Professional Competencies in Computing Education: Pedagogies and Assessment

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ABSTRACT

Competency-based learning has been a successful pedagogical approach for centuries, but only recently has it gained traction within computing. Competencies, as defined in Computing Curricula 2020, comprise knowledge, skills, and professional dispositions. Building on recent developments in competency and computing education, this working group examined relevant pedagogical theories, investigates various skill frameworks, reviewed competencies and standard practices in other professional disciplines such as medicine and law. It also investigated the integrative nature of content knowledge, skills, and professional dispositions in defining professional competencies in computing education. In addition, the group explored appropriate pedagogies and competency assessment approaches. It also developed guidelines for evaluating student achievement against relevant professional competency frameworks and explores partnering with employers to offer students genuine professional experience. Finally, possible challenges and opportunities in moving from traditional knowledge-based to competency-based education were also examined. This report makes recommendations to inspire educators of future computing professionals and smooth students' transition from academia to employment.

CCS CONCEPTS

• **Social and professional topics → Computer science education**; **Computing education**;

KEYWORDS

ITiCSE working group, computing education, competency-based learning, computing pedagogies, computing competencies.

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1 INTRODUCTION

Graduates from a variety of academic programs require much more than knowledge to be successful practitioners and researchers, as they must "do" or "perform" activities in their areas of work, for example, solving an accounting problem, or performing as a musician, or designing an engineering subsystem, or validating a software system [55, 94]. These activities need more than content knowledge: they need skills to apply their knowledge and the professional dispositions to *perform* well in their careers. In short, they need to be *professionally competent*.

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Professional degree programs have used competency as a measure of teaching and learning. Areas such as architecture, law, education, and medicine have incorporated the combination of skills and knowledge within professional settings. However, in computing disciplines, competency-based education has only recently gained traction [35, 103]. Therefore, it is crucial to understand the meaning and application of competency. Many definitions of competency exist. Some dictionary definitions of competence or competency are as follows:

- The possession of sufficient knowledge or skill [78]
- An important skill that is needed to do a job [28]
- The quality of being adequately or well qualified physically and intellectually [132]

Competency thus has different meanings depending on the source. It also has different meanings depending on the context or situation in which competencies are expected and demonstrated. Hence, it is essential to have a clear sense of competency before considering pedagogies and assessments to educate professionally competent graduates from computing degree programs.

For many computing students, the purpose of completing a computing degree is preparation for employment. As such, computing graduates need to be work-ready, i.e., possess computing knowledge and skills, and be ready to perform activities required to succeed in the real world. In short, they need to reach a needed level of functional, real-world competence. As described in CC2020 [35], the dimensions of competency apply knowledge and skills with appropriate dispositions in an authentic task context. Therefore, critical goals for baccalaureate computing programs are to impart knowledge, enable students to practice skills, and develop professional dispositions in the context of explicit activities or goal-oriented tasks in professional settings.

This report relies heavily upon the existing notions of competencies in computing introduced in the Information Technology curricular guidelines [103] and CC2020 [35], as well as other practical competency and skills frameworks, such as ISO 247773-2019 [66], the Institute of Coding's recent accreditation standard [27], and SFIA [119]. In addition, this report has also benefited from earlier ITiCSE working group reports [34, 53] and drawn from the knowledge-based to competency-based computing education report by Clear et al. [33].

The major contributions of this report are:

(1) Improved understanding of competencies used in professions, such as teaching and medical professions, with lessons applicable to computing
(2) Improved understanding of professional competencies and pedagogies appropriate for computing degree programs
(3) Guidance for the assessment of competencies in computing, especially of professional dispositions
(4) Recommendations on next steps for the computing community to embrace a competency-based framework for education

The rest of this paper is as follows. The following section describes a competency model based on content knowledge, skills, and professional dispositions and relates to learning models inclusive of cognitive, affective, and psychomotor aspects of learning. It also discusses the relationship between the competency model and Fink's significant learning model [50]. Section 3 explores signature pedagogies in the professions to help describe how a degree program addresses academic standards, future practice, and professional values and expectations of the discipline. The section also explores professional disciplines other than computing pedagogies, such as medicine, law, engineering, and teacher education. Section 4 provides an overview of pedagogies with an example useful for computing. Section 5 examines the move towards competency-based learning in the different computing disciplines, as well as competency and skills frameworks in the workplace, such as iCD and SFIA [69].

Assessing competencies is the focus of Section 6, with specific questions of how the competency of a computing student in a baccalaureate degree program is determined, how to assess the competent performance of routine activities or tasks, and what tools would be necessary for such assessment. As competency-based learning is relatively new to nearly all computing faculty, Section 7 explores the challenges and opportunities in transitioning from traditional knowledge-based to competency-based education in computing. Section 8 reviews the current status of competencies in computing and makes recommendations for the future. The report concludes with a few final remarks.

2 COMPETENCY-BASED LEARNING

This section presents an integrative model of competency. It contains three interrelated components: content knowledge, skills, and professional dispositions. A performance lens inspired the model into active learning and the *Understanding by Design* framework [136] and its view that content mastery is a means, not the end goal, to develop competencies. The framework's facets reveal that experiencing understanding "in action" combines content knowledge and skills, or *cognitive competencies*, with demonstrating perspective, showing empathy, and having self-awareness, which we refer to as *professional dispositions*. Three competency learning models, Simpson's [108], Miller's [82, 101], and Fink's [51], which are not limited to cognitive competencies, reinforce a conception of competency that emphasizes performative tasks in authentic settings to enable the development of professional dispositions.

2.1 A Performance Lens to Active Learning

There is extensive evidence supporting the effectiveness of active learning as a student-centered teaching practice that improves student learning and retention. Instead of attending and passively listening to a standard lecture, students engaged in active learning have opportunities and appropriate support to ask questions, apply concepts and discover their relationships, or generalize a solution to new situations—all well-known activities that improve learning [18]. Teaching strategies that facilitate active learning include case studies, group projects, think-pair-share, debates, role-playing, or peer tutoring. In computing, active learning activities could include problem-based learning [104, 140], live-coding [100, 106], programming projects (individual, paired [137] or group), and internships. Instead of being a "sage on the stage" in passive learning, a teacher could turn into a "guide on the side" in active learning. The paradigm of instruction dominated by passive lecture-based teaching has shifted to creating learning experiences in which students are active participants in the learning process [86]. Necessary conditions for attaining content knowledge and developing skills are acts of doing and carrying out performative tasks.

Performative tasks suggest work, practice, production, demonstration, presentation, and completion. Such engagement levels are not readily achievable if teaching is only about content knowledge, involving factual information, vocabulary, key concepts, and the basic know-how, techniques, and discrete skills [136]. A performance perspective on learning, advanced by David Perkins [93] and Howard Gardner [54], holds that "understanding a topic of study is a matter of being able to perform in a variety of thought-demanding ways with the topic" [93].

While acquiring knowledge and building basic, routine skills are necessary, they are not sufficient for thoughtful engagement and sustained practice to solve complex problems and integrate solutions in new application domains. Wiggins [136, p. 94] developed the *Understanding by Design* framework that views content mastery as a means, not the end goal, to achieve competencies that graduates will continue to develop in their professions. The framework's six facets are "indicators of how understanding is often revealed in action: performance, products, words, or behavior" [136, p. 94]. Three design facets' understanding includes cognitive learning activities involving explanation, interpretation, and application and adjustment. The remaining three facets center on learners' agency to demonstrate perspective, show empathy, and have self-knowledge.

A performance lens to active learning thus complements cognitive competencies and makes explicit learner's dispositions, such as persistence, adaptability, or self-direction. This report's competency model states that dispositions become inseparable from knowledge acquisition, understanding, and skill development through practice and performance. After the competency construct's theoretical basis is presented, we elaborate on the cognitive competencies, encompassing content knowledge and skill and professional dispositions, mapped to intrapersonal and interpersonal competencies.

2.2 Theoretical Basis of Competencies

Competencies express cognitive, affective, and social human qualities or characteristics. Content knowledge and skill-based competencies are primarily cognitive competencies. Dispositional competencies, however, have affective, volitional, and social-motivational characteristics. Developmental and personality psychology research offer a solid theoretical basis for measuring competencies centered around the whole person concept and the interplay between affective, cognitive, and social human qualities. Personality taxonomies help make sense of the many attributes that characterize human beings to study these personal qualities.

The "Big Five" personality model [57, 77] aligns personality characteristics along five dimensions: extraversion, agreeableness, conscientiousness, openness to experience, and emotional stability, as shown in Table 1. Adapted from the *Education for Life and Work* report [37, p. 29], this version references the American Psychology Association's *Dictionary of Psychology* [14].

Dispositions complement cognitive competencies and expose personal qualities that define intrapersonal and interpersonal competencies [37, p. 33–34]. The report developed a cluster-based

Table 1: Personality model: Big-Five dimensions [37, p. 29]

Personality Dimension	Characteristics
Extraversion	Defines an energetic approach toward the social and material world. Includes: assertiveness, sociability, and positive emotionality.
Agreeableness	Represents a prosocial and communal orientation towards others. Includes: altruism, trust, modesty.
Conscientiousness	Facilitates task and goal-directed behavior, such as thinking before acting, delaying gratification, following norms, and planning, organizing, and prioritizing tasks.
Openness to experience	Describes the breadth, depth, originality, and complexity of an individual mental and experiential life.
Emotional stability	Predictability and consistency in emotional reactions, with the absence of rapid mood changes. Contrasts with neuroticism, which includes feelings of anxiety, nervousness, sadness.

classification of intrapersonal and interpersonal competencies by thoroughly analyzing several reports on skills. They aligned with research-based taxonomies of skills and abilities viewed as malleable dimensions of human behavior.

Intrapersonal competencies, which is defined as "the capacity to manage one's behavior and emotions to achieve one's goals (including learning goals)" [37, p. 3], are structured in three clusters, *intellectual openness*, *work ethic*, and *core self-evaluation*, strongly aligned with corresponding personality dimensions of openness to experience, conscientiousness, and emotional stability, as shown in Table 2 [37, p. 33; 89].

Table 2: Intrapersonal dispositions [37, p. 3]

Cluster	Intrapersonal dispositions
Intellectual openness	Flexibility, adaptability, artistic and cultural appreciation, personal and social responsibility, appreciation for diversity, adaptability, continuous learning, intellectual interest and curiosity
Work ethic	Initiative and self-direction, personal responsibility, perseverance, productivity, grit, metacognition, self-reflection, professionalism/ethics, integrity, citizenship, career orientation
Core self evaluation	Self-monitoring, self-evaluation, self-reinforcement, and physical and psychological health

Interpersonal competencies, defined as "expressing ideas and interpreting and responding to messages from others" [37, p. 3], are organized in two clusters, *teamwork and collaboration* and *leadershlip*, aligned with the remaining personality dimensions in the "Big Five" personality model of agreeableness and extraversion, as shown in Table 3 [37, p.34; 95].

2.3 Cognitive Competencies

The *Education for Life and Work* report recognizes the synergy between knowledge and skills and characterizes the cognitive domain of competence by three clusters: *knowledge*, *cognitive processes and strategies*, inclusive of critical thinking, problem-solving, reasoning, interpretation, decision making, adaptive learning, and executive function, and *creativity* [37, p 32]. It is possible to map these clusters to *content knowledge* and *skill*, as shown below. While content

Table 3: Interpersonal dispositions [37, p. 3]

Cluster	Interpersonal dispositions
Teamwork and collaboration	Communication, collaboration, teamwork, cooperation, coordination, empathy, perspective taking, trust, conflict resolution, negotiation, service orientation
Leadership	Leadership responsibility, assertive communication, self-presentation, persuasion, and social influence with others

knowledge and skills can be distinguished in the abstract, it is likely that they are often indistinguishable in real life and the profession.

2.3.1 Content Knowledge. Knowledge is "the fact or condition of knowing something with familiarity gained through experience or association" [80]. Objectivism and constructivism are two different views of knowledge acquisition according to learning theory. In objectivism [74], knowledge exists independently of any learner. The learner's role is to acquire it, while the teacher's role is to convey it consistently and efficiently for all learners. However, the prevalent view of knowledge acquisition is constructivist [17]. In constructivism, learners construct their knowledge based on prior knowledge and lived experiences and incorporate new knowledge over time through learning activities to align their understanding with nominal or real knowledge. Furthermore, constructionism [92] builds on constructivism by emphasizing the construction of meaningful products for learning, or "objects to think with," which embody concrete representations that help make sense of abstract concepts.

Knowing a sorting algorithm and its complexity, knowing Bayes theorem, or the concept of refactoring are examples of content knowledge, which represents the "know what" aspect of competency. Knowledge in a particular domain means mastery of core concepts and content knowledge of that domain. At the undergraduate level, content knowledge is usually what teachers are experts in and pay extensive attention to when designing their syllabi. Developing a degree program curriculum also gives preponderant consideration to content knowledge: what courses and topics are *covered* by the program.

2.3.2 Skill Learning and Development. A dictionary definition of skill (as applied to knowledge rather than physical tasks) is "the ability to use one's knowledge effectively and readily in execution or performance" [81]. It is defined as "the ability to apply knowledge to perform a simple operation" [66, section 5.4]. In computing, calculating the complexity of an algorithm written in pseudocode, implementing an algorithm as a program based on a design description, or constructing an argument as to why one algorithm is more efficient than another in a specific application are all examples of skills.

Skill develops over time, with deliberate practice [47] and via interactions with others and the world around us [37]. Skill also requires engagement in higher-order cognitive activities that usually involve coupling "hands-on" and "minds-on" practices. The inextricable connection between content knowledge and skills is evident in Polanyi's characterization of explicit versus tacit knowledge [99]. While explicit knowledge codifies in written form or other communication means, tacit knowledge is hard to codify and is primarily transferred through sustained practice, lived experience, observation, and apprenticeship. These are also ways by which people learn and develop skills. Skill is the "know how" aspect of competency.

2.4 Professional Dispositions

A dictionary definition of disposition is "prevailing tendency, mood, or inclination; temperamental makeup; the tendency of something to act in a certain manner under given circumstances" [79]. It encompasses socio-emotional skills, attitudes, and behaviors that characterize the inclination to carry out tasks and the sensitivity to know when and how to engage in those tasks [94]. It reflects the propensity to deal with real-world situations such as tolerance to the ambiguity of requirements or expectations, persistence in working with complex problems, knowing one's strengths and weaknesses, or leveraging differences when working with others. Schussler's view [105] that a disposition "concerns not what abilities people have, but how people are disposed to use those abilities" supports a competency construct that complements and tightly interrelates the cognitive and dispositional aspects of professional competencies.

Our conception of disposition draws on Dewey's concept of habit: "that kind of human activity which is influenced by prior activity and in that sense acquired", which he defines in his book *Human nature and conduct* (1922) [43, p. 41–42] as "readiness to act overtly in a specific fashion whenever opportunity is presented". Decades later, the role of the "mutually constitutive nature of affect and cognition" in student learning continues to remain a challenge for researchers and practitioners [10]. Our attention to the dispositional component of competencies stems from the notion that they cannot dissociate from why people choose to develop them and how disposed people are to perform them by engaging with others and through deep introspection into oneself. That is, disposition reflects the "know why" and "know yourself" aspects of competency.

