Cognitive Architecture of Concepts: Conceptual Meta-Model

Paul Tarabek
Mathematical Department, College of Applied Economy, Ceske Budejovice, Czech Republic, EU,
Educational Publisher DIDAKTIS, SK 81104 Bratislava, Slovakia, EU
For correspondence please contact: didaktis@t-zones.sk

ABSTRACT

The triangular model of the cognitive architecture of concepts is a conceptual meta-model which shows a specific structure of common and scientific concepts and their semantic frames as components of conceptual models. This structure consists of the concept core, concept periphery, the semantic frame, and the relations among all the components of this structure. The core of a concept is composed of a symbol, a representative semantic image (as the core of a category or the prototype), and an intrinsic structure of a concept. The semantic frame consists of the meaning and the sense of the concept. The meaning is a set of all subordinated concepts and images. The sense is a set of all concepts which can be meaningfully connected with the given concept core in speech, thought or symbolic expression (except for subordinated concepts). The meaning and the sense are two disjunctive sets. The periphery of a concept is composed of the set of meaning and sense links to the concepts of the meaning and the sense. Three developmental levels of common and scientific concepts are presented in a frame of the model: empirical, exact, and formal. The empirical is provided as level of the common concepts. The exact and formal are provided as levels of the scientific concepts. The conclusions for science education are discussed.

Keywords: cognitive architecture, concept, conceptual model, conceptual meta-model, semantic frame, level of concept.

INTRODUCTION

The detailed structure of common and scientific concepts which are basic components of conceptual or mental models used as human tools for cognition in science, mathematics, and in everyday life, is a long-term problem in cognitive psychology and science, and also in science education research. The words that we use every day are understood by other people through their interconnections with other words, mental images, and in relation to their meaning, sense, and semantic frame. All these entities form a structure of concepts and the conceptual understanding means that one has integrated in one’s mind all these components into a complete mental conceptual structure. Many results of cognitive science, linguistic and educational research show insights into the structure of language, concepts, and knowledge [6, 7, 10, 14, 15, 16, 18, 21, 22, 26, 27, and 28]; however, the above problem is not completely solved [20]. Most of the research in the domain ‘structure of concepts’ uses the particular point of view where individual attributes of concepts are studied, the concepts are cognitive entities that allow the recognition of things grouped on the basis of physical or functional similarities, and a structure of concepts is modeled very simply e.g. by the semiotic triangle. The Modeling Theory of Science, Cognition and Instruction of Hestenes [10, 11] provides probably the best model of concept (for purposes of cognitive science and science education) expressed by the triad {form, meaning, symbol} where the symbol is a representation of the form and meaning. The form of a concept is its conceptual structure, including relations among its parts and its place within a conceptual system. The meaning of a concept is its relation to mental models [11]. In scientific and also in everyday conceptual systems we use “concepts of…” – it means concepts of space, time, mass, force, energy,… in physics, concepts of set, group, number, relation,… in mathematics, concepts of man, woman, child,… in everyday language, etc. Then the entity ‘concept’ is not a part of a conceptual model or system but a component of a conceptual meta-model that describes system of concepts, knowledge, their architecture and mutual relations as a whole. We need a more detailed theoretical meta-model of the complete structure of common and scientific concepts and their semantic frames to explain their role in conceptual models and reasoning, and also to describe conceptual change in learning1. And finally, the modeling of concept’s structure needs also a holistic point of view where the concept is a system that is not reducible to its components.

