A framework for the digital competencies for teaching in science education – DiKoLAN

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Abstract. In order to systematically introduce (prospective) teachers to teaching in the digital world and to lay the foundations for concepts that are meaningful in terms of physics education, essential aspects of learning with and via digital media must be conveyed. In addition to cross-curricular competencies, it is essential to consider subject-specific competencies for the natural sciences since the formation of subject-specific knowledge on the use of digital media in the classroom (TPACK) is the decisive factor for acceptance behaviour and the intention for later use. The questions remain as to what core competencies must be built up by all (prospective) science teachers by the end of their studies and in which sections of university teacher training this should take place. Since no competence frameworks specific to the teaching of science were previously available, nine researchers from eight universities came together to develop a suitable orientation framework. As a result, this contribution presents the structured and graded framework "DiKoLAN – Digitale Kompetenzen für das Lehramt in den Naturwissenschaften [Digital Competencies for Teaching in Science Education]" (see https://dikolan.de).

1. Introduction

The integration of digital elements into teaching and the corresponding competences of teachers has long been a subject of research. Despite varying degrees of success among the countries involved [1] results show a lack of ICT-oriented teacher training [2]. Also, during the COVID-19 pandemic, minor and major gaps in the preparation of teachers for the digitization of schools have become apparent all

around the world. [3] Many of those parties involved in and around school education complained about glaring difficulties that cannot be attributed solely to the lack of technical equipment in schools and around teachers. In particular, the development of teachers' technological pedagogical knowledge (TPACK) [4] was often neglected in teacher training. A focus on building digital competencies in all parts of teacher training is more urgent than ever. The foundations for this have been laid both for Germany and, in principle, also for other countries. National and international guidelines, standards, and requirements [5] for the promotion of digital literacy skills among students are shaping a changing educational practice in schools and universities. In Germany, with the strategy of *The Standing Conference of the Ministers of Education and Cultural Affairs* (KMK), "Bildung in der digitalen Welt [Education in the digital world]" [6] goes in line the formulated mandate to adapt and restructure teacher training to the new challenges associated with advancing digital transformation. This requires the universities to broadly include digital competencies in the curricula for pre-service teacher training. As a requirement, subject-specific digital competence expectations must also be identified and formulated, as research on TPACK in teacher training has shown that TPACK is the most important factor to change teachers' acceptance behaviour and intention to use digital technologies in the classroom [7]. Structuring and categorizing these competencies in a system that is suitable for curricular allocation and coordination is a central prerequisite for a university-wide and consistent integration of these into courses, e.g., of physics, physics education, psychology, and pedagogy. Therefore, a cross-location binational and interdisciplinary team of physics, chemistry, and biology education researchers came together to structure and formulate an orientation framework for digital competencies for teaching in science education as an initial consensus by extending available frameworks and models of digital competencies.

2. Exemplary models and frameworks related to digital competencies of educators

Competence frameworks for teacher training should, in addition to an orientation towards teaching practice, outline a progression in training and at the same time contain subject-specific concretizations to be able to derive appropriate curricula and assessments. Regarding the extent to which these requirements are considered, currently available models differ greatly. For an overview of available frameworks see [8]. Selected frameworks that provide conceptual orientation for the project presented here are briefly introduced below as examples.

The *European Digital Competence Framework for Educators* (**DigCompEdu**) [9] DigCompEdu, names six competence areas, each consisting of six skill levels depending on the intensity of the use of digital media [10]. Besides professional competencies ("Professional Engagement"), DigCompEdu also covers key areas of planning and implementation of teaching-learning scenarios on a general, non-subject-specific level with the competence areas of digital resources, evaluation, teaching and learning as well as learner orientation (Fig. 1). Although DigCompEdu includes subject-specific competences as a marginal area, these are not specified further. Therefore, DigCompEdu can neither formulate subject-specific competencies and levels nor describe corresponding teaching situations for training and assessment purposes.

