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What about People in Geographic Information Science?

Harvey J. Miller

The title of this chapter is an homage to the classic paper by the late Torsten Hägerstrand, 'What about people in regional science?' (Hägerstrand, 1970).

16.1 Introduction

Our lives consist of activities in space and time. The basic activities that structure our lives, such as family, work, shopping, recreation and socializing, occur at a few geographic locations and for limited temporal durations. People have scarce time and resources to distribute among required (e.g. work, home) and desired (e.g. recreational, social) activities. Societies devote enormous amounts of energy and resources to overcoming spatial and temporal constraints.

Cities exist to compress a multitude of human lives into small geographic spaces to reduce the amount of time and energy required to access activities and resources. Transportation systems allow individuals to trade less time for more space when moving to activity and resource locations, as well as moving the resources themselves from supply to demand locations. Telecommunication systems allow humans to annihilate distance for some types of activities and interactions. Transportation, telecommunication and settlement systems grow and decline in response to human activities in space and time. They influence economic, social and knowledge networks, in turn shaping human activities and their locations in time and space.

1 Geographic information systems (GIS) are convenient platforms for theoretical and
2 applied transportation and urban analysis. The location-based organization of data
3 and information from the cartographic roots of GIS is a good fit with the place-based
4 theories and models inherited from von Thunen's bid-rent theory of land-use. This
5 includes methods such as travel demand models based on spatial interaction theory and
6 market equilibrium models of urban spatial organization. These are *place-based* methods
7 that represent transportation demand and urban form as a function of aggregate spatial
8 units.

9 Place-based representations and methods were developed in an era when data were
10 scarce, computational platforms weak and questions simpler (at least so we thought at the
11 time). Despite growing theoretical and empirical evidence questioning their theoretical
12 foundations (see Boyce *et al.*, 1994; Wegener, 1994), remarkably resilient methods such
13 as the four-step travel demand model and urban equilibrium models still dominate GIS
14 for transportation ('GIS-T' as it is commonly known) and urban GIS. Place-based
15 methods ignore the basic spatio-temporal conditions of human existence and organization
16 discussed above. Due to the drastic changes taking place in transportation, telecommu-
17 nication and settlement systems, ignoring these spatio-temporal conditions is no longer
18 tenable.

19 Important theoretical and policy questions require extending the place-based perspec-
20 tive in GIS-T and urban GIS to encompass a *people-based* perspective. A place-based
21 perspective by itself is no longer viable in a world where transportation and telecommu-
22 nication have altered dramatically the nature of space and time at the core of human
23 existence. The world is shrinking in an absolute sense: transportation and communication
24 costs have collapsed to an incredible degree over the last two centuries (see Janelle,
25 1969). The world is also *shriveling*: relative differences in transportation and telecom-
26 munications costs are increasing at most geographic scales (Tobler, 1999). The world is
27 also *fragmenting*: people and activities are becoming disconnected from location
28 (Couclelis and Getis, 2000). A place-based perspective is increasingly ill suited for
29 answering questions of access, exclusion and evolution in a shrinking but shriveling and
30 fragmenting world.

31 The time geographic perspective of Torsten Hägerstrand offers a people-oriented
32 alternative to place-based tools in GIS-based transportation and urban analysis. This
33 perspective views the person in space and time as the center of social and economic
34 phenomena. Since they recognize constraints imposed by demographic, social, economic
35 and cultural context (Kwan, 1998), time geographic methods are more sensitive measures
36 of differences in accessibility and exclusion. The closely-related area of activity theory
37 concerns the theory, measurement and analysis of how people organize activities in space
38 and time, the relationship between these activity patterns and the evolution of transporta-
39 tion, communication and settlement systems, and how these evolving systems in turn
40 influence the organization of activities in space and time. Space-time activity analysis
41 also offers a more theoretically defensible view of networks and settlement systems as
42 emergent from individual activities and shapers of these activities.

43 In recent years, time geography and activity theory has experienced a renaissance as,
44 encouraged by developments in GIS, researchers have expanded their power and scope.
45 The rapidly improving ability to collect space-time activity (STA) data through
46 information technologies such as cellular/mobile phones, wireless personal digital

1 assistants (PDA), global positioning system (GPS) receivers and radio-location methods
2 is improving the quantity and quality of these data and reducing their cost. GIS allows
3 more realistic and detailed depictions of accessibility and activities in space and time
4 than imagined by the pioneers of time geography in the 1950s and 1960s. These
5 developments can help expand GIS from its place-based representations to encompass
6 the people-based perspective required by contemporary transportation and urban theory.
7 However, much of the work on the 'new' time geography (including the previous work of
8 the author) is *ad-hoc* and disconnected: there is no coherent framework for designing and
9 developing GIS software tools or even thinking about the basic entities that should be
10 represented within a people-oriented GIS.

11 This chapter is an attempt to review and assess time geography, activity theory and
12 GISci/GIS. In it, I review the basic foundations of time geography and activity theory,
13 improvements in geographic information technologies, and the state of the art in
14 implementing time geographic and activity theory constructs within GIS. I also review
15 formal representations of dynamic spatial objects in GIScience (GISci) and its relevance
16 to time geography, with an eye towards developing a coherent framework for a 'people-
17 oriented GIS'. Finally, I identify gaps in the research that must be addressed if time
18 geographic and space-time activity techniques linked to GIS are to achieve breakthroughs
19 in our understanding of human lives and urban environments.

20 A people-oriented GIS should complement rather than replace the traditional place-
21 based GIS. Computational representations of geographic space can still serve as the basic
22 framework with dynamic and mobile objects linked to the geo-spatial framework. This
23 supports the traditional spatial applications of GIS such as inventory and mapping, but
24 also supports advanced analysis of the dynamic and mobile objects within the geo-spatial
25 frame. In some respects, the representational issues discussed in this chapter are not very
26 different from the acknowledged 'object-centered' (vector) and 'space-centered' (raster)
27 representational division in GIS (Goodchild, 2001). There are some recent attempts to
28 bridge this gap and create integrated representations (see Cova and Goodchild, 2002;
29 Yuan, 2001a). However, the objects of interest in this chapter are dynamic, mobile and
30 *active* (they conduct activities that are relevant to analysis). As will be seen, this raises
31 additional and complex representational issues.

32 The next section of this chapter discusses the relevance of a people-oriented GIS
33 in transportation and urban analysis. Section 16.3 reviews the theoretical foundation
34 including time geography, activity theory and GISci theories of dynamic spatial
35 objects. Section 16.4 reviews current and potential tools for a people-based GIS.
36 Section 16.5 concludes this chapter by summarizing the research and development
37 frontiers.

40 **16.2 Relevance**

42 **16.2.1 Activities and Accessibility**

43
44 Accessibility to resources, opportunities and support networks such as employment,
45 health care, education, shopping, recreation, friends and relatives is a central com-
46 ponent of community livability (National Research Council 2001). Accessibility is an

1 individual-level phenomenon with contextual effects related to demographic, social,
2 economic and cultural factors. In most societies, life stage, social class, cultural identity,
3 and even ethnicity, strongly influence the location of key *anchor points* in an individual's
4 life such as home and work locations. The distance between affordable housing and
5 employment opportunities can create severe constraints for some social groups (e.g. see
6 Gober *et al.* (1993)). Scheduling constraints that compel presence at certain locations for
7 fixed time intervals also vary by socio-economic factors and artifacts such as gender roles
8 (Kwan, 1999). Socio-economic and demographic cohorts exhibit distinct space-time
9 activity signatures that are remarkably stable over time, often persisting after many of the
10 original members of the cohort have moved on and been replaced by new members
11 (McNally, 1998).

