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ORIGINAL ARTICLE

Time geography in a hybrid physical–virtual world

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Abstract

Time geography was conceptualized in the 1960s when the technology was very different from what we have today. Conventional time-geographic concepts therefore were developed with a focus on human activities and interactions in physical space. We now live in a smart, connected, and dynamic world with human activities and interactions increasingly taking place in virtual space enabled by modern information and communications technology. Coupled with recent advances in sensing and mobile technologies, it is now feasible to collect human dynamics data in both physical and virtual spaces with unprecedented spatial and temporal details in the so-called Big Data era. The Big Data era brings both opportunities and challenges to time geography. While the unprecedented data collected in the Big Data era can serve as useful data sources to time-geographic research, we also notice that some classical concepts in time geography are insufficient to properly handle human dynamics in today's hybrid physical–virtual world in many cases. This paper first discusses the evolving human dynamics enabled by technological advances to illustrate different types of hybrid physical–virtual space performed through internet applications, digital twins, and augmented reality/virtual reality/metaverse. We then review the classical time-geographic concepts of constraints, space–time path, space–time prism, bundle, project/situation, and diorama in a hybrid physical–virtual world to discuss potential extensions of some classical time-geographic concepts to bolster human dynamics research in today's hybrid physical–virtual world.

Keywords Time geography · Human dynamics · Physical space · Virtual space · Hybrid physical–virtual world

JEL Classification Y80

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1 Introduction

Time geography, which provides a useful framework of studying human activities in a space–time context, is the brainchild of Torsten Hägerstrand (1970). Time geography has been criticized to place too much emphasis on the physical world and treat an individual as an object rather than a living person who can think, feel, experience, and plan. Hägerstrand (1989, p. 2) addresses these critics by stating that "I agree, my way of thinking is admittedly reductionistic in a specific sense. … But one cannot talk about anything without simplifying, that is reducing reality to something smaller than it is. I want to find the bare skeleton of what one could call natural situations." Lenntorp (1999, p. 157) further argues that "we (and Hägerstrand) had tried to establish a world-view, an approach, where time and space would not be looked upon as a composition of the two dimensions but as a frame for analysis."

More than fifty years after the publication of Hägerstrand's seminal paper of "What about people in regional science?" in 1970, our world today is very different from the time when Hägerstrand developed the concepts of time geography. Modern technologies have significantly changed the ways we carry out our activities and interactions, especially in the last couple of decades (Janelle and Hodge 2000; Mokhtarian 2003; Shaw and Yu 2009). Information and communications technology (ICT) such as the internet has enabled us to perform various activities and interactions online like online shopping and online social activities. Mobile technology such as mobile phones has relaxed spatial constraints of staying connected at fixed locations. These changes have created a hybrid physical–virtual world that we now carry out our activities and interactions not only in physical space but also in virtual space. Furthermore, what we do in virtual space often is not independent from what we do in physical space, and vice versa. For example, online orders trigger delivery trips in physical space that generate very different spatiotemporal trip patterns from personal shopping trips. It is critical to revisit the classical concepts in time geography with respect to the new human dynamics in today's hybrid physical–virtual world.

In addition, location-aware technology such as the Global Positioning System (GPS) has made it feasible to track individual locations at unprecedented spatial and temporal resolution levels (Miller 2010). Cookies used in many internet applications collect our activities and interactions in virtual space with unprecedented details, which in turn are used to influence our behaviors in both physical and virtual worlds. Sensing technologies such as the video cameras installed in many public and private spaces and sensors in our automobiles, watches, and phones also constantly monitor us. These technologies together have created the so-called *Big Data* era that collects all kinds of data in both physical and virtual spaces (Kitchin 2014). While the unprecedented data collected in the Big Data era can serve as useful data sources for time-geographic research, they also raise many concerns such as privacy and ethic issues. This paper is not intended to discuss the pros and cons of the Big Data era. Instead, the focus of this paper is to revisit the classical time-geographic concepts and discuss how these concepts should evolve to better serve our needs in today's hybrid physical–virtual world.

The remaining sections of this paper are organized as follows. The next section discusses the major changes from Hägerstrand's time to today's hybrid physical–virtual world from a technological perspective. It is followed by a section of reviewing some key classical time-geographic concepts and discussing how they can be extended to handle human dynamics in a hybrid physical–virtual world. As a shorthand, this paper uses human dynamics to refer to all human activities and interactions in both physical and virtual spaces. This paper ends with concluding remarks and some future research ideas.

2 From Hägerstrand's time to a hybrid physical–virtual world

Time geography is based on a premise that human activities are conditioned by various types of constraints. Technology has played a critical role in human history to reshape the constraints that condition human activities, which in turn often generate new patterns of human dynamics. It therefore is useful to look into how the world today is different from the time when Hägerstrand developed the framework and concepts of time geography.

2.1 Hägerstrand's time

Torsten Hägerstrand (1916–2004) lived in a schoolhouse of a small town in southern Sweden when he was a child (Hägerstrand 1982; Ellegård 2019a, b). His father was a schoolmaster and schoolchildren came from the surrounding areas. Hägerstrand's childhood experienced various daily rhythms in his surrounding environment. He includes his childhood experiences as an example to illustrate some key time-geographic concepts in his article of "Diorama, Path and Project" (Hägerstrand 1982, pp. 326–327) which states:

> "I will now … try to call forth a diorama of which I once was an insider during my first formative years. … The locality was a valley with wooded slopes. At the bottom of it ran three parallel lines of communication. In the middle a small river ... On one side twisted a road ... On the other side the truck line between Stockholm and Malmo … A *Bruk*, that is a foundry and a machine-shop, picked up its energy from one of the bigger waterfalls. Two and a half kilometres to the south-west, a farmers' village spread out on a low drumlin. Both settlements had about 150 habitants."

