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Citation: Besold, T. R., Hedblom, M. M. & Kutz, O. (2017). A narrative in three acts: Using combinations of image schemas to model events. Biologically Inspired Cognitive Architectures, 19, pp. 10-20. doi: 10.1016/j.bica.2016.11.001

This is the accepted version of the paper.

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Permanent repository link: http://openaccess.city.ac.uk/18661/

Link to published version: http://dx.doi.org/10.1016/j.bica.2016.11.001

A narrative in three acts: Using combinations of image schemas to model events

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Abstract

Image schemas have been proposed as conceptual building blocks corresponding to the hypothesised most fundamental embodied experiences. We formally investigate how combinations of image schemas (or 'image schematic profiles') can model essential aspects of events, and discuss benefits for artificial intelligence and cognitive systems research, in particular concerning the role of such basic events in concept formation. More specifically, as exemplary illustrations and proof of concept the image schemas OBJECT, CONTACT, and PATH are combined to form the events BLOCKAGE, BOUNCING, and CAUSED_MOVEMENT. Additionally, an outline of a proposed conceptual hierarchy of levels of modelling for image schemas and similar cognitive theories is given.

Keywords: Image schemas, Cognitive primitives, Concept formation, Formal modelling, Cognitive systems

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Introduction

Already remarkably early during their cognitive development, children are able to reason about cause and effect on object relations and can also conceptualise simple events (Sobel & Kirkham, 2006). This capacity comes about long before the development of language, and before both social or mathematical understanding becomes part of the individual's capacities. Even in the first stages of cognitive development humans are capable to predict the outcome of objects' interactions in simple events. For example, a child early on registers that dropped objects will fall to the floor. It seems absurd that this realisation might be based on a sufficiently complete mathematical understanding of the physics behind gravity (the presence of which is quite doubtful even in grown adults). Instead, the prediction is more likely rooted in a simplified conceptualisation of gravity, or rather, the experienceable effects of gravity learned by some form of 'statistical inference' conducted over the child's sensorimotor experiences and relevant observations from the environment.

Embodied theories of cognition aim to explain how this type of conceptualisation comes about, emphasising sensorimotor processes as a crucial foundation of cognitive development and concept formation (Shapiro, 2011). At present it remains largely unknown how this supposed embodied experience manifests in detail, for example whether as mental representations (Barsalou, 2008) or as neural activations in corresponding areas in the sensorimotor cortex (Gallese & Lakoff, 2005). Still, while there are conflicting views regarding to which degree cognition indeed is or has to be embodied, there is growing agreement that in practice the body's interaction with the environment is a determining factor in the development of an understanding of the world and in the emergence of concepts. This position receives increasing support by independent findings from several disciplines, including cognitive linguistics, psychology, and neuroscience (cf., for instance, the work by Tettamanti et al. (2005); Feldman & Narayanan (2004); Wilson & Gibbs (2007); Louwerse & Jeuniaux (2010)).

Already for reasons of reasoning and representation efficiency—as well as due to the expectable complexity of a theory formation process based on observations from the environment, rather than on experimentation in a scientific setup—it appears unlikely that embodied experiences would mentally manifest as full-fledged theories, in a mathematical sense modelling and explaining the underlying physics of object manipulation. Instead, it seems much more plausible to assume that embodied experiences are used as basis for an abstraction process into generic building blocks, discarding much of the instance-specific and fine-grained information. One approach that aims to capture these abstracted experiences is the theory of image schemas (see Hampe & Grady (2005) for an overview). It suggests that (part of) the embodied experience can be explained using a set of spatio-temporal object relations, with CONTAINMENT, SUPPORT, LINK and PATH-following serving as classical examples. These and similar image schemas are then investigated, among others, in how they manifest in psychological development (Mandler, 2004) and language constructions and acquisition (Hampe & Grady, 2005). Also, for Oakley (2010) 'image schematic profiles' represent how conceptualisations of events can be described using combinations of image schemas.

Starting out from a similar intuition, the present article constitutes a first step in the investigation of the process with which image schematic abstractions can, when combined with one another, actually model simple events (formally). This question is approached from a conceptual level, but also from a formal and computational level with the motivation that modelling image schematic combinations may aid the development of event comprehension in artificial intelligence (AI). For this purpose, the already mentioned PATH-following schema (hypothesised as one of the most basic image schemas) is combined with other basic image schemas to illustrate how a conceptualisation of events such as 'blockage', 'bouncing' and 'caused movement' may develop. In the next section, "Theoretical and conceptual foundations", we summarise essential parts of the theory of image schemas and clarify some basic concepts relevant in the context of this article, as well as in the study of image schemas in general. Building on these conceptual foundations, the section "Formally combining image schemas" then presents the main contribution, namely a (computationally usable) formal model of the combination of several primitive image schemas into a more complex schema. Also, and of equal importance, an initial proposal for a hierarchy of several different levels of models (corresponding to different granularities of conceptualisation and explanation) for notions from the context of cognitive theorising, such as image schemas and similar phenomena, is put forward. Section "Conclusions and future work" then concludes the article, summarising what has been achieved and outlining future work towards a comprehensive formal and computational theory of image schemas applicable also in AI and cognitive systems.

Theoretical and conceptual foundations

In this section, we introduce the necessary concepts from basic image schema theory as developed in previous studies on image schemas, and also clarify the intended meaning of several central notions relevant in this context. Before focusing on image schemas proper, we therefore start with a working definition of the notion of "event".

Conceptualising "events" in the context of image schemas

Throughout this article, events are to be understood as defined, for instance, by Galton (2012). For our purposes an event therefore "*(...) is a temporally bounded occurrence typically involving one or more material participants undergoing motion or change, usually with the result that at least one partipant [sic!] is in a different state at the end of the event from the beginning*".[1] This notion of event is also well-suited to an embedding in the context of narratives (which are to be understood as reports of connected events presented in a sequential manner as mental images, written or spoken words, visual scenes, and/or similar), particularly when allowing for participants that only exhibit a 'derived materiality'. Precluding the more detailed introduction of image schemas in the following section, this is of importance since in the context of cognitive development and concept formation, Mandler & Pagán Cánovas (2014) also conceptualise image schemas from a narrative perspective (and locate them within a conceptual hierarchy of increasingly complex mental constructs): "*Spatial primitives are the first conceptual building blocks, image schemas are simple spatial stories built from them, and schematic integrations use the first two types to build concepts that include non-spatial elements.*"

Introducing image schemas

Simply put image schemas are thought of as generic pre-conceptualisations that allow us to mentally structure our experiences and perceptions. Supposedly learned

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[1] The precise ontological nature and status of events has for a long time been, and still is, an open question and lies outside the focus of the present article. We direct the reader, for instance, to Bach (1986) for a classic account on the classification of events and their internal structure. Alternative proposals have also been made by Mourelatos (1981); Mani et al. (2005); van Lambalgen & Hamm (2005), among others.

from embodied experiences they are often spoken of as object relations situated within a spatio-temporal dimension.

