Chapter 3

Different Types of "Times" in GIS

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It is generally assumed that different types of time and space are used in geographic information systems (GISs), without giving precise definitions. Understanding time and space as types, in the sense often used in the discussion of computer languages, makes precise notions of differences available and relates the notion of type as a model to reality and as an algebra to mathematical theory. Differences are either in the operations applicable to two types or the outcome of the same operations applied to two different types. This can be applied to the notion of types of time, and for each type of time one has to show the applicable operations and their definitions. Different types of time are then recognized by differences in these definitions, which reflect the operations people apply to time facts and the expected outcome according to observations or conventions in different situations. This approach allows us to link models of time to people's basic experiences.

The intuitive notion of differences in types of time is demonstrated with some examples from sport and administration. The notion of type in the theory of programming languages is then briefly reviewed and linked to category theory and multi-sorted algebras. Differences in the applicable operations are detailed and linked to the prototypical basic experiences. For temporal data, the most important relation is order, which establishes the sequence of events typical for a naive understanding of time. Several models based on order are reviewed and models with total order separated from models with partial order. The models most often used map time onto real numbers or integers, and submodels using epsilon tolerances or a container granularity must be differentiated. Intervals between two time points on any of these models can be constructed; even a cyclic time allows meaningful inferences for intervals. Some of the characterization for these models are orthogonal and can be combined. For example, a time model used for planning, that permits multiple variants (branching time) to be combined with a time model that assumes total order. The potential for combinations makes it impossible to construct a single hierarchical taxonomy.

Extending geographic information system (GIS) software with facilities for temporal data is one of the major demands for extending current capabilities. Dealing with time as calendar time and mapping it onto the integer domain is feasible, but does not capture the semantics of time and leaves out most of its important properties. Understanding how time and temporal reasoning processes are conceptually structured is a prerequisite to building support for temporal reasoning into today's GISs. Formal models are necessary to determine the representation of temporal information and the temporal and spatio-temporal reasoning methods.

Treating time as calendar time simplifies the problem, because the powerful model of real numbers is immediately available. It also permits the integration with current GIS software; however, it excludes from treatment all temporal information that is not in this form. In particular, temporal information that is only available as relative order between events cannot be treated, but this is an important data source in geology, archeology, etc. This parallels the spatial situation, where current GIS software cannot deal with qualitative spatial information and only coordinate-based geometry can be entered.

Modeling time is closely linked to the models used to structure space. Initially, NCGIA started research in the representation of space and time with the recognition that space was conceived differently, depending on the circumstances (Mark, 1988; Mark et al., 1989). Zubin (1989) presented a taxonomy, of which was a refinement of the distinction between small-scale and large-scale (geographic) space (Kuipers, 1978). It is also related, but not equal to the spaces discussed in Couclelis and Gale (1986), where algebraic concepts and operations are considered to differentiate spaces. A tentative taxonomy, linking conceptual models with formal models and data structures typically used for implementations were proposed by Frank and Mark (1991). An important issue is to decide if there are generic methods to translate from one spatial concept to another or if there is a single basic concept into which all others can be translated (Goodchild, 1992).

The conceptualizations of time were originally assumed to be independent of the spatial conceptualization (NCGIA, 1989), but strong links were soon found. Lakoff has stressed the strong influence of the use of spatial metaphors for the conceptualization of time (Lakoff, 1987). This metaphorical mapping establishes a first linkage between space and time conceptualizations, details of which are still open for research. Linguists report similarity in the method language uses to express temporal facts and movement in space (Talmy, 1991).

The second linkage between space and time conceptualization is through the *process* to be described, when there are some indications that a specific process determines the temporal conceptualization in a manner similar to the way it determines the spatial conceptualization (Johnson-Laird, 1983). Researchers from this group recognize today that the conceptualization of space depends on the process considered. The process may be a mundane procedure, such as an administrative one where legal rules supply the conceptualization, or it may be the scientific methodology (Campari, 1992). Each process that is in focus provides its own context and conceptual frame for the cognition of space and time.

Among the increasing number of papers on space and time in the GIS context, most abstract time to a date line and discuss the difficult database and data storage issues arising, or issues of specific applications. Nevertheless, research in the conceptualizations of time is beginning to emerge (Barrera and Al-Taha, 1990). There is agreement that differences in the conceptualization of time or space matters for GIS. It influences the use of GISs (Campari, 1991), the user interface (Kuhn and Frank, 1991; Payne, 1991), the internal representation (Frank and Kuhn, 1986; Herring et al. 1990; Egenhofer and Herring, 1991; Gueting and Schneider, 1993), and it also influences the visualization, including the understanding and visualization of data quality (Beard and Buttenfield, 1991).

This chapter first discusses the question of what is meant by stating that there are different types of time. The notion is related to scales of measurements and descriptive models. The use of the notion *type* in computer science links models to both the empirical world and the mathematical theory. Most important here is category theory (Herring et al. 1990; Asperti and Longo, 1991) and algebra (Birkhoff and Lipson, 1970). This leads to a precise and formalizable method to describe differences between models of time. For each type, it gives a set of operations and axioms, which define the effects of these operations. Two types are different if the algebras defined through these axioms are different.

The next sections list a number of examples of time concepts, namely single experience (totally ordered) models versus partially ordered models; continuous, discrete, or solely ordered models of time; cyclic versus linear time models; branching time in the past or in the future; and multi-perspective models of time. Each of these models can be formalized. Precise models contain substantial amounts of detail and reveal a surprising number of variants. They can only be built with sufficient tools, which were lacking until now. Modeling ordered, discrete time has been done (Frank, 1994) and similar efforts for other models are necessary. The concepts of time listed above are orthogonal and can be combined to form more complex meaningful types of time. This explains why a simple hierarchical taxonomy of types of time cannot be achieved.

What Is Meant by Different Types of Time?

