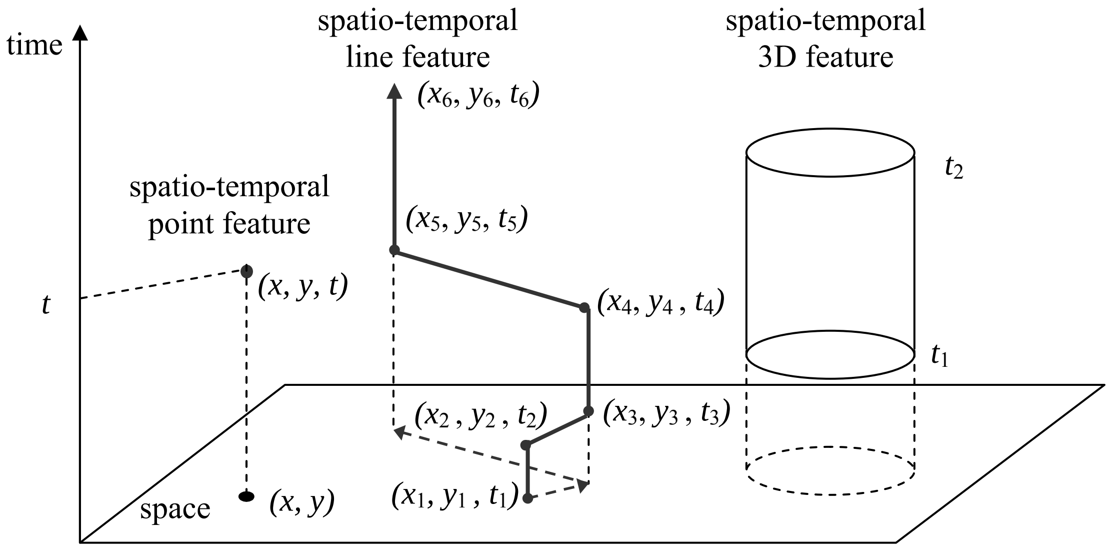


Figure 4.1. Spatio-temporal features in a 3D GIS environment.

objects can be explicitly represented with their spatial and temporal characteristics in GIS.

4.1.2 Operations on spatio-temporal features

The temporal GIS model should support operations on spatio-temporal features to accommodate the extended time-geographic framework. Operations on spatio-temporal features are used to facilitate the exploration of spatial and temporal characteristics of human activities and spatio-temporal patterns of interactions. However, most operations defined in current GIS are applied to features in 2D plane. Analyses on time-geographic objects demand extra effort to handle a third dimension for time. In this study, a *space-first-time-second* strategy is adopted to develop operations for spatio-temporal features. Using this strategy, spatio-temporal features are first projected into the 2D plane, and existing GIS operations are employed to examine certain spatial relationships among them. Features resulting from this step are candidates for certain spatio-temporal relationships. Temporal relationship examinations are then processed on these features to finalize the spatio-temporal operation.

Spatio-temporal intersection is an important operation in the temporal GIS design to support the time-geographic framework. It can be used to find the co-existence relationship among people. Spatio-temporal intersection is a complex operation, which involves examinations for overlaps in both space and time dimensions; discussion on processing a spatio-temporal intersection can also help identify co-location in space and co-location in time relationships among people. The remainder of this section is a detailed discussion of processing the intersection operation on two spatio-temporal lines, which will be frequently used in the model.

Using the 3D environment for the space-time system, the spatio-temporal intersection operation can be considered as a process to locate 3D intersections among features. A line can be constructed as a collection of straight-line segments, thus the discussion of this operation focuses on straight-line cases. Adopting space-first-time-second strategy, two spatio-temporal lines are first projected into the 2D plane for spatial analysis. Depending on its position, a 3D line can be projected into a point (for a vertical one) or a line (for a tilted one) in the 2D plane. Therefore, the projection of two 3D lines in the 2D plane can be two points, a point and a line, or two lines. These situations are discussed separately.

When the projected shapes of the two 3D lines are both points, it indicates that both lines are vertical 3D lines. If the two vertical 3D lines have intersections, their projected points must overlap in 2D space. Conventional GIS operations can help ascertain whether the projected two points overlap. Also, the two lines must overlap in the time dimension. Comparing the minimum and maximum time represented by the lines can identify the temporal overlap. Denoting A_s, A_e, B_s, B_e, R_s, and R_e as the minimum and maximum time for lines A, B, and a possible intersected segment (R) between them (Figure 4.2), the temporal overlap can be determined by simple calculations.

$$\text{Let } R_s = \text{Maximum}(A_s, B_s);\quad R_e = \text{Minimum}(A_e, B_e) \tag{4-1}$$

If $R_s \leq R_e$, the two lines have temporal overlap, which starts at R_s and ends at R_e. When the two vertical 3D lines also overlap in the 2D plane, they have spatio-temporal intersections. If the coordinates for their projected point in the 2D plane are $<x_0, y_0>$, the 3D line resulting from the spatio-temporal intersection of two vertical 3D lines can be represented as $\{<x_0, y_0, R_s>, <x_0, y_0, R_e>\}$. When $R_s = R_e$, the result will become a 3D point instead of a 3D line.

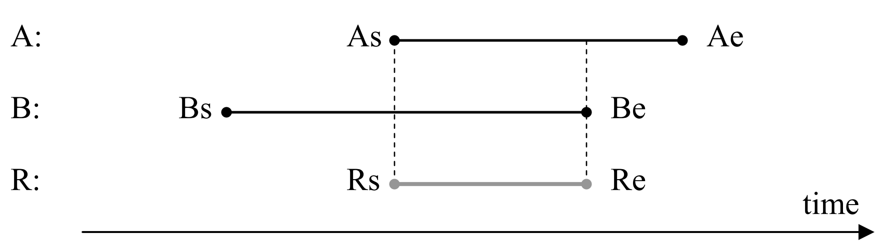


Figure 4.2. Temporal overlap.

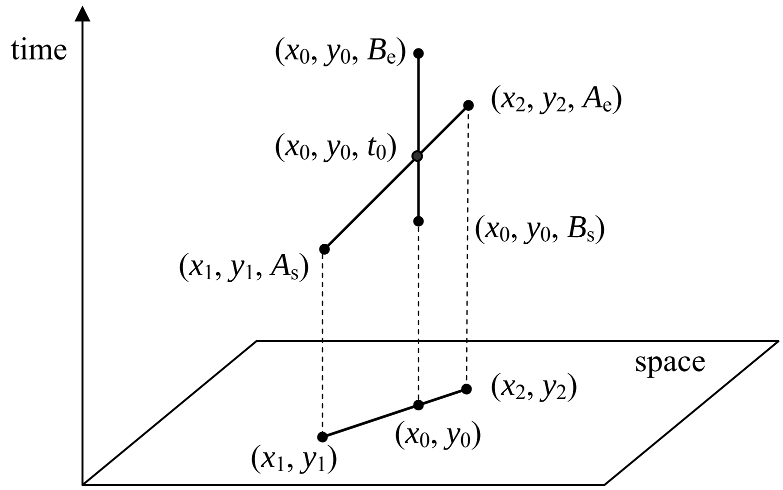


Figure 4.3. A spatio-temporal intersection between a vertical 3D line and a tilted 3D line.

When one of the two original 3D lines is a vertical line and the other is a tilted line, their projected shapes in the 2D plane will be a point and a line, respectively (Figure 4.3). If these two lines have a 3D intersection, their projected shapes must intersect. Conventional GIS operations can be used to check whether a point intersects a line or whether a line contains a point. If they do intersect, it indicates that the tilted 3D line must, at the very least, pass through the location where the vertical 3D line resides in the 2D plane. According to the location of the intersection in the 2D plane, a time value can be calculated for that location on the tilted 3D line through a linear interpolation method based on the time values at the end points of the tilted line. For example, if the tilted 3D line and the vertical 3D line are represented as $\{<x_1, y_1, A_s>, <x_2, y_2, A_e>\}$ and $\{<x_0, y_0, B_s>, <x_0, y_0, B_e>\}$, respectively, and they have an intersection in the 2D plane at $<x_0, y_0>$ as shown in Figure 4.3, the time value (t_0) for the location of $<x_0, y_0>$ on the tilted 3D line can be achieved from the following formula:

$$t_0 = A_s + (A_e - A_s) * \frac{\sqrt{(y_0 - y_1)^2 + (x_0 - x_1)^2}}{\sqrt{(y_2 - y_1)^2 + (x_2 - x_1)^2}} \tag{4-2}$$

If $B_s \le t_0 \le B_e$, the two lines will have a 3D intersection at a point of $<x_0, y_0, t_0>$.

Finding 3D intersections between two tilted 3D lines is more complex. In this case, their projected shapes in the 2D plane are two lines. Again, conventional GIS operations can help find intersections between the two lines. If the projected lines have only one intersection, the time value for the intersected location on each tilted 3D line can be interpolated using formula (4-2). If the two interpolated time values are the same, the two original 3D lines have one intersection and its coordinates can be achieved from the 2D intersection and the interpolated time value. Otherwise, the two 3D lines only pass the same location at different times.

If the projected lines overlap one another instead of having just one intersection, there are various possibilities for the relationship between the two 3D lines (Figure 4.4). Six situations between the two 3D lines are classified based on their directions and temporal relationships. A_s, A_e, B_s, and B_e are used to denote the minimum and maximum time for two tilted 3D lines, *A* and *B*. In Figure 4.4a, two 3D lines have the same direction and they share the same time range (i.e., $A_s = B_s$ and $A_e = B_e$). In this case, the two 3D lines completely overlap and either of them is the result of the 3D intersection operation between them. When $A_s > B_e$ as in Figure 4.4b, the two 3D lines will not intersect no matter what their directions are. When the time range of one 3D line covers the other one (i.e., $A_s < B_s$ and $A_e > B_e$) as shown in Figure 4.4c and 4.4d, the two 3D lines will have one 3D intersection. Depending on the directions of the two lines, the time value (t_0) for

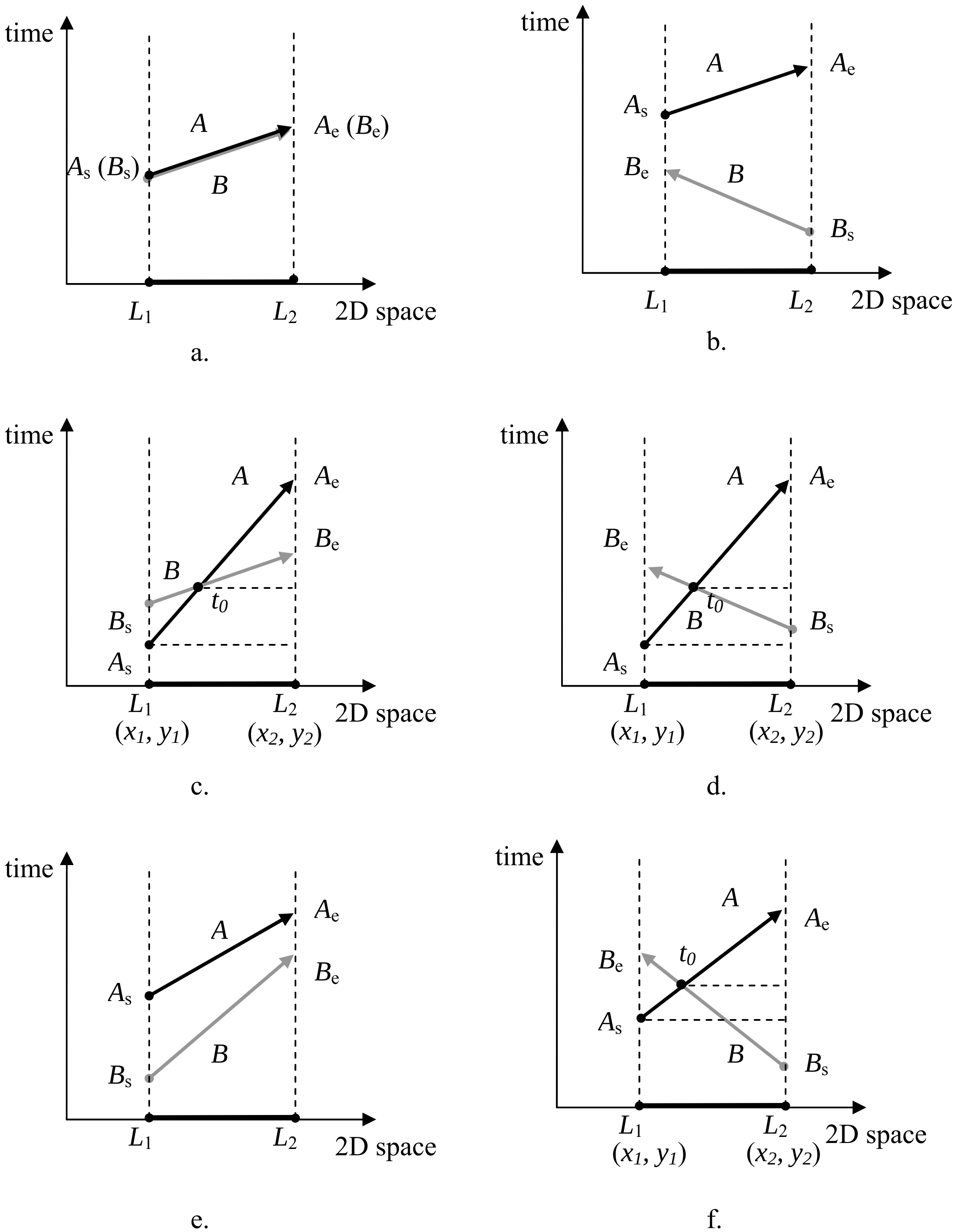


Figure 4.4. Spatio-temporal intersections between two tilted 3D lines.

the intersection is calculated using different formulas. In Figure 4.4c, a ratio relationship can be set up among A_s, A_e, B_s, B_e, and t_0.

$$\frac{B_s - A_s}{A_e - B_e} = \frac{t_0 - A_s}{A_e - t_0} \tag{4-3}$$

Therefore, the time value (t_0) for the intersection in this case is

$$t_0 = A_s + \frac{(A_e - A_s)(B_s - A_s)}{A_e - A_s + B_s - B_e} \tag{4-4}$$

Similarly, when the two lines have different directions as displayed in Figure 4.4d, the time value (t_0) for the intersection can be calculated using the following formula.

$$t_0 = A_s + \frac{(A_e - A_s)(B_e - A_s)}{A_e - A_s + B_e - B_s} \tag{4-5}$$

Once the time value (t_0) is calculated, it can be used to calculate x_0 and y_0 for the intersection based on the coordinates of one original 3D line. For instance, representing line A as $\{<x_1, y_1, A_s>, <x_2, y_2, A_e>\}$, the value of x_0 and y_0 can be calculated by

$$x_0 = x_1 + (x_2 - x_1)\frac{t_0 - A_s}{A_e - A_s} \tag{4-6}$$

$$y_0 = y_1 + (y_2 - y_1)\frac{t_0 - A_s}{A_e - A_s} \tag{4-7}$$

In both cases, the two 3D lines intersect at the point of $<x_0, y_0, t_0>$. When the time ranges of the two lines overlap (i.e., $B_s < A_s \leq B_e < A_e$), the directions of the lines will determine whether they have a 3D intersection. When the two lines have the same direction as displayed in Figure 4.4e, they will not intersect. When the two lines have different directions (Figure 4.4f), they will have one 3D intersection. The coordinates of the intersection can be calculated using the same process for the case in Figure 4.4d.

The intersection operation for spatio-temporal lines and spatio-temporal 3D features can be similarly processed using the same strategy. Because spatio-temporal 3D features represent extrusion results from polygons along the time dimension, their shapes do not change over time. Therefore, they will be polygons after projecting into the 2D plane. Conventional GIS operations can be used to find spatial intersections between polygons and points or polygons and lines. The time ranges of the resulting points or lines can be derived from the original spatio-temporal lines and compared to the time range of spatio-temporal 3D features. Only those portions on the spatio-temporal lines that share the same time range of the spatio-temporal 3D features are included in the results.

These operations together with spatio-temporal features are used to represent time-geographic objects and support manipulations among them in the temporal GIS model. The model is then used to operationalize the extended time-geographic framework for exploring the spatial and temporal characteristics of human activities.