Important parts of the intuitions and conceptual ideas underlying image schemas can be traced back already to, among others, the notion of the Kantian 'schemata' (Kant, 1998). In Kant's theory of schemata, the idea of how non-empirical concepts could be associated with sensory input was introduced. In the first half of the 20th century, Piaget (1952) then looked at human development from infancy to adulthood. According to Piaget, cognitive development goes through four stages before reaching maturity. The first of these is the "sensorimotor period" in which cognitive understanding emerges from sensorimotor experiences. This research hypothesis lies at the foundation of embodied theories of cognition (Shapiro, 2011). In the 1970's, cognitive linguistics and psycholinguistics gained influence in the cognitive sciences and became increasingly connected to theories of embodied cognition as the spatial nature of language was brought to light. During the last decades, eventually research methods from neuroscience became increasingly important in answering questions regarding cognitive phenomena, among others further supporting the main ideas of embodied theories of cognition (cf. Gallese & Lakoff (2005); Feldman & Narayanan (2004); Aziz-Zadeh & Damasio (2008), among others).

Against this backdrop, the theory of image schemas was developed and introduced by Lakoff (1987) and Johnson (1987) simultaneously. Tying back into Piaget's aforementioned theories about development during the sensorimotor period, image schemas are thought to develop in early infancy, as the body physically interacts with and perceives its surroundings. A paradigmatic example is the VERTICALITY (or the UP-DOWN) image schema. It is thought to develop as a result of the body's own vertical axis (Johnson, 1987). Still, as already stated previously, while children quickly learn to predict that objects will fall when dropped—a process spatially unfolding mostly in the vertical dimension—, it is unlikely that they have gained understanding of the physics behind gravity in any mathematical sense (i.e., having developed a mathematical theory of gravity and corresponding force dynamics). Instead it is suggested that the abstracted information presented in image schemas is the cognitive component with which infants make predictions about the world.

Image schemas are often confused to be abstract visual representations, partly due to the (somewhat unfortunate) terminology and partly due to the proportionally high representation of vision in our perception. However, as Oakley (2010) points out, "*image schemas are neither images nor schemas in the familiar sense of each term as used in philosophy, cognitive psychology or anthropology*". Instead, in the same way that embodied experiences are multimodal, so are image schemas. For instance, auditory experiences appear more abstract and have therefore a distinct logic and different expressions than the ones found solely in vision and more concrete situations. As an example, a piece of music may be "shared" between an audience in a completely different way than a piece of cake could be. Also, sounds can be shared by multiple receivers in ways that visually perceived objects may not (and vice versa). The way we abstract away from auditory experiences might, thus, differ greatly from the corresponding process for visually perceived experiences—and similar for other sensory modalities and/or combinations thereof. It is therefore important to make the distinction that image schemas are not simply abstract visual representations but are of a genuinely different nature and quality.

Due to the complexity of trying to exhaustively identify and pinpoint the essential abstract image schemas, there is currently no agreed upon list which captures all the image schemas that are assumed to be involved in human cognition. VERTICALITY, mentioned above is only one of many image schemas presented in the literature. Other commonly mentioned image schemas are, for instance, CONTAINMENT, CONTACT, SUPPORT and PATH.

The motivation behind image schemas

The idea at the core of image schemas is that with the accumulating experience a child has with its environment, image schemas become increasingly fine-tuned and more specialised for the context (Rohrer, 2005). While there are conflicting definitions and terminology in the literature regarding image schemas, the general consensus is that complex image schemas result from combining elements taken from various, simpler image schemas and image schematic components (Oakley, 2010).[2] An example of the complexity of each image schema can be found in the work of Hedblom et al. (2015) where the SOURCE_PATH_GOAL schema has been broken up into a family of movement image schemas structured, among other dimensions, along the usage of the conceptual primitives presented by Mandler & Pagán Cánovas (2014).

One motivation for image schemas is the way in which they offer a cognitive benefit to perform information transfers unto unknown domains. Image schemas model the skeletal knowledge about a concept that can be analogically transferred between different domains (encompassing defining features and relations, but leaving aside details of particular instances). If the image schema CONTAINMENT has been learnt by exposure to everyday events (such as “embraces”, “entering/exiting” houses, and through the simple activity of “eating”), this understanding that “objects can be within other objects” can be transferred to other situations. Having grasped the notion of CONTAINMENT the infant—provided it has sufficient knowledge about the involved objects/domain elements—can predict that water will remain in a glass when poured therein, that people can be in cars, etc. The corresponding knowledge transfer becomes an essential part of cognition and can, as the cognitive development reaches increasingly more abstract understanding in early adolescence (Piaget, 1952), provide a foundation for abstract thought as well. Image schemas can be found to explain abstract concepts in music (Antović, 2009; Antović et al., 2013), mathematics (Lakoff & Núñez, 2000), and time (Boroditsky, 2000). Time is particularly interesting as it often is viewed as a spatial PATH on which events are perceived as ‘physical’ OBJECTs (van Lambalgen & Hamm, 2005).

The way image schemas are used to conceptualise abstract concepts is demonstrated in how image schemas sometimes constitute the transferred information in metaphors (Kövecses, 2010). More concretely, for example, CONTAINMENT is an

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[2] These components are a research field in its own, but they are often considered in image schema research as well. Here, spatial or temporal components construct more complex image schemas. Some influences are Mandler (1992)’s conceptual primitives, Talmy (2005)’s spatial schemas and Wierzbicka (1996)’s semantic primes.

important image schema in the conceptualisation of mental or affective states: "one can *get out of* a depression" and "people *fall in* love". Likewise, the VERTICALITY schema is often used to explain points on the emotional scale "happiness/sadness" and social status, for instance, "to be *high* in spirit", "to feel *down*", and "*to climb* the career ladder". Another important note is that image schemas can be both static and dynamic. From a formal point of view it might be beneficial (i.e. simpler) to focus on the static image schemas alone. However, this comprises a major simplification and is not cognitively adequate, as image schemas also essentially model change over time. The notion of CONTAINMENT is, in its most basic form, defined as the relationship of an inside, an outside, and a border (Johnson, 1987). Yet, looking at cognitive development, it is not this relationship that the understanding of CONTAINMENT seems to stem from. Instead, it appears as though the most important grounds for image schema development lie in the change over time, here the movement IN and OUT of a container (Mandler & Pagán Cánovas, 2014). Mandler & Pagán Cánovas (2014) pointed out that image schemas are "spatial stories" that in early infancy shape cognitive development. Conceptually, an image schema can be seen as a kind of generic event (as characterised above).

