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INVESTIGATING APPLICATION VALIDITY OF CONCEPT MAPS

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Abstract. To ensure the effective use of a concept map it needs to be validated. Two different types of concept map validity can be distinguished, referring to either the validity of the concept map's content or to the applicability for its designated purpose. This paper concentrates on application validity and outlines an empirical investigation demonstrating a validation approach utilising Knowledge Space Theory. Problem solving behaviour was used as a criterion for application validition of a concept map on a subdomain of geometry. By deriving theoretically expectable answer patterns on geometry problems from a concept map and comparing it with empirically collected answer patterns, the concept map's application validity could be investigated and proved.

1 Introduction

Concept maps are tools for representing semantic knowledge and its conceptual organisation (for an overview see e.g. Novak, 1998; Steiner, Albert, & Heller, 2007). They specify the concepts of a knowledge domain and the relations among them, and thus provide a natural way of expressing and presenting domain ontologies. Mathematically defined, a concept map is a directed graph consisting of a finite, non-empty set of nodes which represent the concepts of a knowledge domain, i.e. $C = \{c_1, \ldots, c_n\}$, and a finite, non-empty set A of arcs which represent the relationships between those concepts (Albert & Steiner, 2005). Every arc is an ordered pair from the set of concepts and is characterised by a relation label describing the relationships between those two concepts. Such a combination of two concepts and the labelled relation between them constitutes a proposition (Ruiz-Primo, 2000), i.e. a statement forming an elementary unit of declarative knowledge (Anderson, 1995). This means, a concept map is basically a representation of declarative knowledge. Most commonly, a concept map is depicted by a graph representation (see Figure 1 for an example), although also other forms of representation (e.g. proposition list, matrix) are possible (Steiner et al., 2007).

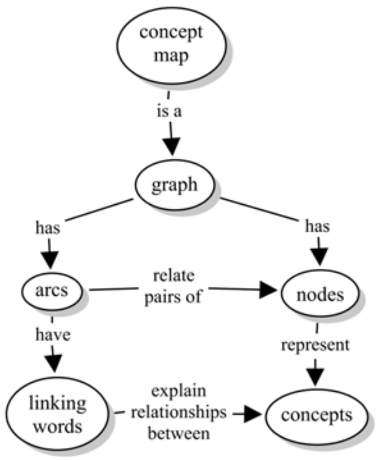

Figure 1. Concept map on what a concept map is (adapted from Steiner et al., 2007).

A concept map constitutes a model of the current knowledge about the world for a given knowledge domain in a given context. For one and the same knowledge domain it is not realistic to assume that only one correct concept map of complete consensus exists; rather there are several alternative concept maps conceivable. This is, because describing and structuring a domain necessarily entails some sort of world view or opinion (Kennedy, McNaught, & Fritze, 2004). Moreover, concept maps will also differ due to their intended purpose and ultimate use. Given a particular purpose, a concept map is needed that represents the knowledge domain with respect to its designated usage and summarising possibly differing perspectives. Having available a well-founded concept map is crucial to ensure its effective and valid use. For instance, for practical use as teaching material in classroom it is critical that a concept map accurately reflects the respective subject domain.

This calls for a theoretical framework for evaluating the empirical validity of a concept map on a specific domain. In the sequel, a concept map to be validated is alternatively also denoted as 'target map'. Different aspects of validity can be distinguished – content validity and application validity – and methodological considerations and approaches suitable for evaluating these validity types have been proposed (Albert & Steiner, 2005; Albert, Steiner, & Heller, 2006). The purpose of this paper is to demonstrate the investigation of a concept map's application validity by an empirical example. In the following section, first the concepts of content and application validity are outlined and an approach for application validation is described. Subsequently, an empirical investigation on the application validity of a concept map for elementary geometry is presented. Finally, the applied validation methodology and implications for further research are discussed.