4.2 GIS Representation of Space-time Paths and Individual Human Activities

A space-time path records the observed movements of an individual in physical space over time. Due to the indivisibility constraint of physical space, each individual has only one observed trajectory in space and time. A spatio-temporal line feature in the temporal GIS design can be used to directly represent an individual's space-time path. The triplets (<*x, y, t*>) stored at vertices of a line record the explicit spatial and temporal information of an individual's movements. With the linear interpolation method mentioned in section 4.1.2, spatio-temporal line features provide continuous representation for space-time paths, which means 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 only can stay in 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 activities and virtual activities take place within their specific space-time contexts. Each activity, as an episode in one's life, therefore 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 can 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 with 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 occurring along the route can be dynamically located based on their linear 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* is coined in this study to locate individual activity events on spatio-temporal line features. Time can be used as a linear referencing system for space-time paths: an activity can have starting time and ending time. If the duration of an activity is very short, it can be considered 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 according to 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 an instant in time. Through temporal dynamic segmentation, the spatio-temporal environment hosting an activity can be retrieved from a space-time path. Figure 4.5 shows several

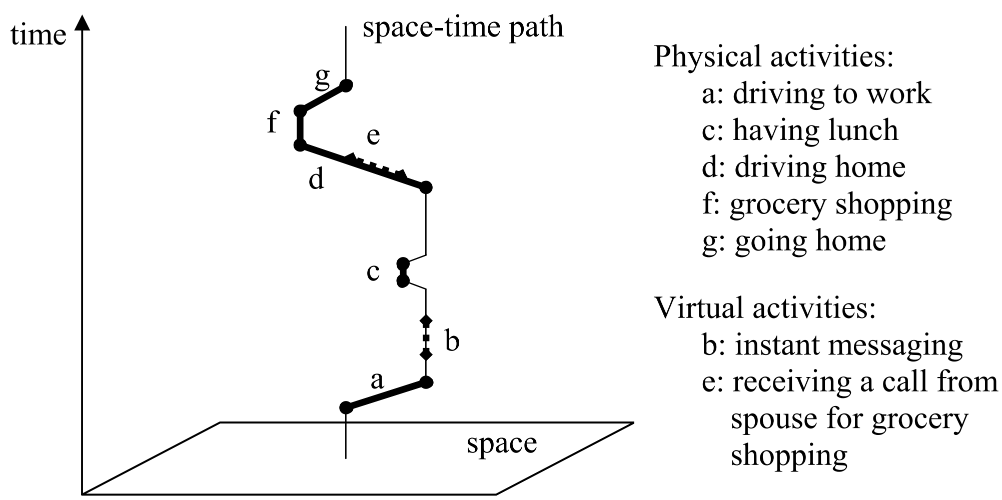


Figure 4.5. Locate individual activities on a space-time path using temporal dynamic segmentation.

physical and virtual activities 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 4.5 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.

4.3. GIS Representation of Space-time Prisms

A space-time prism defines the extent in space and time that is accessible to an individual under specific constraints. The space-time prism of Hägerstrand’s time geography adopts a continuous representation of space. Such an approach implies that every location in space could be reached by people. However, people usually move along road networks and activities take place at particular locations (Miller, 1991). Therefore, it is more meaningful and realistic to implement the space-time prism concept with a disaggregate representation (Miller, 1991; Kwan and Hong, 1998). The network-based approach has been widely adopted in accessibility studies to calculate space-time prisms and potential path areas in GIS (Miller, 1991, 1999; Kwan and Hong, 1998; Miller and Wu, 2000; Weber and Kwan, 2002; Kim and Kwan, 2003; Weber, 2003). This study also takes the network-based approach to operationalize the concept of space-time prism in the 3D GIS design.

Two cones enclose a space-time prism when constraints are present at both origin and destination. The cones define the boundary of the space-time extent that is accessible to a person. One cone starts from the origin and moves upward along the time dimension;

the other begins at the destination and runs downward. In this study, the two cones are called the *forward cone* and the *backward cone,* respectively. A forward cone depicts the range in space that could be reached by an individual with a given time budget. For each point on the cone, the time value of the point indicates the earliest time that an individual could reach this location by starting from the origin at a fixed time. Similarly, the backward cone defines the range in space where an individual could travel to the destination with a given time budget. In a road network, a *shortest-path tree* for a given node is a collection of shortest paths between a given node and other nodes in a network. The shortest path is based on a pre-defined travel cost such as distance or travel time. A shortest-path tree defines the range that an individual could reach from a given location with a given time budget, and is thus frequently used to calculate network-based potential path areas (Miller, 1991; Kwan and Hong, 1998). It is adopted in this study to represent cones of space-time prisms in a network environment and to calculate space-time prisms.

Figure 4.6 shows how a network-based space-time prism is represented in the 3D GIS design. An individual travels in a road network and faces time constraints at both origin and destination. The person can leave location L_1 at time T_1 and have to come back to the same location by time T_2. Thus, the prism is enclosed by two cones. Shortest-path trees from the origin and to the destination can be calculated respectively. The travel time to any other node in the network from the origin (L_1) can be derived from the shortest-path tree. For example, the travel time to location L_2 is t_1. For a location on a link of the network, the travel time to this location can be calculated using interpolation. A linear interpolation method can be used if we assume a person travels along the segment at a constant speed. Therefore, for any location in the network, it is possible to achieve the

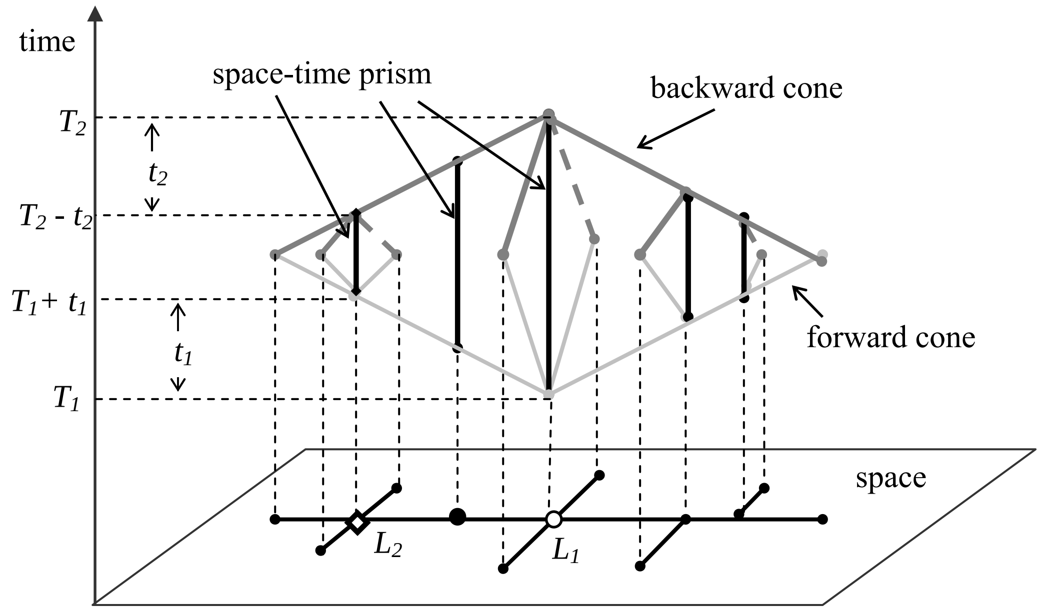


Figure 4.6. A 3D GIS representation of a network-based space-time prism.

exact time when the individual will reach the location. In Figure 4.6, an individual starts from the origin (L_1) at time T_1 and the travel time to location L_2 is t_1. Thus, the time when this individual reaches location L_2 is (T_1+ t_1). Similarly, if the individual wants to reach the destination (L_1) from location L_2 by time T_2, s/he needs to leave before the time (T_2- t_2). If (T_2- t_2) >(T_1+ t_1), it indicates that the person has some time to conduct activities at the location. Otherwise, the location is unreachable to the person under the given constraints. As each location in the shortest-path tree from the origin has a time value, the tree can be displayed in the 3D space-time system. The light gray lines in Figure 4.6 represent the shortest-path tree from the origin and they work as the forward cone of the prism. The dark gray lines represent the shortest-path tree to the destination and they function as the backward cone of the prism. Spatio-temporal line features are used to represent these lines. Therefore, a network-based cone is a collection of spatio-temporal line features in the 3D GIS design. For each node in the network where the time value from the backward cone is greater than that from the forward cone, i.e., $(T_2 - t_2) > (T_1 + t_1)$, a vertical spatio-temporal line is created at the location, starting at $(T_1 + t_1)$ and ending at $(T_2 - t_2)$ along the time axis. The length of the line indicates the time duration the person can stay at the location to carry out activities. A set of vertical spatio-temporal lines is then used to represent a space-time prism (thick black vertical lines in Figure 4.6), which depicts feasible locations in the physical space that can be visited by the individual for activities.

A space-time prism for virtual activities is considered as a subset of a conventional space-time prism that portrays the opportunities for an individual to access virtual space and conduct virtual activities. It can be achieved by intersecting space-time life paths of virtual space access channels with a conventional space-time prism. Two types of space-time life paths are discussed in Chapter 2: space-time life lines for wired access channels, and space-time life cylinders for wireless access channels. They are represented as spatio-temporal line features and spatio-temporal 3D features in the GIS design (Figure 4.7). For a wired access channel, such as a fixed Internet portal, a vertical spatio-temporal line is created at that location (e.g., at location L_1 in the figure). The ends of the line indicate the operation hours of the connection. As shown in the figure, the wired access channel at location L_1 is available from t_1 to t_2. For a wireless access channel, such as a wireless network service area, a spatio-temporal 3D feature is used to portray its availability in space and time. In this representation, it is assumed that the shape of the service area will not change over time. Therefore, the spatio-temporal 3D

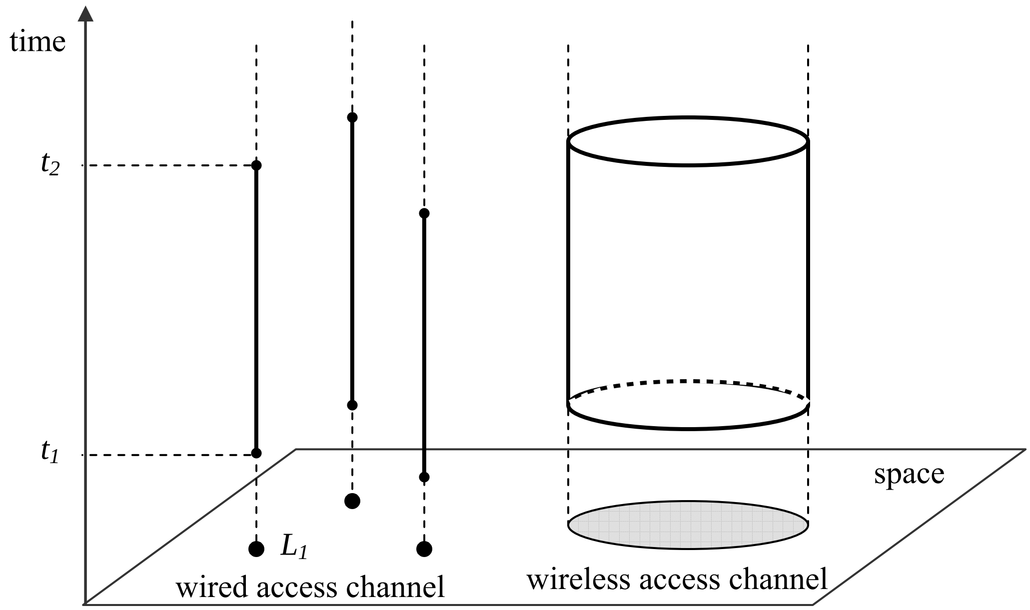


Figure 4.7. A 3D GIS representation of space-time life paths for virtual space access channels.

feature for a space-time life cylinder can be achieved by extruding the shape of a service area in the 2D plane along the time dimension according to the operation hours of the access channel. With representations of space-time life paths for virtual space access channels, intersecting space-time life paths with conventional space-time prisms can derive space-time prisms for virtual activities. Spatio-temporal intersection operations discussed in section 4.1.2 can be used to complete the process (Figure 4.8). Thick black lines that either overlap space-time life lines or fall within space-time life cylinders in the figure portray where and when an individual can reach virtual space access channels and conduct virtual activities. The subset of vertical spatio-temporal lines from a conventional space-time prism is used to represent a prism for virtual activities.

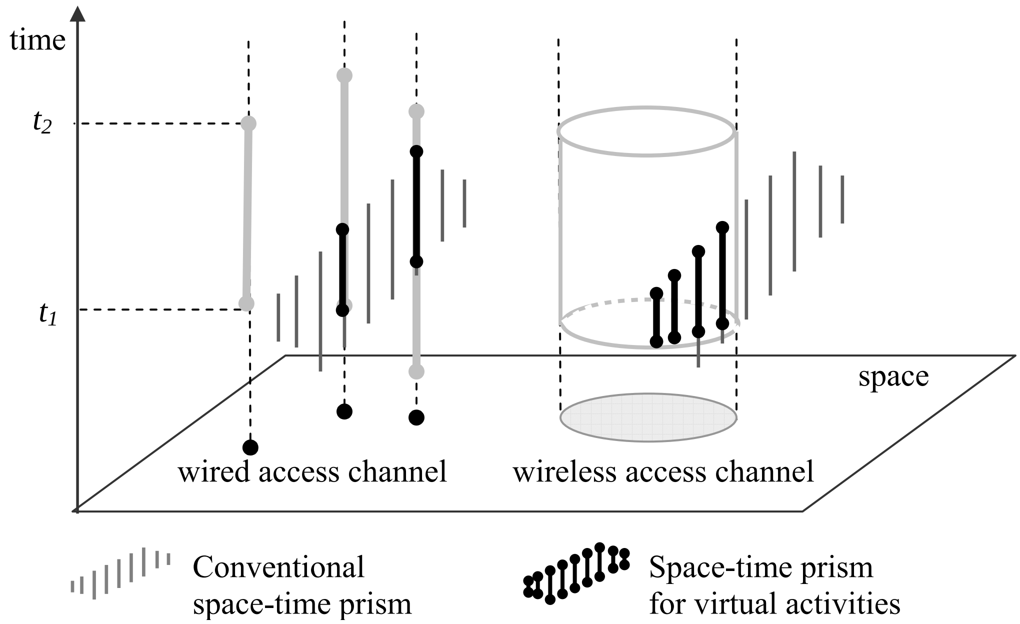


Figure 4.8. A 3D GIS representation of space-time prisms for virtual activities.

4.4 Exploration of Human Interactions in GIS

People are social beings and can rarely avoid interacting with others in the course of ordinary daily life. Hence, it is important for the temporal GIS design to have the capacity to explore interactions among people. As described earlier, people now can interact with each other through four different modes (i.e., SP, AP, ST, and AT). That is, people can relate to each other in different spatio-temporal relationships (i.e., co-existence, co-location in space, co-location in time, and no co-location in either space or time). These spatio-temporal relationships among people are critical to the study of human interactions in both physical and virtual spaces. Can GIS help us effectively organize and visualize different types of human interactions so that we can have a better understanding of the specific spatio-temporal pattern of each interaction? Can GIS assist us in analyzing spatio-temporal relationships of individuals with their space-time paths so that we can find out possible or "hidden" interactions among individuals? Can GIS facilitate the identification of potential spatio-temporal relationships of individuals with their space-time prisms so that we can formulate feasible potential interactions among interested individuals?

Spatio-temporal analysis functions must be developed in the temporal GIS model to answer these questions. By applying representations for time-geographic objects and spatio-temporal operations to them, spatio-temporal analysis functions can be developed to explore various interactions among people. In this section, three selected sets of spatio-temporal analysis functions, which apply to individual activities, space-time paths and space-time prisms, are discussed.

4.4.1 Organizing and visualizing the four types of human interactions

Human interactions can be considered 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 take certain actions 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 must 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 derived 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 for two reasons: 1) an interaction has multiple participants and different interactions may involve different number of participants, and 2) participants may join in an interaction under various spatial and temporal situations due to the existence of virtual space. Therefore, interactions can vary a great deal with respect to their spatio-temporal patterns and this leads to the difficulties in representing them in GIS.

Each interaction has a specific semantic content, which is the subject of an interaction. In the example above, a lecture is the semantic content for the intersection between an instructor and several students. Because all participants involved in an interaction share the same semantic content, that semantic content can be used to organize interactions with their participants, even though the participants join in the interaction with 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 individual participants. 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 content in GIS is displayed in Figure 4.9. Four objects are included in the figure: *activity*, *event*, *person*, and *space-time path*. The general term *activity* is used in the figure instead of interaction since interactions are special cases of activities. The object of *activity* is used to store the semantic content of an activity or an interaction, such as a meeting and a lecture. An *event* is an action (i.e., an individual activity) conducted by an individual to participate in an activity. For example, an instructor teaches in a lecture or a student attends class in a

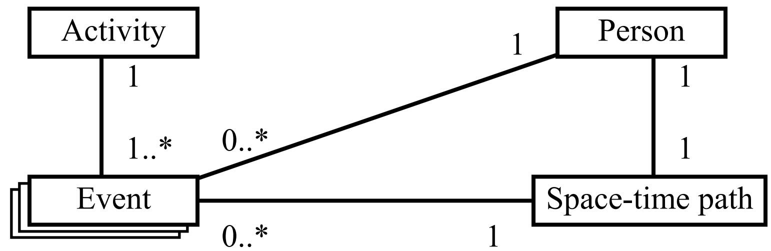


Figure 4.9. Semantic organization of human interactions in GIS.

lecture. The object of *person* contains attribute information of an individual. A *space-time path* records a person's trajectory in space and time. Relationships among these objects are also described in the figure. 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 is an interaction, which involves multiple persons. Each *person* has only 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 the spatial and temporal characteristics of an *event* are available from its corresponding *space-time path*. Zero or more *events* can be associated with a *space-time path* because a person may conduct none or multiple individual activities. In this model, individual activities (*events*) 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. Therefore, the spatio-temporal pattern of an interaction can be visualized and even determined by analyzing spatio-temporal relationships of spatio-temporal line features used to represent individual activities (*events*). If a dataset contains well-documented individual activity histories with interaction information, the interactions recorded in the dataset can be organized and visualized in the 3D GIS design through the method discussed here.

4.4.2 Exploring possible human interactions through spatio-temporal relationships of extended space-time paths

Interactions initiated by people (e.g., arranged meeting or planned videoconference) can be easily defined. However, some other interactions are less noticeable because even people who are involved in the interaction may not realize it. 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 interaction* and *unplanned interaction* to depict the two types of interactions. Under normal conditions, a planned interaction involves well-defined activity content and clearly identified participants who may participate in the interaction through different spatial and temporal conditions. Given well-documented records, this type of interaction can be represented effectively through the semantic organization method proposed in

Figure 4.9. 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 involvements. 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.