Oakley (2010) motivated the role of image schemas in complex conceptualisations such as "going to the library" by what he called "image schema profiles". The conceptualisation of the scenario is described using a series of image schemas, namely:

- SOURCE_PATH_GOAL
- CONTAINMENT
- COLLECTION
- PART_WHOLE
- TRANSFER
- ITERATION

Through conceptualisation of events over time, these image schemas go through "image-schema transformations". Building upon these combinations of image schemas to model conceptualisation of events—and taking the metaphor of image schemas as cognitive building blocks quite literally—we aim to explain how simple events in early infancy may be conceptualised using "image schema combinations" or "image schema profiles".[3]

Work on formalising image schemas

Despite image schemas' original status as an abstract, cognitive phenomenon work on developing a theory and corresponding formalisations has become an increasingly common sight in the context of cognitively-inspired AI. This is mainly due to the prospect of image schemas offering a systematic approach for conceptualisation and concept acquisition based on embodied theories. One major problem, however, is how to formally represent them in an adequate but still computationally usable way.

Research in AI building on the processing of sensorimotor experiences includes connectionist models as, for instance, described by Regier (1996), which learn to classify visual stimuli into linguistic categories. Similar in approach, but with direct connection to the theory of image schemas, is the work by Nayak & Mukerjee (2012), who developed a system that, based on video input of OBJECTs moving IN and OUT of containers, learned the concept of CONTAINMENT. Another system is *Dev E-R* (Aguilar & Perez y Perez, 2015) which models the sensorimotor stages in cognitive development and fine-tunes its knowledge based on the amount of visual stimuli. More theoretical investigations of how image schemas are involved in formal domains have been re-

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[3] Presumably, this approach does not have to be restricted to simple events in early infancy. As stated before, one of the benefits of image schemas lies in their partially generalised nature, which enables transfer of knowledge or expectations onto novel situations. For instance, if the image schema of SUPPORT has been learnt through perceptual exposure of "plates on tables", an infant should have an advantage in inferring that table-like objects such as "desks" can SUPPORT "books" as well. As the environment becomes increasingly complex for the infant, this information transfer could become a fundamental part of cognition and concept understanding. Concepts such as "table" become connected to the SUPPORT image schema, concepts like "cup" to CONTAINMENT, etc. In this way image schemas can also be conceived to provide a form of model and representation for affordances (Kuhn, 2007), and also fairly complex social or abstract concepts could be described by combining image schemas (for example "marriage" could be viewed as a combination of LINK and PATH (Mandler, 2004)).

ported by Lakoff & Núñez (2000). There they illustrate how image schemas—through the experience of embodied metaphors—form the foundations for abstract concepts in mathematics. Using basic image schematic structures such as the PATH-schema they suggest how, for instance, basic arithmetic or a notion of rational numbers can mentally be developed by the child and then, taking into account further experiences and image schemas, be evolved into increasingly abstract mathematical concepts.

While these and similar efforts demonstrate how the development of abstract concepts may be approached in a constructive way within the framework of cognitive science and image schemas, it does not in itself provide any answers on how to formally treat the problem. Frank & Raubal (1999) presented a then up-to-date review of attempts to formalise image schemas. Among others they discussed the progress representing them with calculi or in function representations, and also proposed a method on how to formally structure image schemas using relation calculus both on a large-scale and small-scale. Bennett & Cialone (2014) approached the problem from a linguistic and formal perspective. With the desire to map image schematic language structures to a logic for ontology development, they searched for synonyms to the CONTAINMENT image schema (contain, surround, enclose, etc.) in a text corpus from biology. By relating to the well-known RCC-8 topological relations (Randell et al., 1992), they identified and formally represented eight different kinds of containers. Fuchs (2013) also uses the natural sciences as a domain to identify the role of image schemas. In his work, he outlined how image schemas are involved in narrative by looking closer at the concept of force as frequently evoked in physics. He motivates his research not only by the question of how children learn these abstract concepts in infancy, but also by how image schema narratives may aid education for adults.

Hedblom et al. (2015) conducted a study that aimed to track the different image schemas within one family. Looking at the SOURCE_PATH_GOAL image schema, they represent a multitude of image schemas within a 'PATH-family' (see Figure 1), rather than a single individual theory. The interlinking theories were motivated by "spatial and conceptual primitives" identified from research in developmental psychology (Mandler & Pagán Cánovas, 2014), and expressed in a computationally usable format using the

DOL[4] meta-language (Mossakowski et al., 2015) and an axiomatisation in Common Logic (ISO/IEC 24707, 2007).

In a second study by Hedblom et al. (2016), the possibilities of using formalised image schemas as the conceptual building blocks during formal concept invention were discussed. The corresponding ideas build on Fauconnier & Turner (1998)'s cognitive theory of conceptual blending, a theoretical framework for creative thinking in which novel concepts are developed by means of a selective "merge" of already known concepts. This theoretical framework for concept invention was further formalised in the EU FP7 project COINVENT[5] (cf. Schorlemmer et al. (2014)) building on a more abstract formal rendering of the ideas underlying blending, cf. Kutz et al. (2010, 2014). One of the core ideas of Hedblom et al. (2016) in this context was to introduce formalised image schemas as a means to control the selection of shared aspects during the process of selectively combining the concepts.

The different lines of work described up to this point focused on identifying the different notions within one image schema, or one image schema family. Another contribution to the field is the research carried out by Kuhn (2002, 2007). Working top-down he uses WordNet (Fellbaum, 1998) to extract the image schematic structure from expressions and concepts, followed by formally representing the extracted image schemas. Kuhn (2007)'s work was taken up and further developed by Walton & Worboys (2009) who aimed to express how image schemas are connected to one another and could be combined by visually representing the intersections with bigraphs. Finally, work that particularly aims to model the events that image schematic combinations give rise to has been conducted by St. Amant et al. (2006). They introduce what they call the 'Image Schema Language' (ISL) as a formal way to demonstrate how image schemas link to one another during sequential events. St. Amant and colleagues then further developed ISL by integrating it into an artificial system modelling cognitive development called the 'Jean System' (Chang et al., 2006).