To what extent do academic programs bring to bear professional dispositions in their curricula? For example, are there professional dispositions in baccalaureate degree programs that can be taught, learned, and measured within the limited duration of three or four years of the program of study? These questions capture the very first reaction educators have when exposed to the dispositional component of competency. To examine the relationship between professional dispositions and disciplinary curricula, we consider the computing discipline and present a scenario in which a computing educator integrates and organizes professional dispositions in computing around the problem-solving cognitive processes and strategies.

We assume that the task at hand is solving a real-life computing problem in an application domain. The setting is a semester-long team project guided by the computing course instructor in collaboration with a colleague who is familiar with the application domain. To design a learner-centered scenario, they will consider the prior knowledge, demands, characteristics of the target group, and the aimed learning outcomes to align them accordingly. Teams of 2-3 students in a small class of 20-24 must do the project as a formative assessment and apply software engineering concepts and techniques they learn about in the course. The instructors will also integrate computing content knowledge and skills developed in other courses. This example, as shown below, has the potential of creating many opportunities for students to become aware of, reflect on, exercise, and improve on professional dispositions. The following list of course design elements highlights professional dispositions afforded by student learning experiences that the educator's course design supports.

- **Problem to be solved**: Computing disciplines are problem-solving disciplines. The problems to be solved can be under-constrained or under-specified. The specification may be ambiguous. The solution strategy may be uncertain at first. A desirable disposition of computing graduates is the ability to *handle ambiguity, uncertainty* [16], under-specification. One can promote this by assigning real-life projects with room for elucidating specifications and coordinating team effort to determine the adequate solving strategy.
- **Application domain**: Familiarity with the domain of the problem would help one be a better problem-solver. Having a breadth of knowledge in a variety of domains is a desirable characteristic of a computing graduate. The *openness to acquire knowledge*, even if superficially, is a disposition that is encouraged and taught by projects with different application domains.
- **Problem-solving process**: Dispositions desirable of computing graduates include the ability to *work collaboratively in teams* and *persist* through challenges [16]: both of these dispositions are requirements for solving real-life problems, whether in eliciting specifications, devising solutions, or revising approaches.
- **Tools:** Computing is a fast-changing field. To succeed in the discipline long-term, one has to *learn to learn* and *be a self-directed learner*. People can promote these attributes in a program of study with frequent changes in languages, technologies, and frameworks. A collaborative, project-based experience in a non-computing application domain involving a real client requires integrating computing skills related to different programming languages and tools. It is also an opportunity to develop new dispositions, such as *agility* [36].
- **Ethical and responsible solution**: Computing touches all aspects of human experience today. We use the products of computing to communicate, collaborate, maintain social relationships, work remotely or asynchronously, improve ourselves (e.g., health, career prospects, citizenship)—the list is endless. Thus, the importance of ethics in the design of solutions has never been more critical for computing graduates.
- **Professional environment**: *Professionalism* should be a characteristic of computing graduates in their dealings with peers, their managers, colleagues they might manage, and professionals external to their organization. This trait includes courtesy programming (easily readable, adaptable, and extensible code), oral and written communication, presentation, and other related characteristics.

2.5 Competency Learning Models

This subsection examines different competency models that have been previously proposed and have shown several strengths.

2.5.1 Simpson's psychomotor learning model. The knowledge lens on teaching and learning in a baccalaureate program of study has been influenced heavily by Bloom's taxonomy of cognitive learning outcomes [19]. Despite the 2001 revision to the original taxonomy [11], which includes "execution" and "implementation" in the "apply" level of the taxonomy, this is still very much about "knowing what" and "knowing how" rather than actually "doing," so the perspective is still that of the cognitive lens. However, Bloom and his colleagues originally described two other domains of learning: the affective and the psychomotor. The affective domain attempts to describe emotional responses that may impact a student's learning [72], while the psychomotor domain seeks to characterise the learning of practical tasks involving manipulative or motor skills.

They did not develop the psychomotor domain into a taxonomy of learning objectives, perhaps because it was irrelevant for university-level education. However, other researchers described it later, including Simpson [108]. Simpson further states that, despite the lack of interest in the psychomotor domain by Bloom et al., the domain would be of considerable value to educators in several areas of professional education. Indeed, there have been recent re-statements of the psychomotor domain for areas such as university-level engineering [49]. However, perhaps the most useful articulation of the psychomotor domain, from the perspective of developing competency, was by Dawson [41], who abstracted the essence of the hierarchy as:

$$\text{Observation} \rightarrow \text{Trial} \rightarrow \text{Repetition} \rightarrow$$
$$\rightarrow \text{Refinement} \rightarrow \text{Consolidation} \rightarrow \text{Mastery}$$

The fundamental implication of this expression of the psychomotor learning model is that repeated practice is necessary to attain the desired goal of developing competency. Its basis was the repeated practice aspect that Bowers et al. [23] proposed Simpson's psychomotor learning model as an alternative to Bloom's cognitive learning model for the development of competency in computing degree programs.

2.5.2 Miller's model of assessing clinical competencies. Miller captured the combination of knowledge acquisition, skill practice, and development in his proposal for the assessment of clinicians [82]. Commonly depicted as a pyramid, Miller's model, as adapted by Ramani and Leinster [101] and used extensively across medical education, is shown in Figure 1.

Miller's pyramid has been adopted widely for professional competency assessment in medical and related fields. The model's key feature is to combine competencies in both the cognitive and psychomotor domains. Thus, the lower two levels capture much of Bloom's cognitive competencies, describing the acquisition and application of knowledge (knowledge and skill). In comparison, the upper two levels reflect behaviors, describing repeated practice to consolidate and attain professional competence. For clinical assessment, we can observe and assess a practice either in practical examinations or by observation of real-world practice. But the key is *repeated* practice, rather than a single assessment point. Indeed, Norcini [90] emphasizes the importance of volume (of performing tasks) to ensure valid assessments of competence.

In summary, while the "knowledge lens" of Bloom's cognitive learning model has dominated the development of learning strategies and assessment methods in computing for many decades, there

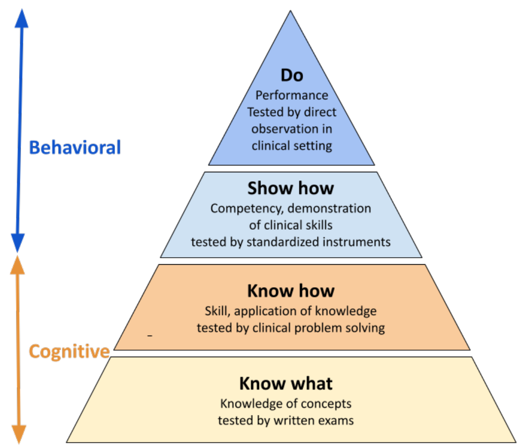

Figure 1: Adapted Miller's clinical assessment model [101]

are other learning models which may be more appropriate for the assessment of competence. For example, both Simpson's psychomotor learning model and Miller's clinical competency assessment model seem applicable. In addition, both emphasize the need for repeated practice in realistic or preferably professional settings.

2.5.3 Fink's significant learning model. Almost two decades ago, Dee L. Fink drew attention to "kinds of learning that do not emerge quickly from Bloom's taxonomy." He enlisted "tolerance, ability to adapt to change" and "learning to learn, leadership and interpersonal skills" as examples of learning that goes beyond Bloom's taxonomy and "even beyond cognitive learning itself" [50, p. 29]. Fink's *significant learning model* complements and broadens Bloom's cognitive and Simpson's psychomotor domain models by centering active learning on the whole person concept of the learner. The three learning categories on the right side of the model, as shown in Figure 2, include content knowledge designated as foundational knowledge, skill development defined as the application, and integrative experiences that connect learning to other "realms of life," including work designated as integration.

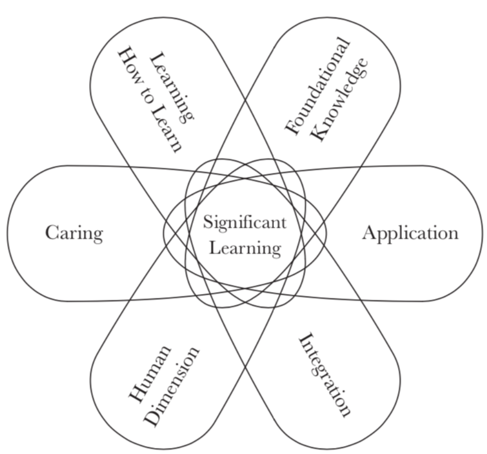

Figure 2: Significant learning model [50, Figure 2.2]

The left half of the significant learning model encompasses three additional categories of learning, human dimension, caring, and learning to learn, that expose affective, emotional, social, and motivational aspects of learning and give depth to the professional dispositions construct:

- Human dimension: Learning about oneself and others; how to discover personal and social
- Caring: Developing new interests, values, and feelings
- Learning to learn: Becoming self-directed learner, inquiring about the subject, becoming a better learner.

All learning dimensions in the significant learning model are synergistic, relational, and interactive, contrasting with Bloom's and other learning taxonomies that are linear or hierarchical. The idea is that learning categories do not manifest in isolation, and there is no prescriptive sequencing that applies to all learning experiences. To convey this idea visually, the model depicts intersecting dimensions displayed circularly to denote one whole: student learning with significant implications beyond the program of study. Moreover, what drives student learning in Fink's model is not the accumulation of content knowledge and its various applications but all the synergistic learning that brings significance to the learning experience and makes a difference in the graduate's career readiness and professional development.

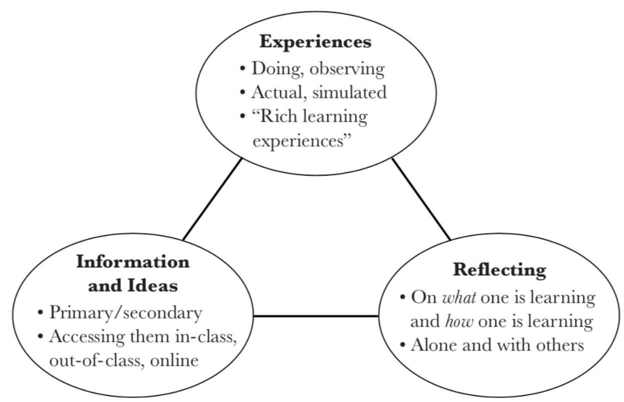

Figure 3: Holistic view of active learning [50, Figure 4.2]

A holistic conceptualization of active learning integrates content knowledge with relevant and authentic experiences of showing and doing with reflection to create and achieve significant learning. What one learns and how one learns, alone and with others, as depicted in Figure 3.

2.6 Integrative Model of Competency

Competency transcends and replaces the current educational practice of framing curricula exclusively in terms of disciplinary subject matter or content knowledge. The concept of learning outcome focuses on the learner's achievements rather than the teachers' intentions, which seems in sync with the learner-centered competency concept. Why not continue to formulate only learning outcomes when we design the syllabus of a course or any other unit of learning in a program curriculum? A helpful definition for learning outcomes is "written statements of what a learner should

Competency ≡ Content Knowledge ∩ Skills ∩ Professional Dispositions in the **Context** of Task and Setting

Figure 4: Mathematical representation of competency

know and be able to demonstrate at the end of a learning unit (or cohesive set of units, course module, entire course, or complete program)" [70, p. 5]. The learning outcome definition does not make explicit the overall purpose of achieving a bachelor's degree. For many students, it is to become job-ready and commence a personally fulfilling professional career that often serves others and society. This report's focus on competencies and their development during a program of study aim at helping educators achieve their graduates' professional preparation goals.

There is extensive confusion and vagueness surrounding competence or competency [53]. This report claims that competence refers to the performance standards associated with a profession or membership to a licensing organization. Assessing some level of performance in the workplace is frequently used as a competence measure. Competencies are what a person brings to the job, conceptualized as qualities by which people demonstrate superior job performance [131]. There is general agreement in education that success in undergraduate education and career readiness requires that students develop a range of qualities [37, 70, 84], typically aligned with competency attainment.

The IT2017 report proposed a definition of competency that "connects knowledge, skills, and dispositions in a professional context" [103, p. 31] and expresses the interplay among them. Figure 4 attempts to provide a mathematical representation of the competency concept as an equivalence of three sets that display a unique intersection of content knowledge, skills, and professional dispositions in the context of the performance task, as well as its setting.

Building on this representation, Figure 5, adapted from Sabin et al. [103, p. 31], depicts the integrative competency model. This context-situated triadic model avoids perpetuating the dominance of the content knowledge lens for undergraduate instruction. It also shifts the focus of curricular guidelines from the body of knowledge to the learners' competencies that a program curriculum should define and develop in their students. An integrative model of competency explicitly situates the interdependence between its constitutive components within the context of the task and the setting in which learners carry out the task. Characteristics of performance tasks that develop competencies include authentic problems, project-based activities, collaboration, diverse teams, and reflective practice. Task setting is also important and might include expert mentorship and other employer involvement, professional tools, workplace-bound projects, internships, and co-op experiences.

We conclude this section by distinguishing the following salient features of competencies.

- Competencies are *forms of expertise* (or manifestations of human competence) specific to a *particular area of work* (or activity) by carrying out *goal-oriented, performative tasks.*
- Competencies demonstrate *how good one is in a particular line of work*, whether on a job, in a profession, through civic engagement, in a community-based organization, or other socially constructed opportunities to do work.
- The *integrative model of competency* has three interrelated components: content knowledge, skill development, and professional dispositions. These components do not manifest in a vacuum. They are *situated in a context* characterized by tasks and their settings.
- The expressive power of competencies does not lie in how much one knows or how well one does a task. Competencies are a *holistic measure of professional expertise.* They include cognitive and performative aspects intertwined with the human side of professional development; they include the affective and social/human aspects of learning and professional development.

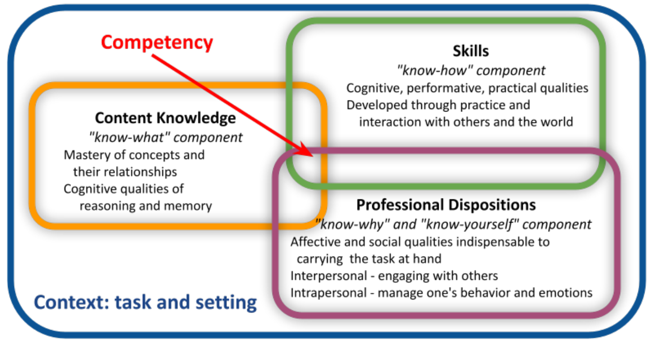

Figure 5: Integrative competency model

3 AN OVERVIEW OF COMPETENCIES AND PEDAGOGIES

This section examines the concept of *signature pedagogies in the professions* that Shulman [107] introduced to capture how future practitioners in professional academic programs, such as law or medical education, are prepared concerning critical aspects of professional work. An understanding of signature pedagogies helps to strengthen any practical perspective on competencies. According to Shulman, "signature pedagogies prefigure the cultures of professional work and provide early socialization into the practices and values" of a professional field. In other words, signature pedagogies directly address three challenges:

(1) Meeting the academic standards of the program of study.
(2) Shaping the character of future practice.
(3) Conveying the values and expectations of the profession.

