[FC-04-008] Time

Abstract

Time is a fundamental concept in geography and many other disciplines. This article introduces time at three levels. At the philosophical level, the article reviews various notions on the nature of time from early mythology to modern science and reveals the dual nature of reality: external (absolute, physical) and internal (perceived, cognitive). At the analytical level, it introduces the measurement of time, the two frames of temporal reference: calendar time and clock time, and the standard time for use globally. The article continues to discuss time in GIS at the practical level. The GISystem was first created as a "static" computer-based system that stores the present status of a dynamic system. Now, GISystems can track and model the dynamics in geographical phenomena and human-environment interactions. Representations of time in dynamic GISystems adopt three perspectives: discrete time, continuous time and Minkowski's spacetime, and three representations: ordinal, interval, and cyclical. The appropriate perspective and representation depend on the observed temporal patterns, which can be static, oscillating, chaotic, or stochastic. Recent progress in digital technology brings us opportunities and challenges to collect, manage and analyze spatio-temporal data to advance our understanding of dynamical phenomena.

Keywords: Domains of geographic information

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Explanation

1. Definitions

- **Phenomenology**: the study of the development of human consciousness and self-awareness as a preface to or a part of philosophy.
- **Time** (noun):
  - an appointed, fixed, or customary moment or hour for something to happen, begin, or end;
  - the measured or measurable period during which an action, process, or condition exists or continues
  - a nonspatial continuum that is measured in terms of events which succeed one another from past through present to future

- **Space** (in mathematics): a set of mathematical elements and especially of abstractions of all the points on a line, in a plane, or in physical space; especially, a set of mathematical entities with a set of axioms of geometric character.
- **Object** (noun):
    - a thing that forms an element of or constitutes the subject matter of an investigation or science
    - a data structure in object-oriented programming that can contain functions as well as constants, variable, and other data structures
- **System** (noun):
    - a regularly interacting or interdependent group of items forming a unified whole, such as a group of related natural objects or forces (e.g. a river system), and a group of devices or artificial objects or an organization forming a network especially for distributing something or serving a common purpose (e.g. a computer system)
    - an organized set of doctrines, ideas, or principles usually intended to explain the arrangement or working or a systematic whole (e.g. a measurement system)

2. Overview

This topic considers time in three different levels. At the conceptual level, we review various notions on the nature of time from early mythology to modern science. At the analytical level, we discuss the measurement of time and introduces the common and universal frames of temporal references. At the practical level, we cover the representation and use of time in GIS to monitor and model the “dynamics” in geographical phenomena and human-environment interactions. Considering recent advance in digital technology, we consider collection, management, and analysis of spatio-temporal data in GIS and highlights the role and significance of time.

3. The Nature of Time

Time is a fundamental concept in geography and many other disciplines. However, the nature of time has long been an open question. Peuquet (2002) in her Representation of Space and Time has reviewed the notions on the nature of time from early mythology to modern science. In sum, these notions are either phenomenological or mathematical, and they are tightly related to human exploration and interpretation of the universe. This section selects and summarizes some notions to advance our understanding of modern representations of time.

The earliest notions on time is from Greek mythology and everyday life. In Greek myth, time is so important that it is personified as Kronos in Hesiod’s Theogony (a.k.a. the god of time, Father Time) (Hesiod 1999). Human sense and perceive time through generation and power successions and an overall forward-moving revolution from Chaos to Cosmos. In this case, time is embedded in multiple linear processes and referenced by discrete events. Hence, time has a discontinuous and sequential nature. During the same periods, human also develop the cyclical view of time to reflect their observations of the nature and their everyday life. In Hesiod’s Works and Days, time is perceptible at various scales: human activities during days and nights, natural events across the seasons, different stages of life, and the repetition of historical events (Richardson 1877, Tandy and Neale 1996). This cyclical, non-linear notions on time are also evidenced in Indian and East Asian philosophy. For instance, Radhakrishnan and Moore (2014) in the book A Source Book in Indian philosophy discusses the movement of the world and argues that “All the systems accept the view of the great world rhythm. Vast periods of creation, maintenance and dissolution follow each other in endless succession”. Chinese philosophy, and Taoist in particular, is deeply rooted in cyclical view of time and considers the universe as an infinity of nesting time cycles (Schipper and Hsiu-huei 1986). These earliest notions on time are phenomenological, primarily relying on the believes or observations of existences and evolutions of the universe (Peuquet 2002).