Stating that there are different types of time or different types of space implies that there are *observable* differences between these conceptual models of space or time. It is difficult to think of time—in the abstract—as existing in different kinds of space, and the same problem applies to thinking of different types of space. Our daily experience indicates that there is only one physical space in which we and all the other things exist. This may explain some of the skepticism that the discussion of differences in models of time meets, for example, as expressed by Barrera and Al-Taha (1990).

The differences are not in the physical (objective) properties of time and space, but are found in the conceptual models for time or space people use. Objective reality is very complex and people use simplified abstractions to reason about the environment; these models are most of the time unconscious. They are abstractions that are effective as they are sufficient to resolve a given problem. They are usually economical and do not contain more detail than what is necessary to achieve these goals (Kuipers, 1983). People can switch to more detailed models if a need arises. The models are often fixed conventions, which are shared in a community, as shown in the following examples.

The question of how to determine the length of time between two events often arises. It is answered differently in different sports, where for some sports, time is measured between the command "go" and the time the runner arrives at the mark. Other sports measure the time between the moment the athlete passes the start line and he or she crosses the finish line. In the first case, reaction time of the athlete is part of the time measured; in the second case, reaction time does not play a role. The times measured according to the one rule cannot be compared with times measured according to the other rule. An observable difference is that only the first measure of time includes a notion of a false start. Similar differences can be found in the determination of the length of a game: when the referee interrupts a game of ice hockey, the time stops; in soccer it continues running.

The same question of determining the length of time between two events is also important in administrative and commercial procedures. Again, different models apply. For example, the time between depositing money in the bank and withdrawing it is measured in days. But the difference is not only in the granularity of the measurements (days versus seconds in sports), but in a number of simplifying assumptions conventionally used. First, all deposits during 1 day are construed as having arrived at the same time, namely, midnight of this day (11:59 PM), and all withdrawals happen in the morning of the day (12:01 AM). Thus, the interval from Monday, June 3, 8:30 AM to Wednesday, June 5, 4:50 PM is not 54 hours 20 minutes, or rounded down to 2 days (48 hours) but only 1 day. Several countries use additional conventions to simplify calculations: months are uniformly assumed to have 30 days and years 360 days (so from February 27 to March 1 there are 3 days).

These conventions seem natural and not much thought is given to them, unless one is forced to realize the differences in semantics between two applications. A single model of time does not fit all situations and the differences between the models must be dealt with. In particular, the models well known from mathematics are high-level abstractions, representing the essence, but not capturing the exact semantics, of these applied models.

Characterizations of Different Types of Time

An early discussion of types of measurements, applicable equally to measurement of time, is found in a landmark paper about the *Theory of Scales of Measurements*. Stevens (1946) points out

> The isomorphism between these properties of the numeral series and certain empirical operations which we perform with objects permits the use of the series as a *model* to represent aspects of the empirical world. (p. 677)

This points to differences in models and related measurement methods and explains the differences in terms of operations applicable to the empirical world and the model. The differences are not attributed to the empirical reality, but rather to differences in real and cognitive operations applied to it.

Cardelli and Wegner (1985) explain types from the mathematical or computer science perspective simply: "Sets of objects with uniform behavior may be named and are referred to as types." Behavior in this context means the outcome of operations, for example, the test if event A is before event B. The types used in computer science are a more refined notion of the scales of measurement of Stevens.

The mathematical background is found in algebra (Birkhoff and Lipson, 1970), where one considers sets of objects and operations applicable to them. Integers for example, are a set of objects with the operations plus, minus, and multiplication. Real numbers are another set of objects (another type) with similar operations, but also a division operation. Discussion of types in programming is important, because "in mathematics as in programming, types impose constraints that help to enforce correctness" (Cardelli and Wegner, 1985, p. 474). Types (and algebras) are the objects studied in category theory (Asperti and Longo, 1991). For an introduction within the context of GIS see Herring et al. (1990). From these foundations, the formal description of semantics, using the methods of denotational semantics, are possible (Scott, 1977; Stoy, 1977).

The differences between types of times in our models reflect differences in our conceptualization of real world situations and the empirical operations typical for them. Different aspects can be characterized as individual algebras and then be combined. The approach followed here starts with a minimal set of operations (or constraints) that capture some temporal aspects. These *traits* (Guttag et al., 1985) are then combined by adding operations and constraints to the original set. The fundamental belief is that the complex behavior real objects exhibit can be modeled as a combination from simple algebras.

Formalizations provide a means to precisely show the semantics of the operations. Commonalties and differences of divergent models of time become apparent. Formalizations also describe how models are combined and, thus, determine which minimal models can act as building blocks. Unfortunately, for GIS the question is not yet resolved theoretically. Even the seemingly well-understood abstraction methods of classification, generalization, and aggregation (Brodie et al., 1984) pose vexing problems when studied in detail in a practical context.

Overview of the Taxonomic Approach (Models of Time)

There are traditional methods of establishing taxonomies, best known from biology, where plant or animal species are organized in a hierarchical subdivision. This is not directly applicable here. The relations between the types discussed are not subset relations (Cardelli and Wegner, 1985). The characteristic properties of the models are described as models that can be combined to produce a much larger set of meaningful models. Many of the characteristics are orthogonal. Actual models of time used in particular circumstances are, therefore, combinations of one variant from each group and a hierarchical taxonomy is insufficient.

One view in the taxonomy results from the temporal objects considered events, which are abstract time points without a duration; or intervals between two events.

A second subdivision results from the interpretation of processes: events arrive on a linear time, which extends from the past to the future; or events are seen as arriving in a cyclic repetitive pattern.

A third subdivision depends on the scale of measurements used to observe time sequence information about events, related to an ordinal time scale; and events timed against a continuous time axis, measured on an interval scale.

A fourth viewpoint follows from the adoption of a viewpoint to observe events there is a single viewpoint and all events are completely ordered (total order); there are sequences of events that are not completely related (partial order); there are variants of planned future actions, which describe possible states of the world (branching); and there are multiple sets of knowledge about the world, which are not congruent.

These are some important considerations in the classification of temporal models. *In lieu* of a taxonomy, a more complex lattice structure among types must be assembled. For illustration, the second, third, and fourth subdivision from above are shown in Figure 3.1.

