Designing Granular Competency Frameworks for Adaptive Learning on the Example of Naïve Bayes Classifiers

André Selmanagić[1], Katharina Simbeck[2]

Abstract: Adaptive learning environments that follow a competency-based learning approach require granular, domain-specific competency frameworks (models) for the continuous assessment of a learner's knowledge and skills as well as for the subsequent personalization of instruction. This case-study describes the iterative creation process for a competency framework in the domain of Naïve Bayes classifiers, including the design principles that led to the framework and the tools used for making it publishable as linked, open data.

Keywords: competency frameworks, competency modelling, adaptive learning, linked data, open data, semantic web

1 Introduction

The personalization of learning to the needs and goals of individual learners is known as adaptive learning [SS20]. Adaptivity is used to help learners reach a desired level of mastery at their own pace [Ca20]. In order to create adaptive learning environments, a model of the domain to be learnt is required [ST03], describing the competencies that are to be developed and the relationships between them.

Naïve Bayes classifiers are one of the basic concepts in machine learning and taught in higher education classes [NM22]. Naïve Bayes is a classification method that uses the probability of observing so-called predictor values given an outcome, to estimate the probability of observing the outcome given a set of predictor values – essentially applying Bayes rule [BBG20]. It is e.g. used in e-mail spam classification to distinguish between spam and no spam based on words. It is called naïve, because it assumes the predictor values (e.g. words) are conditionally independent from each other [BBG20].

We present the development of a shareable, digital competency framework for the domain of Naïve Bayes classifiers. The framework is required for the upcoming development of an adaptive learning environment focussing on Naïve Bayes classifiers. It serves as a granular description of the domain as well as the interrelated competencies within it. This case-study explores how competency frameworks must be structured in terms of granularity and relationships in order to be of use in adaptive learning environments.

[1] HTW Berlin, Fachbereich 4, Ostendstr. 25, Berlin, 12459, andre.selmanagic@htw-berlin.de
[2] HTW Berlin, Fachbereich 4, Ostendstr. 25, Berlin, 12459, katharina.simbeck@htw-berlin.de

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2 Theoretical Background

This section presents the concept of competency, its use in the context of adaptive learning and shows how competencies and learning resources can be aligned via semantic relations.

2.1 Competency

Competency is a vague and fuzzy concept with many different interpretations [KHR09, vB03], which "range from that of a broad overarching attribute to that of a very specific task" [KHR09]. The upcoming IEEE standard "P1484.20.2 Recommended Practice for Defining Competencies" defines competency as "the set of skills and behaviours required in the performance of a task or activity within a specific context" [Fo21]. Competencies can thus be viewed along various dimensions [vB03, Mu17]. They revolve around personal characteristics, like "cognitive and metacognitive skills, knowledge and understanding, interpersonal, intellectual and practical skills, and ethical values" [LD10]. The meaning and thus description of competencies can be generic or specific, depending on the usage of these competency descriptions [Mu17]. They can be more domain-specific or more general [LD10] or may have any other type of context associated with them [vB03]. Proficiency levels can be used to describe the level of competence, e.g. on a proficiency level scale from beginner to expert [de07]. These levels can "express both what an entity knows and can do and how well they know and can do it, and different levels can represent differences in both of these aspects" [Ro21]. [Ro20] call these two aspects attainment levels and performance levels. Multiple related competencies can be organized into competency frameworks or models [Ro21]. These may describe both the structure (relationships between competencies) as well as the proficiency levels associated with each (sub-)competency [Fl13]. Possible relationships are e. g. subsumption (more/less general), prerequisite relations [Pe22], part-of relations [Al15] and equivalence relations (e.g. for merging different frameworks) [Os06]. De Coi et. al argue that relationships between competencies depend on both context and proficiency level [de07], e.g. when a competency requires English language skills, the context (business vs. science) and proficiency level (intermediate vs. fluent) are necessary in order for the competency to be measurable and the framework to be useful. Competencies can also differ by the degree to which they can be measured / inferred from observations [Mu17]. With learning outcomes being "a measurable result of a learning experience" [LD10], competencies with a narrow focus can be written as learning outcomes [KHR09].

