An Approach to Developing Competency Models for Programming Courses

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***Abstract*— This work-in-progress paper is focused on the area of innovative practice in computing education. Existing research has found that many students who graduate from software development and computer science programs do so without acquiring all the necessary skills to become an effective professional developer. This paper advocates for implementation of competency-based education to address this *competency gap*. It does so by presenting a set of methods for developing competency models in practice to assist in the implementation of competency-based education. By providing educators with these recommendations, we hope to offer some tools to help provide students a more effective education and better prepare them for their futures.**

Keywords—computing education, programming, competency-based education, competency modeling.

I. Introduction

Many students in the programming discipline have trouble transitioning to the rapidly evolving professional world [1,2]. This is because some students graduate from programs which leave them under-equipped to enter the workplace [2]. In part this is due to a perceived gap in the competencies anticipated by employers, and those possessed by new graduates. We propose that through pedagogical change, this gap can be addressed, thereby providing students with a higher quality software development education and enhanced preparedness to begin their careers.

Lev Vygotsky's theory of social constructivism emphasized the benefits of collaborative, scaffolded learning environments [3], approaches which lend themselves well to programming education. We advocate for the use of competency-based education as a method to achieve a more learner centered education while addressing the "competency gap" problem presented by new graduates. This is primarily because competency-based education more effectively incorporates the skills and abilities needed to perform in occupational settings [4]. This approach further lends itself to the practice of computing education due to its problem-based nature, one of the focal points of competency-based education.

We aim to offer a framework to help educators best perform the challenging first step of competency-based education — the competency modeling process. This important step is often covered at a high level in the literature, however genuine accounts and recommendations on how to build a competency model in practice are seldom realized. We argue that even existing competency standards offered by the IEEE and ACM are not sufficiently detailed to guide the implementation of a competency-based course.

Informed by a review of seminal works on competency modeling, this work lays out clearly how educators can construct a competency model to guide their course with a goal of student preparedness in mind. Further, the work includes an example case of this process wherein a new competency model is constructed to guide delivery of an intermediate-level college web development course. This example includes discussion of both how the model was constructed, and implications that this process may have for more general course design and delivery.

Our intended contribution is a method for how to perform the competency modeling process in practice, specifically, a competency-based course in the programming discipline. Such an approach will help provide a higher quality education and leave students better prepared to enter the workforce while addressing part of the academia-to-industry competency gap.

II. Background

A. The "Competency Gap"

The International Handbook of the Learning Sciences (IHLS) notes that measured competency "incorporates the range of abilities and skills needed to perform successfully in occupational situations" [4]. Substantial prior work has identified that recent graduates in computer science and related disciplines have difficulty both finding jobs after graduation and transitioning into their roles as a software developer [1,2]. This is because of a gap that exists between students' "academic experiences and industry's expectations" [2]. Fortunately, a competency-based approach can better evaluate students' capacity to transfer skills and abilities learned in some setting to another setting within the same domain [4]. In this case, students learning in a classroom setting transfer their programming knowledge to an industrial setting in the same software development domain. This resonates with the IHLS in its claims that it is the duty of education to help students develop competence necessary for continued learning to facilitate occupational participation [4].

Reference [2] conducted research on the skills gap between students completing CS undergraduate degree programs and the expectations held by the software industry about incoming employees. Their work was motivated by findings from their own review that “many CS graduates feel unprepared for the challenge of their first job” [2]. As a result, new graduates tend to experience significant difficulty transitioning into professional developer roles due to a lack of technical and non-technical skills. The authors also note that CS graduates have “fundamental misconceptions about how software engineering work is performed in industry” [2].

Reference [2] carried out a phenomenography study in which they spoke with 14 CS faculty members across institutions in semi-structure interviews. Through their discussions, they found that faculty members in CS programs felt that curricula should align more closely to the industry expectations of new graduates. Further, these faculty members expressed belief that degree programs should specifically prepare students to enter the software industry. Interestingly, several participants also expressed concern that these goals are not held by program directors and reflected by institutional goals. Finally, even in instances where industry preparedness is a goal shared by programs and instructors, faculty felt that they were not sufficiently equipping students to do so.