The treatment here follows these characteristic properties of time models. The text follows the above list, but to avoid repetition, in later sections only the major additional aspects are discussed, and it is understood that most of the previous results apply. Only a formal treatment with a defined method for combination of the different models can improve on this (Frank, 1994).

Ordinal time

Many models of time assume *time points* as basic objects to describe the time an event happened. These are abstractions, comparable to abstract Euclidean points. Time points have no duration, which can cause some vexing logical problems (Davis, 1990).

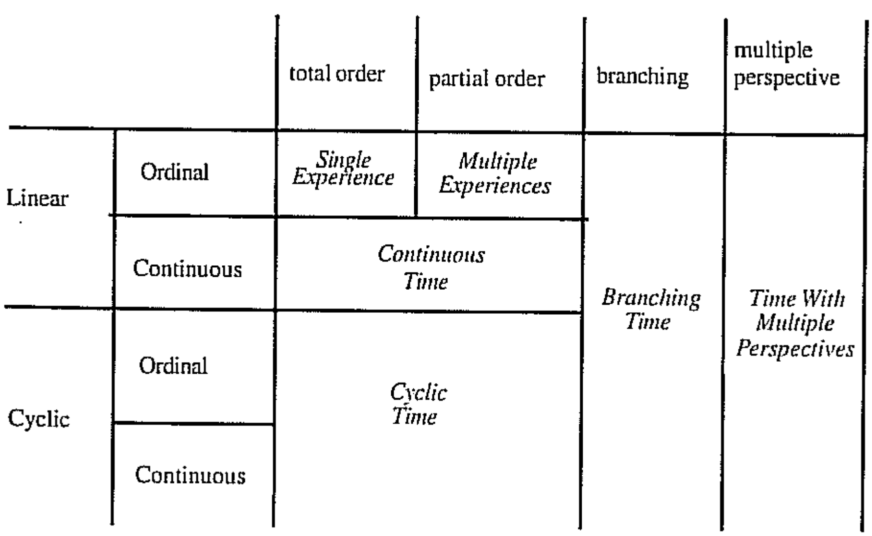

Figure 3.1. Lattice structure among types (italicized items refer to respective subsections).

The traditional method for treating time in a GIS is to map time onto a time line constructed from integer or real numbers (Langran, 1992). Beyond order and equality this provides a host of interesting operations, which include the computation of the length of time between two points in time, the calculation of points a certain amount after or before a reference point, and the calculation of intervals. This is all extremely useful and corresponds—with some limitations—to cognitive models of time. This is also the only type of time with which current GIS software can potentially deal (Al-Taha and Frank, 1991).

Often, less precise information is available; namely, on the relative order of two events. This is typical for geology (Flewelling et al., 1992), archaeology (Allen et al., 1990), and studies of urban development, where the sequence of events can be deduced from observation but exact dates are difficult to come by. Many forms of temporal reasoning are possible with ordinal temporal information.

Mapping time onto integer or real numbers excludes the treatment of temporal information in a GIS when temporal information is available, but not with the precision and detail necessary for this mapping. One observes in the temporal domain in GIS the same as in the spatial domain, where position is mapped to a coordinate value (conceptually a pair of real numbers, implemented with the floating point approximations in computers). This limit can be overcome by including qualitative expressions (before, east) and symbolic reasoning in space and time (Frank, 1992).

For example, from the parcel structure in Figure 3.2 one can deduce that the boundaries e and f were created before boundary h, assuming that the boundaries and the parcels have been created in the order their numbers indicate.

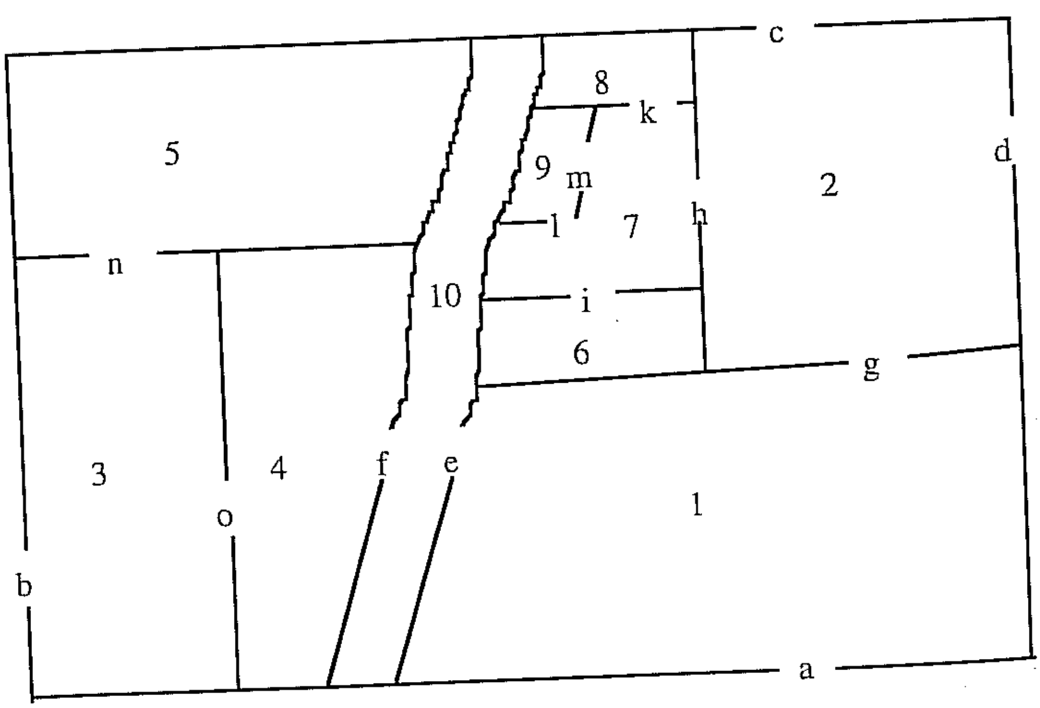

Figure 3.2. A parcel subdivision.