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[4] The DOL language was adopted by the Object Management Group (OMG) in 2016 (DOL FTF-Beta, 2016).

[5] See `http://www.coinvent-project.eu`

Still, in summary it has to be noted that much of the work focusing on formalising image schemas has been conducted with the intention to model language, and little attention has been devoted to the potential of combinations of image schemas as a model for events. In what follows, we will look closer at a few particular image schemas and demonstrate how the combinations of these image schemas gives rise to more complex image schemas and simple events. The conceptual demonstration is combined with a formal logical representation in the section "Formally combining image schemas" in order to motivate how AI and cognitive systems could put the theory of image schemas to use in the modelling of events.

The image schemas OBJECT*,* CONTACT *and* PATH

For the purpose of illustrating the just described idea of combining simple image schemas into more complex ones, the image schemas that will be used in our examples need proper introductions. The main schemas are OBJECT, CONTACT and PATH-following.

The first one, OBJECT, basically describing the objecthood of an entity, is controversial within the research field. The reason for this is that there are inconsistent views on whether this is an image schema, a spatial primitive, or if this kind of concept even is to be counted as image schematic at all (cf. Santibáñez (2002)). Regardless, objects—either as concrete physical entities or in some cases even as abstract notions—are involved in events and need to be considered when aiming to formally represent the latter.

The second important image schema is CONTACT. It consists of two (or more) objects that are physically touching. Important to distinguish here is that the objects are not allowed to be dependent on each other from any force dynamic perspective. If they were to be dependent on each other, two more complex image schemas would come into existence: First, if one object depends on another one, it captures the image schema SUPPORT, and second, if both image schemas depend on each other, this represents a LINK. CONTACT is spatial in nature, and after having been learnt it does not need to be temporal or change over time. From a practical point of view all it requires is a time point (or an interval) t in which the objects are touching.

The third and most important image schema for our purposes is PATH-following. Mandler & Pagán Cánovas (2014) define PATH-following in its simplest form as "*movement in any trajectory*". Children pay much attention to moving objects, favouring PATH to be one of the first image schemas to be learnt (Rohrer, 2005). Often when this image schema is concerned the term SOURCE_PATH_GOAL is used, implying not only a "source" and a "goal" for the movement, but also a particular "trajectory". Consequently, the PATH-following schema has several layers of complexity. Hedblom et al. (2015) presented a hierarchical structure and an axiomatisation of the PATH-following image schema, reproduced in Figure 1. In their hierarchy, the first level is MOVEMENT_OF_OBJECT, and when a trajectory is included they call it MOVEMENT_ALONG_PATH. For the purpose of this paper, MOVEMENT_ALONG_PATH will offer a sufficient level of complexity, with an object x, a path or trajectory p, and time points t_n on the path, which—in a simplified way—illustrate the temporal dimension of the image schema.[6]

In the following section we will now proceed with discussing and formally illustrating how these image schemas may be combined with one another in order to represent simple events.

Formally combining image schemas

In similarity with how LEGO blocks are combined to generate complex structures, image schemas can be combined to generate more complex image schemas and consequently explain increasingly complex scenarios and concepts. This may seem straightforward, however, the following two problems need to be addressed.

- A fundamental challenge is to differentiate between image schema combinations and image schema components with atomic structure. This is a non-trivial problem. Image schemas have a gestalt structure as for each image schema all components are essential (Lakoff & Núñez, 2000). Using CONTAINMENT as

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[6] In reality, path and trajectory may differ as the path represents the actual movement and the trajectory the anticipated movement. However, it is unnecessary to make this distinction at this point.

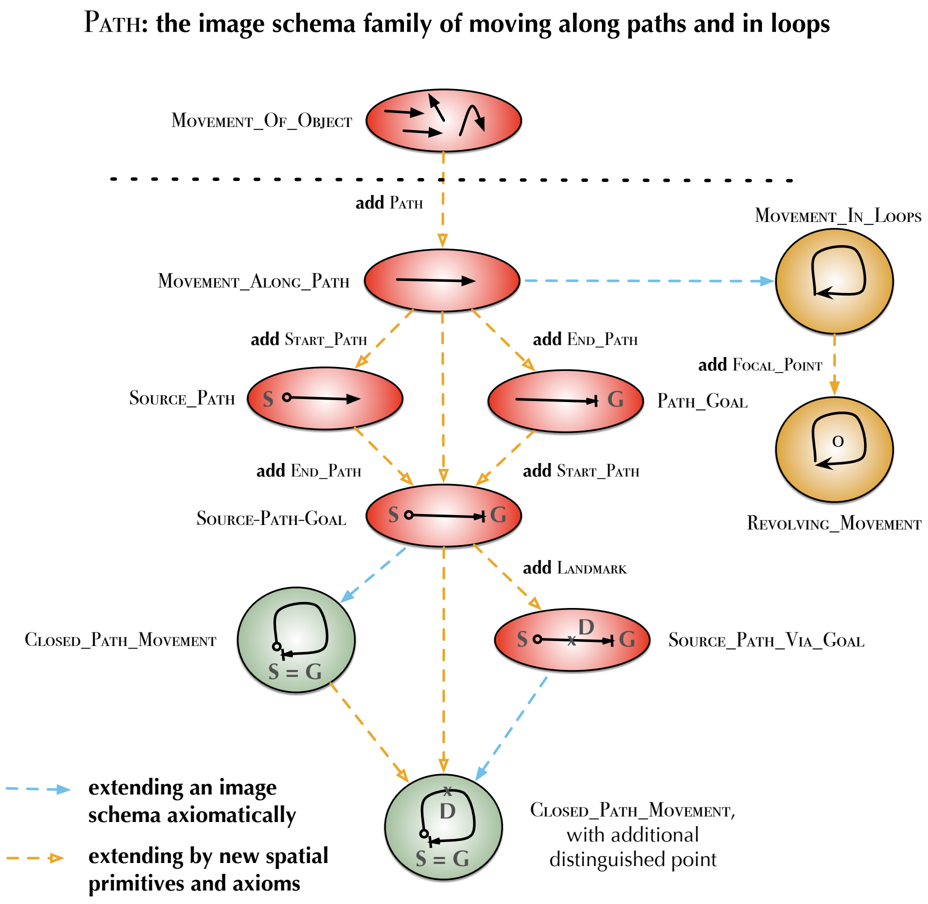

Figure 1: The Path-following family as presented in Hedblom et al. (2015)

an example, it is not possible to have an "inside" without also considering an "outside" and a separating "border". Looking at the cognitive development of CONTAINMENT, movement schemas IN and OUT are the events that form the CONTAINMENT schema in the first place. Yet, these concepts can in turn be defined as combination of PATH and CONTAINMENT. Adding to injury is that CONTAINMENT may have many different structures. For instance, (Bennett & Cialone, 2014) found eight different kinds of CONTAINMENT identifiable in natural language, and it is not always clear where the borders go between different image schemas.