The resulting critical aspects of professional pedagogies concern the three dimensions of student competencies: to **think** and **perform** like a professional, and to **act** with integrity and responsibility in service to the profession. As discussed in Section 4 in the context of computing, educators' actions and practices are specified accordingly into the surface, deep and implicit structure of their pedagogical actions.

Shulman illustrated these structures with brief examples from medical education (bedside teaching and clinical rounds) and legal education (thinking like a lawyer by applying the legal case method of "brutal" instructor-student verbal exchanges) [107]. We aim to align a learner's computing competency as a holistic construct with professional computing pedagogy structures by focusing on more examples.

The concept of signature pedagogies mirrors the triad of our competency definition within a professionally-oriented context. Therefore, this section examines the learner and teacher roles in competency-based learning and teaching and the alignment between desired competencies and appropriate pedagogies. We now present the application of signature pedagogies in other professions.

3.1 Signature Pedagogies in the Professions

Unlike other theoretical approaches towards the development of professional competencies, Shulman [107] focuses on the preparation of novices by educators from the perspective of professional practice and its signature characteristics. Therefore, he distinguishes thinking, performing, and acting with integrity as dimensions of professional preparation in higher education. These crucial aspects should reflect the fundamental ways of teaching and learning in any professional education. A signature pedagogy conveys the culture and social norms, reveals dispositions, values, hopes, ranks, privileges, and, therefore, characterizes a profession. Moreover, signature pedagogies implicitly define how to design and function educational programs, which in turn re-enforces a professionally-oriented pedagogy. Thus, signature pedagogies comprise the entire didactic habitus [20, 21] of educators within a discipline. They also designate how and which competencies educators should foster.

Shulman's model of signature pedagogy in the profession distinguishes three pedagogical structures [107]:

(1) The **surface structure of pedagogy** comprises concrete, operational acts of teaching and learning and represents *what* is explicitly said, presented, and demonstrated in the classroom. It includes content knowledge and literature, the teaching pace, and a learning setting and scaffolding of questioning and answering, interaction and withholding, approaching and withdrawing. Thus, we can think of the surface structure as the blueprint of the pedagogy in the profession, with the necessary pedagogical entities and attributes.
(2) The **deep structure of pedagogy** refers to the underlying assumptions or model of how educators convey content knowledge and facilitate learners' development of skills effectively and how to think and process problems within a profession. In other words, the deep structure of the pedagogy has model-based mechanisms to help transform learning into professional competencies.
(3) The **implicit structure of pedagogy** comprises beliefs, attitudes, and values that learners have the opportunity to experience and reflect on in their professional practice. We refer to it as the hidden curriculum within the educational practice of a profession that aims at helping learners reflect on and frame their own professional identity,

Signature pedagogies define their characteristics described by Shulman as both pervasive and routine, meaning they represent a framework in which teaching and learning usually operate. These boundaries to operate in are persistent over time within a profession, as educators are often unaware that they replicate their previous educational experiences [107]. They thus repeat how they have been taught years or decades ago without reflecting or questioning their pedagogical practice. Further characteristics include the requirement for learners' public demonstrations or performance in a professional setting, whether modeled in the classroom or through an authentic experience outside the classroom. Professional learning encounters are also susceptible to inherent uncertainty, new forms of accountability, visibility of actions, and emotional reactions. In this regard, Shulman stresses the teacher's role in facilitating learning without negative emotions, such as fear and frustration. On the other hand, well sustained positive emotional responses may help support learning or even character formation.

As concluded by Shulman, a signature pedagogy expects to balance surface, deep, and implicit structures. Thus, professional education aims to teach students how to balance and navigate the different tensions among competency's cognitive, practical, and dispositional aspects. Furthermore, since education socializes novices right from the start and thereby influences the mind, heart, and hand of future professionals, rapid changes in a field due to the emergence of new technologies can and should lead to new methods within the pedagogy of a profession.

Chick, Haynie, and Gurung [31] agree with Shulman [107] concerning the resemblance of a profession's signature and its pedagogy in professional programs. Professional pedagogies' methods are somewhat unique, subject-specific, and non-transferable to other disciplines. These methods are also due to the implicit character of some disciplinary learning objectives, which are only conveyed via teaching practices, ways of thinking or problem solving, and more. Chick, Haynie, and Gurung conclude that signature pedagogies are a result of disciplinary and professional differences concerning learning objectives, student learning and teaching strategies [31].

The following sections examine competency and the respective signatures in the pedagogical approach in medical education, teacher education programs, legal education, and engineering programs. These four disciplines illustrate the signature pedagogies proposed by Shulman [107] and particularly address practical competencies as crucial elements of student education. Therefore, they serve as examples for the identification and assessment of practical competencies in computing education.

3.2 Medical Education

The direction of healthcare education, in particular medical education, in the US and Canada, was profoundly impacted by the 1910 Flexner Report [1] commissioned by the Carnegie Foundation. After visiting numerous medical schools in both countries, Flexner detailed these shcools exhibited low quality and made a set of recommendations that schools adopted for the next ten years. The report recommended that medical school be a four-year, full-time program, with a thorough grounding in coursework in the sciences and extensive laboratory and clinical experiences. This approach was adopted not just by medical schools but also, over time, pharmacy schools and nursing schools. It is thus possible to measure learning in terms of content knowledge, measured through exams, and structured time spent in laboratory and professional settings.

However, a great deal of interest has occurred in moving to competency-based assessment in healthcare education in the past decade. For example, Brown University moved in this direction with its adoption of the MD2000 competency-based curriculum [109]. However, the organization that has been most influential in moving medical education in the direction of competency-based assessment is the Accreditation Council for Graduate Medical Education (ACGME) [5]. This organization accredits residency programs, which are hospital clinical placements completed by medical school graduates. ACGME defines a set of six core competencies which it considers to be foundational skills that every practicing physician must acquire. The six core competencies are:

(1) Practice-Based Learning and Improvement
(2) Patient Care and Procedural Skills
(3) Systems-Based Practice
(4) Medical Knowledge
(5) Interpersonal and Communication Skills
(6) Professionalism.

Milestones are then defined for each specialty. These are a set of specialty-specific knowledge, skills, and other attributes that tie to the core competencies. For example, in the Internal Medicine specialty, one of the milestones is "Patient- and Family-Centered Communication" [5]. The milestones are assessed along a scale from 1 to 5, with Level 1 being the level that entering residents are expected to attain, Level 4 the graduation goal, and Level 5 representing an expert level, The expectation is that residents will start at the lower end of the scale and improve as they proceed through the program. Behaviors are then listed for each level for a given milestone. In the Internal Medicine specialty, the "Patient- and Family-Centered Communication" milestone evaluates at Level 1 if the student "Uses clear language and non-verbal behavior to demonstrate respect and establish rapport". A student at Level 4 "Establishes and maintains therapeutic relationships using shared decision making, regardless of complexity" (these are examples of several measures for this milestone).

In all fifty states in the US, a prospective pharmacist must graduate from the Accreditation Council For Pharmacy Education (ACPE) accredited program to obtain a license. ACPE accreditation criteria, "Standards2016" describes four educational outcomes that a person must achieve to practice as a pharmacist successfully: Foundational Knowledge, Essentials for Practice and Care, Approach to Practice and Care, and Personal and Professional Development. The Standards document goes on to further describe these outcomes. For example, for Essentials for Practice and Care, the document states: "The program imparts to the graduate the knowledge, skills, abilities, behaviors, and attitudes necessary to provide patient-centered care, manage medication use systems, promote health and wellness, and describe the influence of population-based care on patient-centered care," and then lists the following elements that comprise the outcome: patient-centered care, medication use systems management, health and wellness, and population-based care.

One characteristic of the medical profession is the requirement for continuing education and professional development. Therefore, both Board certification and state licensure impose such conditions to ensure these professionals remain current.

3.3 Teacher Preparation

In addition to subject-specific knowledge, demonstrating skills and dispositions is crucial in the profession of teaching, and perhaps more so at the levels of primary and secondary education. As an illustration, the two-part Teachers' Standards governing K-12 education in England has eight requirements listed in the first part that all trainee teachers must meet. Only one of which directly relates to subject knowledge while the other seven likely reflect skills or dispositions [123]. The second part could be classified as "professional dispositions" in its entirety. A good teacher must demonstrate certain personal and professional behaviors at work, especially when interacting with students. Because of the profession's history, the debate around how exactly to train teachers to be competent professionals has been happening for a lot longer than many others. Teacher training thus forms a highly relevant case study for us.

In England, the approach to teacher training compares to a pendulum, one swinging back and forth between a school-based or apprenticeship training model on the one hand and college/university-based model of training on the other. The "pupil-teacher" approach of the early 19th century was decidedly in the school-based training camp, with apprentices starting their on-the-job training at 13 years of age, with the training lasting five years.

The approach came under criticism for its poor quality and low levels of professionalism. By the 1880s, the pendulum had begun to swing the other way towards specially designated, centralized training centers for trainee teachers, who would spend half their time there, with the other half spent on school-based practice. A sharper focus accompanied this transition on raising professional and academic standards. The 1902 education act effectively transitioned to a college/university based training model, which continued until the 1980s.

In response to fears that the pendulum may have swung too far away from the practical teaching requirements in the last 30 years, there has been a return to a more school-based, on-the-job approach [102]. We can learn many lessons from this domain, given the considerable emphasis on practical competencies. One lesson may be that we should anticipate such debates and oscillations following any move towards a more competency-based computing education model. Even though training teachers and computing science professionals are two very different contexts, the proportionate focus on on-the-job, apprenticeship style training versus college/university training that the teacher training domain has converged on is still a helpful example.

Today, aspiring school teachers in England have multiple routes for getting the required qualification, but they are all assessed against the Teachers' Standards [123]. These standards were introduced in 2012 and define the minimum level of practice expected of trainees and teachers for being awarded the qualified teacher status (QTS). The standards are partition into two parts:

(1) Teaching, comprising eight standards.
(2) Personal and professional conduct made up of statements that define required standards of behavior and attitudes.

If we map these standards to the definition of competence adopted in this paper, then "Teaching" would map to knowledge and skills, while "Personal and professional conduct" is closest to what we are calling dispositions. Interestingly, the standard– especially its

Figure 6: Using UK Teachers' Standards [124]

second part–has a life beyond the training period. Schools are consistently and regularly measuring teachers against the standard throughout their careers. Figure 6 adopted from the Teachers' Standards [124] illustrates how the standard is used in practice.

There are multiple pathways to becoming a qualified teacher. To understand how teachers are trained towards and assessed against the Teaching Standards, we briefly look at one, the Postgraduate Certificate in Education (PGCE) [113]. PGCE is a one-year graduate program with at least 120 days of practical classroom experience in two schools or more; this is a reflection of the "swing" back towards on-the-job training. The program also includes academic study at a University, which addresses academic standards and professionalism; the lack of these was a concern back in the 19th century in the school-centered "pupil-teacher" program. In addition to University-based assessments, trainees need to compile a portfolio that provides evidence of meeting the Teaching Standards. Continuous feedback and tutoring mechanisms are in place to help the trainee teachers achieve all the elements of the Standards. The trainees become "newly qualified teachers" (NQTs) after the successful completion of PGCE. They still, however, have to undergo a 1-2 year "induction program" as NQTs. During this time, they receive exceptional support from their employer and continue to receive assessment against the Teaching Standards [125]. After meeting all Teaching Standards at the end of this induction, the trainees fully qualify as independent teachers. Assigned mentors play a crucial role in this journey.

There are similar frameworks for conducting and assessing teacher training in other countries around the world. While exact terminologies may vary, the focus on competency is a common theme. For example, in the US, the Council for the Accreditation of Educator Preparation (CAEP), the nationally recognized accreditor, sets standards for providers of teacher training [38]. The standards, among other requirements, include the provision of experiences, "...designed to develop candidate's knowledge, skills, and professional dispositions to demonstrate a positive impact on diverse students' learning and development."

Teacher training thus involves a clear focus to ensure the achievement of competencies and a training structure. This position is not surprising given the nature of the job requiring extensive interaction with children and young adults and a profession responsible for something as crucial as basic education. Moreover, a vast body of knowledge and precedent practice exists in this domain, spanning continents and centuries. Thus, it should prove to be a valuable resource for anyone considering restructuring computing education towards a more competency-based model, including dispositions, even if the context of computing science education and profession is qualitatively somewhat different.

3.4 Legal Education

Before 2014, the bar exam was the primary method of assessing law school graduates' knowledge to practice law in America. However, in 2014, the American Bar Association (ABA) published standards and rules of procedure (ABA Standards) [13] to be used in accreditation visits starting in 2016. These standards required law schools to "develop programmatic student learning outcomes and methods to assess those outcomes" [139, p. 373]. Moreover, they mandated that assessment of student learning must be both formative and summative [139]. Also, in 2014, *Educating Tomorrow's Lawyers* [65], an initiative of the Institute for the Advancement of the American Legal System, launched "Foundations for Practice," a groundbreaking project designed to, among other things, "identify the foundations' entry-level lawyers need to launch successful careers in the legal profession" [112]. What they found was that to be successful, new attorneys need more than legal skills: they also must be able to keep client confidentiality, be on time, honor commitments, have integrity, treat others with respect, listen attentively, respond promptly, be diligent, have a strong work ethic, and pay attention to detail [56]. These changes had a profound impact on legal education in the US from that time forward [139].

Today's standards recognize that for graduates to be successful in the legal field, they must possess certain character traits that go well-beyond legal skills [112]. The 2020-2021 standards [15] state that a law school shall establish learning outcomes that shall, at a minimum, include:

(a) Knowledge and understanding of substantive and procedural law;
(b) Legal analysis and reasoning, legal research, problem-solving, and written and oral communication in the legal context;
(c) Exercise of proper professional and ethical responsibilities to clients and the legal system; and
(d) Other professional skills needed for competent and ethical participation as a member of the legal profession.

Further, the 2020-2021 standards on curriculum [15, p. 18] mandate education in "professional responsibility that includes substantial instruction in rules of professional conduct and the values and responsibilities of the legal profession and its members." These "character traits" or "soft skills" are what we are now referring to as "dispositions."

3.5 Engineering

In the US and several other countries, ABET [2] accredits engineering programs. The accreditation standard has several criteria that define expectations for curriculum, faculty qualifications, facilities, etc. Criterion 3 (Student Outcomes) and Criterion 4 (Continuous Improvement) are most pertinent to this project. Student Outcomes "describe what students should know and be able to do by the time of graduation" [4] and are related to the skills, knowledge, and behaviors that students acquire in their program. Continuous improvement addresses the assessment of student outcomes and how a program uses the results for improvement. As specified in the Criteria for Accrediting Engineering Programs 2021-2022, these outcomes are a mix of skills (e.g., Outcome 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics) and behavioral (e.g., Outcome 7: An ability to acquire and apply new knowledge as needed, using appropriate learning strategies).