However, nothing can be said about when this happened or how much time passed from the first subdivision to the next. Therefore, it is impossible to deduce an unambiguous temporal relationship from this configuration.

Single experience: total order models for time points. The fundamental experience of time for people seems to be events that happen one after the other (Figure 3.3). Events happening to a person are, for example, the objects that they encounter during a journey, and this basic experience is used metaphorically to understand sequences of events in time as a path. Languages reflect this basic experience, and many time metaphors are related to movement of an observer along a path, for example, "A is before B" (note that "before" is primarily a spatial expression before it is a temporal one!).

In this model there are two possible relations between two events A and B: A before B, or A after B, abbreviated as A < B and A > B, respectively. Of importance is the observation that for any two events happening to a person, exactly one of the two relations is true (the problem of events at the same time will be treated in the next subsection). In a total order, all time points can be arranged in a linear sequence and for that reason total orderings are sometimes referred to as linear ordering. Therefore, one can state that an event is immediately preceding (or succeeding) another one. If a new time point C is inserted in the set of time points, say with a relation C < A, it implies that C < B, when B is the immediate successor of A.

Mathematicians construct order relations from a base relation <= ("before or at the same time") and a set of axioms that is true for all A, B, C:

(A <= A)	reflexive
(A <= B and B <= A implies A = B)	antisymmetric
(A <= B and <=B <= C implies A <= C)	transitive

If for any A, B either A<= B or B <= A is true, the relation is called a *total ordering*. The converse relation to "before or at the same time" is "after or at the same time" (>=):

A >= B = B <= A.

Figure 3.3. Total order model.

A strict relation "before" and its converse "after" is then defined as:

A < B implies A <= B and not A = B (before)
A > B implies A >= B and not A = B (after)

For total orderings:

A < B = not A >= B.

In this model of time, the events that created parcel 9 can be modeled and some simple conclusions drawn. Parcel 9 was created by defining the boundaries l and m, which divide it from parcel 7. Parcel 2 shares the boundary h with parcels 6, 7 and 8. Therefore, the conclusions are legitimate, that "7 < 9" and "2 < 7." This also means: not 7 >= 9 and not 2 >= 7, which implies by transitivity not 2 >= 9, therefore, 2 < 9. This means that a total ordering is given by 2 < 7 < 9.

Time with strict equality. The previous model of time can be combined with a simpler one, which is based on the relation "at the same time," that is, two events happening at exactly the same time (Figure 3.4). Mathematically, this is an equality relation with the axioms:

A = A reflexive
A = B implies B = A symmetric
A = B and B = C implies A = C transitive

and there is a connection between the equality model and the ordered model:

A >= B and B >= A implies A = B.

A model of time with equality alone is not very useful, but it is a powerful extension of the natural understanding of the ordered models. The equality model and the total order model can be combined as a *product type*. This means that an instance of the combined model, for example, a set of facts following from Figure 3.2, consists of an instance of the equality model (facts 1 and 2) and an instance of the order model (facts 3 and 4).

Set of facts: (1) 2 < 7, (2) 7 < 9, (3) 6 = 7, and (4) 7 = 8. The combination requires additional rules for deduction, such that A = B and B < C yield A < C (Frank, 1994).

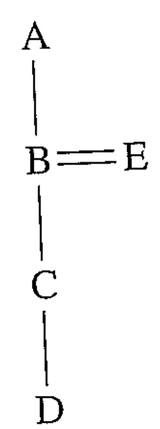

Figure 3.4. Total order model with equality.

Equality with tolerance (semiorder). When are two events at the same time? This depends on the resolution of our observation system. Empirical measurement systems have some inherent error, and results are not completely precise. Thus, a strict definition does observably differ from empirical observations. Some notion of tolerance is needed, for example, allowing a small difference *epsilon* between two measurements that are considered equal. As the ordinal time model investigated here does not provide for the computation of the time difference between events, this is not feasible.

A pragmatic observation system that only determines "before," "equal," or "after" for two events may find that A is before B and B is before C and also find that A is equal to D, and B is also equal to D (Figure 3.5 indicates this situation on a time line). This shows that D is closer to A and also closer to B than what can be differentiated. If data of this nature must be processed, then the regular equality leads to logical contradictions and semiorders must be used.

Measurement theory provides the theoretical base for a solution. It introduces the concept of tolerance as "the just noticeable difference" (Scott and Suppes, 1958; Krantz et al., 1971). Luce has defined semiorders as

"Let S be a set and < and = be two binary relations defined over S. (<, =) is a semiordering of S if for every a, b, c, and d in S the following axioms hold:

S1. exactly one of a < b, b < a, or a = b obtains,
S2. a = a,
S3. a < b, b = c, c < d imply a < d,
S4. a < b, b < c, b = d imply not both a = d and c = d." (Luce, 1956, p. 181).

These observations can be applied to graphs (Roberts and Suppes, 1967; Roberts, 1969) and led to a tolerance geometry (Roberts, 1973) (Figure 3.6). Whenever facts are added in such a tolerance-based system, one must check that none of the axioms is violated. The axioms S3 and S4 can be used for deduction. Deductions proceed regularly (using the same rules as for time with equality and total or partial order).

Multiple experiences (partial order). If events happen to several observers, their relative order is not always known. As a practical experience, if John and Peter both arise in the morning and eat breakfast, etc., for each of them it is known that waking up is before leaving bed or eating breakfast, but it is unknown

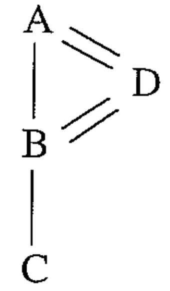

Figure 3.5. Time model with tolerance.