Hägerstrand (1982) discusses the concepts of diorama, path, project, and pace-setters to describe the rhythms organized in a hierarchical order that are embedded in household, workplace, settlement, and parish by day, week and year. This example indicates the influence of Hägerstrand's childhood experiences on the development of time-geographic concepts.

Hägerstrand completed his dissertation of *Innovation Diffusion as a Spatial Process* in 1953 which became an influential contribution. He switched his research focus to time geography mainly due to a major grant funded by the National Bank of Sweden in the mid-1960s when Hägerstrand formed a Research Group in Human Geographic Process and System Analysis at Lund University that has been known as the time-geography research group (Ellegård 2019a). This research group then was funded by the Swedish government to assist urban and regional planning in the 1970s. This line of research supported Hägerstrand to develop various time-geographic concepts and a notation system for time geography. It is worth noting that the concepts of time geography were developed mainly in the 1960s and 1970s when the world and the technology were very different from what we have today.

2.2 Time–space convergence and human extensibility

As technologies advance over time, human dynamics evolves with the changing technologies. For example, invention of telegraph and telephone made long-distance communications in real-time or near-real-time feasible. Introduction of railroads, automobiles, and airplanes significantly expanded the spatial extent that humans could reach within a given time period. Janelle (1973, p. 8) suggests that "Time–space convergence and human extensibility are related concepts which help characterize the impacts of transport and communication innovations." Time–space convergence reflects how the advances in transportation technology have helped reduce travel time (i.e., relative distance) between two places even though the absolute distance remains constant, which creates a "shrinking world" (Janelle 1968, 1969). Janelle (1973, p. 11) further indicates that "Human extensibility is conceptually the reciprocal of time–space convergence. Instead of focusing on the improved abilities for movement over greater distances it may be more appropriate to consider the expansion of opportunities for human interaction." The concept of human extensibility is closely related to time-geographic concepts such as space–time prism that delimits the maximum possible spatial extent an individual can reach within a given time period.

Kirch (1995) argues that, although shrinking world is often considered as the product of technological advances in telecommunications and transportation, such innovations serve as the means through which capital frees itself from the constraints of space. In other words, the changes associated with time–space convergence are closely related to social production and reproduction. We therefore should consider humans as part of the process of shrinking world in addition to technology. In today's world enabled by modern technologies, mobile phones provide us with new freedom in space since we are no longer constrained by the fixed locations of landline phones. Internet allows us to purchase items while stores are closed that offers us with new freedom in time. One interesting research question is how the new freedoms in space and in time modify human extensibility in a hybrid physical–virtual world. These changes in turn suggest a need of revisiting the classical time-geographic concepts to examine how they can be extended to support human dynamics research in an era of new time–space convergence and new human extensibility.

2.3 A hybrid physical–virtual world

Batty (1997, p. 351) indicates that "What is crystal clear however is that the future subject matter and method of geography will be very different as place and space and time itself become virtual in an age where the digital permeates all human activity." Virtual geography suggested by Michael Batty twenty-five years ago is very much a reality today. Taylor (1997) also discusses the emerging geographies of virtual worlds. Major technological advances such as the internet and mobile phones in the last few decades have introduced significant changes to human dynamics. Internet has facilitated various virtual activities such as email, e-commerce, online social networks, teleworking, e-education that have become part of our daily lives today, especially during the COVID-19 pandemic. Mobile phones further enable us to carry out virtual activities almost anywhere and anytime as far as we are connected to the network. In the meantime, most human activities and interactions remain in physical space and some of them are unlikely to become virtual per se such as eating a meal. More importantly, we no longer can treat what happen in physical space and what occur in virtual space as two independent systems since they increasingly influence and are influenced by each other (Mokhtarian 2003; Shaw and Yu 2009). For example, teleworking changes the traffic patterns in physical space. From the perspective of time geography, such changes require adjustments to the classical time-geographic concepts such as space–time path, space–time prism, bundle, etc.

Batty and Miller (2000) discuss the representation and visualization of physical, virtual, and information space. They suggest that "The new information spaces that are emerging are rooted in both the material and ethereal worlds of commodities and flows, and cannot be understood without each other. (Batty and Miller 2000, p. 133)" Couclelis (2009) argues that information and communications technology has loosened the traditionally close links between activity, place, and time. She suggests a new framework of modeling space–time behaviors in a multidimensional space using methods such as the parallel coordinates plot. While most people can understand what physical space means, virtual space is an ambiguous term to many people. Different terms such as virtual space, cyberspace, information space, virtual environment, virtual reality, and virtual world have been used in the literature. For example, Saunders et al. (2011, p. 1079) suggest that "Virtual worlds (VWs) are digital environments in which individuals, groups, and even organizations interact in virtual, nonphysical spaces." Oxford Reference (2022) defines virtual space as "1. A perceived representational space created by computer graphics software that employs a Cartesian coordinate system consisting of X, Y, and Z axes: see virtual reality; virtual world. 2. A metaphorical way of conceptualizing the interactions that 'take place' over a computer network: see cyberspace." Although most definitions of virtual space or virtual world are associated with digital environments enabled by modern ICT, virtual space is broadly defined in this paper that could include online activities and interactions enabled by ICT as well as power relations, social relations, among other relationships in a non-digital environment. For example, our colleagues or research collaborators are examples of a virtual network that can exist in a non-digital environment. Bergmann and Lally (2021, p. 29) further suggest geographic imagination systems (gis) and argue that "Even if many of the space described in human geography prove impossible to map in some strict sense, this does not mean that they cannot be interpreted and engaged visually." For example, international diplomatic relationships could be represented as a network in relational space in support of studies that do not need to include locations in physical space. A virtual space also could be an imagined space that does not exist in the real world.

Regardless a virtual space exists in a digital environment or in a non-digital environment, we can handle it under a framework that includes not only the concept of absolute space but also the concepts of relative space, relational space, and mental space (Shaw and Sui 2020). Since the changing human dynamics today is mainly related to virtual activities in digital environments, this paper selects internet applications, digital twins, and augmented reality/virtual reality/metaverse as examples to shed light on the challenges to time geography under different scenarios of hybrid physical–virtual space.

