Structuring a Wayfinder's Dynamic Space-Time Environment

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Abstract. To travel successfully in a dynamic space-time setting, wayfinders must project the impact of a changing environment onto future travel choices. When making decisions, however, people often fail to consider the impact of future changes. They instead overly rely on current system states. In addition, spatial information systems designed for wayfinders typically focus on current or historic travel information. To address these limitations, this paper presents an approach to structure the dynamic space-time environment of a wayfinder. With this structure, improved spatial information systems can be designed to support wayfinders in dynamic environments. To create this structure, four primitives of space-time wayfinding are presented: maximum travel speed, a starting point, barriers, and compulsions. Combining the speed limitation with each of the remaining three primitives creates distinctive partitions of space-time. To integrate all four primitives, a method of sequentially partitioning space-time is described which results in four partition categories that account for the different constraints of wayfinding. These partitions are described in a cognitively plausible manner using modal verbs *can*, *may*, *must*, and *should*. The creation of this structure along with these descriptive semantics creates a rich representation of the wayfinder's space-time environment and allows for reasoning about space-time decision points and their impact on future possibilities.

1. Introduction

Wayfinding in a spatio-temporal environment is a complex task (Golledge 1999; Davies and Pederson 2001; Sholl 2001), resulting from the dynamic existence and location of objects over time. For example, a route may be available to a wayfinder early in the day, but a scheduled bridge closure later creates a barrier. A travel requirement may be in place for a specific time interval, such as meeting a friend for lunch. Barriers and requirements may also move or change shape over time, as in the case of a forest fire (Yuan 1997). In addition, the wayfinder's location also changes throughout this complex task.

Failing to account for the dynamic nature of the spatio-temporal environment may result in unsuccessful wayfinding. Arriving at the bridge after it closes, or going to the restaurant at the wrong time, may make the wayfinding task impossible. The unidirectional nature of time (Galton 1997; Boroditsky 2000), along with the wayfinder's maximum travel speed, establishes a structure in space-time that defines available choices. For example, choosing not to cross the bridge before it closes precludes travel options on the other side of the river. Other choices may be contingent on previous ones, for example, waiting for the bridge to open may be irrelevant if you have already crossed and do not wish to return.

To account for these changes when planning for and traveling in dynamic spatio-temporal environments, an integrated space-time model is required. In addition, there must be a method for determining the location and time for making decisions, and a means to realize the impacts of these decisions on future possibilities.

A typical strategy used by people in day-to-day decision making is to project possible future states from known patterns and trends (Barlow 1998). When crossing the street, people project both their location and the location of any cars into the future to ensure that they do not intersect in space and time. This process of perceiving and understanding elements in a dynamic spatio-temporal environment and projecting their status into the future is referred to as *situational awareness* (Endsley 1988). In the professional world, success of air-traffic controllers (Andre *et al.* 1998; Durso *et al.* 1999; Azumea *et al.* 2000), pilots (Endsley 1995; Zhang and Hill 2000), and military personnel (NRC 1997; Ellis and Johnston 1999) relies heavily on situational awareness in order to make effective decisions in these spatio-temporal environments.

It has been found, however, that people often fail to consider effectively the impact of future changes when making decisions, but overly rely on current system states (Kerstholt and Raajimakers 1997). A wayfinder may fail to project into the future the impacts a scheduled bridge closure will have on her travel options, and as a result may be unsuccessful in reaching her destination on time. Since wayfinding in a dynamic spatio-temporal environment is particularly complex, it is expected that wayfinders often fail to project future states when determining space-time decision points and reasoning about the impacts of these decisions on future possibilities.

Spatial information systems typically support wayfinders with reference maps and more recently location information derived from GPS data. Route guidance systems are becoming more popular in automobiles and are beginning to account for dynamic traffic conditions (Eby and Kostyniuk 1999). Though increasing the information available to the wayfinder, these systems fail to address the the impact of a changing environment on future travel possibilities.

To address these limitations, this paper introduces an approach that structures and describes the space-time environment of a wayfinder in a manner that will support people's qualitative reasoning capability with complex tasks (Egenhofer and Mark 1995) and provide a framework for the development of more effective spatial information systems. The space-time structure is created by extending into the temporal domain space partitioning symbolic projection techniques for route planning (Holmes and Jungert 1992; Jungert 1992; Chang and Jungert 1996). The resulting space-time structure extends the approaches of space-time prisms (Miller 1991) and geospatial lifelines (Hariharan and Hornsby 2000; Hornsby and Egenhofer 2002) by providing a richer and more complete representation of the wayfinder's space-time environment.

Four primitives of space-time wayfinding are presented: maximum travel speed, a starting point, barriers, and compulsions. The maximum travel speed constrains the wayfinder's rate of movement. When projected through space-time, the maximum travel speed creates a structure that defines travel possibilities. The start point represents the location and time where wayfinding begins. Barriers are the locations in space and time where travel is not allowed, while compulsions represent the space-time requirements of the wayfinder, such as having lunch with a friend.

Combining the speed limitation with each of the remaining three primitives creates distinct partitions of space-time. Combining the maximum speed with the starting point partitions space-time into accessible and inaccessible space based on the wayfinder's capability. The combination of the maximum speed and barriers creates a partition of space-time into accessible and inaccessible spaces based on the barrier's travel restrictions. The last combination considered—the speed limitation with the wayfinder's compulsions—creates a partition that defines where and when the wayfinder should or should not travel in order to meet the requirements. To integrate all four primitives, a method of sequentially partitioning space-time is described, which results in four partition categories that account for the different constraints of wayfinding.