During the Presocratic period, there has been an increasing interest in mathematics and physics, including questions surrounding divisibility of space, time and matter. Anaxagoras introduce the infinite divisibility through his conception of unlimited smallness: “For of the small there is no smallest, but always a smaller” (Curd 2015). In contrast, atomism decomposes everything into infinitely small and separate partials (atoms) with space as their container (void). Built upon the atomism, Plato regarded time as the moving image of eternity and then distinguished Being and Becoming (Cornford 2014). In Plato’s view, the world of Becoming is the world we perceive through our senses, and this sensible world is always changing. The world of Being is absolute and never changes, yet it causes the essential nature of things (forms) we apprehend in the world of Becoming. Hence, Plato’s notion indicated the numerical and discrete nature of time: time can be measured through the perceived revolution of the universe (at the moment, now and here).

Aristotle, a student of Plato, developed the famous conception of “space as place”: objects are located in some place; therefore, place coexists together with objects and is a necessary condition for the existence of objects (Markosian 2016). Based on this conception, Aristotle agreed with the continuous views on time and rejected the notion of atoms and void that may lead to gaps and emptiness. In Aristotle’s view, a moment was not an element of discontinuity. Instead, a moment linked the successive temporal durations and preserved the continuity of time. Beside, Aristotle developed a cosmological model that consists a finite space with two levels – the earthly and the celestial (Peuquet, 2002). The time in the Aristotelian model is infinite and, just like the space, is equally present everywhere. Aristotle’s notions on space have been dominated for 2,000 years.

The realization of the Earth as an ellipsoid can date to the 17th century, as described by Newton in his Principia (Newton 1962). Here, Newton’s notions on space and time are similar to Plato’s notions because they both distinguished the absolute and relative space and time. The Principia distinguished “absolute and relative, true and apparent, mathematical and common” time:

- Absolute, true, and mathematical time, of itself and from its own nature always flows equally without relation to anything external and by another name is called duration: relative, apparent, and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time; such as an hour, a day, a month, a year.
- Absolute space, in its own nature, without relation to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies; and which is commonly taken for immovable space; such is the dimension of a

> subterraneous, an aerial, or celestial space, determined by its position in respect of the earth.

Based on the notions on absolute space and time, Newton developed laws of motion that connect space, time and bodies (objects) and described the motion of bodies (Friedman 2014). Although the laws of motion were originated from Physics, they have much broader impacts: they lead to a move from the cognitively centered view that relies merely on the abstraction of observations to the positivistic view that relies on the objective descriptions through the process of measurement and mathematical formulation.

During 1880s and 1890s, several experiments on light (an electromagnetic phenomenon) showed that light always traveled with the same speed, regardless how fast the light source moves. These experiments conflicted with Newton's laws of motion and were the basis for Einstein's theory of relativity. In Einstein's view, space and time are relative, and they depend on the motion of the observer who measures them. Light is more fundamental than space and time: the speed of light in a vacuum is the same for all observers, regardless of the observer's motion or of the motion of the light source. Consequently, space and time are no longer absolute and independent: "matter tells spacetime how to curve, and curved spacetime tells matter how to move". (Friedman 2014)

In 1908, Minkowski proposed the concept of four-dimensional spacetime that integrated space and time (Stein 1968). In this topic, the terms spacetime, space-time, and spatio-temporal indicate the integration of space and time, terms used here based on existing literatures. In the spacetime, as a flash of light passes from the past to the future, the "present" is defined. All physical reality must be contained within "future" and "past" spacetime, and the "outside" is inaccessible because bodies must travel faster than light to reach it (which is impossible). A moving trajectory of an observer results in a "worldline" inside the future and past spacetime. The spacetime later becomes an essential foundation to Einstein's theory of general relativity discussed above.