THEORETICAL MODELING OF A COGNITIVE ARCHITECTURE OF CONCEPTS

The author’s studies based on the Vygotsky’s concept theory [32], the conception of the ‘semantic frame’ [6, 7, 9], the semantic/semiotic triangle, the conception of natural [21, 22], conceptual [2, 27] and perceptual categories [18], and on widespread ideas of the structuring of conceptual systems were focused on the understanding of mental representations of misconceptions and knowledge in the minds of students and have resulted in the creation of the triangular model of a cognitive architecture2 of common and scientific concepts (TM). This model is a conceptual meta-model that describes the cognitive architecture of concepts and their semantic frames as basic cognitive units of conceptual models (CM) created by humans, where the term ‘concept’ is taken in the same sense that it is used in cognitive psychology and science [27, 30]. It is

1 Learning is described as conceptual change: a change of concepts and/or conceptual structures [1].
2 The term ‘architecture’ implies an approach that attempts to model not only behavior, but also the structural properties of the modeled system [19]. The term ‘cognitive architecture’ used in cognitive science also means “an embodiment of a scientific hypothesis about those aspects of human cognition that are relatively constant over time and relatively independent of task” [23, 24].
also an attempt to model structural properties of mental concepts as components of mental (conceptual) models of intelligent agents (human or artificial) with the acceptance of usual terms of the cognitive sciences.

Model of a Cognitive Architecture of Concepts

The triangular model of a cognitive architecture of common and scientific concept (TM) describes the cognitive architecture of a concept and its semantic frame. The basic components of the model are: the core C, the periphery of a concept, the semantic frame as the meaning M and the sense S of a concept, their mutual connections and also the hierarchical layers of the meaning (see Fig. 1). The model also distinguishes the concept’s meaning and sense as two disjunctive sets [4, 9], i.e. the sense is not a part of the meaning [13]. The model distinguishes three phases in the development of common/ scientific concepts: empirical, exact, and formal. The level of the common concepts is the empirical. The levels of the scientific concepts are the exact and formal.

Core and Periphery of Concept

The core of an external concept is composed of three components: a symbol (e.g. a word or assembly of symbols: a word and a sign/icon), a representative semantic image – RSI, and an intrinsic structure of the concept – the internal components of the concept and the relations among them. The core of a mental concept is composed of three components: a mental word and/or mental sign/icon, a mental RSI, and a mental intrinsic structure of a concept – the internal components of the concept and the relations among them. The mental RSI is the dominant structured image that emerges in the mind after one says a given word and may appear in the mind during a thought operation with the mental word or symbol. The mental RSI may be a mental prototype [21, 22]. The external RSI is a part of an external concept. The external RSI as a core of a conceptual category [2, 18, and 26] contains a list of characterizing properties – the attributes of objects in the extension of the related concept. The list of attributes is applied by judging the similarity between the RSI and the mental representation produced by an object as it is experienced. The external RSI as a prototype contains a list of characteristic/critical features that the object in extension of the related concept trends to possess. Thus the RSI corresponds to the prototype of the natural category [22] or the perceptual category [18] and the mental RSI is an image form of the prototype. The intrinsic structure is a system of relations among attributes or among characteristic features of a prototype. For example, the attributes of a triangle are three vertices and three sides. The intrinsic structure is a system of relations among the constituent vertices and sides of the triangle. The attributes of an iron ball are its mass, volume, and spherical shape (given by its radius and surface). The intrinsic structure is a system of relations between the volume and the mass, between the radius and the volume, and between the radius and the surface. Highly abstract concepts possess no intrinsic structure. For example, the attributes of a mass point are its mass and zero volume. There is also no intrinsic structure between the mass and the ‘volume’ of the mass point. The mental intrinsic structure is a mental model of the external intrinsic structure.

The periphery of an external/mental concept is composed of the set of meaning and sense links from the concept’s core to the concepts of meaning and sense. The relation to the superordinate concept belongs also to the periphery.

Meaning of a Concept

The meaning M is composed of the set of all cores of subordinate concepts and sets of images referring to the given concept’s core and also of the set of meaning links from the core to the subordinate concepts and images (see Fig. 1). In the meaning of the concept, we can differentiate hierarchical meaning layers. In Fig. 1, three layers M1, M2, and M3 are distinguished. The meaning layer M1 is the set of the most abstract concepts which are subordinated to the given concept core and divide the whole class of denotata into disjoint subclasses.