12 Individuals also differ with respect to the transportation resources and information
13 technologies (IT) available to overcome the constraints imposed by space-time anchor
14 points. Because of the sparseness of the space-time network imposed by many public
15 transportation systems in many parts of the world, such as the United States, individuals
16 who are unwilling or unable to drive an automobile due to lack of resources, different
17 abilities, or preference, are often at a disadvantage, shaped by socio-economic and
18 demographic factors. A persistent digital gap exists between IT haves and have-nots and
19 it is another dimension of differential accessibility among social groups as more
20 resources and activities occur in *cyberspace*, the information space created by networked
21 computers and IT (Shen, 2000).

22 23 **16.2.2 Information Technology, Lives and Cities**

24 The conditions that underlie our daily lives and influence the performance and develop-
25 ment of our urban infrastructure are undergoing fundamental changes. These are due to
26 the development and adoption of new IT and improvements in transportation and logistics
27 systems that support the information economy and high consumption lifestyles. The
28 increasing ability to manipulate and transmit data bits, combined with well-developed
29 and managed systems for transporting atoms, are altering the fundamental relations
30 between space, time, and human activities. Information technologies are not only
31 influencing where people work, live, recreate and socialize, but also changing the very
32 nature of the activities that occur in the home, office and automobile (Moss and
33 Townsend, 2000).

34 There is a need to revise the theoretical shortcomings associated with traditional
35 transportation and urban analyses in light of fundamental changes in individuals' abilities
36 to interact across distance. The root of many of the changes occurring in the post-
37 industrial city is an increasing disassociation between places and activities. The
38 increasing power and scope of IT means that activities are becoming more person-
39 based rather than place-based: activities are increasingly a function of the person in time
40 and space rather than places. For example, with mobile computing and telecommunica-
41 tions, a person may work in an office, at home, in a coffee shop, or even in a public park.
42 Place-based transportation or urban models generally only recognize work at the first
43 location and not at the others. The increasing fragmentation of activity from space means
44 that the assumption of strong structural correspondence between spatial and functional
45 relationships at the basis of classical transportation and urban theory is increasingly
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1 untenable (Couclelis and Getis, 2000). Because of its place-based orientation, traditional
2 transportation and urban theory is ill equipped to address many of the key questions
3 regarding emerging lifestyles, urban form and differential access to activities and
4 resources among social groups in the information age.

5 There is little detailed knowledge about the impacts of IT on lifestyles and life
6 activities beyond some broad brushstrokes and generalities. The simplistic 'death of
7 distance' argument in the popular press (e.g. Cairncross, 1997; Mitchell, 1995) does not
8 hold up against evidence of the continuing draw of the city for home and work even for
9 supposedly 'footloose' people and businesses such as high-level decision making and
10 creative work (Graham and Marvin, 1996). Traditional urban theory views cities as land
11 use configurations when in reality these are complex Webs of individual activities,
12 actions, reactions and interactions (Golledge and Stimson, 1997). An increasing number
13 of these activities and actions occur in cyberspace rather than geographic space.

14 15 **16.2.3 The Worldviews of GIS-T**

16
17 Are current GIS suitable for the brave new worlds of transportation and urban analysis?
18 Goodchild (2000) identifies three major worldviews required for current and potential
19 GIS for transportation (GIS-T). Traditional GIS-T applications in transportation involve
20 *map* representations for static inventory and display of transportation facilities and
21 related geographic objects. One-dimensional networks derived from road center-lines and
22 variable length, or 'dynamic' (which is not the appropriate term) segmentation data
23 models, are examples of this perspective.

24 The emerging *navigation* perspective requires more demanding representations of
25 geographic reality that can support routing applications, possibly in real time. This
26 includes requirements for more complex topologies possibly across multiple modes (see
27 Spear and Lakshmanan, 1998), dynamic attributes (e.g. congestion levels, travel speeds,
28 temporary conditions such as obstructions), two-dimensional representations of trans-
29 portation facilities and support for 'off-network' travel such as in parking lots or across
30 unrecognized roads. All of these require dynamic attributes represented within the
31 framework of static map geometry.

32 The *behavioral* perspective deals with the behavior of discrete objects within a
33 dynamic geometry. A GIS must be able to represent space-time 'paths' (Hägerstrand
34 1970), 'trajectories' (Smyth, 2001) or 'lifelines' (Mark and Egenhofer, 1998; cited in
35 Goodchild, 2000) as well as the information that emerges when these entities are
36 aggregated. GIS tools should be able to maintain consistent linkages between individual
37 objects and aggregate outcomes such as origin-destination flows in transportation links
38 and between geographic locations as well as the evolution of transportation, telecom-
39 munication and settlement systems.

40 Commercial GIS software has made little progress beyond the traditional map world-
41 view (Goodchild, 2000). Developing a GIS toolkit for answering increasingly important
42 questions surrounding access and equity in a shrinking, shriveling and fragmenting world
43 requires liberating GIS from its place-based representations to include people-based
44 representations. Fortunately, there is a coherent body of theory to support the design of
45 these systems as well as emerging technologies that allow detailed space-time data and
46 information to be captured, handled and understood.

16.3 Theory

16.3.1 Time Geography

Hägerstrand's (1970) time geographic framework is a powerful and elegant perspective for analyzing constraints on individuals' participation in activities and opportunities. The time geographic framework recognizes that activity participation has both spatial and temporal dimensions. Activities occur at specific locations for limited time periods. Transportation resources allow the individuals to trade time for space, to travel and participate in activities at dispersed locations. Travel is anchored by certain activities that are relatively fixed in space and time. For example, a person's work often cannot be easily rescheduled or moved in space, at least in the short-run. The space-time framework dictates the *necessary*, but not *sufficient*, conditions for most human interaction.

At the heart of time geography is the notion that all activities and events that make up an individual's existence have both spatial and temporal dimensions. The basic conceptual tool in the framework is the *space-time path*, which traces the movement of an individual in space and time. In addition to tracing movement in geographic space from location to location, it also traces simultaneous movement in time. Figure 16.1 illustrates a space-time path. Note that the path is vertical when the individual is stationary in space (but always moving in time) and that a shallower slope indicates that the person is moving faster (i.e. they are trading less time for more space).

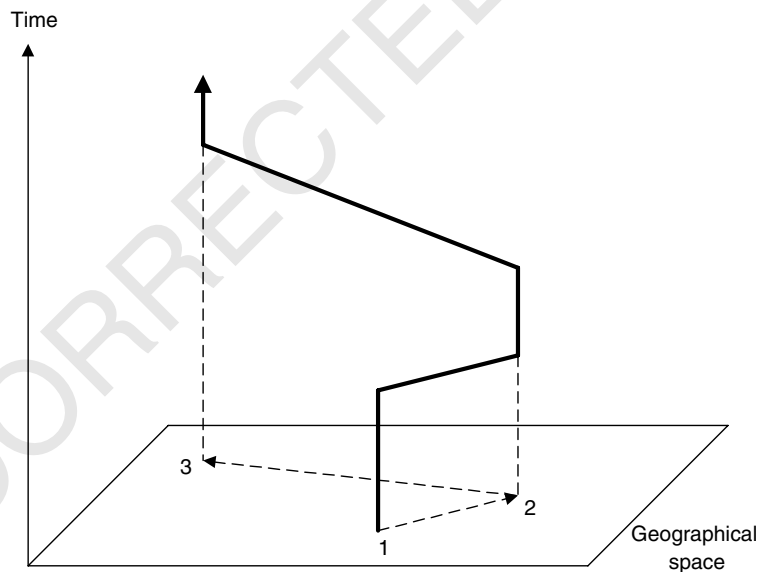


Figure 16.1 The space-time path

The following types of constraint dictate the locations that the space-time path can occupy:

1. *Capability constraints* limit the activities of individuals through their own physical capabilities and/or the resources they can command. For example, individuals with private automobiles can generally travel faster through space than individuals who walk or rely on public transportation.