2.2 Adaptive Learning

Adaptive learning (AL) is a "learning process in which the content taught, or the way such content is presented, changes or 'adapts' based on individual student responses" and which "dynamically adjusts the level or types of instruction based on individual student abilities or preferences" [OW14]. As such, AL "can increase motivation, engagement and understanding, maximizing learner satisfaction, learning efficiency, and learning effectiveness" [SS20]. Adaptive learning is closely connected to competency-based learning, which is a "pedagogical approach that focuses on the mastery of measurable student outcomes" [HJN17], that encourages tailoring learning experiences to the learner and using evidence to improve and adapt learning [DL21]. In order to assess the learner's needs and adapt the instruction accordingly, AL environments make use of various models: most importantly learner, domain, instructional and assessment model. The domain model "houses domain-related bits of knowledge and skill, as well as their associated structure or interdependencies" [ST03]. The learner model is used for capturing what a person knows and does, the learner characteristics, e g. knowledge, learning style, goals, or demographics [VDC11]. A learner model "thus must be based in some way on a domain model" [Pe22]. The assessment model describes how to infer what the learner knows [Es16], his / her level of competence. Learner, domain and assessment models are inherently interconnected, as the competencies a learner is supposed to develop and which are being assessed do always belong to some subset of the domain [Es16, Pe22]. The instructional model can be seen as the didactical component that encompasses the instructional strategy [VDC11], e.g. for developing competencies in a certain order.

2.3 Competency Frameworks as Directed Acyclic Graphs

Modelling knowledge and competencies for the learner, domain, instruction and assessment model often involves the use of directed acyclic graphs for competency frameworks, e.g. in IEEE Simple Reusable Competency Map [Os06], Experiential Competency Application Framework (ECAF) [Ro21], Bayesian Networks in Evidence-Centered Assessment Design (ECD) [Al15] and Hasse diagrams in Competence-based Knowledge Space Theory (CbKST) [RKA13]. Based on similar examples, Essa claims in his second principle for next generation adaptive learning systems, that "Directed Acyclic Graphs (DAG) are optimal for formally representing knowledge domains" [Es16].

2.4 Linked Data, Competency Data Formats and Alignment

In line with the vision of a semantic web of linked, machine-readable data, several data format standards for defining competency frameworks exist, e.g. CTDL [KSS17] and CASE [1E22]. Using web-based competency repositories, such as the open-source competency management software CaSS (Competency and Skills Service), competency frameworks and competencies can be distributed using their unique URI, which "enables training and talent management systems to reference and apply the same competencies" and have shared understanding of them [Ro20]. Similarly, specifications such as LRMI [BC15] and AMB [Ko22] exist for the description of learning resource meta-data as part of the semantic web, aiming to improve the shareability of learning resources. In order to use learning resources for the development of competencies (e. g. in AL environments), both need to be aligned [Ro20]. In the semantic web, this is only a matter of linking data. AMB, for example, provides meta-data fields like "assesses", "competencyRequired" and "teaches" for referencing competencies using their URIs [Ko22].

3 Method and Results

The competency framework was created iteratively, starting with the formulation of design principles, followed by multiple prototypes created using different software.

3.1 Design Principles

As evident from the theoretical backgrounds, the concept of competency is vague, leaving a lot of choice in the design of competency frameworks. In ECAF, for example, proficiency levels of a competency are treated as though they are separate competencies, which results in each level having “its own set of child competencies and its own set of relations to other competencies” [Ro21]. This treatment shows that the distinction between (sub)competencies and proficiency levels is blurry. Following, the term *competency* will thus serve as an umbrella term for all of these: competency, sub-competency, competency field / cluster, learning outcome and a competency’s proficiency levels.