2.3.1 Internet applications

We now carry out many activities and interactions in virtual space via a wide range of internet applications. We connect with people via email and online social networks. We use software such as Zoom to conduct online meetings or online teaching. These online activities connect us with physical entities (e.g., other people in a Zoom meeting) and/or virtual entities (e.g., finding information at google.com) via the internet. For most of these virtual activities and interactions, our locations in physical space often are less relevant than who/what we are connected with. In other words, the focus is mainly on the connections in a relational space while the locations in absolute space play a secondary role when we study these virtual activities and interactions (Shaw and Sui 2020).

These connections in virtual space are good examples of human extensibility in a hybrid physical–virtual world (Janelle 1973; Yu and Shaw 2008; Shaw and Yu 2009). If both ends of a virtual connection are physical entities, we can associate this virtual connection with the locations of the physical entities in absolute space. If either end or both ends of a connection is a virtual entity (e.g., Google), we encounter a challenge of representing the location of the virtual entity in physical space using the classical notation system of time geography. For example, where is Google in physical space? It could be represented by the street address or the (x,y) coordinates of the Google headquarters in Mountain View, California. However, most virtual activities with Google have nothing to do with the Google headquarters. Instead, we interact with a Google website (e.g., www.google.com in the USA or www.google.co.uk in the UK). In this case, the physical location of a Google website is less relevant to such virtual activities. Instead, the unique identity (ID) of these virtual entities (e.g., URL) is critical to establish these connections in virtual space, which can be represented as the links connecting the nodes in a network like a social network graph. This deviates from the classical time-geographic notation system that requires every activity be tied to a specific location in absolute space. In other words, time geography in a hybrid physical–virtual world should be able to properly manage relations in addition to locations. Since physical entities also can be assigned with a unique ID (e.g., social security number of each person, international mobile equipment identity (IMEI) of each mobile phone), we can keep track of both physical entities and virtual entities in a relational space represented as a network. We can further integrate the connections in a relational space with the physical locations in absolute space via their unique IDs. One important characteristic of this type of internet applications is that all physical entities (e.g., a person) and virtual entities (e.g., Google) exist in the real world.

2.3.2 Digital twin

Jones et al. (2020, p. 36) conduct a literature review of digital twin and attribute the origin of digital twin to Michael Grieves, who describes "the Digital Twin as consisting of three components, a physical product, a virtual representation of that product, and the bi-directional data connections that feed data from the physical to the virtual representation, and information and processes from the virtual representation to the physical." IBM[1], on the other hand, indicates that "A digital twin is a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making." and "A digital twin is a virtual model designed to accurately reflect a physical object." Since digital twin is a virtual model of what exist in physical space, constraints and other classical time-geographic concepts remain valid to entities in digital twins as they share the same locations and characteristics in physical space. However, one major difference between a digital twin and its counterpart in real world is that we can apply simulation models in a digital twin to investigate possible outcomes of various processes that have not occurred in the real world yet. In other words, digital twins allow us to examine different scenarios by varying a person's goal and/or situations to study potential human activity patterns while following the basic principles observed in the physical world.

2.3.3 Augmented reality (AR), virtual reality (VR), and metaverse

Augmented reality (AR) refers to an interactive digital platform based on the objects in a real-world environment that is enhanced by additional computer-generated information on top of the real-world objects. This is an example of integrating physical space with virtual space such as the Pokémon Go game. Users can experience an interactive environment with virtual information that could influence human behaviors in physical space. Similarly, different human behaviors in physical space also can lead to different virtual information provided in an AR environment. Augmented reality therefor could change the ways a person understands and interacts with the surrounding environment that are related to the time-geographic concepts such as situation and diorama.

Virtual reality (VR), on the other hand, is an immersive and interactive digital environment to provide a simulated experience. Virtual space created by VR can emulate physical space in the real world that is similar to a digital twin. VR also can create imagined spaces that are very different from the real world. Bos (2021, p.2) argues that "Whilst VR technologies offer much to the teaching and the dissemination of geographical research, such an emphasis overlooks the broader implications

[1] https://www.ibm.com/topics/what-is-a-digital-twin.

of VR concerning the mediation of space and time, the representations of people and places, and embodiment in virtual environments." When people work in a VR environment, they are at a particular location in physical space (e.g., home) while they also could experience very different locations in virtual space (e.g., virtual office). This deviates from a basic principle of time geography that a person can be at only one location at a given time point.

Metaverse has received significant attention since Facebook changed its company name to Meta in October 2021. Metaverse, which was coined by Neal Stephenson in a 1992 science fiction novel of *Snow Crash*, can be understood as a future version of today's internet applications with a virtual world that co-exists with the physical world with possible interactions between the two worlds via AR/VR technologies. Although some critical technologies required to support a fully developed metaverse are yet to be realized, our world is clearly moving in this direction. It is not far-fetched to imagine we live in an intertwined physical–virtual world when cumbersome VR headsets are replaced by light-weight eyeglasses or other better devices down the road. As we work, shop, and socialize in an immersive virtual environment, we also fulfill our physical activities in the real world (e.g., collaborate with our co-workers, virtual try-ons of clothes and shoes before placing an order).

