Propagating the Adoption of CS Educational Innovations

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ABSTRACT

In this report, we survey the existing scholarship in STEM higher education regarding what motivates, encourages, and inhibits educators' decisions to adopt teaching innovations. After reviewing common theoretical foundations and considerations for adoption and dissemination studies, we identify challenges for encouraging adoption among educators in higher education. When possible, we provide evidence-based recommendations from the literature on how to overcome these challenges. We then consider the relevance of scholarship from general higher education and other STEM disciplines to the context of computer science in particular, discussing similarities and areas of divergence that would affect dissemination efforts. In order to better guide change agents in propagating beneficial teaching practices, tools, and resources, we conclude by summarizing best practices for promoting the adoption of innovations in computer science higher education.

CCS CONCEPTS

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

KEYWORDS

educational adoption, educational propagation

ACM Reference Format:
Cynthia Taylor, Jaime Spacco, David P. Bunde, Zack Butler, Heather Bort, Christopher Lynnly Hovey, Francesco Maiorana, and Thomas Zeume. 2018. Propagating the Adoption of CS Educational Innovations. In *Proceedings Companion of the 23rd Annual ACM Conference on Innovation and Technology in Computer Science Education (ITiCSE '18 Companion), July 2–4, 2018, Larnaca, Cyprus.* ACM, New York, NY, USA, 19 pages. https://doi.org/10.1145/3293881.3295785

1 INTRODUCTION

The computer science (CS) education research community devotes considerable time, energy, and money to developing innovative teaching tools, materials, and methods. Unfortunately, it has proven hard to translate these discoveries into widespread improvements in CS classrooms. Many of us have experienced creating materials only to see them sit unused, with little apparent adoption by others in the discipline.

This problem is not unique to CS, it is a common theme observed throughout STEM (science, technology, engineering, and mathematics) educational research. Evidence suggests that most faculty understand that research-based, student-centered teaching practices are more effective than lecturing [54, 123], and yet many faculty in STEM disciplines still rely heavily on traditional, instructor-centered teaching methods [36, 72, 121]. For example, a recent study of 821 computer science instructors in the U.S. found that most CS faculty use lecturing as their most frequent mode of delivering content to students [82]. However, the study also found that a majority of faculty used at least one student-centered practice in their classrooms, at least on an experimental basis. The key, therefore, is to uncover evidence-based strategies for encouraging educators to try out and routinely use innovative teaching practices more regularly.

Getting other educators to adopt materials and teaching strategies is itself a hard problem, one that has historically been often overlooked. Many educational researchers and developers do not consider how to persuade faculty to adopt their innovations, or how to support faculty through the adoption process as they change their teaching to incorporate evidence-based practices [55, 71, 75, 125]. Recent work has shown that successful propagation of new educational methods requires more than simply publishing evidence of their effectiveness [10, 55, 71].

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ITiCSE '18 Companion, July 2–4, 2018, Larnaca, Cyprus
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ACM ISBN 978-1-4503-6223-8/18/07…$15.00
https://doi.org/10.1145/3293881.3295785

In this paper, we attempt to help those interested in promoting the use of educational innovations in CS higher education by summarizing existing scholarship on propagation and innovation adoption among university-level educators in computer science and in other STEM disciplines. After defining important terms (section 2) and reviewing a few useful theoretical frameworks (section 3), we summarize research on propagation in STEM generally (section 4) and then in CS more specifically (section 5). We recap best practices for propagating projects (section 6), discuss possible future work (section 7), and offer some concluding remarks (section 8).

Our intended audiences are individual faculty who want to encourage wider adoption of evidence-based teaching among their peers, and CS education researchers and developers who wish to promote the innovations that they have developed. Throughout this paper, we use the terms *faculty* and *instructor* interchangeably to represent any individual who teaches students in higher education. This subsumes graduate student lecturers and professional instructors through full professors in the U.S. system; lecturers and demonstrators in the United Kingdom; professors and lecturers in Germany; *professore a contratto* through *professore ordinario* in Italy; and so on.

Aspects covered in this report were chosen specifically because they are salient to faculty and developers. For example, while we briefly discuss the importance of programmatic or systemic influences on faculty adoption, providing guidance at length on how to affect change at that level by administrators is beyond the scope of this report. That being said, we hope that at least some of the research and practical implications we discuss may also be of use to groups such as university administrators.

We focus on higher education—postsecondary degree levels offered beyond compulsory education—because lower-level education systems (e.g., K-12 in the U.S.) often differ substantially in organizational structure, faculty autonomy, and hurdles to adoption [91, 95]. Our use of the term *university* is intended to refer to any institution that grants postsecondary degrees or certificates, including career or technical education institutions (e.g., associate degree-granting), colleges, and universities.

Our method for creating this literature survey centered on collecting and reviewing existing scholarship in the area of adoption and propagation of innovations in undergraduate higher education scenarios. An initial list of relevant research work was identified by keyword searches, and by asking colleagues and relevant authorities on the subject for literature suggestions. The initial list was subsequently expanded through following citation chains. After reviewing articles (typically as a group or in pairs), we clustered, extracted, and discussed recurring themes and examples. Please note that while the literature we review here is broad and encompasses many important themes, it is not comprehensive. For example, most of the research on faculty adoption in STEM education that we were able to locate was conducted in the United States and Europe, and was written in English. As such, lessons learned may not be entirely transferable to environments with different academic structures or different national contexts. Nonetheless, we hope that this work provides practical insights for postsecondary-level educators who intend to encourage adoption among their peers, and for education developers who design and test new instructional tools, curriculum, and pedagogy.

2 THE VOCABULARY OF PROPAGATION

In this section, we define the terms from that literature that we will use throughout the rest of the paper.

2.1 Educational Innovations

We use the term *innovation* to refer to any novel teaching technique, strategy, tool, or learning resource that could be used by an instructor—especially modern-era, effective (or promising) instructional techniques that benefit student learning and engagement. This term therefore encompasses educational practices and tools that are described in other literature as research-based instructional strategies (RBIS) [16, 74]; evidence-based instructional practices (EBIPs) [90]; student-centered instruction, teaching, or approaches [63, 64, 87]; active learning [98, 111]; and high-impact educational practices [87, 88]. We acknowledge that the titles used by other scholars to refer collectively to innovative teaching have important distinctions, and that combining them under one umbrella term inadvertently downplays important scholarly debates. However, the principal concern of our paper is to discuss barriers and promising solutions to increasing the diffusion and dissemination of these innovations, and not to weigh in on the innovations themselves or their larger, theoretical classifiers.

That being said, the discussion presented in this paper applies to at least three broad types of educational innovations that faculty may find useful to conceptualize: instructional technology, curricular innovations, and pedagogical innovations [107]. *Instructional technology* refers to software or hardware that can be incorporated into teaching, such as clickers (or similar student response systems), automated grading programs, plagiarism detection programs such as MOSS, lecture video recording, content-specific software, and websites such as Piazza and GradeScope. *Curricular innovations* refer to modifications that are made to what is taught, and when it is taught. This includes course content, materials, assignments, and topics, as well as the sequence in which those topics are presented to students in a course and throughout the entirety of the degree program. Examples of recent curricular innovations include Objects-First approach to CS1 (in which students are introduced to programming via the Object Oriented paradigm) and newer topics such as Security or Parallel Programming being offered as a single course session, a course, and/or as a programmatic concentration. *Pedagogical innovations* refer to modifying the instructional methods an educator uses, or how a course is taught and how content is conveyed to students. Examples include Peer Instruction (PI), Process Oriented Guided Inquiry Learning (POGIL), Inverted (or Flipped) Classrooms, Jigsaw Learning, and Just-In-Time Teaching.

This taxonomy is of practical value because propagating different types of innovations requires addressing unique considerations. For example, faculty in computer science may have a relatively high degree of autonomy in selecting their in-class instructional methods (pedagogy), but may be constrained by committees or social pressure when modifying course content or topic sequencing (curriculum) [106]. They may have to seek approval from deans or procurement contract officers when adopting certain types of proprietary instructional technology. In other words, each type of innovation may have different stakeholders who need to be consulted or persuaded during the adoption process. These are certainly not the only types of educational innovations.

Many innovations that improve students' performance, sense of belonging, and commitment to the major take place out of class or are implementable at an institutional level, including extracurricular programs such as Girls Who Code, living-learning communities, summer internship programs and co-ops, Research Experiences for Undergraduates (REUs), etc. However, in this work we focus on instructional technology, curricular, and pedagogical innovations because they are the main types that could reasonably be adopted by a single instructor, without greater institutional efforts, and because they are the innovations most commonly addressed in the literature.

2.2 Adoption

Adoption occurs when the use of an innovation becomes significant to the instructor in her or his teaching. In other words, adopting an innovation requires using it beyond a limited, experimental basis. Although some scholars [86, 127] differentiate between adoption, conceptualized as the initial trial by an individual, and implementation, conceptualized as routine use at a systemic level, we follow the example set by Rogers [116] and use these terms interchangeably in this paper.

A *change agent* is anyone who actively advocates for and promotes the use of an innovation to potential users. Typically, a change agent will be either a developer (e.g., the designer or inventor of an innovation), or a champion of the innovation. A *champion*, who is a specific type of change agent, is a member of the community of potential users who evangelizes among their peers by offering encouragement, direct support, and advice to others so that they will successfully implement an innovation. In this case, champions are typically faculty members who have successfully adopted the innovation personally and subsequently try to convince their colleagues and peers to do likewise. In this paper, change agents are also referred to as *propagators*.