The purpose of the competency framework for Naïve Bayes is to provide information for various aspects of the upcoming AL environment. With competency statements being a description of the domain, the framework should act as a central part of the domain model and guide the creation of learning resources. Competency statements will be used by learners for goal-setting, self-evaluation and progress-monitoring [SNA09]. Both general competencies (e.g. “Conditional Probability”) and specific competencies (e.g. “Calculate Conditional Probability of 2 Events”) may be displayed to the user. The competency framework will also be used in the instructional model, as recommendation algorithms like CbKST use semantic relationships such as “requires” / “is based on” between competencies to create personalized learning paths [RKA13]. Formative assessments play a key role for updating learner models in AL environments [DL21]. The competency framework thus holds viable information for the assessment design, e.g. within the competency statements or in the form of semantic relationships between competencies (e.g. rollup rules for calculating competency measures from sub-competencies [Os06]).

Subjective terms and clustering in competency frameworks hinder the validity, reliability and reusability of such frameworks. The use of proficiency levels with widely interpretable terms like “beginner”, for example, has been critiqued for their inconsistency and context-specificity [Da19]. As every kind of model is the result of inherently subjective activities (e.g. simplification) and created from a certain point of view, “objectivity” must generally be achieved by social agreement [Pi18]. We thus argue that in order to fulfil the potential of reusability, while still addressing the pragmatic needs of AL environments a layered approach to competency modelling should be followed. This means that a competency framework is a composite of multiple frameworks (“layers”) merged using graph operations: from more agreeable information (e.g. competency statements and prerequisite relationships) to more context-specific application-oriented information (e.g. proficiency levels), effectively allowing a separate distribution and re-use of this information. Based on the considerations above, the following design principles for the creation of competency frameworks for AL environments were formulated:

Formulation of competency statements: (1) Specific competency statements should be written using the ABCD (audience, behaviour, condition, degree) method, in which a topic/concept is combined with an action verb (B=behaviour) and a measurable performance objective (D=degree) [CH10]. Action verbs can be taken from Bloom's taxonomy as proposed in [KHR07]. Note that Bloom's taxonomy levels are not a measurement of proficiency but a classification of cognitive complexity [AKB01]. Nonetheless, the advantage of these verbs lies in their widespread use in education and their original intent of providing a certain specificity and measurability [NDP20]. More general competencies (e.g. competencies that subsume / group others) are described using topics / concepts alone. At this stage, competency statements should be monolithic, though constructing statements themselves semantically via hyper graphs as in [Da20b] should be an area of further research. (2) Vague proficiency levels (e.g. "beginner") should be avoided. The basic idea of dividing the measurable performance of a competency into sub-competencies along a proficiency scale though is valuable. Thus, performance criteria should be added directly as the D for degree part of the statement.

Framework structure and relationships: (3) Following the layered approach, the framework should be constructed in the form of multiple subgraphs. (4) The core graph contains the specific competency statements (e.g. "Calculate conditional probability of 2 Events"), grouped by more general competencies (e.g. "Conditional Probability") using subsumption and part-of relationships, effectively dividing the domain into subdomains. This graph should have the highest reusability across different usage contexts. (5) The learning path graph additionally links the competencies of the core graph using prerequisite relationships such as "requires", "is based on" or "desires". (6) Other subgraphs are more specific to the requirements of the respective AL environment. The learning progression graph, for example, groups competencies into progression levels (e.g. "beginner" and "advanced"), which are mainly used for learner (self-)monitoring. Despite the similarity to proficiency levels, the term progression level is used here to denote the subjectivity of this grouping. (7) The measurement graph may add assessment information by adding more granular sub-competencies and the aforementioned rollup relationships.

The design principles stated above were revised according to the workshop discussions. The framework presented in the next chapter was designed using an older set of principles, which lacked the layered approach, resulting in a single competency framework mixing reusable competency statements and subjective groupings based on proficiency.

3.2 Iterative Approach

Principled assessment design methods like ECD and instructional design methods like ADDIE contain analysis and design phases, in which subject matter experts are involved [Br09, Al15], e.g. in the design of competency frameworks. For this project, the primary author, who is a computer scientist with experience in machine learning and teaching in higher education, takes on this role. The Naïve Bayes classifier was chosen as a domain, because it is a basic machine learning algorithm. For the extraction of competencies, various learning resources (e.g. machine learning books, online courses and video tutorials) were reviewed and their structure (order of knowledge elements etc.) analysed. Knowledge elements were copied to a digital whiteboard and clustered according to topic.