A subject-specific training oriented towards teaching activities is necessary, however, to enable prospective teachers to use digital media in the physics classroom in a meaningful way. The lack of specificity in the technical area also means that, for example, scientific content that is related to digitization and would be relevant regarding content selection, cannot be easily identified or located. Since none of the three assessment versions address student teachers via appropriately formulated items, the contribution of DigCompEdu to university teacher training is limited to being used as an orientation framework for the prospective requirements of school teaching and the derivation of appropriate, further specified competence goals. The competence framework does provide descriptions of demarcated competence levels but does not explicitly give any indication of a meaningful integration of these levels in a multi-phase training.
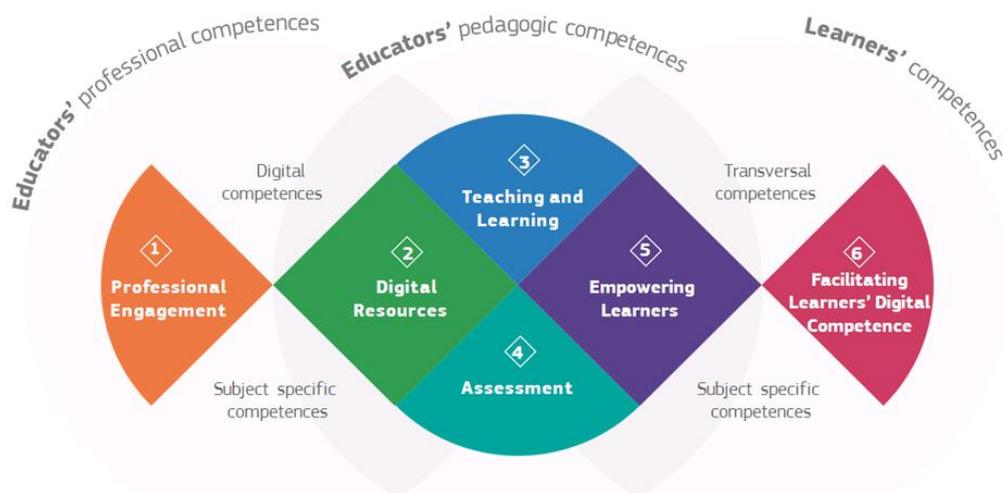
Figure 1. The *DigCompEdu* framework [9].

In the **digi.kompP** framework, however, the three teacher-training phases are explicitly considered [11] (Fig. 2). The model assigns digital competencies to eight categories and provides a meaningful graduation of competencies as well as starting points of individual training phases in a very targeted manner, so that university teacher training (phase 1) is clearly separated from subsequent phases. In addition, competencies that are required already at the beginning of the course are explicitly integrated (phase 0). The digi.kompP framework [11] assigns the structure of individual competency areas to phases in the teacher training programs: (A) *Digital competences and information literacy* start before the study (phase 0). At the beginning of the study programs (phase 1), competences are built up in (B) *Digital living*. This is followed by (C) *Designing digital materials*, (D) *Digital teaching and learning*, (E) *Digital teaching and learning in the subject*, (F) *Digital administration*, (G) *Digital school community, and finally* (H) *Digital-inclusive professional development*. Note that competence development continues in the first five years of professional life (phase 2). As in the case of the DigCompEdu, the categories are based on professional or school practice. The necessity to also integrate a subject-specific perspective is taken into account by the competence level E: *Digital teaching and learning in the subject*. However, these competences are formulated in general terms rather than being specific to a particular topic.

Figure 2. The digi.komP framework [11].