To describe the resulting partitions of this space-time structure in a cognitively plausible manner, a method of employing the modal verbs *can, may, must,* and *should* is presented. Though each modal verb is used in many ways during normal conversations, *can* is related to a positive ability (capability); *must* denotes obligation or compelling force; and *may* is associated with permission or lack of a potential barrier (Sweetser 1990). In addition, we include one other modal verb, *should*, as a weaker form of must. In an inherently physical and dynamic act, such as wayfinding, describing spatial and temporal constraints modally provides insights for argument and reasoning.

The result of creating this space-time structure and linking modal verbs to its partitions allows a wayfinder to reason about space-time decision points and their impact on future possibilities. For example, the wayfinder can consider the following queries: Where *can* I go given some time limit? Where *may* I go given barriers in my environment? Where *must* I go? Where *should* I go and still meet my requirements? When is it possible to go to a location given my other requirements? If I go to some space-time point, is it still possible to meet my requirements? Developing a framework for queries such as these provides additional decision support tools for wayfinders traveling in dynamic space-time environments.

The remainder of this paper continues with a summary of approaches for structuring a wayfinder's environment, to include symbolic projections and space-time prisms (Section 2). In Section 3, the four wayfinding primitives used in this approach are introduced. Section 4 describes the three distinct partitions of space-time, resulting from combining the wayfinder's maximum speed with each of the remaining primitives. Section 5 describes the sequential partitioning technique that combines all four partitions and creates the integrated structure of the wayfinder's space-time. Section 6 presents an approach for using modal verbs to describe these partitions and Section 7 provides conclusions and suggestions for future work.

2. Structuring a Wayfinder's Environment

Numerous methods of structuring a wayfinder's environment have been proposed in the past. Many focus on the spatial structure of the environment alone, while others attempt to integrate the temporal component of wayfinding. This section reviews in particular those spatial (Section 2.1) and spatio-temporal (Section 2.2) approaches that form the basis for later discussions in this paper.

2.1. Spatial Structure for Wayfinding

Spatial approaches to wayfinding typically consider a flat, 2-dimensional space in which they aim at identifying optimal paths. A popular structure of a wayfinder's environment identifies barriers and calculates the Euclidean shortest path around them (Lee and Preparata 1984; Stefanakis and Kavouras 1995; Hershergery and Suri 1999). More complex approaches classify the environment's objects as obstructers or facilitators, which allows for pragmatic navigation through the environment (Epstein 1997). Other approaches organize space hierarchically based on different functionalities (Timpf 2002). When emphasizing human perceptive and cognitive lines, image schemata and affordances have been used to structure the space of wayfinders in built-up environments (Raubal *et al.* 1997; Raubal and Egenhofer 1998).

A method based on *symbolic projections* (Holmes and Jungert 1992; Jungert 1992) partitions the traveler's 2-dimensional space around barriers, enabling qualitative spatial reasoning about routes. These symbolic projections record objects' extents along the horizontal and vertical axes (Figure 1), resulting in strings of object locations associated with each axis (Chang and Jungert 1986; Jungert 1988). When specifically applied to wayfinding, the focus of the symbolic projection approach is the partitioning of space by projecting the extents of barriers.

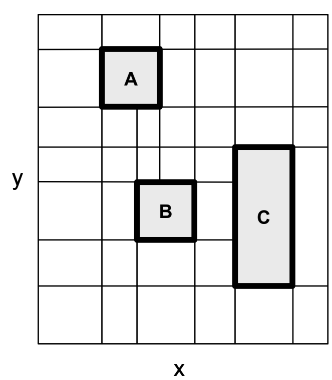

Fig. 1. Structuring the space of a wayfinder through symbolic projection techniques. Barriers A, B, and C are projected onto each axis, creating a grid representing travel possibilities.

2.2. Spatio-Temporal Structure for Wayfinding

Since wayfinding is often time-related, a comprehensive approach to reasoning in this environment requires an integrated space-time model. A foundation of such a space-time model considers an *n*-dimensional space, denoted by S, and one orthogonal dimension of time, denoted by T, on $\Re^{n+1}$. The case of two spatial dimensions (x-y plane) and an orthogonal dimension for time (ascending z-axis) yields a three-dimensional space-time cube, analogous to the foundation of Hägerstrand's Time Geography (Hägerstrand 1967). In this setting, the wayfinder is modeled as a 0-dimensional point object, whose location in space and time is referenced by (x_i,y_i,t_i). As time progresses, this point object traces a space-time path (Miller 1991) from the origin (x_0,y_0,t_0) to the destination (x_1,y_1,t_1), also modeled as a geospatial lifeline thread (Hornsby and Egenhofer 2002). An immobile object would trace a vertical line in the space-time cube, whereas an object moving at a constant speed creates a sloped space-time path, with flatter lines representing faster travel and steeper lines standing for slower travel. Projecting such a space-time path onto the x-y plane creates the *route* traveled through space (Miller 1991).