2 Application Validity of Concept Maps

When considering the validity of a target map, two types of validity can be distinguished – content and application validity (Albert & Steiner, 2005). Content validity refers to the question whether the concept map constitutes a valid model of a part of the current knowledge about the world. For giving evidence of content validity, an approach comparing the target map to empirically gathered individual concept maps has been suggested. Here, we focus on application validity, which refers to the question whether a concept map serves the purpose for which it has been designed. In other words, the practical usability and usefulness of a target map is addressed. For analysing this type of validity relevant situational performance can be utilised (Albert & Steiner, 2005). Situational performance in this context means behaviour in real-world situations that does not consist in performing a concept mapping task, as for example problem solving, answering questions, or even social behaviour in given situations. As naturally a person's understanding of a domain is reflected in his/her behaviour in given situations, situational performance constitutes a suitable criterion for validation. A type of situational performance has to be chosen, that is related to the purpose and intended application of the respective concept map. Depending on the purpose (e.g. presenting learning material, describing social skills) that is foreseen for a target map, different kinds of situational performance (e.g. problem solving, behaviour in social situations) will be appropriate. As a concrete approach for examining application validity of a concept map we suggest to utilise Knowledge Space Theory. This approach assesses the target map's ability to predict relevant situational performance. After introducing the basic notions of the theoretical framework in the sequel, the proposed validation methodology is sketched.

2.1 Knowledge Space Theory

Knowledge Space Theory (Albert & Lukas, 1999; Doignon & Falmagne, 1999; Falmagne, Koppen, Villano, Doignon, & Johannesen, 1990) provides a formal model for structuring and representing knowledge based on prerequisite relationships. A knowledge domain is characterised by a finite, non-empty set Q of problems. The knowledge state of a learner is represented by the subset of problems that he or she is capable of solving. Due to mutual dependencies among the problems of a domain, not all subsets of problems are expected to be observable knowledge states. These dependencies are captured by the so-called prerequisite relation. If two problems a and b are in a prerequisite relation, from a correct solution to problem b the mastery of problem a can be surmised. In other words, problem a is a prerequisite problem for problem b. Assume for example two problems of basic algebra, an addition of variables and a linear equation. The first problem can be regarded as a prerequisite for the second one, as being able to solve the equation will certainly entail being also able to solve the addition. A prerequisite relation can be depicted by a Hasse diagram (see Figure 2 for an example), where descending sequences of line segments indicate a prerequisite relationship.

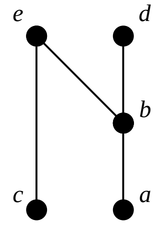

Figure 2. Example of a Hasse diagram illustrating a prerequisite relation on a knowledge domain $Q = \{a, b, c, d, e\}$ (adapted from Falmagne et al., 1990).

According to the prerequisite relation illustrated in Figure 2, from a correct solution to problem b the correct solution to problem a can be surmised, while the mastery of problem e implies correct answers to problems a, b, and c. The collection of knowledge states corresponding to a prerequisite relation, including the empty state Ø and the whole set *Q*, constitutes the so-called knowledge structure $\mathcal{K}$. The knowledge structure corresponding to the prerequisite relation shown in Figure 2 is given by

$$\mathcal{K} = \{Ø, \{a\}, \{c\}, \{a, c\}, \{a, b\}, \{a, b, c\}, \{a, b, d\}, \{a, b, c, e\}, \{a, b, c, d\}, Q\}.$$

The possible knowledge states are naturally ordered by set-inclusion, as can be seen in Figure 3. Given a knowledge structure, there are various possible learning paths from the naive knowledge state (empty set ∅) to the knowledge state of full mastery (set *Q*). The knowledge structure depicted in Figure 3 suggests to present learning objects related to problem *a* (or, equivalently, *c*) first. Subsequently, material related to problems *b* or *c* (*a*, respectively) should be presented, and so on. One possible learning path is indicated by dashed arrows in Figure 3, describing the successive steps of the learning process. Thus, given a learner's knowledge state, a knowledge structure provides useful information which learning content should be presented next, but also which previously learned material should be reviewed. Furthermore, a knowledge structure builds the basis for an efficient adaptive knowledge assessment that allows for determining the current knowledge state of a learner. Through exploiting the structure inherent to the knowledge domain and taking into account previous answers of an individual, only a subset of problems has to be presented.