- The first problem naturally leads to a second, namely the differentiation of a family of the same image schema and combinations of different image schemas. We previously already repeatedly mentioned how PATH-following in essence appears as a "family" of several kinds of movement. One corresponding suggestion is that image schemas should be structured in a hierarchical fashion to represent how image schemas become increasingly complex (cf. Hedblom et al. (2015) for PATH, and Santibáñez (2002) for a discussion on OBJECT). Naturally, hierarchically structuring one image schema family differs from combining completely different image schemas.

Trying to pinpoint the nature of image schema combinations, we give a few examples. It is simple to combine the image schema LINK with PATH into LINKED_PATH, as it is cognitively intuitive to visualise two objects that move together and react to stimuli in the same way. Based on information transfer of image schemas, this combination is also used as a means to explain abstract concepts. A real life example is the conceptualisation of the concept "marriage", where two individuals are taken to go through life together (Mandler, 2004). Similarly, PATH can be combined with SUPPORT (or CONTAINMENT), resulting in the concept "transportation" (Kuhn, 2007). This is particularly interesting because it illustrates how image schemas become part of the definition of what concepts are.

Another metaphorical example is the idiom "*to hit the wall*". In most contexts, this does not mean to physically crash into a wall, but instead implies some form of mental breakdown, often preceded by long-term stress or exhausting efforts. The idiom captures the image schema of BLOCKAGE. It is clear that BLOCKAGE is not an atomic image schema but rather a temporal combination of several ones. Breaking it down, we have two OBJECTs, at least one PATH, or MOVEMENT_ALONG_PATH, and at least one time point when the two objects are in CONTACT. Connecting it to the idiom we see how the PATH is related to time and processes that precede the "crash". This is one of the most common ways to use image schemas as abstractions as, for example, is evident from "time is a path": to conceptualise the abstract notion of time in terms of the concrete (and sensorially accessible) concept of space.

In the next subsection, we will first consider different levels of granularity and conceptualisation regarding how image schemas can be modelled, before subsequently developing a concrete example of how image schema combinations may result in more complex image schemas when seen from a temporal point of view (and, thus, can represent simple events).

One process, different perspectives: On distinct levels of modelling image schemas

Based on his research in vision, Marr (1982) famously introduced three levels of analysis of cognitive information processing systems: a *computational level*, explaining what a system does in terms of inputs, outputs, and a hypothesised functional mapping between them, an *algorithmic* or *representational level*, describing precisely how the system does what it does (i.e. which representations are used, what processes are used to build and manipulate the former, etc.), and an *implementation* or *physical level*, specifying the physical implementation of the system. These levels are fundamentally different from each other and answer different questions concerning the nature and mechanics of the system, yet all three are mutually co-determining/co-constraining. For research in cognitive science and neuroscience, the Marrian levels have proven to be highly valuable since they allow researchers to structure their respective studies according to the question(s)—and corresponding level(s)—which shall be addressed, and to interrelate different findings concerning one overall system or capacity to each other by identifying correspondences across levels.

In a way analogous to Marr's introduction of the three levels of cognition, we propose different levels of computational modelling for image schemas and similar notions from the realm of cognitive theorising for application in AI and cognitive systems research. Due to their very nature, image schemas can be modelled on several qualitatively distinct levels of granularity and detail, each of which corresponds to another perspective and addresses one or several different questions.

1. **The Third-Level Model:** Dynamical modelling, building models describing the general and abstract dynamics of the system without specifying or taking into account concrete object properties or empirically-grounded information.

2. **The Second-Level Model:** Observational modelling, building models describing (some of) the observable/sensorially accessible object, event, and process properties and dynamics.
3. **The First-Level Model:** Qualitative mathematical and physical modelling, building models involving simplified notions of force dynamics and trying to describe the underlying object and process properties on an initial level of simplified, explanatory theory (as commonly done, for instance, in naive physics or qualitative reasoning).
4. **The Zeroth-Level Model:** Precise/quantitative mathematical and physical modelling, building detailed simulations involving complex force dynamics and trying to describe and predict the underlying object and process properties as physically accurate as possible.

In this hierarchy, the third-level model corresponds to the abstract system dynamics on a purely conceptual level and, thus, to the hypothesised general notion of image schemas independent of concrete instantiations. The second-level model corresponds to what we assume to be the *cognitive level of image schemas* in that it accounts for concrete cases as perceived and experienced, for instance, by a child along its developmental trajectory (and, thus, supplying the "data" for the hypothesised statistical inference in concept formation). The first-level model corresponds to a common level of detail used in AI and cognitive systems when representing physical domains and reasoning in them. It pays attention to the observable properties and dynamics of the domain, in addition introducing governing laws on a naive level adequate for reasoning about a model's qualitative evolution but strongly simplified from a purely mathematical/physical point of view. The zeroth-level model, then, corresponds to the currently best available accurate model of the respective domain and process, allowing for detailed simulations also targeting precision concerning quantitative aspects.

While conceptually orthogonal to Marr's levels, we see similar advantages in the suggested quadripartition. While on the level of cognitive theorising it seems most plausible that image schemas in their most general form (among others allowing for seamless transfer across domains or cases) are best described on the third-level, the second- and first-level offer adequate granularities for studies of concrete image schemas from a cognitive perspective (second-level) or an AI/cognitive systems point of view (first-level). Finally, the zeroth-level offers an as-close-as-possible model approximation to the actual phenomenon as encountered in the world.

Returning to the PATH schema and our declared goal of developing an example for how image schema combinations may result in models of events, in the following subsection we will now elaborate a second- and first-level model illustrating how the PATH schema can explain the concepts of BLOCKAGE, BOUNCING, and CAUSED_MOVEMENT.

The image schema combinations BLOCKAGE*,* BOUNCING *and* CAUSED_MOVEMENT

In order to explain how image schema combinations model events, we further combine the PATH schema to explain BLOCKAGE, BOUNCING, and two different forms of CAUSED_MOVEMENT. The latter four concepts can be divided into four different scenarios.[7] They all start at the same situation with MOVEMENT_ALONG_PATH, but, dependent on object properties, different outcomes take place. While these are continuous, temporal events, for the sake of simplicity the individual events will be divided into (and fixed to) three time points t_1, t_2, t_3. We also need to specify two generic objects, in our example a circle o_1 and a square o_2.