As mentioned in Chapter 2, people can interact with each other through four different modes according to their spatio-temporal characteristics, which are known as SP, AP, ST, and AT interactions. When represented with space-time paths, these interaction modes present specific spatio-temporal patterns. The patterns have been identified and named as four spatio-temporal relationships of space-time paths in Chapter 3: 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 being stuck in a 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 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 co-location in time and 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 into the 2D plane. If the projected lines fall within ICT-enabled locations, the original space-time paths share 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, it indicates the relationship of no co-location in either space or time, and they might have had AT interactions. The results from these spatio-temporal analysis functions for space-time paths can help researchers reveal possible human interactions.

4.4.3 Exploring potential human interactions through spatio-temporal relationships of extended space-time prisms

A space-time prism depicts feasible opportunities in space and time available to an individual to conduct potential activities. If people are going to have interactions, they must be able to form a proper spatio-temporal pattern in the future to carry out a particular type of interaction. As discussed in Chapter 3, studying the spatio-temporal relationships of prisms can help identify potential interactions of different modes among people. Therefore the temporal GIS design needs to provide analysis functions to identify spatio-temporal patterns of prisms. As discussed in section 4.3, sets of vertical spatio-temporal lines are used to represent prisms for both physical and virtual activities in this design. Thus, the analysis functions of identifying spatio-temporal relationships of prisms can be implemented by operations applied to spatio-temporal line features. The four spatio-temporal relationships are used again to explore the four types of interactions.

Testing whether the two sets of virtual spatio-temporal lines overlap in the 3D environment identifies the co-existence relationship among prisms. The 3D line intersection function discussed in section 4.1.2 can be used to discover intersections among sets of vertical spatio-temporal lines. If two prisms do intersect, the result will be a new set of vertical spatio-temporal lines representing feasible opportunities among the individuals to carry out potential SP interactions.

Examining whether overlap exists among the projected features of different sets of spatio-temporal lines in the 2D plane can determine the co-location in the space relationship of prisms. A positive result indicates potential interaction among examined individuals, with the individual who can visit a location first as the initiator and the other individual as the receiver of potential AP interactions.

For potential ST and AT interactions, tele-presence is involved and prisms for virtual activities are required in the analysis. Identification of the co-location in time relationship is a process determining whether different sets of vertical spatio-temporal lines overlap in time dimension. An overlapping time period is determined by comparing pairs of minimum and maximum time values of each prism for virtual activities. Then the portion of each prism falling within the overlapped time period is calculated and extracted to form a new set of vertical spatio-temporal lines. The result portrays the potential ST interaction opportunities among individuals.

The relationship of no co-location in either space or time describes the spatio-temporal pattern of individuals engaging in AT interactions. If an individual has an opportunity to access virtual space after another individual initiates an AT interaction, they will be able to complete the potential AT interaction. Therefore, as discussed in Chapter 3, if the time span of a prism for virtual activities falls at least partially after the minimum time value of another prism of an initiator of potential AT interactions, the two individuals will be able to complete the interactions. Working with vertical spatio-temporal lines, the function will determine the minimum time value in the prism of a potential AT interaction initiator and extract portions of other prisms falling after the time value. The extracted sets of vertical spatio-temporal lines portray the feasible opportunities for the individuals to complete potential AT interactions with the initiator.

4.5 Summary

In this chapter, a temporal GIS design is developed to accommodate the extended time-geographic framework. By simulating the 3D orthogonal system used in time geography, the 3D environment in the temporal GIS design enables the integrated representation of space and time. Such an environment extends the capability of GIS to handle time-geographic objects and concepts of the extended time-geographic framework. Basic types of spatio-temporal features are created and used to represent extended space-time paths and prisms, and basic operations (e.g., intersection) on spatio-temporal features are discussed and developed using a space-first-time-second strategy. A concept of temporal dynamic segmentation is coined and applied to space-time paths for locating individual activities in both physical and virtual spaces. The concept of temporal dynamic segmentation enhances the continuous representation of space-time paths in GIS and opens up opportunities to represent various features on space-time paths. Analysis of spatio-temporal relationships among time-geographic objects is made possible through their representations with spatio-temporal features in the design. Selected spatio-temporal analysis functions are discussed in this chapter. With these functions, the temporal GIS design is able to organize and visualize explicit interactions among individuals with their specific spatio-temporal patterns, identify spatio-temporal relationships of space-time paths to locate possible human interactions, and examine spatio-temporal relationships of space-time prisms to explore potential human interactions. The temporal GIS design provides an effective operational representation of the extended time-geographic framework and offers powerful support for exploring human activities and interactions at the individual level.

CHAPTER 5:

A TEMPORAL GIS PROTOTYPE SYSTEM

The temporal GIS model designed for the extended time-geographic framework is implemented with a prototype system. The purpose of the prototype system is to provide a proof-of-concept test for the feasibility of the design and to demonstrate the effectiveness of the design in exploring spatial and temporal characteristics of human activities. This chapter describes how the design is implemented in a commercial GIS software package with customized and extended functions. A small dataset containing hypothetical individual activities is created and used to demonstrate the ability of the system to handle human activities and interactions with their spatio-temporal characteristics.

5.1 The Prototype System and the Implementation Platform

A prototype system is set up in this study to handle human activities in a selected scenario, which includes individual activities and interactions carried out in a day by a group of individuals. In the prototype system, users are able to investigate spatio-temporal relationships among these individuals and explore the spatial and temporal characteristics of their activities and interactions. Selected functions are developed in the prototype system to generate, represent, and visualize space-time paths and prisms for activities in both physical and virtual spaces, and to analyze spatio-temporal relationships of space-time paths and prisms. With these functions, the prototype system can help researchers gain a better understanding of the spatio-temporal patterns of human activities and interactions in both physical and virtual activities.

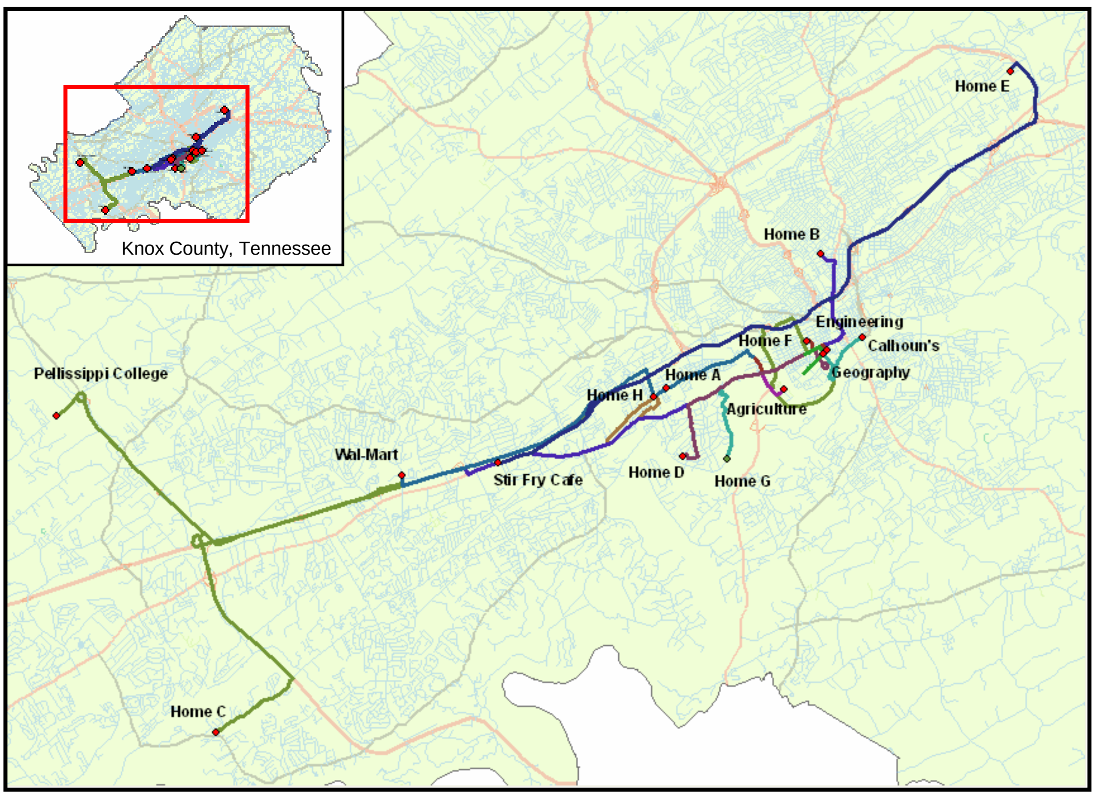
A hypothetical dataset with the daily activities of several individuals is generated to demonstrate the functionality of the prototype system. The dataset consists of 77 individual activities of ten persons in a day simulating possible scenarios taking place among people in a university on one Friday; it includes both physical and virtual activities taking place in Knox County, Tennessee. Interactions among these ten persons are also recorded in the dataset and all four interaction modes have examples in the dataset. Figure 5.1a shows some activity records in the dataset. Each individual activity in the dataset is recorded 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 is used and trips for all travel activities in the dataset are created based on the network according to their origins and destinations. Figure 5.1b displays a 2D map containing all trips in the dataset.

ArcGIS, a commercial GIS software product of Environmental Systems Research Institute, Inc. (ESRI), is chosen as the implementation platform for the prototype system. A fundamental issue in implementing the prototype system in ArcGIS is whether ArcGIS can support the representation of time-geographic objects. ArcGIS does not support a 3D system of space and time. However, ArcGIS provides representation and visualization for 3D spatial features (ESRI, 2002). This 3D representation in ArcGIS is adapted to simulate the space-time system of the extended time-geographic framework.

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



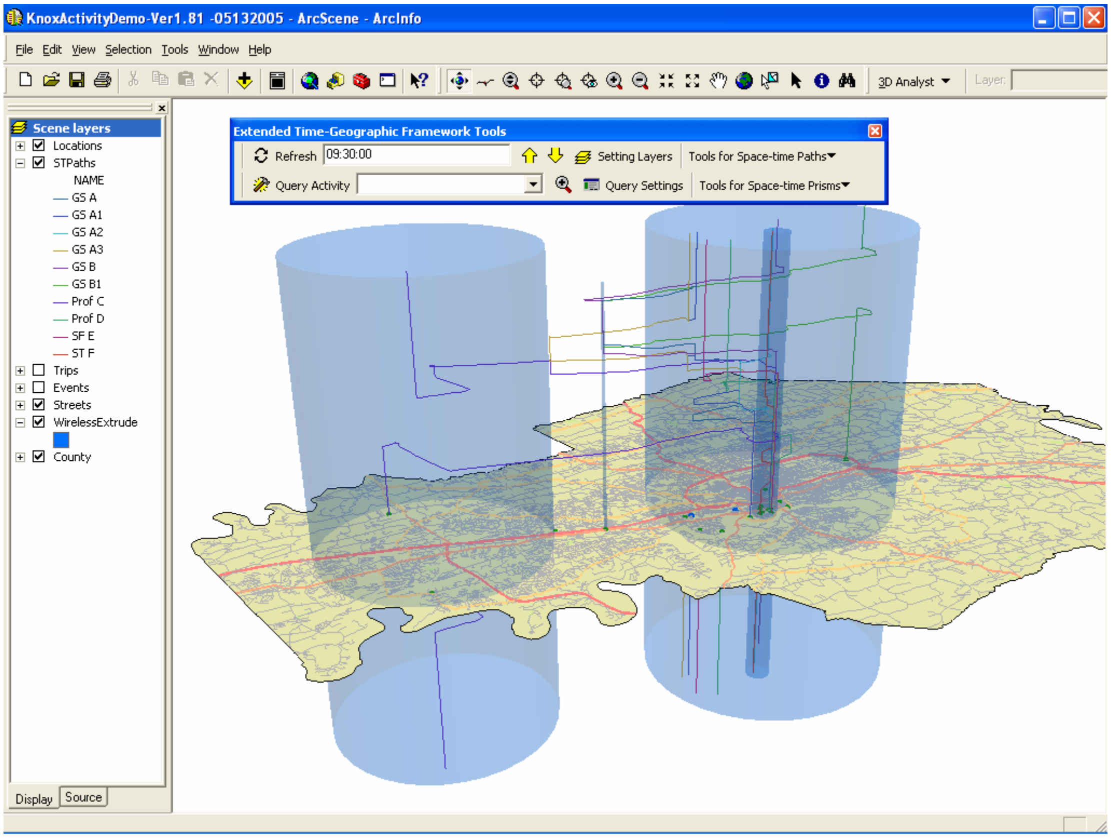
b. Travel activities in the hypothetical dataset

Figure 5.1. A hypothetical dataset with individual activities in a day.

In ArcGIS, conventional features in 2D space can have an optional *z* domain to represent the third spatial dimension. If only two spatial dimensions are considered for a feature's location, the *z* domain will not be used. However, if all three spatial dimensions are considered, the *z* domain can be enabled to carry a value indicating the feature's position in the third spatial dimension. Therefore, spatial objects in 3D space are represented as features with *z* values in ArcGIS. In the prototype system, the *z* domain is used to represent the time dimension instead of the third spatial dimension. With this approach, features with *z* values are used to represent time-geographic objects. In ArcGIS, *Point* and *Line* features with *z* values represent points and lines in 3D space; they are used to represent spatio-temporal points and lines in the prototype system. *MultiPatch* features, each of which is made of a series of 3D surfaces to display 3D features in ArcGIS (Zeiler, 2002), are used to represent spatio-temporal 3D features in the prototype system. As *MultiPatch* features in ArcGIS are used to represent the surface of 3D features rather than true solid 3D features, they are adopted in the prototype system to facilitate visualization of spatio-temporal 3D features, but are not used for analysis. With this approach, time-geographic objects (e.g., space-time paths, space-time prisms, and space-time life lines and cylinders) can be stored and managed in ArcGIS. Moreover, spatial features in 3D space can be visualized in ArcGIS. ArcScene, which is the 3D viewer of ArcGIS, provides an interactive 3D visualization environment for spatial features. With time-geographic objects represented as 3D features in ArcGIS, such an environment can be used to visualize time-geographic objects and explore their spatio-temporal relationships.

The prototype system can take advantage of existing functionality in ArcGIS for general spatial data manipulations. The hypothetical dataset, including time-geographic objects, can be stored and organized in a personal geodatabase of ArcGIS, which is a Microsoft Access database file (Zeiler, 1999). Using ArcGIS as the implementation platform, the prototype system can concentrate on developing functions for time-geographic objects instead of re-inventing functions for basic spatial data handling. The prototype system includes new functions not available in ArcGIS. The ArcGIS software package provides an environment for developers to customize interfaces and extend functionality of ArcGIS. The entire ArcGIS program is built on ArcObjects, which is an object library containing all components and functions for storing, managing, visualizing, and analyzing spatial data in ArcGIS. Taking an object-oriented programming approach, ArcObjects is composed of numerous classes. Each class may have several component object model (COM) interfaces through which users can access properties and methods of the class. ESRI makes the object library available to advanced GIS users to facilitate customization in ArcGIS. A built-in programming environment, Visual Basic for Applications (VBA), is provided in ArcGIS for users to access ArcObjects and build customized functions (Zeiler, 2002). The prototype system uses the VBA program with ArcObjects to implement selected functions in temporal GIS design for the extended time-geographic framework.

The prototype system is developed in ArcGIS using the hypothetical dataset. Customized functions for time-geographic objects are developed using the VBA program with ArcObjects. These functions are organized into a customized toolbar in ArcScene to take advantage of its 3D visualization function. Figure 5.2a provides a screen capture of the prototype system. Four sets of tools are included in the toolbar (Figure 5.2b). The first set of tools is used to facilitate visualization of time-geographic objects. The second and



a. A screen capture of the prototype system

b. The customized toolbar for the prototype system

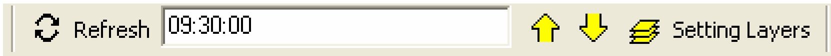
Figure 5.2. An implemented prototype system in ArcGIS.

third sets of tools are designed to assist in the investigation of historical human activities and interactions, and the foundation of these functions is the space-time path. The second tool set includes functions to generate space-time path related features and analyze spatio-temporal relationships of space-time paths. The third tool set focuses on visualizing spatio-temporal patterns of the four types of interactions among individuals. The last set of tools contains space-time prism functions to investigate potential human activities and interactions in both physical and virtual spaces. The rest of this chapter describes how these functions are implemented in ArcGIS and how they can help investigate the spatio-temporal characteristics of human activities and interactions.

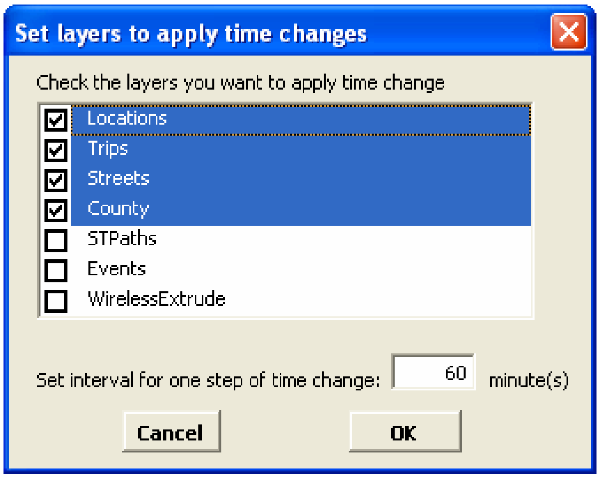
5.2 Tools for Visualization of Time-geographic Objects

ArcScene provides an interactive environment to visualize 3D spatial features. There are built-in functions in ArcScene designed to facilitate the visualization of 3D features, such as zooming in and out, and viewing features from different angles by turning them around in three dimensions. These functions are used to facilitate the visualization of time-geographic objects in the prototype system.