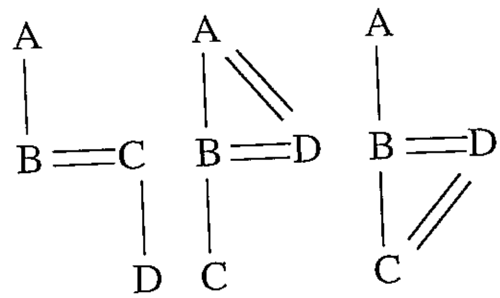

Figure 3.6. Time lines for axioms S3 and S4.

whether John woke up before Peter. This is similar to events encountered along different paths, walked by different persons. If David encounters first the Church and then the store, and Ted sees in sequence the Station and the School, for each path the relative ordering is established, but nothing is said about the order of events along different paths (Figure 3.7).

As another example, in Figure 3.2, one observes that parcel 1 is before parcel 7 and also parcel 2 is before parcel 7, but nothing is known about the relation between parcel 1 and parcel 2. Orderings in which it is not known for every element if it is before or after another one, but the relation may be unknown, denoted by "#," are called *partial orderings*. To represent the situation in Figure 3.2, a partial order model for time points is required.

In a *partial ordering*, for any A, B: A < B, A = B, A > B, or A # B. This invalidates the standard assumptions as not (A >= B) implies A < B (it is A < B or A # B).

A set with a partial order relation is called a *partially ordered set* or *poset*. Subsets of a poset may be totally ordered; this is, for example, the case for each sequence of events that apply to a single parcel (and all its predecessors). The elements in a poset can be linearly ordered, but there is more than one possible solution (topological sorting). A special case of a poset is a *lattice*. The intersection of the successors of two points have a single earlier point. The same concept can be applied to a family of partitions of the plane (as in Figure 3.2),

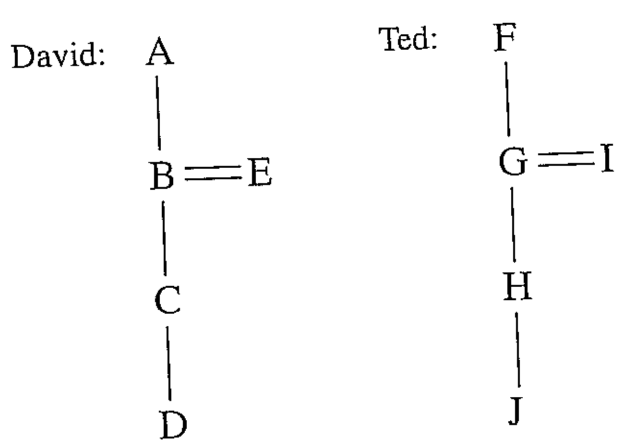

Figure 3.7. Two different experiences.

where partitions of different levels of subdivisions form a lattice (ordered by a "refinement" relation). Exploration of the relations between temporal order relations and the order relation in the lattice of partitions in geometric space is a challenging research question.

Combinations of ordinal time models. Just considering points in time and order relations between them, a surprising number of different models are used. The differences are small, but significant for reasoning in many practical situations where order of events matter, not the least all administrative and legal proceedings. These differences are thus relevant for GIS, as far as a GIS is used to support such proceedings (e.g., a land parcel database with legal information about ownership and mortgages).

A partial order model can be combined (in the same way as the total order model) with the models for equality. In general, the models can be combined but the details of these combinations cannot be described precisely without a formal framework. Just for points in time with an order relation, at least six different ordinal models for time points result: the order relation may be total or partial; there may be an equality relation included or not; and equality may include a tolerance or not.

All six combinations of these components are possible and meaningful. Most realistic—and probably necessary to model for the example considered—is the model with partial order and tolerance. It is also the most complex to formalize and implement.

The models are alternatives but can even be combined in a hierarchical fashion with other models. For example, a time model based on a regular calendar can be combined with an ordinal model to capture temporal historic data: most events are related to a time scale with a given granularity (years or, for some dense periods, days). Events within the time units are only related to an ordinal scale, for instance, the movements of a battle are not timed, but their sequence is given.

Interval time (events measured on an interval scale)

The conventional method to determine time with respect to a fixed scale, which is assumed to be globally synchronized and structured, is to use days, month, years, and so on. This represents the fundamental experience of cyclic astronomic processes, which are used to impose a measurement scale on time. This measurement scale is called an interval scale, which is not to be confused with the time intervals discussed in a later section. For most applications in GIS the naive view of global synchronization of time scales should be sufficient, but in principle, synchronization of clocks on a global scale is an issue (Lamport, 1978). In exceptional cases, a GIS may deal with time measurements on non-synchronized calendars, but this is disregarded in the rest of the chapter. A continuous model, relating time measures to real numbers, and a discrete model, measuring time with integers, are often used and are therefore discussed here.

Continuous time. Time is conceptualized as a continuous stream regularly floating. Time is dense, meaning that between any two events, another one can be inserted, and it is regularly progressing; thus, the calculation of intervals makes sense. This model is preferred in physics (except in quantum physics) and all sciences that build models similar to physics, using differential equations, etc. With this model, a powerful analytical mathematical and statistical apparatus becomes available.

In this model, we have total order by mapping *before* onto *less* on the real numbers of time measures. Similarly, *at the same time as* is mapped onto *equality* on real numbers. Most operations defined for real numbers can be applied and make conceptual sense. For example, modeling a continuous process like moving from a to b in space, that takes from 8:30 AM to 12:00 noon to complete, one can state that at 10:15 the halfway point is reached. The process of continuous movement along a path also establishes a particularly simple morphism between temporal and spatial situations (Figure 3.8).

Often a simplification is achieved by introducing an epsilon value, assuming that any measurement could deviate a small amount from the correct value and two measurements differing only by this much are considered equal. In such situations, it is not permitted to use a transitivity rule for epsilon tolerances, because it would lead to logical contradictions. If a is equal to b (a~b, that is, $|a-b| < e$) and b~c, c~d, ..., x~y, one must not conclude by transitivity that a~y, because possibly a and y are not within an epsilon tolerance ($|a-y| > e$). Practically, this problem is well known from calculations of line intersection in map overlay. An extension of the rules given above for tolerance spaces must be applied here to avoid this problem.