The Engineering Council accredits engineering programs in the UK based on standards and learning outcomes specified by the Accreditation of Higher Educations Programmes (AHEP) Standard [126], currently in its fourth edition. The standard consists of learning outcomes grounded in five engineering-specific areas of learning: science and mathematics, engineering analysis, design and innovation, the engineer and society, and engineering practice. Evaluation of programs is carried out by licensees of the Engineering Council, who represent specific areas of engineering and therefore assess learning outcomes concerning their specialty area. Learning outcomes are largely skills-based, for example, in the area of Engineering Analysis, "C3. Select and apply appropriate computational and analytical techniques to model complex problems, recognizing the limitations of the methods employed."

While AHEP, with its remit of accreditation of programs, does not appear to focus on dispositions in the learning outcomes, it does expect programs to provide some or all of the requirements that allow graduates eventually to register as an "Incorporated Engineer" (IEng) or a "Chartered Engineer" (CEng). Registration of individuals as an IEng or CEng is governed by the UK Standard For Professional Engineering Competence (UK-SPEC), which has a focus on *competence* and *commitment* [127]. These two terms together cover knowledge, skills, and dispositions view of competency, as discussed in this paper.

The standard defines *competence* as "...the ability to carry out a task to an effective measure. Achieving competence requires the right level of knowledge, understanding, skill, and a professional attitude." The requirement of *commitment* is described as follows: "Registered engineers and technicians demonstrate a personal and professional commitment to society, their profession, and the environment. They are required to show that they have adopted a set of values and behaviors that will maintain and enhance the profession's reputation."

The applicants are assessed against five generic areas of "competence and commitment":

(A) Knowledge and understanding
(B) Design and development of processes, systems, services, and products
(C) Responsibility, management or leadership
(D) Communication and interpersonal skills
(E) Professional commitment

These five areas of competencies are then divided into sub-areas. Finally, the standard describes them in detail and illustrates activities and evidence that could show their achievement.

Applicants for IEng or CEng have their competence and commitment assessed against this 5-dimensional framework through a peer-review process. The applicants must submit evidence against each sub-competency, and if a shortfall exists, the institution makes suggestions to address them. Once the application for registration has been successful, a commitment to maintaining and enhancing competence is expected by carrying out CPD (Continuing Professional Development) activities.

For our purposes, concerning the definition we are using for competence, we can map area A fairly directly to Knowledge, with areas B, C, and D loosely mapping to Skills, and regions C and E to Dispositions. As such, the highly structured framework of IEng/CEng professional registration for defining, assessing, and then maintaining and enhancing competencies serves as an instrumental case study.

Many other countries have accreditation boards in engineering as well. For example, in Japan, the Japan Accreditation Board for Engineering Education (JABEE) accredits engineering programs [68]. They also specify learning outcomes, although some of these appear to be more knowledge-based than skills- or behavior-based, such as "(c) Knowledge of mathematics, natural science and information technology, and ability to apply, and (d) Knowledge of the related professional fields, and ability to apply." The learning outcomes are made more specific by discipline-based standards. So, for example, the corresponding professional fields mentioned in outcome (d) are specified for each domain, such as chemical engineering or mechanical engineering.

In India, the National Board of Accreditation [85] handles engineering accreditation. Its basis is also learning outcomes, called Program Outcomes in this case. They specify these using skill-based terminology, for example, "Communicate effectively on complex engineering activities with the engineering community and with society at large, such as being able to comprehend and write effective reports and design documentation, make effective presentations, and give and receive clear instructions."

4 COMPUTING PEDAGOGIES: PRACTICAL PERSPECTIVES

This section introduces the high-level concept of signature pedagogies within the computing profession. The application of each dimension of the signature pedagogy to computing is then presented using a simple example to relate signature pedagogies to competencies. Section 5 then explores competencies that are important in computing, contributing to the signature of the computing profession.

As the signature pedagogy in the computing profession is determined by its surface, deep, and implicit structures, it needs consideration to embody these structures in the computing pedagogy. Using Shulman's triad structure [107], we identify the following characteristics of the professional computing pedagogy:

(1) Surface structure: Explicit competency statements, computing content knowledge, and relevant literature about the computing curricula are the basis of the concrete, operational acts of teaching and learning in a computing program.
(2) Deep Structure: Higher education pedagogical practices in computing focus on showing how to conceptualize and practice problem-solving and participate in sustained and deliberate practices of applying and integrating competencies through project-based and original work in a professional

setting. Their basis consists of the computing competency model of interleaved content knowledge, skill development, and professional dispositions in the context of specific goal-oriented tasks, including tasks in a professional setting.

(3) Implicit Structure: Affective goals, personal beliefs, attitudes, and values facilitated by educators and supported by pedagogical methods.

Table 4 outlines how computing educators foster competency-based student learning and the development of professional computing competencies on the surface, deep and implicit structure of their pedagogy. It applies Shulman's dimensions to the pedagogical practices of the computing disciplines guided by our collective experiences in computing education and practice.

Table 4: Signature pedagogy in the computing profession

Pedagogy structure	Mapping to students' professional computing competencies
Implicit structure of pedagogy	Focus on dispositional competencies: remain up-to-date on recent developments, literature, or controversies within the discipline and in the profession; learn new technology/tools/APIs on your own; take on professional challenges; engage to participate in social events related to the profession; volunteer to join round tables or panels; practice reflection; learn from feedback to formative assessments.
Deep structure of pedagogy	Focus on skills development and practical competencies: work on community/service-learning projects; apply self-regulated learning strategies; benefit from professional settings and organization-specific workflows, new platforms/technologies, educator/practitioner team-teaching, teacher/student job shadowing, didactic case consultations among teachers, cognitive apprenticeship, active learning, discussion of cross-cutting issues, ethics case studies.
Surface structure of pedagogy	Focus on knowledge and cognitive competencies: study using curricular lectures, exercises, seminars, etc. Read and study literature, worked examples, solve exercises and problems as instructed by educators.

4.1 Surface Structure Pedagogy Applied to Computing

In the surface structure context, it is worth reviewing the ACM Curricular Reports (see section 5.2) and the competency expectations in the workplace (see section 5.4). The curricular reports characterize the surface structure of computing education [64, 91, 110] very well and its shift towards competency-based learning and teaching. Moreover, the relevance of competence, performance and readiness for the professional practice [103] is explicitly addressed along with "meta-cognitive skills, demonstration of knowledge and understanding, interpersonal, intellectual and practical skills, and ethical values" [122]. The IT2017 report [103] reframes the focus on content in terms of competencies, including career readiness, affective goals, and the conceptualization of dispositional competencies. This recent shift indicates a transformation of computing education itself, as the notion of competencies is still a fairly new concept [103] in the computing disciplines. Similarly, the expectations of the workplace along with the respective competencies or skills frameworks imply, for instance, "levels of responsibilities" in addition to knowledge [117] and competencies as the ability to perform certain tasks with observable outcomes as in the European e-Competence Framework [67]. Including the professional dispositions into the surface structure of professional computing pedagogy is an appreciated and important development in preparing computing graduates.

4.2 Deep Structure Pedagogy Applied to Computing

The identification of signature pedagogies in computing is a relatively recent endeavor. Christie [32] points out that the computing education community is changing rapidly as it is a relatively young discipline. For example, we can consider computer science a field of study with a wide range of knowledge, skills, and dispositions in various domains (i.e., programming, operating systems, algorithms, artificial intelligence, etc.). Christie [32] discusses the elements of a computer science signature pedagogy concerning introductory and upper-level classes, where introductory courses do not always represent a discipline's signature pedagogy, or at least not the bigger picture.

As soon as computing students reach upper-level classes, the deep structure of the pedagogy changes, for instance, from individual assignments towards group work, projects, complex problem solving, and more extensive collaboration [32]. It is only from this point onward that students begin to think and act as if they are professionals in the discipline [32]. In fact, it is common practice in the computing profession to collaborate across disciplines and to work in teams throughout the process of analyzing and solving problems [32].

Additionally, Christie points out that most educators in the computing community do not share a common basis in educational preparation and concerning educational research of their discipline [32]. Nonetheless, the attitude towards pedagogical aspects of teaching and learning computing in undergraduate degree programs has shifted during the last two decades, with an increasing number of conferences, publications, and events devoted to computing pedagogy. These changes have resulted in a significant body of research and theoretical pedagogical frameworks to shape the discourse in computing education.

4.3 Implicit Structure Pedagogy Applied to Computing

The implicit structure of signature pedagogies addresses students' goal to act with integrity and express ethical values, beliefs, and attitudes that shape their professional identity. In computing, the focus on problem-solving is used for the organization of some professional dispositions by referring to the application domain, the problem, tools, the problem-solving process, the solution, and the clients (see section 2.4). We assume that students can learn and assess abilities within the limited duration of a baccalaureate program. The scope and quality of these formal educational processes, however, continue to be evolving.

By recognizing the professional dispositions component of competencies, we affirm that the competencies of interest are human competencies: they belong to and are developed and owned by human beings–learners and professionals-to-be in computing degree programs, and lifelong learners and professionals in the computing workplace. One cannot dissociate competencies from how disposed people are to perform them by engaging with others and through deep introspection into oneself.

4.4 Interaction between Signature Pedagogies and Competencies

An example of mapping learners' competencies to teacher's pedagogies in the case of Linux system administration appears in Table 5. The table illustrates how signature pedagogies, according to Shulman [107] and competencies intersect in the specific context of computing. The example shows Shulman's concept of pedagogical practice in computer science and students' competencies.

The surface structure pedagogies are typically encountered in the classroom, whether in a course module or multiple class instances of different courses with scripting and Linux-type operating system as part of the curriculum. The focus is on cognitive competencies specific to Linux system administration. An internship experience in Linux system administration may enable deep structure pedagogies. One example of dispositional competency is engaging in collaborative learning through pair programming to practice the responsibility of giving and accepting help from peers. Another example stems from understanding and appreciating the role of service aspects of system administration in an organization.

Ideally, knowledge, skills, and professional dispositions should all receive consideration when promoting and assessing competencies. In this sense, the third column is idealized and preferable to the first two columns. However, as one moves from the bottom left cell to the top right cell of the table, the emphasis changes from teaching to learning, and tenable assessment changes from purely summative to more formative.

5 COMPUTING COMPETENCIES

The computing disciplines' bodies of knowledge contain three parts: areas, units, and topics. These elements track recent developments in rapidly changing computing fields. The disciplines that produced curricular reports include:

- information systems (IS2010) [6]
- computer science (CS2013) [110]
- software engineering (SE2014) [12]
- computer engineering (CE2016) [64]
- information technology (IT2017) [103], and
- cybersecurity (CSEC2017) [91].

Except for IT2017, all these reports take a knowledge-based approach to undergraduate computing education. It is beneficial to note that these reports have migrated toward competency-based learning.

5.1 Background

It is helpful to see how educational computing begins to transform from knowledge-based to competency-based learning. In 2017, the Accreditation Committee of the European Quality Assurance Network for Informatics Education (EQANIE) published new program outcomes for accreditation of business informatics or information systems or related programs in consultation with members and stakeholders [52]. EQANIE describes program outcomes as "quality standards for knowledge, skills, and competencies that graduates of an accredited course should have achieved as the educational base for practicing their profession or for post-graduate studies." The European Commission's Digital Competence Framework 2.0 (DigComp 2.0) [30] has identified the critical components of digital competence in five areas: (1) information and data literacy, (2) communication and collaboration, (3) digital content creation, (4) safety, and (5) problem-solving.

The IT2017 project was the first of the ACM/IEEE baccalaureate curriculum projects to embrace the concept of competency as the primary characteristic of curriculum definition. The IT2017 report [103] heralded a shift from the knowledge area, knowledge unit, learning outcome, topic mindset, and redirected emphasis toward performance. The report stated that "competence refers to the performance standards associated with a profession or membership to a licensing organization" and that "assessing some level of performance is frequently used as a competence measure, which means measuring aspects of the job at which a person is competent."

Independently of IT2017, the MSIS2016 report [122] introduced competencies at the master's level. The report indicated that "competencies represent a dynamic combination of cognitive and metacognitive skills, demonstration of knowledge and understanding, interpersonal, intellectual, and practical skills, and ethical values." Furthermore, the Software Engineering Competency Model from 2013 defined competency as the "demonstrated ability to perform work activities at a stated competency level" [111]. These three publications suggest that competency combines knowledge, technical skills, and human behavior within a computing context. Similar themes emerge within the popular literature [37, 45, 46, 89].

5.2 Computing Curricular Reports

5.2.1 Information Technology Report. The Information Technology IT2017 report [103] articulated competency-based learning. Instead of continuing the tradition of framing curricular guidelines based on a body of knowledge approach, the report adopted a competency-based approach because almost all graduates from information technology degree programs enter industry and the workplace. Competency relates to workplace performance; that is, what a graduate's preparation would bring to a job. The report reflected career readiness and professional development. That is why it proposed a working definition of competency and made the need to consider dispositions in combination with knowledge and skills explicit and clear. These three interrelated dimensions of competencies had the following interpretations.

The knowledge dimension, labeled "know what", designates content mastery and understanding of core concepts. Skills refer to strategies and capabilities that develop over time through deliberate practice and interactions with others. Skills also require engagement in higher-order cognitive activities and become the "know how" dimension of competency. Finally, dispositions encompass socio-emotional skills, behaviors, and attitudes that characterize the inclination to carry out tasks and the sensitivity to know when and how to engage in those tasks [95]. This "know why" and "know yourself" dimension of competency is often a basis for industry hiring and appeal, but also the most challenging for computing programs to adopt competency-based learning in their curricula.

Table 5: Mapping learner competencies and teacher pedagogical practices using a Linux system administration example

	Knowledge	Knowledge, Skills	Knowledge, Skills, Dispositions
Implicit structure	Teacher prompts discussions on social issues relevant to system administration; introduces selected ethics case studies; uses think-pair-share as an effective collaboration practice to learn concepts.	Teacher challenges learners to define and exemplify ethical and malicious hacking; stresses the need to protect systems with regular updates; assigns team projects requiring a plan and demonstration of how to do regular system updates and security patches in an organization.	Teacher motivates and guides learners in a community project requiring system administration expertise in the nearby school district; shares own experiences in the profession; asks learners to answer situational interview questions related to adaptability and empathy using evidence from their internship and team project experiences.
Deep structure	Teacher supervises an internship or project which requires a new scripting language. Learners analyze similarities and differences among scripting languages.	Teacher supervises an internship or project involving the use of tools with which the student is not already familiar, along with completely new organizational workflows. Learner practices critical reasoning and decision making, information literacy using new sources, and communication with the internship supervisor.	Teacher draws attention to self-direction, initiative, and perseverance competencies, and their role in developing new skills; designs reflection prompts to help learners acquire desirable elements of professional conduct such as conflict resolution.
Surface structure	Teacher curates content related to Linux fundamentals and bash scripting fundamentals; designs learning progressions; assigns appropriate level "check your understanding" and coding exercises with automatic feedback.	Teacher models system administration tasks using worked examples; assigns practical problems students do in-class using pair programming.	Teacher presents fundamentals of effective communication, discusses service aspects of system administration

5.2.2 The CC2020 Report. The Computing Curricula 2020 (CC2020) project [35] is an initiative launched jointly by several professional computing societies. The CC2020 report summarizes and synthesizes curricular guidelines for computing academic programs that grant baccalaureate-level degrees. In addition, the report provides a portfolio of resources helpful to students, industry, government agencies, educational institutions, and the public globally. It also aims to reflect state-of-the-art computing education and practice and provide insights into the future of computing education for the 2020s and beyond. The participating societies engaged a global task force of fifty individuals from twenty countries and six continents representing academia, industry, and government organizations.