Most often, the exact path through space-time is unknown. One method of handling this uncertainty is to determine the set of all possible locations that an object can travel to between time intervals. With a given start point and a constant maximum speed, a half cone is created in space-time, which represents the set of all possible locations the traveler can reach (Figure 2a). If a destination point is added to this scenario, a second half cone extending back in time is created and whose intersection with the first half cone creates a potential path space (Figure 2b), referred to as a space-time prism (Miller 1991) or lifeline bead (Hornsby and Egenhofer 2002). This lifeline bead represents the set of all possible space-time points that the object may have occupied between the origin and the destination, based on heuristics about the object's maximum travel speed. The aggregate of simply connected beads (Figure 2c) forms a lifeline necklace (Hornsby and Egenhofer 2002).

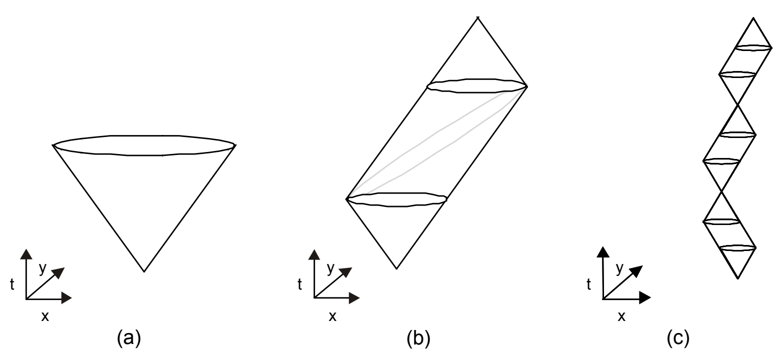

Fig. 2. Possible travel locations in a space-time volume: (a) a cone, (b) space-time prism or lifeline bead, and (c) a lifeline necklace.

Time Geography considers three classes of constraints that restrict individual movement and shape space-time prisms (Pred 1977). *Capability constraints* restrict movement based on physiological needs, such as sleeping or eating, and the speed limitations of available transportation. *Coupling constraints* limit travel by the requirements to meet other people or objects in space and time. *Authority constraints* restrict travel as a result of certain activities being only available at certain times. This paper presents an alternative classification of travel constraints modeled as four wayfinding primatives which are described in the next section.

The space-time prisms are projected onto the spatial surface to represent accessibility, a qualitative spatial measure used by travelers (Weibull 1980; Miller 1991; Kwan 1998; Miller 1999). While these concepts support the analysis as to whether two or more individuals could have met, they say little about space-time inside or outside the prisms, as well as the effects of barriers on their shapes.

3. Integrated Space-Time Structure for Wayfinding

To provide a richer and more complete structure to the space-time environment of the wayfinder, a systematic approach is presented, which builds on a set of wayfinding primitives. The framework for this space-time environment is that space and time are bound, creating an $n+1$ dimensional space-time *container*, denoted by $ST_{(n+1)D}$. This container creates a closed world of the wayfinder's environment with the following assumptions:

- The wayfinder experiences time as being continuous and unidirectional (Boroditsky 2000).
- All objects related to the wayfinder's task must be contained in ST.

In addition, to simplify this discussion and presentation we consider a space-time environment with one spatial dimension, such as a road or rail segment. This simplification creates a 2-dimensional space-time *container* ST_{2D} that allows us to represent these concepts in planar maps and diagrams.

Within this framework, the following primitives structure the wayfinder's space:

- the maximum speed limitation of the wayfinder (L);
- space-time information of the start point (O);
- space-time information of compulsions through which the wayfinder *must* pass (M); and
- space-time information about barriers that the wayfinder *must not* travel through (¬M).

Each of these primitives adds a set of constraints to the space-time environment of the wayfinder. The maximum speed limitation constrains the rate of travel through the environment. This speed limitation provides a method of projecting through space-time the impacts of the remaining three primitives and allows the wayfinder to reason about space-time decision points and their impact on future possibilities. The second primitive, the wayfinder's start point, establishes the origin in space and time, thereby constraining future possibilities. The remaining two primitives, compulsions and barriers, are more complex, and each is discussed below.

3.1. Compulsions: the *M-Space* of Wayfinding

A compulsion represents the space-time task requirements of the wayfinder, or the *where* and *when* the wayfinder must be in the future. This approach assumes independence of compulsions. A compulsion cannot be contingent upon another, and disjunctive compulsions, as in one or the other, are not allowed. The—possibly empty—set of compulsions, in combination with the start point, is referred to as *M-space*.

Compulsions come in various shapes and sizes. The following list gives examples:

- A 0-dimensional space-time point compulsion represents a requirement at a specific location and time (M_1 in Figure 3). For example, "you *must* be at my office at 10:00 am." This is the type of compulsion typically modeled in the space-time prism and geospatial lifeline approaches.
- A compulsion may also occur over larger areas of space. In these cases, since the wayfinder is modeled as a point object, the requirement is to travel to some point in the compulsion space. A compulsion with a spatial extent at an instance of time is modeled as a horizontal line in ST_2 (M_2 in Figure 3).
- Often a compulsion occurs over a temporal interval. The extreme case is a compulsion that requires a wayfinder to occupy a location continuously. Scenarios that are more interesting occur when the compulsion is active for only a subset of the available time. Consider the case where a compulsion lasts only until a certain time. For example, "you *must* stay home until 8:00 am." In this case, the wayfinder's travel possibilities are completely restricted until after the compulsion disappears (M_3 in Figure 3).
- An alternate compulsion arises when you *must* occupy some location after a specified time. For example, "be home by 10:00 pm" (M_4 in Figure 3).
- A combination of these two types models the compulsion that begins and ends inside the space-time container (M_5 in Figure 3). For example, "you *must* be at work from 8:00 am to 5:00 pm."
- Compulsions may also occur over both a spatial extent and a temporal interval (M_6 in Figure 3).
- In addition, compulsions may themselves travel through space-time. A requirement to intercept a moving object would be a compulsion of this type. Moving point compulsions are modeled as a sloped line through space-time, representing the speed of the compulsion object (M_7 in Figure 3).
- A compulsion also may change shape and size over time (M_8 in Figure 3).