2.3 Propagation

Propagation, also called scaling, is the act of increasing the user base of an innovation. *Dissemination* refers to intentional activities, both passive and active, that someone engages in for the purposes of "spreading the word" about an innovation. Although many people conflate these two terms, they differ in that propagation explicitly requires that others adopt the innovation, whereas simply spreading awareness and knowledge of the innovation amounts to successful dissemination. *Diffusion* has been achieved when a sizable group become sustained users.

Defining successful propagation is difficult, and highly dependent on the particular innovation. Very few educational innovations have been widely adopted and fewer, if any, have become industry standards. For example, Peer Instruction (PI) is a pedagogical innovation in which students select multiple choice responses before and after discussing prompting questions in small groups throughout a class [96]. Since its development in the 1990s, PI has become one of the most widely adopted innovations in physics education [74]. Yet, in a 2008 survey, Henderson and Dancy [74] found that only 64% of physics faculty reported being familiar with PI and only 29% of faculty reported having adopted it, out of 490 physics faculty across the U.S. (the study included 722 participants, 490 responded to these specific survey items). Related research [16, 37] indicates that even this level of self-reported adoption may not reflect a sufficient standard of fidelity in the adoption of PI, meaning that necessary components prescribed by the developer may be absent in some implementations. (A longer discussion on fidelity is presented in subsection 4.4.) The most widely used innovation in physics education being used by less than a third of physics instructors indicates that definitions of successful propagation need to be highly contextualized.

3 THEORETICAL FOUNDATIONS

The main goal of theory is to create conceptual models that help to organize ways of thinking and understanding the world. In this section, we discuss different theoretical frameworks for change, innovation adoption in general, and adoption in higher education contexts in particular. We also draw attention to the implications of these theories for people intending to advocate for the use of a new teaching innovation.

3.1 Diffusion of Innovations

Stages of Adoption. In his influential book, *Diffusion of Innovations*, Rogers [116] established a theoretical model of the stages or steps that someone progresses through when adopting an innovation. As defined in Figure 1, Rogers' five stages are: *knowledge*, *persuasion*, *decision*, *implementation*, and *confirmation*. (For a good summary of these steps, see Robinson [115].)

An important implication of this model is that, depending on what stage they are at, a potential adopter will have specific considerations, concerns, and interests that influence their behavior. Describing how an innovation increases students' engagement, for example, may be important for a potential adopter during the knowledge and persuasion stages, but not important during the implementation stage. Conversely, it may be essential in the implementation stage to collaborate with a potential adopter to adapt an innovation to a larger class size than the one in which it was developed, even if that was not a consideration during the persuasion and decision stages. A stage model of adoption directs a propagator to consider what strategies and messages will be most effective in encouraging new users to try the innovation at each step, even if not every potential adopter progresses linearly through the stages or moves through every stage on their way(s) to successful adoption. Rogers' five-stage theoretical model serves as an excellent starting point for considering what these steps are. Throughout the majority of our current paper, we focus primarily on practical insights for encouraging adoption among faculty who are at the persuasion and decision stages; however, many of the insights may also be applicable to the knowledge stage.

Innovation diffusion scholars have combined, unpacked, or elaborated on components of Rogers' model in useful ways. For example, there is a vibrant academic debate over which innovation characteristics are essential for attracting potential users during the persuasion stage, and whether these characteristics are universally important or are context- or innovation-dependent. These attributes, as Rogers calls them, include benefits and drawbacks such as the innovations' relative advantage, complexity, observability, cost, etc. While it is beyond the purview of our paper to summarize these debates or to

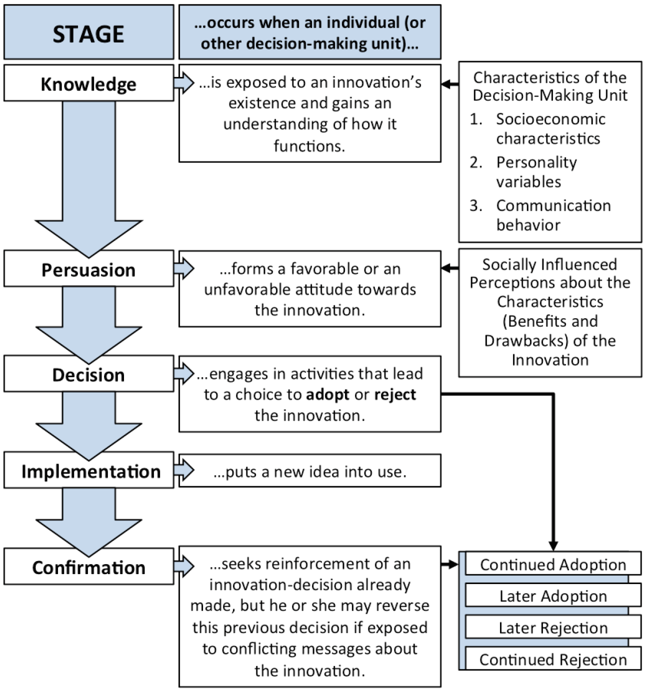

Figure 1: Rogers' five stage model of the adoption process, adapted from [116] p.170.

describe the full list of hypothesized characteristics, notable contributions have been made directly or indirectly by a variety of authors [39, 40, 49, 99, 127, 132]. On a practical level, propagators may benefit from addressing the following considerations that are important to potential adopters:

- In what specific ways is the new innovation an advantage over what it is replacing?
- How well does the innovation fit with the potential user's existing processes, practices, technologies, and beliefs?
- What costs and risks, especially regarding time, are adopters likely to incur?
- How useful and easy to use is the innovation?
- How prevalent is it in departments of different types?
- How might using it influence the faculty member's reputation among students and/or colleagues?

These, and other practical implications of this theoretical component are discussed in greater detail in section 4.

Also of particular utility, Henderson and Dancy [73] implicitly simplify Rogers' five stage model into three phases: identifying a problem with a current practice, gaining knowledge about a new practice that addresses the problem, and then applying the new practice. In this model, Henderson and Dancy expand the knowledge stage by incorporating three levels of cognizance: (1) knowledge that the practice exists, (2) "how-to" knowledge that is necessary for using the practice effectively, and (3) knowledge about why the practice works, so that unintended problems can be more easily solved if and when they arise.

The key counsel these theoretical models offer for propagators is the notion that potential adopters go through distinct, interrelated steps when adopting an innovation, and that different groups of potential users may be at different stages at any one time. Regardless of which specific model one finds useful, identifying the stage occupied by the intended target audience can suggest the types of support, messaging, and information to best advance them toward adoption. For an instructor who is designing a new course prep and trying to make a decision about which innovation would be right for the course, emphasizing awareness knowledge about the existence of various instructional options might be highly beneficial. For an instructor who is actively trying to incorporate an innovation into their teaching on a trial basis (i.e., the implementation stage), more technical, how-to knowledge support may be required. Developers of educational innovations should develop concrete plans to address the needs of potential adopters for each stage.

Types of Adopters. Just as potential adopters can be classified by where they are in the adoption decision process, adopters can also be differentiated into ideal-type categories based on the relative timeliness of their adoption. Rogers [116] categorizes potential adopters into five general groups according to where they fit on a scale of innovativeness, which is based on the relative percentage of people who have adopted the innovation as it progressively diffuses throughout a given population. Depicted in Figure 2, these categories are: innovators, early adopters, early majority, late majority, and laggards. Rogers describes these groups as follows. A small number of people, *innovators*, are venturesome and will eagerly try out untested innovations, and are typically willing to be part of iterative improvements (e.g., beta-testing an innovation). Conversely, on the other end of the spectrum are *laggards*, who tend to be traditionalists and will typically only change their current practice(s) after an innovation has become an unavoidable standard within the field. Most adopters lie between these two poles, based on when they adopt and their general openness to change. *Early adopters* are typically respected opinion leaders within a community, in part because their proclivities balance the experimentality of innovators with the deliberative judiciousness of the early majority adopting group. *Early majority* adopters, in turn, are slightly in front of the curve and are often convinced by the testimonials of early adopters. *Late majority* adopters, typically expressing more caution and skepticism than earlier groups, are willing to use an innovation only because they feel that it has been sufficiently tested and debugged by a sufficiently large user base.

The key point for encouraging innovation adoption is that there are different types of potential adopters, who have different needs and perspectives, and who will likely proceed with varying degrees of enthusiasm or skepticism throughout the adoption decision process. Therefore, messages will resonate very differently depending on where a potential adopter falls on this continuum. It may not be productive to spend significant resources searching for ways to convert laggards. However, identifying innovators and early adopters, and being responsive to their feedback, may be useful—and even necessary—to propagate the innovation to later-stage adopters. Earlier adopting groups should be harnessed to advocate for the innovation as champions; early user groups' testimonials and input may convince members of the next adopting group about the effectiveness

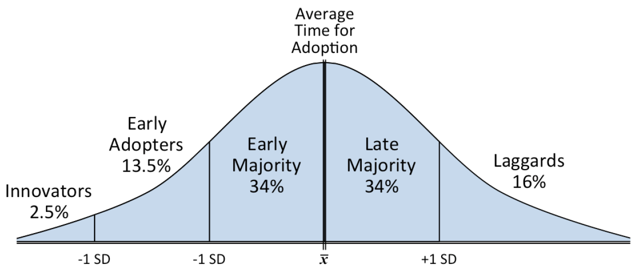

Figure 2: Rogers' five adopter types based on the time at which adoption occurs, adapted from Rogers [116], p.281. Partitions in the continuous variable are determined by standard deviations (SD). Areas under the curve represent approximate proportions of adopters who fit within each innovativeness categorization.