2. *Coupling constraints* define where, when, and for how long, an individual has to join with others to produce, transact or consume. Coupling constraints define space-time bundles of individuals existing in a particular space and time. For example, having to be at work for certain time periods is a coupling constraint. *Space-time bundles* or groupings of individual space-time paths within a limited domain of space and time (see below) are evidence of these constraints.
3. *Authority* or 'steering' *constraints* impose certain conditions of access in particular space-time domains. For example, a private shopping mall can impose more constraints than a traditional city center on individuals' space-time autonomy since private space can be more effectively restricted from occupancy during certain hours and days and for some purposes. Gated suburban communities can prevent certain 'undesirable' individuals from occupying their space, particularly at certain time periods (e.g., from dusk to dawn).

A *space-time prism* (STP) is an extension of the space-time path that measures accessibility to events in space and time. Figure 16.2 illustrates a simple STP. In this, the person must be at a given location (say work) until time t_1 and then must return again at time t_2 . If we measure or assume an average travel velocity, we can delimit the *potential path space* (PPS) showing all locations in space and time that the person can occupy. If he or she wants to visit an activity location, its space-time path must intersect the potential path space. Projecting the PPS to the two-dimensional geographic plane

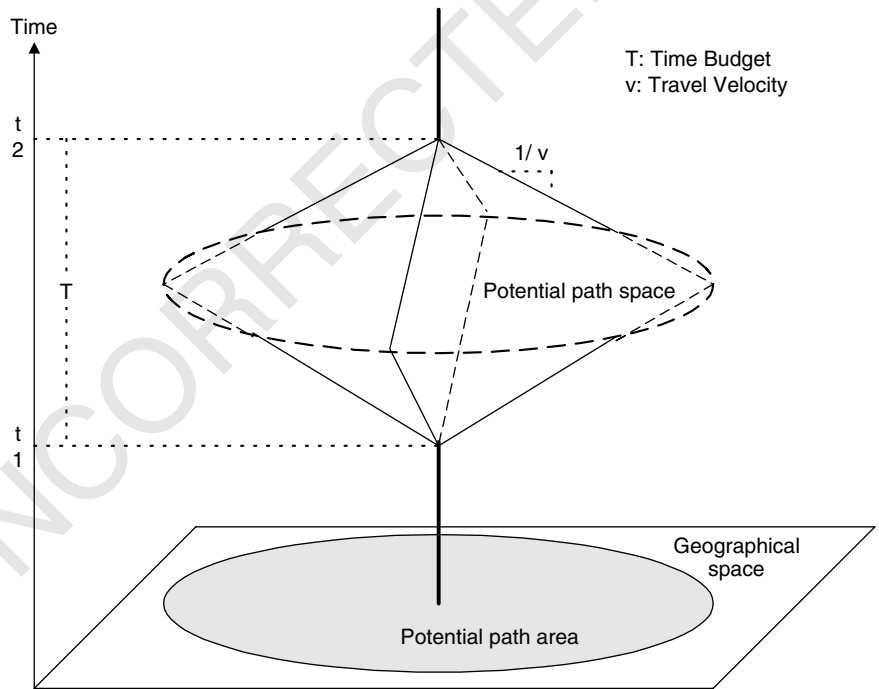


Figure 16.2 The space-time prism (reproduced from Wu, Y.-H. and Miller, H.J. (2002). Computational tools for measuring space-time accessibility within transportation networks with dynamic flow, *Journal of Transportation and Statistics*, 4, 1-14)

1 delimits the *potential path area* (PPA). These are the set of geographic locations that the
2 person can occupy. This is a simple example: the STP, PPS and PPA can be more
3 complex with non-coincident fixed locations and different travel metrics (see Burns,
4 1979).

5 Although the fundamental level of analysis in time geography is the individual and its
6 path through space and time, time geography provides conceptual linkages between the
7 individual and the broader socio-economic system. A space-time *project* consists of the
8 specific tasks required to complete any goal-directed behavior. The tasks associated with
9 a project usually have a logical order, e.g. task A must be completed before task B and so
10 on. This concept can be applied at a variety of scales including the individual, family,
11 society, and the state, as well as for national and transnational organizations. At aggregate
12 levels, the requirement for tasks to be sequenced logically and coordinated with other
13 individuals leads to the formation of activity *bundles* or the convergence of two or more
14 space-time paths, or the convergence of a single space-time path with one or more
15 physically tangible resources such as equipment, materials or buildings. Activity bundles
16 tend to form at *stations*, which are fixed locations with limited temporal durations that
17 support activity bundling, usually conceptualized as *tubes* in space and time. Examples
18 include offices, retail outlets and schools. The activity bundle and station concepts
19 provide a direct interface between the external actions of the individual with the
20 observable workings of the socio-economic system (Pred, 1981).

21 Applying the project concept at broad levels such as a city, region or nation also leads
22 to the concept of an *activity system*. This is a synoptic view of space-time activities as a
23 market where a finite supply of time must be allocated among competing activities. Time
24 demand results from the interplay among the population of the system and the multitude
25 of interrelated projects at the individual and organizational levels (Golledge and Stimson,
26 1997).

27 The emphasis on time in time geography provides a natural fit with emerging
28 perspectives that view time as the scarce commodity of the information economy and
29 accelerated modern lifestyles (see Gleick, 1999; Goldhaber, 1997). This can provide an
30 effective link between the geographic space of traditional transportation and urban theory
31 with the cyberspace of the information age. Locations in cyberspace can be treated as
32 logical locations in information space or related to geographic locations or different
33 geographic scales of interaction. There has been some preliminary conceptual work
34 formulating these linkages (e.g., Adams, 1995; Batty and Miller, 2000; Kwan, 2000a).

36 16.3.2 Activity Theory

37 Activity theory focuses on people rather than places as the source of travel and location
38 demands. Individuals participate in periodic activities that have varying levels of
39 necessity and urgency. The resources that satisfy these activities are sparsely distributed
40 in space and time, i.e., at few locations and for limited time intervals. This can include
41 requirements that other individuals be contemporaneous in space, time or both (such as
42 work or socializing). Individuals must distribute their limited time among these activities,
43 using transportation to trade time for space when traveling to activity locations. They can
44 also substitute *in-situ* activities that do not consume transportation services, for example,
45 using IT. Aggregate-level outcomes such as transportation system performance, urban
46

development, lifestyle decisions and long-term mobility both condition and are conditioned by these individual-level activity sequences (Ben-Akiva and Bowman 1998; Bhat and Koppelman, 2000; Thill and Thomas, 1987). Wang and Cheng, (2001) provide an elegant summary of the basic components in activity theory (based on Axhausen, 1994) and Table 16.1 summarizes these entities.

Table 16.1 Basic components of activity theory

Entity	Definition
Activity	The main purpose carried out at a location, including any waiting time before or afterwards. Activities can be classified into different types depending on purpose
Activity frequency	The number of times the activity occurs during a given time period
Activity destination	The location where an activity occurs
Trip	Movement between two activity destinations
Transport mode(s)	Methods of conveyance used to perform a trip
Activity program	Set of activities to be performed within a given time period
Activity schedule	The planned ordering of activities in space and time within a given time period
Activity pattern	The activities in space and time actually conducted within a given time period
Activity space	A composite of the locations where an individual conducts routine activities
Physical environment	Spatial configuration of activity destinations and transportation services between these destinations
Institutional environment	Set of formal rules that regulate the individual's activities in space and time (e.g., store hours, working hours)

A major application of activity theory is empirical measurement and analysis of *space-time activity* (STA) data, or records of where and when individuals conducted activities over a daily, weekly or monthly cycle. Empirical measurement of STA behavior dates back to Chapin (1965), the landmark study in Halifax, Nova Scotia in the 1970's (Goodchild and Janelle, 1984) and continued in transportation studies in the early 1990s in cities such as Boston, Salt Lake City, Portland and Dallas-Forth Worth, USA (Greaves and Stopher, 1998). These efforts need to be continued and expanded to track changes in the impacts of IT on daily lives and urban form.