An at least structurally implemented technical reference is part of the **TPACK** framework (Fig. 3) [4]. The intersections of PK, TK and the explicitly subject-oriented CK result in the need for different subject-specific knowledge and competence requirements for digital teaching. In this way, technical aspects can be considered in the formulation and development of competencies and integrated into questions of teaching and learning in teacher training.
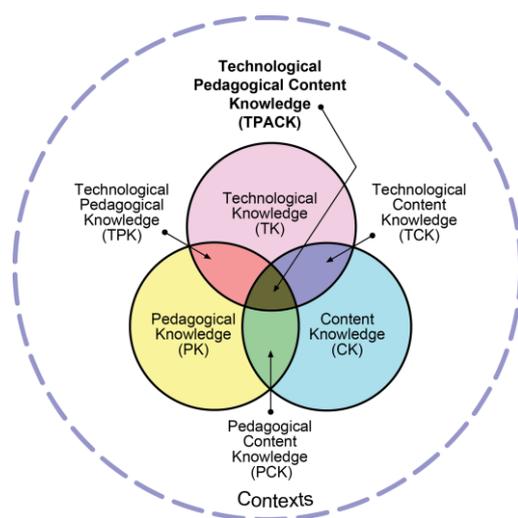
Figure 3. The *TPACK* framework (http://tpack.org).

3. Methods

From the didactic perspective of biology, chemistry, and physics, a corresponding framework was developed by an inter-university working group: that is, the Digital Core Competencies Working Group. The members of the working group have different backgrounds in the subject-specific university teacher training for the natural sciences in Austria and Germany (i.e., biology, chemistry, and physics education). Most members have been awarded as experts in digital teaching of the respective subjects by the Joachim Herz Foundation. The working group developed the framework in several meetings that included discussions with other invited experts from outside the working group. Building on didactic knowledge as well as didactic models and in connection with the strategy of the KMK and DigCompEdu, the structured and graded framework "Digital Competencies for Teaching in Science Education (DiKoLAN)" focuses on the digital perspective of classroom activities. For the natural sciences involved, this can support an adaptation and expansion of already existing university teaching while taking digital skills into account.

University teacher training is mostly geared towards the practical requirements of teaching practice in the educational science parts. Hence, the competencies required for this are often structured according to typical fields of lesson design (including visualizing, presenting, communicating). For teacher training in the natural sciences, this is supplemented by the elements of the science method as a central lesson component [12]. In the research report of the expert group of the European Commission "Science Education for Responsible Citizenship" [13], the importance of scientific competencies for active and responsible participation in society and their necessity for all citizens is emphasized. One of the recommendations made in the report is that science education must be an intrinsic and ongoing component of all school and extracurricular education, from early childhood education in kindergarten through adulthood, to enable lifelong learning. According to this report, a basic scientific education is indispensable for a culture of scientific thinking in which decisions are made based on evident facts and scientific considerations. Elements of the scientific method are often systematized and classified in the literature [14]. For example, general interdisciplinary practices (e.g., search for information, communication) are delimited from and compared with subject-specific working methods (e.g., measurement, data acquisition, logging, drawing, modelling and mathematics). Such classifications are often a useful way of structuring of content in teaching the natural sciences and in teacher training. Moreover, to adequately represent the natural sciences, teacher education needs to discuss the use of digital technology as part of scientific practices [15]. It therefore makes sense to structure digital competencies with reference to manageable fields of activity or application areas of teaching as well as to elements of the science method as a central component [12].

Universities are fundamentally faced with the problem that the time resources for training students are limited and that little scope is available for "new" content. Therefore, the DiKoLAN orientation framework should be understood as a structuring aid for an interdisciplinary and integrative approach.

Elements of existing courses and study programs should be specifically expanded to include a digital component, with which, for example, selected subject content can be better presented and understood. For the university setting specific (competence) goals in these areas, it should generally be noted that these cannot target fully trained teachers, but only describe an interim status that can be used in the following training phases. This applies to the digital area as well as to the previous "analogue" teacher training, where it is unquestionably accepted that university graduates or trainee teachers may not have reached the level of competence of in-service teachers.

4. Results

The orientation framework "DiKoLAN – Digitale Kompetenzen für das Lehramt in den Naturwissen-schaften [Digital Competencies for Teaching in Science Education]" [16] separates seven central areas of competence (Fig. 4), based on both teaching-learning scenarios in schools as well as courses taught at universities.