	INTENDED TYPE OF CHANGE	
CHANGE TARGET	**Prescribed**	**Emergent**
Individual	Convince faculty to use a specific innovation or set of innovations.	Develop reflective faculty/ educators who are open to innovative teaching.
Environment/ Structure	Enact policy that requires and encourages innovative teaching.	Build shared vision among all stakeholders; develop an ecosystem that encourages innovative teaching.

Figure 3: Model of change theories mapped to change strategies, adapted from Borrego and Henderson [18], p.224.

and robustness of the innovation, and can also create momentum for the propagation of an innovation.

3.2 Building Capacity

Another useful theoretical model for adoption concerns thinking about both individual and systemic change as iterative capacity-building. Based on extensive literature reviews of education research, Borrego, Henderson, Beach, and Finkelstein [18, 70, 75] present a four-quadrant typology of educational change theories, shown in Figure 3. The two dimensions of their model consist of (1) the target of the change, either individuals' behavior or the environment and organizational structure, and (2) the desired outcome, which is either prescribed or emergent change. *Prescribed change* refers to a targeted, final state or outcome that is intended before the change process begins. *Emergent change* allows for desired outcomes to evolve and develop as part of the change process [16].

Most diffusion and dissemination efforts tend to focus on prescribed changes for individual faculty members, for example by encouraging an instructor to implement a new classroom practice and then have them gauge the degree to which implementation was successful [18]. Individual emergent change efforts typically center on encouraging individual faculty to make whatever types and degrees of change they feel is needed and possible for their classroom(s). For example, many institutions have an organizational unit such as a center for teaching and learning that is dedicated to faculty development; these centers encourage individual emergent change in that learning center personnel typically provide one-on-one consultation (and in some cases, funding), facilitate discussion groups, and host workshops, talks, and other events on implementing innovations. These centers typically encourage faculty to become reflective and adaptive educators, rather than advocating for the use of a single innovation.

Structural change, either prescribed or emergent, has historically been difficult to achieve within and across universities in the U.S. (and elsewhere), in part because of academia's organizational anatomy [18, 24]. Organizational sociology informs us that academic institutions are shaped by symbolic negotiations between management (administrators) and various levels of labor (faculty, staff, and students) concerning the defining characteristics and operational contours of the organization. In these negotiations, diverse stakeholders implicitly and explicitly contest the relative centrality of "market" imperatives like fiscal solvency, profit, prestige, and accountability, against "mission" imperatives such as social responsibility, community service, fundamental/pure research, humanism, ethics, and tradition. In addition to these usual organizational drives, members of academic organizations must also continuously resolve disputes over other competing values like academic freedom and the relative importance of research, teaching, athletics, campus community and belonging, and inclusion [11, 22, 50, 67]. Compared to other organizational forms, universities typically exhibit relatively high levels of worker autonomy; less stable and less clear processes and protocols; greater fluctuations in personnel, populations served, and service boundaries; and greater variation in the time, effort, and involvement required of different personnel over time to fulfill essential functions [24]. Given these considerations, it is of little surprise that empirical studies repeatedly caution that non-consensual, "top-down" mandates for individual adoption often fail in higher education [38, 60, 70]. In cases where structural changes have succeeded, such as the SCALE-UP project (a student-centered active learning environment for undergraduate programs) [51], there has been an emphasis on collaboration between faculty and administration, significant buy-in from both groups, a rewards system that encourages voluntary usage, and ancillary support structures for training, feedback, and problem-solving [18].

Propagators should think of prescribed structural change in terms of enacting policies that encourage, but do not force, faculty to adopt specific innovative teaching strategies. For example, as will be discussed in section 6, policies can be (consensually) developed to stipulate how experimentation in teaching should be positively evaluated by committees in tenure and promotion cases. A policy of this type will require action by strong leadership (e.g., regents, provosts, deans, chairs, etc.) who are committed to change, *and* input from faculty, who must actively respond to the opportunity to participate in establishing reasonable policies. Similarly, emergent structural change would need administration and opinion leaders like prominent faculty to engage with other members of the organization (faculty, students, and staff) to build consensus on clear mission and values statements and feasible initiatives that support innovation adoption activities. Manifestations of this support can include devoting sufficient resources for faculty to travel to and attend educational conferences, awarding course buyouts or research credit to allow faculty the time to redesign courses using research-backed strategies, or funding the activities of (and advertising for) centers for teaching and learning.

There are several other lessons that we can derive from Figure 3. A narrow focus on prescribed changes for individual faculty may miss key points of friction, such as how departmental culture, and the environment in which faculty work, can prevent highly motivated faculty members from adopting new innovations. Evidence for this effect has been uncovered in at least one qualitative research project in CS higher education, which found that fellow CS faculty negatively influence adoption by their colleagues [106, 107]. So rather than pitching a prescribed change for individual faculty, it may be more useful to build a culture of emergent openness to innovation by encouraging colleagues to try aspects of an innovation or to try at least something new in their teaching.

The other side of this lesson is that leaders and the governance of institutions—university presidents, provosts, deans, chairs, steering committee members, and other administrators—often wield considerable influence, and can make the change process much easier, or much more difficult. Institutional leadership can allocate resources and draw positive attention towards innovative teaching. It is therefore wise to include administrators and other decision makers in the propagation plan if possible.

4 LESSONS FROM THE BROADER STEM LITERATURE

We have already covered some structural- and individual-level considerations in the previous section, but we wish to lay out empirically-based challenges and solutions for propagating innovations in greater detail. This section draws broadly from the existing literature on adoption of innovations in STEM education in order to enumerate a number of different challenges, or points of friction, that impact adoption and dissemination.

4.1 Designing Adoptable Innovations

Most innovations never reach a substantial level of diffusion [71, 125]. In this section, we explore design issues that contribute to innovations being underutilized or ignored by potential adopters, and best practices for designing innovations.

Planning for Adoption. Many innovation developers focus on proving the effectiveness of their innovation, and only consider adoption at the end of their project, or not at all [75]. Having a concrete propagation plan in place early on significantly increases the likelihood of adoption, yet a study by Stanford et al. [125] found that few innovators develop this type of a plan in association with developing their innovation. Work by Henderson and others emphasizes the importance of having a good adoption strategy from the beginning [55, 71].

Successfully adopted projects often found potential users early on, and included their feedback in real time. Identifying potential users and designing the innovation with their interests in mind can be key to a successfully adopted innovation [71]. Iterative design and testing was the most commonly mentioned factor in interviews with promoters of well-adopted innovations [85]. The feedback process often uses different groups of people (instructors, students, etc.), and Froyd et al. [55] emphasizes the importance of collecting and incorporating feedback from a diverse group of faculty (including from a variety of teaching contexts such as large, research institutions; liberal arts colleges; minority-serving institutions, community colleges, etc.) when developing an innovation. These faculty can then go on to become early adopters of the project, and take on the role of champion to aid in propagation [55].

Community Building. Creating a community of practice can aid with widespread adoption of an innovation. A *community of practice* (CoP) is a group of people "who share a concern, a set of problems, or a passion about a topic, and who deepen their knowledge and expertise in this area by interacting on an ongoing basis" [135]. A particular type of teaching-focused CoPs is *faculty learning communities*, which bring together faculty and staff from across disciplines and areas of expertise to collaboratively enhance teaching and learning through seminars and activities, and community-building [18]. By creating and sustaining a transformative learning community around an innovation—as has been done by advocates of process-oriented guided inquiry learning (POGIL) [89]— or around shared values for progressive teaching, members can co-create supporting materials, assessment resources, successful case studies, best practices etc.; look for and collaborate on funding opportunities; share other pedagogical practices; and share best practices for propagation [58].

For example, Herman and others [79, 80] led a successful, institution-wide effort to increase faculty use of evidence-based innovations at a research-extensive, doctoral-degree granting university. They created small faculty learning communities, with each community focused on adding an innovation to a particular course. Each community had to include several tenure-track faculty members, and each received a grant from the institution to help implement the necessary changes in their course. They received support from their institution's center for teaching and learning, and were evaluated yearly to determine how successful they were.

Gehrke and Kezar [56] report on several large (2,500 to 7,000 members) communities of practice aimed at the adoption of educational innovations by STEM faculty. Those who participated in a community of practice on innovations—and believed in their value—reported being more able to effect departmental and institutional change. Participating faculty reported that receiving personal support from the CoP was very important to them in their efforts [56].

Similarly, Mouza et al. [101] describe a model of CoPs for teachers' professional development based on content, pedagogical strategies, and follow-up classroom support during the academic year. The authors determined that participants' empowerment was a key success factor for their success. Recent experiences have successfully built CoPs by incorporating students for the purposes of propagating innovations, such as the 2030 Agenda of the Sustainable Development, are reported by Borges et al. [15].

In the development of larger communities of practice, Scimeca et al. [119] propose a multi-stage approach that can support the networking and propagation process. This requires an initial champion to join the network, who then reaches out to and gains the participation of colleagues in the same department or primary unit. Then in the third phase, these members reach out to new colleagues in other departments and institutions, scaling the innovation nearly autonomously by engaging in what is essentially a multilevel marketing campaign. The authors identify sharing complementary and common goals among the key factors in supporting of a CoP.

Sustaining Momentum. Another important consideration is that even for successful innovations, it takes a long time to develop a critical mass of adopters. A survey of widely-adopted educational innovations in STEM found that the median adopted innovation had 15 years of propagation work and had been supported by $3.1 million USD in funding from diverse sources [84]. Hiring staff and creating a diverse group of participants is also mentioned as being helpful by successful propagators [85], and this of course also requires significant funds. When starting the development of an innovation, researchers should keep a long timeline in mind.