A similar study was conducted by [1], in which these authors addressed concerns that “graduating computer science students are deficient in their skills and understanding of concepts that will be important in their future careers”. They concluded that graduating CS students tend to lack technical and non-technical abilities necessary to be a successful software developer, which coincides with [2]. Their conclusions were supported by reports of the expectations of managers and hiring personnel in the software industry, as well as detailed accounts of the experiences of software developers of various experience levels. In their discussion, they recommended that their findings be used by educators to evaluate students more carefully in the areas of teamwork, personal skills, ethics, leadership, design, and the development process. However, the authors present methods for how such evaluations might be performed.

Both [1] and [2] discussed the presence of a gap between new graduates in CS programs and the expectations held by individuals in the software industry. In both cases, this gap resulted in students encountering difficulties transitioning into their careers. In both studies, the authors discuss a lack of “skills”, “knowledge”, “abilities”, “soft skills”, “values”, and “qualities”. They mention that the lack of these qualities is the root of the difficulties experienced by students attempting to enter the industry. We consider this to be competency gap between graduates and industry expectations.

B. *Competency-Based Education*

Competency-based education (CBE) is a framework for curricular design, which emphasizes the demonstrated achievement of the learner. When CBE is applied, it allows the learner to function autonomously or semi-autonomously, selecting their own objectives, goals, experiences, and evaluation methods in a self-guided way [5]. This “complete” implementation is known as self-directed learning [6]. A more typical implementation of CBE involves the predefinition of competencies as a set of objectives and the evaluation process is designed beforehand. In this environment, the student is given freedom to encounter knowledge in a natural way while being evaluated against predefined competencies.

A 2014 survey found that 34 universities offered CBE-evaluated programs, with an additional 18 having such programs in development, several of which are in the information sciences [7]. Additionally, in a 2015 Department of Education survey, over 600 institutions claimed to be designing or implementing some form of CBE program [8]. Though that number only continues to rise, the segment of universities offering CBE programs is small compared to all higher education. Both the U.S. Government and the National Science Foundation have offered additional financial aid to students in CBE programs at participating universities [8].

The potential of CBE has shown to be significant. In several studies, CBE students demonstrated an increase in attention, accelerated academic progress, and increased attention [9], while offering 9.35% more correct answers on exams than traditional classrooms [10]. As education technology becomes more prevalent, the issuing of digital certifications for competencies has received attention for its potential to further motivate students and track their progress [11].

CBE begins with a competency model upon which students are evaluated. A competency model is defined as the collection of knowledge, skills, abilities, and other characteristics that are needed to perform a task effectively [12], called reusable domain knowledge [13]. A collection of competencies that are targeted by a course is typically called its competency model which is composed of several atomic competencies. These models, once defined, can include not only learning objectives, but future potential job requirements as well [12].

C. *Competency Modeling*

The process of modeling competencies requires great care and attention to detail. One obstacle the work must overcome is an apparent lack of literature that clearly outlines the competency modeling process in an academic setting. Further, all the published works reviewed in preparation for this proposal fail to disclose a model any more detailed than what this section will go on to define as the “core competencies”. When papers do disclose their competency model, those in software development or computer science often only go so far as to say that software developers should have a competency in “programming” or similar [14].

References [15] and [16] both provide valuable information on competency modeling outlined in this section. Although both works intend to inform the process in an industrial context where HR or management personnel intend to evaluate employees, the underlying information can easily be adapted to an academic context. We aim to synthesize the information presented by these authors to guide the competency modeling process.

Regarding the form of a competency model, [15] states that a competency model is first defined as a set of several "core" or "key" competencies. They are careful to point out that "core competencies" in an industrial context can sometimes mean different things, but in [15], it refers to a set of top-level competencies from which a more detailed model is refined. These authors suggest that each core competency should be defined using a title, a descriptive definition, and a set of sub-competencies that compose it. Then, each sub-competency should be outlined at three levels indicating low, moderate, and high proficiency.

