Cognitive Structures of Space-Time

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Author contribution statement

CMS conceptualization and visualization the model, writing the original manuscript and editing subsequent versions, SDC conceptualization the model, wrote and edited the manuscript, VW conceptualization the model and edited subsequent versions, BC conceptualization the model and writing manuscript. Everyone contributed to the original hypothesis and discussions.

Keywords

causal cognition, causal structure, causality, Space-Time, compositionality

In review

Abstract

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Causation refers to relation, while space-time constitutes an abstract schema for causal connections between events, objects, and processes. Moreover, the mental representations of such events and relations seem to afford compositionality. Considering these notions, we posit an interplay between the physical structural properties of space-time and the compositional and operational modalities upon object and relational representations available to the reasoner therein. This hypothetical relation is defined and discussed. For instance, a “topological-temporal” schema, motivated by causal considerations from narrative information, might license talk of temporal precedence, succedence, and concurrency between some events, but not necessarily the duration of events, which requires an augmented “metric-topological” temporal schema to speak of the temporal distance between points in time. Therefore, our proposed model emphasizes that hierarchies of structural properties of certain space-time schema are important to explore, together with attendant considerations on the levels of complexity of settling causal queries within them. This discussion motivates advanced contributions to the psychological, physical, and philosophical discourse on causal cognition.

Contribution to the field

Causal Cognition relates to the understanding of causal relations, when and how they are identified to make relevant inferences. Nevertheless, theoretical foundations of cognitive processes underlying space-time cognition are highly neglected and devoid of interdisciplinary insights. In this perspective paper, we linked recent advances on the foundation of physical theories with a general cognitive model based on layers of hierarchies. Firstly, the notion of a stratified space and time is highlighted. Thus, space-time is hierarchically structured when the mind composes and decomposes their manifolds. Secondly, the stratified nature of space-time has strong implications for empirical studies investigating, for instance, whether humans and animals come to conceptualize the physical layout through perception (e.g. object recognition, motion perception), or there are higher-level cognitive processes involved in these perceptual abilities (e.g. imagery, navigation, planning, coordination). Finally, the model provides a theoretical background for further studies leveraging our reasoning about how space and time are entangled in cognitive processes and why.

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ABSTRACT

Causation refers to relation, while space-time constitutes an abstract schema for causal connections between events, objects, and processes. Moreover, the mental representations of such events and relations seem to afford compositionality. Considering these notions, we posit an interplay between the physical structural properties of space-time and the compositional and operational modalities upon object and relational representations available to the reasoner therein. This hypothetical relation is defined and discussed. For instance, a “topological-temporal” schema, motivated by causal considerations from narrative information, might license talk of temporal precedence, succedence, and concurrency between some events, but not necessarily the duration of events, which requires an augmented “metric-topological” temporal schema to speak of the temporal distance between points in time. Therefore, our proposed model emphasizes that hierarchies of structural properties of certain space-time schema are important to explore, together with attendant considerations on the levels of complexity of settling causal queries within them. This discussion motivates advanced contributions to the psychological, physical, and philosophical discourse on causal cognition.

In review

Keywords: Causal Cognition, Causal Structure, Causality, Space-Time, Compositionality.

1 INTRODUCTION

This article posits a hierarchy in the cognition of spacetime, analogous to a ’layer cake’ structure, where layers correspond to different aspects of causality. We derive the foundations of the layer-cake structure from physical accounts of causality, supported by a brief mathematical background. Investigating the cognitive structures of space-time governing causal cognition is central to the understanding of a general theory of intelligence in humans and artificial beings. Nevertheless, in psychology, research lags in providing a concise and systematic review of the correspondences of empirical causal structures and spatial-temporal cognition.

Given that neither space nor time can be directly accessed – we can only glean their structure by observing and interacting with objects and events – how do we establish coherent models of spacetime? Towards an answer, here is proposed that cognitive models are hierarchical, where lower layers encode structurally simpler data than higher ones, and the structure of spacetime emerges from mutual constraints between layers.

We take the most primitive representation layers to be topological, which refers to whether objects and events are ”connected”. Topology does not distinguish between the types of the lines (e.g. curved or straight); only connectedness – however defined – and its absence, disconnectedness, need be perceived. In the perception of spatial-temporal entities, connectivity and disconnectivity compositionally characterise more complex features such as being ’before’, ’after’, ’in front’, ’behind’, ’having holes’, ’discreteness’ etc.