Sense of a Concept

The sense of a concept consists of the set S1 of assigned concepts which can be meaningfully connected with the given concept core (except for subordinated concepts) in symbolic expression, speech or thought and sense links from the core to the assigned concepts (see Fig. 1). We can divide sense links into qualitative, attributive, cognitive, operational, and contextual types. Qualitative sense links are the links to concepts which express potential qualities. Potential qualities are properties characterizing denotata of subordinate concepts belonging to the meaning. The connection of potential qualities to a given concept results in its division into subordinate concepts. For example, the potential qualities of a tree are expressed as ‘broad and flat leaves’ or ‘needles’. Thus the class of trees is divided into two disjoint subclasses: deciduous trees and conifers.

Attributive sense links are the links to concepts which express the attributes of a given concept. Attributes are the relevant properties characterizing the denotata class of a given concept. According to these properties, we are able to categorize an observed object, phenomenon, event or entity into a denotata class. For instance, the concept ‘body’ has its mass as an attribute. The concept ‘husband’ has two attributes: married and adult. The attributes are used in definitions together with superordinate concepts. For instance, in the definition “Body is a mass object”, ‘object’ is a superordinate concept while ‘mass’ is an attribute. In the definitions “Solid body is a mass object with constant volume and shape” or “Liquid is a mass object with constant volume and variable shape”, ‘mass object’ is a component of the concept triad.

---

1 In cognitive psychology, cognitive science and science education research, the term ‘concept’ is used in both meanings:
- the ‘mental’ concept as an element of mental models of reality in the human mind, and also
- the ‘external’ concept as an element of conceptual models of reality (scientific or expressed by common language). See also the Stanford Encyclopedia of Philosophy, http://plato.stanford.edu/.

2 Ibid.

3 Mental words are units of the mental language [33] or the Language of Thought [8] and also parts of mental concepts whereby human beings express mentally the things, objects, processes, and entities which they are thinking. The Language of Thought Hypothesis (LOTH – Fodor) postulates that thought and thinking take place in a mental language. The Language of Thought consists of a system of representations that is physically realized in the brains of thinkers.

4 Mental signs are derived from conventional signs, symbols, and icons of common or scientific language and have the same semantic content.

5 Some concepts have no typical attributes (e.g. birds). These concepts belong to natural categories [21] where we cannot speak about typical attributes. We can speak about characteristic or critical features/properties when the attributive links connect the given concept with the concepts expressing characteristic/critical features/properties.

6 The term ‘intrinsic structure’ corresponds to the term ‘form as a structure of the prototype’ in Hestenes [10]. The form is a component of the concept triad.
a superordinate concept and ‘constant volume’ and ‘constant/variable shape’ are attributes. In the definition “A husband is a married and adult man” the ‘man’ is a superordinate concept – ‘married’ and ‘adult’ are attributes.

**Cognitive sense links** are links between the core of the given concept and concepts that are related to physical and natural law (rule, principle) together with this concept. For example, if we consider Newton’s second law in the form \( F = m \cdot a \), the cognitive links of the force \( F \) are given by this formula, e.g. ‘\( a \propto F \)’, ‘\( F \propto F \)’, and from the light of the Newtonian conception, the link ‘\( F \Rightarrow a \)’ (a force causes the acceleration) also belongs to the above ones. If we consider mental conceptual knowledge systems, students have a mental cognitive link ‘\( F \Rightarrow a \)’ from the concept ‘force’ to the concept ‘acceleration’ if they understand that a force causes the acceleration of a body’s motion or the curving of its trajectory. Another cognitive link is ‘\( a \propto F \)’, i.e. the acceleration is directly proportional to net force (when mass is constant), or ‘\( a \uparrow F \)’, i.e. the acceleration has the same direction as the force.

**Operational sense links** are the links between the core of the given concept and concepts that belong to physical or mathematical definitions using variables together with the given concept. These links are also expressed by operational definitions, or correspondence rules for assigning measured values to states of the physical system [10] which are realized by mathematical formulas or thought operations.