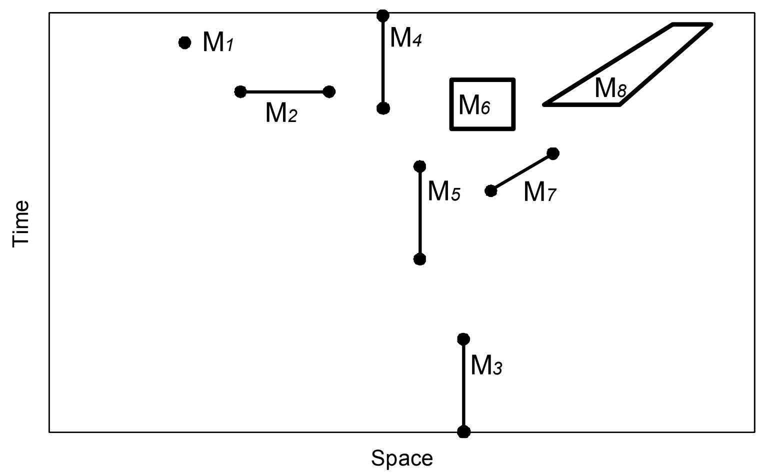

Fig. 3. Various compulsion shapes: a space-time point compulsion (M_1); a compulsion with a spatial extent at an instance of time (M_2); spatial point compulsions at various temporal intervals (M_3 M_4 M_5); a compulsion over both a spatial and temporal interval (M_6); a moving point compulsion (M_7); and a compulsion that changes shape and size over time (M_8).

An additional characteristic of *M-space* is that there is a distinction between compulsions that are required to be occupied the entire time and compulsions that only require occupation at some instance of the temporal interval. The compulsion, "Go to the post office after 4 pm," does not compel the wayfinder to spend his entire evening at the post office, whereas the compulsion to have lunch with a friend requires occupation of the compulsion space for the entire time.

3.2. Barriers: the *¬M-Space* of Wayfinding

Barriers constrain the wayfinder by disallowing travel through them. These spaces are referred to as *¬M-spaces*. *M-space* and *¬M-space* do not themselves partition space-time in that there are points in the wayfinder's space-time container that are neither compulsions nor barriers. Barriers are classified into those that partition space and those that do not. For example, a river running entirely through the wayfinder's space will create a partition, whereas a lake will not.

Barriers, as with compulsions, vary in size and shape. The following list gives examples:

- A typical temporary barrier has a spatial extent, and begins and ends within the wayfinder's space-time environment. For example, closing a section of road for 2 hours ($\neg M_1$ in Figure 4).
- Partitioning barriers may themselves have minimal area, but by partitioning space, they may constrain movement over a large spatial extent. For example,

closing a bridge creates a point barrier that constrains movement to one side of the river ($\neg M_2$ in Figure 4).

- Barriers may also change size over time. For example, a forest fire modeled in this way would appear, increase in size, and then decrease until it goes out ($\neg M_3$ in Figure 4).

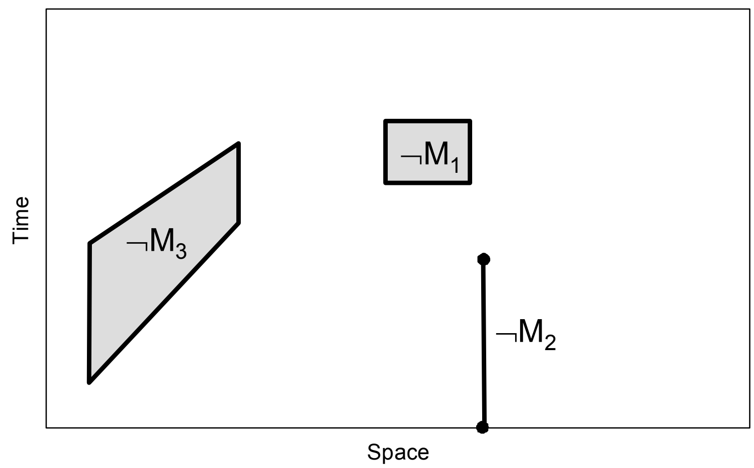

Fig. 4. Various barrier shapes: a barrier within a spatial extent beginning and ending within the wayfinder's space-time environment ($\neg M_1$); a spatial point barrier that lasts until a specified time ($\neg M_2$); and a barrier appearing, increasing in size and then decreasing until disappearing ($\neg M_3$).