3. Measurements of Time

The acquisition and arrangement of knowledge are inevitably relied on our sensory experiences. Despite the debates on absolute or relative, and continuous or discrete nature of space and time, space and time lay the innate and intuitive basis for us to sense and perceive the world. In other words, cognitive interpretations of space and time are built upon the awareness of their existence. This view was first proposed by Kant in his principle of "subjective a prior" (Kant 1955) and has been extensively studied later in the field of cognitive psychology. It agreed with the dual nature of reality: both external (absolute, physical) and internal (perceived, interpreted, cognitive), and considered space and time as the context for us to perceive, understand and represent the reality.

This section considers time as an essential part of reference frames for us to observe and measure the reality. First, this section introduces calendar time and clock time as the two most commonly used frames in accord with two distinct ways we observe and measure the external physical time. Then, this section introduces the standard time as the universal reference for used internationally.

3.1 Calendar Time and Clock Time

The calendar is a measurement system that organizes intervals of time at various levels and give them names for social, religious, commercial and administrative purposes. Calendars are based on the perceived motions of the Moon and the Sun in relate to the Earth, the rotation of the Earth, and the interpreted cyclitic view of time. The basic measurement units include:

- **Date/Day**: the basic unit that corresponds to the alternation of day and night.
- **Month**: the observed cycle of lunar phases.
- **Year**: the perceived seasonal changes in weather, ecology and daylight durations
- **Week**: an interval of exact seven consecutive days, each is a weekday that is named after the classical planets or gods of a pantheon.

The clock is a physical mechanism that measure duration and elapsed time that are shorter than natural units in calendars. For instance, a sundial uses a gnomon to cast a shadow of sunlight on a set of markings to indicate local time (in hours) within one day. The water clock, the hourglass and the pendulum clock are all driven by the gravity of the Earth and used to indicate hours in a day and even minutes in an hour. The most accurate device nowadays are atomic clocks that use the frequency of electronic transitions in certain atoms as the basis to define the second (within a minute). The International System of Units (SI) defines second based on the 133Cs atom and has used it as the basic unit of time since 1967. Beyond second, the smallest time interval that can be measured directly, as of Nov. 2016, is on the order of 850 zeptoseconds (850×10−21 seconds).

3.2 Standard Time

Since the industrial evolution, a universal understanding and agreement on the measurement of time has become increasingly necessary. In 1847, Greenwich Mean Time (GMT) was developed as the first standard time for use by the British railways, navy, and shipping industry. GMT was defined by the mean solar time at the Royal Observatory, Greenwich in the UK. Using GMT as the foundation, 41 nations officially agreed to a universal time at the 1884 International Meridian Conference. Meanwhile, the Greenwich meridian was commonly used as the Prime Meridian.

In 1963, the Coordinated Universal Time was first officially adopted as the standard time, and its abbreviation UTC was first officially adopted in 1967. Since then, the system has been adjusted several times. The current version of UTC is based on Temps Atomique International (TAI) and adjusted by leap seconds considering that Earth’s rotation is slowing. Here, days are identified by the Gregorian calendar, seconds are SI seconds, and minutes and hours are adjusted to reflect the irregular day lengths. Time zones are regions with the same standard time used locally for legal, commercial and social purposes. Hence, these time zones tend to follow the country boundaries and the subdivisions of each country. The time zones are described as positive or negative offsets from UTC in whole hours (e.g. UTC+08:00, UTC-06:00) and may have some other conventional names (e.g. Beijing Time, Chicago Time). Some of the time zones located at higher latitudes also adopt Daylight Saving Time (DST).

The Global Positioning System (GPS) time is implemented by atomic clocks that started timing at midnight on Jan. 6th, 1980 (UTC00:00). The GPS time is transmitted as the number of weeks spent since the start time and the number of seconds since the beginning of the current week. The GPS time is always 19 seconds behind the TAI time; and conversions between the GPS time and the UTC time need to account for the leap seconds (TAI=GPS+19s=UTC+LS).