16.3.3 Representing Dynamic Spatial Objects

Time geography and activity theory provide a powerful perspective from which to view the interactions between people, transportation, telecommunication, socio-economic and settlement systems. Although these two perspectives are highly complementary, they have different conceptualizations of the person and his or her activities in time and space. A true people-oriented GIS should encompass both theories through a unified representational theory and tools that can support both and exploit their commonalities and complementarities. Representational principles from GISci can allow rigorous

1 development of time geographic and activity theory and the functional requirements for
2 GIS software to support these theories and models.

3 Spatial objects can exhibit three major types of change that often occur in concert but
4 nevertheless can be meaningfully separated (Yuan, 2001b). One class is *motion* or change
5 in the position or geometric form of the object over time. The second class encompasses
6 changes in the temporal identity of the object; we refer to this as *life* (Frank, 2001). A
7 third is change in the semantics or non-spatial attributes of the object; referred to as the
8 object's *state*. The next three subsections review GISci and related literature that
9 addresses these types of change in spatial objects. The discussion suggests linkages
10 between this literature and time geography/activity theory that should be explored in
11 greater detail (and rigor) in continuing research and software development.

12
13 *Motion*. As Galton (1995, 1997) points out, any theory of motion should incorporate
14 theories of time, space, position and objects. With respect to time, essential properties
15 include *duration* and *direction*: the former consists of *intervals* or 'chunks' of time
16 bounded by *instants*. Direction is determined by an ordering of intervals and instants.
17 Another issue is temporal *granularity* or the minimum resolution for measuring time.
18 This results in two natural idealizations of time, namely, *dense* (or continuous) and
19 *discrete* time, where the former allows infinitely fine subdivisions while the latter consists
20 of finite intervals. The theory of space is analogous to the theory of time, although spatial
21 ordering is more complex and can be absolute (e.g. contiguity) or relative (e.g. north).
22 The basic entities of space are the fundamental entities in physical reality, e.g., points,
23 lengths, areas and volumes. Traditional space theories such as point-set topology are too
24 primitive in the sense that they allow arbitrary spatial objects that have no meaning in
25 physical reality and therefore are irrelevant to motion.

26 With respect to motion, important properties of objects include whether they are
27 conceptualized as rigid or non-rigid, unified wholes, or comprised of parts, individuals or
28 collectives and are concrete or abstract. *Rigid* objects maintain a constant shape and size
29 while *non-rigid* objects, in addition to position, can change size and shape. In practice, it
30 can be difficult to separate motion from changes in size or shape. Some objects' motions
31 are best represented as a unified *whole*. Other spatial objects can be best described in
32 terms of the movements of its *parts*, such as an object that maintains its overall position
33 although each part is moving (e.g. a spinning phonograph or compact disc). Motion of a
34 *collective* is sometimes best described by the motions of its constitute individuals, but
35 some collective motion, such as the flow of water in a river, cannot be reduced to the
36 movements of discrete individuals. Finally, some spatial objects have physical existence
37 (*concrete*) while others are *abstract* in the sense that they are uniform but non-essential
38 properties such as political entities or ownership (these are sometimes referred to as
39 'shadows'; see Frank, 2001).

40 The *position* of an object is the region of space it occupies during a given unit of time.
41 This can be exact or qualitative. The concept of position allows a definition of *motion* as a
42 mapping from time to position: for each time unit a position of the object can be
43 specified. If space is discrete, direct motion can only occur between neighboring
44 positions. If time is discrete, then the discrete time unit places an upper limit on apparent
45 motion. If both space and time are continuous, than motion is continuous and we need to
46 specify its exact position at each moment in time (subject to the temporal granularity).

Table 16.2 Conceptualizing motion for time geographic entities

Entity	Movement properties		Objects	Position	Motion
	Time	Space			
Space-time path	Dense	Dense	Rigid Whole Individual Abstract	Exact	Continuous
Space-time prism	Dense	Dense	Non-rigid Whole Individual Abstract	Exact	Continuous
Activity bundle	Dense	Dense	Rigid Parts Collective Abstract	Exact	Continuous
Trip	Discrete	Discrete	Rigid Parts/Whole Individual/Collective Abstract	Inexact	Discrete
Activity pattern	Discrete	Discrete	Rigid Parts Collective Abstract	Inexact	Discrete
Activity space	Discrete	Dense	Non-rigid Whole Individual Abstract	Inexact	Discrete

However, exact positions can be aggregated into *locations* or the sum of all positions occupied by the object over a time interval (Galton, 1997).

Table 16.2 is a tentative conceptualization of motion properties for some time geographic and activity theory entities. Several broad observations become evident. First, there is a discontinuity between time geography and activity theory with respect to the apparent (represented) motion of entities: time geography conceptualizes its entities as moving through continuous space and time where (theoretically) the position of the entity is known exactly at all times. In contrast, activity theory treats time and space as discrete: motion is an interaction between two activity locations and, beyond the demand for transportation services it generates, its exact spatio-temporal geometry is irrelevant. However, these movement conceptualizations will be merged as new IT facilitates real-time geo-location in activity analysis and a corresponding closer integration of time geography into activity theory (see Section 16.4).

Another observation from Table 16.2 concerns the diversity of moving objects. Some objects such as the space-time path are rigid, comprised of individualistic entities that are abstract in the sense that they have no physical existence in the real world. While the individual has a physical existence, his or her path is abstract. In contrast, the space-time prism is non-rigid: its boundaries and form can change. Space-time bundles are best understood as collectives of rigid parts. The trip can be treated as a rigid, whole, individual and abstract object, except when two or more individuals share a trip (e.g. pooling cars), in which case it may be best represented as a collective of parts.

Table 16.2 provides an initial foray into a theory of motion that can support the spatial objects of interest in time geography and activity theory. If we are to have detailed functional requirements for a people-oriented GIS, a unified and rigorous theory of motion for this domain is required. Nevertheless, due to the requirements to support diverse spatial objects and motions, a people-oriented GIS will have some difficult design challenges.

Table 16.3 Major life events (based on Frank 2001; Medak 2001)

Life events	Definition
Create	New object comes into existence
Destroy	Object's existence is terminated (although information on the object may be maintained)
Kill	Similar to <i>Destroy</i> but allows object to be <i>Reincarnated</i> at a later time
Reincarnate	Re-active an object that was previously <i>Killed</i>
Evolve	Combination of <i>Create</i> and <i>Destroy</i> : one object is destroyed but a new object is created that has information about its ancestor
Identify	Retain the identity of an object that is merged with other objects
Spawn	New objects are created from an existing object (and the existing object continues its identity)
Aggregate	Two or more objects merge into a collective object (but retain their identities)
Disaggregate	Inverse of <i>Aggregate</i>
Fusion	Two or more objects merge into a collective object (and lose their identities)
Fission	A single object is broken into parts that become new objects

Life. Life refers to essential changes in the identity of a spatial object over time. Several types of life changes (reviewed in Frank, 2001; Medak, 2001) can occur to spatial objects. Table 16.3 summarizes these generic life events.

A *lifestyle* is a coherent set of life events that are appropriate for a particular domain. For example, in time geography it is logical for space-time paths to be created, destroyed, identified, aggregated (e.g., space-time bundles) and disaggregated. A space-time path may also spawn a new space-time path (i.e. the individual represented by the path has a child). It makes less sense for space-time paths to be killed, reincarnated, evolved, fused or fissioned. Therefore, the life events *Create*, *Destroy*, *Identify*, *Spawn*, *Aggregate* and *Disaggregate* form a lifestyle for the space-time path (Frank, 2001). A formal theory of lifestyles for time geography and activity theory would help identify the types of dynamic spatial operations that a people-oriented GIS needs to support. This theory is still an open research question.