A more complex, computationally dense and higher up layer might construct metric spaces and Euclidean structure. An example of a constraint between topology and metrics that may arise in some setting is *‘objects are connected if and only if they have zero distance from each other’*.

The layer-cake organization of spatial structures may be preserved among the fields of physics, mathematics and also psychology, leading to a natural hierarchical organization from topological space (less complex), to metric spaces (more complex). In the following sections, we explore this toy model in the context of physical causal structures (Section 2), psychological models (Section 3) and discuss its implications (Section 4).

2 LAYERS OF STRUCTURE IN PHYSICS

In review

In Physics, the analysis of the spaces representing potential states of physical systems often takes the form of a layer-cake of increasingly rich structure. The layer-cake is not merely a mathematical decomposition, but is informed by some conceptual underpinning: such as how agents interact with the subject matter, and more specifically, how the subject matter enables/restricts this interaction, or how the subject matter interacts with itself.

A first example is the analysis of relativistic space-time structure as for example in Geroch (2013); Ehlers et al. (2012). Here the levels arise from how agents interact with space-time. In Geroch (2013), like in many other such approaches, the first layer is called *causal structure* (Figure1A). It arises from the light-cones that specify which points of space-time (in the future) the agent can affect, and which points of space-time (in the past) the agent can be affected by. Mathematically, these light-cones give rise to a partial order $(P, \leq)$, where for $a, b \in P$ we have $a \leq b$ if space-time point a can affect space-time point b. Often this partial order is taken as a starting point for the development of new physics, for example, when studying quantum causality (Henson et al. (2014); Fritz (2014)), and even when crafting theories of quantum gravity (Bombelli et al. (1987); Sorkin (2003)). A second layer arises from the notion of a clock (Figure1A), which measures the progress of time and hence provides a temporal metric structure atop the partial order of events. Next comes the full space-time metric, followed by dynamical data, among others.

Moving from relativity to quantum theory (QT), following John von Neumann von Neumann (1932); Birkhoff and von Neumann (1936), the first layer is again a partial order, where ordering encodes entailment with respect to agents observing properties of quantum systems, that is, $a \leq b$ if observation of property a guarantees observation of property b. The following layers include conceptually informed universal algebraic equational structure (Piron (1976)). Note that also the entailment relationships can be viewed as a form of informational/epistemic causal structure, as it involves a guaranteed observation given a premise. This branch of quantum theory has mostly vanished from current activity within physics, but has been adopted within psychology in the field of quantum cognition (Busemeyer and Bruza (2012)).

Much more recently, in the category-theoretical analysis of quantum theory (Abramsky and Coecke (2004); Coecke and Duncan (2011); Coecke and Kissinger (2017)), rather than the interaction of agents with the subject matter, the lower levels of the layer-cake are informed by how the subject matter interacts with itself. This lowest level is fundamentally *topological*, and more specifically, what topologists call low-dimensional topology (in fact, as low-dimensional as its gets.). The structure only expresses what is connected and what is not, without bringing any other geometric notions into play. In this approach, explicit graphical wiring at once formulates and represents connectivity, so it suffices to understand the concept of 'wire' to understand this lowest layer of quantum theory (Figure1B). This, in fact, leads to an alternative justification for having this particular layer as the basis: wires are, *a priori*, conceptually primitive for human reasoners (Coecke (2005), for the indication from the title, namely "Kindergarten quantum mechanics"). An educational experiment is expected to take place during 2020 (see Coecke (2009)), aiming to show that quantum theory presented in topological terms would enable high-school students not only pass a graduate-level quantum theory exam, but even outperform university students who are taught the conventional presentation.

Within the topological approach, the notion of causality has been proven to be equivalent to the relativistic notion of causality (Kissinger et al. (2017)). Thus causality can be formulated higher up in the layer-cake (Coecke and Kissinger (2017)), synthesised and restrained by more primitive data (Figure1B). In fact, there are multiple presentations on the move from lower topological level to full-blown quantum-theory, cf. Coecke and Kissinger (2017); Selby et al. (2018), but the topological level is always the beating heart of this approach. As it turns out, natural language is governed by exactly the same topological structures, the reason being that the structure of grammar itself (Lambek (2008)), exactly matches the topological structures of QT (Coecke (2013, 2017)). Furthermore, even more general cognitive models appealing to a wide range of human senses have been shown to be governed by the same structures (Bolt et al. (2018)). The starting point here were Gärdenfors' conceptual spaces Gärdenfors (2014) which aim to closely resemble human senses, and the interaction of these senses is again governed by basic topological structures.