As CC2020 describes, knowledge-based learning involves a collection of knowledge areas for a discipline subdividing them into knowledge units. Each unit contains a set of learning outcomes often associated with a group of topics. Teachers transfer knowledge to students through experience, notes, textbooks, or other means. Students then expect to work toward demonstrating what they have learned. Although almost all universities worldwide produce graduates through knowledge-based learning, the CC2020 report suggests that this learning paradigm may no longer be appropriate for the computing field. Technology now influences new ways of learning that employ many non-traditional learning formats, thereby challenging traditional methods. Furthermore, universities can produce computing graduates who may be intellectually able but face challenges in workplace settings. Therefore, CC2020 concludes that knowledge-based learning may be less effective in a contemporary environment and may not be helpful when a changing world demands technical skills and human behaviors in computing and engineering.

CC2020 [35] adopted a definition of competency as comprising knowledge, skills, and dispositions within the performance of a task. The *knowledge* aspect of competency is a regular inclusion in computing coursework in colleges and universities. However, the meaning and application of *skill* and *disposition* have had significantly less focus. As with the IT2017 report [103], knowledge is the "know what" dimension; skills are the "know how" dimension and dispositions are the "know why" dimension. The task is the construct that frames the skilled application of knowledge, which makes dispositions concrete. Figure 5, which was seen earlier, illustrates this CC2020 meaning of competency.

5.2.3 MSIS2016 Report. The 2016 Master of Science in Information Systems (MSIS2016) report [122] indicates a curricular model identified by a set of graduate competencies. In this context, the term "competency" refers to graduate-level ability to perform specified tasks successfully. Competency becomes an integrative concept that brings together graduate-level knowledge, skills, and attitudes. The report also identifies awareness, novice, supporting (role), and independent (contributor) as four category attainment levels. The MSIS2016 curricular model suggested that programs should not expect to prepare students to attain competencies at the same level in all competency categories. Professional profiles have diverse needs that a program desires its graduates to achieve. That is, programs should determine the level at which their graduates should attain each competency category.

5.2.4 IS2020 Report. The 2020 Information Systems (IS2020) report [73] is a modern update of the IS2010 report. The report addresses competency modeling the CC2020 approach. The IS2020 report attempts to align a prose competency statement with the "know what, know-how, know why" of the knowledge, skills, and dispositions components of the competency that fulfills the task. Using a modified competency template, the three principal features of competencies include (a) a prose task statement and title,

(b) a knowledge-skills-dispositions structure, and (c) competency metadata. The IS2020 model curriculum's competency-based architecture establishes some of the hierarchical categorizations of the MSIS2016 model curriculum to make the aggregate set of competencies easier to navigate. The model's highest level comprises realms where the information systems competency realm divides into competency areas, which decompose to competency categories and ultimately to competencies.

5.2.5 DS2021 Competencies Report. The Computing Competencies for Undergraduate Data Science Curricula (DS2021) [40] describes a competency model guided by IT2017 [103] and CC2020 [35], as well as CS2013 [7]. The DS2021 report sets up a Competency Framework for describing various data science knowledge areas, referring to it as the Body of Knowledge. The knowledge areas include AI, Big Data Systems, Analysis and Presentation, Computing and Computer Fundamentals, Data Mining, and Professionalism. It localizes both skills and dispositions within these knowledge areas. As DS2021 did not intend to be a full set of curricular guidelines, this report only reviewed this document sparingly. A future complete Data Science Curricular Guidelines is likely to provide a strong direction for competency-based learning.

5.3 Other Computing Competency Frameworks

There have been other attempts to express computing curricula from a competency-based perspective. Two of the earliest were the software engineering competency model and the software assurance competency model, dating back to 2013.

5.3.1 Software Engineering Competency Model. The software engineering competency model (SWECOM) [111] describes software engineers' capabilities in developing and modifying software-intensive systems. The model specifies skill areas, skills within skill areas, and work activities for each skill. Also, activities occur at five levels of increasing proficiency. The SWECOM suggests that competency is a combination of knowledge, skill, and ability. The competency model includes cognitive attributes, behavioral attitudes, and technical skills. It also defines competency levels to be that of a technician (able to follow instructions), an entry-level practitioner (can assist in performing activities with some supervision), a practitioner (able to perform actions with little or no supervision), a technical leader (capable of leading and directing participants), and a senior software engineer (capable of creating new processes and modifying existing methods). Competency is central to the model and provides a modern view to generate excellence in computing education.

5.3.2 Software Assurance Competency Model. The 2013 Software Assurance (SwA) Competency Model [60] specifies competency as a representation of the set of knowledge, skills, and effectiveness needed to carry out the job functions associated with software assurance. As with the Software Engineering Competency Model, five proficiency levels include a technician, professional entry-level, practitioner, senior practitioner, and expert. These competency levels distinguish different levels of professional capability relative to knowledge, skills, and effectiveness. In addition, the report identifies representative activities which demonstrate attainment of each level of competence for each knowledge unit within a knowledge area.

The competency level identified as professional entry-level indicates explicitly that the individual "possesses application-based knowledge and skills and entry-level professional effectiveness, typically gained through a bachelor's degree in computing or equivalent professional experience." This provides a goal for undergraduate education in software assurance and acknowledges that degree programs are unlikely to deliver higher levels of competence.

5.4 Workplace Competency Expectations

When recruiting computing graduates, employers are not always looking for theoretically-grounded graduates whom they can train to contribute to their company. Instead, in many cases, particularly with small businesses, employers are looking for a rapid return on their investment in a new graduate; they need to know what they can do in the real world before offering a graduate a job.

Doing things in the real world, where the consequences of any errors or omissions can matter, is not the same as demonstrating knowledge, skills, and dispositions within the safety of an educational environment. Consider the difference, for example, between "flying a flight simulator" and "taking control of a real plane cockpit, with real passengers on board".

Defining the tasks and activities needed in the workplace is often articulated within a competency or skills framework, which seeks to describe the activities independent of context, technology, or methodology. This section provides a brief introduction to three of the leading competency frameworks for computing.

5.4.1 The iCD Skills Framework. The "i Competency Dictionary" (iCD) framework is developed, maintained and promoted by the Information Promotion Agency (IPA) [69]. The IPA is an organization governed by the Ministry of Economic, Trade, and Industry of Japan. As such, this framework is "pushed" to the industry users rather than developed by industry. The IPA also manages the IT Engineer Examination (ITEE) taken by approximately 600,000 applicants each year. The ITEE has 13 examination categories aligned with four task areas of the iCD. The iCD framework is used predominantly in Japan and by Japanese companies. Still, it is in use in over 24 countries, with Hitachi being one of the largest employers utilizing iCD with a workforce of over 20,000 people. As of September 2017, over 1,000 companies had licensure.

The iCD framework leverages existing Bodies of Knowledge such as the Software Engineering Body of Knowledge (SWEBOK) [22], Project Management Body of Knowledge (PMBOK) [98], and the Body of Knowledge of Software Measurement (SQuBOK) [105]. Consequently, it does not attempt to reinvent the wheel but rather leverages existing, well-accepted bodies of knowledge (BOKs) to underpin the framework. The BOKs typically define knowledge that an IT professional could expect to have and are often used by higher education institutions to guide curriculum decisions. However, there remains a gap between the knowledge expressed in the BOKs and the expected competencies in the workplace. The iCD attempts to bridge this gap.

The iCD framework utilizes a layered approach to defining tasks performed in the workplace and the skills needed to complete those tasks; these are maintained in a task dictionary and a skills dictionary, respectively. The skills dictionary also contains soft skills such as creativity, execution and practice, and communications.

Each of the task and skills dictionaries begin with a definition of high-level tasks and skills (Layer 1 - Major Task or Skill)) respectively. Each task or skill in Layer 1 partitions into finer granularity tasks and skills in Layer 2, and then each task or skill in Layer 2 partitions further into even more granular tasks and skills in Layer 3. The task dictionary continues to identify even finer-grained tasks for each task in Layer 3. Still, the tasks in Layer 4 (Assessment Items) help guide an employee's annual evaluation by identifying typical attributes of a task in Layer 3 (Minor Tasks). The task dictionary identifies upwards of 2,000 assessment Items.

The skills dictionary identifies five skills categories: methodology, technology, related knowledge, enterprise IT human skills, and specific skills. Layer 4 of the skills dictionary maps to the various BOKs. Layer 3 of the skills dictionary identifies 84 skill categories. Each skill is given a Likert-like score between 0 and 4 during evaluation. Scores of 5-7 are defined across each skill category and used to evaluate the social contribution of the IT profession relative to that skill. The score a professional earns for each skill at Layer 3 broadly defines an individual's skill set.

A task × skill correspondence table identifies the skills necessary to accomplish each task. However, given the number of tasks and the number of skills identified, this task *times* skill table is potentially vast and unwieldy. A task × skill table with 500 Layer 3 task elements and 400 Layer 3 skills would have 20,000 cells. Even though not every job requires every task and every skill, the table is still demanding to complete. It is also challenging to view the table and quickly appreciate the competency level of each employee.

The iCD seems primarily aimed at HR since it measures the performance of IT professionals within the organization. This evaluation typically occurs on an annual basis using the Layer 3 tasks (Minor Task Category). However, Layer 2 tasks (Middle Task Category) are useful to reduce the overhead and workload in evaluating employees. With such a fine-grained model for assessing an IT professional's competency, it remains unclear how a degree program could effectively utilize the iCD to develop competent graduates that are workforce-ready immediately upon graduation.

Maintenance of the iCD framework is critical for its continued relevance. The computing landscape changes rapidly with the introduction of new technologies such as IoT, cloud computing, and deep learning finding their way into organizations. These updates occur manually, but the English version lags behind the Japanese version by one year. The IPA also makes an Application Service Provider (ASP) available to support iCD utilization only in Japanese. The regular update of the framework also poses challenges for any degree program utilizing the framework to guide curriculum development. There is typically a 3-4 year lag between new skills identified and institutions able to produce graduates with that skill. The sheer size and complexity of the iCD framework also pose a challenge to degree programs as there is only a limited amount of space within a degree program to introduce and develop the competencies within a student. Degrees are not infinitely expandable. Hence it is unlikely that any institution will be able to address all of the competencies. The iCD framework does little to help institutions identify those competencies that are of most value to the industry.

5.4.2 The SFIA Skills Framework. SFIA [117] describes professional skills and competencies required across the broad field of computing, including information and communication technologies, digital transformation, and software engineering.

In the current version (v8), SFIA recognizes more than 120 technical skills. Note that this use of "skill" is different from that used in other frameworks, such as i-CD] that employers have indicated are important for their IT functions [119]. SFIA also defines seven levels of responsibility [118] with which these skills may be deployed, depending on an individual's experience and enterprise needs. The levels of responsibility range from follow(1), assist, apply(3), enable, ensure/advise, initiate/influence to set strategy/inspire/mobilise(7). Each level of responsibility is characterized by a set of category descriptors: autonomy, influence, complexity, knowledge, and business skills. Many of the characteristics identified correspond to dispositions articulated in CC2020.

Typical tasks and activities relate to each skill defined at a particular level. The framework is essentially a two-dimensional matrix with the rows representing skills and the columns representing the levels of responsibility. Since not all skills are necessarily relevant at each level of responsibility (strategic planning, for example, is unlikely to be relevant for a novice recruit), skills are defined only at levels that are generally appropriate. Thus, a person can demonstrate competence in a skill at a particular level by performing the tasks and activities set out in the framework and showing the level's generic responsibility characteristics.

SFIA does not seek to define complete jobs or roles since workers in different contexts may need different combinations of SFIA skills. Typically, a job or role would combine a small number of skills at similar levels. So, for example, a graduate recruit should probably be aiming at developing competence at level 3 "Apply" (the practitioner level) in two or perhaps three skills.

Navigating 120+ separate skills can be challenging, but a hierarchical grouping of the skills mitigates this into six categories and 17 sub-categories. There are also half a dozen focused views that draw together subsets of the skills that are relevant for domains such as Big Data/Data Science or Information and cybersecurity [120].

SFIA is now the most widely adopted skills and competency framework, with users in over 180 countries ranging from small employers, through professional bodies and multi-national corporations to public sector organizations and governments [117]. It is the reference framework for IP3, which sets standards for computing professional bodies to certify individual professionals (IP3P) and technologists (IP3T) [115]. SFIA has been translated from English into 11 languages, with more planned. Since its launch in 2000, the document was updated and maintained by its global community on a three-year cycle through an open and collaborative process.

The SFIA Foundation is non-profit, and SFIA is free to use for most individual and non-commercial applications. However, a modest annual license fee for commercial use contributes to managing the updates and producing supporting materials.

5.4.3 e-CF. The European e-Competence Framework was developed based on input from stakeholders in the European IT sector. Its first publication occurred in 2008. This alternative to SFIA is aimed at European IT professionals. Like SFIA, it is competency-based, providing 41 competencies and five levels.

A competency is defined, in e-CF 3.0, as a "a demonstrated ability to apply knowledge, skills and attitudes for achieving observable results." It defines a skill as the "ability to carry out managerial or technical tasks," and an attitude is defined as a "cognitive and relational capacity," tying together skills and knowledge. Examples of knowledge include knowledge of programming languages, or testing techniques, or ICT service delivery requirements. In addition, competencies are grouped into areas that correspond to an IT lifecycle view: Plan, Build, Run, Enable, and Manage. The framework also specifies five proficiency levels for each competency, as well as knowledge examples and skills examples, which provide more factual information for each competency, tied to the terms "knowledge" and "skills" in the definition of competency. The proficiency levels are e-1 Associate, e-2 Professional, e-3 Senior Professional/-Manager, e-4 Lead Professional/Manager, and e-5 Principal. Not all competencies are associated with each of the five proficiency levels.

The 41 competencies in e-CF cover an extensive range of business/organizational areas, including Sustainable Development and Technology Trend Monitoring in the Plan area, Application Development, and Testing in the Build area, user support and service delivery in the Run area, information security strategy development and sales management in the Enable area, and risk management and business change management.