4.2 Convincing Faculty

In this section, we describe common issues faculty have described as being barriers to adoption, and how propagators can help support faculty in overcoming them. It is important to note that many of these barriers are self-reported by faculty, and thus reflect their perception of the barriers [73]. These perceptions can change after instructors adopt an innovation, as shown by Turpen et al. [128] in their interviews with instructors who had and had not adopted Peer Instruction (PI). They found that instructors who had adopted PI reported different difficulties and barriers than those who had not.

Awareness. One of the main methods of dissemination thus far has been telling instructors that a particular innovation is more effective than instructor-centered methods of conveying material to passive students. Recent work suggests that most faculty already know that lecture is less effective than active learning and other research-supported methods, and are aware of many specific innovations available to them [34, 36, 43, 128]. For example, Dancy and Henderson [36] surveyed 722 physics faculty and found that 87% were familiar with at least one evidence-based strategy, while only 48% were currently using one. Ebert-May et al. [43] compared faculty who had participated in a postdoc training on using evidence-based teaching practices against a control group of other faculty at the same institutions who had not gone through the program, and found that they had the same opinions towards student-centered versus instructor-focused instructional techniques. Thus, any dissemination effort likely does not need to emphasize establishing a baseline attitude against lecturing. Messaging would be better spent concentrating on the specific advantages of the particular innovation in question, using terms that faculty will find convincing.

Furthermore, education researchers who focus on the ineffectiveness of traditional methods such as lecture can cause instructors who use those methods to feel defensive, as if they are being called "bad teachers" [73]. Education researchers can be seen as dogmatic evangelists, especially when they are not responsive to the needs of the populations they profess to serve [73]. Developers should be careful in how they present their innovations to faculty, and what they say when recruiting faculty, in order to not alienate potential users.

This does not mean that proving the effectiveness of a innovation is unnecessary. As Seymour [121] points out, providing convincing proof of effectiveness is a necessary, but not sufficient, step in convincing faculty to adopt an innovation. Henderson et al. [70] found that, at least within Physics Education Research, the majority of publications that claim successful outcomes do not present strong supporting evidence, often only reporting faculty and student attitudinal data. Even studies that present more concrete evidence may be summarily dismissed by their target audience on the pretext of being inherently biased towards the new innovation [73], a perspective shared by at least some computer science faculty [8]. Propagators should therefore place more emphasis on the concerns and considerations of their target audience—a theme we will cover more thoroughly in subsection 5.1. Also, evaluation studies conducted by developers should strive to move beyond attitudinal data and, preferably, use pre-post test designs that incorporate less subjective measures for performance, engagement, attendance, etc. Such a move may enhance the credibility of these studies among STEM faculty.

Evidence strongly suggests that promoting the awareness of a specific innovation is best accomplished through word of mouth [17, 52, 55], since most faculty rarely reference or use educational academic publications when designing or adopting new teaching practices [32, 70]. Word of mouth is most convincing when it comes from faculty with strong personal and/or institutional teaching reputations [8, 83], or from faculty who work in similar institutional contexts [8, 128]. As previously discussed, Froyd et al. [55] suggest involving a variety of diverse faculty in project development, who will later provide word-of-mouth advertisement for the innovation. As an example of this, finding champions to promote an innovation has been helpful in promoting the SCALE-UP approach [52].

Propagation efforts can also involve student champions and ambassadors, whose efficacy is based on the surprisingly high level of formal and informal influence that students exert on faculty members' decisions to adopt and routinely use teaching strategies [6]. Examples in this direction range from world-wide initiatives with high school students sponsored by the Biogen Foundation [13] to experiences guided by professors or domain experts [12, 25].

Time and Effort Constraints. Faculty who have not adopted a certain innovation frequently cite the time and effort needed to adapt the innovation or to convert their courses as being the reason behind their non-adoption. Turpen et al. [128] interviewed physics instructors about using Peer Instruction (PI), and found that 57% of the instructors they interviewed mentioned the time commitment to convert to PI as a barrier to using it. Likewise, Brownell and Tanner [21] discusses time as a major barrier to biology faculty adopting research-based instructional strategies, and the inherent tension between time spent on teaching and time spent on research. Time has been cited as the largest barrier to faculty adoption by electrical and computer engineering faculty [54], physics faculty [36], engineering faculty [48], and faculty across disciplines [117].

In order to minimize faculty time and effort necessary to adopt "intrinsic motivation course conversion," Herman [78] designed the innovation so that it could take place entirely in teaching assistant-led discussion sections, requiring no changes by the faculty themselves. Sabagh and Saroyan [117] suggest a course release or reduction of service expectations for instructors trying new innovations in their classrooms. Department chairs and other administrators trying to increase faculty adoption of innovations could consider policies which reduce other duties for faculty who commit to implementing a new innovation in their classes.

Formal Training and Mentoring. The skill involved in successfully implementing a specific innovation can be a barrier for faculty adopting it. Faculty interested in adopting Inquiry-Based Learning (IBL) mentioned that their lack of skill in implementing it was a common concern, prior to taking an IBL workshop [66]. Some faculty adopting Peer Instruction reported difficulties after using it, including having issues getting students to engage with activities, and having trouble finding good in-class clicker questions [128]. Physics faculty who had not adopted any innovations mentioned lack of support from educational researchers as a key reason they had not adopted [73].

Supporting faculty during the semester in which they initially try a practice has been suggested as a best practice to combat faculty struggling with implementation [71, 73]. Hayward and Laursen [66] found higher adoption rates in a workshop that created an email list to support faculty during their first semester trying IBL than in otherwise identical workshops that did not provide ongoing support, and Derting et al. [41] cite ongoing support as one of the keys to the FIRST IV workshop's success.

Fit with Existing Practices. Robinson [115] and Rogers [116] describe how an innovation's compatibility with existing practices is an important factor in whether or not it will be adopted. As such, it is critical to understand the potential adopter's current practices, attitudes, technologies, and processes, and how one's innovation will fit with these. The easier it is for faculty to use an innovation, and the more it fits in with existing practices, the more likely faculty are to both use the practice initially and to continue using it.

Covering Sufficient Content. Faculty worry that time spent in class using innovative teaching will prevent them from "covering" as much discipline-specific content as they can using a one-way information delivery method like lecturing, especially if that content is necessary to lay a foundation of prerequisite knowledge for later courses [8]. Hayward and Laursen [66] looked at math faculty adopting Inquiry-Based Learning (IBL) and found that content coverage was instructors' biggest concern prior to implementing IBL. Froyd et al. [54] also found this to be the most commonly cited factor among Electrical and Computer Engineering faculty, with 28% of the faculty they interviewed mentioning this as a barrier to using educational innovations. Turpen et al. [128] also consider this a key concern in faculty implementing Peer Instruction.

Rethinking the idea of "coverage" can help combat this. In both Inquiry-Based Learning (IBL) and Peer Instruction (PI), the focus is on students gaining deeper knowledge on a more narrow set of subjects [66, 128]. Faculty likely will have different opinions about the utility of students having limited (and possibly incomplete) knowledge about a range of topics, compared to students knowing a smaller range of topics more thoroughly, as it relates to instructors' abilities to scaffold sequenced course content. For topics that are prerequisites for future classes, collegial discussion, and departmental buy-in and support, can be key, as adoption may require substantial curricular restructuring to adjust the topics covered in each course.

Student Resistance and Student Evaluation of Teaching. Faculty are very concerned with the possibility that a new innovation might have a negative impact on their student evaluations, especially in the first term of adoption. Hayward and Laursen [66], Turpen et al. [128], Finelli et al. [48], and Barker et al. [8] all find concerns about student resistance to instructional change (or lack of student "buy-in") to be a barrier to adoption in their instructor populations, with Hayward and Laursen [66]'s IBL instructors citing it as their single biggest barrier to adoption. One qualitative study in computer science found that students influence faculty to try out and routinely use innovations not only through formal, end-of-term course assessment surveys, but also through the inferences that faculty make from students' performance and attendance, the degree to which students look like they are paying attention, and verbal comments that (opinionated) student make [6]. This study concluded that faculty should be wary of extrapolating from only a few students' opinions when deciding to try out and routinely use an innovation; dissatisfaction among some students may not be representative of the entire class.

Seidel and Tanner [120] studied student resistance behavior towards active learning in a biology course, and argued that resistance might come from other teaching behaviors, rather than the innovation itself. They suggest a number of ways instructors can combat student resistance, including explaining to students why they are using a specific innovation, providing structure for student-to-student interactions, and giving students a forum for their concerns. These techniques, combined with clearly informing students about larger learning goals, as well as making explicit other implicit components of classroom culture like how to communicate and collaborate in acceptable ways, have been described elsewhere as "framing" the classroom, and ironically, constitute its own innovation [7, 9].

Students' roles in innovation adoption are not limited to being users and evaluators; students can act as change agents as well. In a qualitative study among computer science faculty, some faculty described adopting an innovation that they learned about from their students [6]. Cook-Sather et al. [29] suggest actively engaging students in class design when possible, in order to empower students and increase student buy-in.

Leveraging Identity. Identity is a complicated, multifaceted, situationally dependent and constructed sense of self. An instructor will probably have multiple professional identities: teacher, researcher, adviser, mentor, trend-setter in their field, campus leader, someone who is "ahead of the curve", and so on. These identities may be in tension with each other, for example if their identity as a dedicated researcher conflicts with their identity as an engaged teacher [21].

Brownell and Tanner [21] identify three ways in which professional identity works against instructors adopting new innovations: (1) graduate school training focuses on research rather than teaching, (2) scientists are afraid to identify as teachers, and (3) professional culture considers teaching to be lower status than research. They suggest that cultural change to address these factors is necessary before broad adoption of pedagogical innovations is possible.

