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A Cognitive Approach for Modeling Lifelong Competence Development

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Abstract:

Lifelong competence development is a fundamental premise for an information society, as well as major aim and challenge. Facing the variety of learning programs and qualification measures, problems emerge in supporting lifelong learning. Efficient competence development necessitates providing learners with learning opportunities which are appropriate for their current knowledge and for their individual learning goals. A related problem is the comparison of learners' competencies when these have been assessed in very different situations, at different ages, and with different methods. This work discusses the advantages of formally modeling competence and performance, which enables determining learners' latent, unobservable competence states based on their observable performance on a set of assessment methods.

1 Introduction

Lifelong competence development is a fundamental premise for an information society, as well as major aim and challenge for research and development. Lifelong learning and continuing acquisition of competencies are important factors for individual success and the success of the whole society. There is little doubt that such factors will gain even more importance in the future, especially in a society which assets are primarily based on knowledge, competence, and know-how. Such viewpoint is emphasized, for example, by efforts of the European Commission, e.g. by the campaign "2010 - ePortfolio for all" (www.eife-l.org) or the IST[1]-project TENCompetence (www.tencompetence.org), which aims at developing and establishing technology supporting efficient lifelong competence development.

The concept of lifelong learning has been associated with four main purposes in the literature: preparing individuals for managing their adult lives, distributing education throughout individuals' lifespan, fulfilling an educative function for the whole life experience, and identifying education with the whole life (for an overview see [7]). Originally a universal visionary concept; today, lifelong learning constitutes an integral part and central principle of national and international policies [20]. As lifelong learning refers to the assumption that individuals learn at all stages of their life, all levels of education and training need to contribute for realizing a lifelong learning framework. For this, provision in education has to be strengthened and diversified and universal access to learning needs to be ensured.

[1] Information Society Technologies (IST) research framework of the European Commission (http://cordis.europa.eu/ist/)

Strategies for realizing lifelong learning include increased involvement at the pre-school level, instilling desire and ability to learn in compulsory education, broadening and diversifying educational opportunities in secondary education, adapting higher education to demand, and strengthening and updating adult education [20]. However, facing the variety of existing curricula, learning programs, and qualification measures, problems emerge in making lifelong learning and continuing qualification efficient and effective. Technology supporting these aims should not only assist learners in orientating in the large body of learning opportunities and in planning individual learning, it must also enable the comparison of individual competencies. For realizing a framework of lifelong learning at the European level, an individual should be able to freely choose among learning environments, jobs, and countries for enriching his/her knowledge, skills, and competencies. Therefore, educational qualifications, certificates, and diplomas need to be part of a coherent system for properly evaluating and recognizing them [18]. In this way, comparableness between qualifications or competencies acquired in different educational programs, institutions, and countries could be ensured.

1.1 Planning individual competence development

Efficient and effective competence development requires providing learners with integrated learning opportunities which are suitable and appropriate for their current knowledge and for their individual learning goals. To give a very simple example, a JAVA developer who wants to learn C# programming shouldn't be provided with learning opportunities covering programming basics but with such covering the differences between JAVA and C#.

This principle is the basis of many adaptive or personalized eLearning solutions, however, on a small scale (e.g., limited to a specific domain of knowledge). Generally, these adaptive eLearning systems, e.g. ALEKS (http://www.aleks.com), ELM-ART [29], or KBS Hyperbook [22], attempt to compete the one-fits-all approach of traditional eLearning [10][13], accounting for certain requirements and preferences of a learner. Primarily, adaptive or personalized approaches provide adaptive navigation and adaptive presentation of contents [3][5][9][13][14]. Adaptive navigation refers to guidance through learning objects by, for example, a customized hyperlink structure or format. The degree of freedom granted within such system is determined by a specific underlying learner model. Adaptive presentation refers to a customized presentation of learning objects. On the one hand this might concern the visual or auditory design; on the other hand this might concern the amount or grade of details of presented learning contents.Whilst adaptive, personalized eLearning systems already successfully provide adaptivity and adaptability regarding the learning objects and test items of a specific limited domain and focused on a certain point in time, approaches to facilitate lifelong learning in terms of efficiency and effectiveness must address the same issues, however, based on a much larger scale of content (e.g., including job-specific competencies) and on a much wider timeframe.

1.2 Assessing and comparing competencies

One of the most important indicators for (lifelong) learning processes and learning success are assessments results; gathered in very different situations, at different ages, and with different methods. Thus, questions for research, for example in view of a global labor market and global competition, might concern cross-cultural aspects and how different learners' competencies (e.g., the ones of a programmer graduated in Austria and the ones of a programmer graduated in the UK) can be compared with each other. This comparison is important in order to:

(a) enable adaptive support of learners in planning individual learning paths,
(b) support learners in navigating through the large body of learning opportunities,
(c) support learners' presentation of accredited achievements and competencies, and
(d) enable employers to identify persons fulfilling the requirements of a specific position.