**Contextual sense links** are the links between the core of a given concept and all other concepts that may be meaningfully connected with the given concept in statements, propositions, sentences, etc. This term does not designate qualitative, attributive, cognitive and operational links. For instance, the concept ‘force’ can be meaningfully connected in sentences with the concepts ‘motion’, ‘action’, ‘field’, ‘space’, ‘time’, etc.

### Developmental Levels of Concepts

Besides the description of concept formation through the Vygotian phases [29], the triangular model distinguishes three levels in the development of concepts: **empirical, exact, and formal**.

**Empirical level of concept**

The representative semantic image (RSI) is formed and subsequently connected to the concept core at the empirical level. The RSI is an image prototype which includes all features that are characteristic for the denotata class referred to the concept. The core of the concept consists of the word and the RSI. The meaning consists of two meaning layers M2 and M3 and their links to the core or their links to each other. The layer M2 is a set of subordinate concepts. The layer M3 is a larger set of concrete mental semantic images. The sense of the concept is comprised of all assigned concepts, which may be meaningfully linked to the core C in statements, propositions, sentences, empirical physical laws (set S1) and all sense links. The sense links involve contextual, qualitative, attributive and cognitive ones. At this level, besides the relational approach, a **natural laws’ approach** is also exploited, i.e. the cognitive agent searches for certain laws in the studied universe. These laws have the form of the so-called **laws of phenomenon**, which are empirical causal laws of the type ‘phenomenon ⇒ phenomenon’ or ‘entity ⇒ phenomenon’. These laws of phenomenon are formulated as simple factual statements describing attributes and behavior of the objects, the course of phenomena, processes, etc. It is obvious that these laws are generalizations of empirical experiences coming directly from observation. In connection with Aristotle, these laws and corresponding statements are of the type “Heavy bodies fall downwards and light bodies (smoke) rise upwards.”. “Bodies fall downwards faster if they are heavier, and slower if the resistance of the environment (determined by size of the body and the density of the environment) is bigger.” The empirical concepts at the empirical level are concepts of common language i.e. CS (common sense) concepts of Hestenes [10] or cluster concepts of Niedderer [17]. The mental empirical concepts are components of conceptual models created as phenomenon-based conceptions of pupils/students [3].

**Exact level of concept**

The exact concepts at the exact level are components of scientific conceptual models and conceptual knowledge systems. This level attains these concepts, which refer to the physical quantities represented by symbols. We call this type of concept the **symbol concept**. The mental exact concepts are components of mental conceptual models and conceptual knowledge systems created as model-based conceptions of pupils/students [3].

The core of the symbol concept is composed of the word, the RSI, the symbol and the intrinsic structure. The meaning of the symbol concept is composed of all three meaning layers M1, M2, and M3, the meaning links of their elements to the core and meaning links between the elements of the sets M1, M2, and M3. The abstract subordinate concepts comprise the meaning layer M1. The subordinate concrete concepts comprise the larger set M2. The mental semantic images of denotata comprise the set M3.

The core can be separated from the meaning and the mind can operate independently with it with the help of symbolic formulas. The symbol concept may have several related classes M1 of referential concepts – several meanings which comprise the **meaning field**.

The sense of the symbol concept consists of the set S1 and all sense links. The set S1 consists of all assigned concepts, which may be meaningfully linked to the core C in statements, propositions, sentences, physical laws, rules, principles, etc. The sense links are as follows: contextual links, links to the actual and potential qualities, attributive links, cognitive links, and operational links.