This report has focused on undergraduate computing majors, which typically contain a much narrower set of topics. One can reasonably expect a graduate of such a program to have learned only a small subset of these competencies. For a computer science or software engineering major, for example, a graduate would most likely have acquired competencies from the Build area: application development, component integration, testing, and documentation production. An MIS graduate may have developed competencies from the Plan area: IS and business strategy alignment, business plan development and architecture design, and competencies from the Manage area such as project and portfolio management, risk management, and process improvement. In addition, it may not be possible to develop some of these competencies in a classroom setting. For example, competencies such as user support, service delivery, and solution deployment may not be teachable in an academic environment. Thus, the e-CF seems more suited to the needs of IT organizations that have experienced employees than to the needs of academic departments seeking to integrate the assessment of a smaller set of competencies. Furthermore, although the extensive lists of knowledge and skills examples provided for each competency are very useful, there is no mention of assessment tied to these lists.

5.4.4 Graduate Competency and Employment. The purpose of assessing graduate competencies is to communicate to prospective employers what graduates have demonstrated that they can do in a real-world setting to facilitate the recruitment process.

All three of the frameworks described in Section 5.4 seek to describe what tasks and activities employers need their staff to perform, as well as a range of other qualities corresponding to professional dispositions. However, the frameworks differ in three key ways: availability, granularity, update frequency. Communicability is a consequence of these three. In addition, it is worth noting that i-CD, e-CF, and SWECOM are "pushed" by the relevant professional bodies or governments, whereas users developed SFIA for users.

i-CD is available in English and Japanese but is used primarily in Japan. It is updated annually, but it is unclear how much change there is in the higher hierarchies of tasks or skills. It may be difficult to ensure that graduates demonstrate all tasks within a second- or third-level entry in either hierarchy. Communicating student achievements against such a granular structure could prove a significant challenge.

e-CF is available in a range of European languages but has yet to build an ecosystem of users and support structures outside the EU. Nevertheless, a few European higher education institutions have recently adopted it as a target against developing curriculum. e-CF is the least granular of the three frameworks. However, with only 41 roles defined to date, each is broad. Yet, a single role may be too demanding (broad) and too narrow (specialized) for many students.

SFIA is available in 12 languages, including English, and is used globally, despite the modest license fee required for commercial use. Updated triennially, as is e-CF, it is now attracting interest in higher education to frame curricula.

Some try to argue that a three-year update cycle means that neither SFIA nor e-CF can include the "latest techniques." However, this overlooks the level of abstraction inherent in both frameworks: being both technology and vendor-neutral, they also express tasks and activities in a way that neither excludes new techniques nor preserves superseded approaches.

5.5 Communicating Computing Competencies

For several decades, bodies of knowledge and curricular recommendations for computing have offered a common language and vocabulary for describing what students should know when they graduate. Similarly, for employers, IT skills and competence frameworks have provided a common language and vocabulary for describing what people can do. The expansion of curriculum recommendations in IT2017 and CC2020 from a focus solely on knowledge to include "competency" represents a significant step towards bridging the gap between these two disparate "common languages." A major motivation for expanding these recommendations to include competency is to prepare students better for the workplace.

Given this worthy goal, it is then crucial to express students' achievements that are understandable to potential employers. Unfortunately, the CC2020 model of competency, while a significant advance for educators, is presented from an academic perspective that may not promote communication with employers.

Employers have developed a range of skills and competency frameworks for use in the workplace, including those discussed earlier. In addition, some larger employers have their internal competency frameworks, which share many characteristics with the "public" frameworks. Earlier attempts to incorporate employers' needs into curriculum models resulted in the SWECOM and SWACOM frameworks, focusing on subsets of computing and IT.

Suppose the goal is to communicate to potential employers which competencies a graduate has demonstrated. In that case, key issues will include the language to use and the number of competencies to describe. This duality suggests the use of one of the workplace frameworks, as outlined in Section 5.4.

A framework offering appropriate levels of abstraction and granularity best supports communication so that a student's "competency transcript" might include up to a dozen or so entries. Of the workplace frameworks described here, SFIA would appear to offer a better level of abstraction for this purpose in comparison with the other two industrial frameworks. In a three- or four-year baccalaureate degree program, students should be able to gain the knowledge and skills to underpin up to a dozen SFIA skills at Levels 1, 2, and 3. Given appropriate workplace opportunities, competence in one or two: this number of achievements should be readily communicable to prospective employers [27]. The SWECOM and SWACOM models seem to have comparable granularity and could be appropriate. However, they have some restrictions in scope compared with the industrial frameworks.

This report has explored how to smooth students' transition from education to employment by suggesting how to realize the ideas in CC2020 and how to express the resulting student competencies in terms that correspond to workplace competency statements. Section 4 explored pedagogies to develop competencies in computing. In addition, this section has explored the range of models and frameworks for describing competencies. Finally, section 6 discusses ways to assess the various aspects of competency, both in a teaching context and also in the workplace.

6 ASSESSING COMPUTING COMPETENCIES

We previously presented an integrative model of competency and a profession-driven model of pedagogy. We also discussed teaching and learning competencies in different professional study programs, such as medicine, law, and teacher preparation, and we included perspectives on competency-based learning in computing programs. This collection of ideas leaves open the question of ways to evaluate or assess competency. Specifically, the questions are:

- How is the competency of a computing baccalaureate graduate determined?
- Given competency X, what learning or performative tasks and in what setting produce evidence in support of the attainment of competency X? What artifacts and processes characterize the tasks?
- What assessment methods are used to interpret assessment data obtained from students performing the required tasks in the given setting? What instructional design tools should educators utilize to assess students' competencies and provide meaningful, clear, and targeted feedback?

Educators define and evaluate student outcomes of a program of study to determine the effectiveness of the program. The process of evaluating student outcomes takes into consideration the assessment of student learning at the course level. In addition, employers evaluate worker performance, particularly for promotion or advancement. The "act of judging or deciding the amount, value, quality, or importance of something, or the judgment or decision that is made" is a dictionary definition of assessment [29]. In an educational context, assessment generates data of student learning and interprets that data to determine what a student knows, what a student can do, and what a student aspires to be.

6.1 Traditional Assessment Approaches

A three-pillar view of assessment [87, p. 44] ties the proposed integrative model of competency and model of profession-driven pedagogy to the following assessment activities

What to assess—based on the integrative model of competency

- Formulate competency statements at the appropriate granularity level (program of study, course, module, assignment), inclusive of all competency components and mindful of the competency task and setting
- Define criteria and standards of the expected student performance

How to observe, assess, and get assessment evidence—based on the model of profession-driven pedagogy

- Design observable learning activities that develop stated competencies through performative tasks
- Explain to students why they engage in those learning activities and how the required tasks tie to which competencies
- Collect evidence from student participation.

How to interpret the assessment evidence —based on clearly defined criteria and standards

- Primary purpose of evaluating assessment data is to give student feedback and improve student learning
- Include formative or forward-looking assessment to help students develop competencies, in particular dispositional competencies.
- Tie feedback and interpretation of student work to competencies and communicate that to students.

Assessment evidence can be direct or indirect. A direct assessment provides concrete evidence of whether students have specific knowledge, perform a designated task, demonstrate a certain quality or skill in their work, or hold a particular value. An indirect assessment provides evidence of students' perceptions of their learning and learning environment or characteristics associated with learning [128]. Direct assessments include course-embedded assignments and tests, portfolios, standardized examinations, pre-tests and post-tests, and supervisor evaluations; indirect assessments include surveys, focus groups, and interviews. Direct assessments evaluate student competence and actual performance, whereas indirect assessments evaluate perceived learning, apparent performance, or supposed capability.

Viewing assessment as a measurement of student learning is limiting. It may have detrimental effects if it overlooks the role of "assessment for learning," that is, to improve student learning and teachers' pedagogies. Measuring how much students have learned after a learning experience, or summative assessment, is "backward-looking" assessment: it examines whether the student has learned x or not. More supportive of student learning is formative assessment or "forward-looking" assessment [51, p. 94] that charts the road forward by answering the question: "given that the student has learned x, is the student prepared to do y?" The assessment best suited to competency-based learning arguably is "authentic performance", which Wigigns [135] frames as authentic tasks coupled with performer-friendly feedback. Authentic tasks "anchors testing in the kind of work people do, rather than merely eliciting easy-to-score responses to simple questions" [135, p. 21]. Feedback is an integral part of an assessment for improving student learning. Fink outlines four characteristics of authentic, forward-looking feedback: it is immediate, frequent, based on clear criteria and standards, and communicated with empathy and in a friendly manner [51, p. 106].

A common, practical assessment tool is the rubric: a scoring guide communicates assignment expectations and scores student performance against these expectations. Benefits include [129]:

- Clarifying assignment components, expectations, and criteria for the instructors and students
- Providing more consistent student-to-student assessment
- Allowing for timely and detailed feedback to promote student learning.

Rubrics have helped assess content knowledge for decades. They should also help assess skills and dispositions to assess competency, as suggested in the following sections.

6.1.1 Assessing Content Knowledge. Assessment of content knowledge is the most straightforward of the three components of competency, both in computing and general education. The tasks used for assessing content knowledge are relatively easy to design, grade, and scale, as they primarily consist of students taking quizzes or exams. However, it is very tempting to fall into the trap of using the assessment of content knowledge as a proxy for assessing other components of competency.

The challenge in devising a competency-based assessment is not how to assess content knowledge—most teachers know how to do this—but how not to over-assess it at the expense of evaluating skills and dispositions. For example, it is essential not to guide syllabus design by subject matter coverage to avoid the over-assessment of content knowledge. As Gardener notes, "The greatest enemy of understanding is coverage—I can't repeat that often enough..." [55]. Although content knowledge does require some degree of assessment, the question is: where should the focus be?

Threshold concepts are proposed as the overarching abstraction for calibrating how much content knowledge and assessment should occur. Cousin defined threshold concepts as the key concepts in a domain that form the basis for future content knowledge development [39]. A focus on teaching and assessing only threshold concepts mitigates the tendency to "stuff" the curriculum with content. In addition, it will help teachers avoid assessing students against a large body of potentially irrelevant content.

6.1.2 Assessing Skills. Assessing skills is not as simple as evaluating mastery of concepts. Here, it is essential to ensure clear quality criteria for interpreting to what extent students demonstrate the performance task's skills expectations, which contextualizes the competency. As discussed in Section 2.3.2, skills involve applying content knowledge and engaging in processes that require strategies, practice, and other cognitive and dispositional components of the competency. Thus, for the assessment of skills to be valid, it must measure the "know how," which goes beyond the assessment of content knowledge only (the "know what").

Taking conventional exams is an inappropriate task for assessing skills. Work required by take-home assignments and projects is better suited to provide directly observable evidence to evaluate skills. Teachers can frame the performance task as an authentic problem to test expected skills and use rubrics to spell out expected criteria to measure student performance. A high proportion of skill-oriented tasks emphasize skills learning and become a source of evidence for skill assessment. The authors propose considering problem-based learning (PBL) activities to target skill development in students. PBL enhances learning by getting students to solve problems rather than limiting their education to a "hierarchical list of topics" [62] and learning of topical knowledge. PBL tasks mimic the "real-world" experience of computing graduates have in the workplace. There is a precedent for PBL adoption in software engineering education [42]. Although developed independently, a closely-related pedagogical strategy is project-oriented (PO) learning. It is now combined as project-oriented problem-based learning (POPBL), which aligns remarkably well with the learning and assessment of skills. Dolog et al. [44] note:

> "From a student perspective, POPBL means working with real-life problems, which meets students' interests and enhances their motivation. Additionally, POPBL further develops the students' ability for critical thinking; develops their problem-solving skills and project management skills; improves communication, negotiation, and conflict resolution skills; and strengthens analytical and methodological skills, that is, transferable skills."

As discussed in section 2, Bloom's taxonomy focuses solely on cognition. Simpson's and Miller's hierarchies both imply repeated practice to achieve the higher levels. Bowers [23] argues that it is possible to address the skills gap observed by employers by pivoting from "cognitive competence" captured in Bloom's taxonomy to "operational competence" expressed through Simpson's hierarchy [108]. Assessment of skill development requires some framework that captures the skills needed in a structured manner. Such frameworks should derive from, or at least align with, the computing industry's expectations and inform profession-driven pedagogies in computing education.

Hayashiguchi et al. [58] suggests one approach to using an industrial skills framework to design a curriculum and its assessments. The approach requires a "task dictionary"—a collection of tasks needed for an IT business—and a "skill dictionary" which are the skills necessary to perform specific tasks. The two lists can then be combined as a Task × Skill matrix, as indicated in Table 6. Such a matrix captures the skills required to perform specific tasks. For example, in the Task 3 row in Table 6, the circles under Skill 1 and Skill 6 indicate these are required to achieve Task 3. The utility of such a matrix is that one can locate skills needed for specific tasks and—more pertinent for the academic context—identify tasks that require (and hence assess) particular skills.

Several frameworks could create the "skill dictionary," discussed in Section 5.4: The Japanese "i Competency Dictionary" (iCD) framework, SFIA [117], which has global usage, and the European e-Competence Framework (e-CF), aimed specifically at European IT professionals. Once choosing a framework, possibly adapted for the academic environment, we could use a Task × Skill matrix to identify tasks requiring the skills in the dictionary, the process of learning these skills, and assessments designed around those tasks.

6.1.3 Assessing Professional Dispositions. The assessment of professional dispositions is perhaps the trickiest of the three components of competency. The assessment process is challenging due

Table 6: Example Task × Skill matrix [58]

		Skill List						
		Skill 1	Skill 2	Skill 3	Skill 4	Skill 5	Skill 6	Skill 7
Task List	Task 1	◦		◦				
	Task 2		◦			◦		◦
	Task 3	◦					◦	
	Task 4			◦				
	Task 5				◦			◦
	Task 6		◦			◦		

to the contextualized nature of competencies and the specification of standards or expectations for meeting dispositions. According to Weinert [134], the range of performance tasks and their settings define competencies. One can assess competencies and communicate effective feedback by engaging students in authentic tasks that "supply valid direction, intellectual coherence, and motivation for day-in and day-out work" of competency learning and development [135, p. 21]. The more realistic the tasks, meaning the more they replicate real-world situations, the more students experience behaviors that manifest dispositions.

A suitable way to have students learn and exercise dispositional competencies is to give students the opportunity for work-based learning (WBL). Some computing degree programs incorporate a significant element of WBL, such as the graduate apprenticeship programs in Scotland [121] or the co-op programs in Canada [59]. However, a more common approach is to have credit-bearing internships during the academic year or term breaks.

Placing and assessing students in a workplace setting is not always practical or even possible, as discussed in Section 7.3. In such cases, universities can revert to simulated environments in a laboratory setting to assess dispositions. Teachers can also emphasize group work or teamwork in such environments to mirror real-life situations more closely. Teachers and peers can use appropriate rubrics to evaluate students against different dispositions.

Table 7 is an example of such a rubric. The eleven dispositions are from the competency chapter of the CC2020 report. For example, assume the experience is a laboratory session in circuit analysis where students work in four-person groups. For each student, the instructor completes the rubric heading as a record of the session's assessment. The instructor would then check the level of attainment for each disposition. After completing the session, the instructor would convert each checkmark to a number and compute the average dispositional score. In this way, the instructor could calculate dispositional scores for each group in the laboratory.