To construct the model, [15] recommends using one of seven different methods to establish the model and a second from that set to establish validity. These methods, in no specific order, include literature review, focus groups, structured interviews, behavior event records, work logs, surveys, and observational data. Then, they similarly recommend the use of multi-rater feedback when the model is being used for competency evaluation to establish reliability. Finally, the authors note that models should be updated regularly as the trends and requirements of the targeted job or field change.

Reference [16] provides an equally valuable set of recommendations that very closely align to those provided by [15]. These authors similarly suggest that competency models should be developed "top down", starting with more generic competencies, and refining into more specific ones. Reference [16] is primarily targeted at the industrial application of competency models as well, but it explicitly states that competency models can serve a valuable purpose in several domains including personal and career development, and academia.

While [16] recommends that core competencies be established based upon organizational goals, we apply this logic to establish models based upon the learning objectives of a specific course. The authors reference the Society for Industrial and Organizational Psychology as defining a competency model using a literature or organizational document review coupled with interviews for validation, much like in [15]. The two works continue to coincide as [16] defines a core competency as a descriptive title and a thorough definition in addition to a description of the levels at which its sub-competencies will be evaluated. They too, suggest defining competencies at three levels such as beginner, intermediate, expert, or unsatisfactory, satisfactory, exceptional (See table I).

This approach allows for individuals to be evaluated at a level of detail beyond "pass/fail" and can provide them with feedback on how they can improve to a higher level of competency. These authors further suggest that competencies be defined using technical and organization language to be as specific and descriptive as possible. Finally, these authors call out that the competency-based practices combine the two most predominant approaches to organizational (and consequently educational) development, action research and social constructionism.

Additionally, [17] surveyed 99 papers on CBE in engineering education spanning a timeframe of 17 years. During their review, they noted several similarities among publications implementing CBE, as well as several flaws. 75% of the papers reviewed used rubrics as a competency assessment tool and the authors of the review agreed that rubrics are suitable and appropriate tools for the assessment of written, oral, and project-based CBE assignments. They further suggested that rubrics with detailed descriptors at each of multiple levels of performance can "homogenize" assessors through increased inter-rater reliability and minimized subjectivity of each criterion. This conclusion supports our suggested implementation of rubrics to assess competencies.

TABLE I. EXAMPLE LEVELS OF PROFICIENCY [15]

Low Proficiency	Moderate Proficiency	High Proficiency
Selects employees based on initial impressions developed from reading the resume and an interview.	Identifies the competencies required to perform the job and uses the competencies as a guide in selecting employees.	Selects employees based on a careful analysis of the competencies required for the job. Bases interview questions (or other selection techniques) on the required competencies.

Unfortunately, [17] found that the methods of many of the reviewed works lacked any evidence an attempt to establish validity or reliability of their competency models. Further, only 17 out of the 99 papers explicitly defined the competencies they were measuring. The lack of a thoroughly defined competency model creates concern regarding grader bias and subjectivity due to lack of definition when measuring reliability. Additionally, it fails to provide students with a sense of certainty in the model being used as a foundation for their evaluation. One of our goals is to not only construct a clear and detailed competency model, but also to be transparent about the contents of the model and the process through which it was created.

III. DOING COMPETENCY MODELING

The following section is an account of how we suggest competency modeling be performed in an academic context. This intends to guide the design of a university web programming course given our experiences. Our chosen references in competency modeling suggest beginning a competency model by defining an operational objective in a corporate setting [15,16]. For competency modeling in an academic context, we suggest beginning by defining or selecting one or more primary learning objectives.

A. Resource Selection

Beginning with the selection of resources upon which to base the competency model, we performed a literature review of a wide variety of texts from reputable publishers on web programming. A selection of 7 texts across the areas of CSS, HTML, and JavaScript was used to develop our model. Such a wide variety was chosen to perform a comparative analysis among the chapters and contents of multiple sources on the same subject. This process coincides with the recommendations of [15] and [16] in using literature review as a method for establishing a competency model.