This comparison, however, is not a trivial problem because educational contents of curricula, for example in computer science, and the focus of education often vary significantly between different schools and universities, different countries, or different cultures. Even among individuals with the same educational background differences may occur when those learners have the possibility to focus on certain topics or to choose certain courses. Thus, when aiming for facilitating lifelong learning by means of providing learners with appropriate learning paths and learning opportunities, we have to break down competencies into a sufficiently fine granularity and we need an underlying model that allows us to process this vast amount of data.

1.3 Competence vs. performance

The concept of competence is a vital element of our society. From our point of view, a major problem when considering individual competencies is the often unclear differentiation between latent competence and observable performance. To date a variety of definitions of competence exist (e.g., [6][26]). *The American Heritage Dictionary of the English Language*, for example, states: "Competence means the state or quality of being adequately or well qualified; a specific range of skill, knowledge or ability". This and many other definitions have in common that they describe competence as an abstract, latent, not directly observable quality. For an adequate development and assessment of competence, however, latent competencies must be associated with observable behavior or achievements. An early distinction between latent competencies and observable performance was introduced by Chomsky [12] in the framework of linguistic theory. He distinguished a speaker's competence to use and understand a language and the performance, which includes grammatical mistakes and non-linguistic features like hesitations. Today, this distinction has a much wider application, especially in the field knowledge and learning psychology. Still, in practice the concepts of latent competencies and related observable performance often lack a thoroughly differentiation, operationalizations are often one-two-one mappings of underlying competencies and performance, and often the same labels are used for both concepts. From a scientific point of view, this is not an utilitarian approach; it is fraught with difficulty as demonstrated with following examples:

Imagine an exam in trigonometry. Students might be allowed to use a mathematical formulary and a pocket calculator. If two students master a certain task of the exam, can we conclude that these students do have the same competencies with regard to the task? We cannot; one student might have the necessary competencies to master the task without using the formulary, another student maybe mastered the task only by chance, incidentally choosing the right formula from the formulary. Or imagine three other students who didn't master the task. One student might not have the competence to fully understand the task and its formulation. Thus, it would not be efficient or successful to teach that student how to use a formulary. Another student might fully understand the task and also might be able to choose the right formula, but maybe this student is not able to use a required function of the calculator. In this case it would not be efficient or successful to teach this student how to understand trigonometry tasks. Finally, a third student might have the necessary competencies to master the entire task but might have problems to concentrate on the tasks during an exam. Thus, it would not be useful to teach this student math.

These examples demonstrate that it is not only necessary to break down certain types of competencies [11] to a certain level of granularity, but also to separate competencies from performance and to adapt learning to individual needs. This is especially true for lifelong learning when the aim is to have a continuous model of competence development, to track the development during a long time span, and when competencies are assessed with many different instruments (e.g., observations, tests, achievements).

Such aims require a clear and probably standardized, definition of competencies in a given domain and a cognitive framework that allows distinguishing latent competencies and observable performance and, further on, that provides a formal model of competencies and their interrelations. A sound framework to achieve such goals might be the *Competence Performance Approach* (CPA).

2 Competence structures

Knowledge Space Theory (KST) [1][2][16][17], is the basis for several approaches to competence structures, which provides a set-theoretic framework for organizing a domain of knowledge and for representing the knowledge based on *prerequisite relations*. A knowledge domain is represented by a finite set Q of problems. The *knowledge state* of a learner is described by a subset of problems that s/he is able to master. Due to prerequisite relations among the problems of a domain, not all subsets of problems are possible knowledge states. If two problems $a, b \in Q$ are in a prerequisite relation $a \precsim b$, we can assume from mastering problem b a mastering of problem a. To give an example, image five problems of the domain of basic algebra, an addition, a subtraction, a multiplication, a division, and an equation. For five problems the set of all possible knowledge states is 2^5; if we assume that addition, subtraction, multiplication, and division are prerequisites for solving equations, not all 32 knowledge states will occur, because it is highly improbable that a student will be able to solve equations but no addition problems.

The collection of possible knowledge states corresponding to a prerequisite relation, including the empty set $\varnothing$ and the whole set Q, is called a *knowledge structure K*. To account for the fact that a problem may be solved in different ways and thus may be associated to different sets of prerequisites, the notion of a *prerequisite function* has been introduced, which, as a generalization of a prerequisite relation, associates a family of subsets of Q with each problem.