The symbol concepts attain the symbolical level at the parametric level of scientific conceptual models and conceptual knowledge systems and continue at the structural level. The **parametric level** of the scientific conceptual models and conceptual knowledge systems is characterized mainly by the fact that the natural (physical) laws are described by mathematical language as relational or functional links between the (physical) quantities. The laws, which had at the lower – empirical level the **verbal form**, attain at this level the so-called **parametric form** expressed usually by the functional dependence \( F = (h_1, h_2, ..., h_n) = 0 \) where \( h_i \) (\( i = 1, 2, ..., n \)) are the values of the parameters \( S_1, S_2, ..., S_n \) describing the processes, attributes of the objects, phenomena and the like. Typical parametric physical laws are e.g. Galileo’s law of free fall, Kepler’s laws, Gay-Lussac’s volume law for gases, Proust’s law, Dalton’s law, etc. The parametric level is further characterized by the fact that every law describes certain specified class of phenomena and there are no links between individual laws. This level was attained for instance in pre-Newtonian mechanics or electrodynamics before Maxwell. Besides the natural laws’ approach of formulating laws in the mathematical language, there is also an explanatory approach leading to the creation of new concepts, links, models, principles and laws in the form of partial hypotheses explaining the form of existing laws. Besides the laws in mathematical language, the verbally formulated laws – principles are also a part of scientific conceptual models at the parametric level. Conceptual models and knowledge systems at the parametric level contain space-time models of the studied universe, which form the framework for the physical parametric laws.
The process of idealization leads to creation of idealized concepts (i.e. concepts referring to the class of idealized denotata) enabling the description of the phenomena by means of physical quantities. These concepts are, for instance, distance, displacement, speed, velocity, acceleration, time, mass, momentum, force, etc. Many mathematical concepts are also idealized concepts. However, the process of idealization concerns also concepts, which do not describe physical quantities; in physics, there are, for example, the concepts: ‘point mass’, ‘solid body’, ‘centre of gravity’, etc; in mathematics, the geometric concepts ‘line segment’, ‘point’, ‘line’, ‘triangle’, etc. The idealized concepts are abstract thought-constructions and their denotata are entities, unlike the concepts at the empirical level, which denotata are mostly material, i.e. their denotata are objects, phenomena, events, and processes in reality.

The structural level of the external conceptual knowledge systems is characterized by the creation of complex structures of scientific knowledge, which have the form of closed scientific theories explaining all parametric laws and rules discovered in the preceding stage at the parametric level of cognition. For example, mechanics attained the structural level with Newton’s theory (Newton’s laws of motion), electrodynamics with Maxwell’s theory, etc.

At the structural level of the scientific conceptual knowledge systems, the idealized concepts from the parametric level are completed into the definitive form, which is characterized by the possibility of the separating of the meaning layers from the core. In the concept structure, the sense links dominate and integrate the concept into the structural network of scientific theory.

New concepts, necessary as building blocks of a new theory, are created at the structural level. Such concepts are, for instance, ‘energy’ in mechanics, ‘entropy’ in thermodynamics, ‘operators’ in quantum mechanics, etc.

**Formal level of concept**

The concepts at the formal level, known as formal concepts, are components of mathematical theories or formal theories in physics and do not use a meaning in thought operations in physics and mathematics. The formal concepts are fully determined by sense links, and especially by operational links in operational definitions. The other sense links are as follows: contextual, qualitative, attributive and cognitive links. The core of the formal concept is composed of the word and the symbol. The RSI may also be there, but it is unimportant. The core is fully separated from the meaning layers M1, M2, and M3, i.e., the usage of formal concepts in thought operations in physics and mathematics needs no meaning substructure. The formal concept may have more added meanings as various interpretations of the concept core in reality. It can be also a fictitious reality. The concepts usually attain the formal level at the formal level of scientific conceptual knowledge systems but they may attain the formal level earlier – at the structural level of conceptual knowledge systems.