States. In time geography and activity theory, the state of an object comprises the relevant socio-economic, demographic and cultural attributes, and the activity (or activities) conducted at a given moment in time. Activities can span the gamut of human experience, including production, education, shopping, socializing, community activities, recreation, entertainment, church, and political behavior, as well as the use of transportation and telecommunication services to participate in these activities (Golledge and Stimson, 1997). Consequently, systematic classification of activities is a critical decision in STA research design.

Unfortunately, there are almost an unlimited number of activity classification systems available to the researcher. Activity classification systems are often 'one-off' schemes developed for particular research projects and standardization is required for comparisons across studies (Golledge and Stimson, 1997). Some national and international classification systems have been developed (see United Nations 2000). Nevertheless, detailed

1 comparisons across different studies can be difficult since there is no universal agreement
2 with respect to the fundamental categories of human activities. Nor is it clear that this is
3 even possible. Even if a universal classification system is not possible, there is still a need
4 to translate between the classification systems developed for different cultural, geo-
5 graphic and temporal settings.

6 A related challenge is determining the linkages and interrelationships among activities,
7 particularly with respect to space-time projects. At the individual level, some tasks (e.g.
8 purchasing gasoline) may be required to support other activities (e.g. traveling to a
9 grocery store to buy food) in order to support a broader project (e.g. hosting a dinner
10 party that evening). At the organizational and higher levels, these interactions become
11 even more complicated and there is still little understanding of how project-related tasks
12 lead to the formation and dissolution of activity bundles at some stations in space and
13 time. Without an understanding of these activity linkages, it will be difficult to under-
14 stand the emergence of aggregation spatio-temporal systems (such as cities) from
15 individual behavior and how these aggregate systems in turn constrain individual
16 behavior.

17 18 19 **16.4 Tools**

20
21 As discussed above, IT is changing lifestyles in ways that are poorly understood.
22 However, IT can also facilitate the collection of more accurate, comprehensive and
23 detailed STA data, including data on IT-mediated interactions. GIS can allow the capture,
24 representation, analysis and exploration of massive STA databases, potentially leading to
25 unexpected new knowledge about the interactions between people, technologies and
26 urban infrastructures. This section reviews current and emerging GIS tools that can
27 support time geography and activity theory, including existing attempts to enhance these
28 concepts and theories using GIS.

29 30 **16.4.1 Collecting Space-Time Activity Data**

31
32 There are four traditional methods for collecting space-time activity (STA) data. *Recall*
33 methods require subjects to recall and report activities during some previous time period.
34 *Stylized* recall methods require subjects to report 'normal' activities that occur during
35 some typical time period. *Diary* methods require subjects to record activities in a diary,
36 either in a free-format manner or at pre-determined time periods. 'Beeper studies'
37 complement this approach by prompting subjects via a pager at selected time intervals to
38 record their current activities. *Prospective* methods are typically game-based and
39 employed in conjunction with other methods to investigate the effect of potential changes
40 in the activity environment.

41 These traditional methods for recording STA data all have substantial problems. The
42 recall method relies on the subjects' abilities to remember activities and their locations at
43 a later time period. Stylized recall methods suffer from definitional problems with respect
44 to 'typical' activities during a 'normal' time period. These definitions can be vague, fluid
45 and variable among individuals and over time (Golledge and Zhou, 2001). Previous
46 research suggests that the best data are obtained from activity diaries (Ettema *et al.*, 1996;

1 Pas and Harvey, 1996). Nevertheless, this method has significant problems. Free-format
2 diaries offer little guidance to individuals with respect to specifying activities and
3 locations and therefore can have high degrees of recording error. These data can also
4 be difficult to code. Individuals are sometimes unwilling to report certain activities and
5 often under-report short trips and the number of stops during a multi-purpose trip (Brog
6 *et al.*, 1982; Golledge and Zhou, 2001; Purvis, 1990).

7 New IT can greatly enhance the collection of activity data (Greaves and Stopher,
8 1998). Global positioning systems (GPS) combined with recording devices such as
9 personal digital assistants (PDA), in-vehicle navigation systems, and cellular/mobile
10 telephones can allow for more accurate and detailed recording of activities in space and
11 time (Murakami and Wagner, 1999). Although currently limited by clumsy keypads and
12 pen interfaces, continuing advances in voice recognition software and natural language
13 processing will allow voice interfaces to be integrated into in-vehicle navigation systems,
14 cell/mobile phones and PDAs, as well as the activity diary software that could be
15 designed for these platforms. This will greatly facilitate diary methods for collecting
16 activity data by reducing the burden on subjects through easier, more natural data entry,
17 perhaps even reducing under-reporting and related errors. GPS receivers can also collect
18 network travel time information during the travel event, allowing calibration with
19 aggregate travel time data (see Guo and Poling, 1995). Even without an activity-
20 recording device, the detailed location and time information available from a vehicle-
21 mounted GPS receiver can facilitate the subjects' memory of the activity purpose after
22 the event using recall methods (Stopher and Wilmot, 2000).

23 Although a potential improvement over traditional methods, there are some problems
24 with GPS-based activity recording that must be resolved if they are to be effective
25 in collecting STA data. An obvious difficulty is the reliance of the receivers on line-of-
26 sight communication with the GPS satellite constellation. This can be problematic in city
27 centers where tall buildings can block line-of-sight communication. It also negates
28 tracing activity patterns within architectural structures such as shopping malls. The
29 present state of the technology is limited to motorized vehicle-based travel due to the size
30 and weight considerations; however, these problems will be resolved over time as
31 technological improvements allow smaller GPS receivers even down to the size of a
32 microchip. A subtler problem is automating GPS receiver data collection. If these are
33 vehicle mounted they can automatically activate when the engine starts, but personal
34 devices need to be activated manually, which can lead to under-reporting problems
35 similar to activity diaries (Golledge and Zhou, 2001).

36 The rise of *location-based services* (LBS) through wireless communication networks
37 offers another vehicle for collecting STA data. LBS provide specific, targeted information
38 to individuals based on their geographic location, typically through wireless communica-
39 tion networks and devices such as PDAs, cell phones and in-vehicle navigation systems
40 (Benson, 2001). LBS are widely expected to be the 'killer application' for wireless
41 Internet devices: some predict worldwide deployment levels reaching one billion
42 devices by 2010 (Bennahum, 2001; Smyth, 2001). LBS technology can allow for
43 analysis of individuals trajectories in space and time combined with users' information
44 access patterns (Smyth, 2001).

45 LBS technologies require a high degree of positional accuracy as well as complete
46 coverage across geographic space to be effective. GPS can play a central role, although

1 this will need to be complemented by other technologies for the reasons discussed above.
 2 Inertial navigation systems such as gyroscopes and accelerometers can complement GPS
 3 technology for in-vehicle LBS. Personal devices can exploit the wireless communication
 4 network through high precision radiolocation methods that use the angles of arrival,
 5 absolute arrival times or relative differences in arrival times of signals at the base station
 6 to calculate the user's location (see Zagami *et al.*, 1998). Hybrid systems that use more
 7 than one method provide the best accuracy, particularly in challenging environments for
 8 signal propagation such as urban areas (Reed *et al.*, 1998).

9 LBS offer several advantages for collecting STA data. Non-response biases may be
 10 lower since these technologies will be more ubiquitous and accepted than special-
 11 purpose, 'unusual' data collection efforts. Changes in space-time activity behavior
 12 induced by the data collection effort may also be lower. Finally, LBS can lower the
 13 per-unit cost of collecting STA data since new technologies and special data collection
 14 efforts are not necessary: STA data are required by LBS and therefore will be a necessary
 15 by-product of these services (Smyth, 2001).