Figure 4. The DiKoLAN framework (https://dikolan.de).

In addition to four interdisciplinary areas, which include knowledge, skills, and abilities to implement digital communication, presentation, documentation, and research, three areas specific to the natural sciences are explicitly highlighted. These include the handling and instructional embedding of digital acquisition systems, the skills to process data digitally and to perform and use computer-based modelling and simulations. While the more general areas address competencies that may also be of interest in subjects other than science, the more subject-specific areas address competencies that are mandatory for teaching science (i.e., biology, chemistry, and physics). The competence areas are supported by technical core competencies. These contain the necessary general basic skills and abilities to use hardware and software in general (e.g., being able to connect a laptop with a beamer, wired or wireless). The legal framework must also be considered. Moreover, resulting consequences do not only differ for universities compared to schools, but also vary in Germany among the sixteen federal states due to the different federal legislation. Table 1 lists the nine areas of competencies in DiKoLAN along with a describing definition. For each of the areas it is defined which competencies a prospective teacher should have at the end of the teacher training at the university: The competence expectations for a single competence area are divided into three levels of competence (*Name, Describe,* and *Use/Apply*) and,

Table 1. Definitions of competence areas included in DiKoLAN.

Competence area	Definition
Documentation	The competence area *Documentation* (DOC) comprises the individual ability to use digital tools for the systematic filing and permanent storage of data and information in order to use them professionally. This also includes taking, editing, and integrating photos, images, and videos, combining, and saving different media, structuring and archiving information, and displaying processes and contexts.
Presentation	The competence area *Presentation* (PRE) describes the individual ability to use digital media in a targeted and addressee-oriented manner for the knowledge acquisition and communication process as well as the knowledge of the limits and potentials of different digital presentation media.
Communication/ Collaboration	The competence area *Communication/Collaboration* (COM) comprises the individual ability to plan synchronous or asynchronous work of individuals or groups with digital tools towards a common goal and to carry it out with learners. For this purpose, shared files or products are created and processed, common data pools are created and processed, and systems for assigning rights are planned and implemented.
Information Search and Evaluation	The competence area *Information Search and Evaluation* (ISE) includes the individual ability to use digital tools to obtain information on given subject areas or to solve problems, and to structure and evaluate them. For this purpose, search targets are defined, various information sources are integrated and evaluated.
Data Acquisition	The competence area *Data Acquisition* (DAQ) describes the individual ability to collect data directly or indirectly with digital tools by entering data, digitizing analogue data, taking images, and making films, using probes, sensors, and programs (or apps), and obtaining data from documentation media such as images or videos.
Data Processing	The competence area *Data Processing* (DAP) describes the individual ability to process data with digital tools. This includes filtering, calculating new quantities, processing, statistical analysis and merging of data sets.
Simulation and Modelling	The competence area *Simulation and Modelling* (SIM) describes the individual skills to perform computer-aided modelling and to use existing digital simulations in a targeted and addressee-oriented manner for the knowledge acquisition and communication process as well as the knowledge of limits and potentials of models and simulations in the process of knowledge acquisition.
Technical Core Competencies	The competence area *Technical Core Competencies* (TCC) describes the basic individual skills and abilities to name, describe and use common connection systems and interfaces (e.g., HDMI, USB, and their connector formats). Furthermore, wireless connection standards should be named and their range as well as connection processes should be described. The aim is to be able to set up and use functional working environments independently, and to solve arising technical problems.
Legal Framework	The competence area *Legal Framework* (LEG) describes the individual ability to identify legal issues when using digital media and platforms in schools, such as data protection regulations for the processing and storage of personal data, licensing regulations, age and content restrictions and copyright. This also includes basic knowledge needed for clarification in this regard before use.

based on the TPACK framework [4], into four main areas of teacher action (*Teaching, Methods/Digitality, Content-specific contexts,* and *Special tools*) (Fig. 5). In accordance with this gradation, explicit knowledge facets are listed first and then concrete actions for applying the knowledge in planning lessons are derived.