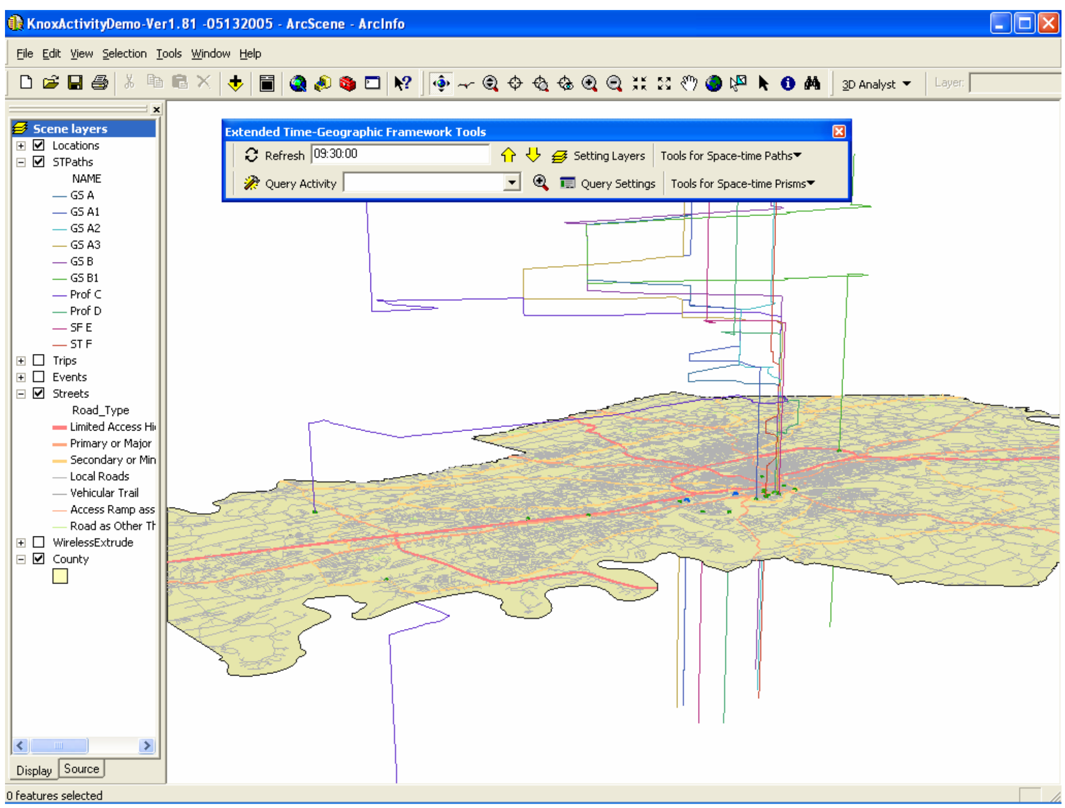
Also, extra tools are developed to enhance the ability of ArcScene to visualize time-geographic objects and they are grouped as the first set of tools in the customized toolbar (Figure 5.3a). In ArcScene, a layer can be assigned with a base height, and all features in the layer can be raised along the *z* dimension. This function is used to facilitate the visualization of time-geographic objects. In the prototype system, users can select layers and set them to stay at a designated time. Therefore, these layers can work as the background for time-geographic objects while referring to the designated time. This



a. Tools for space-time visualization



b. The interface to set background layers and time step for visualization



c. Background layers to facilitate the 3D visualization

Figure 5.3. The 3D visualization environment for time-geographic objects.

process involves conversions between *z* values and time values. Because the prototype system deals with human activities during one day, seconds are used as the measurement unit for time. Therefore, one unit in *z* dimension refers to one second. Using zero in *z* dimension to label the starting time of a day (i.e., 00:00:00), the *z* value for any point in time in a day is achieved by calculating the accumulated seconds from 00:00:00. For example, the time 14:30:25 is represented with a *z* value of 52225 (i.e., 14*3600 + 30*60 + 25 = 52225). Thus, the maximum *z* value in the system is 86400, which refers to the end of a day (i.e., 24:00:00). Once a reference time is decided, the reference time value is converted into a *z* value based on the method discussed above. The *z* value then is set as the base height for the selected layers, which will be displayed at the corresponding position in *z* dimension as background layers. Given a *z* value, a reverse process can determine what time value it refers to.

Tools in Figure 5.3a help users control the background layers and reference time. The text box in the toolbar displays the reference time, which is calculated from the *z* value for the current base height of background layers. The background layers can be moved up or down along the time dimension at a pre-specified time step by clicking the up or down arrow icon in the toolbar. Each click will change the base height of the background layers by a value corresponding to the pre-specified time step. Once the background layers are at a new position, the text box will automatically update the reference time value by converting the new base height to a time value. Users also can input a new time value in the text box and click the “Refresh” button to re-locate the background layers to a new position in *z* dimension. Users can determine which layers will be included as background layers and the particular time step when the up and down arrow icons are clicked. A dialogue window as shown in Figure 5.3b is available to set these preferences when the “Setting Layers” button is clicked. Figure 5.3c shows that a polygon layer for Knox County and a line layer for the street network of Knox County work as the background layers displayed at a reference time of 09:30:00 for a set of space-time paths. With these customized tools, ArcScene provides an effective and interactive environment for users to visualize time-geographic objects.

5.3 Functions for Space-time Paths and Individual Human Activities

5.3.1 Tools for exploring historical human activities

One major objective of the extended time-geographic framework is to help explore spatial and temporal characteristics of historical human activities and interactions. In the prototype system, just like cases in the real world, a dataset containing individuals’ daily activities is the beginning point for examinations of spatial and temporal characteristics of historical human activities. Therefore, functions are needed to generate space-time paths and support spatio-temporal analysis on them. The flowchart in Figure 5.4 displays how the daily activity data is processed and what functions are implemented in the prototype system to support selected analyses on historical individual activities.

In Figure 5.4, the objects in shaded boxes represent spatial features with geometry, while those in white boxes represent tables without geometry. *Travel Diary Data* contains complete travel activity records for each individual in the dataset. As travel activity is a specific type of activity, records in *Travel Diary Data* are only a subset of those in the *Individual Activity Table*. *Travel Diary Data* is a feature class, which means it stores the trip shape of each travel activity. A customized function is needed to generate

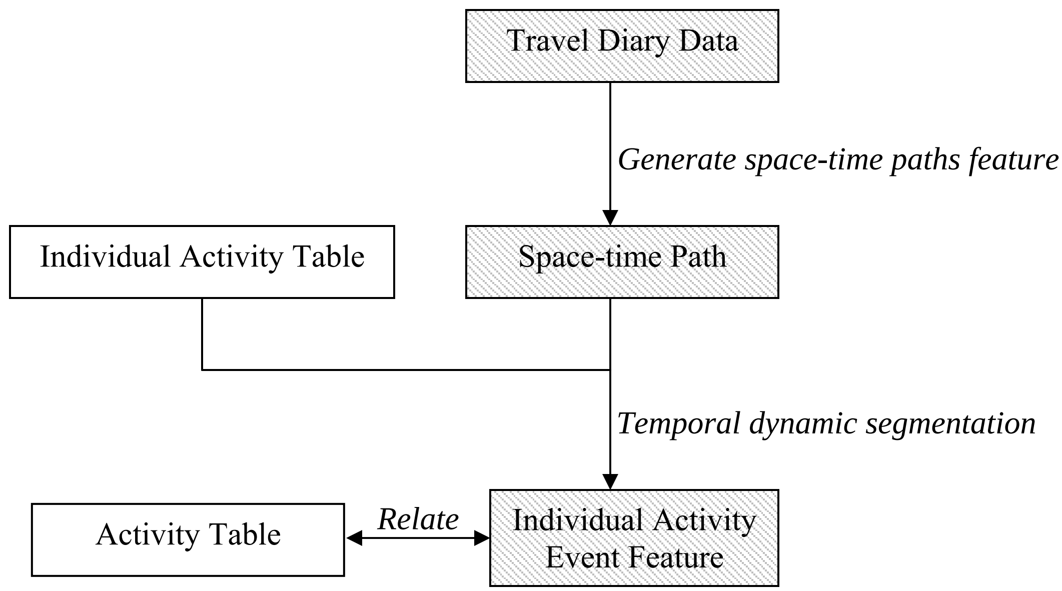


Figure 5.4. A flowchart of exploring historical human activities.

space-time paths for individuals with their trips recorded in *Travel Diary Data*. The generated *Space-time Path* is stored as a feature class. With the existence of space-time paths, functions are developed to analyze their spatio-temporal relationships. The *Individual Activity Table* contains each individual activity with its temporal information. Individual activities in the *Individual Activity Table* can, therefore, be located on space-time paths in *Space-time Path* through temporal dynamic segmentation. The result will be stored as an *Individual Activity Event Feature*, which is also a feature class. The *Activity Table* contains semantic content for activities (including interactions) taking place among the individuals in the dataset. Event features in the *Individual Activity Event Feature* will be related to activities in the *Activity Table* through the relationship shared by them. Therefore, events involved in the same activity content are connected. The spatio-temporal pattern of an activity (interaction) can be visualized and explored through related event features.

Two tool sets in the customized toolbar are dedicated to the exploration of historical human activities described in the flow chart of Figure 5.4. "Tools for Space-time Paths" includes five functions, which are used to generate space-time paths, locate individual activity events on space-time paths, and analyze spatio-temporal relationships of paths. The name and brief description of each function in this tool set is listed in Table 5.1. The third tool set is used to visualize spatio-temporal patterns of four types of interactions when an individual activity event feature class and an activity table are available. Four components are included in the tool set as shown in Figure 5.5. The "Query Settings" button provides an interface used to set up the relationship between an individual activity event feature class and an activity table so that individual activity events are correctly related to their activity content. Once the relationship is correctly set up, the list box in the toolbar will be populated with all activities recorded in the activity table. Users can select one activity from the list and click on the "Query Activity" button to view the spatio-temporal pattern of the activity. Individual activity event feature(s) related to the selected activity will be highlighted by flashing once in the view. If multiple individuals are involved in the activity, users can visualize the spatio-temporal pattern of the interaction based on the relative space-time position of the individual activity event features. Users can click on the magnifier button to zoom in to the space-time extent of the activity if the pattern is difficult to view at the current angle. These tools are an effective approach to visualize spatio-temporal patterns of interactions.

Table 5.1. Functions in the tool set of "Tools for Space-time Paths"

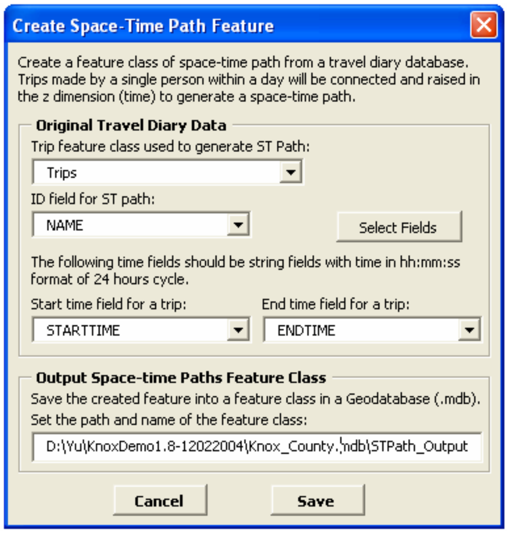
Function Name	Description
Create ST Path Feature	Generate a feature class for space-time paths from a line feature class containing travel diary data.
Create Event Feature	Generate a feature class for individual activity events by locating each individual activity from an activity diary data table on its space-time path through temporal dynamic segmentation.
Find Co-existence Relationship	Given a feature class of space-time path, this function finds out intersections of any pair of space-time paths in the feature class.
Find Co-location in Space	Given a feature class of space-time path and a point feature class for locations, this function finds out all cases when a space-time path passes by or stays at a location in the point feature class and reports their corresponding time values.
Find Co-location in Time	Give a feature class of space-time path and a fixed time, the function finds out the location for each space-time path at the time.

Figure 5.5. Tools for visualizing well-documented human activities and interactions.

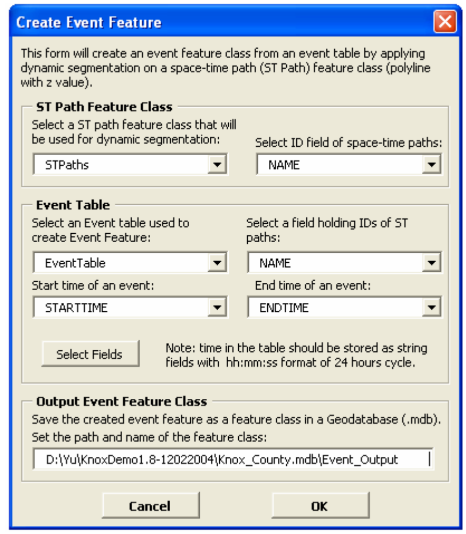
5.3.2 Generating space-time paths from travel diary data

A space-time path depicts an individual's trajectory in space and time. It is composed of a sequence of stays in specific locations and movements between these locations (Wang and Cheng, 2001). The trips made by a person form a chain, which means the ending location of a person's trip is the starting location of the next trip. Therefore, a complete record of a person's trips can be used to generate a space-time path.

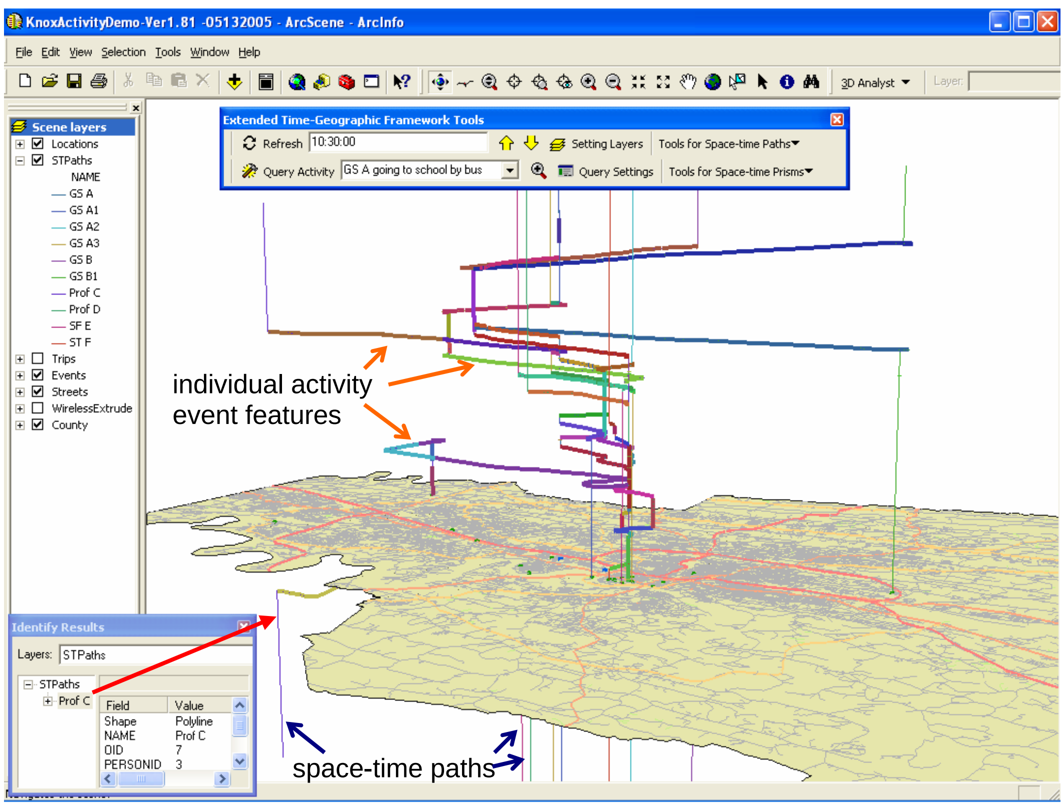
In the prototype system, a function is created to generate space-time paths for individuals with their trip data. Figure 5.6a displays an interface created in the prototype system. The procedure will select all trips of one person and sort them in time sequence. The starting and ending times of each trip are stored in the record; the time values are converted into *z* values and assigned to the starting and ending points of the trip. Assuming a person travels at a constant speed, the procedure calculates the *z* value for any intermediate point along the route using linear interpolation, which determines the point's *z* value from the *z* value of either the starting or ending point of the route and the point's relative location along the route. Therefore, every vertex in the trip shape has its own *z* value for temporal information. Between every pair of trips adjacent in the time sequence, a link is used to connect the ending point of an early trip with the starting point of the next trip. With the two points representing the same location, the link will be a vertical line in the 3D system, indicating a person's stay in the location. Two extra links are added to the starting point of a person's first trip and the ending point of the last trip so that each space-time path starts at 00:00:00 and ends at 24:00:00. These two links indicate that the person remained in the starting location from 00:00:00 until the start time of the first trip, and remained in the ending location after the last trip until 24:00:00.



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 5.6. Space-time paths and individual activities in the prototype system.

After assembling all time-stamped trips and the added links in time sequence, a new polyline with *z* values is created and used to represent the person's space-time path. Using trips in the hypothetical dataset, a new feature class is generated by running the function. It contains ten polylines with *z* values, representing space-time paths for the ten individuals in the dataset. Figure 5.6c shows the 3D visualization of these space-time paths when they are brought into ArcScene.