Container time (with differing granularity). A discrete model of time can be built with varying degrees of resolution (in the sense of an epsilon associated with each measurement), but also with different levels of granularity. The concepts are similar but behave differently, and have a different experiential base: epsilon tolerances result from the experience of a continuum (e.g., space or time) where objects can be moved in incremental amounts. Granularity is a container concept.

Two events are considered equal under a tolerance if they are not separated by more than the tolerance. On the other hand, two events are considered equal in a granularity model if they fall within the same time unit, considered as a container. For example, subdivision A became effective 31st December 1903, subdivision B effective January 1st, 1904. Using a large granularity of 1 year, the two events are not at the same time, but using a much smaller tolerance (say, 1 week) they are at the same time (Figure 3.9). The legal and administrative

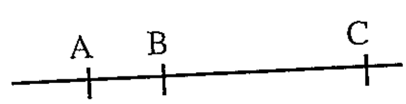

Figure 3.8. Continuous time.

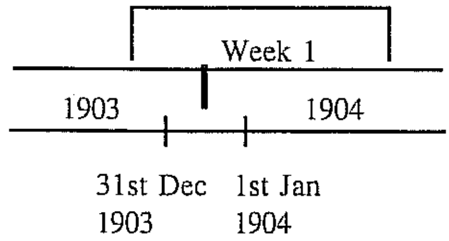

Figure 3.9. Time with differing granularity.

system very often applies a granularity concept (*in lieu* of a tolerance)–for example, the tax year is a container with sharp boundaries (seconds may decide if a person is born in 1993 or 1994, with considerable effects on tax assessment). The granularity as a container leads to a logically simpler order (isomorphic to integer) and avoids the problem of epsilon tolerances and the added logical complexity of tolerance spaces.

Cyclic time

Some processes in space and time are cyclic; prototypical is the astronomic movement of celestial bodies. These astronomical cyclic processes were originally used to measure time. Many other processes are cyclic or at least in first approximation cyclic. In this class fall many natural processes that are strongly influenced by the cyclic astronomic processes, for example, the annual cycles of bird migration, the tide, or the daily migration of animals.

The order relation for points on a cyclic time scale as usually defined is meaningless. Any point is before *and* after any other point (morning is before evening, but also the morning comes after the evening). Locally, time on a cycle can be ordered (i.e., 9:00 AM is before 9:15 AM and 23:45 PM before 0:20 PM), but is 12 noon before or after 12 midnight? Transitivity is certainly violated: spring is after summer and summer before fall, fall is before winter and winter is before spring. Transitivity would lead to a statement that spring is after summer, violating the first fact in our chain (Figure 3.10).

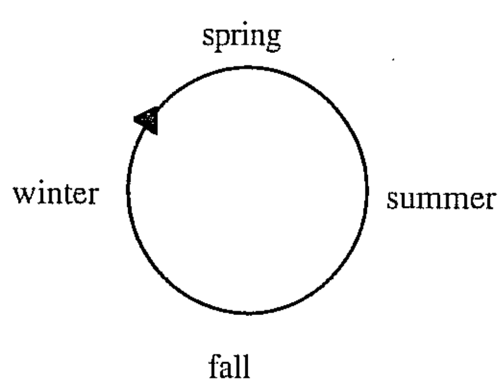

Figure 3.10. Cyclic time.

However, there are relations such as "immediately before" and "immediately after," which have meaning. If time differences can be computed (i.e., on time observations on an interval scale), then a relation "A is before B" would have the meaning that the distance in direction before is less than the distance in direction after.

Branching time (future, past)

Planning often consists of using scenarios where sequences of actions are foreseen, often with multiple alternatives, depending on future decisions (Figure 3.11). This is regularly used to study implications of today's decision on the freedom for future decision making or future reactions to external influences. The results of the scenarios represent possible future states, only one of which will be actually reached. Such time models can be constructed over an interval time scale or use a simple ordinal scale (even with partial order).

The branching model of time must be differentiated from a partially ordered model: in branching models of time, the same events can occur on different branches (as the branches represent alternate world scenarios) and do not necessarily link the branches. In partial order models, events occur only once, even if they are linked into more than one sequence.

Branching time is not only used for the planning of future actions, but can also be applied to analyze possible sequences of past actions that have led to a known current situation. Sequences with alternatives that indicate which hypothetical initial situations could have led to the current one are built and compared. Both these methods of investigation require support from the GIS, support that is linked to the treatment of time and must be coordinated with it. Application areas include planning, history, and archeology.

Time with multiple perspectives

Temporal models of reality cannot be totally synchronized with reality. Between an event in reality and incorporating it into the information system (the model), a delay occurs. Some GIS applications require not only modeling of reality, but also of the knowledge of reality; then it is important to record when an event

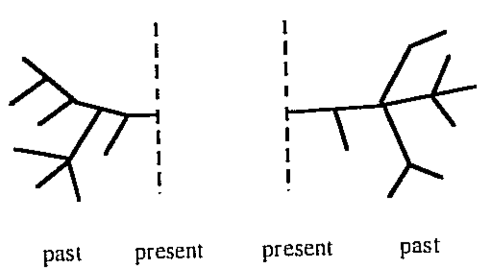

Figure 3.11. Branching time.

happened, as well as when it became known in the system. Typically these two perspectives are called "valid time" and "transaction time" (Snodgrass, 1992). Reasoning in such models of time takes into account (1) when events happened and (2) what was known at a given point in time, which allows us to ask, "Who owned parcel 1 on December 31, 1993?" as well as "Who owned parcel 1 on December 31, 1993, as shown by the records on Jan. 5, 1994?" (Al-Taha, 1992).

Reasoning with time (intervals)

Two points in time, A before B, define an interval from A to B. An ordered model of time is sufficient for the definition of intervals, even if no length can be calculated. Important is the condition that A is before B. Thirteen relations among intervals are usually defined following a proposal by Allen and Hayes (1985), which translate into the terms of totally ordered time without any problems (Figure 3.12).

The condition of order (A is before B) is insufficient in partial order models of time. First, intervals are only defined if A and B are related, and second, a rule to deal with ambiguous cases is-necessary (Figure 3.13). For example, one cannot determine if interval A–C is before or after interval E–F, because there is no known relation between C and E. Equally, there are different paths for the interval A–B.