	Teaching (TPACK)	Methods, Digitality (TPK)	Content-specific context (TCK)	Special tools (TK)
Name	**MD.U.N1** List suitable alternatives to scientific digital data acquisition for use in schools. **MD.U.N2** Name specific scenarios for an appropriate use (pupil-, subject- and target-oriented) of digital data acquisition and associated measurement strategies in various teaching-learning settings, e.g. ◆ Investigating variations in skin temperature during sports or when smoking by thermography using thermal imaging cameras ◆ Determination of the nitrate concentrations in waters by computerised measurement ◆ Analysis of wing beat frequencies of insects with mobile devices	**MD.M.N1** State further aspects on which the use of digital data acquisition in learning and teaching may have an impact, like for example ◆ the time required ◆ the organisational structures ◆ the type of presentation ◆ methods ◆ media knowledge/training ◆ interests and motivation ◆ personal and social consequences	**MD.F.N1** Introduce scientific scenarios and contexts of digital data acquisition (e.g. video analysis, ECG recording, determination of pH values). **MD.F.N2** Name measuring equipment with digital data acquisition (e.g. thermal imaging cameras, mobile devices with cameras, integrated and external sensors) meeting the current requirements of scientific research. **MD.F.N3** State corresponding measurement systems and relevant safety standards **MD.F.N4** Name remote-controlled laboratories (e.g. telescopes) for experiments that cannot be performed on site.	**MD.T.N1** Name several fields of application for digital data acquisition like ◆ for analysis of multimedia material (e.g. colorimetry, video analysis) ◆ for computer-aided recording of measured values with school-specific systems (e.g. for ECG, pH, temperature, current, voltage, movement measurements) ◆ with laboratory/measuring equipment that provides measurement data for further processing (including digital scales, thermal imaging cameras) ◆ with mobile devices with built-in sensors for data acquisition (e.g. camera, gyroscope, acceleration, light and biometric sensor) ◆ with mobile devices having external sensors
Describe (including necessary procedures)	**MD.U.B1** Describe didactic requirements for the use of digital data acquisition (daq) systems in teaching (e.g. individually adapted user instructions), effects of daq on the respective teaching methods (e.g. enabling research-based exploratory learning by mobile devices), access to basic competences, knowledge acquisition and NOS concepts enabled by digital systems.	**MD.M.B1** Describe pedagogical requirements as well as advantages and disadvantages arising methodically from the use of digital data acquisition, e.g. with regard to the aspects as listed under MD.M.N1.	**MD.F.B1** Describe selected scientific scenarios of digital data acquisition as examples.	**MD.T.B1** Describe at least one possibility of technical implementation for each type of digital data acquisition including necessary procedures in terms of current hard- and software and associated standards. **MD.T.B2** Describe the measuring characteristics (e.g. measuring range, measuring accuracy, resolution, sampling rate, fields of application, limitations) of the systems.
Use/Apply (practical and functional realisation)	**MD.U.A1** Planning and realization of complete teaching scenarios using digital data acquisition in consideration of appropriate social and organisational structures.		**MD.F.A1** Implementing data acquisition and data recording in a scientific context, e.g.: ◆ carrying out an electrocardiography, ◆ carrying out a titration, ◆ quantitative investigation of impact tests.	**MD.T.A1** Perform setup, calibration, and data acquisition for at least one example each of the above-mentioned range of application for digital data acquisition.

Figure 5. Exemplary excerpt from the competence expectations for the area of *data acquisition* in DiKoLAN [16]. Structure of the competency expectations based on the *TPACK* framework [4] and according to competence levels *Name*, *Describe* and *Use/Apply*.