The Second-Level Model: Looking at the event structure

The second-level model describes observable properties and dynamics. For readability's sake, in the following the descriptions of the different events at time points t_1, t_2 and t_3 will be given in natural language, but—as obvious from the structure and level of descriptions—could equally well and without major effort be provided using high-level modelling languages such as, for example, description logic (or even propositional logic) theories describing the individual events, and the already previously mentioned DOL language (Mossakowski et al., 2015) outlining the temporal evolution of the model and relations between events.

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[7] There are alternative variations of these scenarios.

As shown in the concept graph in Figure 2, the succession of events starts at t_1 with a MOVEMENT_ALONG_PATH schema, corresponding to the circle moving in direction of the resting square (Figure 3). At t_2, the circle reaches and touches the square (Figure 4), resulting in a CONTACT setting. At this point, at t_3 several alternative further steps of evolution are possible (corresponding to the branching of the concept graph on the right-hand side of Figure 2): either the circle comes to rest against the square in a BLOCKAGE image schema (continuing the setting of Figure 4), the circle bounces off the (still resting) square in the case of BOUNCING (Figure 5), or one of two forms of CAUSED_MOVEMENT obtains, either with the circle coming to rest and the square moving away from it (Figure 6) or with both objects in motion (Figure 7).

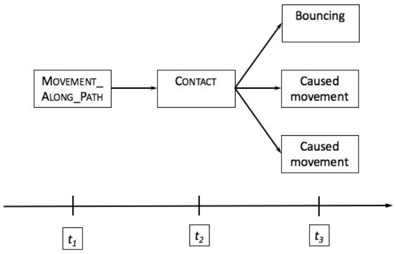

Figure 2: A concept graph of the temporal evolution and event structure in the PATH example.

The First-Level Model: Grounding the observed dynamics in a naive physics theory

The previous second-level model gives a description of the observable dynamics and interactions of the domain elements making up the respective image schemas. In the following, the high-level conceptualisation is grounded in a fairly expressive and detailed first-order logic (FOL) formalisation. While not yet reaching the level of accurate physical theory and force dynamics, the corresponding granularity of description

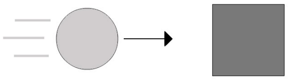

Figure 3: At t_1: Object o_1 is in MOVEMENT_ALONG_PATH, object o_2 is at rest.

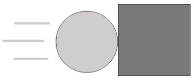

Figure 4: At t_2: Objects o_1 and o_2 are in CONTACT

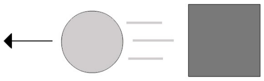

Figure 5: At t_3: Bouncing: Object o_1 is in (reverse) MOVEMENT_ALONG_PATH, object o_2 at rest at time t_3.

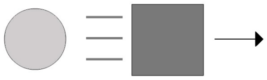

Figure 6: At t_3: Caused movement (i): Object o_1 is at rest, object o_2 is in MOVEMENT_ALONG_PATH

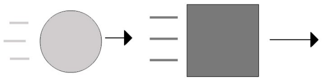

Figure 7: At t_3: Caused movement (ii): Object o_1 is in MOVEMENT_ALONG_PATH, object o_2 is in MOVEMENT_ALONG_PATH

allows to perform naive physics reasoning, approximating simple theories about motion, energy, and interaction of the involved domain elements going beyond the directly observable realm and providing a first level of explanation.

In order to handle the differences in sorts between the domain elements, we resort to a many-sorted FOL language. In terms of modelling approach, we restrict ourselves to explicitly encoding the observable "external behaviour" of the involved objects as grounding facts, and relegate the underlying energy and force dynamics to the level of reasoning and inference conducted by the system. Also, without loss of generality, several simplifying assumptions are made in this example: Each object in motion follows a respective path p. This object-specific path p is assumed to be determined/defined by an oriented notion of kinetic energy (i.e., a notion of directionality is added to the concept of energy), and defines the only relevant spatial dimension (i.e., for each object we are dealing with a one-dimensional space along the path/trajectory). At each point in time each object is charged with at most one type of energy (i.e., energy conversion or transfer is instantaneous, and energy conversion within an object is absolute), a charge with elastic energy can externally be observed (e.g., through warming up of the object or through a deformation in shape), kinetic energy is fully determining motion-related physical properties such as an object's velocity, and in absence of external influences energy is fully conserved (i.e., the model is loss-free).

In Figure 3, object o_1 is moving on the path p towards the second object o_2.[8] Formally this can be represented as shown in Table 1.

In Figure 4, the second time point illustrates how the two objects 'collide'. This is an important point because it is here that the image schema of BLOCKAGE comes into play. Formally speaking, two interesting changes take place, namely, there is suddenly contact between the OBJECTs. A formalization is given in Table 2. If t_3 is identical to t_2 in terms of spatial configuration of the objects, the MOVEMENT_ALONG_PATH (o_1) has been hindered and the concept of BLOCKAGE has been demonstrated.

At time point t_3, three different (and mutually exclusive) scenarios may take place. First, the scene in t_3 could be identical to t_2, resulting in BLOCKAGE and a conversion of the kinetic energy of o_1 into elastic energy stored in o_1 and possibly in o_2. This possibility has been formalized in Table 3.

Alternatively, dependent on the object properties, the kinetic energy may be redirected within the same moving object o_1 (resulting in BOUNCING) or (partially or entirely transferred to the previously resting object o_2 (CAUSED_MOVEMENT). In Figure 5, BOUNCING takes place as the object o_1 is still in MOVEMENT_ALONG_PATH but on a generally different path p than previously (corresponding in the model to a

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[8] It would also be possible that o_2 moves along p as long as it has a velocity lower than o_1 or is moving in the opposite direction. Similar results would occur. The model could remain the same, simply adding a "velocity correction" by defining the respective kinetic energy of o_2 as new zero energy state and from there on considering the relative kinetic energy of o_1 with respect to o_2.