In review

3 LAYERS OF STRUCTURE IN COGNITION

According to previous considerations, cognition may mirror the physical structures of spacetime, or the physical structures suggested by human theories may only reflect a basic cognitive structure of human thinking[1]. Independently of these two options, the layer-cake structures given by physical theories seem to be present in our developmental understanding of spatial and spatial-temporal structure (Section 3.2). Therefore in this section, a layer-cake model is discussed as hierarchical levels of cognitive complexity, inheriting, to some extent, all the mathematical properties coming from previous developments in physics DisCoCat/InConcSpec (Coecke et al. (2010); Bolt et al. (2018)), without having to develop a new one.

3.1 Topological Layers of Cognition

The model presented here is a general framework to develop specific implementations according to requirement. The main ingredients are the division/synthesis of causal structure in terms of more primitive structure, and organizing these composite structures into layers corresponding to constraints and affordances of causal relations, and the developmental order.

We propose that the first layer compounds Topological relations, and consequently, that comprehension of causal relations across space and time prioritizes topological structures. It implies that early or primitive forms of causal cognition and specifically spatial cognition would not be highly conceptual, only involving simple notions of proximity, separation, order, enclosure, connectivity, and boundedness. As discussed later, such conceptualization may be through non-symbolic category formation where subjects have restricted

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[1] That issue together with the neural realizability will be discussed elsewhere.

access to verbal codes: for example, fundamental ideas about space are developed in infancy by motor and perceptual mechanisms and rely strongly upon sensory/perceptual data. Diagrammatically, two objects *A* and *B*, are topologically related if there is an event that connects them, which is defined by the relation *R(A,B)*. These connections are usually described by wires and objects by nodes. Under this notation, wires are relational events and circles are static objects (Figure2.

The relation events *R(A,B)* and *S(C,D)* connecting the objects of cognition described by *A*, *B*, *C* and *D* correspond to fundamental and basic notions, that eventually lead to the understanding of spatial relations. Later, other types of relation emerge, such as the effects between objects, which correspond to object interactions across primitive notions of time. These interactions define processes notated by boxes, such as *f*. More specifically, such interactions may correspond to a causal processes according to a partial order relation (Figure2A). In other words, the object *A* and *B* become causally related systems under the partial order, written $A \leq B$, meaning in the abstract that information flows unidirectionally from *A* to *B*, thus defining a second layer of structure upon systems. Notably, causal relations defined in this way among objects are not necessarily unique, as exemplified by the case of *C* and *D*. Following the notation from previous works (Coecke and Kissinger (2017)), now wires become objects/systems and boxes the causal processes among them (Figure2A).

Empirically, we abduct events from *observations* of relational spatial properties. In contrast, *processes* may encompass unobservable intervening dynamical factors (e.g. forces), which need to be constructed or reconstructed in further levels of complexity: processes correspond to abstract components of mechanisms. Therefore, the second layer would correspond to the representational/relations space associated with causal interactions, governed by the partial order relations mentioned above. We hypothesise that the gradual emergence of concepts, syntax, grammar would be associated with such higher layers, as these permit representation and reasoning with counterfactual and imaginary phenomena not immediately constrained by past experience and direct perception.

A consequence of this division is that constraint-satisfying structure on any layer, in turn, places constraints on how further layers are defined. Viewing foundational layers as abstract schema or cognitive resources (and their neural realizations) shapes the modes of access to that structure, constraining how relations take place in that schema. For instance, when we take processes in spacetime to be mutually exclusive, we can begin to fill in complex narratives. If we know that a battle and a wedding took place in the same valley, mutual exclusivity of processes and linear temporal ordering allow us to raise a fruitfully constrained set of alternative models: either the battle came before the wedding, or *vice versa* .

Hence, any layer may be viewed as an abstract space upon a lower layer, the higher further specifying instances of structure compatible with those of the lower (Figure2B). In Figure2A, the higher layer carries the particular refinement of metric structure. The precise nature of cognitive metric structures is a question for future research, and not our chief concern here. No matter the metric, according to the layer-cake model, representation and reasoning in metric spaces is more computationally intensive than in topological spaces, because higher layers carry a greater informational capacity than lower ones, and carry more constraints and affordances for the reasoner to navigate.