4. Combining Wayfinding Primitives

Combining the maximum travel speed with each of the remaining three primitives creates a distinctive structure that partitions space-time and defines the accessibility related to that combination. These structures are created by projecting the maximum travel speed limitation through space-time from the start point, and each barrier and compulsion. This procedure is similar to that used in the symbolic projection technique's partitioning of a wayfinder's space. The partitions created from these three combinations are assigned a symbol and its complement to indicate the accessible and inaccessible spaces created from each combination (Figure 5). This section continues by introducing in more detail *C-space* (Section 4.1), *Y-space* (Section 4.2), and *H-space* (Section 4.3)

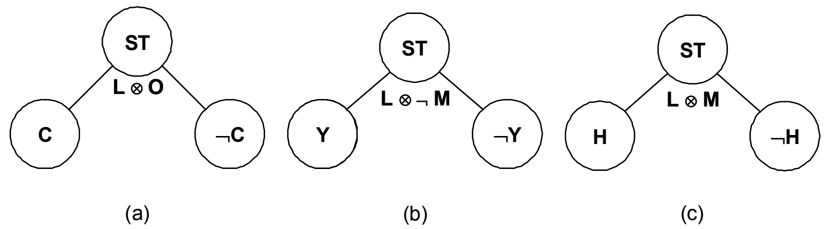

Fig. 5. Three accessibility partitions of space-time, ST, by wayfinding primitive combinations: (a) speed limitation, L, and start point, O, create *C-space* and *¬C-space*; (b) speed limitation and barriers, ¬M, create *H-space* and *¬H-space*; and (c) speed limitation and compulsions, M, create *Y-space* and *¬Y-space*.

4.1. The *C-Space* of Wayfinding

Combining a wayfinder's maximum travel speed and start point partitions the space-time container into two spaces: *C-space* as the set of locations that can be accessed from the start point and *¬C-space* as the inaccessible space. This process is analogous to generating the half cone used to create a lifeline bead. *C-space* and *¬C-space* are simply connected; the separation of *¬C-space* into two areas (Figure 6) is only a side effect of the planar graphical presentation. The following observations are made about this structure:

- Any valid space-time path must be fully contained within *C-space*.
- If the wayfinder's maximum speed increases, the *C-space* also grows in space and time.
- The reverse holds true as well, that is, decreasing the maximum travel speed shrinks the *C-space*.

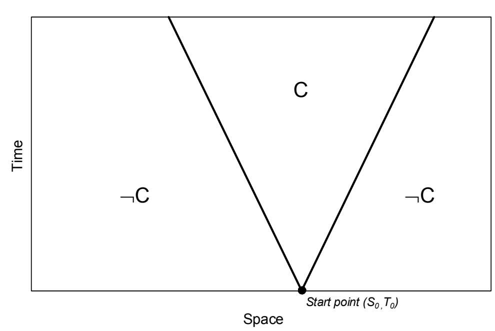

Fig. 6. Partitioning of the space-time container into *C-space* and *¬C-space* as an implication of the wayfinder's start point and maximum travel speed.

4.2. The *Y-Space* of Wayfinding

A wayfinder's maximum travel speed and a set of barriers partition space-time into additional accessible and inaccessible spaces. The inaccessible spaces, referred to as *¬Y-spaces,* result from the absolute travel restriction of these barriers. The accessible spaces that remain are referred to as *Y-spaces.*

The maximum travel speed projections through space-time create a *¬Y-space* before and after each temporary barrier with a spatial extent (Figure 7a). The *¬Y-space* before each barrier is a danger area where, if a wayfinder enters, it is impossible not to encounter the barrier. For example, if an explosion occurs when the wayfinder is in this region then injury will occur. Another way to describe this situation is that the inaccessible space (i.e. *¬Y-space)* is beyond the reaction time of the wayfinder.

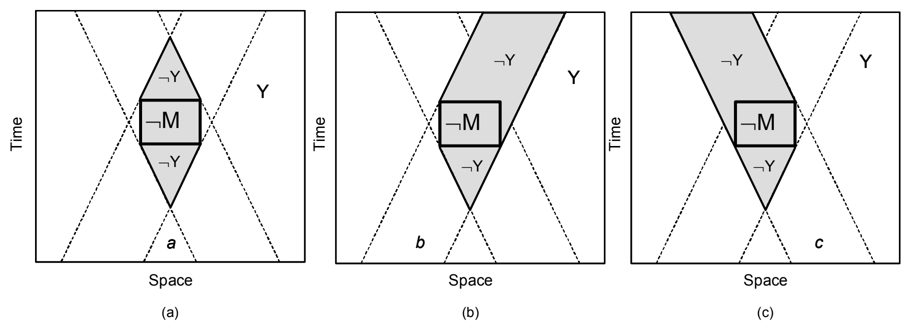

Fig. 7. A barrier combined with the maximum travel speed limitation partitions space-time: (a) when the wayfinder is in *region a*, *¬Y-space* is created before and after the barrier; (b) when the wayfinder is in *region b*, additional *¬Y-space* is created after the barrier; and (c) when the wayfinder is in *region c*, a different *¬Y-space* is created.