**Aristotelian and Newtonian Level of the Concept ‘force’**

Two developmental levels were indicated by the study of students’ concepts in the process of education. For example, the empirical level (called the Aristotelian level\(^9\)) of the concept ‘force’ was identified by the students’ formulation “force is needed to keep a body in motion”, and similar expressions. The Aristotelian law “force causes (violent) motion” came directly from an observation as a generalization of empirical experience. This (or a similar) conception of force in students’ minds is called the Aristotelian preconception. The symbolical level (called the Newtonian level\(^10\)) was identified by the students’ formulation “force causes a change of motion of the body – acceleration, deceleration or the curving of its trajectory” and similar expressions. Both of these developmental levels were demonstrated by the answers of students from grade 6 to 12 [29]. The empirical level of concept means the common sense of the concept [10] and the symbolical level corresponds to the scientific sense. The significant differences between the Aristotelian and Newtonian level of the concept ‘force’ are depicted in Fig. 2.

**CONCLUSIONS**

The Triangular Model of the cognitive architecture of common and scientific concepts (TM) is a theoretical construct based on knowledge and terms of cognitive psychology, cognitive sciences, and educational research with the acceptance of usual terminology. Cognitive architecture is a specific structure consisting of the concept core, concept periphery, the semantic frame as the meaning and the sense of the concept, and the relations among all components of the conceptual structure. The model distinguishes three phases in the development of common and scientific concepts: empirical, exact, and formal. The level of the common concepts is empirical. The levels of the scientific concepts are exact and formal. The model distinguishes also an intrinsic and an external conceptual structure. The intrinsic conceptual structure means a system of relations among attributes or among characteristic features of a prototype as a part of the concept’s core. The external conceptual structure is expressed by the semantic frame and relations to other concepts and shows the place of the given concept within a conceptual system where the meaning and sense are two disjunctive sets. The TM is a conceptual meta-model which shows the cognitive architecture of concepts as components of external common and scientific conceptual systems. Secondly the TM is an attempt to model a cognitive architecture of mental concepts as components of the mental (internal) conceptual systems with the acceptance of the usual terms of cognitive sciences. Therefore the TM might be also appropriate to model components of conceptual and mental models in Hestenes’ Modeling Theory of Science, Cognition and Instruction [10, 11, and 12]. Thirdly the TM allows us to understand a structure of concepts and their semantic frames in learners’ minds and to define a conceptual understanding. The conceptual understanding of a given concept means that one has built the complete structure of this concept and its semantic frame – the complete cognitive architecture – in his/her mind.

The method of the semantic mapping similar to concept mapping was derived from the TM. A difference from the concept mapping is given by specific dimensions of the semantic mapping. The semantic maps have two dimensions: vertical (the direction to the meaning – subordinated concepts and semantic images and to superordinate concept) and horizontal (the direction to the sense). In the sense are distinguished more links: attributive, cognitive, operational, contextual, and links to potential qualities. The semantic maps of the concept ‘force’ at the empirical (pre-scientific) and exact (scientific) level designed in [29] represent models of cognitive architecture of the Aristotelian preconception and Newtonian conception of force and clearly show the differences between both concepts. Thus the theoretical conception of the TM is also useful in educational research to understand substantial differences between the empirical (pre-scientific), exact (scientific), and formal levels of the concepts.

---

\(^9\) The Aristotelian level of the concept ‘force’ is an Aristotelian preconception/Aristotelian mental model concerning acting forces [5].

\(^10\) The Newtonian level of the concept ‘force’ is a component of the mental (Newtonian) model of the Newton second law [5].
FIGURE 1. Model of cognitive architecture of common and scientific concepts
The rectangular boxes represent the components of the cognitive architecture (core C, S1, M1, M2, M3), the dashed boxes represent subsystems (semantic frame – meaning M and sense S), the dotted box represents a complete concept (core and periphery), and the arrows represent links between the components of the cognitive architecture of concept. The dotted-dashed (green) link expresses the ‘connection’ of observed objects, events, and entities to the given concept by the RSI.

FIGURE 2. Significant differences between the Aristotelian (empirical) and Newtonian (exact) levels of the concept ‘force’ as was found in the students’ answers [29]. The Aristotelian preconception means a first level of human cognition flowing from a common experience.
REFERENCES