5. Discussion

The framework presented here provides, for the first time for the natural sciences with respect to the German education system and teacher education a detailed overview of digital competencies that should be acquired during pre-service teacher training. A detailed description of DiKoLAN and the underlying concepts was published by the Joachim Herz Foundation together with presentations of 23 established teaching projects related to DiKoLAN [17]. From the perspective of teacher professionalization, the connectivity of the proposed orientation framework DiKoLAN in the subject-unspecific European framework for digital competencies of teachers DigCompEdu is given (Fig. 6). DiKoLAN specifies essential elements of the teaching-related competence areas depicted in DigCompEdu for university teacher training in the natural science subjects. Based on this, the pupils' competencies focused in area 6 of DigCompEdu can then be addressed in teaching, to reach the competency expectations formulated in "Education in the Digital World" (KMK, 2016). The aspects of evaluation, assessment and feedback depicted in competence area 4 of DigCompEdu are essential elements of teacher action. However, since this area is primarily concerned with responding to pupils, the development of competencies in this area should be addressed in the practical phase, for example, for Germany in the 12 to 24 months in-service traineeship, and for other countries maybe in early in-service years. Hence, these are not yet considered to be core competencies in DiKoLAN, which is intended for university teacher training. To break down the competence expectations within a competence area, DiKoLAN uses the TPACK framework. The TPACK framework is a structuring aid for specifying and defining the content of individual areas of competence, as the acquisition of competence can be easily assigned to the various parties involved in university teacher training based on the individual areas of knowledge (Tab. 2).
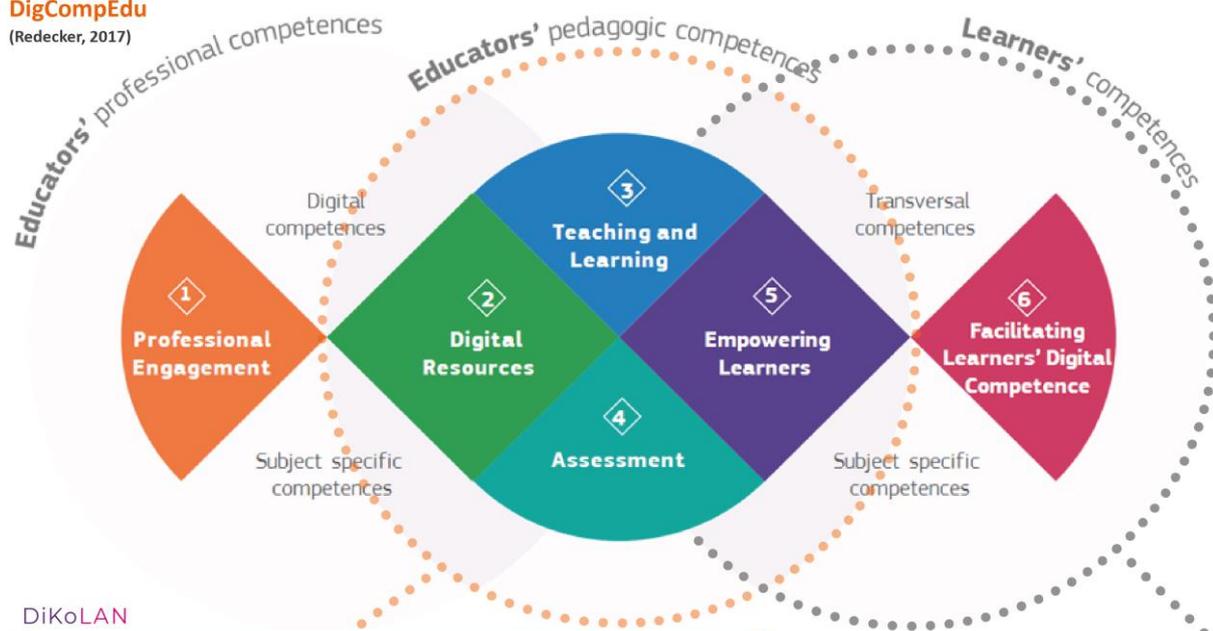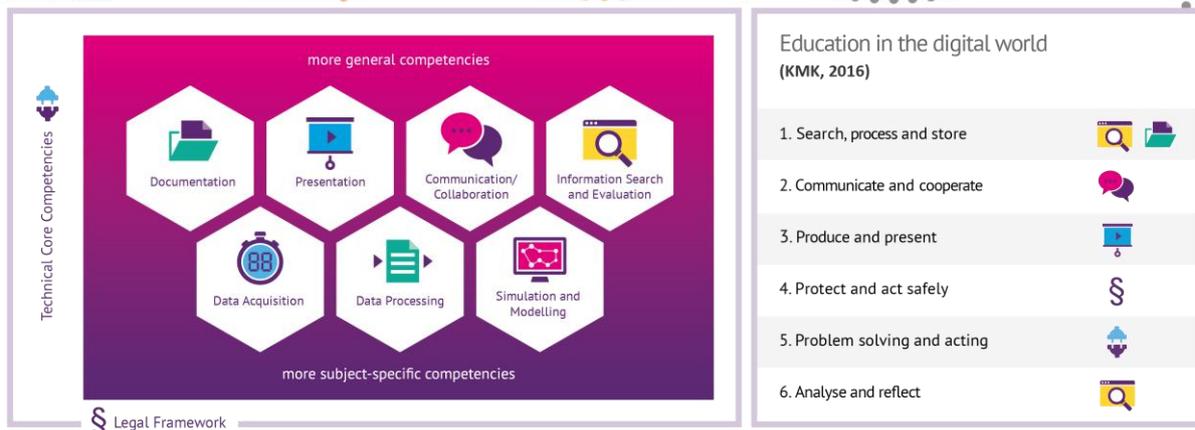
Figure 6. The competencies of the orientation framework DiKoLAN form a science-related specification of the areas 1-5 in DigCompEdu. They enable teachers to promote the KMK standards (area 6 in DigCompEdu) in students.