5.3.3 Locating individual activities on space-time paths through temporal dynamic segmentation

Each individual activity is an episode in one's life and occupies one specific portion of a space-time path. A new concept – temporal dynamic segmentation – has been coined in this study to help locate an individual activity on a space-time path with starting and ending times. Temporal dynamic segmentation is implemented in the prototype system to generate individual activity event features with an individual activity table and a feature class of space-time paths.

Figure 5.6b displays the interface of the function to locate individual activities on space-time paths. It requires a space-time path feature class and an individual activity table as inputs. Reading in an individual activity record from the table, the procedure first finds the individual's space-time path from the space-time path feature class and then locates the two points on the space-time path representing the starting and ending times for the individual activity. The two time values are converted into *z* values. Because a space-time path is a polyline with unique *z* values along the shape, a *z* value can be used to locate a point along the line. Starting from the bottom of the space-time path, the *z* value for each vertex in the polyline is compared to the inquiry *z* value for the starting/ending time of the individual activity. If the inquiry *z* value falls at a vertex along the polyline with the same *z* value, that vertex is used to represent the point with the inquiry *z* value. If it falls in between the *z* values of two adjacent vertices in the polyline, a linear interpolation method is used to calculate the location of the inquiry *z* value. Once the two points for starting and ending times of the individual activity are located in the space-time path, the portion of the polyline between the two points is extracted and constructed into a new polyline with *z* values, which is an event feature representing the individual activity. Therefore, the event feature has spatial and temporal characteristics extracted from the space-time path. The output of the function is an event feature class of polylines with *z* values, containing all individual activities recorded in the table. The thicker line segments on space-time paths in Figure 5.6c are individual activity event features generated from the dataset. When several persons conduct multiple activities during the same time period (e.g., calling another person on a cellular phone while driving), some of the segments can overlap with each other.

5.3.4 Organizing and visualizing human interactions

An interaction, which is considered to be a special type of activity, necessitates the actions of multiple individuals. In Chapter 4, a semantic approach is proposed to manage well-documented human interactions by organizing action events of participants under the semantic content of an interaction. This approach is realized in the prototype system to organize explicitly recorded interactions and to facilitate exploration of spatio-temporal patterns of interactions by visualizing them in ArcScene.

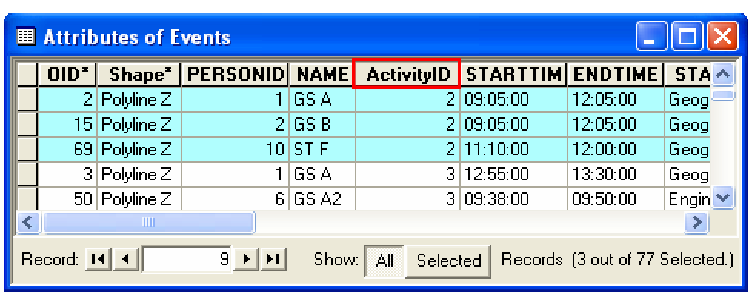
An activity table is generated, with each record representing a unique activity (or interaction) stored in the original individual activity table. The activity table contains an ID field to unambiguously identify an activity and a text field to describe the semantic content of the activity. An event feature class for individual activities can be created through temporal dynamic segmentation as mentioned in the previous section, and it contains spatio-temporal characteristics of actions performed by individuals to carry out specific activity content. Each record in the event feature class also contains a field for activity ID, indicating to which activity this event belongs. The semantic connection between *activity* and *event* described in Figure 4.9 is implemented as relationship class in ArcGIS. As shown in Figure 5.7, an activity table can be related to an event feature class through the common field shared by them, which is the activity ID. If several records in


Attributes of ActivityTable

OBJECTID*	ActivityID	Description
2	2	GIS Lab
3	3	Email between GS A and GS A2
4	4	GS A going home by bus
5	5	Note from GS A to GS A1
6	6	GS A driving to tennis court

Record: 9 Show: All Selected Records (1 out of 60 Selected.)

Activity table


Attributes of Events

OID*	Shape*	PERSONID	NAME	ActivityID	STARTTIM	ENDTIME	STA
2	Polyline Z	1	GS A	2	09:05:00	12:05:00	Geog
15	Polyline Z	2	GS B	2	09:05:00	12:05:00	Geog
69	Polyline Z	10	ST F	2	11:10:00	12:00:00	Geog
3	Polyline Z	1	GS A	3	12:55:00	13:30:00	Geog
50	Polyline Z	6	GS A2	3	09:38:00	09:50:00	Engin

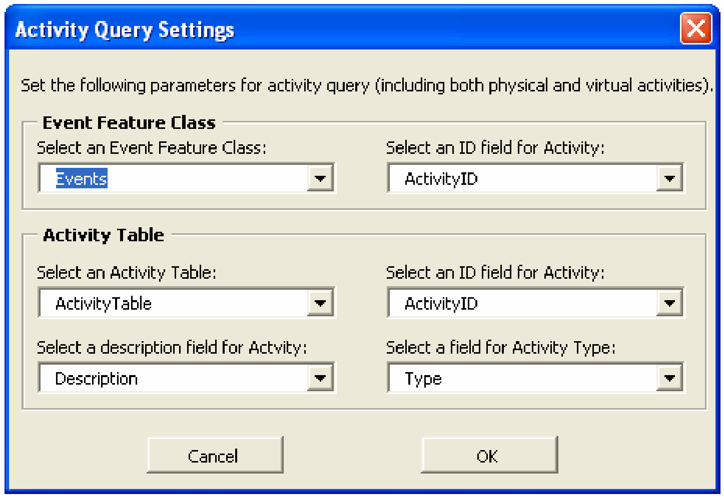
Record: 9 Show: All Selected Records (3 out of 77 Selected.)

Event feature class

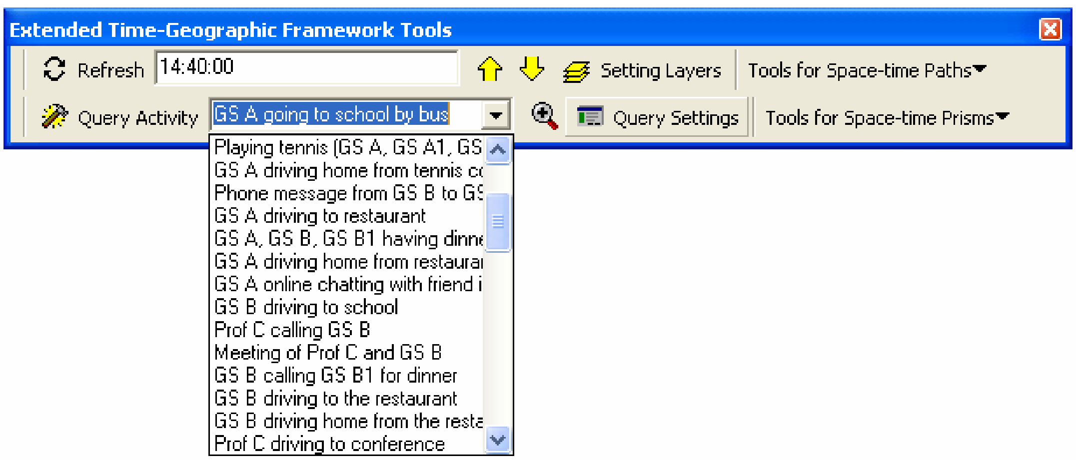
Figure 5.7. The relationship between activity table and event feature class.

the event feature class have the same activity ID, they belong to the same activity (more specifically, an interaction), which has the description of semantic content in the activity table. For example, the highlighted record in the activity table in Figure 5.7 is an activity described as a GIS lab, which has a value of 2 as activity ID. Three highlighted records in the event feature class have value 2 for their activity ID field. Therefore, the three events are connected to the activity of a GIS lab.

Using the tools in the customized toolbar, interactions recorded in the hypothetical dataset can be organized and their spatio-temporal patterns can be visualized in ArcScene. When the "Query Settings" button on the toolbar is clicked, a dialogue box (Figure 5.8a) is brought up to guide users in setting up the relationship between an activity table and an event feature class. Once the correct relationship is set up, an activity list is automatically created and displayed in the dropdown list box in the toolbar (Figure 5.8b). As all four types of interactions are included in the dataset, their spatio-temporal patterns can be visualized and explored in the 3D environment. Figure 5.9 provides examples of all four types of interactions. In case 1, two graduate students attended a lab at school together. This is an ST interaction and they share a co-existence relationship; their event features, displayed as red line segments, overlap. Case 2 is an AP interaction, in which a person left a note for his/her roommate in their apartment and the roommate picked it up at a later time. The two persons have a co-location in space relationship. As displayed in the figure, event features for this interaction (the red line segments) share the same location, but not the same time period. An ST interaction is described in case 3 – one person called another using a cellular phone while driving. It is a co-location in time relationship. The red tilted line segment indicates that the caller was

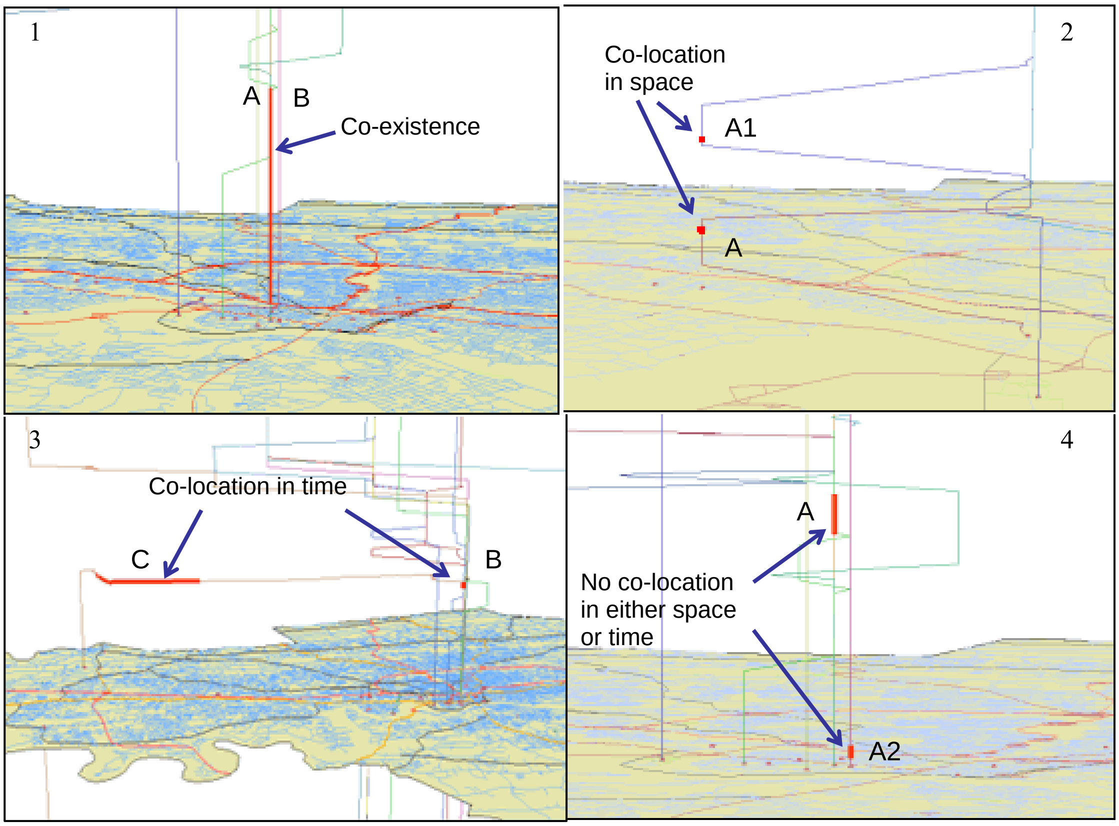


a. The form to set the relationship between activity table and event feature class



b. Activity list

Figure 5.8. Functions for visualizing interactions in the prototype system.



1. Graduate students A and B attended the same lab session
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 an e-mail to A, which was received by A later

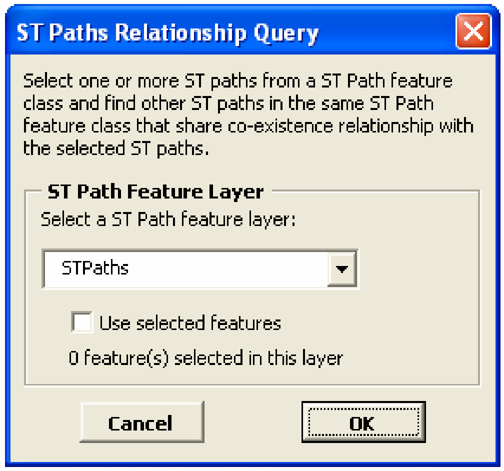
Figure 5.9. Visualization of human interactions in the prototype system.

moving during the interaction, while the vertical red line segment indicates that the other person was staying in a fixed location. Although these two line segments do not overlap in 2D space, they share the same time period. In case 4, a person sent out an e-mail and the other person received it at a later time. This is an AT interaction and the participants have a relationship of no co-location in either space or time. In this figure, the two event features, highlighted as red line segments, do not overlap in either space or time. However, they are related due to the same interaction content as an e-mail communication.

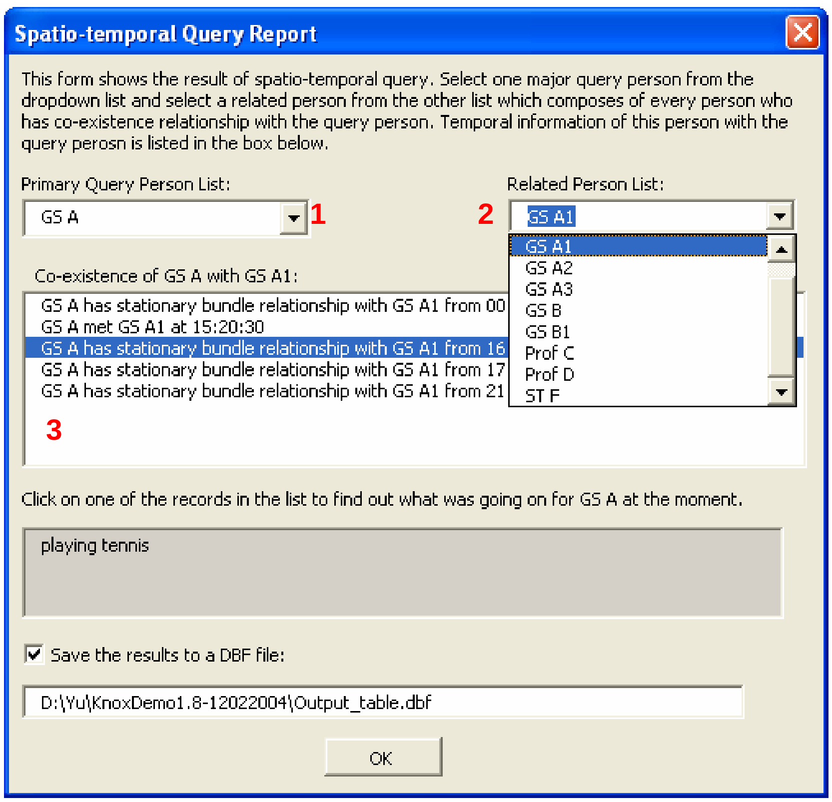
5.3.5 Analyzing spatio-temporal relationships of space-time paths

Spatio-temporal analysis functions are needed to identify possible interactions among people, including missing records of planned interactions and unplanned interactions. Selected functions are implemented in the prototype system to assist in meeting this need. Three analysis functions applied to space-time paths are developed to examine their spatio-temporal relationships: co-existence, co-location in space, and co-location in time.