These emergent hierarchies are subjective to the reasoner, and not an objective feature of reality: hence, we can speak distinctly of perceived vs. objective causality. In other words, while the seemly real characteristics of spacetime affect how we conceptualize spacetime, our conceptualization in turn dynamically constrains and directs further conceptualization.

In review

Finally, a word of caution when interpreting the topological hypothesis as stated above is that different conceptions of causality and topology exist, as these are not uniquely defined concepts across disciplines, and not even in pure mathematics, where a field like topology has several very different branches of study that are qualitatively different. For example, taking path-connectedness as the primitive – where one identifies possible paths that one can take between points in space – will cause one to identify all points on the surface of a table as '*essentially the same*', whereas homology theory – where one identifies the characterising holes of a structure – will cause one to treat drinking mugs and donuts as '*essentially the same*'. The layer-cake model accommodates any and all particular formulations of topology, as it is synthetic: the fundamental ingredient of defining higher structures atop lower ones remains in play.

3.2 Supporting Evidence for the Layer-Cake Structure

There is evidence explaining how adults, children, and infants are sensitive to the topological properties mentioned above. Biederman and Cooper (1991, 1992) show that humans can complete perceptual stimuli in the absence of size, location, and orientation information, highlighting that recognition processes can be independent from the Euclidean spatial features in more abstract fashion. In fact, such topological properties may be essential to the processes of spatial cognition. Research on how topological and metric properties are established by cognitive mechanisms provides consistent evidence that people cannot act within or orient themselves to their environments unless provided spatial and temporal information constituting their physical reality (Chen (2005); Han et al. (1999); Müsseler (1999)). These results suggests the primacy of topology over more complex data.

In review

There is literary consensus that topological data underpins spatial ontologies. While Marr (1982) Marr (1982) posits a sophisticated *motion correspondence process* in the perception of an entity through time, simple topological transformations also enable observation of apparent motion (Chen (1982, 2005); Ögmen and Herzog (2010)). Rock and Palmer (1990) Rock and Palmer (1990) stress the law of 'connectedness' in early perceptual analysis, and the topological perception hypothesis suggests that shape-changing transformations experienced in the phenomenal world rely on topological transformations, for example, projected in retina with the aid of three kinds of topologial properties: connectivity, the number of holes, and the inside/outside relationship.

While attention and memory are well known cognitive resources with roles in spatial cognition (Doherty et al. (2005); Rohenkohl and Nobre (2011); Shimi et al. (2014)), various studies on object perception posit a stage where perceptual organization occurs before feature analysis. Chen (1982) Chen (1982) reports a series of experimental findings showing the precedence of topological feature detection in the visual system, further supporting the view that topological features form conceptual foundations. Pomerantz's (Pomerantz (1981); see also Todd (1998)) configural superiority effect supports the hypothesis, in the sense that features can be observed even in response to stimuli that are not fully configural, as configural information is already present at early stages of visual hierarchy (see also Fox et al. (2017), for neural evidence).

The developmental evidence is in accord with the layer-cake hypothesis. Using both linguistic and nonlinguistic tasks Piaget (1959), and Piaget and Inhelder (1971) pioneered the argument that infants' perceptual space is qualitatively different from that of adults. At the beginning fundamental spatial concepts are not Euclidean, but topological, which involves some concepts such as proximity, separation, order, enclosure, long before it becomes metric. This suggests that the infant's space must be quite fluid, not objective, nor occupied by rigid shapes or sizes, or contain higher order relations as experienced in three-dimensional space-time. Infant studies further inform us that primitive forms of spatial-temporal properties are detectible based on some basic principles very early on. For instance, infants appear to show sensitivity to moving objects along ‘continuous’ paths, and also pay attention to interactions only if they are causally in contact (see Leslie (1984); Leslie and Keeble (1987); Spelke et al. (1992); Spelke (1994); Spelke et al. (1995a), see also Darcheville et al. (1993), for how infants learn about space as a function of the temporal intervals). However, they do not perceive objects to be related on the basis on noncausal qualities such as colors, forms, edges, or surfaces (Kellman and Spelke (1983)). Instead, they rely on simple forms of spatial-temporal information to distinguish different types of objects and events (see Slater et al. (1994); Spelke et al. (1995b); Needham et al. (1997); Wilcox and Baillargeon (1998); see also Kaufman et al. (2003), for evidence how spatial-temporal stimuli are processed by different visual streams). These studies propose consistent evidence for the early sensitivity to topological spatial-temporal features such as continuity, connectivity, and their causal aspects.