Davis (1990) defines intervals in partial-order time models such that all points in the interval are totally ordered. A more restrictive definition allows only for intervals that are single linearly ordered sequences between start and end. The difference between the models is observable, as we found in the partial-order time models. Using the definition of Davis, not for any point A< B an interval of the kind A–B is defined (but an interval could be defined with an-

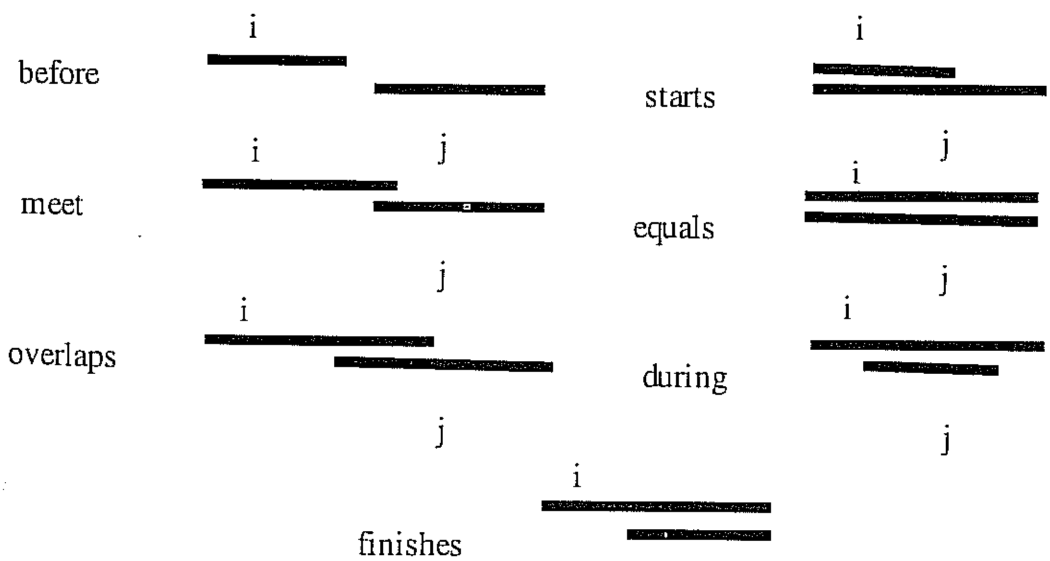

Figure 3.12. Relations between linear intervals, following Allen and Hayes (1985).

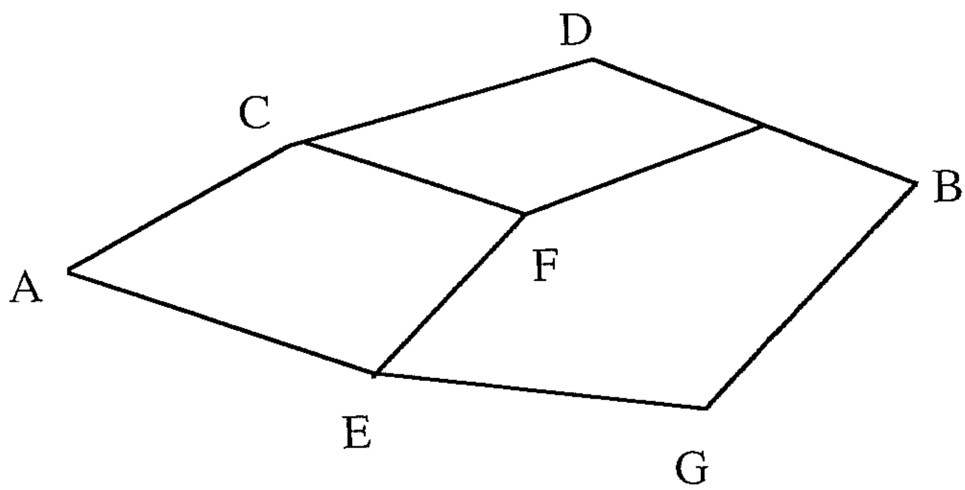

Figure 3.13. Ambiguity of intervals in partial order time.

other definition). This difference influences, for example, how a user interface must be built.

For cyclic time, for any two points an interval is defined and the test for "start before end" is meaningless (Figure 3.14). Given the cyclic structure, the relations "before" and "after" for intervals (Allen and Hayes, 1985) coalesce to a single "before/after," but there are two other relations, which could be called "complement" (A and B complete the cycle) and "overlaps twice" (A and B overlap at their end and at their start). The complement is best defined by stating that start (I) = end (J) and start (J) = end (I).

Discrete time models require decisions if the intervals are open, closed, or semi-closed, meaning if the first or last time units are part of the interval or not. There is not a correct choice, but different circumstances customarily treat intervals differently: a work week from Monday to Friday is including both limits, but "9 to 5" does not.

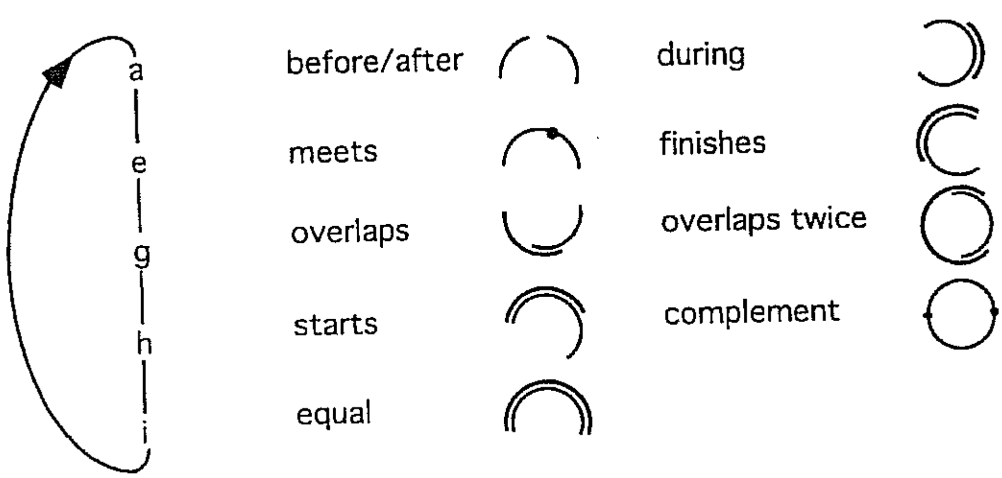

Figure 3.14. Relations between cyclic intervals.