The co-existence analysis function is designed to identify the co-existence relationship between two individuals. Figure 5.10a shows the interface of this function. The input of this function is a feature class of polyline with z values containing space-time paths. When the function is executed, each space-time path is paired up with all other space-time paths, and the program searches for intersections between each pair of space-time paths. A procedure for locating intersections between two polylines in 3D environment is developed in the prototype system. During the process, the polylines are decomposed into collections of straight-line segments. Locating the 3D intersections



a. The form for co-existence analysis

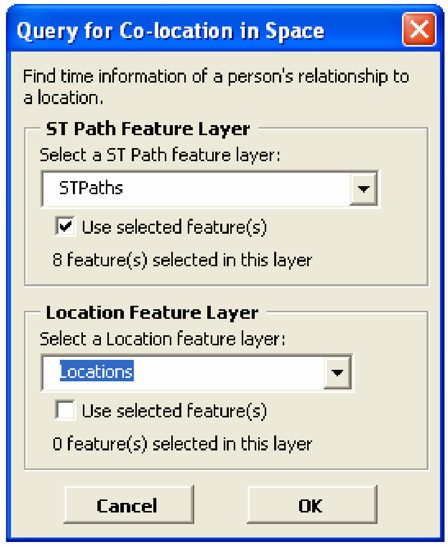


b. The result report form for co-existence relationship

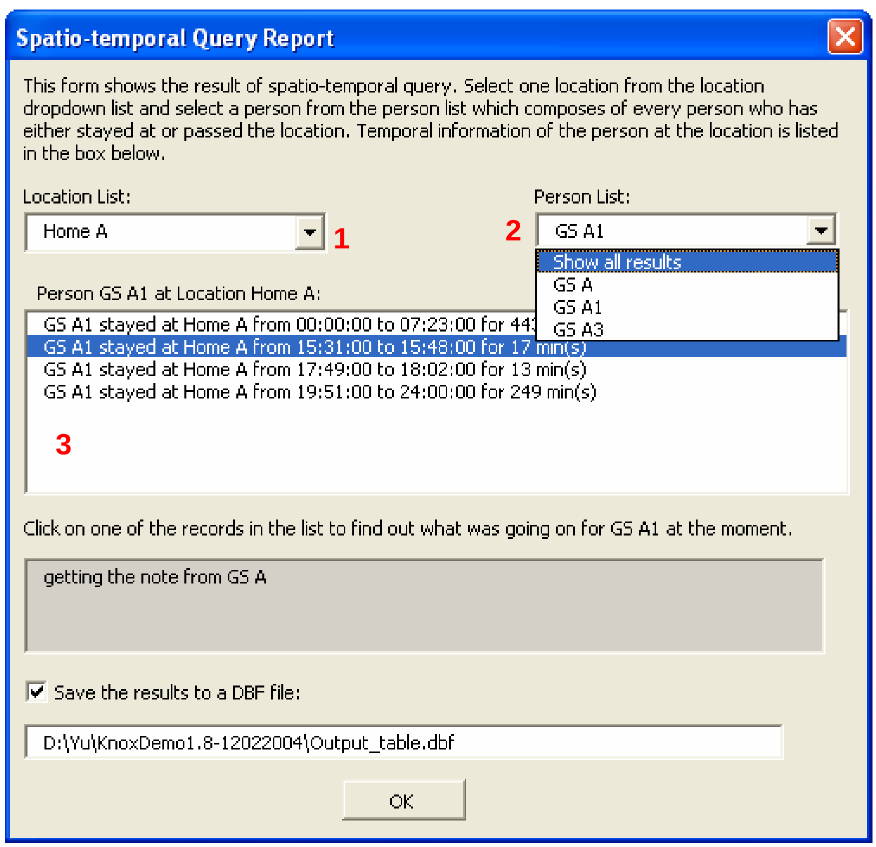
Figure 5.10. Co-existence analysis of space-time paths.

between polylines is processed by examining the relationship between pairs of straight-line segments from the two collections. Each pair of straight-line segments is projected onto the 2D plane as lines (for tilted 3D lines) or points (for vertical 3D lines). In ArcObjects, a COM interface named *ITopologicalOperator* is available for *Point*, *Polyline*, and *Polygon* classes (Zeiler, 2002). Through the COM interface, a method of *Intersect* can be used to calculate intersections between two shapes (point, line, or polygon) in the 2D plane. This method is used to examine the intersections of the shapes projected from the original straight-line segments. If the projected shapes intersect, the z value of the intersection on each straight-line segment is interpolated based on the z values of the end points of the segment. If the interpolated z values for the two segments are the same, the two segments have a 3D intersection. All co-existence relationship cases between every pair of space-time paths are identified with their time durations. The result is organized and displayed in a customized report form; users can interactively check the intersections between any pair of individuals. Figure 5.10b is the result of executing the co-existence relationship analysis function on the hypothetical dataset. The report form contains all cases of co-existence relationship shared between any two persons. Users can select a particular person from the dropdown list labeled “1” in the report form and all individuals who have a co-existence relationship with that person are listed in the dropdown list labeled “2.” If a specific person is selected from the second list, the text box labeled “3” will display all intersection cases between the two selected persons and their time durations. Each record in the result indicates that two individuals share a co-existence relationship; if such a relationship lasts longer than a certain time duration, the two individuals might have had SP interactions during that time. The result can also be saved as a dBase file (DBF file) for further analysis.

The co-location in the space analysis function in the prototype system is designed to find all individuals who visited a particular location. As shown in Figure 5.11a, the input of this function is a point feature class containing locations and a feature class of polylines with *z* values for space-time paths. Given a location and a space-time path, the function can check whether the individual (the owner of the space-time path) passed by or stayed in the location. In the process, the polyline with *z* values for the space-time path is broken down to segments, which are straight lines in 3D. The straight lines are projected onto the 2D plane and become either lines (for tilted 3D lines) or points (for vertical 3D lines). These projected lines and points are used to check for intersections with the point feature representing the location. If a projected line intersects with the location point, it indicates that the person passed by this location. The passing-by time can be derived from linear interpolation based on the *z* values of the end points of the original tilted 3D line segment. If a projected point overlaps the location point, it indicates that the person stayed in the location. The stay duration can be computed from the *z* values of the end points of the original vertical 3D line segment. Figure 5.11b shows the analysis result, which is organized and displayed in a similar report form as the one for co-existence analysis. Dropdown list "1" is a list of locations. When a location is selected, all persons who had visited this location are populated in list "2." If a person is selected, the temporal information for the person's visit(s) to this location is displayed in the text box labeled with 3. If the result shows that several persons visited the same



a. The form for co-location in space analysis



b. Result report form for co-location in space analysis

Figure 5.11. Co-location in space analysis of space-time paths.

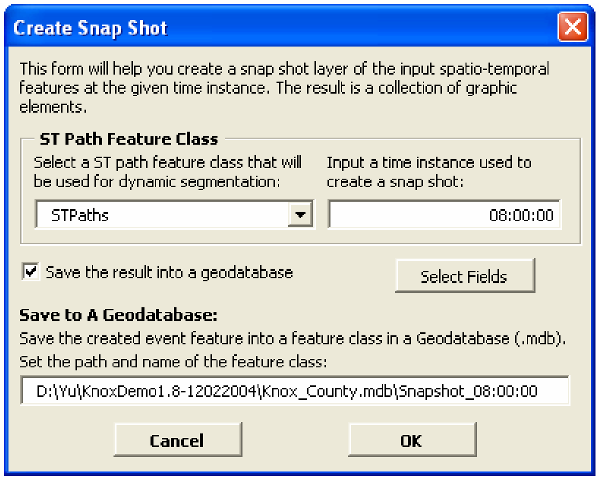
location during different time periods, it implies that they might have carried out AP interactions. Users also have the choice to save the result into a dBase file.

The co-location in time function is developed to create a snapshot of locations of individuals at a specific time. Given a time value, the function will locate a position on a space-time path through temporal dynamic segmentation, which includes the individual's location at that time. The input of this function is a feature class of polylines with *z* values for space-time paths and a time value (Figure 5.12a). The snapshot result is stored as a point feature class, with each point feature representing a person's location at the moment. The big dots in Figure 5.12b are locations for the ten individuals in the dataset at 8AM. With the Knox County street network as the background, users can easily ascertain where the individuals were at that time. If some of the locations have virtual space access channels at that time, the individual might have had ST interactions.

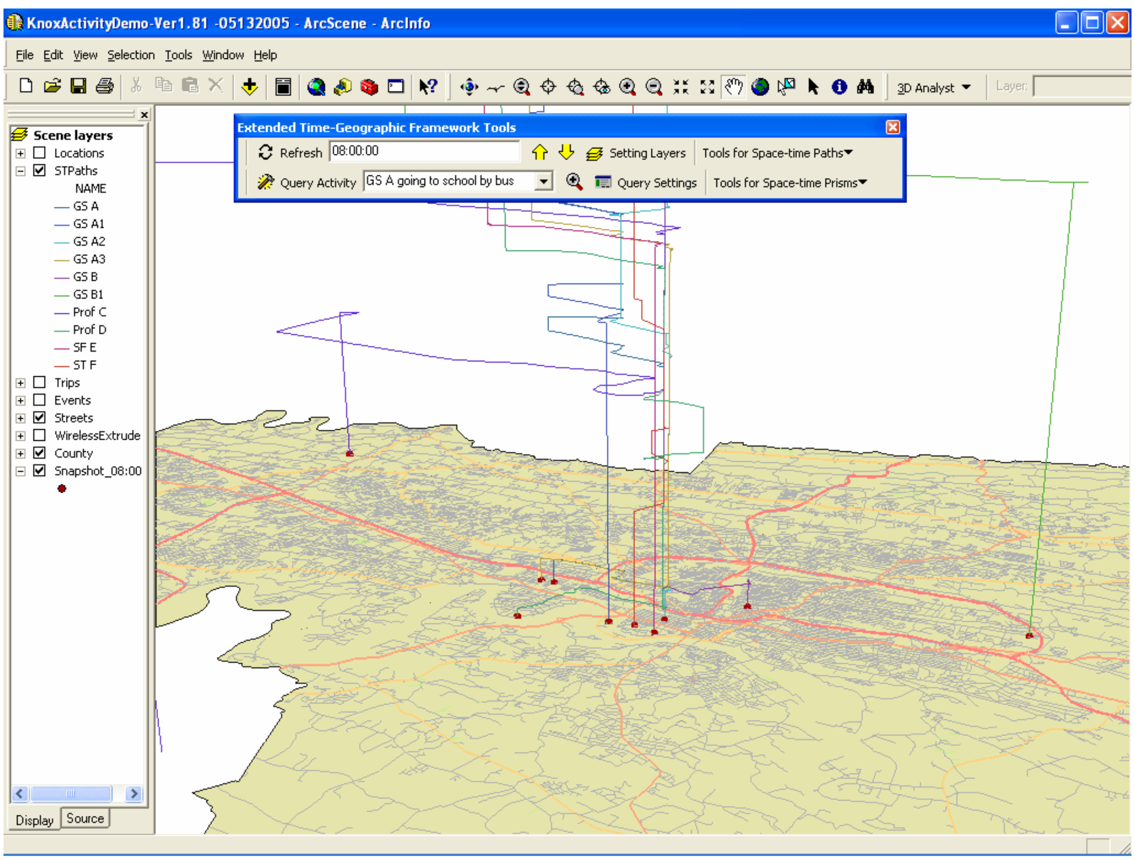
5.4 Functions for Space-time Prisms

5.4.1 Tools for exploring potential human activities

Resembling the role of space-time paths in analyzing historical human activities, space-time prisms are important for identifying potential activities and interactions. Conventional space-time prisms can be used to efficiently portray potential human activities in physical space. However, these days an increasing number of human activities are carried out in virtual space. As discussed in Chapter 4, a network-based space-time prism has been adopted in this study to identify opportunities for potential virtual activities. The flowchart in Figure 5.13 describes how space-time prisms for physical and virtual activities are calculated in a network environment. Selected functions



a. The form for co-location in time analysis



b. Locations of ten individuals at 8AM

Figure 5.12. Co-location in time analysis of space-time paths.

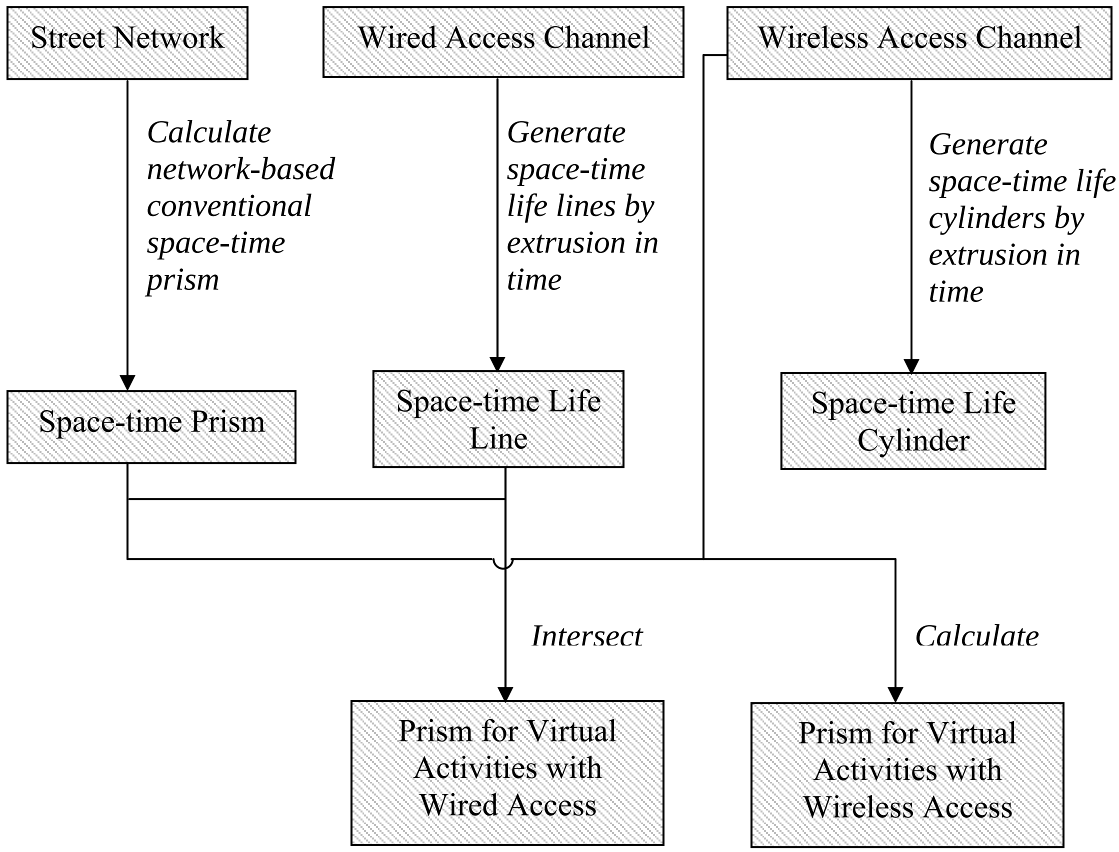


Figure 5.13. A flowchart of exploring potential human activities.

are also developed to explore potential human activities and interactions in the modern society.

All boxes in the flowchart of Figure 5.13 are shaded, which indicates that all of them are represented as spatial features with geometry. *Street Network* is a network defining the spatial extent of people's movements. Based on *Street Network* and a set of space-time constraints, a function can be developed to calculate network-based space-time prism, *Space-time Prism*, which only defines opportunities for potential physical activities. Chapter 3 indicates that space-time life paths for virtual space access channels are needed to generate space-time prisms for virtual activities. *Wired Access Channel* and *Wireless Access Channel* define the 2D locations where people can access virtual space through wired and wireless connections. With information on the operation hours for access channels, *Space-time Life Line* and *Space-time Life Cylinder* can be generated by extruding the shapes representing access channels along the time dimension. By intersecting *Space-time Prism* with *Space-time Life Line*, *Prism for Virtual Activities with Wired Access* can be achieved. As mentioned, *Space-time Life Cylinder* is not represented as a solid 3D feature in the prototype system and is for visualization purposes only. Therefore, *Prism for Virtual Activities with Wireless Access* is achieved through an operation applied to *Space-time Prism* with *Wireless Access Channel*, instead of with *Space-time Life Cylinder*. With representations of prisms for physical and virtual activities, spatio-temporal analysis functions based on prisms can be developed to explore opportunities for potential interactions among people through the four different interaction modes.

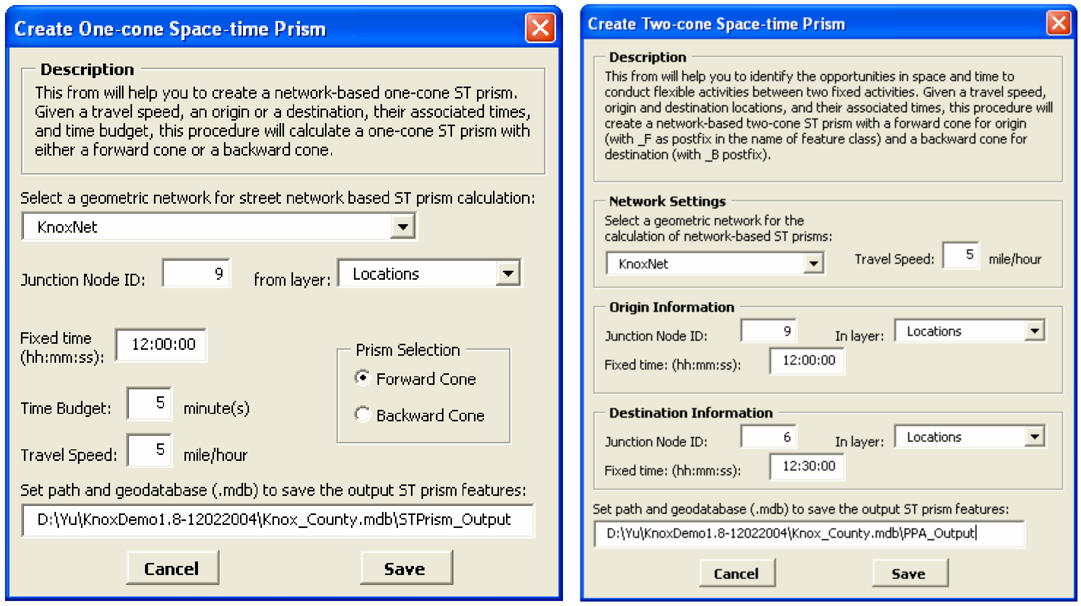
Selected functions of manipulating space-time prisms are implemented in the prototype system. These functions are grouped into a tool set in the toolbar named "Tools for Space-time Prisms. " The tool set includes nine functions, which are developed to generate space-time life paths for virtual space access channels, calculate network-based space-time prisms for physical and virtual activities, and analyze spatio-temporal relationships of prisms for potential interactions. Table 5.2 provides the names of the functions with their brief descriptions. Details of their implementations in ArcGIS are provided in the following sections.