Second Life, which was first released in 2003, is considered by some people as a metaverse predecessor (Villar 2022). Second Life allows users to play a particular role with a chosen avatar, meet and interact with other participants, participate in various activities, and use a virtual currency to make transactions or build something in this virtual world created by the players collectively. Users can experience fantasy lives with new or even multiple identities under norms and rules that could be different from what we have in the real world. Although Second Life has some characteristics similar to metaverse, one key difference is that metaverse intends to better integrate our lives in physical space and in virtual space. In other words, metaverse intends to offer a more intertwined physical–virtual world than internet applications and digital twins as our work, shopping, and social activities become harder to separate between physical space and virtual space. Many major companies around the world have purchased land in metaverse to conduct their businesses and sell their products (Candelon et al. 2021). New human dynamics in metaverse also brings new challenges. For example, how do we protect property rights such as digital arts or digital land properties in metaverse? Technologies such as blockchain and non-fungible token (NFT) have been developed to address these challenges in metaverse. Such an intertwined physical–virtual world could operate very differently from the world when the classical time-geographic concepts such as constraints, space–time path, space–time prism, and diorama were developed by Torsten Hägerstrand more than fifty years ago. There is an urgent need of extending various time-geographical concepts to make them capable of supporting human dynamics research in today's hybrid physical–virtual world.

This section presents an overview of an evolving world from Hangerstarnd's time to today's hybrid physical–virtual world enabled by modern technologies. Time-geographic research has benefitted from the large and diverse of data collected in the Big Data era. In the meantime, the new human dynamics in today's hybrid physical–virtual world presents new challenges to time geography that has traditionally focused on human dynamics in physical space. The next section discusses potential extensions of some key classical time-geographic concepts to better support human dynamics research in today's hybrid physical–virtual world.

3 Extending classical time-geographic concepts in a hybrid physical–virtual world

Humans carry out various activities and interactions at different locations and times in order to fulfill their physiological, economic, social, and other needs (Shaw et al. 2016; Shaw and Sui 2018, 2020). There are some basic principles assumed in classical time geography. For example, it takes time to overcome distance in physical space as shown in the notation system of space–time path and space–time prism. An individual person is indivisible and can only be at one location at a time although their ideas and feelings are divisible (Hägerstrand 1982). As we move into an increasingly hybrid physical–virtual world, human dynamics is no longer restricted to the opportunities in physical space. It therefore is critical to revisit the classical time-geographic concepts and examine how they can be extended to better accommodate new human dynamics in today's hybrid physical–virtual world.

3.1 Constraints

Hägerstrand (1970) suggests three types of constraints, which are capability constraints, coupling constraints, and authority constrain, that condition human behaviors in a space–time context. Capability constraints are mainly related to our biological needs (e.g., spend time to eat and sleep) and the tools we can use to facilitate activities. Recent technological advances such as vacuum robots and mobile phone apps have significantly expanded the tools available to carry out various activities and interactions in both physical and virtual spaces. These tools help us overcome certain constraints and lead to changes in human activity patterns.

Coupling constraints indicate the needs of having people, tools, and/or other entities together at a particular location and during a particular time period to carry out a specific activity. For example, a bus ride requires a passenger to be coupled with a bus and a bus driver during a specific time period and over a specific route. Technology advances in today's hybrid physical–virtual world have relaxed many coupling constraints. For example, we now can check out an e-book without having to go to a library and interact with a librarian. An autonomous bus relaxes the coupling constraint with a bus driver while it requires new coupling constraints of having various sensors installed on the bus. Furthermore, remote work and online teaching during the COVID-19 pandemic have significantly changed the daytime population distribution patterns and traffic patterns since virtual coupling replaces physical coupling of these activities.

Authority constraints are related to control areas or domains, Hägerstrand (1970, p. 13) considers a domain as “a time–space entity within which things and events are under the control of a given individual or a given group.” For example, owners of restaurants and grocery stores can choose the operation hours to control the access to their physical domains. Virtual domains such as Facebook or Zoom, on the other hand, usually control the access via user account and password. One major advantage provided by virtual domains is that users can access them from almost anywhere and anytime as far as they have internet connections. Overall, the concept of constraints in time geography remains valid today although the nature and the scope of constraints have changed significantly from Hägerstrand's time to today's hybrid physical–virtual world.

3.2 Space–time path

Space–time path is one of the best-known concepts in time geography. A space–time path tracks an individual's movements across space and over time. The graphic notation of space–time path focuses on individual movements in physical space and has been criticized being too physicalistic (Hägerstrand 1989; Shaw 2012). Hägerstrand (1982, pp. 323–324) points out that "The fact that a human path in a time geographic notation seems to represent nothing more than a point on the move should not lead us to forget that at its tip – as it were – in the persistent present stands a living body subject, endowed with memories, feelings, knowledge, imagination and goals … People are not paths, but they cannot avoid drawing them in space–time." The above statements clearly remind us that the living person behind a space–time path should be a focus of human dynamics research.

The classical notation of space–time path is limited to activities and locations in physical space. As human dynamics is increasingly taking place in virtual space, one critical challenge is how to represent the locations of virtual entities (e.g., Google, Amazon) in the classical three-dimensional (i.e., 2D space + 1D time) space–time notation. Based on the Google example discussed above, Google can be associated with a specific location in physical space (e.g., location of the Google Headquarters) or it can be represented by a unique ID in virtual space (e.g., www.google.com). In a hybrid physical–virtual world, we should allow multiple representations of Google to accommodate various types of activities associated with Google (e.g., travel to Google Headquarters in physical space vs. conduct an online search at www.google.com in virtual space) based on their specific application needs.