These early fundamental ideas about space-time develop largely by embodied motor and sensory activities. Young children experience the most primitive spatial-temporal properties via watching, touching, and movement. The development of symbolic cognitive resources, such as memory and language, enables spatial-temporal properties to become more representational, allowing young children to mentally evoke objects in their physical absence. Understanding of or paying attention to metrics and Euclidean structures emerge as a function of the development of these internal and external resources and models (e.g. a child learns how to stack the smaller object into the big ones, or improve projective and perspective taking skills.). *Contextual* consistency of spatial models appears to develop later than spatial models of individual closed objects. For instance, at early stages, children may draw human beings bigger than a house in size, while the orientation of both human and house may respect gravity, and relative placement of appendages and windows all correct for both human and house. The primary context in which size consistency is obtainable is the embodied motor-sensory paradigm: at the same physical distance from a human and a house, the human image has a smaller angle of subtension in the infant’s field of vision.

The developmental literature underlines the myriad ways in which spatial-temporal properties are experienced and employed in service of causal cognition, in accord with the layer-cake hypothesis where causal relations are predicated upon spatial-temporal foundation layers. The most studied spatial-temporal attributes in causal cognition literature are properties high in the layer-cake: distance, duration, velocity, and spatial-temporal incongruences (Bullock and Gelman (1979); Bullock et al. (1982); Siegler and Richards (1979); Wilkening (1981); Wilkening and Cacchione (2011)). Given that these studies sample either older children or adults, a comparison between these and early infancy studies implies that the more children/humans are able to utilize spatial-temporal properties in Euclidian fashion, the better they can acknowledge causal relations. Although the grasp of causal relations requires the organization of connections across space and time in topological sense and this is critical for visual function at any age, the genuine understanding of cause-effect relations matures when we define the richer causal geography of spacetime.

4 CONCLUSIONS AND FUTURE RESEARCH

The layer-cake hypothesis provides a meta-model of spacetime cognition. The main argument of this conceptual model is that spatial and temporal qualities increase in their complexity across mutually constraining layers of description, ranging from the topological to metric, temporal, and causal, for models of physical or virtual/abstract spaces. It is the layer-cake taken as a whole that can be considered the full model. The hierarchical organization of layers is a novel form to study this complexity of the spatial-temporal relations in both physics and psychology, providing rich enough model to capture not only the

In review

interaction of multiple dimensions of abstractions, but the internal dynamics of constructing cognitive models from empirical data, fed by the reciprocal interactions between perception, action, and reasoning about space, time, and causality.

The layer-cake hypothesis is adaptable but crucially for science, defeasible, as it must always be instantiated to provide concrete models. These instantiations compatibly formalise a broad range of current approaches to cognition of causality across space and time. Previously, Newcombe and Shipley (2015) and Uttal et al. (2013) studies underlined how the intrinsic/extrinsic and static/dynamic relations between entities inform us about the characteristics of spatial elements, which may be modelled as graphical calculi on suitably encoded layers of a layer-cake. Developmental origins of thinking about past, current, future situations (Friedman (2003); McCormack and Hoerl (2005)), either in segmented, speeded, or imagined protocols (Dündar-Coecke et al. (Submitted)) may be formalized in the physicist's language of logics upon partial orders on events, again amenable to graphical and layer-cake methods of representation and reasoning. Layer-cake models are well-suited to novel developmental studies in calibration and approximation of spatial-temporal attributes on virtual displays (Dündar-Coecke (2019)), where the spatial environment is distanced from the young reasoner by a layer of abstract representation, as layer-cakes have tunable levels of abstraction built-in. The question of whether this paradigm finds implementational reality inside brains (as suggested by Signorelli (2018)) and the discussion of the feasibility of layer-cake models in terms of neural structure will form part of further extensions to this programme[2].

In review

CONFLICT OF INTEREST STATEMENT

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AUTHOR CONTRIBUTIONS

CMS conceptualization and visualization the model, writing the original manuscript and editing subsequent versions, SDC conceptualization the model, wrote and edited the manuscript, VW conceptualization the model and edited subsequent versions, BC conceptualization the model and writing manuscript. Every author contribute to the original hypothesis and discussions.