In its original formalization, KST is rather behavioral, focusing on the observable performance without referring to the competencies that underlie that performance. Among others [15][18], one extension, which incorporates explicit reference to the competencies that are required for mastering the problems of a domain is CPA by Korossy [23][24]. The basic idea of CPA is to assume a basic set E of abstract, cognitive competencies that are relevant for mastering the problems of a domain. The *competence state* of an individual is the collection of all available competencies of that person, which is not directly observable but can be uncovered on the basis of the observable performance on the problems representing the domain. As in KST, prerequisite relations are described on the set of competencies establishing a *competence structure C*, which contains all possible competence states. Utilizing *interpretation* and *representation functions*, families of subsets of competencies (competence states) can be mapped to problems, which can be mastered with the given competencies and vice versa. By the assignment of competencies to the problems of a domain, also a “problem structure” – which may be a surmise relation or a surmise function - on the set of problems is induced.

To illustrate this approach, assume a knowledge domain that is represented by a set of four problems (e.g., test items), $Q=\{a, b, c, d\}$. Consider the set $E=\{V, W, X, Y, Z\}$ of

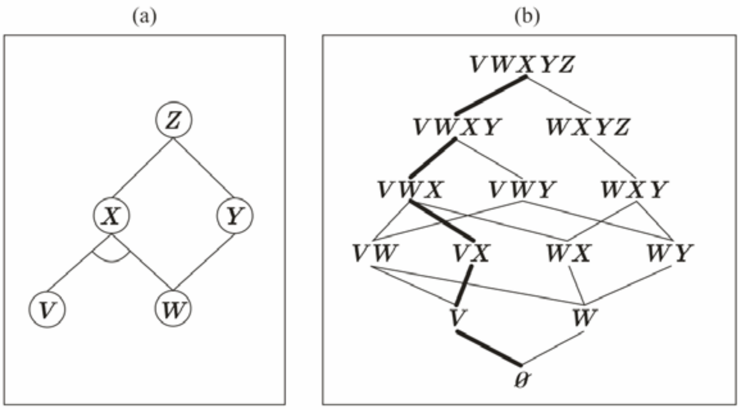

Figure 1. Panel (a) displays the AND/OR-graph for a prerequisite function among five competences (V to Z). The bended line below competence X indicates a logical or. Panel (b) shows the competence structure established by the prerequisite function. The bold line indicates a valid learning path.

competencies that are relevant for solving these problems. A prerequisite function that might exist among these competencies is demonstrated by the And/Or-Graph in Figure 1a. Thus, if a student has competence *X* we can assume that this student also possesses either competence *V* or *W* or both; if a student possesses competence *Y* we can assume that this student at least possesses also competence *W*. The prerequisite function establishes a competence structure (Figure 1b), which includes only thirteen possible competence states from a total of 2^5 states. Table 1 lists an interpretation function, which associates competence states that are adequate for mastering a given problem. This means, for solving problem *a* one of the two competence states *{V, X}* and *{W, X}* is necessary or sufficient; a student that is in one of these two competence states (or a superior one) will be able to master this problem. Given the interpretation function, the representation function specifies the subset of problems that can be solved in each competence state.

Table 1. *Interpretation function.*

Problem	Competence states
a	*{V, X}, {W, X}*
b	*{W, Y}*
c	*{V, W, X}, {W, X, Y}*
d	*{W, X, Y, Z}*

The outlined approach entails several advantages. Given the performance, i.e. the subset of problems a student could master, the latent cognitive competencies underlying that problem solving performance can be identified. Due to the utilization of representation and interpretation functions no one-to-one mapping of performance (e.g., responses to test items) to competencies is required.

3 Applications

As mentioned, CPA might be a promising approach for modeling lifelong competence development and making it more efficient and effective. In the following, several areas are outlined within which CPA was successfully applied.

3.1 Longitudinal observations

With regard to lifelong learning, it is important to keep track on individual development of competencies over a long period of time. CPA allows the mapping of a variety of different assessment instruments of a certain domain to one competence structure. This means that it is possible to identify the actual competencies of a person once with a school exam and many years later with a different instrument, e.g. achievements at the workplace.

This strength of CPA was applied, for example, in the domain of children's understanding time, distance, and velocity concepts, as a tool for modeling the developmental course [4] including misconceptions. In recent work learning paths are utilized to analyze longitudinal data in this domain.