The instructor may modify the eleven dispositions from the CC2020 report or add other dispositions of particular interest based on the learning task and its setting.

6.2 The Importance of Considering Context

The integrative model of competency 2.6 stresses the need for content knowledge to underpin the application of necessary skills with appropriate professional dispositions in the context of performance tasks and their settings.

The context has two aspects: the performance task and the setting to carry out the task. The range of tasks is broad and diverse. Preferential emphasis on a specific competency component shapes

Table 7: Rubric example for disposition

Disposition	Score					Score Value
	0	1	2	3	4	
Adaptable		✓				1
Collaborative				✓		3
Inventive					✓	4
Meticulous		✓				1
Passionate				✓		3
Proactive					✓	4
Professional				✓		3
Purpose-driven	✓					0
Responsible			✓			2
Responsive				✓		3
Self-directed				✓		3
Totals	1	2	1	5	2	
	Average Score					2.45

the tasks students demonstrate their learning and development of the competency. For example, ordinary tasks to practice and develop cognitive competencies are examinations and working on problem sets. In this case, the setting is in or outside class, proctored or open resources, primarily individual, or, if formative, might include peer feedback. To exercise skills that demonstrate strategies and processes encountered in the workplace, conducting authentic projects is more suitable. The setting can be at school or the client's site and may involve professional tools and platforms and external audiences, such as industry experts or workplace supervisors.

Section 6.1.3 argues that it is best to assess dispositions in a work-based learning environment. From the perspective of prospective employers, a person can demonstrate competencies only by meeting four conditions: (1) in a real-world setting by (2) completing the specified tasks, (3) repeatedly, and (4) over an extended period. That is, a single demonstration of a task is insufficient, even if it deploys appropriate content knowledge and the needed skills with impeccable dispositions.

An alternative articulation of "competency" is set out in ISO 24773 [66, Section 5.5]:

> "Professional competency indicates more than the ability to exercise only one specific skill or to produce a simple work product – it indicates that an individual succeeds consistently in achieving the objective, and is reliable at the professional level."

The following section presents one possible approach to assessing real-world competency for students in a work-based environment. In this approach, assessing genuine competency is conditioned by offering students work-based opportunities, such as internship placement, with a realistic prospect of reviewing and improving their achievements.

6.3 Assessing Professional Competency

Skills and competency frameworks such as SFIA and iCD were developed to meet a real need in the industry - to state what an individual is competent to do. It follows that such frameworks are only of value if there are some means of assessing individuals' competence against the skills described in the frameworks.

Table 8: iCD diagnostic criteria for task completion [69]

Diagnostic Level	Diagnostic Criteria
L0	No knowledge or experience
L1	Has knowledge based on training
L2	Can carry out with support or has such experience
L3	Can carry out independently or has such experience
L4	Can instruct others, or has such experience

The SFIA Foundation has developed detailed guidance for both self-assessment and assessment by a supervisor or independent assessor [116]. The straightforward guidelines are comprehensive but assume a thorough familiarity with SFIA. They aim at the periodic assessment of individuals in permanent employment; they are probably inappropriate in an academic placement context.

The iCD framework assumes an annual assessment of individuals' performance by (knowledgeable) line managers as part of an appraisal process. The assessment items are at the lowest level of the hierarchies for tasks and skills, so several thousand are available. Although this seems excessively complex for a teaching environment, the generic diagnostic criteria for scoring the ability to perform individual tasks, as shown in Table 8, may be helpful.

However, the critical point about students on work placements or internships is that faculty members do not routinely supervise them. Therefore, it follows that assessing student achievements during placements or internships requires an arms-length approach. It will typically rely on either a post-placement report written by the student or, preferably, a portfolio that assembles contemporary evidence of the student's achievements during the placement.

It is here that the use of an established industrial skills framework is crucial. Frameworks, such as SFIA, provide a "common language", developed by employers, for the tasks performed by employees across the IT sector. Referencing the contents of a student's portfolio against tasks in a skills framework provides an abstraction layer that enables faculty to assess the extent of students' achievements. The portfolio contents should also be validated (but not assessed) by their workplace supervisor(s) to confirm that students are not over-claiming against the chosen framework.

Supervisors' validation of portfolios directly addresses that academicians are unlikely to be expert practitioners in the particular tasks students have completed. Supervisor validation can also confirm the context or complexity of the tasks and the student's participation mode [63].

Students' portfolios will need to include evidence of their successful completion, more than once, of several related tasks to constitute evidence of real-world competence (section 6.2). Given that the purpose of the assessment is to convey to prospective employers what a graduate has demonstrated they can do in the workplace, the granularity of the assessment is crucial. For this reason, the iCD framework seems too granular, with an excessively rigid hierarchy, and e-CF too coarse. SFIA and SWECOM seem more appropriate. A SFIA skill, at a particular level, groups together a small set of cognate tasks; competency in a SFIA skill is both a reasonable target for a student and has sufficient breadth to be communicable to employers.

Table 9: Assessment evidence and criteria for technical achievement (weight: 16) [24]

Items of evidence
• Portfolio entries showing completion of components from a SFIA skill in a real-world environment
• Supervisor comments confirming the accuracy of the portfolio entries
Quality criteria
• There is more than one portfolio entry for at least 85% of the components
• There is more than one portfolio entry for at least 50% of the components
• Supervisor comments evaluate achievements against their context
• Portfolio entries based on evidence rather than assertion

To support its competency-focused accreditation standards, the Institute of Coding in the UK developed a criterion-based scheme for assessing student portfolios by mapping them to a single SFIA skill [24]. The approach, which the SFIA Foundation has endorsed, simplifies the complete SFIA assessment guidance so that academics assessing a portfolio need only sufficient knowledge of SFIA to infer, from a student portfolio, how to map against which SFIA skill. The assessment is in two parts: technical achievements and reflection and demonstration of the SFIA generic responsibility criteria. The first of these now follows.

The portfolio must include multiple entries to complete each of the activities specified in the selected SFIA skill to meet the competency definition. The students' workplace supervisor should verify these entries. The scheme sets out the items of evidence required and a set of quality criteria for those portfolio entries in Table 9.

A similar set of evidence and quality criteria occurs for the student's reflection on their technical achievements in Table 10.

Table 10: Assessment evidence and criteria for reflection (weight: 9) [24]

Items of evidence
• Reflective ad-hoc portfolio entries for achievements across skill
• Portfolio identifies area(s) of personal development
• Portfolio identifies instances of personal/professional accountability for achievements
Quality criteria
• The style of portfolio entries is appropriately professional
• Reflection based on evidence rather than assertion
• Personal development claims supported by comparison of achievements across the period of experience
• Recognition of accountability related to (potentially) customer-facing achievements

Assessing the portfolio involves locating entries corresponding either to activities defined for the selected SFIA task or to the other items of evidence required. For example, some evidence, such as reflection, or supervisor commentary, could be in separate documents submitted alongside the portfolio. Reading the portfolio and supporting documents should result in a map of which criteria (items or evidence, quality criteria) are satisfied by the portfolio; the two aspects of technical achievement and reflection are then scored using the marking scheme in Table 11. For example, using the weightings shown in Tables 9 and 10 of 16 and 9 for technical achievement and reflection, respectively, gives an overall score between 0 and 100.

Table 11: Technical achievement and reflection rubric [24]

Evidence Present	Criteria Satisfied	Score
All items	100%	4
	75%	3
	50%	2
	< 50%	1
1 item missing	100%	2
	> 50%	1
2+ missing or None	-	0

For the Institute of Coding scheme, the threshold for "competency" is 85. There is also a threshold of 65 for "partial competency," termed "proficiency," in the final IoC scheme, for students who have succeeded in at least half of the SFIA activities. Bowers [26] presents a worked example of the mapping process based on extracts from a fictitious portfolio.

In addition to technical achievements and reflection, competency against a specific SFIA skill requires demonstration of the SFIA generic responsibility characteristics for the appropriate SFIA level, which address, among other things, many of the dispositions presented in Section 2.4. For consistency with existing BCS accreditation processes, the Institute of Coding chose to use the assessment approach developed by BCS, the British Chartered Institute for IT, for its Registered IT Technician (RITTech) registration. RITTech is the BCS certification at the level of IP3T [115] that maps directly to SFIA level 3. For contexts outside BCS accreditation, the Institute of Coding also proposed a simple assessment process that is at least as rigorous as the RITTech scheme [25].

There are 23 generic responsibility characteristics for SFIA Level 3, the level of responsibility appropriate for new- or near-graduates (including placement students), representing a broad range of behavioral traits and dispositions. Of these, 17 are crucial to ensure that a degree program designed to develop competence against one or more Level 3 SFIA skills would meet the statutory frameworks and benchmarks for computing degrees in the UK. These 17 characteristics are denoted "core" for assessment purposes.

IoC assessment of the generic responsibility characteristics requires that a student's portfolio contains evidence that:

- the majority of the core characteristics have been demonstrated;
- the majority of the core characteristics have been demonstrated more than once;
- most of the generic responsibility characteristics, including those that are not core, have been demonstrated several times.

In the IoC scheme with 23 characteristics, 17 of which are core, we set the thresholds for these three criteria at 13, 26, and 44. The last threshold makes sense only if we can count a maximum number of entries against any criterion: this maximum is three.

The application of this part of the assessment scheme is similar to that for technical achievement and reflection. The portfolio, any subsequent student reflection, and supervisor validation are scanned for (validated) entries that demonstrate one or more of the generic responsibility characteristics. For convenience, the IoC scheme includes a spreadsheet to insert entries and calculate the outcome.

Although this assessment scheme maps a portfolio against SFIA, one could readily adapt it to other skills/competency frameworks with a similar level of abstraction and granularity. Furthermore, adjusting the specific criteria to meet local requirements is possible, as are the relative weightings. Still, it would then be necessary to validate the resulting scheme to ensure it would not lead to unwanted outcomes [24].

Section 6 presented ideas for assessing competency in an educational environment. These views are neither definitive nor exhaustive, but this report argues that they motivate further engagement with these emerging challenges.

7 CHALLENGES AND OPPORTUNITIES

Competency-based learning is relatively new to most computing faculty, students, and institutions. Transitioning from traditional knowledge-based to competency-based education has both challenges and opportunities. The CC2020 report addressed these aspects, summarized in part in the sections that follow.

7.1 Inertia to Change

The CC2020 report [35] provides a comprehensive overview of computing education related to undergraduate (bachelor's) degree programs, where competency may need to become the standard for recommended computing curricula. Knowledge-focused curricula place much emphasis on information; however, competency enhances knowledge (knowing what) through a skilled application (knowing how) inspired by purpose (knowing why). This expanded perspective enhances student learning by coordinating the ability to act effectively, competently, and ethically as professionals. Therefore, the competency approach is an excellent way to conduct professional business by bringing valuable benefits through a competency-based curriculum. Skills define the knowledge applicable to the relevant situation and provide the competence required for a successful practice. The intertwined aspects of competency (knowledge, skills, and dispositions) offer a comprehensive vocabulary for explaining a curriculum, including the realistic learning goals of teachers and students who aim to serve the profession.

With new ideas and inventions coming out almost every day, computing curricula are constantly changing. Such curricula must be flexible and adaptable to change. One way to address this challenge is to include innovation, entrepreneurship, and hands-on makerspace activities within computing programs. In engineering, for example, an introduction to discovery in the first semester has existed for some time to benefit students. Computing students should have a similar experience. Graduates of computing programs must succeed in a rapidly changing technological world. Computing programs do face the challenge of providing students with new and futuristic experiences. Therefore, computing faculty members must have the ability to educate students at the beginning of their studies to produce competent computing graduates. There is no single way to develop the trilogy of knowledge, skills, and dispositions. However, the overall goal is to produce computing graduates who can enter the workplace efficiently, attend graduate school, or make constructive contributions to society.

Knowledge transfer is the foundation of academia and universities, where scholars have disseminated knowledge to students for hundreds or thousands of years. They do this by lecturing, using personal knowledge, textbooks, notes, and other knowledge transfer mechanisms. Then, they use tests, exams, or other assessment methods to ensure that students acquire the necessary knowledge. This approach is the traditional way of teaching and learning. However, in today’s world, students can learn a subject in non-traditional ways by using the internet, video clips, wikis, professional development experiences, MOOCs, and other publicly available online resources. In addition to the traditional teaching model, instructors can encourage students to study in groups (e.g., learning in pairs), set up learning groups of three or four students (e.g., group learning), and introduce other learning strategies. By exploring new learning methods, students can develop unique competency attributes and build communication and teamwork skills.

Skills transfer may be challenging for instructors who expect students to develop computing skills with little guidance. This position is not productive. Computing departments should specify the set of skills that each student should master before graduation. Due to the uniqueness of each computing program, it may not be possible to determine how instructors develop these skills. Therefore, teachers and computing departments should guide how students develop their computing skills as essential for computing competency.

Disposition transfer may be the most challenging part of a teacher’s ability to promote competency. Educators often do not understand how to convey one or more dispositions, which is plausible because this understanding may not be part of their education. The CC2020 report highlights eleven dispositions: adaptable, collaborative, inventive, meticulous, passionate, proactive, professional, purpose-driven, responsible, responsive, and self-directed. An academic computing department should specify a set of human behaviors that students should achieve by graduation. Students can acquire these characteristics by observing workplace attitudes, behavioral patterns of individuals and peers, or attending professional behavior seminars. Students can learn dispositions through repetitive practice, modeling, collaboration, course experiences, internships, and other interactive experiences.

In curriculum design, local adaptability is vital. Such adaptability is challenging because it largely depends on the characteristics of institutions and the interests and skills of their teachers and staff. Complicating factors influencing curricular design include the type of institution, expectations for degree programs, the range of degree options pursued by students, enrollment preparation and background, faculty and staff resources, and the interests of the faculty members. It is crucial to find the right balance between these factors to create a viable path. A unique curriculum is not for everyone. Each university should consider different models and design an implementation plan that meets its purpose.

7.2 Education-Workplace Relationship

Businesses, governments, and industries can help support the education process in many ways. Some suggestions include providing teachers with the tools to develop student competency, guide students to work on projects, provide special lessons for classes, and become part-time teachers. Also, the industry can help by conducting field trips, providing in-house training for faculty, staff, and students, developing industry sponsorship of capstone experiences, and serving on industry advisory boards. Industry and government could also promote professional practices by bringing students and faculty outside campus environments, such as visiting local companies and building strong relationships between students and industry.

By partnering with industry and government, teachers can develop student competencies in the curriculum by providing opportunities for mutual benefit and building a higher degree of trust between teachers and businesses. In the long run, the opportunities for cooperation, practice, and internships should allow students to understand life better in the workplace. Students are also more likely to establish contacts with an employer and return to that company after graduation.

Industry advisory committees are essential for developing robust and meaningful computing programs. Industry and government professionals are reliable resources for understanding the needs of the workplace. These groups help link computing programs to the needs of industry and government. They also establish a personal connection between a computing program and students. Therefore, all computing programs should require the presence of a professional advisory board.