Sorts:

time, *object*, *spatial*, *energy*

Subsorts:

kinetic, *elastic* : *energy*   *path/trajectory* : *spatial*

Entities:

$t_1 < t_2 < t_3$: *time* o_1, o_2 : *object* e_1: *energy* p_1: *path/trajectory*

Predicates:

circle, *square* : *object*   *movementAlongPath* : *object* × *path/trajectory* × *time*

inFrontOf : *object* × *object* × *path/trajectory* × *time*   *energyContent* : *object* × *energy* × *time*   *definesPath* : *energy* × *path/trajectory*

energyType : $\textit{energy} \times \textit{time} \to \{\textit{kinetic}, \textit{elastic}\}$ *energyValue* : $\textit{energy} \times \textit{time} \to \textit{real} \times \{N\}$

Facts of MOVEMENT_ALONG_PATH:

$\textit{circle}(o_1)$ $\textit{energyContent}(o_1, e_1, t_1)$ $\textit{energyType}(e_1, t_1) = \textit{kinetic}$ $\textit{energyValue}(e_1, t_1) > 0$ $\textit{definesPath}(e_1, p_1)$

$\textit{square}(o_2)$

$\forall e : \textit{energy} : \neg \textit{energyContent}(o_2, e, t_1)$

Laws of MOVEMENT_ALONG_PATH:

$\forall$o, o' : *object*, t : *time*, e : *energy*, p : *path/trajectory* : $(\textit{energyContent}(o, e, t) \land \textit{energyType}(e, t) = \textit{kinetic} \land \textit{energyValue}(e, t) > 0 \land$

$\land\, \textit{definesPath}(e, p) \land \neg \textit{inFrontOf}(o', o, p, t)) \to \textit{movementAlongPath}(o, p, t)$

$\forall t_i, t_{i+1}$: *time*, o, o' : *object*, p : *path/trajectory* : $(\textit{movementAlongPath}(o, p, t_i) \land \neg \textit{inFrontOf}(o', o, p, t_i)) \to \textit{movementAlongPath}(o, p, t_{i+1})$

Table 1: The situation at time t_1 with o_1 in MOVEMENT_ALONG_PATH towards the resting o_2, together with some basic governing laws of the domain.

Additional predicates:

contact : *object* × *object* × *time*

Additional facts of MOVEMENT_ALONG_PATH:

$\textit{inFrontOf}(o_2, o_1, p_1, t_2)$

Additional laws of MOVEMENT_ALONG_PATH:

$\forall$o, o' : *object*, t : *time*, e: *energy*, p : *path/trajectory* : $(\textit{movementAlongPath}(o, p, t) \land \textit{inFrontOf}(o', o, p, t)) \to \textit{contact}(o, o', t)$

$\forall$e : *energy*, o, o' : *object*, t_i, t_{i+1} : *time* : $(\textit{energyContent}(o, e, t_i) \land \neg \textit{contact}(o, o', t_i)) \to \exists e' : \textit{energy} : \textit{energyContent}(o, e', t_{i+1}) \land$

$\land\, \textit{energyType}(o, e', t_{i+1}) = \textit{energyType}(o, e, t_i) \land \textit{energyValue}(o, e', t_{i+1}) = \textit{energyValue}(o, e, t_i)$

Table 2: The situation at time t_2 in which o_1 remains in MOVEMENT_ALONG_PATH but just established contact with the still resting o_2 (i.e., no transfer or conversion of energy has yet taken place). In case no contact to another object is established at a certain point in time, kinetic energy (and, consequentially, also the corresponding MOVEMENT_ALONG_PATH) remain unaltered.

different path with kinetic energy of same absolute value). The formalisation is given in Table 4.

Additional predicates:

$\mathit{blockage} : \mathit{object} \times \mathit{object} \times \mathit{time}$

Additional facts of MOVEMENT_ALONG_PATH:

$\mathit{inFrontOf}(o_2, o_1, p_1, t_3) \quad \mathit{contact}(o_1, o_2, t_3)$

Additional laws of MOVEMENT_ALONG_PATH:

$\forall o, o' : \mathit{object}, t_i, t_{i+1} : \mathit{time}, e : \mathit{energy}, p : \mathit{path/trajectory} : (\mathit{contact}(o, o', t_i) \land \mathit{inFrontOf}(o', o, p, t_i) \land \mathit{contact}(o, o', t_{i+1}) \land \mathit{inFrontOf}(o', o, p, t_{i+1}) \land$

$\land\, \mathit{energyContent}(o, e, t_i) \land \mathit{energyType}(e, t_i) = \mathit{kinetic} \land \mathit{energyValue}(e, t_i) > 0) \rightarrow \mathit{blockage}(o, o', t_{i+1}) \land (\exists e', e'' : \mathit{energy} : \mathit{energyContent}(o, e', t_{i+1}) \land$

$\land\, \mathit{energyType}(e', t_{i+1}) = \mathit{elastic} \land \mathit{energyContent}(o', e'', t_{i+1}) \land \mathit{energyType}(e', t_{i+1}) = \mathit{elastic} \land \mathit{energyValue}((e' + e''), t_{i+1}) = \mathit{energyValue}(e, t_i))$

Table 3: The situation in which BLOCKAGE comes to be the case, with o_1 and o_2 in contact and both resting at time t_3 (i.e., all kinetic energy has been converted into elastic energy stored in one or both objects).

Additional facts of MOVEMENT_ALONG_PATH:

$\neg \mathit{contact}(o_1, o_2, t_3)$

Additional laws of MOVEMENT_ALONG_PATH:

$\forall o, o' : \mathit{object}, e, e' : \mathit{energy}, t_i, t_{i+1} : \mathit{time} : (\mathit{contact}(o, o', t_i) \land \mathit{energyContent}(o, e, t_i) \land \mathit{energyType}(e, t_i) = \mathit{kinetic} \land$

$\land\, \mathit{energyValue}(e, t_i) > 0 \land \neg \mathit{contact}(o, o', t_{i+1}) \land \neg \mathit{energyContent}(o', e', t_{i+1})) \rightarrow \exists e'' : \mathit{energy}, p : \mathit{path} : \mathit{energyContent}(o, e'', t_{i+1}) \land$

$\land\, \mathit{energyType}(e'', t_{i+1}) = \mathit{kinetic} \land \mathit{energyValue}(e'', t_{i+1}) = \mathit{energyValue}(e, t_i) \land \mathit{definesPath}(e'', p)$

Table 4: The situation with o_1 in MOVEMENT_ALONG_PATH along a (generally different) path p and o_2 continuing in a resting state at time t_3.

In Figure 6 and 7, the two cases of CAUSED_MOVEMENT are represented. They take place as the energy in o_1 is (entirely, as in 6, or partially as in 7) transferred onto o_2 which triggers a MOVEMENT_ALONG_PATH along a—in general potentially different—new path p. The final formalisation can be found in Table 5.