16 We should also note that LBS can benefit from the time geographic and activity
 17 analysis available through a people-based GIS. One possible benefit is supporting *space-*
 18 *time queries*. Queries such as 'Which locations can I reach in 15 minutes?', 'Who can
 19 attend this event?' or 'Can I meet my friends at the pub this evening?' are in fact queries
 20 against space-time prisms. Another area is in *adaptive mobile computing*. Adaptive
 21 mobile computing refers a mobile computing and communication system adjusting itself
 22 in response to current and anticipated user events (Kanter, 2001). Demand for LBS will
 23 be high and also highly uneven across space and time. Strategies must be developed to
 24 ensure real-time or near-real-time responsiveness in a situation when many users want
 25 information at the same time (Miller, 2001).

26 There are, of course, important privacy and ethical issues surrounding the tracking and
 27 recording of individuals' activities in space and time. The author shares these concerns
 28 but contends that these data can be used in an ethical and respectful manner using
 29 standard or perhaps expanded human subjects review protocols in place at most
 30 universities and research institutions. The application or modification of these protocols
 31 to the primary STA data collection or the use of secondary (LBS-derived) data are not the
 32 subjects of this current chapter but are highly worthwhile research topics. Regardless of
 33 academic debates, the private sector will be using LBS to market products and services
 34 more effectively; and it would be nice if we can find ethical ways to use these data to also
 35 make our cities more livable and sustainable.

36 37 **16.4.2 Extracting Activities and Projects**

38
39 As noted in Section 16.3, there is no universally accepted standard classification for
 40 human activities and linkages among activities to form space-time projects at the
 41 individual, organizational and settlement system levels are not well understood.

42 STA data collection methods often involve textual descriptions in natural language:
 43 recall, diary and game methods all use subjects' textual descriptions of activities to some
 44 degree. Voice-based interfaces in PDAs, cellular phones and in-vehicle navigation
 45 systems mean that natural language narratives will become an even more important
 46 and potentially rich source of activity data.

1 Kuhn (2001) develops a method for designing GIS software to support human
 2 activities in geographic space. The method extracts the ontology of activities in
 3 geographic space based on natural language textual descriptions. The method is based
 4 on a type of ‘activity theory’ that represents human activities and the objects to which
 5 activities are directed as the basic units of analysis (see Engeström and Miettinen, 1999).
 6 The method exploits the inseparability of semantics and objects and the hierarchical
 7 nature of many activities and objects. For example, activity hierarchies range from goal-
 8 directed actions to lower-level actions that satisfy higher-level goals. The method
 9 consists of the following generic steps:

- 10 1. select a natural language text describing activities in a domain;
- 11 2. extract actions from the verbs found in the text;
- 12 3. identify the object classes that afford these actions from the nouns in the text;
- 13 4. order actions according to relations among the verbs;
- 14 5. produce an *action hierarchy* that comprises a hierarchical theory of the domain.

15
 16 Kuhn (2001) uses the German traffic code as a case study. While this is an ‘easy’ case
 17 study since legal codes tend to be complete and consistent, the method appears promising
 18 for developing ontologies of human activities and projects in geographic space. The
 19 method could be applied to data modeling and designing analytic and exploratory time
 20 geographic software. In addition to their use in software engineering, STA ontologies
 21 could guide research design. Extracting and formalizing STA ontologies across different
 22 socio-economic and geographic settings can support evaluation of classification systems
 23 as well as derive mappings between different systems. Formal STA ontologies are also a
 24 potential source of direct scientific knowledge.

25 26 **16.4.3 Data Models**

27 Similar to any GIS-based analysis and modeling, time geography requires careful
 28 database and system design. Due to the requirements for representing time and mobile
 29 objects, both of which are not handled well by the static, place-based perspective of most
 30 GIS software, the design challenges are particularly onerous in this domain, but tools and
 31 data models are emerging at the research frontiers in GISci.

32
 33 *Spatio-temporal Data Modeling.* Traditional vector and raster GIS data models are
 34 inadequate for representing the mobile spatial entities of interest in time geography and
 35 activity theory. Vector GIS is limited since it uses location as a basis for organizing data.
 36 Each time an entity’s location changes, the locational basis and the associated properties
 37 (attributes, topology) of the corresponding object in the database must be updated. While
 38 this may not be a major difficulty for point objects, entities that have complex geometry
 39 or non-rigid boundaries cannot be represented well. Raster GIS offers slightly more
 40 flexibility in this regard. In this case, each location in space (subject to a finite spatial
 41 resolution) has a unique attribute. By varying these attribute values sequentially, we can
 42 simulate the movement of the mobile entity over time. However, this approach is
 43 awkward since the entire raster field must be updated in each time step to simulate the
 44 movement of just a few entities (Bian, 2000).

45 There are a number of spatio-temporal data models that can be adapted to represent the
 46 dynamic spatial entities of increasing interest in transportation (Miller and Shaw, 2001).

1 A *space-time object model* proposed by Yearsley and Worboys (1995) integrates abstract
2 spatial data types with a geometric layer to construct a higher-level topological data
3 model. A geometric object can belong to several higher-level spatio-temporal objects.
4 Each geometric object is linked to both real time (when the event occurred in the real
5 world) as well as 'database time' (when the database records the event). *OOgeomorph* is
6 an object-oriented approach that represents dynamic spatial processes as spatio-temporal
7 aggregations of point objects (Raper and Livingstone, 1995).

8 The *three-domain model* treats time as a temporal object instead of an attribute. In
9 contrast to the location-centric emphasis of most spatio-temporal data models, spatial,
10 temporal and semantic domains have equal emphasis in this design. An event list
11 represents time while a spatial graph maintains the history of spatial object changes such
12 as birth, death, merging and splitting. Semantic objects have unique identifiers and
13 therefore can maintain identity across these changes. Domain links associate objects
14 across the location-centered, semantic-centered, and time-centered perspectives (Yuan
15 1996, 2001b).

16 The *event-based spatio-temporal data model* (ESTDM) maintains spatio-temporal data
17 as a sequence of temporal events associated with a spatial object (Peuquet and
18 Duan 1995). A base layer maintains the initial spatial configuration of an attribute. An
19 event list maintains time stamps of when a change occurs and points to the set of
20 locations and features that changed at that point in time. The ESTDM does not
21 maintain object identity beyond its spatial location and therefore cannot handle
22 processes such as merging and splitting (Yuan, 2001a). Yuan (2001a) integrates
23 aspects of the space-time object, *OOgeomorph* and ESTDM models to formulate a
24 conceptual framework for dynamic geographic processes that display properties of
25 both fields and objects.

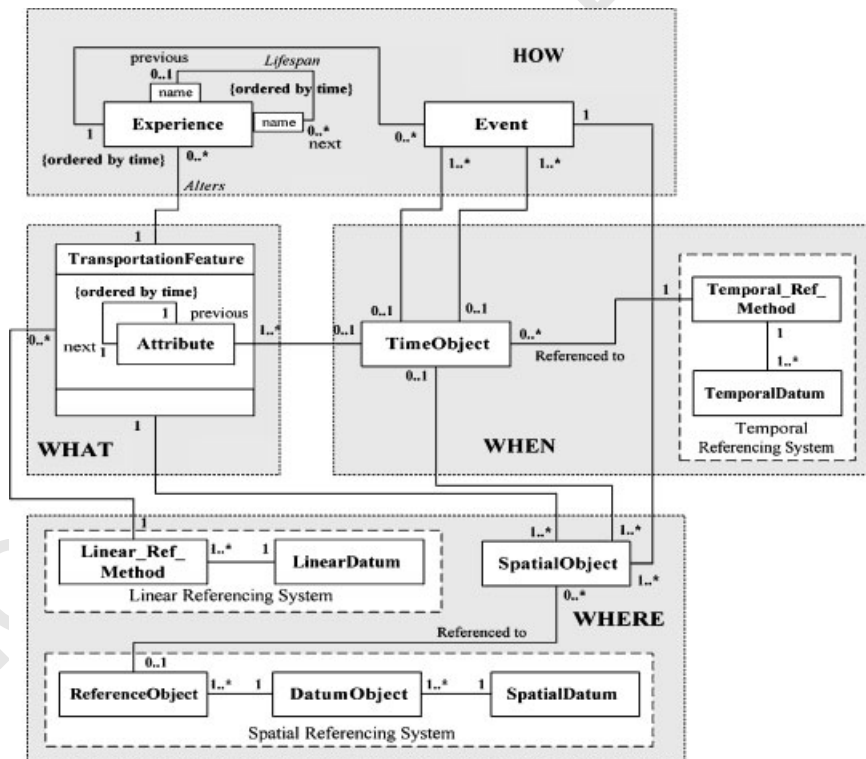
26
27 *Data Models for Mobile Entities.* Object-orientation (OO) is a natural strategy for
28 representing the behavior of mobile entities over space and time (Bian, 2000). Objects
29 can easily represent several critical attribute dimensions of mobile entities. One
30 dimension is physical attributes: these are the non-spatial properties of the entity. A
31 second dimension is geometry, including size and shape. The third dimension is motion
32 attributes, including direction, speed and acceleration. As Galton (1995, 1997) argued,
33 this latter dimension requires a mapping of time to positions. Westervelt and Hopkins
34 (1999) and Bian (2000) use OO for modeling the behavior of mobile entities through
35 continuous space, specifically, predator-prey relationships among land animals and fish
36 growth in aquatic environments respectively.