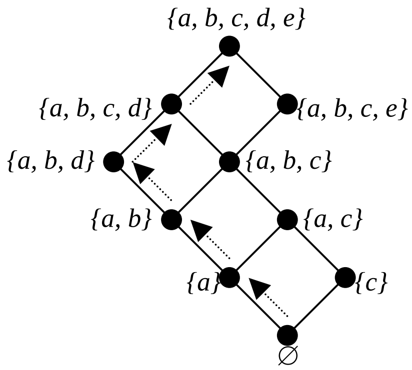

Figure 3. Knowledge structure $\mathcal{K}$ corresponding to the surmise relation illustrated in Figure 2. The dashed arrows indicate a possible learning path.

2.2 *Validation Methodology*

Assume a concept map representing the declarative knowledge of a particular knowledge domain, for which application validity is to be examined. For testing the target map's ability to predict relevant situational behaviour, problem solving has been identified as an appropriate measure of performance to be used as validation criterion. To this end, a set of typical problems is chosen, representing the domain in the sense of Knowledge Space Theory. For each problem the declarative knowledge that is required for solving the respective problem is determined by identifying the problem with a substructure of the target concept map. This means, each problem is mapped on the concept map, by assigning the subset of propositions required for mastering the respective problem (Albert & Steiner, 2005; Steiner & Albert, 2008). Each proposition could be considered as an atomic skill or competency in the sense of competence-based extensions of Knowledge Space Theory (e.g. Düntsch & Gediga, 1995; Falmagne et al., 1990; Heller, Steiner, Hockemeyer, & Albert, 2006; Korossy, 1999). Based on the problems' representation by substructures of the target map, dependencies between problems in terms of a prerequisite relation can be derived by set inclusion. Assume, for example, a problem *X* that is represented by the propositions *{P3, P7, P8, P9, P13, P15}* of a concept map, and another problem *Y* that has been associated with propositions *{P3, P7, P9, P13}*. As the representation of problem *Y* constitutes a subset of that of problem *X*, it is assumed that *Y* is a prerequisite for *X*. The dependencies derived in this way serve for establishing a knowledge structure that collects the set of possible knowledge states. The knowledge states constitute answer patterns that are expected to be observable, provided that the target map validly represents the domain. The next step in the validation approach is therefore to collect empirical answer patterns on the set of problems. It can then be investigated whether the observed answer patterns correspond to the predicted knowledge states, for example by using a discrepancy index describing the similarity between the knowledge structure and the set of answer patterns (e.g. Doignon & Falmagne, 1999). As the target map has been used for establishing the knowledge structure, the empirically obtained answer patterns serve as validation criterion. If the empirical answer patterns correspond well to the predicted knowledge states, the concept map can be considered to be valid – provided that both, the chosen set of problems as well as the sample of persons are adequate and representative.

3 An Empirical Example of Application Validation

The methodological considerations presented above have been applied in an empirical context in order to illustrate the procedure of validation and to demonstrate its significance and usefulness.

3.1 Method

For examining application validity of a concept map 44 subjects (20 male and 24 female) ranging in age from 18 to 59 (M = 26.23, SD = 8.77) were tested in single investigations.

Having in mind an educational and learning context, the knowledge domain of elementary geometry, more precisely a small subdomain on right triangles and the theorems in right triangles was chosen for the empirical investigation. Based on textbooks and school curricula a concept map was generated that was intended to be usable as learning material in classroom (see Figure 4 for an extract).

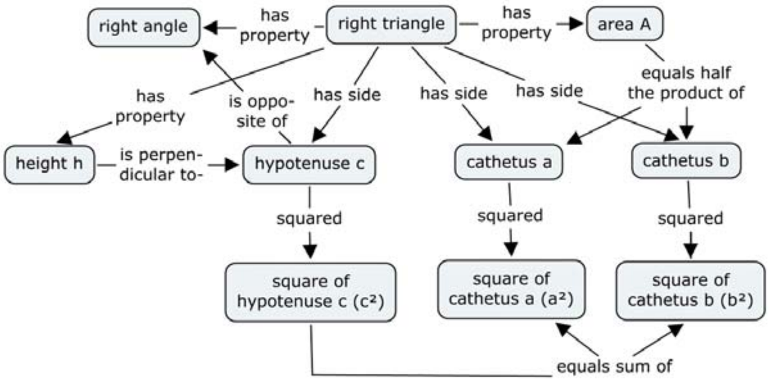

Figure 4. Extract of the target concept map on right triangles.