Figure 1 illustrates an example of representing activities in a hybrid physical–virtual space based on the space–time path concept. In this example, the space–time path shows a person left home in the morning and drove to work at the Google headquarters. This person then joined an online meeting via Zoom in the morning, walked to have lunch at a nearby restaurant, had an in-person meeting after lunch, did some online searches via Google, and received a mobile phone call from a friend via AT&T wireless service while driving home after work. This person then watched YouTube videos after dinner at home. This figure demonstrates how a classical space–time path can be extended to accommodate human extensibility enabled by modern technology in today's hybrid physical–virtual world. For virtual activities via AT&T Wireless, Zoom, YouTube, and Google, the location of another end of these virtual interactions can be associated with a specific location in physical space

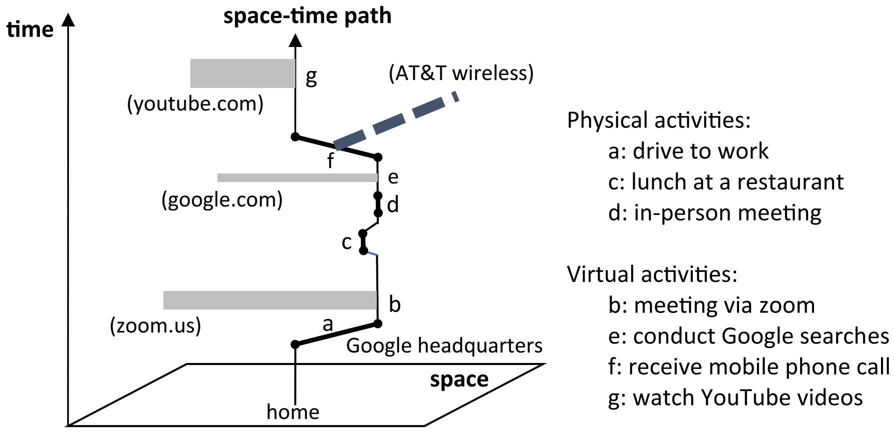


Fig. 1 A space–time path for both physical and virtual activities

if it is needed in a study (e.g., AT&T wireless phone call with a friend who is at a particular location represented by the other end of the dashed bar in Fig. 1). When a study is not concerned with the specific locations of other parties in a virtual interaction, the other end of these virtual interactions could be placed anywhere in the notation system as long as they are identified by a unique ID (e.g., zoom.us, google.com, youtube.com) such as the shaded bars in Fig. 1. Similarly, we can link all individuals who participate in a Zoom meeting through their unique IDs based on the concept of a relational space such as the widely used social network graphs that represent the connections among all entities and ignore their specific locations in absolute space (Shaw and Sui 2020). Alternatively, we can associate this zoom meeting to the specific locations of each participant in physical space and the specific time period that each participant attends this meeting via Zoom. In other words, interactions can take place between people (e.g., phone calls or zoom meetings) or between people and an entity (e.g., a person interacts with Google servers for online searches). The two ends of an interaction can be associated with either locations in physical space or entities in virtual space. Such an extended space–time path concept that accommodates human activities and interactions in a hybrid physical–virtual world has been implemented in studies such as the space–time dynamic segmentation method developed by Shaw and Yu (2009).

When we move into metaverse with AR/VR that have intertwined physical–virtual activities, it requires additional considerations beyond virtual activities performed through internet applications or simulations in digital twins. In a metaverse environment, we can live in virtual worlds that co-exist with the real world and we can purchase virtual properties and have social gatherings in a virtual world that is parallel to our lives in the real world. For example, Hyundai Motor Company has launched a "Hyundai Mobility Adventure" metaverse space in 2021, which allows people to experience Hyundai's products and future mobility solutions, on the Roblox platform. Boston Consulting Group has opened a headquarters in metaverse using the Sandbox platform for public conferences, internal gatherings, and recruiting events.

Fortune magazine has reported on December 3, 2021 that "a plot of digital land in Decentraland sold last week for $2.43 million worth of the platform's cryptocurrency (618,000 MANA)—higher than the price of the average "real-world" Manhattan apartment." Although the extended space–time path shown in Fig. 1 is capable of handling a hybrid physical–virtual world performed through internet applications and digital twins, it falls short of properly supporting metaverse applications that have virtual worlds and the real world intertwined with each other. In a metaverse environment, a person can have a space–time path in physical space as well as one or more space–time paths in other virtual worlds. In this case, a person can have more than one space–time path and appears to become divisible although the physical human body is still indivisible. Furthermore, space–time paths in physical space and in virtual space are not completely independent from each other. For example, although spatial reference systems in physical space and in virtual space may be very different in metaverse, we all have fixed 24 h a day to manage our multiple space–time paths in a hybrid physical–virtual world.

3.3 Space–time prism

A space–time prism delimits the spatial extent that an individual could reach under an assumed travel speed between a give pair of origin and destination and within a given time period. This space–time prism concept has been widely used in accessibility studies (e.g., Miller 1999; Kwan 1998, 1999; Miller and Wu 2000; Kim and Kwan 2003; Schwanen and de Jong 2008; Neutens et al. 2012). In the meantime, there have been efforts aiming at making more realistic estimation of space–time prism (e.g., Kobayashi et al. 2011; Chen et al. 2013; Song and Miller 2014). However, most of these studies focus on the movements in physical space without paying much attention to virtual activities. Since the travel time taken to overcome spatial separation has become almost negligible in virtual activities, the classical space–time prism concept is no longer adequate to study human dynamics in a hybrid physical–virtual world.

Yu and Shaw (2008) extend the classical space–time prism concept for studying potential human activities and interactions in both physical and virtual spaces. They suggest a dual role of physical space as a carrier of physical activities and as a connector to virtual activities in a hybrid physical–virtual world. Based on a classification of communication modes into synchronous physical (SP) presence, asynchronous physical (AP) presence, synchronous virtual (SV) presence, and asynchronous virtual (AV) presence (Table 1), they illustrate how virtual activities can be considered with the classical space–time prism concept (Fig. 2). This approach treats physical space and virtual space as two separate spaces and can handle scenarios of most internet applications and digital twins. However, it falls short of integrating virtual activities and physical activities in a hybrid physical–virtual world such as metaverse applications.