37 OO can also provide necessary linkages between mobile entities and placed-based data
38 on transportation systems and related land-uses. The *multidimensional multi-modal*
39 *location referencing system* (MDLRS) conceptual data model being developed through
40 the US National Cooperative Highway Research Program (NCHRP) supports relation-
41 ships between mobile entities and fixed geographic entities. The MDLRS data model
42 extends the functionality of linear location referencing system (LRS) data models that
43 allow the determination of an unknown location within a transportation network based on
44 reference from a known point (Vonderohe *et al.*, 1997). The MDLRS supports locational
45 referencing of entities in four dimensions (the three dimensions of geographic space and
46 time) relative to a transportation network and related geographic entities. This allows

1 transportation analysts to reference data collected through GPS receivers and other
 2 position-aware technologies (Koncz and Adams, 2002).

3 The MDLRS foundation is the three-domain strategy since this allows representation
 4 of dynamics that is not possible in other spatio-temporal data models (Yuan, 1997).
 5 *Transportation Features* are atomic real world or virtual entities within the transportation
 6 system. *Spatial Objects* maintain the spatial properties (geometric, topological) of a
 7 Transportation Feature while *Time Objects* maintain the temporal properties of a
 8 Transportation Feature or its behavior, either in real world or database time. *Event*
 9 *Objects* represent occurrences that generate changes in the attributes of the Transportation
 10 Feature while *Experience Objects* record those changes as a history of the
 11 Transportation Feature. This supports a full range of temporal referencing, storage
 12 strategies and topological relations for analyzing change (see Koncz and Adams, 2002).
 13 Figure 16.3 illustrates the basic MDLRS object model using unified modeling language
 14 (UML) notation (see Booch *et al.*, 1999).

15 The MDLRS supports the movement navigation of entities within the transportation
 16 system through a *Conveyance* object and the temporal attributes of the Transportation
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43 **Figure 16.3** The multidimensional location referencing system (MDLRS) object model
 44 (reproduced from Koncz, N. and Adams, T. (2002) A data model for multi-dimensional
 45 transportation applications, *International Journal of Geographical Information Science*, **16**,
 46 551–569. Figure 2, p. 555)

1 Feature and Event objects. The *Conveyance* object represents anything that moves within
 2 a spatial or temporal reference frame and contains the navigation methods *Track*
 3 (descriptive) or *Route* (prescriptive). Positions are expressed as a function of time
 4 along a *Traversal*, where this consists of positions referenced to the transportation
 5 network.

6 The MDLRS is a potential breakthrough in referencing and linking data on mobile
 7 entities, transportation infrastructure and geographic data. However, in its basic form it
 8 does not support well some of the concepts required by time geography and activity
 9 theory. Events are tied to transportation features and the mobile entity in the MDLRS
 10 does not directly support relevant attributes such as socio-economic and demographic
 11 factors and activity plans (although it does allow differences between planned and
 12 executed routes). The MDLRS cannot easily support stations or activity locations where
 13 space-time paths bundle with each other and with resources. These weaknesses are
 14 understandable, since the MDLRS function requirements center on referencing the
 15 transportation infrastructure and the vehicles that operate within it. Extending this system
 16 to support time geography and activity theory is a worthwhile effort.

17
 18 *Data Models for Activity Analysis.* Due to the increasing prominence of activity-based
 19 approaches to transportation and urban analysis, as well as increasing abilities to collect
 20 STA data, there have been several recent attempts to develop conceptual and logical data
 21 models to support activity analysis. Despite the complex, many-to-many relationships
 22 inherent in these data, including the relationships between individuals, households,
 23 travel, activities and their spatial and temporal dimensions, one of the major challenges
 24 in developing activity-based data models is to eliminate redundancy as much as possible
 25 (Shaw and Wang, 2000). Another consideration is representing complex temporal
 26 dynamics where an individual is sometimes moving along a continuous space-time
 27 trajectory but at other times is stationary in space (Wang and Cheng, 2001). As mentioned
 28 in Section 16.3, this is required to link the continuous spatio-temporal representations of
 29 time geography with the discrete spatio-temporal representations of activity theory.

30 Shaw and Wang (2001) develop a relational data model for handling disaggregate STA
 31 data. The central entity of their model is the 'trip' or a movement from one location to
 32 another. Other data such as the trip location (spatial), trip timing (temporal), the trip
 33 maker (a person within a household of other trip makers) and relevant trip attributes are
 34 linked to the trip. Trip locations are represented as paths through a network maintained
 35 using a variable-length segmentation model. While effective at maintaining data on
 36 multi-stop/multi-purpose trips, this data model does not contain the support for activity
 37 data required by time geography and activity theory. In these theories, it is activities and
 38 projects in space and time that drive travel and telecommunication demand.

39 Wang and Cheng (2001) formulate a STA data model that encompasses activities and
 40 projects to a greater degree. Figure 16.4 illustrates their conceptual data model using
 41 entity-relation notation (see Elmasri and Navathe, 1994). For clarity, the entity's attributes
 42 are suppressed; see Wang and Cheng (2001) for the complete depiction. The *Household*
 43 entity allows capturing of interactions among individuals and their activity patterns as
 44 required in time geography and activity theory. Each *Person* in the Household has a
 45 planned *Activity Program* that can be realized as an *Activity Pattern*. An *Activity Pattern*
 46 links the *Person* to a *Location* in one of two ways, namely, either by staying at (*Stay_At*) a

1 location while performing an activity or by traveling between (*Travel_Between*) locations
2 to perform planned activities. Their data model also enforces space-time constraints
3 among activity and travel locations and timings.

5 **16.4.4 Exploring and Visualizing Space-Time Activity Data**

6 A difficulty with analysis of STA data is the combinatorial explosion of the information
7 space. Decisions such as the number of activities within a time period, sequencing,
8 timing, interaction mode and route choice are interlinked, implying an information space
9 that is exponential with respect to choice dimensions (Ben-Akiva and Bowman, 1998).
10 Consequently, traditional methods for activity analysis require substantial reduction of
11 the information space.