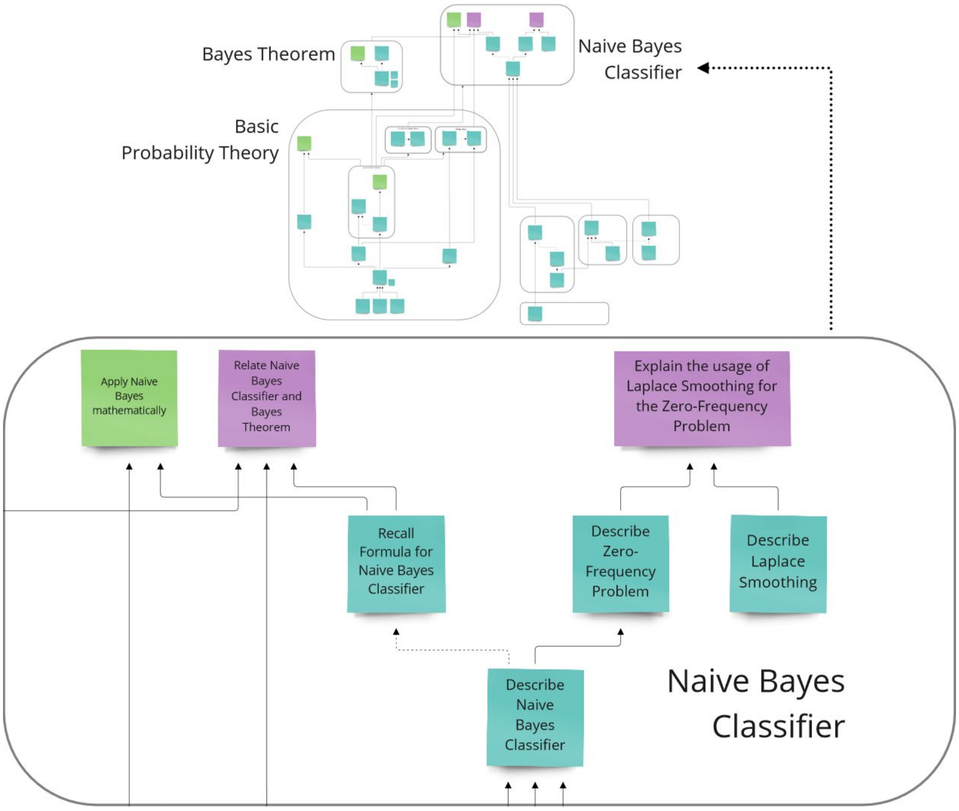

Figure 1: First iteration of the Naïve Bayes classifier competency framework in the form of a graph created with a digital whiteboard (top: overview, bottom: zoomed into upper rectangle). Boxes are color-coded by Bloom level (blue: remember, purple: understand, green: apply).

The creation of the competency framework followed an iterative approach. The first prototype was created using the digital whiteboard software Miro[3]. The graph was constructed from bottom to top, where competencies reference prerequisite competencies below them. To enhance readability, more general competencies that subsume others or have them as parts were defined as boxes around the more specific ones. The competencies were also color-coded in terms of their Bloom cognitive taxonomy level. Figure 1 shows an overview and a cutout of the digital whiteboard. It contains topics (general competencies) such as “Conditional Probability”, “Bayes theorem” or “Naïve Bayes Classifier”, specific competencies like “Define Conditional Probability”, “Relate Naïve Bayes Classifier and Bayes theorem” and “Apply Naïve Bayes Mathematically” as well