At a fundamental level, faculty are persuaded to change through positive social experiences, which means change agents must leverage what is important to their audience. One way to appeal to an instructor's identity as a researcher to adopt a new pedagogy is for them to have the opportunity to publish about their experience implementing the innovation [21]. Another way is for instructors to present at conferences [56], or have opportunities for funding. A final way is to become part of a faculty learning community or community of practice [31, 135].

Other Resources. A prominent popular press book on creating change is *Switch: How to Change When Change is Hard* [68]. Probably the most useful construct is the metaphor of the Elephant and the Rider, first introduced by Haidt [65]. The rider represents our rational, conscious selves, while the elephant represents our subconscious, irrational side and our unconscious habits. The rider, the rational self, can orchestrate decisions, but ultimately our habits and predilections must also be appeased for sustained change to occur. Consequently, a lesson from this research is that faculty may not be convinced solely by cold, hard facts, but also through rich narratives and experiences, and through positive social pressure and encouragement. This model also explains aspects of propagation such as the need to provide support during adoption and the importance of an emotional appeals in combination with evidence of the innovation's effectiveness.

The interested reader is also encouraged to examine the book by Henderson et al. [71] on designing educational innovations for propagation. It is not a broad literature survey, but gives recommendations based on their work (which we also cite and discuss here).

4.3 Institutional Support

Institutional support can be key to helping faculty feel more comfortable when adopting new innovations. This can include colleagues and administrators offering technical support and social approval for innovative teaching, rewarding experimental teaching in promotion and tenure decisions, or providing the type of classroom formats that are needed to be able to use the desired innovation. For certain innovations, Wieman et al. [136] argue that the department, not the individual, is the most likely unit of change, so getting overall buy-in is very important to changing the culture. This is especially necessary with resource-intensive projects such as the one Weiman and colleagues reported on, which hired professionals to train faculty in a department and to support the redevelopment of courses. Likewise, the SCALE-UP project, which required using special classrooms, reported that administrative support was the most important factor in successful implementations [51]. Cuban [33] argues that widespread reform in teaching is not possible given the emphasis on research in modern universities, and offers histories of reform attempts in two departments at Stanford as evidence. The Association of American Universities recommends cultural change to support innovation in teaching at all levels of academia, including the department, the university, and across the discipline [108]. Finelli et al. [47] developed an administrative change plan to gain administrative support for faculty using innovations, including creating faculty personas representing the needs of faculty at different stages of adoption.

Promotion and Tenure Considerations. Tenure pressures can preemptively prevent pre-tenure (a.k.a. tenure-track) faculty from trying innovations if they have both teaching and research responsibilities. Faculty from a variety of disciplines have reported that even when their review committees communicated that teaching and research productivities would be afforded equal (or similar) consideration in tenuring and promotion decisions, in practice a greater emphasis was given to research activities [62, 76, 92]. As graduate students and junior faculty, faculty are trained in research processes and enculturated to base their understanding of professional identity on research prowess; little, if any, attention or importance are given to the knowledge and skills that faculty must learn to become competent educators [21]. Consequently, faculty are more likely to devote disproportionate time, energy, and attention to their research in order to, from their perspective, accrue status in the profession [21]. More concerning, very few faculty are able to be highly productive in both research and teaching, especially if their teaching involves adopting evidence-based practices [44]. When the reward system privileges research, there are fewer systemic-level incentives for junior faculty to adopt new teaching; by the time faculty are tenured, they may have developed habits and curriculum that make change much more difficult.

In addition to the overvaluation of research in higher education (and perhaps because of it), many departments lack clearly defined, robust standards for assessing and rewarding teaching performance and outcomes [61, 76, 128]. Rather than holistically examining teaching behaviors and their outcomes on learning and engagement, and rather than conducting formative assessment in which faculty are given advice and opportunities for iterative improvement, teaching evaluations are often based exclusively on end-of-term student surveys. The importance of these surveys for tenure cases makes students' opinions of innovations especially important for pre-tenure professors [48]. Instructors are highly sensitive to the fact that even a successful innovation can result in lower course evaluations for the first term it is used, due to implementation difficulties [6]. Furthermore, limited time and resources often constrain faculty from trying new innovations, because the time required to learn about and apply innovative teaching practices is seen by faculty as reducing research productivity [113].

Seymour [121] discusses at length the need for different means of evaluation, focusing on student learning gains, in order to successfully propagate effective STEM teaching. Both Seymour [121] and Brownell and Tanner [21] call for teaching to be weighed more heavily in tenure decisions, for departments to reward experimentation with teaching, and for more holistic assessment of teaching, focusing on iterative improvement and moving beyond student evaluations.

Colleagues as Change Agents. An instructor's choice to adopt an innovation is highly situational. A potential adopter will want to know not only that an innovation works in general, but also that it works for their particular type of students and for their specific class or classes [128]. As such, their colleagues are poised to be able to make the most convincing arguments that an innovation will work, as they have the most experience working in the same context.

Borrego et al. [17] found that "word of mouth," or verbal recommendations made between colleagues, is the way most department chairs find out about educational innovations. Likewise Foote et al. [52] report that most instructors who adopted SCALE-UP, an active learning environment for undergraduates, learned about it from colleagues. In fact, research indicates that faculty recommendations for an innovation increase adoption among their peers [38, 61, 72]. However, crafting suitable, supportive messages are important. One study found that in interviews, CS faculty lamented how difficult they felt it was to convince even one other person in their departments to adopt an innovation or to support change [107]. Another study found that the key to overcoming resistance and achieving successful propagation was for change agents to provide positive encouragement and support, rather than peer pressure or coercion [113]. The NETI workshops, for example, specifically train participants not only to implement research-based practices, but to become effective change agents within their institutions [45]. Physics faculty who had adopted Peer Instruction frequently mentioned colleagues in their department who had provided guidance, support, or teaching materials [128]. Since difficulties with implementation can be a critical issue to faculty, having a local faculty member who can support and mentor them is valuable. More formalized support communities, formed around small groups of instructors, have also been successful in fostering the use of innovations among engineering faculty across a number of courses [79, 80]. Henderson et al. [69] suggest co-teaching as an effective way to expose new faculty to innovations and to convince potential users of their effectiveness *in situ*. First identifying sympathetic potential users to approach is important; Quardokus and Henderson [112] suggest using social network analysis to determine which faculty members have strong reputations and dense social connections, so that they can be targeted within a department to best affect overall adoption.

Infrastructure Issues. Institutional issues such as class size, physical layout of classrooms, and course scheduling can all present barriers for faculty. In interviews conducted by Turpen et al. [128], 31% of instructors mentioned class size as a barrier to adoption, 31% mentioned lack of an appropriate classroom, and 17% mentioned course scheduling issues. Likewise in faculty interviews by Finelli et al. [48], 8 of 26 faculty mentioned physical class space as a barrier, and 3 mentioned class size. Foote et al. [52] found that among faculty who use SCALE-UP, those with a classroom designed to support it spent more time doing activities with their students, while faculty who did not have such a classroom spent more time lecturing. The choice of classroom in which a course is scheduled, which instructional technology is provided to an instructor, when a class is scheduled, and a wide variety of other affordances are frequently controlled by the department or institution.

For innovation designers, this means that departmental support becomes more important the more requirements an innovation has, e.g., if it requires a specific technology, an unusual amount of time, extra or specially trained teaching assistants, etc.

4.4 Fidelity of Implementation

A major challenge to successful propagation is ensuring that the features essential for an innovation's success are identified in its description. The term(s) used to define or describe an innovation may mean different things to different faculty, and faculty frequently modify or exclude components of the instructional practice as they adopt it [16, 36, 52, 57, 73, 74, 124]. For example, Turpen et al. [128] observed six professors who self-reported using Peer Instruction in physics and found that there were substantial differences between faculty in how they implemented PI, and between how instructors' implemented PI and the classical description of the innovation as prescribed by the innovation's developer. Specifically, none of the observed professors included a phase for individual students to answer a question, a component of PI that Vickrey et al. [133] determined was of paramount importance to the effectiveness of the innovation.

Consequently, low-fidelity implementations may not achieve the same benefits or successes as the original innovation. Andrews et al. [4] measured student learning in 29 biology classes teaching natural selection, and found no correlation between active learning activities and student learning. However, they did find correlations between student learning, instructors' explanations of why misconceptions are incorrect, and instructors' use of active-learning exercises to make a substantial effort toward changing misconceptions. This indicates that instructors may need specific guidance in how to properly use innovations, and what aspects of an innovation are okay to modify and what must be left as-is.

Additionally, the issue of fidelity has implications for evaluating new innovations. Stains and Vickrey [124] argue that in order to measure how widely an innovation is used, evaluators must not just accept instructors' self-reports of using a specific technique. Instead, evaluators should develop a rubric of components to assess the innovation's Fidelity of Implementation (FOI). Walter et al. [134] designed and validated a survey aimed at measuring faculty use of innovations while avoiding instructor self-report bias. Borrego et al. [16] reports a first step towards understanding how closely faculty adhere to prescribed instructions for 11 major research-based instructional strategies; unsurprisingly, the fewer components an innovation has, the higher the fidelity of implementation.

5 COMPUTER SCIENCE COMPARED TO STEM

Now we turn the discussion to research that has been conducted in computer science contexts specifically. We answer two questions: how well do these results about propagating educational innovations in other STEM disciplines apply to CS? And second, what additional considerations apply specifically to CS?

5.1 Similarities between CS and STEM

There appears to have been relatively less research on the propagation of educational innovations in computer science compared to other STEM disciplines, but overall, findings seem to be similar. In this section, we review empirical studies conducted within CS higher education contexts.