Advantages of formalising image schemas revisited

Besides clarifying the inner structure and the consecutive expansion steps leading from the basic MOVEMENT_ALONG_PATH to the more complex schemas, the just exemplified type of formalisation helps to make visible the consequences the modularity of image schemas has in language. In the same way as image schemas in themselves can be found in metaphoric expressions (e.g. "fall from grace" (VERTICALITY)), their combinations and expansions can embody more complex metaphorical expressions. For instance, the expressions "to hit the wall" (BLOCKAGE), "to be a sounding board"

Additional predicates:

$\mathit{inCausedMovement} : \mathit{object} \times \mathit{time}$

Additional facts of MOVEMENT_ALONG_PATH:

$\neg \mathit{contact}(o_1, o_2, t_3)$

Additional laws of MOVEMENT_ALONG_PATH:

$\forall$*o, o' : object, e: energy*, t_i, t_{i+1} : *time* : $(\mathit{contact}(o, o', t_i) \wedge \mathit{energyContent}(o, e, t_i) \wedge \mathit{energyType}(e, t_i) = \mathit{kinetic} \wedge$
$\wedge\, \mathit{energyValue}(e, t_i) > 0 \wedge \neg \mathit{contact}(o, o', t_{i+1}) \rightarrow \exists e', e'' : \mathit{energy} : \mathit{energyContent}(o, e', t_{i+1}) \wedge \mathit{energyType}(e', t_{i+1}) =$
$\mathit{kinetic} \wedge \mathit{energyContent}(o', e'', t_{i+1}) \wedge \mathit{energyType}(e'', t_{i+1}) = \mathit{kinetic} \wedge \mathit{energyValue}((e' + e''), t_{i+1}) = \mathit{energyValue}(e, t_i)$
$\forall$*o, o': object, p,p',p" : path/trajectory*, t_i, t_{i+1} : *time* : $(\mathit{movementAlongPath}(o, p, t_i) \wedge \neg \mathit{movementAlongPath}(o', p', t_i) \wedge$
$\mathit{inFrontOf}(o', o, p, t_i) \wedge$
$\wedge\, \mathit{contact}(o, o', t_i) \wedge \mathit{movementAlongPath}(o', p'', t_{i+1})) \rightarrow \mathit{inCausedMovement}(o', t_{i+1})$

Table 5: The situation with o_2 in CAUSED_MOVEMENT at time t_3.

(BOUNCING) and "to set things in motion" (CAUSED_MOVEMENT) abstractly encompass not only the original image schemas but also the emergent properties from their combinations.

From a cognitive systems- and AI-oriented perspective, formalising image schemas in a first-level model using many-sorted FOL or similar expressive formalism has the advantage that these representations offer a reasonable compromise between the required richness of language—indispensable for modelling the dynamic character and the, at times, complex inner mechanics underlying more complex schemas—and the availability of and integrability with existing systems and approaches. For example, using the representation employed in the previous section, the formalised image schemas could directly be interfaced with the Heuristic-Driven Theory Projection (HDTP) analogy-engine (Schmidt et al., 2014). HDTP has been conceived as a mathematically sound theoretical model and implemented engine for computational analogy-making, computing analogical relations and inferences for domains which are presented in (possibly different) many-sorted FOL languages: source and target of the analogy-making process are defined in terms of axiomatisations, i.e., given by a finite set of formulae. HDTP follows a generalisation-based approach to analogy-making: given both domains, (restricted) higher-order anti-unification is used to compute a common generalisation encompassing structurally shared elements common to both input domains (mapping phase) and this generalisation then guides the analogical alignment and knowledge transfer process of unmatched knowledge from the source to the target domain used for establishing new hypotheses (transfer phase).

As already stated earlier, image schemas model the skeletal knowledge about a concept that can be analogically transferred between different domains. HDTP's generalisation-based approach offers a possibility—e.g., through iterated generalisation over different instantiations of a certain image schema—to explicate this shared skeletal knowledge and obtain increasingly abstract axiomatisations of the image schema under consideration. Also, HDTP has successfully been used to model concept blending on the theory level for abstract domains (Martinez et al., 2014) and concrete domains (Besold & Plaza, 2015).

Another alternative, suggested by Hedblom et al. (2016) is to handle image schemas via HETS, a proof management system supporting conceptual blending via colimit computation (Mossakowski et al., 2007). In similarity to how HDTP would utilise the image schematic concepts for analogical reasoning, HETS would use them as generic space for information transfer in computational conceptual blending and thus, in some sense, perform formal concept invention. Moreover, HETS is of particular general interest as a tool to manage entire families of image schemas and their inter-relations. First, it has full DOL support (including various reasoning engines), which means that a large number of well-known KR languages on different levels of expressivity can be used, and that various qualitative modelling approaches can be employed. Secondly, it serves as backend to the online theory repository platform Ontohub[9], which facilitates the collection, inter-relation and reasoning with formalised image schemas (Codescu et al., 2017).

Similar approaches to the ones just described could be used to automatise the combination between image schemas once the latter have been encoded as shown in the previous section.

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[9] See `https://ontohub.org`

Conclusions and future work

How to represent events, and the relationship to concept formation and concept processing in general, is not only a non-trivial problem for understanding developmental psychology, but also important for AI and cognitive systems research. Embodied theories of cognition help advance research in AI, computational models of reasoning, and robotics, as generic conceptual building blocks such as image schemas may be used to build conceptualisations of concepts and events. Rooted in these ideas, this article aimed to—while maintaining the cognitive inspiration—formally illustrate how image schemas can be combined with one another to model simple events. The image schemas OBJECT, CONTACT and PATH were combined in a temporal dimension, resulting in the more complex image schemas, and simple events: BLOCKAGE, BOUNCING and CAUSED_MOVEMENT. Moreover, this image schematic way of presenting events may not only help AI systems to reason about scenarios, but in accordance with the hypothesised—and increasingly experimentally justified—role of image schemas in language development, in the long run also could help to improve natural language comprehension tools.

Natural next steps are to evaluate the work presented here in more complex workflows using systems such as HDTP and HETS, and to provide a fully implemented and practically evaluable system as proof of concept of how image schema combinations model simple events and support concept invention. On the level of theory development, the proposed hierarchical structure of modelling levels will have to be revisited, further developed, and evaluated both concerning conceptual ramifications as well as practical applications.

Acknowledgements

The authors would like to thank Till Mossakowski (Otto-von-Guericke University Magdeburg) for helpful comments and discussion.

Funding: This work was supported by the Future and Emerging Technologies (FET) programme within the Seventh Framework Programme for Research of the European Commission, under FET-Open Grant number: 611553 (COINVENT).

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