For examining application validity of the target map it had to be related to situational behaviour referring to the intended use of the concept map. Assuming that the target concept map was foreseen to be applied to teach a subdomain of geometry, problem solving behaviour in the same knowledge domain seemed to be an appropriate kind of situational performance to be used for validation purposes. To this end, a collection of ten geometry problems was adapted from Korossy (1993). These problems constituted typical and representative problems of the knowledge domain in question (see Figure 5 for an example).

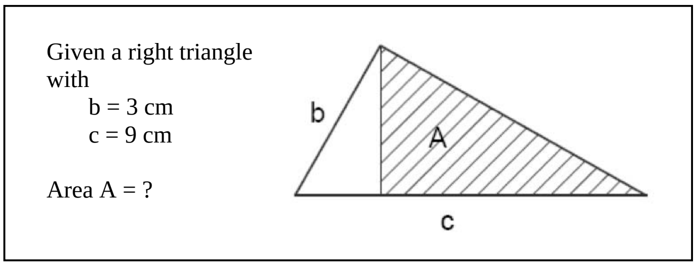

Figure 5. Example of a geometry problem used for the investigation of the target map's application validity.

For investigating application validity, the target map was used for establishing a knowledge structure on the geometry problems. This means, each of the ten geometry problems was mapped onto the concept map by identifying the propositions representing the knowledge necessary for solving it. Here, it had to be taken into account that most of the problems could be solved in several different ways using the theorems in right triangles. For the geometry problem presented in Figure 5, for example, two solution ways are applicable. Thus, first the different solution strategies for each problem were identified and collected based on cognitive task analysis (Korossy, 1993). For every problem, each solution way was then associated with the relevant propositions of the concept map.

For deriving dependencies in terms of a prerequisite relation, the problems' representations (more precisely, their solution ways) were compared to each other by means of the subset relation. In a first step, subset relations between solution ways were identified and documented. These were interpreted as preliminary prerequisite relationships among the respective problems. As most problems were represented in two or more ways on the target map, corresponding to their different solution strategies, the derived prerequisite relationships could potentially be ambiguous, namely if for a certain pair of problems two solution ways indicated a prerequisite relationship in one direction (e.g. problem *X* is a prerequisite of problem *Y*), whereas the comparison of two other solution ways indicated a prerequisite relationship in the inverse direction (i.e. problem *Y* is a prerequisite for problem *X*). Therefore, in a second step, the preliminary assumed dependencies between problems were cleaned up, by eliminating the few arising contradictory prerequisite relationships while retaining only definite ones.

The resulting prerequisite relation established for the ten geometry problems on the basis of their representation on the target map is illustrated in Figure 6. The knowledge structure corresponding to this prerequisite relation consists of 41 knowledge states, and thus considerably reduces the set of on principle possible answer patterns (i.e. 1024). For instance, each knowledge state containing problem *d* also contains problem *a*, and a knowledge state covering problem *g* necessarily also contains problems *c*, *a*, and *f*. The knowledge structure derived in this way served as a basis for investigating the target map's application validity. The knowledge states collected in the knowledge structure constitute answer patterns on the 10 geometry problems that were expected to be observable.

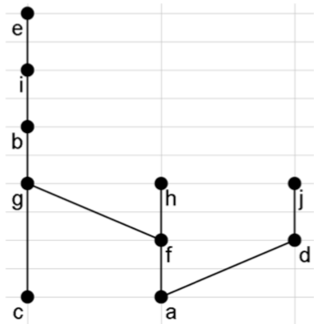

Figure 6. Hasse diagram depicting the prerequisite relation established on the ten geometry problems.

In order to examine whether these theoretically derived and expectable answer patterns predict empirical answer patterns well, the geometry problems were presented to the participants of the empirical investigation. The problems were presented in randomised order and each problem was depicted on a separate sheet. First, three warm-up exercises were presented, which were not taken into account for data analysis, but rather served for making the subjects familiar with the problem solving task and for reducing test anxiety. Subsequently, the ten geometry problems were presented in randomised order. Participants should work at least three minutes on a problem, at maximum ten minutes. This was to ensure that a person being able to solve a problem also brought this ability out, on the one hand, and to limit the duration for one single investigation on the other hand. The average duration for working on the problems was 66 minutes (*SD* = 12.38).