[3] Miro | Online Whiteboard for Visual Collaboration, https://miro.com

as the precedence relationships between such competencies. For the second iteration, the competencies and their relationships were modelled as linked data using the competency management software CaSS. In this iteration, progression and performance levels were added to the framework. Sub-competencies of topics like “Conditional Probability” were subjectively grouped into attainment levels from “beginner” to “expert” for progression tracking. Specific competencies were divided into sub-competencies according to performance levels. For Bloom verbs like “calculate” reusable performance scales (as proposed by [de07]) with multiple criteria were developed for better measurability (see Table 1). For the sake of readability, the competence statements used the level label as a reference to the performance level (e.g. “Calculate Conditional Probabilities of 2 Events: Beginner” references the row “beginner” in the table). At this level of granularity, the description of competency proficiency levels begins to merge with the assessment design of the tasks assessing these competencies. In order to not be overly task-specific, the terms used in the performance dimensions were designed to leave detailed rubrics up to the assessment designers, but are as such up to subjective interpretation. The competency framework for Naïve Bayes classifiers can be found online.[4]

Calculate Conditional Probabilities of 2 Events	Level Label	Correctness	Execution Time
The learner is able to calculate the conditional probabilities of two events, where the result is at least {Correctness} and the calculation takes a {Execution Time} execution time.	Uninformed	incorrect	long
	Beginner	sometimes correct	long
	Intermediate	mostly correct	medium
	Advanced	always correct	medium
	Expert	always correct	short

Table 1: Performance levels for a competency based on multiple performance criteria. A template string is used for creating the complete competency statement.

4 Discussion

The iterative design approach and the use of different design tools (Miro, CaSS) for the different iterations has proven useful in the creation of the framework. In the next iteration, the framework will be split according to the layered approach presented above. Following iterations must address the main drawback of the current iteration: its creation by a single author. In order to be valid and reliable, competency frameworks that truly provide a shared understanding of the domain should be socially constructed within a mutual process involving multiple subject matter experts [Da20, Ro20]. But even then, compromises will have to be made in order to reduce the complexity of human competence into a model [Pi18]. As an example, let us consider a competency that should only be taught once a certain level of competence was demonstrated for its prerequisite competency “Calculate Conditional Probability of 2 Events”. Such a scenario requires a relationship between the

[4] https://gitlab.com/adaptive-learning-engine/naive-bayes/competency-framework

first competency and a sub-competency (performance level) of the second. But into how many sub-competencies should the required competency be divided and which of these should be referenced? Should sub-competencies target different performance criteria simultaneously as in Table 1 or should sub-competencies for all possible combinations of criteria exist, resulting in more specific “levels” to choose from? Is it better to use vague terms like “mostly correct” or measurable though arbitrarily chosen thresholds like “80% of the time correct”? In the authors’ opinion, the assessment of competencies requires clearly defined, measurable competency statements, while the use of prerequisite relations for determining a learner’s readiness for further learning does benefit from fuzzy descriptions (as 75% vs. 80% correctness may be negligible). While the authors have no answer on how to address such contradictory requirements, applying fuzzy graph theory [MMM18] to competency frameworks is a potential area of future research in this regard.

While the creation of the first competency framework prototype using a digital whiteboard enhanced the readability of the graph due to complete freedom in node positioning and grouping using boxes, the process of moving nodes and creating edges was tedious. Meanwhile, CaSS does not provide any graph visualization. Further research should be conducted on enhanced visual editing techniques specifically for competency frameworks.

The competency framework presented here will be an integral part of an adaptive learning environment teaching Naïve Bayes classifiers that is currently in development.

5 Conclusion

Digital competency frameworks contain valuable information for various aspects of adaptive learning environments. Distributing competency frameworks in the form of globally accessible, linked, open data as part of the semantic web allows the alignment of (open) educational resources with competencies (see 2.4). The semantic relationships between competencies (e.g. prerequisites) and between competencies and learning resources (“teaches”, “assesses” etc.) provide the necessary information for creating customized learning paths in adaptive learning environments. Especially for assessing competencies and subsequently adapting the instruction in AL environments, competency frameworks need to divide the domain into granular sub-competencies. In order to provide a guiding example, we described the iterative process of creating a competency framework for the domain of Naïve Bayes classifiers, including the formulation of design principles, prototyping the framework in graph form on a digital whiteboard and modelling the meta-data as well as distributing the framework using the modelling software / repository CaSS.

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