Computing programs should consider including work-study or cooperative (co-op) programs as part of their curriculum. These experiences usually allow students to enter industry or government before graduation. They typically provide credit to students and enable students to earn salaries when contributing to businesses and governments. The cooperative plan has both challenges and benefits. One of the challenges is that students are more likely to graduate beyond a regular period, such as four years. Each computing program must assess whether the collective experience fits the needs of the institution and the interests of its students.

All computing programs should consider internships as an essential part of the degree program. An internship is an experience that occurs over a brief period, such as during summer recess or when there are no scheduled courses. Internships can be full-time or part-time. Many computing programs around the world require them as part of student learning. Students usually earn internship credits, and in many cases, the industry pays students for their services.

7.3 Barriers to Internship Experiences

Section 6.1.2 poses an argument that the best setting for evaluating disposition in the workplace. In many disciplines and countries, the standard mechanisms for providing a workplace setting to students are internships, apprenticeships, or clinical placements. These mechanisms require tight collaboration between the educational institutions and the workplace setting to allow practical assessment. This approach has been quite successful in the healthcare domain.

For example, in the US, competency-based assessment of both skills and dispositions has been emphasized and codified in the Accreditation Council for Graduate Medical Education (ACGME) standards for residency programs and the Accreditation Council for Pharmacy Education (ACPE) standards for pharmacy. Residency programs, by their nature, are workplace-based, and pharmacy education involves extensive clinical placements, where competency-based assessment occurs. This requirement is possible in the healthcare domain because healthcare professionals typically graduate from accredited programs to obtain licenses. Healthcare employers must hire licensed graduates, meaning they are interested in collaborating with educational programs on residencies and clinical rotations.

This situation does not exist in computing, as graduates are not required to have a license or hold degrees from accredited programs in many countries, including the US. Many companies do not require a computing degree at all, preferring to rely on their assessments of computing skills to make hiring decisions. In addition, employers who hire computing graduates are diverse, spanning small startups, high-tech behemoths, regional and national government agencies, hospitals, financial companies, and retail companies, among others.

It is also challenging for educational institutions to establish collaborative agreements across such a diversity of employers or create standardized student placements as is the norm in healthcare. In the US, employers at smaller work-sites may not have the time or resources to conform to university requirements for awarding academic credit. Some universities, especially institutions with formal co-op programs, such as Rochester Institute of Technology and Northeastern University, have established strong collaborations with employers to provide oversight of internships. However, at many other schools, students with paid internships do not apply for academic credit, thus essentially "flying under the radar" making it difficult to track these internships. In the US, this is aggravated because students often need to pay extra summer tuition, which can be very expensive, to receive academic credit for internships. This may not be a major consideration in other countries where university tuition is much lower. In addition, students doing summer internships often prefer to take internships in their hometowns, which may be distant from their universities, posing additional obstacles to collaboration and oversight.

7.4 Teaching and Assessing Competencies

Developmental psychology's dynamic view of competence holds that personality characteristics change in response to life experiences and structured interventions [37, p. 38]. Almund et al. [8, 9] make the case that personality traits "are more malleable over the lifecycle compared to cognition, which becomes highly rank stable around age 10". They focus on prediction evidence on correlations between personality traits and education attainment.

Competencies can be learned and developed through a range of meaningful tasks carried out in multiple contexts: academic, workplace, civic, and personal life experience. In the cognitive domain, practice and feedback are critical to the development of deep knowledge and effective skills characterizing a given competency [87]. Labeled as the power of practice, this strategy is not sufficient. Feedback on the quality of skill development is equally important. Thorndike "demonstrated long ago that practice without feedback produces little learning" [37, p. 80]. Informed by cognitive load theory and based on cognitive demands on learners' working memory) [97, 114], learning experiences fall into three categories:

- Extraneous processing results from poor instructional design and does not lead to achieving the learning goals.
- Essential processing means to help a learner develop mental representations of essential content to cope with content knowledge complexity.
- Generative processing, or making sense of new content knowledge by organizing and connecting it to learned or existing conceptual understanding, is characterized by demanding sustained effort and is conditioned by learners' motivation [75, 76, 97, 114].

Developing cognitive competencies should reduce extraneous processing to manage essential cognitive processing and promote generative processing experiences.

Teaching strategies and interventions to develop intrapersonal competencies include [37, p. 88–95]:

- Change students' attributions of their struggling performance to abilities they perceive as fixed, such as lack of aptitude in programming, and create frequent opportunities for structured reflections on transitory factors, such as lack of familiarity and insufficient preparation, specific barriers to their weekly preparation, and ways by which the instructors, peers, or team members could help [138, 141].
- Reduce stereotype threat and increase students' self-affirmation of their positive characteristics through reflection on values that are personally important to them [141].
- Integrate and assess metacognitive activities by which students stay on task, monitor their understanding, self-correct errors, and reflect on their strengths and weaknesses in task-related specific content areas.
- Self-regulated learning strategies of goal-setting, keeping track of progress, staying on course by managing or changing learning strategies, and reflecting to understand oneself better relate to the work ethic and conscientiousness cluster of intrapersonal competencies. To teach them, instructors might model these strategies to guide students to experience and reflect on them.

We note that determining the effectiveness of existing assessments of self-regulated learning, such as self-reports and observational methods, is still a work in progress.

Teaching strategies to develop interpersonal competencies include [37, p. 95–97]:

- Design and integrate collaborative settings for student work in and outside class to develop participatory skills such as understanding and asking questions, elaborating on particular work decisions, and contributing to the shared understanding of the task at hand.
- Design responsive social settings with clearly defined and shared criteria which students adopt and by which they evaluate their own and their peers' performance. Create conditions that facilitate and emphasize practice with asking for, giving, and accepting help from peers, peer tutors, course instructors, or faculty advisors.

7.5 Needs of Diverse Workplaces

The need to support diverse workplaces and a diverse student body poses several challenges to assessing competencies, especially dispositions. In some fields, such as education, to function in a diverse workplace is explicitly a disposition. For example, the Educator Disposition Assessment [133], which is an instrument used to evaluate teacher candidate dispositions in the field of education, includes the following disposition: "Appreciation of and value for cultural and academic diversity." In the area of graduate medical education, one of the measures includes: "Responds to each patient's unique characteristics and needs." A milestone in pediatrics is: "Seeks to fully understand each patient's unique characteristics and needs based upon culture, ethnicity, gender, religion, and personal preference." The dispositions listed in Computing Curricula 2020 [35] do not explicitly list as a disposition the ability to communicate or work in a diverse setting; however, we can include this goal among the measures of some of the listed dispositions.

A major challenge is that assessment of dispositions may be prone to bias if not done carefully. In the area of graduate medical education, studies have found gender bias in faculty evaluations of emergency medicine residents on personal characteristics such as *hardworking*, *cheerfulness*, *open to feedback*, and *professional* [83], evaluations of internal medicine residents on competencies such as *professionalism* and *interpersonal and communication skills* [71].

Bias in employer assessment of dispositions was also a point of study. When employers interview job candidates, they evaluate the candidate on competencies which include both skills and dispositions. Hora [61] analyzed dispositions such as teamwork and work ethic desired by a group of manufacturing companies. They found that these dispositions were matched tightly to the particular characteristics of the company and its current employees, meaning that there is the potential for bias against job applicants from cultural groups not well represented at a particular company. It specifically proposed that educators work with students to help them develop behaviors that correspond to dispositions desired by companies.

Finally, student evaluations of professors, which often assess characteristics that are similar to dispositions, have been shown in many studies to exhibit gender and racial bias [88]. Therefore, it is critically important to develop assessments, particularly for dispositions, that avoid cultural, gender, racial, and other biases. Jung and Rhodes [48] argue to tie the assessment of disposition to behavioral competencies rather than assessment of beliefs about character. We should be careful that our picture of a computing professional who fits into a workplace does not contain stereotypes such as "people in computing love e-gaming."

The focus of the current paper is on competencies for students entering the workplace in computing. Therefore our discussion and recommendations have a professional and employer-based tilt. However, many students take computing courses for other reasons, and many computing departments offer minors and even majors in computing where the focus is not on standard computing careers. Assessing these students will likely require a different set of competencies and dispositions. Navigating 120+ separate skills can be challenging, but a hierarchical grouping of the skills mitigates this into six categories and 17 sub-categories. There are also half a dozen focused views that draw together subsets of the skills that are relevant for domains such as Big Data/Data Science or Information and cybersecurity [120].

8 DISCUSSION

This report explored the status of competency in education in general and its application in computing education in particular. It suggested ways academic programs can improve their pedagogy and feedback to student learning of professional competencies. Discussed below the issues, recommend ways to enhance competency-based learning in computing education, and suggest future studies and work possibilities.

8.1 Competency Review

In brief, this report has explored competency and its relation to computing education and profession. The report has focused on an integrative model of competency. It also showed the connection to professional pedagogy with aligned assessment methods. In addition, there are challenges facing learning focused exclusively on cognitive competencies contrasted to learning that integrates dispositional competencies. Many computing programs focus on content knowledge alone, while skill development often receives insufficient attention. Moreover, attention to dispositions, which prompts the realization of cognitive and performative competencies, is either lacking or non-existent in the specification of academic computing programs.

Elements of disposition for competency should not remain hidden within a curriculum in computing education. Instead, educators should develop integrative learning models [130] that rely on content knowledge, development of skills, and cognitive learning strategies. Additionally, they should also include motivational and volitional aspects of learning to reinforce the mutually constitutive nature of affect and cognition in student learning [10]. This effort to stop neglecting the "human" side of learning [96] draws particular attention to intrapersonal and interpersonal competencies [37] and the affective and social characteristics of learning goals. An integrative model of competency centers learning and professional competency development around the "whole person" who acquires and expresses those competencies. The three key characteristics of the integrative competency model are as follows.

(1) Attributing competencies to the "whole person" requires that educators recognize the presence of all three dimensions of competencies (cognitive, affective, and social) and their intrinsic interdependence and dynamics.
(2) The knowledge, skills, and dispositions lenses into the composition of a particular competency consist of one or more knowledge elements, skills elements, and dispositions elements, which together bring coherence to that competency.
(3) Learning, developing, and practicing professional competencies reveal dependency relationships among learners. Competencies do not exist in isolation, and different individuals will experience different progressions.

These key characteristics have several implications for teaching and assessing. As the most complex component of competency, dispositions are challenging to teach and evaluate. They usually require new methods and instruments depending on didactic settings, class sizes, and learning objectives. Not every disposition is observable and can be assessed in every context or by a single assessment. Formative assessments and supervision, including instruments for self-reflection and feedback, can serve as a starting point toward evaluating professional dispositions. Peer reviews, learning journals, and cognitive wrappers are constituents of the didactic inventory commonly exercised by educational scientists and teachers. Students still need more introspection in computing education to reflect on their learning processes and behavioral patterns in projects, group work, or internships. This iterative process should be accompanied by feedback and help students become more self-conscious of their (professional) practice in computing.

8.2 Recommendations

Recommendations on computing competency derive from discussions in earlier sections. One suggestion is to encourage computing programs to develop relevant sets of competencies in existing programs. In addition, the curriculum should promote an increasing emphasis on skills and dispositions. Students expect to establish realistic expectations to create an awareness of competency when they graduate and enter the workplace. For graduates entering post-baccalaureate studies, they will have gained a level of maturity commensurate with expectations.

It is the case that not all aspects of computing education can take place formally in the classroom. There will always be a need for students to learn in a work environment. Therefore, computing programs are strongly recommended to foster or require experiences beyond the classroom, such as internships or co-op programs where students can work on exciting real-world problems while being part of the profession. These types of learning activities are ideal settings for the enhancement of competency-based learning. In addition, these hands-on study units should become mandatory and supervised by practitioners and educators to assure the relevance and, above all, reflection upon the learning process. Consequently, teachers should use formative assessment methods for the competency-based review of students' learning processes.

Recent efforts in academic computing communities have proposed competency-based learning that students should attain. As mentioned in this work, several computing disciplines have already produced competency-based curricular recommendations. This approach and strategy should continue regarding updates of existing curricular guidelines and new computing curricular recommendations. It is essential to elevate computing curricula beyond the knowledge level. Existing and new computing guidelines should promote competency as a combination of knowledge, skills, and dispositions in context. Computing programs should provide students with multiple experiential environments where students immerse themselves in many hands-on and collaborative settings to enhance skills and dispositions in learning.

In the US and several other countries, ABET's Computing Accreditation Commission (CAC) accredits computing programs in computer science, cybersecurity, data science, information systems, information technology, as well as other general computing programs [2]. ABET's student outcomes, as previously discussed in Section 3.5, describe "the skills, knowledge and behaviors that students acquire in their program of study." If ABET's CAC begins to emphasize all three aspects of Student Outcomes in its CAC Accreditation Criteria [3], it inherently will be requiring all of its accredited computing programs to focus on competencies.

The structural integration of dispositions should become an opportunity for the computing education community to strengthen professional competency for teaching and learning. New forms of assessments need to go along with that development. Increasing transparency and eliminating barriers between different forms of education (i.e., from vocational training toward higher education) could be another positive side effect. Alternate ways of instruction should align with these forms. The support of instructional designers, for instance, can prove to be helpful in this respect as a step further than the surface structure of computing education.

9 FINAL REMARKS

This report provided an overview of competencies in computing and ways to assess competency elements beyond knowledge. It also addressed challenges, opportunities, and recommendations surrounding competency. Although the material presented is interesting in its own right, some topics would benefit from deeper analyses. Computing education researchers might want to conduct empirical studies of computing skills and dispositions or consider different versions of research for the future. For example, the following ideas could receive deeper consideration, such as applying and using iCD [27] or SFIA [117] skills frameworks and using formative assessment to give feedback to the development of dispositional competencies. Innovative approaches in the development of competency could also induce alternative pedagogical techniques and procedures.

Concerning the discussions for both skills and dispositions, applications could accept more improvement through data tables, graphs, and other attributes. It may also be worthwhile to research and engage in greater depth alternate ways to teach and assess skills and dispositions. Methods to evaluate competency could undergo investigation and testing. The expectation is that many sections and subsections of this work could emerge as novel studies and publications. Moreover, future interdisciplinary approaches or other efforts can use this report as a basis for further analysis or educational research across disciplines.

It is crucial for academia and other stakeholders in higher education become proactive to promote competency-based learning in all computing programs worldwide. Readers can do this on a local or regional basis and then let computing organizations expand the process. It is also essential to have organizations promote and develop competency-based computing curricular guidelines for different computing areas.

The promise is that adopting a competency model and the implementation of professional pedagogy will continue in the future. At the same time, further research, practice, and preparation related to competency-based education at all levels of the computing community can help overcome challenges and support wider adoption. Finally, future work in competency-based teaching and assessment in computing education should foster a collective understanding of competency and help promote successful competency-based student learning. In all, such a competency-based framework of education will pave the way to describing and developing the profession of computing.

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