12 Econometric and statistical approaches require *a priori* specification and testing
13 multidimensional utility functions or shallow first-order summaries of inter-activity
14 linkages from data (see O'Kelly and Miller, 1984). Utility maximizing approaches
15 include behavioral models that also require *a priori* specification of utility structures,
16 meaning that few alternatives within the universe of plausible structures can be explored
17 (see Kitamura, 1984). Rule-based reasoning systems construct activity and travel
18 schedules based on decision heuristics derived from cognitive science (see Garling
19 *et al.*, 1994; Hayes-Roth and Hayes-Roth, 1979; Vause, 1997). Simulation methods
20 derive plausible choice sets and simulate individual choices from those sets (Ben-Akiva
21 and Bowman, 1998). All of these techniques can only explore a very small subset of the
22 complex and vast information space of space-time activities in geographic and cyber-
23 space.

24 New IT for data storage, integration and analysis can break the combinatorial barrier
25 that has prevented full exploration and discovery of the spatio-temporal patterns in
26 activity data. Data warehousing techniques are available for integrated and efficient
27 storage of digital geographic data (Bedard *et al.*, 2001). However, existing conceptual
28 database design and storage/access techniques for geographic data warehousing must be
29 modified to handle the temporal dimension of STA data.

30 Data mining and exploratory visualization techniques for digital geographic data are
31 also emerging (see Miller and Han, 2001). There are so far only a few techniques
32 available that can address STA data; most techniques are oriented towards analyzing flow
33 data within network structures (see Marble *et al.*, 1997). Huisman and Forer (1998),
34 Kwan (2000b) and van der Knaap (1997) develop cartographic visualization techniques
35 for exploring STA patterns. Arentze *et al.* (2000) apply decision tree induction methods
36 to STA data. Joh *et al.* (2001) adapt multidimensional sequencing methods from genome
37 research to measure similarities among activity patterns.

39 **16.4.5 Time Geographic Analysis**

40 An unrealistic assumption of the STP is that travel velocities are uniform and continuous
41 across time and space. In most settlement systems, travel is restricted to transportation
42 networks. Travel velocities within these networks vary by location and time based on the
43 capacity of the infrastructure, and the movement of other individuals through the system.
44 If STPs are to be useful as a technique and not just a conceptual device, the assumption of
45 a uniform velocity across time and space must be relaxed.
46

1 Miller (1991) relaxes the uniform velocity across space assumption by developing an
 2 algorithm for constructing a network *potential path tree* (PPT). This network analog to
 3 the PPA demarcates all nodes in a transportation that a person can reach given fixed
 4 anchor locations, a time budget and travel times within the network. A problem with this
 5 approach is that it focuses on nodes and can leave unresolved gaps in the network. Miller
 6 (1999) adopts a network based market area delimitation technique developed by Okabe
 7 and Kitamura (1996) to construct the *potential network area* (PNA). This shows all
 8 locations within a network that a person can occupy. Miller (1999) and Miller and Wu
 9 (2000) show that space-time constraints can be integrated into traditional accessibility
 10 measures and calculated for locations within a network using the PNA. Figure 16.5
 11 (Colour Plate 5) illustrates a PNA-based accessibility measurement. O'Sullivan *et al.*
 12 (2000) develop GIS methods for calculating space-time access to public transportation;
 13 this illustrates that STP products can be extended to multi-modal travel. Wu and Miller
 14 (2001) relax the uniform velocity across time assumption by developing time-dependent
 15 STP measures and developing computational tools linked to a dynamic network flow model.



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37 **Figure 16.5 (Plate 5)** High accessibility locations within a network calculated using a
 38 potential network area (reproduced from Miller, H.J. and Wu, Y.-H. (2000). *GIS software for*
 39 *measuring space-time accessibility in transportation planning and analysis, Geoinformatica,*
 40 *4(2), 141–159. Figure 10, p. 157; with kind permission of Springer Science and Business Media)*

41
42 The time geographic tools discussed above still only recognize physical movement and
 43 travel. They do not recognize the ability of some individuals to use IT as a substitute or
 44 complement for transportation. They are also still loosely place-based: although acces-
 45 sibility is attributed to individuals, these individuals are identified through the locations
 46 of fixed geographic anchor points such as home and work.

1 Some progress is being made in disconnecting the STP from geographic space. Adams
2 (2000) develops graphical representations of space-time paths in both physical and
3 virtual space. *Extensibility diagrams* are extensions of the space-time path that encom-
4 pass communication at a range of geographic scales from local to global. Extensibility
5 diagrams can illustrate general characteristics of the relationships between IT and
6 transportation in activity participation. Individuals can be compared with respect to the
7 frequency, duration, time and geographic scale of travel, incoming communication and
8 outgoing communication. However, these visual tools are only viable for very small
9 datasets, even though geographic space is restricted to only a crude ordinal scale (local,
10 regional, national, etc). Tools with higher spatial resolution are still needed along with the
11 ability to support synoptic summaries, spatio-temporal aggregation, drill-down analysis
12 and other exploratory and data mining techniques.

13 Another weakness of time geography is that it ignores the fact that people often have
14 imperfect information and uncertainty about transportation system performance and the
15 outcomes from travel (Hall, 1983). Although Hägerstrand (1970) argued that we should
16 ignore preference and choice and instead focus on constraints, lack of information can be
17 as strong a constraint as lack of time. In addition, we must consider imperfect
18 information if we are to extend the theory of accessibility from its transportation context
19 to encompass cyberspace. Since IT is about information search and retrieval, it is difficult
20 to imagine an integrated theory of accessibility that assumes omnipotent beings.

21 Some initial but limited efforts have been made. Hall (1983) analyzes the impact of
22 uncertainty about transportation system performance (i.e. travel velocity) on the potential
23 path space. He also analyzes the impact of random coupling constraints and simple
24 random search for activity locations. Kwan and Hong (1998) integrate cognitive con-
25 straints (e.g., preferences or lack of information) into a STP through an effective but
26 ad-hoc overlay procedure. An extended research effort is required that re-examines time
27 geography from its foundation, reformulates it as an analytical theory (similar to Burns
28 (1979)), and develops computational tools that recognize imperfect information.

31 16.5 Conclusion: Research and Development Frontiers

32
33 Place-based representations and methods were developed in an era when data were
34 scarce, computational platforms weak and questions apparently simpler. Urban and
35 transportation theory and policy for a shrinking, shriveling and fragmenting world
36 requires a people-based perspective. This perspective focuses on individuals in space and
37 time and their interactions using transportation and telecommunication infrastructure
38 and services. The increasing availability of digital data on people and objects in space
39 and time and abilities to store, process and understand these data can make it possible.
40 The deployment of location-based services (LBS) means that the private and public
41 sectors will be collecting and using space-time activity (STA) data to sell and promote
42 their products and programs. Researchers should also use these data and tools to
43 make our transportation, telecommunication and settlement systems more livable and
44 sustainable.

45 There has been a great deal of research in domains such as time geography, activity
46 theory and GISci to support an extension of the place-based perspective in GIS to a

1 people-based perspective. Research and development efforts along the following frontiers
2 will provide better support for a people-based perspective in GIS:

- 3 1. a rigorous, formal representational theory of the dynamic spatial objects of interest in
4 time geography and activity theory;
- 5 2. new data collection protocols and methods that exploit advances in IT, position-aware
6 technologies and LBS, including exploiting detailed but noisy spatio-temporal
7 referencing data as well as extracting activities and projects from incomplete and
8 perhaps inconsistent vocal descriptions and queries from LBS;
- 9 3. new database designs that can support activities and project planning by mobile
10 entities, their socio-economic and demographic characteristics and their movements
11 within a detailed, georeferenced representation of the transportation infrastructure;
- 12 4. efficient geospatial data warehousing techniques for handling massive, noisy STA
13 data;
- 14 5. spatio-temporal data mining and exploratory visualization techniques that can handle
15 the massive, noisy data STA data;
- 16 6. enhanced versions of the space-time path, prism and other constructs that can be
17 disconnected from geographic space and referenced within cyberspace (information
18 space loosely connected to geographic space);
- 19 7. a time geography that recognizes imperfect information, information search and
20 learning.

21 22 23 **Acknowledgments**

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25 this chapter.

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