Barriers that partition space create additional *¬Y-spaces* that are dependent on the location of the wayfinder. For example, as shown in Figure 7b, a wayfinder in *region b* finds that the barrier creates a *space-time shadow* of *¬Y-space*. This *shadow* differs if the wayfinder is located in *region c* (Figure 7c). An example of this type of barrier is a closed bridge over a space-partitioning river. The inaccessible space resulting from the barrier, the blocked bridge, is dependent on what side of the barrier the wayfinder is located. As opposed to the *¬C-space*, the partitioning nature of the barrier creates *¬Y-spaces* that are not simply connected and in fact represent disconnect spaces.

4.3. The *H-Space* of Wayfinding

The combination of maximum travel speed and the set of compulsions create a third partition of space-time into *H-space* and *¬H-space*. The *H-space* represents *where* and *when* the wayfinder should travel while still meeting the required compulsions.

The remainder of space-time that is inaccessible as a result of meeting these compulsions is *¬H-space.* The *H-space* in a 2-dimensional spatial world is a lifeline bead and a sequence of valid compulsion objects in space-time create a connected sequence of *H-space*s as in a lifeline necklace (Figure 8, Hornsby and Egenhofer 2002).

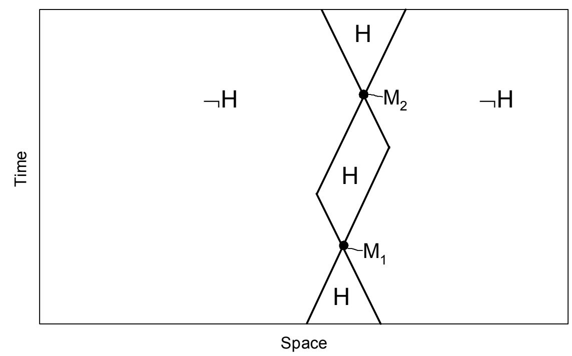

Fig. 8. Partitioning space-time into *H-space* and *¬H-space* as a result of the wayfinder's maximum travel speed and space-time point compulsions M_1 and M_2.

The various compulsion shapes (Figure 3) create different *H-spaces* and *¬H-spaces*. The implication of a compulsion over a spatial region is a much wider *H-space* than a space-time point compulsion, indicating the additional flexibility afforded to the wayfinder (Figure 9). An additional characteristic of a compulsion occupying a spatial extent is—due to the maximum speed restrictions of the wayfinder—the creation of spaces before and after each compulsion that allow us to reason that if the wayfinder travels through these spaces the compulsion absolutely will be met, denoted by H^*, or absolutely was met, denoted by H^{**} (Figure 9).

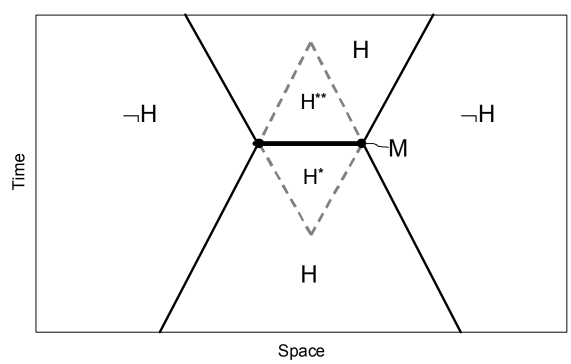

Fig. 9. A compulsion with a spatial extent creates a larger *H-space* than that created by a space-time point compulsion. In addition, spaces can be identified that indicate that the compulsion absolutely will be met (H^*) or absolutely has been met (H^{**}).

The different compulsions occurring over a subset of the available time in ST create distinctive *H-spaces*. Consider the case where a compulsion lasts only until a certain time. For example, “you *must* stay home until 8:00 am.” In this case, the wayfinder’s travel possibilities are completely restricted until after the compulsion ends and *H-space* equals the *M-space*. After the compulsion ends, the travel possibilities expand, as shown in the increasing size of the *H-space* (Figure 10a). The alternate compulsion that the traveler *must* occupy some location after a specified time creates a similar *H-space*, but oriented temporally in the opposite direction. For example, “be home by 10:00 pm.” In this case, the wayfinder’s *H-space* continually decreases as the compulsion nears until it equals the *M-space* (Figure 10b). The *during*-compulsion over a temporal interval creates an *H-space* shape that is the union