3.2 Results

Out of the ten geometry problems on average five were solved correctly (*M* = 4.82, *SD* = 2.47). For comparing the empirical answer patterns to the theoretical knowledge structure the minimal symmetric distances between empirical and theoretically expected answer patterns were calculated (Garnier & Taylor, 1992; Kambouri, Koppen, Villano, & Falmagne, 1994). The minimal symmetric distance between an answer pattern and a knowledge structure is defined as the distance to the nearest knowledge state. Assume for example the answer pattern *{a,d}* for the five problems presented in the exemplary knowledge structure presented in Figure 3. This answer pattern is actually not part of the knowledge structure, the nearest knowledge state is given by *{a,b,d}* (and *{a}*, respectively) and differs in one problem (i.e. *b*) from the answer pattern. Thus, the distance between the answer pattern *{a,d}* and the knowledge state *{a,b,d}* is one. Assuming that the knowledge structure is correct, in this case it is deemed that in solving problem *b* a careless error has occurred. The minimal distance averaged across all response patterns constitutes a measure for the correspondence between empirical and theoretically predicted knowledge states and gives evidence of the validity of the established knowledge structure and thus, of the target map. The theoretical minimum distance is given by 0, meaning that no deviation from the knowledge structure occurs, i.e. the answer patterns fully correspond to the predicted knowledge states.

The maximum possible distance is given by half the number of items (i.e. n/2 for even, or respectively, (n-1)/2 for odd numbers of items). Hence, for the present investigation with 10 geometry problems the greatest possible distance was 5.

The average symmetric distance between the 44 empirically collected answer patterns and the hypothesised knowledge structure was 0.77 (*SD* = 0.73) (see Table 1). When calculating minimal distances between an empirical data set and a theoretical knowledge structure, it has to be taken into account that trivial answer patterns (i.e. none or all problems mastered) on principle do not provide any information of the validity of the specific theoretical structure, as these knowledge states are contained in any knowledge structure. In the present investigation, only two trivial answer patterns (no problem solved correctly) occurred. Hence, when considering only non-trivial answer patterns for the calculation of mean distances an only slightly higher average distance (*M* = 0.81, *SD* = 0.73) resulted.

Distance	*Frequency* (*44 subjects*)
0	17
1	21
2	5
3	1
mean distance	0.773 (*SD* = 0.73)

Table 1: Frequency distribution of minimal distances and mean distance for the present investigation.

These results for the comparison between theoretical and empirical knowledge states are definitely encouraging and argue for the properness (more precisely, the validity) of the established knowledge structure. For a statistical test of the knowledge structure’s validity Heller (2001) suggested to use a frequency distribution of the symmetric distances. Assuming the null hypothesis that the empirical data comprises no structure, the validity of the knowledge structure is estimated by using a one-dimensional χ^2 statistic. The distribution of distances for the items’ power set (i.e. all answer patterns) is utilised as a basis for the test. It is examined whether the distribution of distances for the empirical answer patterns differs significantly from the distribution for the expected patterns. For the present investigation the null hypothesis could be rejected (at a 1 % level of significance; $\chi^2_{0.99} = 15.08$ and $\chi^2_{obs} = 172.21$), which argues for the validity of the knowledge structure and hence of the concept map.

In sum, the data analysis leads to the conclusion that the empirically collected answer patterns on the geometry problems correspond well to the theoretically predicted answer patterns (i.e. knowledge structure) as derived from the representation of the geometry problems on the concept map. As the correspondence between knowledge structure and empirical performance can be interpreted as a measure of application validity, the target map can be regarded to be validated and is ready for use.

3.3 Discussion

For the geometry problems used in the empirical investigation actually also a somewhat different knowledge structure had been established and investigated in the past, based on an underlying competence modeling (Korossy, 1993). The respective structure was even more restrictive, featuring only 25 knowledge states (compared to 41 knowledge states in the present investigation). It appeared of course interesting to compare the goodness of fit of the structures in the two investigations. To this end, the distance agreement coefficient DA (Schrepp, 1999) was calculated, which constitutes a measure for the fit between a knowledge structure and an empirical data set, while taking into account the size of the knowledge structure. The resulting DA for the present investigation was 0.349 compared to a DA of 0.356 for the investigation and knowledge structure of Korossy (1993). Thus, this measure indicates marginally better results for our investigation.