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[2] An extra hypothesis derived by previous discussion is to consider that causal cognition and space-time are additionally constructed among relations between each other, cognitive and neural capabilities may shape our conception of space-time while simultaneously space-time, as relational to us, is constraining and shaping our cognition.

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FIGURE CAPTIONS

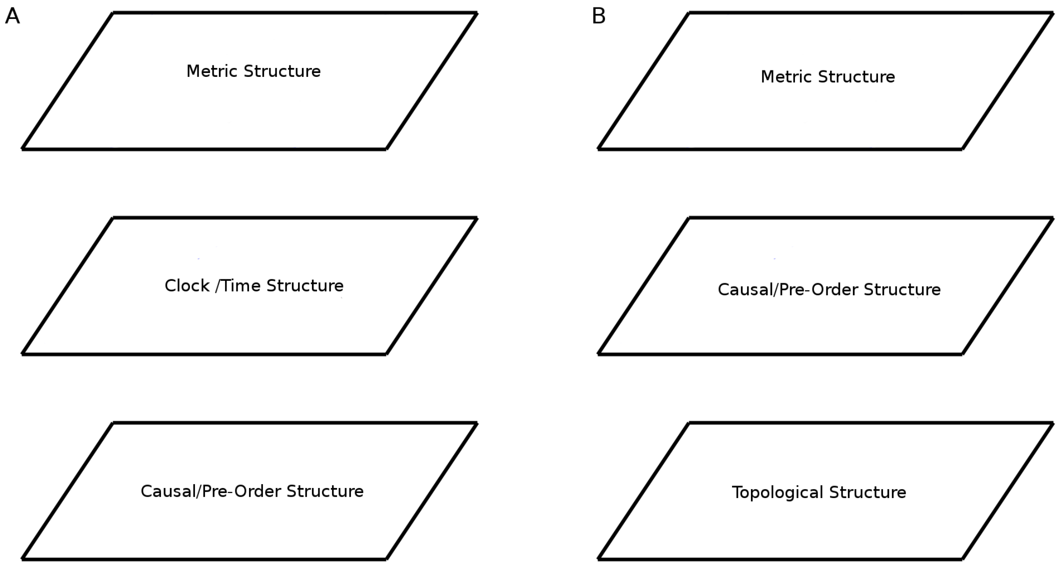


Figure 1. Layer-Cake Structure. A) The layer structure of Relativistic Space-Time. B) The layer structure of Causal process theories and the hypothesized layer Causal structure for Cognition.