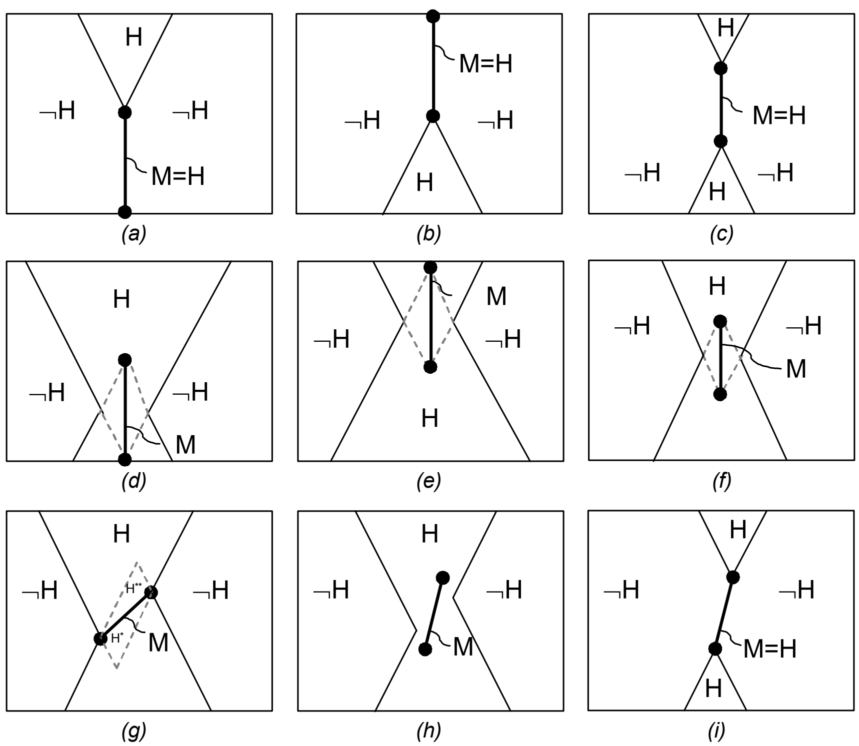

Fig. 10. Various *H-space* shapes resulting from different compulsion types: (a) compulsion to continually occupy until a specified time; (b) compulsion to continually occupy after a specified time; (c) compulsion to continually occupy during a temporal interval; (d) compulsion to occupy for an instant until a specified time; (e) compulsion to occupy for an instant after a specified time; (f) compulsion to occupy for an instant during a temporal interval; (g) compulsion to occupy for an instant moving faster than wayfinder; (h) compulsion to occupy for an instant moving slower than the wayfinder; and (i) compulsion to occupy continuously moving slower than the wayfinder.

of the two previous examples (Figure 10c). The implications of compulsions that do not require the wayfinder to occupy the compulsion space during the entire temporal interval create different *H-spaces* than those that do. These *H-spaces* are larger, indicating additional flexibility (Figure 10d-f).

The *H-space* created by a moving compulsion varies depending on whether its speed is greater than the wayfinder's maximum travel speed. A compulsion that moves faster than the wayfinder's maximum speed cannot be a valid compulsion to occupy for its entire time, but may be a valid compulsion to occupy for an instant. The *H-space* created is similar to a compulsion over a spatial extent (Figure 10g) and, therefore, spaces are created that allow us to reason about whether or not the wayfinder absolutely will meet or absolutely did meet the compulsion. Moving compulsions slower than the wayfinder may be of either type, creating *H-spaces* similar to non-moving compulsions (Figure 10h and 10i).

5. Sequential Partitioning of the Wayfinder's Space-Time Environment

The wayfinding primitives may instead of separately partitioning space-time, sequentially partition each other in a hierarchical manner. The first partition of space-time is created by combining the maximum speed limitation and the start point, yielding *C-space* and ¬*C-space*. The *C-space* is then partitioned by a set of barriers (¬M) into *Y-space* and ¬*Y-space*. This process is run once more by partitioning *Y-space* with the compulsions (M) into *H-space* and ¬*H-space*. This sequential partitioning of space-time is represented graphically as shown in Figure 11. The leaf nodes of this graph indicate the resulting spaces from a sequential partitioning of space-time: ¬*C-space*, ¬*Y-space*, ¬*H-space*, and *H-space*.

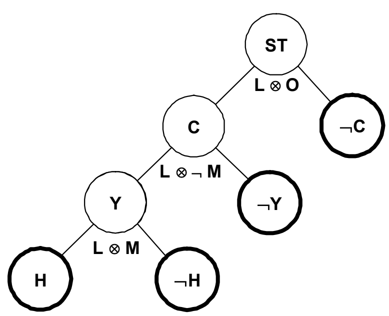

Fig. 11. Sequential partitioning of space-time with the four wayfinding primitives. Space-time is partitioned by the speed limitation L and start point O into *C-space* and ¬*C-space*. *C-space* then is partitioned by the speed limitation and the barriers ¬*M* into *Y-space* and ¬*Y-space*. Finally *Y-space* is partitioned by the speed limitation and compulsions *M* into *H-space* and ¬*H-space*. The four highlighted spaces occupying the leaf nodes of the graph indicate the results of a combined sequential structuring of wayfinder's space-time environment.

To illustrate the sequential partitioning technique, consider a wayfinding environment consisting of a maximum travel speed, a start point (S_0, T_0), a compulsion M, and two barriers $\neg M_1$ and $\neg M_2$. The maximum travel speed, combined with the wayfinder's start point, partitions space-time into *C-space* and *¬C-space* (Figure 12a). The *C-space* is then partitioned by combining the barriers with the maximum travel speed to yield *Y-spaces* and *¬Y-spaces* (Figure 12b). Finally, *Y-space* is partitioned by combining the wayfinder's compulsion with the travel speed limitation creating *H-spaces* and *¬H-spaces* (Figure 12c).