Table 2. Links between scope of application, related knowledge, and parties involved in teacher training who should provide respective knowledge.

Scope	Knowledge	Who should provide appropriate knowledge?
Teaching	TPACK	Institutes of physics education, physics education research groups
Methods, Digitality	TPK	Institutes of media informatics, media pedagogy, or media didactics
Content-specific context	TCK	Subject-related institutes, e.g., experimental physics, theoretical physics
Special tools	TK	All participants along the teacher training chain

For example, to be able to use a computer-assisted data acquisition system in the classroom teachers require subject-specific (TCK), media-didactic (TPK) and subject-didactic competencies. The competencies, which are mainly oriented towards the subject-specific working methods (TCK), can be addressed in the courses of the respective subject studies (e.g., in the beginners' lab course). It is advisable to acquire the competence expectations with a media-didactic focus (TPK), for example, in

the context of the courses of media pedagogy, while the competence expectations with a subject-didactic focus (TPACK) are best addressed in the courses of subject didactics. In accordance with the content objectives, the competency expectations are addressed at different levels in the respective courses: For example, in the physics lectures, the competency expectations are addressed more at the level of naming and describing, while students learn how to apply them in the internships.

However, this framework is subject to constant change. Some basic competencies are quite stable over time, while others are due to a rapidly developing digitalization. This applies not only to the field of education, but also to scientific research in the natural sciences. The use of new approaches such as 3D printing [18], augmented reality [19], eye tracking [20], or artificial intelligence [21] can also change teaching and learning [22] and thus the digital skills required by the teacher. In addition, we are seeing increased use of remote and virtual labs in research and teaching [23]. This type of experimentation is present in DiKoLAN but can and must be expanded. At the latest, if these topics prove useful in the long term, these must also be reflected in teacher training. Moreover, since it is currently unclear what will result from distance learning [24] during the COVID-19 pandemic (e.g., flipped classroom concepts [25]), we have not yet adapted DiKoLAN in this regard. This can and may need to be done in the future.

6. Acknowledgements

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