In review

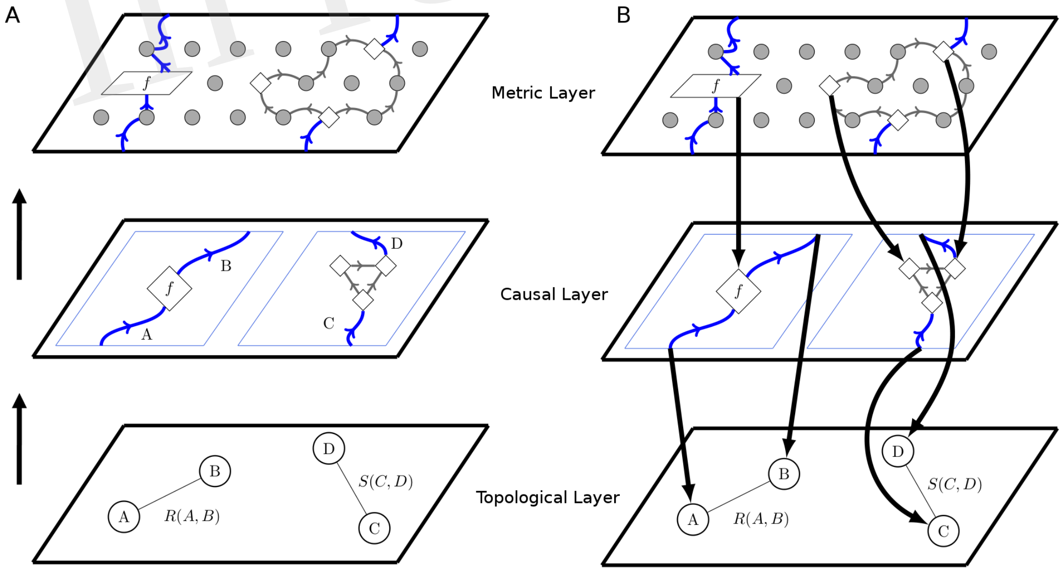
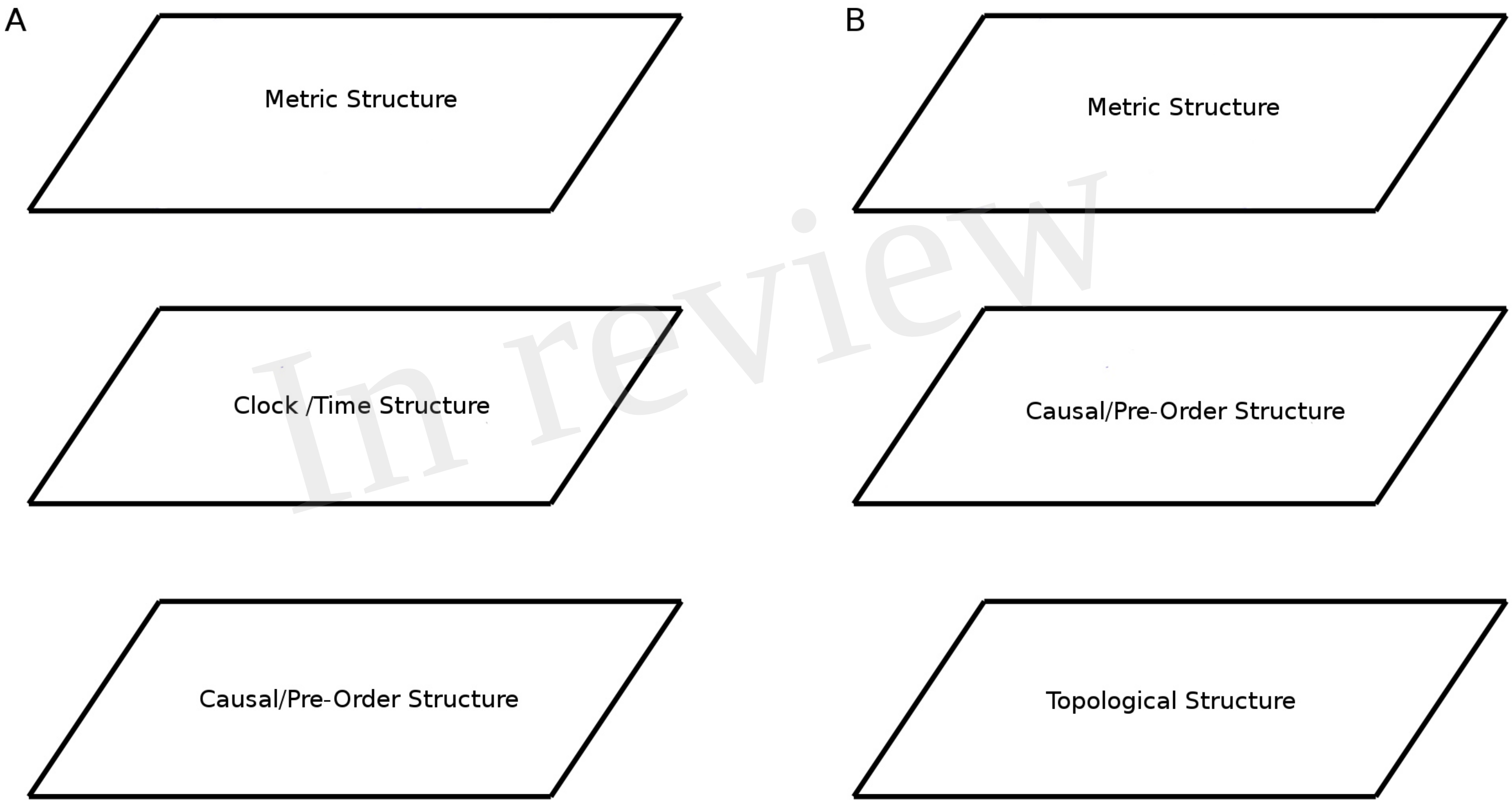