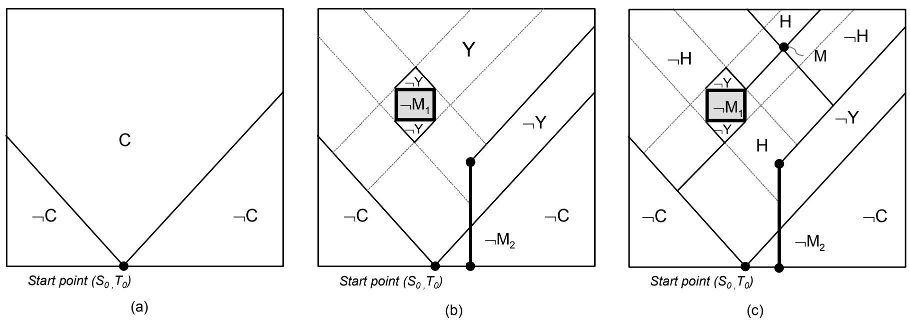

Fig. 12. The structuring of a wayfinder's space-time environment by sequential partitioning: (a) combining the speed limitation and start point to partition the space time container into *C-space* and *¬C space*; (b) partitioning *C-space*, by combining the barriers and maximum travel speed into *Y space* and *¬Y-space*; and (c) partitioning *Y-space* by the compulsion into *H space* and *¬H-space*. Spaces influencing potential *¬Y-spaces* are delineated by dashed lines.

6. Describing Partitions with Modal Verbs

To describe the partitions of the structure created with this approach in a cognitively plausible manner, the modal verbs *can, may, must,* and *should* are used. Modal verbs indicate whether things, events, or relations are actual, possible, or necessary (Johnson 1987). Sweetser (1990) argues that the meaning of modal verbs as used in the physical or social realm are similarly used for argument and reasoning. In an inherently physical act, such as wayfinding, describing spatial and temporal constraints modally provides insights for argument and reasoning of the wayfinding task.

Though each modal verb is used in various ways during normal conversations, in this approach *can* is related to a positive ability (capability); *must* denotes obligation or compelling force; and *may* is roughly associated with permission or lack of a potential barrier (Sweetser 1990). Johnson relates each of these modal verbs to various image schemata, which structure knowledge through abstract high-level experiential gestalts of common situations (Johnson 1987). For example, *must* is a compulsion; *may* is the removal of restraint; and *can* is enablement. In addition, we include one other modal verb to describe a wayfinder's space-time structure, *should*, indicating a weaker form of *must*. Defining a wayfinder's compulsions (*must*), cabilities (*can*), and permissions (*may*) while traveling through a volume of space-time provides a concise, yet simple description of a wayfinding scenario.

Modal verbs are associated with the various wayfinding primitives and the partitions of space-time. We begin by assigning the modal verb *must* (M) to compulsions and *must not* (¬M) to barriers. The modal verb *can* (C) effectively describes the accessible partition of space-time created by the combination of the start point and maximum travel speed, or the space that the wayfinder's capability allows travel to. Its complement *cannot* (¬C), describes the inaccessible spaces of this partition. The modal verb *may* (Y), effectively describes the partition of *C-space* that the wayfinder has access to based on temporary barriers in space-time. Again, its complement *may not* (¬Y) is employed to describe the spaces made inaccessible as a result of barriers in space-time. Finally, the modal verbs *should* and *should not* are employed to describe *Y-space* and *¬Y-space,* respectively. A summary of these modal verb assignments, along with example usages, is shown in Table 1.

Space	Modal Verb	Example Usage
M	*must*	"You *must* be home by 5:00 pm."
¬M	*must not*	"You *must not* cross the railroad tracks."
C	*can*	"I *can* be at the restaurant at noon."
¬C	*cannot*	"I *cannot* get to the post office by 2:00 pm."
Y	*may*	"You *may* cross the river, because the bridge is open."
¬Y	*may not*	"You *may not* be in the library at 9:00 pm, because it closes at 8:00 pm."
H	*should*	"To get to the restaurant by noon, I *should* cross the bridge before it closes."
¬H	*should not*	"To get to the post office by 5:00 pm, I *should not* go first to the grocery."

Table 1. Assignment of modal verbs to the primitives and partition spaces of the wayfinder's space-time environment.

7. Conclusions

This paper introduced an approach to structure and describe the dynamic space-time environment of a wayfinder. This structure allows for better situational awareness by providing a mechanism to reason about space-time decision points and the impacts of these decisions on future possibilities. Four primitives of spatio-temporal wayfinding were identified: the maximum travel speed, the start point in space and time, a set of barriers, and a set of compulsions. Leveraging existing space-time prism concepts with symbolic projection techniques provides a framework for combining the speed limitation with the remaining wayfinding primitives to create various forms of accessible and not accessible spaces. It was shown that the combination of the speed limitation with the start point partitioned space-time into accessible and inaccessible spaces based on the wayfinder's capability. Combining the speed limitation and the barriers created accessibility partitions based on the constraints of these barriers. The combination of speed limitation with the wayfinder's compulsions partitioned space-time into those areas that the wayfinder should and should not travel through to meet the requirements. These three partitioning mechanisms were then integrated into a sequential partitioning scheme that creates four partition categories of a wayfinder's space-time environment: *¬C-space*, *¬Y-space*, *H-space,* and *¬H-space*. To describe these spaces in a cognitively plausible manner, the modal verbs *can, must, may,* and *should* along with their complements were assigned to appropriate primitives and partition spaces.

The structure created with this approach could be represented as a directed graph. The partitions would be the nodes of the graph, and the edges would represent the ability of the wayfinder to travel between these partitions in space and time. By employing a graph to represent this structure, a rich set of theoretical and applied techniques can be leveraged to develop the structure and answer queries. For example, a simple least cost algorithm could be used to determine if a proposed compulsion is located in *H-space (should)* and, therefore, can be added to the wayfinder's travel plan. In addition, a search of the directed graph would indicate what travel options are available to the wayfinder.

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