Ni [106] conducted a study of CS instructors who attended pedagogy workshops; findings showed that believing whether or not an innovation was effective was not, by itself, a significant predictor of faculty adoption decisions. The best predictor was faculty excitement about the innovation, indicating a willingness to overcome barriers to adoption. Later interviews by Ni et al. [107] identified instructors' main barriers to adoption as needing to convince a colleague to change as well, concerns about students' backgrounds and preparation, and the effect of being able to adequately prepare students for other courses.

An earlier ITiCSE working group [104] investigated the propagation of program visualization tools among CS faculty and found that a large majority of respondents reported that the time required to adopt such a tool was a barrier to adoption. Notably, in addition to the time to learn to use the tool and to adapt it to their particular circumstance, the most frequently cited challenge was the time required to find good examples to use in class, a challenge that developers could potential mitigate for potential users. This working group also suggested that evaluations of educational innovations need to include a component focused on the adopting instructor's experiences, along with the impact on student learning.

Fossati and Guzdial [53] interviewed 14 CS instructors from primarily large research institutions in the U.S. about changes that they had successfully and unsuccessfully implemented. The authors found that faculty members' decisions to change their teaching predominantly followed an intuitive process, that begins with faculty identifying a problem such as wanting to engage the whole class, increasing student collaboration, use authentic assignments with real-world data, etc. Evidence that triggered change was typically informal, most commonly involving discussions with students and anecdotal reports, and/or reflections or intuitions by the instructor. Some faculty expressed that "there is an explicit need for constant change in teaching Computer Science". Research evidence was uncommon throughout the process. Implementation failures were often a result of context: ideas did not necessarily transition well between different courses, different groups/backgrounds of students, or other existing teaching strategies.

In interviews and focus groups with 66 CS faculty from a wide range of institutional contexts, Barker, Hovey, and Gruning [8] found that faculty often adopted a new teaching practice in order to solve perceived problem with student learning or engagement, or to support student diversity. CS faculty learned about innovations they later tried from attending conferences like SIGCSE, ASEE, FIE, ITiCSE, and the NCWIT Summit; through conversations with colleagues and role models when discussing problems they encountered; or from seeking materials and advice while designing new course preps. Faculty weighed the costs and benefits not only for themselves (time, energy, ability to cover material, etc.), but also (and especially) for their students. In fact, a related paper based on the same dataset found that multiple forms of formal and informal student feedback heavily influence faculty's decisions to adopt and routinely use an innovation [6]. In Barker et al. [8], the authors reported that institutions influence adoption through tenure and promotion considerations, providing infrastructure, and through departmental culture, as constructed by the perceived attitudes of one's peers. The degree to which these institutional features were supportive or inhibitive of adoption varied by institutional type (research institutions versus small teaching colleges, etc.).

To investigate the prevalence of these themes throughout the field of CS eduction (at least in the U.S.), Hovey, Barker, and colleagues [82, 83] then conducted a survey of 821 computer science educators from approximately 595 institutions. Among the 72% of respondents who reported having tried a new teaching practice for a specific class, over 90% agreed or strongly agreed that their decision was motivated by considerations for students' understanding of content, engagement, and/or performance. Stressing an innovation's direct benefits for students' learning, growth, and participation in class is therefore likely to persuade more faculty than explaining its direct, personal benefit to faculty themselves.

The authors [83] also found that "fit" with how faculty believe students learn (e.g., implicit theories of learning and intelligence), "fit" with existing resources, and having the necessary knowledge about how to implement the innovation (i.e., knowledge about the requisite logistics and resources) were also important for over 80 percent of respondents (per survey item, not across cases). Fifty-nine percent agreed or strongly agreed that wanting to be more inclusive of diverse and underrepresented students factored into their adoption decision. Depending on the specific type of innovation, speaking to faculty members' interest in promoting diversity and students' social skills is likely to encourage faculty with these interests to try innovations specifically intended to improve students' course experiences [81].

Hovey et al. [83] also found that CS faculty learned of an innovation they later adopted primarily through presentations/workshops (40%) and in conversations with another faculty member (38%), and in some cases, through research, popular or blog-based media, or other publications (16%). Presenter/author's reputation for teaching, as well as that of their home institution, and the similarity of the teaching context (institution and student type), were influential aspects that encouraged faculty to try the innovation in most cases, whereas the reputation for research among the presenter or their institution were less important. Propagators will likely be more successful if they can secure a champion to advocate for the use of the teaching practice who is a notable, highly regarded CS educator from a highly reputable college or university known for the quality of its undergraduate education.

Hovey et al. [83] also asked faculty about an innovation they have not (yet) tried. Similar to studies in other STEM disciplines, responses indicate that not having enough time was the strongest inhibitor of adopting the specific practice. Other common reasons included satisfaction with current teaching methods, and unfamiliarity with or lack of access to the necessary resources and logistics. Less than a quarter of respondents faced problems with physical class setups, and surprisingly, less than 10 percent agreed to some level that tenure concerns played a role in their having not (yet) tried an innovation (even when controlling for tenure status and attitudes towards the importance of teaching or research in tenuring decisions [81]).

Other studies in CS have found that instructors consistently change the materials that they adopt (i.e., adapt them) to suit their specific circumstances [46, 91], and that CS faculty also tend to teach using the same approaches they experienced as students [95]. A study by Levy and Ben-Ari [94] looked at computing instructors who had been exposed to an innovation—in this case, a visualization tool— when they were learning content themselves, and found that many instructors used it in their own courses in a similar fashion. However, they also found some instructors were resistant to doing so, even when requested. These observations have been made in studies of non-CS STEM faculty as well [16].

Overall, this growing body of literature indicates that many of the lessons found across STEM education are applicable to the CS context. However, further studies within the discipline are suggested in order to establish stronger validity for these connections and to expand findings. For example, we were unable to find research on CS faculty adoption that employed either quasi-experimental, experimental, or pre-post test study designs. Similarly, while a plethora of studies exist that advocate using a certain innovative teaching practice in CS education, we were unable to find many studies that could help to establish a baseline on the diffusion of a single teaching practice throughout CS higher education, much less assess the diffusion of the gamut of teaching practices used in CS courses. Of the two recent research projects we were able to locate, Grissom et al. [63, 64] found that CS faculty were likely to classify their teaching as *both* student- and instructor-centered, although the frequencies for specific practices used in the PIPS survey instrument were not provided, and the data is attitudinal. The other study was conducted by Hovey et al. [82] in conjunction with the adoption study previously described in this section; they found that when contextualized by a specific, lower-division course each respondent had taught recently, most CS faculty self-reported using lecturing more frequently than any of the other practices and tools. But, faculty also reported having used at least one of the student-centered practices in one or more class sessions during that semester. While this study provides a preliminary indication of the state of the field of CS education, the set of items used in their survey was limited to just 11 practices and tools and usage was constrained to a single, lower-division course by the survey prompt (to increase validity). These limitations mean that this study omits upper division or advanced CS courses (which may have smaller class sizes), and it excludes many, many commonly used instructional choices. Therefore, surveying more computing faculty with a more comprehensive "practices" inventory, and surveying the same faculty in regular intervals, is highly recommended. Without studies of this nature, it is difficult to assess how well specific innovations diffuse through CS education over time.

The existence of similarities between adoption studies in CS and in other STEM disciplines does not necessarily mean there are not specific features inherent to CS that may uniquely impact propagation efforts. Researchers have cautioned that faculty and developers wishing to promote an innovation in a higher education discipline need to be aware of potentially idiosyncratic features of that field [61, 102], and computer science is no exception. The following subsections describe some of these features, and the opportunities and challenges they offer for propagating educational innovations in CS.

5.2 Diversity of Programming Languages

One feature that sets CS apart from other disciplines is the use of different programming languages by different faculty and different institutions, which has been identified as a barrier to adoption [106]. This characteristic is potentially relevant to many innovations since it changes how the material is presented to students, what they create, and how they can be evaluated. Language adaptability is most important in low-level courses, when students are mono-lingual and their knowledge of programming is extremely brittle. The language issue is thus related to another potential difference between CS and many other STEM fields: students cannot be assumed to have had exposure to the subject before college. As loose evidence of this, in the U.S. in 2018, approximately 65,000 students took the Advanced Placement® (AP) exam for "Computer Science A," compared to an approximate 171,000 students who took the exam for "Physics 1" and 260,000 students who sat the exam for "Biology" [14]. Therefore, students' first exposure to a programming language is important, and using that language for more than one course is important so that students can scaffold knowledge off existing mental constructs without being bogged down in the extraneous cognitive load of having to learn a new language.

In principle, it is generally possible to translate between programming languages, but adapting materials that were developed in a different language is a barrier to adoption since it requires additional work on the part of adopters. For example, adapting a series of Process-Oriented Guided Inquiry Learning (POGIL) exercises from Python into Java will take time to rewrite the code, which may deter faculty from trying the exercises. To mitigate the language issue, change agents can provide materials in different languages, but doing so is challenging given the variety of languages in use at different institutions [122]. It may be helpful to prepare materials in a format that facilitates the automatic generation of different versions (e.g. [28]).