The discussions in this section reveal that (1) the temporal frames of reference are either cyclical or linear; (2) some universal measurement units of time include second, minute, hour, day, week (weekdays), month, and year, (3) the smallest time interval that can be measured directly exists and determined the precision of measurement, and (4) the time intervals have various temporal relationships to describe their relative "locations" in time (e.g. the TAI time is 19 seconds after the GPS time). The next section will adopt these views and discuss how time is conceptualized, represented and used in Geographic Information Systems (GISystems) and GIScience.

4. Time in GIScience

The first GISystem was known as the Canada Geographic Information System (CGIS) developed by Dr. Roger Tomlinson in 1968 to collect, store, analyze and distribute the data collected for the Canada Land Inventory. The information in the system may be added to or modified over time, but these changes may not be necessarily maintained. Therefore, the CGIS is "static" per se and focuses only on the world in the Present (Here and Now). However, the world is ever-changing, and our knowledge of the world is evolving. This requires us to choose appropriate perspective and representation of time in order to investigate the dynamics of geographical phenomena and human-environment interactions. This section introduces the three perspectives on time, the three representations of time, and the four types of temporal patterns in the dynamical GISystems. The section also discusses how the observed temporal patterns determine the appropriate perspective and representation of time. Please note that the perspectives and representations of time are built upon conceptual notions and analytical measurements on time discussed earlier.

4.1 Discrete Time, Continuous Time, and Spacetime

The dynamics of geographical phenomena are results from changes in locations, entities, or both. A change is considered as an event if it is perceivable, measurable and significant for the field of study (e.g. a change in the ownership of a land parcel). The representation of changes and events relies on different views on time and its relationship to space as well as the practical needs. The three main views on time (conceptually) are discrete time, continuous time and spacetime.

As discussed in Section 3, time was treated as a dimension independent from space and viewed as discrete or continuous before Minkowski. In the discrete view, we observe a phenomenon and its state at given points in time and then compare the observed states at different time (points) to understand the process. In the continuous view, we observe and compare a phenomenon and its state at the start and end of each period of time, which is usually associated with the lifetime of an entity/event. For instance,

- To study individuals' movement in urban environment, we can track their locations at certain frequency (discrete view) or record their activity locations and the corresponding durations at each location (continuous view).

- To study changes in land ownership, we can record every change in location or ownership of each land parcel and the corresponding time stamp of such change (discrete view); or we can archive the locations and ownership status of each land parcel and the corresponding duration of such status (continuous view).

The third view on time adopts Minkowski's four-dimensional spacetime. In the spacetime view, we observe changes in space and time simultaneously instead of changes over time. For instance,

- The traffic data cube (Shekhar et al. 2001) organizes traffic volumes as a multi-dimensional cube that integrates space and time. Each cell in the cube stores the total number of vehicles within a given spatial scale and a certain time interval. Slicing the cube by time enables us to investigate changes in spatial distribution of vehicles; slicing the cube by spatial unit enables us to investigate changes in traffic volume at spatial locations.
- Time geography (Hägerstrand 1970) represents an individual's movement in spacetime as a space-time path. Figure 1 shows space-time paths of two adults and one children in a family during a weekday (modified from Ellegård and Lenntorp 1993, p25). Each family member has his/her own space-time path that describes his/her activities and trips in spacetime. The interactions between family members create bundles, either at an activity location or along a trip. Given the capability, coupling and authority constraints of an individual, a space-time prism (STP) delineates all "feasible" space-time paths. Since a STP contains all location and time that are accessible to the individual, it can be used to measure individuals' accessibility to resources and opportunities available at locations during certain periods (Miller 2005).
- For mobility in urban areas, individuals' movements are usually restricted by transportation networks. Network-time prisms (NTPs) are defined to capture additional constraints imposed by the networks such as speed limits and one-way restrictions (Kuijpers and Othman 2009). Recent studies have attempted to improve the analytical and computational representation of STPs and NTPs to refine the prism-based accessibility measures (e.g. Liao 2019, Kuijpers et al. 2017, Miller 2017).