5.4.2 Calculating and representing network-based conventional space-time prisms

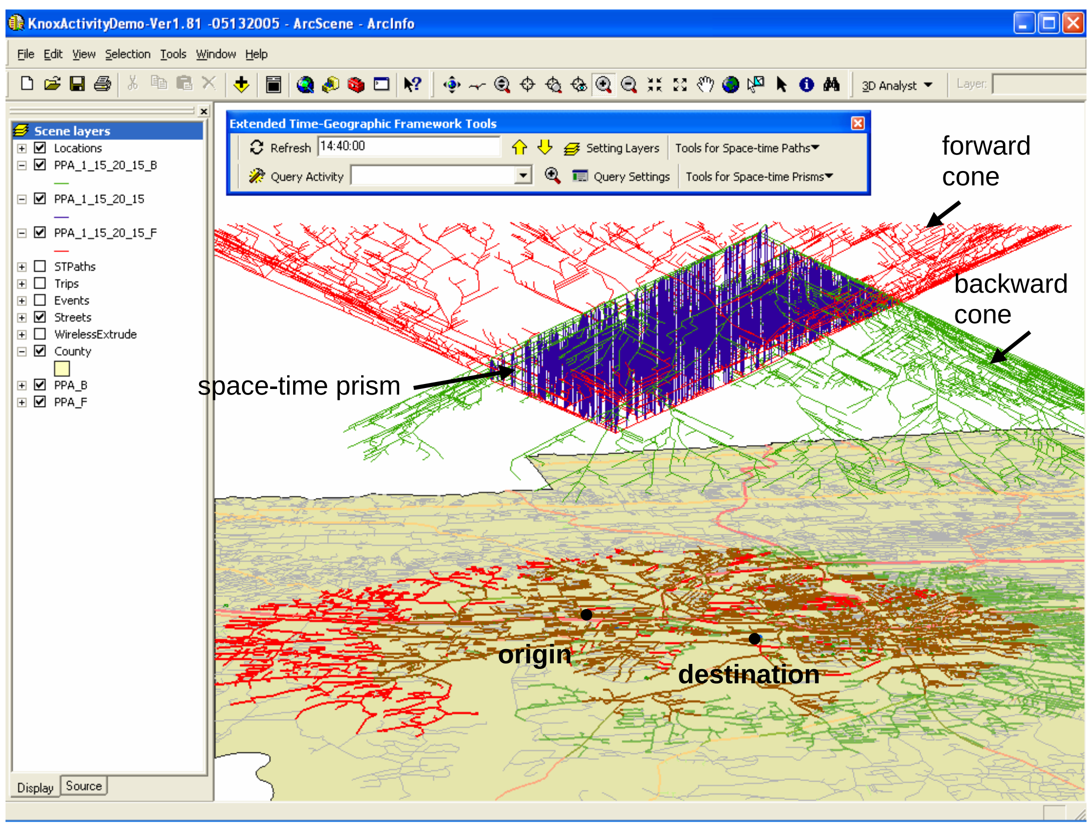
The prototype system provides functions to calculate network-based space-time prisms. A geometric network is created for the street network of Knox County. In ArcGIS, a geometric network is used to store topological information and process path searching in a network. As constraints can be applied to one location (origin or destination) or both locations to calculate a space-time prism, two interfaces are created to calculate a prism with either one cone or two cones (Figure 5.14a). In the interface, users can choose a network on which the prism is created and set spatio-temporal constraints for the prism. For example, to create a prism with two cones, a user needs to enter locations for origin and destination, starting time at the origin and ending time at the destination, and travel speed (assuming a constant speed of travel). The time budget for travel can then be computed by comparing the times at the origin and the destination, and the maximum travel distance can be decided by multiplying the travel speed by the time budget. A *ForwardStar Class* in ArcObjects is designed to help navigate through a geometric

Table 5.2. Functions in the tool set of “Tools for Space-time Prisms”

Function Name	Description
Create One-cone ST Prism	Based on a street network and space-time constraints on either origin or destination, calculate a space-time prism with one cone.
Create Two-cone ST Prism	Based on a street network and space-time constraints on both origin and destination, calculate a space-time prism with two cones.
Create Life Paths for Facilities	Create space-time life paths for virtual space access channels with their operation hours. Space-time life line features are created for wired connections and space-time life cylinder features for wireless connections.
Create ST Prism for Virtual Activities with Wired Access	Intersect space-time life lines with a space-time prism to generate a ST prism for virtual activities with wired access.
Create ST Prism for Virtual Activities with Wireless Access	Create a ST Prism for Virtual Activities with Wireless Access using a space-time prism and a wireless access channel feature class with information of operation hours.
Analysis of Potential SP Interactions	Find the co-existence relationship between two conventional ST prisms.
Analysis of Potential AP Interactions	Find the co-location in space relationship between two conventional ST prisms.
Analysis of Potential ST Interactions	Find the co-location in time relationship between two prisms for virtual activities.
Analysis of Potential AT Interactions	Find the relationship of no co-location in either space or time between two prisms for virtual activities.



a. Forms for creating ST prism with one cone and two cones



b. A case of space-time prism with two cones

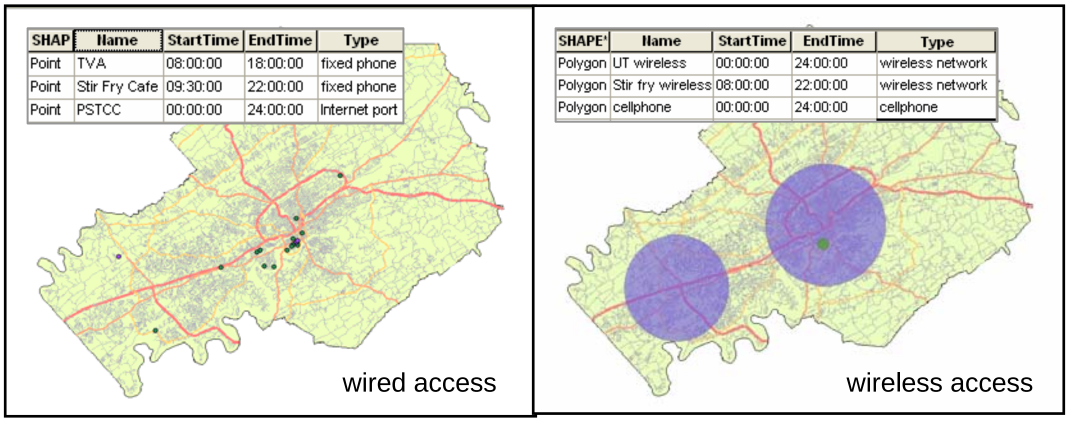
Figure 5.14. A network-based conventional space-time prism.

network (Zeiler, 2002). A user can use the *ForwardStar Class* to query the connectivity between nodes and links in a network. Using the *ForwardStar Class,* Dijkstra's shortest path algorithm is implemented in the prototype system to search for shortest paths. A shortest paths tree, which covers a portion of the network that can be reached within the maximum travel distance, is calculated on the selected network for the origin and the destination respectively. A cumulated travel time is recorded for each node in the shortest paths tree. The projected time of reaching a node in the shortest-path tree for the origin is then calculated by adding the cumulated travel time at the node to the fixed time at the origin. Similarly, the projected time of leaving a node in the shortest-path tree for the destination is calculated by subtracting the cumulated travel time at the node from the fixed time at the destination. The projected time for each node is converted and attached to the node as its *z* value. Therefore, a shortest-path tree is stored as a feature class of polylines with *z* values in the prototype system and serves as a cone to a prism. With two cones available, the program starts to check nodes in the network that are included in both shortest-path trees and retrieve their corresponding *z* values from the two cones. If the *z* value from the backward cone is larger than that from the forward cone at a node, it indicates that the individual can reach and stay in this location under the given constraints. Therefore, the node should be included in the space-time prism. A vertical spatio-temporal line is created at the location, with the lower end of the line having the *z* value from the forward cone and the higher end having the *z* value from the backward cone. A collection of these lines is used to represent a conventional space-time prism and it is also stored as a feature class of polylines with *z* values in ArcGIS. Therefore, for a prism with two cones, three feature classes are created by the function, with two for the cones and one for the prism.

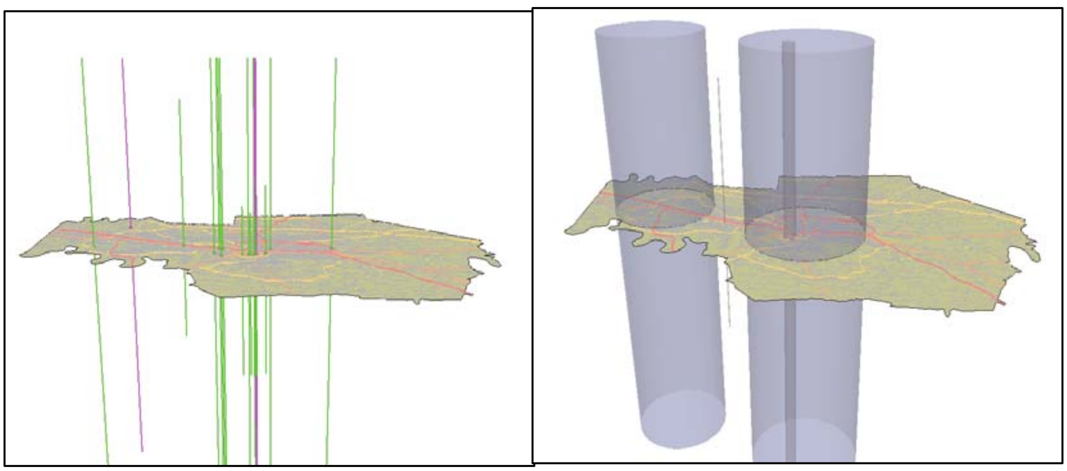
Figure 5.14b displays a two-cone space-time prism created from the street network of Knox County. A person plans to leave his apartment (the origin) at 3PM and needs to arrive at a tennis court (the destination) by 3:20PM. S/he drives a car and travels at an average speed of 15 mph. The forward cone is displayed in green lines and the backward cone is displayed in red lines. The prism is represented by vertical purple lines enclosed by the two cones. The purple lines indicate where the individual can visit under the constraints, and the length of each purple line indicates how long s/he can stay in that location. These lines portray the opportunities in space and time that are available in which to conduct potential activities.

5.4.3 Creating space-time life paths and space-time prisms for virtual activities

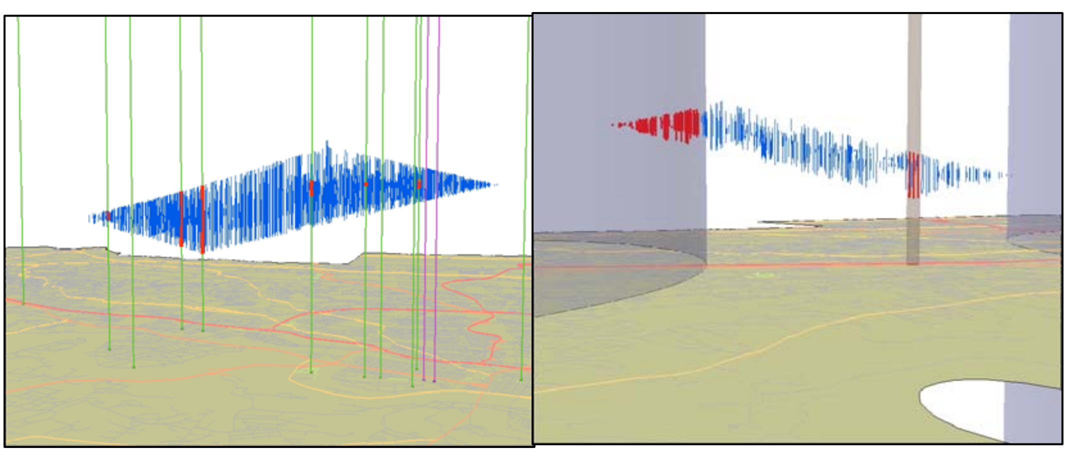
Space-time life paths for virtual space access channels describe where and when the channels are available. Wired access channels (e.g., fixed phone lines and wired Internet ports) are point-like features, while wireless access channels (e.g., cellular phone service areas and wireless network areas) can cover regions and are represented as polygon features in GIS. Figure 5.15a shows some sample virtual space access channels in Knox County, with a point feature class for wired connections and a polygon feature class for wireless connections. The operation hours for these connections are stored in the attribute tables of the feature classes as shown in the figure. Their space-time life paths are vertical lines and cylinders, respectively, in the 3D environment. A function of “Create Life Paths for Facilities” is developed in the prototype system to generate space-time life lines for



a. Wired and wireless access channels



b. Space-time life lines and cylinders



c. Space-time prisms for virtual activities

Figure 5.15. Space-time life paths and prisms for virtual activities.

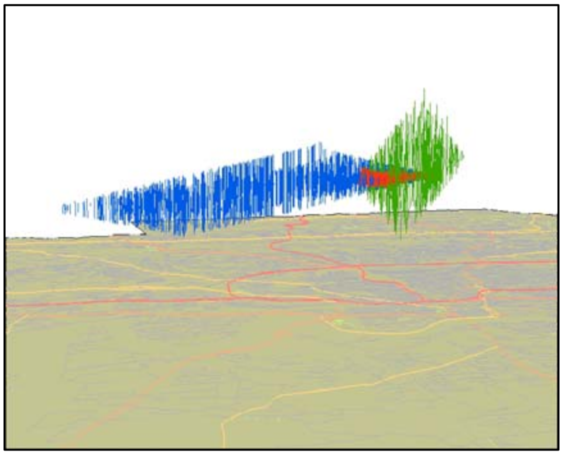
wired access channels and space-time life cylinders for wireless access channels by extruding their shapes along the *z*-axis according to their operation hours. A class in ArcObjects, *GeometryEnvironment*, is used in the program to generate the space-time life paths. Through a COM interface *(IExtrude*) of the class, a method (*ExtrudeFromTo*) is available to extrude a geometry along the z-axis between two specified z values. After extrusion, a point becomes a 3D line and a polygon becomes a *MultiPatch*. Therefore, a *z*-value-enabled *Polyline* feature class and a *MultiPatch* feature class are used to represent and store space-time life lines and cylinders, respectively, in ArcGIS. Figure 5.15b displays the space-time life paths, which are generated from the access channels shown in Figure 5.15a by extruding them along the time dimension according to their operation hours.

A space-time prism for virtual activities is a subset of a conventional space-time prism, which defines where and when people can access virtual space. It can be achieved by intersecting a conventional space-time prism with space-time life paths of virtual space access channels. Therefore, a *z*-value-enabled polyline feature class is also used to represent prisms for virtual activities in ArcGIS. Two functions, “Create ST Prism for Virtual Activities with Wired Access” and “Create ST Prism for Virtual Activities with Wireless Access,” are available in the prototype system to derive prisms for virtual activities. Prisms for virtual activities with wired access are derived by intersecting conventional prisms with space-time life lines. As both prisms and space-time life lines are represented as *z*-value-enabled polyline features in ArcGIS, the intersection function applied to vertical 3D lines is used to complete the operation. However, as space-time life cylinders are represented as *MultiPatch* features, which are not solid 3D features, a work-around method is implemented in the prototype system to complete the task. Instead of the *MultiPatch* feature class, the polygon feature class defining the regions of wireless access channels is used. The program finds the *z*-value-enabled polylines of a conventional prism whose projected shapes in the 2D plane fall into the region of the polygon feature class. Then, the maximum and minimum *z* values of each resulting polyline are compared to the *z* values representing the beginning and ending times of the access channels' operation hours. Only those portions of the lines falling within the time range of the access channels are extracted and saved into a new *z*-value-enabled polyline feature class, which represents prisms for virtual activities. Figure 5.15c provides examples of prisms for virtual activities derived in the prototype system. Line segments highlighted in red illustrate the opportunities to conduct potential virtual activities because an individual will be able to access virtual space at the moment.

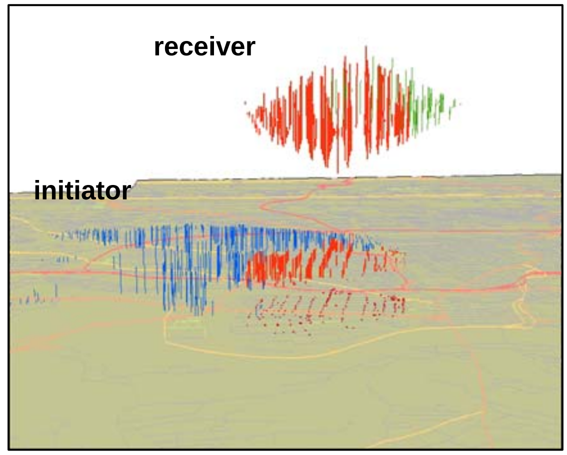
5.4.4 Analyzing spatio-temporal relationships of prisms for potential human interactions

If two individuals want to conduct a certain type of potential interaction, their space-time prisms must share a specific spatio-temporal pattern. The prototype system offers analysis functions to identify the spatio-temporal relationships of prisms to help explore different types of potential human interactions. Four functions are developed to explore potential SP, AP, ST, and AT interactions among individuals by identifying relationships of co-existence, co-location in space, co-location in time, and no co-location in either space or time among their prisms. As prisms are represented as feature classes of polylines with *z* values, these functions are realized by investigating the relative position of 3D lines.