We suggest paying special attention to the publication date of resources when performing this step of the modeling process. This is primarily due to the rapidly evolving nature of the practices in some areas of software development, especially web development. This feature of certain areas of software development (specific to certain languages, technology stacks, etc..) creates a situation in which outdated materials could be used which could result in outdated competencies being modeled and required of students. Such an outcome would only continue to leave gaps in student competencies.

B. Model Construction

Following the selection of source materials, the competency model can be constructed. As mentioned previously, we suggest using a comparative literature review to compare the contents of multiple recent texts on the same subject or area to gain a better understanding of its important concepts. Following this process, the validity of the model should be established using a second method suggested by [15] and [16]. We suggest the use of structured interviews conducted with subject matter experts in the software industry, ideally in the same area as the material being modeled. This allows for the model to be both checked for conceptual relevancy by expert practitioners and for its contents to be evaluated against their expectations of a new college graduate.

Following the literature review approach, we found the most success in using chapter headings to define top level competencies. This allowed us to identify a set of 6 top level competencies composed of HTML, CSS, JavaScript, Information Architecture, Full Stack Development, and Source Code Control. Based on the content and similarities among the texts reviewed, we concluded that this set of core competencies is suitable for a college-graduate-level web developer. Subsequent steps of this process involve the examination of the contents of each chapter or chapters used to select the top-level competencies to define several sub-competencies therein. We found the most success in using section headings to define most sub-competencies while some closer examination revealed a few additional items. At this point, we recommend adding an additional level of detail to the competency model beneath each sub-competency including a statement of how the student can demonstrate their competency in this area. In our case, these sentences took a form like "Demonstrate the ability to use [technology or technique] to [perform some action]." These components were especially helpful in the model implementation stage.

C. Model Implementation

This section briefly discusses how our model was implemented in the classroom and how assignments were created or modified to incorporate the model. It is only a glimpse into this process as the focus of this paper is our method for performing the competency modeling process. Still, we feel that interested individuals may find this information helpful.

First and foremost, we made the competency model readily available to students from the beginning of the course and clearly conveyed to them how the methods of the course may feel different from those they are accustomed to. Based on [17], a series of sequential milestone CBE activities were designed to individually evaluate each top-level competency by its sub-competencies. Highly detailed rubrics were created with one item dedicated to evaluating each sub-competency at three levels with detailed descriptions. The descriptions of each category allowed students to clearly see the reason for which they received their evaluation. We were careful to make rubrics available to students when they were initially given their assignments to convey our expectations of them transparently.

IV. Conclusions

This work presents the following set of recommendations on how to perform the competency modeling process with the goal of delivering a competency-based college course.

1. Begin by defining one or more learning objectives.
2. Select several, recent texts to inform the model content.
3. Comparatively review the selected texts, using chapter headings to define top-level competencies and chapter content to inform sub-competencies.
4. Define all competencies and sub-competencies at three or more levels of proficiency.
5. Validate the model with professionals currently in the industry related to the course.
6. Provide students with the model up-front and evaluate them using rubrics derived directly from the model.

These recommendations are derived from a review of literature on competency-based education and competency modeling and informed by our experiences in implementing what we learned from this review. Our goal is to provide educators with the information necessary to begin the competency modeling process to reduce the difficulty of implementing competency-based education. We hope to advocate for the use of CBE as a method of mending the industry-academic competency gap, especially in software development education, with an end goal of helping educators provide a higher quality education to their students.

Future work includes the use of a second method of competency model establishment as presented by [15] and [16] to validate our established model with industry professionals. It is anticipated that this approach will further uncover important 'soft' skills such as collaboration and motivation not included in textbooks.

Ongoing work includes the implementation of our established model and methods in the course for which it was constructed, and the evaluation of student impressions of CBE. Preliminary results suggest that students perceive an increase in feelings of motivation and accomplishment when working in the presence of a competency model. Further, they express feelings of a better concept of their progress toward competency when evaluated against the model.

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