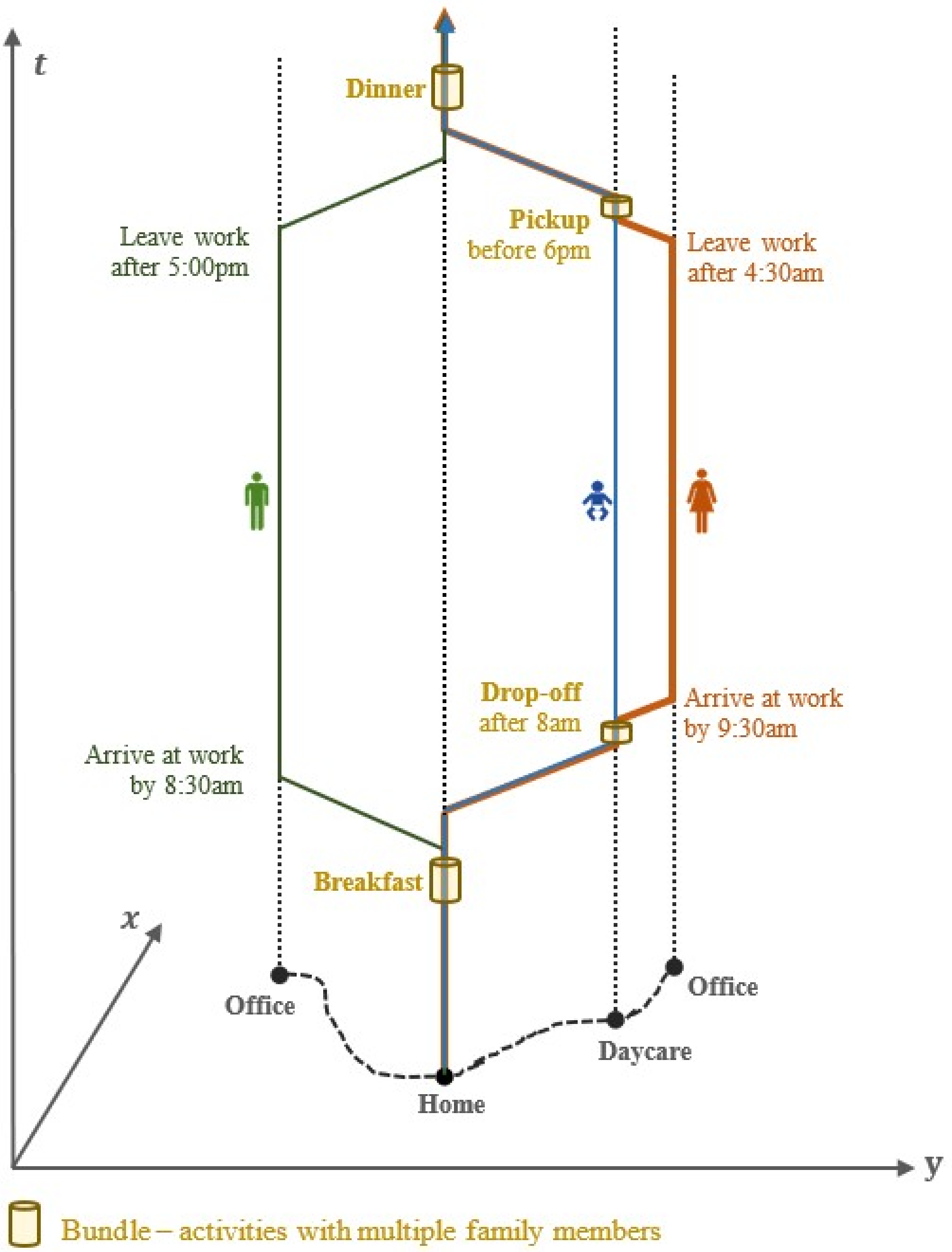

Figure 1. Space-time paths with constraints of three family members in a weekday. Source: author; after Ellegård and Lenntorp (1993).