Internet access today is not ubiquitous at all locations in physical space yet. The locations in physical space that do not have access to internet therefore can be considered like holes in Swiss cheese. When satellite-based internet access such as the

Table 1 Communication modes based on their spatial and temporal constraints. (Adapted from Janelle 2004)

Spatial	Temporal	
	Synchronous	Asynchronous
Physical presence	SP	AP
	In-person meeting	Traditional bulletin board
Virtual presence	SV	AV
	Phone call	E-mail
	Zoom meeting	Mobile messenger app

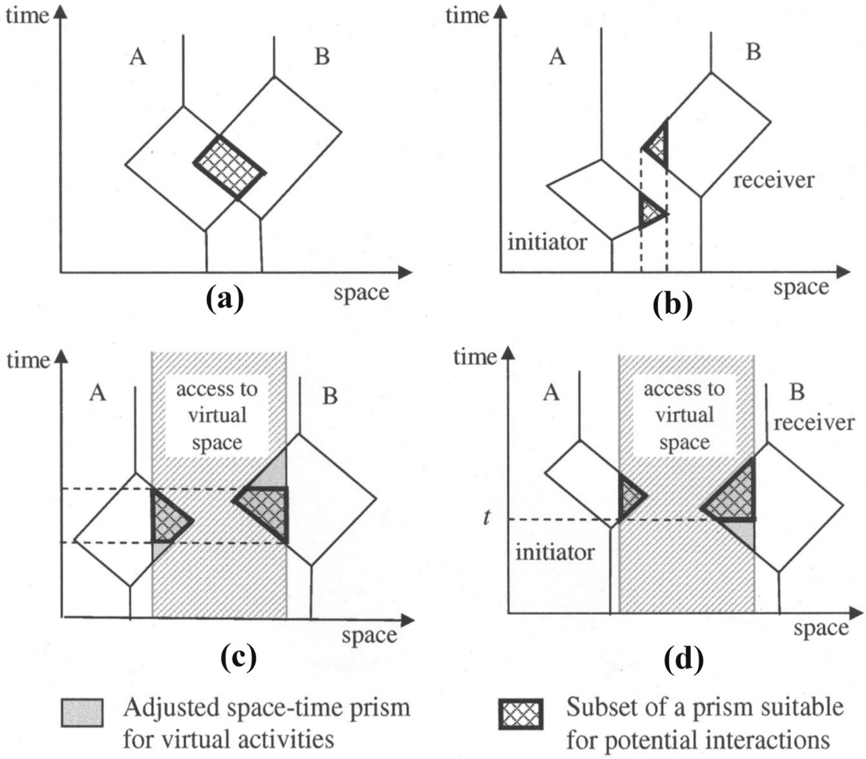


Fig. 2 Spatio-temporal relationships of prisms and potential interactions: **a** potential SP interactions; **b** potential AP interactions; **c** potential ST interactions; **d** potential AT interactions. (*Note*: Initiator is the person who initiates a communication and receiver is the person who receives a communication.) (*Source*: Yu, H. and Shaw, S-L. 2008. Exploring potential human activities in physical and virtual spaces: A spatio-temporal GIS approach. International Journal of Geographical Information Science 22(4), 409–430)

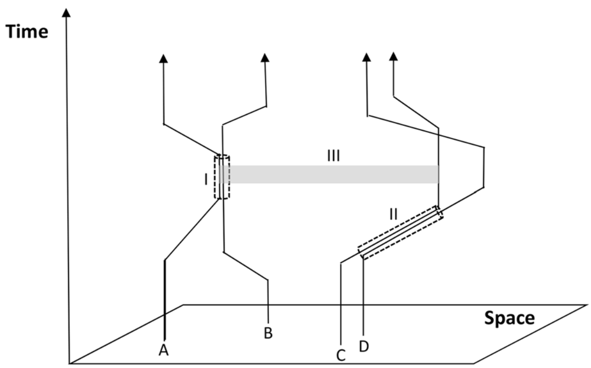
Starlink project by SpaceX becomes available, the holes in Swiss cheese will disappear and space–time prism will become a space–time cube that allows internet access everywhere and all the time except for constraints such as access cost and system malfunction. In other words, the space–time prism concept may become irrelevant to most virtual activities and interactions in the near future. When geographic proximity constraints in physical space are removed in virtual space, the identity of individual persons becomes more critical in a virtual space than their locations in physical space. This shift of focus has important implications to many application areas such as accessibility research (Miller 2018). For example, the concepts of proximity, distance, and accessibility should be defined differently in physical space and in virtual space, respectively. Physical distance may be replaced by topological distance in virtual space, and proximity in virtual space could be defined by relations rather than physical distances.

3.4 Bundle

Hägerstrand (1970) defines a bundle as a grouping of several space–time paths under the context of coupling constraints. Many activities we perform in our daily lives require a coupling relationship with other people or entities such as attending an event with other people at a particular facility. Bundles can be either a stationary bundle at a fixed location (e.g., in-person meeting in an office shown as the segment I in Fig. 3) or a mobile bundle (e.g., carpool with a friend shown as the segment II in Fig. 3).

Hägerstrand (1970, p.15) also indicates that "A further kind of bundle deserves some passing comments. Telecommunication allows people to form bundles without (or nearly without) loss of time in transportation." When we move from a physical space to a virtual space, bundles are no longer a grouping of space–time paths with close spatial and temporal proximity. For example, when several people participate in a Zoom meeting together (see the segment III in Fig. 3), it forms a bundle in virtual space since these people are coupled together to carry out a particular activity. In other words, we need to extend the classical bundle concept to allow virtual bundles through connections in virtual space in addition to physical bundles defined by spatial and temporal proximity in physical space. Virtual bundles can be defined as clusters of individuals and/or entities that share virtual interactions with each other at the same time. In a metaverse environment, we need to handle these different types of bundles among space–time paths in physical space as well as space–time paths in virtual space to manage the complex interactions and relationships in a hybrid physical–virtual world.