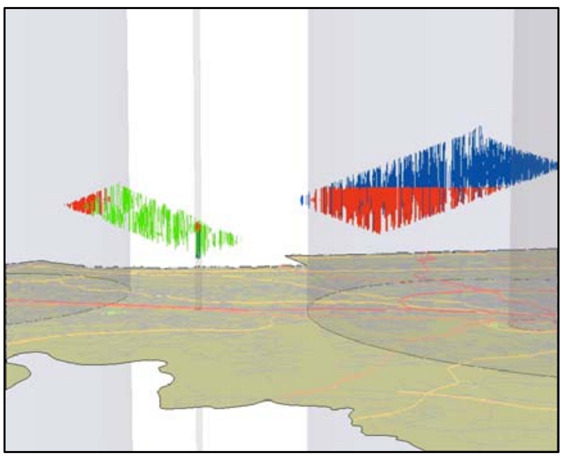
Figure 5.16 provides examples for exploring potential interactions conducted in the four different modes. Figure 5.16a shows a case of potential SP interactions analysis. With the prisms of two individuals, the "Analysis of Potential SP Interactions" function is included, which implements the intersection method for 3D vertical lines and finds overlaps between the two sets of *z*-value-enabled polylines (co-existence relationship). The result is saved as a new *z*-value-enabled polyline feature class and displayed as red lines in Figure 5.16a. It defines opportunities for potential SP interactions, such as face-to-face meetings, between these two individuals. A case for exploring potential AP interactions is demonstrated in Figure 5.16b. With prisms of possible initiator and receiver for an AP interaction, the "Analysis of Potential SP Interactions" function searches for overlaps in space between the prisms (co-location in space). If the projected shapes in the 2D plane of two *z*-value-enabled polylines from the two prisms share the same location, it implies that both individuals can reach that location. Furthermore, if the polyline of the receiver falls behind the polyline of the initiator along the *z*-axis, the two individuals will be able to conduct potential AP interactions in that location. The result is stored as a new point feature class containing all feasible locations. In the attribute table of the new point feature class, each location record is attached with two ID fields, which refer to the corresponding polylines in the two prisms. With these ID fields, users can easily associate the location with the duration of the individuals' potential stays in the location. The information can be used for further investigations. The potential AP interactions between two individuals are shown as red segments in the two prisms in Figure 5.16b.



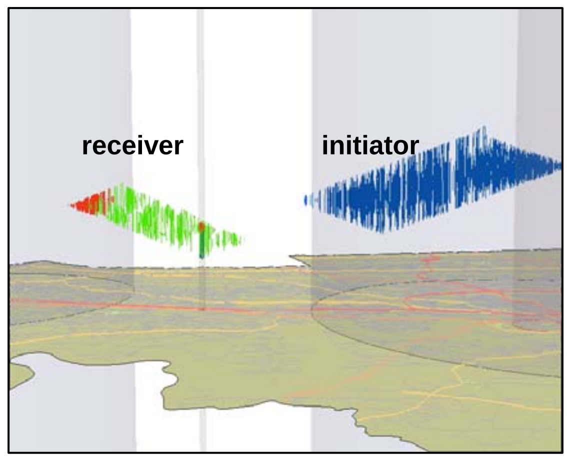
a. A case for potential SP interactions



b. A case for potential AP interactions



c. A case for potential ST interactions



d. A case for potential AT interactions

Figure 5.16. Spatio-temporal relationship analyses for exploring potential interactions.

For exploration of potential interactions though tele-presence, prisms for virtual activities are required. Figure 5.16c illustrates a case for exploring potential ST interactions. The "Analysis of Potential ST Interactions" function is developed to identify the co-location in time relationship between two prisms for virtual activities. Using the minimum and maximum time values represented in the input prisms, the program first determines their time overlap. The derived overlapped time period is used to extract portions of the prisms that fall within the range. A new *z*-value-enabled polyline feature class is created for each prism in which to store output. The result is shown in Figure 5.16c as highlighted red lines. The two individuals can access virtual space during the same time period, and thus they are able to carry out potential ST interactions, such as instant messaging over the Internet. Finally, Figure 5.16d shows a case of exploring potential AT interactions with prisms for virtual activities. The "Analysis of Potential AT Interactions" function is programmed to find the minimum time value in the prism of an AT interaction initiator and extract all portions of the prism from the AT interaction receiver. The result is saved into a new *z*-value-enabled polyline feature class. As shown in Figure 5.16d, the red lines indicate that the receiver is able to access virtual space after the initiator does so. Therefore, they can complete potential AT interactions.

5.5 Summary

Using ArcGIS as the implementation environment, the temporal GIS design for the extended time-geographic framework is realized with a prototype system. The prototype system takes advantage of ArcGIS's 3D representation capability and implements the space-time framework in ArcGIS, with the *z* dimension representing time. Feature classes with z values, which are used for representations of 3D features in ArcGIS, are adapted to accommodate time-geographic objects. Spatio-temporal analysis functions applied to time-geographic objects are also realized through operations on 3D features. Using existing functions in ArcGIS and customized VBA programs with ArcObjects, the prototype system is set up in ArcScene, which is the 3D viewer of ArcGIS, including a customized toolbar containing selected functions for the exploration of spatial and temporal characteristics of human activities. Using these tools, users can generate time-geographic objects such as space-time paths, space-time life paths, and space-time prisms, interactively visualize them in a 3D environment, and analyze their spatio-temporal relationships. The functionality of the prototype system is demonstrated using a hypothetical dataset.

As a proof-of-concept test, the successful implementation of the prototype system indicates the feasibility of the temporal GIS design for the extended time-geographic framework. With analysis functions for time-geographic objects supported by the extended time-geographic framework, the prototype system provides an effective environment in which to investigate the spatio-temporal patterns of human activities and interactions and is a useful approach for studying human activities.

CHAPTER 6:

CONCLUSIONS

6.1 Summary of the Study

The existence of virtual space enabled by ICT enhances our capacity to conduct daily activities. Now that we can choose to conduct activities or interact with others through tele-presence in virtual space, the spatial and temporal distributions of our activities have been greatly affected. Considering the close relationship of activities and transportation, the changing spatio-temporal pattern of human activities can lead to important changes in transportation systems (Mokhtarian *et al.* 1995; Pipkin, 1995; Zumkeller, 1996). Gaining a better understanding of the new spatial and temporal characteristics of human activities plays an essential role in studying the impact of ICT and virtual space on the transportation systems of our society. However, limited progress has been made in providing a useful method of exploring spatio-temporal patterns of human activities in both physical and virtual spaces. Based on this research need, this study focuses on developing an effective approach to the problem.

This study extends Hägerstrand's time-geographic framework to examine the relationship of physical and virtual activities and their constraints in a space-time context. A temporal GIS design is developed to incorporate the concepts in the extended time-geographic framework, supporting representations of time-geographic objects and a selected set of spatio-temporal analysis functions. A prototype system is created by implementing the temporal GIS design in ArcGIS with customized programs. Working with a hypothetical activity dataset, the prototype system demonstrates how the framework and GIS design can be used to facilitate explorations of the spatial and temporal characteristics of human activities.

This study advances Hägerstrand's time geography by extending it to handle human activities in both physical and virtual spaces. Based on a conceptual model of the relationship of physical space and virtual space, this study identifies space-time constraints applied to virtual activities. Considering human beings as extensible agents (Janelle, 1973; Adams, 1995, 2000; Kwan, 2000a), the concept of space-time path is extended to represent both physical and virtual activities, with physical activities only affecting the physical proximity of a space-time path, and virtual activities reaching out from a space-time path and having impact over distance. Using extended space-time paths, the spatio-temporal characteristics of the four different interaction modes (i.e., SP, AP, ST, and AT) are represented and visualized as four types of spatio-temporal relationships of the paths (i.e., co-existence, co-location in space, co-location in time, and no co-location in either space or time). The identified spatio-temporal relationships are also used to identify possible interactions among people with extended space-time paths. Moreover, the concept of space-time prism for virtual activities is developed to illustrate opportunities for potential human activities. Two forms of prisms for virtual activities are constructed based on different types of virtual space access channels, which are wired connections and wireless connections. With this extended concept of prism, potential human interactions via the four different interaction modes can be determined by identifying the four spatio-temporal relationships. With these extensions, the time-geographic framework is used to investigate both physical and virtual activities in their space-time contexts providing a powerful mode for examining human activities.

This study also contributes to the GIS research field. In order to operationalize the extended time-geographic framework, a temporal GIS design is developed to incorporate time-geographic objects and concepts. The temporal GIS design adopts a 3D environment to simulate the 3D orthogonal space-time system used in time geography. Time-geographic objects are represented and visualized as spatio-temporal features defined in the 3D environment. For example, space-time paths are represented as spatio-temporal line features and space-time life cylinders as spatio-temporal 3D features. Based on an approach of representing and calculating potential path areas in a network environment (Miller, 1991; Kwan and Hong, 1998), a new 3D representation of network-based space-time prisms is developed in the temporal GIS design. A space-time prism is represented as a collection of vertical spatio-temporal lines, each of which provides space-time explicit description for an individual's potential visit to a location under given constraints.

Basic spatio-temporal operations applied to spatio-temporal features are also developed in the GIS model to facilitate selected spatio-temporal analyses needed in the extended time-geographic framework. These operations are used to identify spatio-temporal relationships among spatio-temporal features. A concept of temporal dynamic segmentation is devised in this study to enhance the continuous representation of space-time paths in GIS. Using time as a linear referencing system, any point on a spatio-temporal line feature can be located according to its time, and spatial information of the point can be retrieved from the line. Therefore, an individual activity recorded with starting and ending times can be located on its corresponding space-time path and visualized in the 3D environment. Using ArcGIS as the implementation platform, the temporal GIS design is realized in a prototype system. Through customized VBA programs with ArcObjects, the prototype system is capable of storing, representing, and visualizing time-geographic objects in ArcGIS, and supporting spatio-temporal analyses on them. The successful implementation of this prototype system indicates the feasibility of the temporal GIS design and the effectiveness of the temporal GIS for operationalizing the time-geographic framework. Although the design focuses on incorporating the time-geographic framework, it offers valuable insights for integrating space-time representation in GIS.

Finally, the prototype system provides powerful tools to investigate spatial and temporal characteristics of human activities. With a hypothetical dataset, the prototype system demonstrates its ability to generate space-time paths, represent individual physical and virtual activities, calculate prisms for physical and virtual activities, visualize space-time paths and prisms interactively from various spatial and temporal angles, and support spatio-temporal analyses on space-time paths and prisms to identify possible and potential interactions between people through different interaction modes. Built upon a theoretical foundation of the extended time-geographic framework and an operational temporal GIS design, the prototype system represents an effective means of examining human activities in both physical and virtual spaces with their spatial and temporal characteristics. This can be useful for investigating the impact of ICT on transportation systems and urban form in a modern society.

6.2 Potential Applications of the System

In addition to transportation studies, the system developed in this study can be applied to other research domains involving human activities. The space-time path concept can help study spatial and temporal characteristics of human activities in physical space. Incorporating the notion of human beings as extensible agents, extended space-time paths can facilitate spatio-temporal analysis of virtual activities. Space-time prisms provide a way to examine potential activity opportunities available to individuals under specific constraints. With a running prototype system, the temporal GIS design presents a feasible and useful system with which to tackle activity-related problems from a spatio-temporal perspective. The following three scenarios provide a brief picture of how the system can be used to solve problems involving activities in physical space, activities in both physical and virtual spaces, and identification of potential human activities.

People's physical movements are an important element in some research, such as studies of traffic congestion, migration, and the spread of infectious disease. As the system provides useful functions to investigate human activities in physical space, it can provide valuable inputs to help tackle these research subjects. For example, tracking the spread of an infectious disease is an important issue in the study of public health. The spreading of some infectious diseases is closely related to people's movements and depends on physical contacts. Space-time paths record trajectories of people's physical movements and spatio-temporal analysis functions on space-time paths can help identify spatio-temporal relationships of people. Therefore, the system can be used to help track the spread of infectious diseases. For instance, if an individual was examined and found to carry Hepatitis B, researchers would need to determine t whether a group of people had been exposed to the disease. Those individuals who had shared a co-existence relationship, such as physical contact with the infected person, or who had shared a co-location in space, such as visiting the same restaurant shortly after the infected person, may have a higher risk of disease exposure. With space-time paths representing historical movements of the infected person and people in the exposure group, analysis functions in the system could be used to identify co-existence and co-location in space relationships between the infected person and other people. The analysis result can provide valuable information to determine the high-risk population of the infectious disease.

The system can handle both physical and virtual activities based on an extended time-geographic framework and can help solve problems involving activities in both physical and virtual spaces. Homeland security became a high priority concern in the United States after September 11, 2001. The monitoring of suspicious behavior, especially interactions of suspects, plays an important role in preventing terrorist activities. Suspects can conduct activities and interactions in either physical space (e.g., meetings) or virtual space (e.g., e-mails or phone calls). When activity reports of suspects for several weeks are received from different intelligence sources, analysts in the Department of Homeland Security can put these activity reports together and examine interaction links through both physical and virtual spaces using the system developed in this study. Spatio-temporal analysis functions can also help identify “hidden” interactions among the suspects through their spatio-temporal relationships. With these visualization and analysis tools, the system can help analysts monitor activities and interactions of suspects, and provide investigators with insightful information to determine whether unusual contacts have occurred among the suspects. The information thus derived can help analysts narrow down the target of suspect(s) needing further surveillance and investigation.

Location-based services (LBS), which provide services based on the locations where users are, present a fast growing market in today's world. The implementation of LBS requires the support of a framework with explicit representation of space and time. Researchers start to recognize the potential of time-geographic frame on supporting LBS (e.g., Raubal *et al.*, 2004). Therefore, the system developed in this study can support LBS and advance their services. Space-time prisms can be used to define the potential activities in space and time available to an individual under certain constraints, such as the individual's current location, destination, travel capability, and time budget. For example, someone wants to find an Italian restaurant for dinner after the afternoon sessions of a conference and then return for the evening sessions. S/he has a total of two hours and prefers at least one hour for dinner at a restaurant within walking distance from the conference site. Where are the restaurants that meet the requirements? Using a PDA with wireless connections, the person can submit the request. The LBS provider can use functions in the developed system to calculate a space-time prism for the person and use the extent in space and time to search for Italian restaurants. The suitable restaurants can then be displayed on the PDA. More advanced LBS services can also be supported by the system. With representations of prisms for physical and virtual activities and analysis functions applied to them, the system can determine potential interactions through the four different modes among people. These functions provide fundamental support for advanced LBS services such as activity planning and scheduling.

The system developed in this study supports space-time explicit representation for human activities in physical and virtual spaces and provides fundamental spatio-temporal analysis functions. Such a system opens opportunities to investigate human activities involved in various research domains in a space-time explicit approach. As shown in the scenarios described above, the new approach can be applied to various problems and provides valuable information for practical application.

6.3 Future Research Directions

This study has demonstrated that Hägerstrand's time-geographic framework can be extended to investigate spatial and temporal characteristics of human activities efficiently, and temporal GIS can be used to operationalize the framework to analyze actual conditions. The system provides an effective approach to studying human activities and can be useful to research domains other than transportation. Therefore, the system can be advanced in many directions. The three most relevant and important future research directions are discussed below.

A conceptual model has been developed in this study to describe the relationships between physical space and virtual space. In this study, the extended time-geographic framework emphasizes one aspect of the intersection, which indicates that physical space provides support to virtual space. The extended concepts of space-time path and prism based on this idea are developed to include virtual activities. However, there is another aspect of the intersection, which reveals that virtual space can feed information back to physical space and alter travel patterns in physical space. Current studies (Salomon, 1986; Mokhtarian, 1990; Mokhtarian and Meenakshisundaram, 1999) have shown that virtual activities can have various impacts on physical activities, such as substitution, complementarity, and modification. The mechanism between physical activity and virtual activity is quite complex and it remains a research challenge to researchers. The fact that both physical and virtual activities can be represented on space-time paths means that their contextual relationships can be preserved through space-time paths. For example, a virtual activity such as achieving traffic information from the Internet at an earlier time leads to a modified trip route at a later time. An individual's space-time path may represent different shapes in space and time according to whether or not the individual has access to virtual space as s/he faces different space-time constraints for carrying out activities. Efforts can be made to identify the different shapes of space-time paths for individuals with and without virtual space access. The temporal GIS design can be advanced to include function to compare and identify different shapes of space-time paths and help gain a better understanding of the relationships between physical and virtual activities.

This study does not consider non-spatial characteristics of virtual space access channels for virtual activities. This assumes that virtual space is homogenous inside, which implies that individuals have the same experience in virtual space despite how individuals are connected to virtual space. However, like physical space, virtual space is not homogenous. For example, the transmission speed of information in virtual space can vary significantly according to different types of connections. A virtual activity, such as downloading a digital file, may take one minute through a 10MB Ethernet connection, while it may take hours through a 56KB dial-up connection. Therefore, the connection speed to virtual space may significantly impact the time spent for a virtual activity. Also, the Internet or a telephone network may experience congestion, similar to that of a transportation network, which can affect the performance of virtual activities. More characteristics of virtual space need to be considered to provide a more accurate picture of virtual space. Which characteristics of virtual space should the system include and how will they interact with characteristics of physical space to constrain individuals from conducting activities? Further research can be done to answer these questions and gain a better understanding of human activities in virtual space.

Extra efforts can also be made to enhance spatio-temporal analysis functions in the temporal GIS design. Even with ICT, co-existence is an important spatio-temporal relationship in our society. In this study, the co-existence relationship among people is identified as overlaps of space-time paths. However, a co-existence relationship can be defined differently in different application domains, and the term *spatio-temporal cluster* is used to describe more relaxed cases of a co-existence relationship. For example, a cluster in a study of daily activities is defined as multiple people staying in the same building during the same hour, while a cluster in a migration study is defined as people living in the same city in the same year. This presents issue of scale in identifying spatio-temporal relationships (Yuan *et al.*, 2004). In order to better support various application domains, the system must allow users to define clusters based on different spatial and temporal scales. Also, quite often a large dataset is involved in spatio-temporal clustering analysis. Current analysis function in the prototype system is designed to identify the co-existence relationship between two space-time paths, and an exhaustive search approach is adopted. This will become very time consuming when processing large datasets for clustering analysis. Heuristic algorithms and spatio-temporal indexing methods can be developed to improve the system's performance in searching spatio-temporal clusters of space-time paths in a large dataset. With this capability, the temporal GIS design, which incorporates an extended time-geographic framework, will be more efficient in handling spatio-temporal characteristics of human activities and will strengthen its support when tackling activity-related real world problems.

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