The representation of the geometry problems on the concept map, which was used for establishing the knowledge structure, only considered solution ways of the problems using the theorems in the right triangle (i.e. Pythagorean, Altitude, and Euclidean Theorem). Actually, there were also alternative ways for solving the geometry problems (applying trigonometric functions or quadratic equations). As the target map represented only the knowledge domain on theorems in right triangles, those alternative solution ways were not presentable and not intended to be captured. Consequently, for the purpose of application validation only answer patterns using the solution approaches addressed and used for establishing the knowledge structure should be considered. In the present investigation, eight out of the 44 participants partly used such alternative solution ways. When excluding the answer patterns of the respective eight persons from data analysis and calculating the average minimal symmetric distance between the empirical data and the theoretical knowledge structure for the remaining sample, though, the result changes only marginally (M = 0.778, SD = 0.75 for the reduced sample compared to M = 0.773, SD = 0.73 as resulting for the whole sample).

The performance measure chosen for application validation actually involved not only declarative but also procedural knowledge. This is, as the solution of the geometry problems does not only require to know the theorems in the right triangle on a solely factual, declarative level, but rather also requires ability in terms of procedural knowledge, i.e. on how to apply the declarative knowledge elements. The target map in this investigation naturally only covered declarative knowledge, such that the establishment of the knowledge structure relied only on the problem's declarative representation on the target map. Therefore, the concept map's predictive power was investigated using a more comprehensive situational behaviour and thus, an even stricter and more delicate validation criterion. Consequently, the results of the investigation are even more interesting and confirmatory for application validity. However, somebody might claim for an alignment of target map and represented problems. Here, we see two possibilities: either to use problems or questions that require only declarative knowledge or, alternatively, to include procedural knowledge elements in the target map.

4 Summary and Conclusion

A concept map reflects the perspective of its authors and the purpose for which it has been constructed. Hence, given a particular purpose a concept map is needed that validly represents the knowledge of the domain in question, integrating possibly different perspectives, and referring to the designated use of the concept map. A critical precondition for an efficient use of a concept map is that it validly represents the knowledge domain in question. This calls for scientifically sound and systematic methods for concept map validation. Here, two aspects of validity are relevant, referring to the question whether a concept map adequately reflects the knowledge of the respective domain (content validity), on the one hand, and referring to the issue whether a concept map serves the purpose for that it has been designed (application validity), on the other hand. For content validation an approach utilising empirically collected concept map as a criterion has been suggested, whereas for application validity an approach utilising relevant situational performance based on Knowledge Space Theory can be pursued (Albert & Steiner, 2005). This paper focuses on application validity and outlines an empirical demonstration of the proposed validation procedure for a target map on geometry. Application validity was examined through representing typical geometry problems of the knowledge domain as substructures of the concept map and in this way deriving prerequisite relationships among problems by set-inclusion. The identified prerequisite relationships gave rise to a knowledge structure predicting expectable answer patterns on the set of problems. This theoretically derived knowledge structure was compared to empirically collected answer patterns, yielding that they correspond well to each other and thus arguing for the validity of the established structure. As the structure was derived from the target map, in this way the map can be regarded as validated w.r.t. application validity. This constitutes a well founded starting point for the practical application of the concept map.

All in all, the results of the investigation presented in this paper are encouraging and militate in favour of the applied approach for application validation. In general, the knowledge structures established and validated in the course of such an application validation can be re-used, e.g. in the context of technology-enhanced learning, for personalising learning experiences (Steiner & Albert, 2008). This perspective of reuse would mean shared and reduced costs and argues for the real-world utility of the approach presented. Further research should try to underpin the significance of the proposed methodology and broaden these initial encouraging results. Moreover, also the empirical demonstration of a content validation approach would be desirable. By further empirical use of the methodologically proposed procedures, their contextual conditions of use and applicability can be further investigated and opportunities for improvement and refinement can be identified.

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