Fig. 3 Bundle types–(I) stationary bundle of persons A and B, (II) mobile bundle of persons C and D, and (III) virtual bundle of persons A, B and C



3.5 Project and situation

Hägerstrand (1982) indicates that the concept of project is to help geographers with two things. One is to go beyond the static patterns on flat maps and think our world as a world on the move with incessant permutations. The other is to use the concept of project to relate events that happen to the striving for purposes and goals of various projects. Hägerstrand (1982) then presents situation as a position or condition at the moment or a position with regard to surroundings. Situations are not static and can evolve over time that interact with projects. The concepts of project and situation bring us back to the fundamental driving force behind human dynamics, which is to meet our needs through various activities associated with different projects. These projects guide human activities and interactions to achieve the project goals. Situations are related to the concepts of capability, coupling, and authority constraints that affect our opportunities of achieving various project goals. The classical concepts of project and situation are equally applicable to human dynamics in a hybrid physical–virtual world except that constraints now are in different forms due to the changes introduced by modern technology. For example, taking an online class or participating in a virtual community event in metaverse is driven by a project goal and each event has to consider various situations such as advanced registration for the online class, membership of the metaverse community, and time availability.

3.6 Diorama

At the broadest level, Hägerstrand (1982) indicates that diorama should include everything contained in the part of the world. However, it is not feasible to include everything in a study from a practical perspective. Hägerstrand (1982) therefore suggests that diorama covers only a limited number of path-makers and projects which are interdependent in a situational sense within a diorama. Diorama therefore refers to the landscape or the environment within which humans carry out various activities to accomplish different projects under evolving situations. Hägerstrand (1982, p. 338) further argues that "without a diorama approach, the revealing power of time-geography cannot be fully explored." Lenntorp (1999, p 155) also suggests that life as a drama–"Every drama has three elements–namely actors, roles (expressed by behaviors, activities), and the scene." Every person is part of the drama and no one can sit as an audience. The scene in this drama analogy reflects the concept of diorama in time geography.

In today's hybrid physical–virtual world, human dynamics takes place in both physical and virtual worlds that are intertwined with each other. The classical time-geographic framework focusing on absolute locations in physical space is insufficient to tackling the new human dynamics today. Shaw and Sui (2020) propose a new space-place (splatial) framework, which integrates the concepts of absolute space, relative space, relational space, and mental space along with the concepts of location, locale, place identity, and sense of place, to better pursue human dynamics research in a hybrid physical–virtual world. In this space-place framework, the *absolute space/location* approach tackles questions such as “Where are the different objects?” with a focus on absolute locations in physical space. The *relative space/locale* approach addresses questions such as “What are around us?” that places an emphasis on the context and surrounding environments. The *relational space/place identity* approach handles questions such as “What are related to us?” that focuses on the connections among different people and/or entities. Finally, the *mental space/sense of place* approach answers questions such as “What do people have in mind?” that deals with the cognitive and mental aspects of human dynamics. This human-centered, space-place framework has potential of addressing the classical time-geographic concepts with absolute locations in physical space, situations defined by the surrounding environment as a relative space, connections in virtual space as a relational space, and the person at the tip of each space–time path as a living entity with feelings and ideas handled in a mental space. In other words, this space-place framework extends the focus on locations in absolute space in classical time geography to include approaches of locale in relative space, identity in relation space, and sense of place in mental space to deal with the concept of diorama in a more comprehensive manner.

4 Concluding remarks

As indicated by Thrift and Pred (1981, p. 27) that time geography “is a discipline-transcending and still evolving perspective on everyday workings of society and the biographies of individuals,” the concepts in time geography should evolve with the changing environment, technology, and society to remain relevant and useful. For example, climate change has introduced new situations to the low-lying lands near the sea level and to the regions that experience more frequent extreme weather such as floods or severe droughts. Recent technology advances have significantly altered the constraints to human dynamics that lead to an increasingly hybrid physical–virtual world. Paradigms in human societies also have evolved, for example, from a global approach to a more nationalist approach in recent years. Although there have been many studies applying the time-geographic concepts in different fields over the years, there is a lack of attention to ensure that the classical concepts in time geography evolve with the changing world.

This paper aims at encouraging more time-geographic research to investigate the evolving changes to everyday workings of society and the biographies of individuals. We first compare the environment under which Torsten Hägerstrand grew up and developed the time-geographic concepts with the changing human dynamics in today’s hybrid physical–virtual world enabled by modern technologies. This paper then revisits the classical time-geographic concepts of constraints, space–time path, space–time prism, bundle, project/situation, and diorama to discuss if and how they need to evolve with the new human dynamics in today’s hybrid physical–virtual world.

There exist two major challenges of applying the time-geographical concepts in empirical studies (Shaw 2012). The first challenge is the cost and time needed to collect data at the individual level and within a space–time context to support time-geographic studies. The Big Data era now produces many large and diverse data sets that can help partially address this challenge as modern technologies have made it feasible to trace and track activities and interactions in both physical and virtual spaces at an affordable level of cost and time. The second challenge is the lack of computational functions to support data processing, data analysis, and data visualization needs of time-geographic studies. This challenge is like a capability constraint that prevents many researchers from pursuing time-geographic studies even if they have access to useful big data sets. While we are making the classical time-geographic concepts better match with the evolving world, one research need is to design and develop a set of computational functions to operationalize various time-geographic concepts and support human dynamics research in today's hybrid physical–virtual world. We can use open-source geographic information systems (GIS) software to start building some basic functions based on the approaches discussed in this paper. This effort will enable and benefit both researchers and practitioners to use the time-geographic framework and concepts in their work. Another important research need is to gain further insights into the human dynamics in today's hybrid physical–virtual world. For example, the COVID-19 pandemic has caused many important changes to human dynamics in physical space, in virtual space, and the interactions between physical space and virtual space. Many data sets have been collected during the pandemic period that await innovative research ideas to gain insights into the changing human dynamics that time geography can serve as a useful framework to pursue impactful research in this evolving world.