4.2 Ordinal, Interval, and Cyclical Time

While observing dynamic phenomena, we can adopt different representations of time. The most common three representations are ordinal time, interval time and cyclical time. They reflect how we perceive time and temporal relationships.

- **Ordinal Time**: metaphorical representation of events and their sequences. For instance, the expression "picking up children after work" describes the temporal relationship between two events using the word "after". This is in accord with the

earliest form of time in our cognition (e.g. Hesiod’s Works and Days discussed in Section 3).
- **Interval Time**: measurement of events’ durations on an interval scale. For instance, the UTC time is an interval time using SI second as the basic measurement unit (see Section 3.2). The expression “sleep from 9:00 pm to 6:00 am the next day” describes the duration of the status “sleep” using the civil time. Figure 2 shows main categories of temporal relationship between the durations of two events X and Y (Allen 1984).

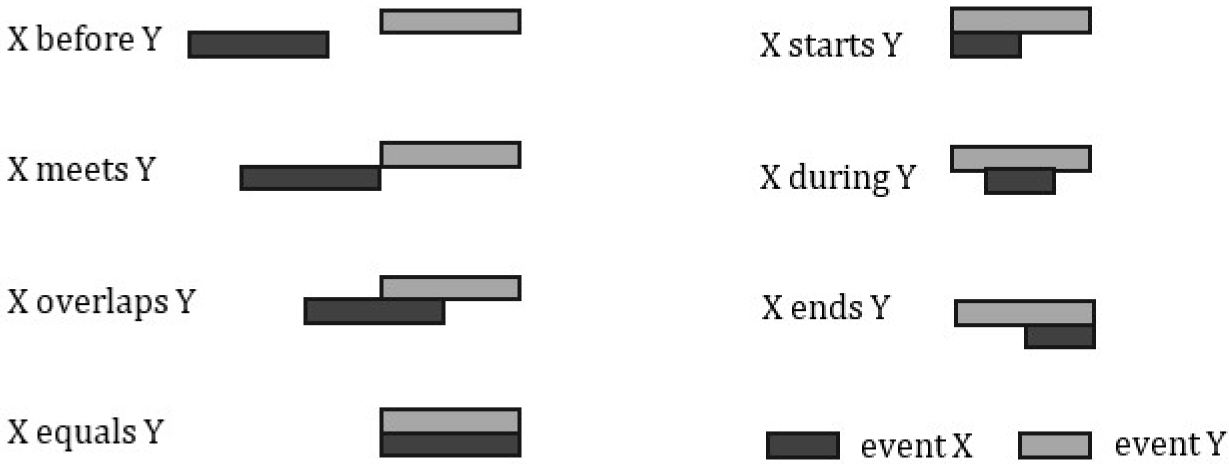

Figure 2. Temporal relationships between time intervals. Source: author, after Allen (1984).

- **Cyclical Time:** representation of time for cyclic process. Months and seasons, weekdays and hours are based on astronomical cyclic processes. The annual cycle of bird migration and the daily rise and fall of the ocean (tides) can also be represented by cyclical time with repeating stages (event). And each of these stages can be further represented by a time interval.

4.3 Static, Oscillating, Chaotic, and Stochastic Temporal Patterns

The world is a dynamic system that is changing and evolving, and so are the natural systems and our interactions with them. Behaviors of these dynamic systems lead to the temporal patterns we observe and affect how we conceptualize and represent time. The behaviors of dynamic system can be categorized into four classes (Wolfram 1984), and this section discusses the appropriate views and representations of time for each class.