3.2 Competence development

Besides identifying competencies, a further major advantage of CPA is that it allows determining a person's current competence level by personalized, adaptive competence testing. Furthermore, individual learning paths can be defined on the competence level. Due to the prerequisite relations between competencies the development of competencies cannot occur along arbitrary paths. Referring to the example presented before, a student who is in the competence state *{W, Y}* cannot directly proceed to competence state *{V, W, X, Y, Z}* because competencies *V*, *X,* and *Z* are lacking (Figure 1b demonstrates a valid learning path for this example). Thus, CPA allows very detailed planning of competence development along learning paths and adapting teaching to individual needs with regard to learning objectives. If a student is, for example, in competence state *{W, Y}* it would be most efficient to teach this student competence *X* instead of *V* in order to reach competence state *{W, X, Y, Z}*, which allows the student to master problem *d*.

3.3 Technology-enhanced Learning

During the last years, the approaches of KST and CPA were increasingly integrated into adaptive eLearning systems [21] such as the research prototypes APeLS (http://css.uni-graz.at/demos/apels) or RATH (http://css.uni-graz.at/rath), as well as the successful commercial eLearning platform ALEKS (www.aleks.com). Moreover, this formal, computational approach contributes and contributed in the past to state-of-the-art eLearning projects under the IST[1]-framework, e.g., EASEL (css.uni-graz.at/projects/easel/easel.htm), EleGI (www.elegi.org), iCLASS (www.iclass.info), or ELEKTRA (www.elektra-project.org). These approaches to eLearning attempt to adapt to the learner's knowledge state or competence state respectively by providing personalized navigation support and personalized presentation of contents on the basis of a learner's performance in adaptive assessments.

3.4 ePortfolios

A further example to demonstrate the importance of clear definitions of competencies and their separation from assessment instruments are ePortfolios. During the last years ePortfolios gained more and more importance and attention. These portfolios are dynamic collections of authentic and diverse evidence that represents which competencies a person has acquired over time [8]. They provide (a) profiles of competencies, (b) opportunities for learners to document their competencies in different contexts, (c) opportunities for reflection in different contexts to integrate learning experiences, and (d) opportunities for a more holistic approach to learning [25]. ePortfolios' gain of currency is fostered, for example, by the European Union's initiative "2010 - ePortfolio for all" (www.eife-l.org). Another example for the importance of ePortfolios as a platform for recording, tracking, and presenting individual competencies is CampusCanada (http://campuscanada.ca), which aims at bridging the workplace and academic opportunities by permanent and accredited individual records.

To achieve such dynamic, comparable, and sound collections of competencies it is necessary to develop standardized competence databases, which clearly define competencies of certain knowledge domains. Moreover, competencies must be related to performance and achievements and, in a next step, possibilities for the (self-) assessment of competencies might advantageously be integrated. Only if the competencies of a person from one part of Europe assessed with a school test are directly comparable to the competencies of a person from another part of Europe assessed by an evaluation at the workplace, these attempts can be a substantial gain and progress. The framework of CPA presented in this paper is able to provide a sound starting point for future steps in this direction.

4 Conclusion

CPA, as an extension of KST, is a sound and well-elaborated psychological framework, which can be utilized to model competencies and their interdependencies and, furthermore, to assess latent competencies by observable performance. A major advantage of CPA is its formal mathematical nature, which can easily be implemented in computational systems, such as adaptive tutorial systems.

Thus, this approach gives the edge to set up a detailed model of competencies of a domain. Learners' competence states can be determined by different methods and at different ages. On this basis, learners can be provided with learning opportunities that are appropriate and suitable for their competence states. At the same time this approach enables the flexibility of different learning paths to reach a certain individual learning goal. Moreover, the competencies of different learners, at different ages, and further on from different countries can be compared by detailed competence and performance profiles and learners can present their competences in a corresponding way, for example with ePortfolios.

Even if such demands are rather visionary, a road map for future developments is to establish a standardized catalogue or database of competencies in certain domains of knowledge / competence. For instance, such catalogue might be based on ontologies and might include information about the mapping of performance to certain competence states. This enables incorporating the advantages of CPA in technological approaches to lifelong competence development (e.g., semantic web technologies).

Still, major challenges exist, which are addressed by recent and future research. For example, it's necessary to model errors, which likely occur in empirical responses to test items (i.e., careless errors and lucky guesses [15][27]). This requires the extension of deterministic competence-performance models by probabilistic components. Another major issue is the validation of prerequisite relations among competencies and the resulting competence structures. Currently, various coefficient-based methods to compute the "fit" of a proposed knowledge or performance structure to a given set of empirical response data exist [28]. The question challenging research is how unique the relationship between a set of competencies and a set of performance indicators (e.g., test items) is. In a next step goodness-of-fit measures can be developed. This is no trivial task because already performance structures might be difficult to validate, thus, attempting to distend validations to the latent competence level is even more difficult.

Even if future work must address existing problems, CPA provides a promising cognitive and methodological basis for the requirements of modeling and assessing lifelong competence development and for making another step towards a more effective, efficient, and satisfying lifelong learning.

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