Comparison of length of time between two points

The length of intervals can, at least in some cases, be compared, without a need to have time measures expressed on an interval scale. Two examples: if an interval starts at the same time and one ends before the other, the first one is shorter than the second one; if two intervals meet (i.e., the second starts when the first ends), then the length of the interval from the start of the first one to the end of the second one is longer than any of the two original intervals.

Davis (1990) gives six axioms applicable to intervals between time points in a totally ordered space that can be used to qualitatively compute the length relations of intervals.

Calculation of length of time intervals

How long is it from Monday to Friday? Obviously, a work week is 5 days, though this is not the standard definition of length calculation by subtracting the first point from the last, which would yield Friday – Monday translated to 5 – 1 = 4. Bank interest from Monday to Friday is paid for 3 days only. Again, for different circumstances different rules apply, and so far it is not visible which rules are preferred when.

For the calculation of the length of an interval the length from start to end is considered positive, and the length from end to start negative. This definition gives a length of time between any two points. A particular case provides intervals for cyclic models of time: an interval in a cyclic time model has arbitrary start and end points (there is no order between points in time!). The lengths of the interval are, therefore, to be calculated strictly from start point to end point forward and the result is always positive (for any two points):

length i (s, e) = if $s < e$ then $e - s$ else $(e - s + \text{cycle})$

With this definition the test for "before" and "after" in ordered cyclic time becomes a test if length (s, e) is more or less than half the cycle length.

Combinations of models for time intervals

For each of the models for time points at least one time interval model can be constructed. For every model, a comparison between length of intervals is possible and for intervals over discrete or continuous models with measures on an interval scale, even length calculations can be achieved.

These definitions seem arbitrary—everything goes. The problem is to construct sets of consistent reasoning rules. In most circumstances the length of the interval A–B–C should be the arithmetic sum of the length of the two parts A–B and B–C (this is not true for the bankers' model for payment for interest where A–B–C is 1 day more than A–B plus B–C). Inconsistency can cause logical problems—in principle, if any contradiction is included in a logical system, anything can be logically deduced. The mechanical reasoning processes used in GISs are more lenient, but, nevertheless, the results are difficult to predict.

The second, more difficult, problem is the translation between two models or the combination of models for complex reasoning. A simple example for a translation would be to translate a work interval to an interest payment interval—the work interval is 2 days longer (it figures!).

Conclusions

Time is modeled differently for different applications. People select the model most suitable for the problem at hand. They use a number of models depending on the circumstances. These models most often are closely related to fundamental experiences. Some of these models rely on metaphorical usage of spatial experiences and models, while others are related to fundamental spatio-temporal experiences such as the movement along a path.

These models are different in that they show different behavior (i.e., reasoning using one or the other leads to different conclusions). Models of time are, thus, *types* in the terminology of computer science and the methods of describing types are applicable. Algebraic methods of specification can capture their behavior and point to the differences between them. In this framework, formal methods become applicable. Of particular interest are methods of combining small constituents to build more complex models.

Temporal and spatio-temporal reasoning often seem complex. The models that govern these reasoning processes seem confusingly different in details. Constructing complex models from simple elements is a way to better understand the differences between models. A large class of models can be built from a small number of variants of models for time points. From this follow corresponding models for intervals and the comparison and calculation of length of time. The difficulty in this construction is to combine different alternatives on each step in a consistent form.

This chapter primarily considered the situation where all the information is available and showed how different models of time lead to different reasoning rules. More realistic are systems in which additional information is acquired; this leads to monotonic reasoning systems, where new facts may lead to additional conclusions. In a temporal GIS, changes can be added as new timed facts that do not supersede previous knowledge. But realistic GISs must also include provisions for changing data that prove to be in error when better knowledge becomes available. Models for dealing with error correction and other improvements of existing data are more difficult, because they are non-monotonic.

A direction for future research that is of particular interest to GIS is the interaction between temporal and spatial reasoning, caused by the linkages between spatial and temporal aspects of process behavior. A simple example is the movement of a vehicle in space. Points reached later are also more distant from the start point. Assuming constant speed, the distance from the start is directly proportional to the time passed. This can be seen as an isomorphism, a structure-preserving mapping from operations in time to operations in space.

More interesting are processes that leave a record in space, where spatial properties of the record are linked to temporal aspects. Geological processes of sedimentation relate the order from bottom to top of sediments to the chronological sequence of the sedimentation processes. Again, we observe an order-preserving mapping—the order of the layers in space and the order of the sedimentation processes in time is the same (Flewelling et al., 1992). Similar observations can be made for effects of human activities on landscape (Papagno, 1992). Properties of such spatio-temporal process models that may help to characterize them are *accumulative* (i.e., from the accumulated record the history can be fully determined). Examples would be a geological record of sedimentation (but no erosion steps), where each sedimentation phase has left its imprint and none are missing; *proportional* (i.e., the longer a phase lasted the larger the spatial record); and *order preserving* (i.e., phases leave their traces in the order they occurred).

The opposite includes processes that amalgamate the different inputs and actions to a product so as not to reveal either the order or the components that went into it (a prototypical example would be melting of metals or cooking). Accumulative processes can be linked to lossless algebraic models (i.e., the whole sequence of inputs can be reconstructed from the current state), whereas other processes involve loss.

The hypothesis proposed here is that there exist multiple, non-compatible time models, linked to processes and to the corresponding space models. This chapter has provided some characterization and classification methods for these different time models and has described them as *generalized models of time*.

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