- Static: evolution leads to a stable, homogeneous state; any randomness in the initial pattern disappears eventually. In this case, we observe and record the point in time when the system becomes stable and when other systems “shake” this stable state. An ecosystem (in a spatial region) in equilibrium is an example static system, which is built upon the balance of species at three levels of the food web and may be affected by other ecosystems and natural systems.
- Oscillating: evolution leads to a set of separated simple stable or periodic structures. In this case, we observe and recorded the sequences (ordinal time) and possibly the durations (time intervals) of these separated structures. The astronomical cyclic

processes, the annual and/or daily cycle of animal migration, and the opening hours of public services within a week are example oscillating behaviors.
- Chaotic: evolution leads to a chaotic pattern that is deterministic yet sensitive to the initial states of the system. In this case, we usually observe the system state at a given frequency (discrete time) or the duration and location of each event (continuous time), and then model the observed changes and their temporal patterns to predict system state in the "near future". A most typical example is weather forecasting in meteorology, which predicts the condition of the atmosphere at a given location by collecting data about its "current" condition and interpret the temporal patterns of the collected conditions. Due to the chaotic nature of the system, it is almost unlikely to get a "true accurate" prediction.
- Stochastic: evolution leads to complex localized structures, sometimes long-lived that can only be models statistically. Similar to chaotic behaviors, we observe stochastic behaviors at given points in time or during certain time intervals. But due to the stochastic nature, we can only model the system behavior using a collection of random variables indexed by time. The erosion-sedimentation processes, the changes in land use/land cover (LULC), and the human residential mobility and daily commuting in urban environments are typical examples that are modeled as stochastic processes. Some stochastic models use discrete representations of time (e.g. random walk, Markov chain, sequential alignment), while others adopt continuous time (e.g. Brownian motion, semi-Markov process, long short-term memory network (LSTM)).

4.4 Spatio-Temporal Data Collection, Management, and Analysis

Advances in digital technology allow us to collect massive spatio-temporal data, derive useful information and advance our knowledge about the "dynamics" in geographical phenomena and human-environment interactions. This section focuses on the temporal aspect and discusses the collection, management, and analysis of spatio-temporal data.

- **Data Collection**: As discussed in section 3, the most accurate device nowadays are atomic clocks that use second as the basic measurement unit for time, and the smallest time interval that can be measured directly is on the order of 850 zeptoseconds as of 2016. However, data collection usually applies larger time intervals as the temporal resolution. For remote sensing systems, the temporal resolution refers to the length (time interval) for a satellite to complete one entire orbit cycle (a.k.a. the revisit period) and collect data for the same "place" (the area covered by a satellite image). Each remote sensing system has its own temporal resolution(s). For instance, Moderate Resolution Imaging Sensor (MODIS) has a coarse resolution of 1 day to 2 days; Land Satellite (Landsat) have a medium resolution of 16 days; and Quickbird has a high resolution of 1 day to 3 days.

Beside satellite images, location-aware devices such as smartphone can collect geographical locations of mobile objects at discrete time stamps. The temporal resolution of data collected by these devices is determined by the navigation satellite system that sends signals (e.g. GPS, Galileo, BeiDou). For instance, navigation messages of the Global Positioning System (GPS) have a resolution of 1.5 seconds. The devices (receivers) also have their own frequencies to receive or transmit signals. For instance, Automatic Vehicle Location (AVL) systems usually track vehicles locations every 30 seconds to 2 minutes to support the management of transit fleet and the evaluation of transit performance (Tilocca et al. 2016).

Other types of spatio-temporal data such as census and land-use survey usually have much lower temporal resolution, which are determined by how frequent the data is collected and published by the corresponding agencies. For instance, the U.S. Constitution requires that a census of the population should be taken every 10 years, while the American Community Survey (ACS) provides 1-year, 3-year and 5-year estimates within the 10 years. For human mobility at higher temporal resolutions (e.g. hourly, daily), recent studies have applied data collected by mobile devices and location-based services (e.g. Gonzalez et al. 2008, Hasan et al. 2013, Greenblatt and Shaheen 2015).