5.3 Rapid Evolution of Content

Related to programming languages, computer science is somewhat different from many other STEM fields due to the relatively fast evolution of our course content, as it adapts to technological developments. Artificial intelligence and cybersecurity, for example, have become much more prominent in computing programs in recent years, in some cases even becoming their own concentrations within degree-granting institutions. Speedy evolution of content can be positive for change agents promoting curricular change, because our professional organizations release new curricular recommendations (e.g. [118]) fairly frequently based on innovations within computing. If pedagogical and curricular innovations are incorporated into these recommendations, it potentially sparks changes at many different institutions. This change strategy was recently used for parallel computing [23] and programming languages [3]. However, a limitation of this approach is its regional restriction: although ACM and ABET are both international organizations, most of the impact of their curricular recommendations is currently in the United States. Furthermore, there is some risk of associating specific pedagogical and curricular techniques with accrediting organizations: recommendations may feel like tacit mandates, which could discourage further innovation and may also spark resistance in the name of academic freedom.

Even without an innovation being directly incorporated into new curricular recommendations, curricular and technology changes mean that instructors need to update their courses, and they may include pedagogical innovations while making these updates. One example is the Objects-First paradigm for CS 1, which was supported by the rise of object-oriented programming. Objects-First is the only well-propagated, content-based innovation identified in a cross-disciplinary study out of 43 well-propagated educational innovations [84]. This suggests that content-based innovations are hard to disseminate, but that the fast evolution of CS can provide an advantage over some other fields.

On the other hand, the fast evolution of CS, combined with its relative youth as a discipline, can also cause barriers to propagation. The resulting churn in content requires faculty energy, which has the potential to distract from other kinds of changes. In addition, it has led to a lack of consensus about the topics covered in each course [110]. This prevents change agents from being able to target a specific course. It also increases the burden on potential adopters to change other parts of their curriculum or adapt an innovation in order to adopt it. While consistency among courses from different institutions is a broad goal, there are ways to address it. Accreditation bodies such as ABET and professional groups like the ACM can leverage their power to make specific curricular recommendations. Additionally, widespread use of Concept Inventories can lead to more agreement on course content. *Concept Inventories* (CIs) are multiple choice exams designed to cover core concepts of a course [59]: they are designed to be broad enough that any student taking the course at any institution can successfully pass the CI for that topical area [1]. Part of CI development is working with instructors to develop a broad consensus on the learning goals, topics, and essential concepts for a particular course [1]. This information, and the test itself, can promote consistency in course design across institutions. While there are currently few CIs written for CS, the number available is growing [126]; for example, learning goals have already been made for CS1 [59] and CS2 [110].

5.4 The Geek Gene

Another, somewhat unique feature of CS is the prevalence of faculty who implicitly ascribe to a theory of innate intelligence. Evidence indicates that many computer science educators believe that there is some sort of "geek gene" genius—an unteachable talent—that is necessary for students to succeed in computing [93, 97]. Despite research that has problematized [114] and debunked [2, 109] the evidence on which this "instructional folklore" is largely based (bimodal grade distributions), and despite research that supports the alternative "growth mindset" model that shows students' intelligence increases through persistent effort [19, 35, 42, 100], some faculty continue to believe that a certain, irreducible percentage of students are inherently unable to learn how to code, no matter what the educator does. As a result, these faculty may be disincentivized to invest time, resources, and effort into adopting innovative teaching methods, in part because the underlying logic behind many innovations is, implicitly, based on the growth mindset framework.

While this phenomenon is not isolated to CS, it is more pronounced in CS than in many other STEM disciplines. As shown in Figure 4, research by Leslie et al. [93] among U.S. academics indicates that relative to those in other STEM fields, computer scientist instructors are more likely to believe in "field-specific abilities," or the idea that innate brilliance is prerequisite for success in the discipline. Field-specific abilities are operationalized through four themes such as the opinion that being an elite scholar in the discipline "requires special aptitude that just can't be taught," and scores are the average of responses for personal agreement and the level of agreement they anticipate other people in their field would give. Evidence suggests that CS academics are more inclined to believe in an innate theory of intelligence than fields with higher levels of gender and racial parity, thus establishing links between fixed mindsets and women's and minorities' underrepresentation in CS [93, 103]. Faculty who believe in innate intelligence are likely to transmit that implicit theory to students, which research suggests can contribute to a defensive classroom climate, students' lowered self-esteem and helplessness in the face of challenges [103], and the triggering of stereotype threats for underrepresented students [5], especially among those students who are only moderately domain-identifying [105].

Some propagation strategies may be able to avoid friction with innate intelligence believers if messages focus on relative advantages to the faculty member (e.g., time or cost savings, interesting change-of-pace, etc.), and pay less attention to benefits to students. However, convincing faculty to adopt innovations may require addressing their erroneous beliefs in order to create an emergent, innovation-supportive ecosystem and shared vision (previously discussed in subsection 3.2). On an individual level, engaging a peer in interpersonal conversation, in which one patiently asks questions using non-confrontational language, can help guide an innate intelligence believer through a self-discovery process to critically reflect on the implicit foundations for why he or she believes in innate abilities, and to help that person understand how preexisting assumptions about students influence teaching behaviors and student outcomes [97]. More systemic approaches, advocated for by the National Center for Women and Information Technology (NCWIT) Extension Services for Undergraduate Programs (ES-UP), include presenting evidence to the department, inviting guest speakers to talk about growth mindset, and offering in-house workshops or seminars on learning theories for faculty development. While these strategies carry interpersonal and political risks, addressing fixed mindsets is essential to achieving critical mass of student-centered teaching throughout CS.

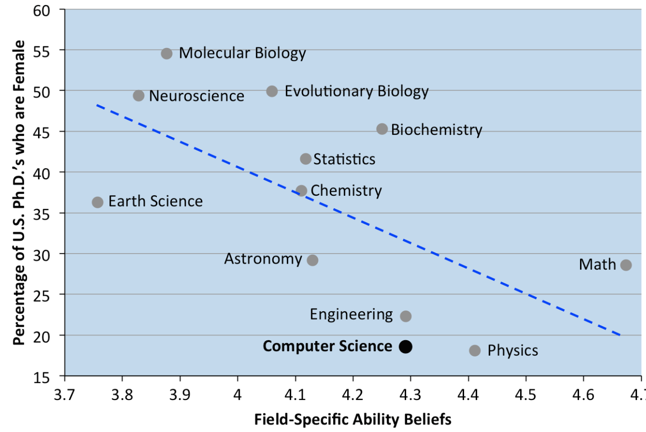

Figure 4: Belief in the fixed mindset ("field-specific ability beliefs") and gender representation among academics by STEM discipline, adapted from Leslie et al. [93], p.263. Higher numbers along the x-axis represent stronger beliefs that success in the discipline requires innate talent, rather than hard work.

5.5 Enrollment Trends

Despite the fluidity of our field, the CS education community often has strong agreement in identifying our most important problems, which are often related to student recruitment, enrollment, performance, and retention. The main motivation for innovation a decade ago was a desire to attract and retain students [107]. Now, the main motivations are to attract and retain members of underrepresented groups, to increase accessibility [77], and to manage booming enrollments [26, 27]. This feature of CS impacts dissemination efforts. In interviews [8] and surveys [83], some CS faculty have mentioned that their desire to improve inclusion and diversity within computer science was a motivation for trying new teaching innovations. This drive may not have the same immediacy or weight in most other disciplines, given that CS undergraduate programs in the U.S. have among the lowest concentrations of women and non-White, non-Asian students [129, 130].

Being aware of the current "important problems" can potentially be helpful if an innovation can be framed as a solution to one of them. Enrollment problems are pressing at many institutions, and many faculty are looking for ways to teach larger classes effectively. These faculty may be more receptive to an innovation if they can be convinced that the innovation overcomes an issue with larger class sizes, for example if students look bored or are not coming to class [83]. However, the gravity of these major trends may negatively impact faculty receptiveness to innovations related to other issues, since the "big issue" problems can divert a lot of time and attention.

The current boom in undergraduate CS enrollment is creating a propagation opportunity because so many departments are hiring new instructors [27]. Many of these new faculty are likely to not have preexisting course preps for their new classes, and to have not become entrenched in their teaching habits, so their switching cost to adopt various educational innovations is lower. Research has shown that professional development has greater effect on new instructors' teaching practices than those of more established instructors [43], and that new faculty will subsequently continue to use what they learned [41]. In addition to being easier to change, new faculty potentially offer greater impact for propagation efforts since they are at the beginning of their careers and will thus be able to use innovations for a longer time.

Another CS-specific trend that increases the number of instructors new to CS is the growing recognition of how computing is vital in other disciplines. This appears at the pre-college level in programs such as CS4All (http://www.cs4all.io/) and in universities through CS+X degree programs (i.e. major in computer science plus a related discipline, such as biology or psychology). These trends mean that not only are there more (interdisciplinary) students in CS courses, but also that instructors in other disciplines are now having to cover computing topics. These faculty are not necessarily new to teaching *per se*, but being new to the subject (content area) means they may be more receptive to new innovations related to teaching CS material [95].

5.6 Split Conference Venues

Compared to other disciplines, although the CS education community has a measure of cohesion in terms of focus, it is also fragmented by our conference structure. CS does not have a single, comprehensive conference for the entire field, unlike some other STEM disciplines such as the American Chemical Society (ACS) or the Joint Mathematics Meetings (JMM). Instead, each research area has its own conferences—CS education, for example, has specific conferences such as ITiCSE, SIGCSE, and ICER.

This loosely-coupled structure makes it difficult or impossible for some faculty to attend education-oriented talks, and it fragments the CS community by topical area. Faculty who have limited resources for professional development may skip educational conferences in order to attend research-focused conferences. CS education conferences are geographically separate from other topical CS conferences—effectively siloing education from other CS research—so faculty must choose between types of conferences they want to attend, and not only where to present their work, but also what kind of work they can do. Furthermore, conferences may be unaffordable for faculty who work at institutions that are underfunded or have strained resources, which tend to be institutions that serve minorities and economically vulnerable populations [20].