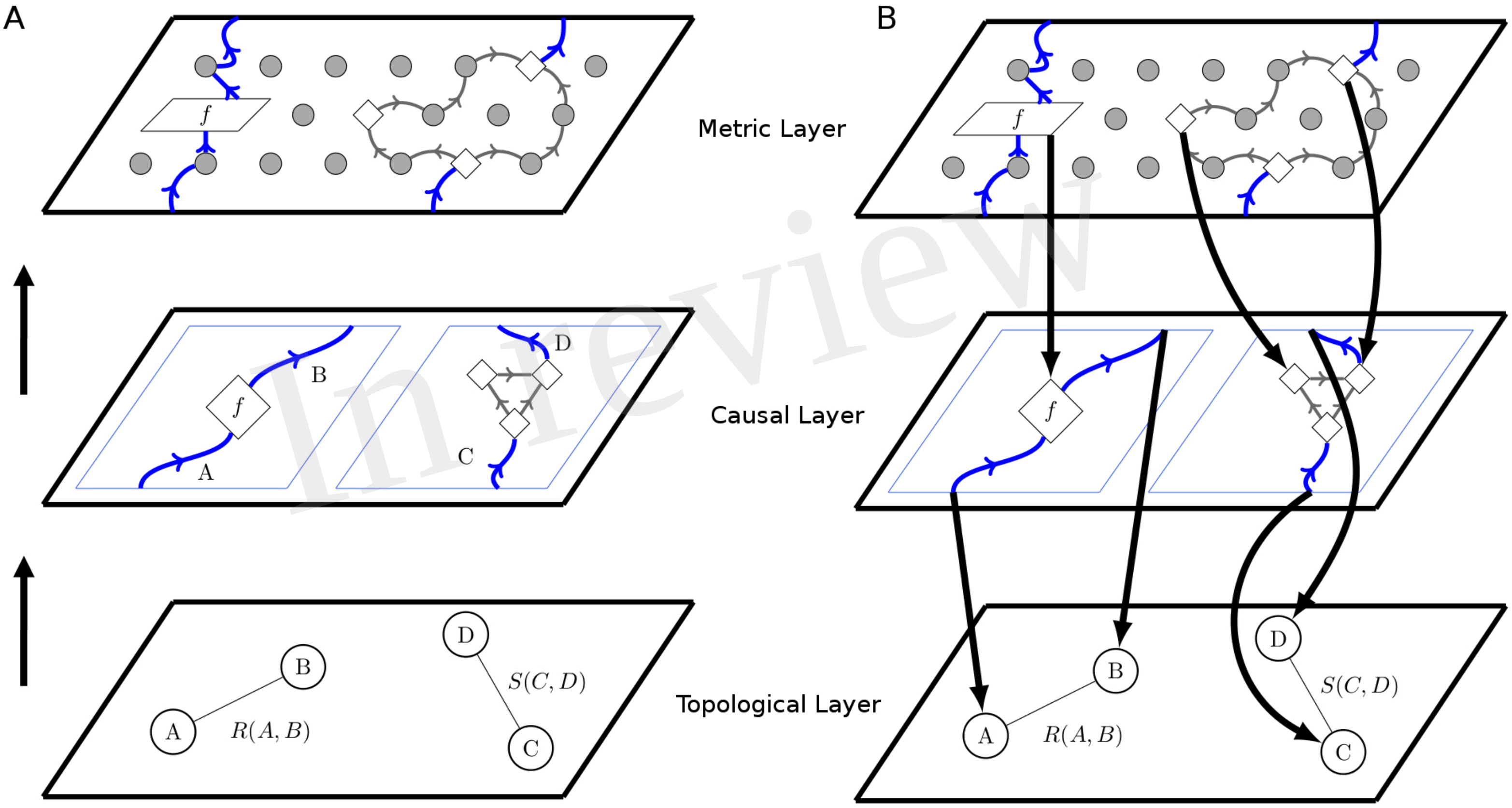
Figure 2. Layer Structure for Cognition. A) Topological Structure is relational and increase in complexity as we rise through the layers. In the topological layer, circles represent objects and wires topological relations between objects. Then, causal structure, in the form of process theories is build on top of topological relations from the lower layer. In this second pre-order or basic causal layer, objects become represented by wires and causal relations by processes. Finally, the metric layer adds metric structure, which elaborates causal structure in a suitable, spatial and temporal setting. This condition is given by the black dots in the figure. B) This layer division generates a hierarchical structure, where higher layers are structurally constrained by the data of lower layers as well as they can influence part of the lower configuration.

Figure 1.JPEG



In review

Figure 2.JPEG



In review