- **Data Management**: Spatio-temporal databases have been developed to integrate spatial and temporal data models. The spatio-temporal data models define the data types, relationships, operations and rules that allow us to maintain the integrity of the data and query and analyze the collected data (Pelekis et al. 2004). The three types of times in spatio-temporal databases are valid-time (when an even occurs/observed), transaction-time (when an event is recorded), and user-time (when an additional event is registered by users) (Snodgrass and Ahn 1985). And the three major forms of temporal queries are simple temporal query (at a given time), temporal range query (during a time interval), and temporal relationship query (proximity or topology) (Yuan and McIntosh 2002). Siabato et al. (2018) reviews spatio-temporal models in GIS and summarizes the 18 major trends in modeling dynamics in geographic phenomena (Table 1, full version in Table E of Siabato et al. 2018). These approaches recognize the five dimensions (levels) of modeling: processes, events, actions, movements and dynamic objects (Pelekis et al. 2004, Worboys 2005) and reflect the role of time while we sense and perceive the external reality (as discussed in Section 3).

Table 1. Spatio-temporal Modeling Trends (Siabato et al. 2018)

Modeling Approaches	Modeling Approaches	Modeling Approaches
Snapshot method	Semantic-based	Moving Objects
Time-stamping	Event-based	Graphs-based
Base state amendment vectors	Process-based	Lifespan-based
Space-time composite model	Ontology-based	Agents-based
Domain-based modeling	Feature-based (entity-based)	Kinematics
Object-oriented	Identify-based	Ontological foundations
	Conceptual modeling extensions	

- **Data Analysis**: Driven by the increasing availability of spatio-temporal data, many methods and tools have been developed to analyze the data, extract useful information, and discover knowledge. The three basic approaches are visual exploration, statistical analysis/modeling and data mining/machine learning. Andrienko et al (2003) focus on the temporal dimension and proposes a catalogue of visualization techniques and tools to support exploratory analysis of spatio-temporal data. The data is organized into “when” and “what + where” components; the two search levels are elementary and general levels; and the two cognitive operations are identification and comparison. Different combinations of these elements can support certain exploratory tasks. For instance, elementary “when” and elementary “what + where” describe characteristics of an object/location at a point in time, while general “when” and elementary “what + where” describe the dynamics of characteristics of this object/location over time. A visualization tool may focus on one or several exploratory tasks and have the corresponding combinations of these essential elements. Recent visualization tools (frameworks) follow this catalogue and are usually created for a specific practical field (e.g. VAUD for urban data by Chen, et al. 2017), certain types of data (PerSE for calendar data by Swedberg and Peuquet 2017), or certain tasks (e.g. Viola for anomaly detection by Cao et al. 2017).

Visual exploratory analysis can provide some preliminary knowledge about dynamic patterns and support further quantitative analysis and modeling of the temporal patterns. Statistics and data mining are two common approaches. Statistics focus on hypothesis test and goodness of fit from mathematical perspective, while machine learning focuses on algorithms and models from computational perspective. Cressie and Wikle (2015) introduce existing spatio-temporal statistical methods in their book Statistics for Spatio-Temporal Data. Some of these methods are exploratory such as spatio-temporal LISA (Local Indicator of Spatial Association). Some methods examine the spatio-temporal covariance (e.g. Taylor’s frozen turbulence hypothesis that relates temporal to spatial fluctuations in the turbulent flows). And some methods rely on the hierarchical modeling of time series, which are known as hierarchical dynamical spatio-temporal models (DSTM) (e.g. reduced-dimension DSTM for long-lead forecasting of tropical pacific sea surface temperatures).

Compared to statistical analysis and modeling, data mining focuses on extracting interesting patterns and associations instead of investigating the correlation/causality, and contains three phases: training, test and validation (Fayyad et al. 1996). For data with spatial and temporal components, the multi-dimensional nature of the data, the underlying spatial dependencies, and the potential spatio-temporal correlations bring new challenges for spatio-temporal data mining (Shekhar et al. 2010). Studies have developed many data mining methods to advance our understanding of dynamics in physical environments (see, e.g., review by Lausch et al 2015) and human mobility (see, e.g., review by Lin and Hsu 2014). And many programming languages also include packages for data mining such as Scikit-learn in Python (Pedregosa et al. 2011), Weka for Java (Hall et al. 2009), and CLARANS in R (Ng et al. 2002).

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