One current solution is to co-locate education with technical conferences. In other words, exposure to innovative teaching can be accomplished by holding education sessions in the same location as topical or regional research conferences, such as the Usenix Workshop on Advances in Security Education (ASE), which is co-located with Usenix Security. However, while co-locating is a partial solution, it may not be feasible for general techniques: for example, it is unclear where pedagogies such as Peer Instruction or POGIL could be presented. In addition, not every area has an education-related workshop; we are not aware of one for algorithms or theory, for example.

5.7 Online Distribution of Innovations

An increasingly common method for sharing or finding CS education innovations is through online distribution. Several studies have looked at increasing the usefulness of online repositories in CS [46, 91]. The ability to search by topic and the inclusion of different versions of materials are important features [46]. Some publicly available repositories accept open submissions and offer peer-reviewed materials, such as EngageCSEdu (https://www.engage-csedu.org/). Publicly-funded innovations are also often distributed though portals run by the funding agency, such as Scientix (www.scientix.eu) in the European Community (EC) and Ensemble (www.computingportal.org/) in the United States. Both of these projects support and nurture a community of practice, the heart of which is composed of teachers, professors, and educators, with the involvement of professionals, stakeholders, and policymakers to support the whole community in promoting innovative learning resources, pedagogical approaches, and technological and communications tools. Sponsored websites of this nature typically have higher visibility than innovator self-run websites, and can provide features such as searchability, and at least in Scientix, translation services for any of the languages spoken inside the EC, which can overcome language barriers.

6 SUMMARY OF BEST PRACTICES: A GUIDE FOR INNOVATORS

Here we summarize the lessons gleaned from the existing literature, and provide some guidance to innovators and champions who wish to propagate an innovation. This is not exhaustive, but collects the most critical points of friction and potential solutions.

Plan for propagation. It is important to consider how an innovation may be propagated from the outset of its development. For instance, consider how evidence for the value of the innovation will be collected, and keep in mind that while strong evidence for the effectiveness of the innovation is not the only factor that will influence its adoption, it is still important to evaluate the innovation and publish the evidence. However, simply publishing about the innovation in conferences and on project web sites is not sufficient to promote adoption—active and interactive forms of dissemination will be required, including workshops with strong follow-up, personal contacts, and the like. As the innovation is being developed, consider who can, and will, be potential adopters. What needs do they have? Developing an innovation based on the needs of a particular set of faculty and students at one institution may not fill the needs of a wider community, particularly in CS where curricula, programming languages, and technologies are not standardized. It is critical to involve target users early in the innovation's development: getting feedback and iterating on the form of the innovation will help make it valuable to a wider variety of practitioners.

Plan for adoption and adaptation during development. Be aware that faculty will want to, and need to, adapt the innovation for use in their particular context. (We believe this is especially true for curricular and technological innovations.) Consider including some commonly-expected adaptations in the scope of the innovation, but also create materials that allow for further adaptation and provide guidance on what aspects are essential to the innovation's effectiveness. It may not be possible to study what specific facets of the innovation lead to effectiveness in the classroom, but give as much guidance as possible to potential adopters so that they do not accidentally "adapt-out" necessary features.

Identify receptive faculty and speak to their needs. Most CS faculty are interested in improving their teaching, and are not opposed to trying a new innovation. As such, it is not necessary to convince them to change their current teaching mode by bringing to attention their current teaching; this approach may in fact be counterproductive. Instead, address faculty members' interests. The biggest concern is usually the time and effort required to integrate a given innovation into their current set of practices, and the strongest motivator for most CS faculty is how the innovation will positively influence their students' learning and engagement. Work with potential adopters to see how the innovation may speak to their particular needs, and assist them with its integration into their teaching. Faculty may be early adopters who are more willing to jump on board, or may be a bit more skeptical and want to see more evidence of past success. In the beginning, propagation efforts should focus on those who are most receptive, but use an innovation's early successes to build the case for it.

Support faculty during adoption. Faculty will need the most support during the term(s) when they first use the innovation in their course. Make sure to be available for discussions with them during their preparation and course delivery. As the project scales, this support should come from others beyond the creator(s) of the innovation, ideally from a community of early adopters. A healthy community can also help sustain a project beyond the initial excitement and funding.

Involve diverse champions. When recruiting adopters, try to reach out to different communities. A diverse group of early adopters can become champions of the innovation in their own communities, whether it is a particular department, type of institution, or other existing communities of practice. Faculty with strong reputations for teaching are likely to be particularly persuasive for others. Students can also be successful champions and ambassadors for your work. A healthy community of diverse champions can help with recruiting more adopters, and with providing support to new adopters by champions who are better able to understand the situation in which new adopters find themselves.

Intentionally craft persuasive messages. Design the messages and marketing associated with promoting your innovation to address the concerns and considerations of your target audience(s). Thoughtfully crafting "selling points" champions can use about the benefits of the innovation regarding student learning, performance, and engagement are likely to be particularly persuasive, but it is also important to ask questions and then explain how the innovation fits in with potential adopter's existing practices and implicit (or hopefully, explicit) theories of student learning and intelligence. It may be necessary to encourage emergent change among faculty by letting them dabble in aspects of an innovation, or by supporting them in trying less time- or energy-intensive innovations, before they are ready to try your innovation. It may also be necessary to guide potential adopters through self-exploration in order to first establish a foundation of innovation- and diversity-supportive theories and mindsets.

Get institutional buy-in. Faculty do not work in isolation, but rather within a departmental and university ecosystem. Incorporating an educational innovation requires significant effort that will take time away from other activities. It is therefore important to engage administrators (department chairs and deans) to see the value in this effort, ideally including it in mission and values statements, plans of work, evaluations, and/or the tenure process. This can be done in different ways depending on the circumstances. If a potential adopter has been identified, the innovator can work with them to engage their administrators. Alternatively, an innovator can work through department chairs to get support and identify faculty, for example, to lead or attend a workshop.

Consider what resources will be needed. Getting an innovation widely adopted will take a significant amount of time and effort. Even if a research grant is obtained to create the innovation and perform initial studies, this generally only gets you to the point of a very small number of adopters, if any. Continuing the project will require additional resources. This may take the form of a project team member (perhaps staff or a student) dedicated to maintaining web sites and coordinating with the community, travel funding to facilitate workshops at conferences and universities, resources for updating materials and potentially for conducting ongoing studies, etc. Some of these may be achieved with small amounts of funding and it is important to keep supporting new adopters. Without continued effort, further adoption is unlikely.

7 DISCUSSION

Many of the challenges to adoption of educational innovations are difficult to overcome, especially by a single team of developers. Overall changes to the culture of the field, including more study of the current state of educational innovations specifically in CS, would require significant time and effort, but could have valuable results.

The findings of this paper have relied on a review of the substantial literature in adoption of innovations in higher education, but much of this work has been done in other STEM fields. While many facets of this work likely transfer into CS, some may not. Comprehensive studies of adoption specific to CS would be very helpful. This could involve additional surveys of instructors about current practice and barriers to adoption, as well as meta-analyses of papers written about adoption. A previous meta-analysis of SIGCSE papers as a whole was performed in 2004 [131], but the field of CS education research has changed a great deal in the intervening years, and a new analysis may yield valuable results.

Of course, some barriers to adoption are systematic in nature, and therefore require a system-level approach to change. As discussed above, possible changes include providing better incentive structures for faculty to adopt new evidence-based practices, acknowledging both the time spent doing so and their value to an institution's educational mission, and fostering faculty learning communities that build both capacity and an emergent supportive culture for innovative teaching. In addition, effective propagation, of either one's own innovation or an adopted innovation, takes a significant effort that is not often recognized. While this is to some degree a problem unique to each university, there may be top-down strategies to drive change through accreditation agencies and professional societies. While we have addressed some considerations in this paper regarding systemic change, our review on this matter is far from comprehensive. We strongly advocate for more studies, including a summary of existing literature within CS contexts specifically.

For educational researchers and developers, it may also be the case that in order to appropriately motivate instructors in both adoption and propagation, there needs to be ways to measure effort and results. For example, if an innovator wants to claim success in terms of their innovation being adopted, what counts as successful adoption? We suggest that success can be thought of in terms of scaling, sustainability, and fidelity of implementation. Other metrics are possible, and different metrics may apply for propagators and adopters. Educational researchers should consider how to create common assessments for innovation, and also implement more studies to track the dissemination of innovations in CS education.

Finally, we note that in other STEM disciplines, there is a significant presence of science education researchers embedded within the discipline. This does not (yet) appear to be the case in CS. Promoting the idea of CS education research as an important field of study, and integrating such researchers into CS departments could go a long way toward helping all CS programs develop and sustainably use better educational practices [30].

8 CONCLUSION

In order for Computer Science researchers to get their innovations used in classrooms, we must move beyond a dissemination model that considers publishing attitudinal results or holding a workshop to be sufficient [55, 71, 125]. Researchers must consider how educators will use their innovation from the inception of its development, design for ease of adoption, and develop long-term support models for adopters [55, 71]. Moreover, if we want to be a discipline that supports effective teaching, we must create support for faculty to try new teaching methods at all levels, within our departments and our discipline as a whole [21, 108, 121].

ACKNOWLEDGEMENTS

We thank the working group coordinators and the anonymous reviewers for their valuable suggestions for improving this article. This work was partially supported by a grant to Knox College from the Mellon Foundation, and through financial support from the National Center for Women and Information Technology (NCWIT) The last author acknowledges financial support from a Fellowship for Innovation in Digital Higher Education by the state of North Rhine-Westphalia, Germany, and the Stifterverband.

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