References

Batty M (1997) Virtual geography. Futures 29(4/5):337–352

Batty M, Miller HJ (2000) Representing and visualizing physical, virtual and hybrid information spaces. In: Janelle DG, Hodge DC (eds) Information, place, and cyberspace: issues in accessibility. Springer, Berlin, Germany, pp 133–146

Bergmann L, Lally N (2021) For geographical imagination systems. Ann Am Assoc Geogr 111(1):26–35

Bos D (2021) Geography and virtual reality. Geogr Compass 15(e12590):1–13

Candelon, F., Tordjman K.L. and Lafolie, A. 2021. Conquering the metaverse: 3 ways that businesses can find real customers in virtual worlds. *Fortune* December 3, 2021.

Chen BY, Li Q, Wang D, Shaw S-L, Lam WHK, Yuan H, Fang Z (2013) Reliable space–time prisms under travel time uncertainty. Ann Assoc Am Geogr 103(6):1502–1521

Couclelis H (2009) Rethinking time geography in the information age. Environ Plan A 41(7):1556–1575

Ellegård K (2019a) Introduction: the roots and diffusion of time geography. In: Ellegård K (ed) Time geography in the global context: an anthology. Routledge, Oxford, pp 1–18

Ellegård K (2019b) Introduction: origin and social context. In: Ellegård K (ed) Thinking time geography: concepts, methods and applications. Routledge, Oxford, pp 3–10

Hägerstrand T (1970) What about people in regional science? Pap Reg Sci Assoc 24(1):7–21

Hägerstrand T (1982) Diorama, path and project. Tijdschrift Voor Economische En Socile Geographie 73(6):323–339

Hägerstrand T (1989) Reflections on "what about people in regional science? Pap Reg Sci Assoc 66(1):1–6

Janelle DG (1968) Central place development in a time-space framework. Prof Geogr 20(1):5–10

Janelle DG (1969) Spatial reorganization: a model and concept. Ann Assoc Am Geogr 59(2):348–364

Janelle DG (1973) Measuring human extensibility in a shrinking world. J Geogr 72(5):8–15

Janelle DG, Hodge DC (eds) (2000) Information, place, and cyberspace: issues in accessibility. Springer, Berlin

Janelle DG (2004) Impact of information technologies. In: Hanson Susan, Giuliano Genevieve (eds) The geography of urban transportation. The Guilford Press, New York
Jones D, Snider C, Nassehi A, Yon J, Hicks B (2020) Characterising the digital twin: a systematic literature review. CIRP J Manuf Sci Technol 29:36–52
Kim H-M, Kwan M-P (2003) Space-time accessibility measures: a geocomputational algorithm with a focus on the feasible opportunity set and possible activity duration. J Geogr Syst 5:71–91
Kirch S (1995) The incredible shrinking world? Technology and the production of space. Environ Plan d: Soc Space 13(5):529–555
Kitchin R (2014) Big data, new epistemologies and paradigm shifts. Big Data Soc 1(1):1–12
Kobayashi T, Miller HJ, Othman W (2011) Analytical methods for error propagation in planar space–time prisms. J Geogr Syst 13:327–354
Kwan M-P (1998) Space-time and integral measures of individual accessibility: a comparative analysis using a point-based framework. Geogr Anal 30(3):191–216
Kwan M-P (1999) Gender and individual access to urban opportunities: a study using space–time measures. Prof Geogr 51(2):210–227
Lenntorp B (1999) Time-geography: at the end of its beginning. GeoJournal 48:155–158
Miller HJ (1999) Measuring space-time accessibility benefits within transportation networks: basic theory and computational procedures. Geogr Anal 31(2):187–212
Miller HJ (2010) The data avalanche is here. Shouldn't we be digging? J Reg Sci 50(1):181–201
Miller EJ (2018) Accessibility: measurement and application in transportation planning. Transp Rev 38(5):551–555
Miller HJ, Wu Y (2000) GIS software for measuring space-time accessibility in transportation planning and analysis. GeoInformatica 4(2):141–159
Mokhtarian PL (2003) Telecommunications and travel: the case for complementarity. J Ind Ecol 6(2):43–57
Neutens T, Delafontaine M, Scott D, De Maeyer P (2012) An analysis of day-to-day variations in individual space–time accessibility. J Transp Geogr 23:81–91
Oxford Reference, 2022. Virtual space. https://www.oxfordreference.com/view/https://doi.org/10.1093/oi/authority.20110803120011855?rskey=dk3kAo&result=2. Last accessed on November 26, 2022.
Saunders C, Rutkowski AF, van Genuchten M, Vogel D, Molina Orrega J (2011) Virtual space and place: theory and test. MIS Q 35(4):1079–1098
Schwanen T, de Jong T (2008) Exploring the juggling of responsibilities with space-time accessibility analysis. Urban Geogr 29(6):556–580
Shaw S-L (2012) Time geography–its past, present, and future. J Transp Geogr 23:1–4
Shaw S-L, Sui D (2018) Human dynamics research in smart and connected communities. Springer International Publishing AG, Cham
Shaw S-L, Sui D (2020) Understanding the new human dynamics in smart spaces and places: toward a splatial framework. Ann Am Assoc Geogr 110(2):339–348
Shaw S-L, Yu H (2009) A GIS-based time-geographic approach of studying individual activities and interactions in a hybrid physical-virtual space. J Transp Geogr 17(2):141–149
Shaw S-L, Tsou M-H, Ye X (2016) Editorial: human dynamics in the mobile and big data era. Int J Geogr Inf Sci 30(9):1687–1693
Song Y, Miller H (2014) Simulating visit probability distributions within planar space-time prisms. Int J Geogr Inf Sci 28(1):104–125
Taylor J (1997) The emerging geographies of virtual worlds. Geogr Rev 87(2):172–192
Thrift N, Pred A (1981) Time-geography: a new beginning. Prog Hum Geogr 5(2):277–286
Villar, T. 2022. What is Second Life? A brief history of metaverse. https://www.makeuseof.com/what-is-second-life-history-metaverse/, accessed on November 26, 2022.
Yu H, Shaw S-L (2008) Exploring potential human activities in physical and virtual spaces: a spatio-temporal GIS approach. Int J Geogr Inf Sci 22(4):409–430